Cost, time and environmental impacts of the construction of the new NMIT Arts and Media building

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Cost, time and environmental impacts of the construction of the new NMIT Arts and Media building.

A report written under contract to the New Zealand Ministry of Agriculture and Forestry

Lead author:

Stephen John	University of Canterbury

Assistant authors:

Kerry Mulligan	University of Canterbury
Nicolas Perez	University of Canterbury
Simon Love	ScionResearch
Ian Page	BRANZ

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Department of Civil and Natural Resources Engineering

University of Canterbury

Christchurch, New Zealand

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- Carl Devereux (Aurecon Group)
- Ross Davidson (Davis Langdon)
- Colin Anderson (Arrow International)

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- Stuart Anderson (Ministry of Agriculture and Forestry)
- Graeme Jones (Arrow International0
- Gerard McDonnell (ISJ Architects)
- Jason Guiver (formerly with HunterBond)

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Chapter 1 - Introduction

This report was produced by the University of Canterbury for the Ministry of Agriculture and Forestry under Expression of Interest MAF POL 0910-11665.

The report covers extensive research carried out on the construction of the new Arts and Media building at Nelson Marlborough Institute of Technology in Nelson, New Zealand, between March 2010 and June 2011. The collaborative research programme was directed by the Department of Civil and Natural Resources Engineering at the University of Canterbury (UC), Christchurch.

Major contributions to the research programme were made by third-party industry consultants and reported in separate documents – a copy of all the original reports is included in the Appendices ;

- ScionResearch - *Carbon and Energy Footprint of a new three storey building at Nelson Marlborough Institute of Technology (NMIT),* Simon Love (2011).
- BRANZ (Building Research Association of New Zealand) - *Nelson-Marlborough Institute of Technology Arts Building – An assessement of life cycle costs for alternative designs* (BRANZ report E568), Ian Page (2010).
- Aurecon Group and ISJ Architects (working together) – *NMIT Alternative Structural Design*; Ref. 210688-001 (August, 2010).

All the chapters in this report have either been written by the lead author, Stephen John (UC) or are edited and abbreviated from these three reports by Stephen John and incorporated in the appropriate context. Significant contributions were also made by Kerry Mulligan, working as a researcher at UC (Chapter 6 Cost and Timing) and by Nicolas Perez, PhD student (UC) (Chapter 5 Building Energy).

Where appropriate, each main chapter begins with its own *Introduction* and *Summary* and a *Discussion* section appears towards the end. Thus this report has only a short, separate Discussion chapter which comments on the science of making comparisons between buildings. A list of relevant references appears at the end of each chapter.

The report is structured as follows:

Chapter 1 **Introduction.**

Chapter 2 **Executive Summary.**

A summary of the full programme of research, analyses, results, discussions and conclusions.

Chapter 3 **Background.**

Background information positions the project and details research objectives, project organisation and the project team. This section also provides information about closely related research and background to the involvement of NMIT and MAF in the construction of the Arts and Media building.

Chapter 4 **The Buildings.**

Key to the success of this project was the need to design similar buildings where the main structural elements were either timber, concrete or steel. This chapter is an edited version of the work of Aurecon Group and ISJ Architects presenting an overview of the structural and architectural features of the Timber Arts and Media complex and the alternative Concrete and Steel designs.

Chapter 5 **Building Energy**.

An accurate estimate of the annual operational energy consumption of each building design was essential to provide summarised data to the LCA and LCC studies. This chapter is the work of Nicolas Perez and covers much of his work which will be published for his PhD in November 2011.

Chapter 6 **Cost and Time of Construction**.

This chapter meets the key objective of this report, to provide cost and time of construction information on the new Timber Arts and Media building and to make comparisons with the alternative Concrete and Steel designs. (Cost estimates provided by Davis Langdon; construction schedules by Arrow International).

Chapter 7 **Life Cycle Costing (LCC).**

Analysis and reporting by BRANZ. This extends the cost analysis of the preceding chapter to cover both 60 and 100 year lifetime costs, and the effect of changes in the cost of energy and different rates of return.

Chapter 8 **Carbon and Energy Footprinting.**

Analysis and reporting by ScionResearch. This chapter employs LCA to compare the environmental impacts of energy and global warming potential of all the building designs over their full lifetime. Two end-of-life scenarios are presented.

Chapter 9 **Discussion.**

This chapter offers the author's views on the validity of making comparisons between different building designs and how the research is structured to be scientifically rigorous and 'fair'.

The Appendices contain data and further information relevant to this report, as well as the original reports provided by ScionResearch, BRANZ and Aurecon Group.

The new Arts and Media complex at Nelson Marlborough Institute of Technology. (Photo courtesy of Irving Smith Jack Architects.)

Chapter 2 - Executive Summary

This report covers a collaborative research programme led by the University of Canterbury for the Ministry of Agriculture and Forestry (MAF POL 0910-11665) between March 2010 and June 2011 on the construction of the new three storey Arts and Media building at the Nelson Marlborough Institute of Technology in Nelson.

The research provides detailed information on the cost and time of construction of a 'real' open-plan, multi-storey building which uses engineered timber as the main structural material and compares this to similar, virtual designs in concrete and steel. It demonstrates that innovative design and modern materials and construction techniques position timber as a strong and viable alternative to conventional concrete and steel for large, commercial buildings both in initial construction and over the full building's lifetime, whilst also offering a lower environmental impact.

The research modelled the performance of four similar buildings – the Timber, Concrete, Steel and TimberLow buildings – over the full life cycle to investigate the influence of construction material on energy use and global warming potential (GWP) (life cycle assessment by ScionResearch) and life cycle costs (by BRANZ).

All buildings are designed to the same level of modern seismic damage resistant design. Both of the Timber buildings utilise a framework of massive laminated veneer lumber (LVL) beams and columns and pre-fabricated floor units made from LVL, covered with a reinforced concrete topping, and lateral loads are resisted by post-tensioned LVL shear walls. The Concrete and Steel buildings employ conventional structural materials – pre-cast concrete and pre-fabricated steel. All buildings are designed for low energy consumption. The TimberLow building incorporates additional design features to further reduce energy consumption.

ISJ Architects and Aurecon Group engaged as indpendent consultants state that equivalency is established between the building designs, enabling objective and in-depth comparison across a number of criteria including building methodology, energy use and cost.

The table below shows the estimated full commercial costs of three alternative Arts and Media building designs and the combined time for fabrication, delivery of materials and on-site construction of the structural framework of each building.

Structural Material	Construction Cost (excluding consultant fees)	Time for Construction of Structural Elements (days)
Timber	$5,352,000	58
Concrete	$5,140,000	74
Steel	$5,325,000	56

The 'real' Timber and alternative Steel buildings can be considered to have the same construction cost, whereas the Concrete building is 4% cheaper, equating to approximately $200,000 in a total cost of $5.3 million, largely due to the reduced cost of the upper floors and the shear walls in the Concrete building.

The life cycle cost study shows that for both a 60 and 100 year lifetime, the initial cost of the building dominates and on-going costs are very similar for all four buildings – beyond the initial construction, future cash flows add only another 20% to the lifetime costs at present-day value. The additional construction cost of the energy efficient TimberLow building ($5,489,000) is not shown to be cost effective, even over a 100 year lifetime.

Davis Langdon, the independent quantity surveyors providing the cost estimates for the buildings, confidently predict that the construction of a multi-storey, commercial building using timber as the main structural material, will be no more costly than using either concrete or steel. As the use of timber in such multi-storey buildings becomes more widespread and post-tensioning technology for timber buildings matures, it is anticipated that cost savings will be realised.

The construction schedules produced by Arrow International show that the structural part of the Timber and Steel buildings takes a similar time of between 11 - 12 weeks to construct (fabrication and on-site erection), representing 22% of the total construction time of the entire building. The Concrete building takes nearly four weeks longer, with a much greater proportion of time (35%) required for on-site erection. All other parts of the construction process take a similar length of time for all buildings. From the recent extensive experience gained as Project and

Construction Manager for the Arts and Media building, Arrow confidently predict that future multi-storey timber buildings will be at least as fast to construct as those in either steel or concrete.

At an operational level, savings in both cost and time could be achieved by;

- The early establishment and maintenance of good communications between all parties involved in the construction process, including the open sharing of common drawings on compatible and integrated software platforms and the clear specification of all requirements, particularly the level of finish on timber elements.
- All parties understanding and recognising realistic lead-times for LVL supply, the production of shop drawing and fabrication, so that structural elements are available on-site, as and when required. Suitable storage, with protection from all adverse weather, either at the fabrication plant or on-site would help to reduce on-site delays and maximise the use of crane time and labour.

The following should be carefully considered, from both a cost and time perspective when designing future multi-storey timber buildings;

- Timber structural elements and innovative 'drop-in' timber flooring systems offer the opportunity to significantly reduce and even eliminate wet trades on-site, removing the need for expensive propping and providing easier access within the construction site.
- Early post-tensioning of structural elements can remove the need for expensive and time-consuming lateral bracing of the structural frame.
- The use of conventional lining materials and suspended ceilings would allow a much lower level of finish on LVL elements (services would also be hidden above suspended ceilings).
- Alternatives to a concrete topping to achieve the required acoustic performance of the floors.

The results of detailed energy usage analysis of the Arts and Media complex (78.0 kWh/m^2/yr) demonstrates that timber multi-storey buildings can offer comparable energy consumption and indoor comfort conditions to similar buildings built from conventional heavy-mass concrete (78.6 kWh/m^2/yr). The TimberLow design could further reduce energy consumption by around 15%.

The life cycle assessment (LCA) demonstrated that the increased amount of timber used in the construction of the 'real' Timber building – displacing concrete and steel - led to an 8% lower GWP over the building's lifetime than that of either the Concrete or Steel buildings, whilst the GWP for the TimberLow building was more than 25% less than for Concrete or Steel. The emissions of greenhouse gases during the construction phase (the 'embodied emissions') for both Timber buildings are very low, because of utilising a significantly lower proportion of non-renewable fossil fuel energy in the production of timber compared to other construction materials.

The timber 'framework' of the Arts and Media building. (Photo by Andy Buchanan)

Chapter 3 - Background

This chapter presents background information on the Research Project, its objectives, organisation and those involved in the research, as well as brief notes on some previous closely related research. Background on the origin of the landmark Arts and Media building at NMIT and the involvement of MAF is also covered.

3.1 - The Research Project

The broad Research Objectives for this project were set out in the Ministry of Agriculture and Forestry (MAF) Agreement for Project Grant and Delivery document MAF POL 0910-11809, April 2010.

The University of Canterbury was engaged as the Principal Investigator, acting to bring together the expertise and experience of University of Canterbury staff and post-graduate students, several other NZ research organisations and professional construction industry consultants under a collaborative umbrella.

The research project ran from April 2010 through to June 2011.

3.1.1 - Research Objectives

The agreed research objectives are summarised below;

- To analyse the cost of construction, the construction sequence and time of construction of the new, timber three storey Arts and Media building at NMIT (the *Timber* building) by monitoring various aspects of the construction process '*as it was taking place'* through the period April 2010 to January 2011.
- To provide alternative building designs using either concrete or steel (respectively the *Concrete* and *Steel* buildings) as the main structural material and a low-energy timber design building (the *TimberLow* building).
- To compare the estimated cost of construction and length of time of construction of the Timber, Concrete and Steel buildings.
- To provide a Life Cycle Costing (LCC) analysis of the Timber building and compare this to the Concrete, Steel and TimberLow buildings.
- To report the energy consumption and global warming potential of the Timber building and compare this to the three alternative designs using Life Cycle Assessment (LCA) methodology.

3.1.2 - Project Organisation

The University of Canterbury, as the Principal Investigator, led and managed the research programme. However, because the scope of the programme extended beyond the expertise available at UC and the project demanded the use of building industry and economic expertise, parts of the research were sub-contracted to specialist organisations.

3.1.3 - The Project Team

The following organisations and individuals have been directly involved in this research project.

Department of Civil and Natural Resources Engineering, University of Canterbury.

The Timber Engineering group at the University of Canterbury is at the forefront of research into innovative technology and materials for the construction of multi-storey, open-plan timber buildings.

The Timber Engineering team at UC has developed the world-first post-tensioned *Pres-Lam* timber technology used in the Arts and Media complex. This is marketed in New Zealand and Australia by the Structural Timber Innovation Company Ltd. (STIC) as the "EXPAN building system incorporating *Pres-Lam* technology". The structural design by Aurecon was based on extensive experimental testing and detailed computer analysis at the University of Canterbury.

- Andy Buchanan, Professor of Timber Engineering.
- Stefano Pampanin, Associate Professor in Civil Engineering.
- Alessandro Palermo, Senior Lecturer in Civil Engineering.

The specific work for this research report was carried out by:

- Stephen John, Researcher and Project Leader .
- Nicolas Perez, PhD. student – researching energy use in light-weight, commercial timber buildings.
- Kerry Mulligan, Researcher.

Ministry of Agriculture and Forestry

MAF is the Government's principal advisor on forestry, including policy development and engagement at the domestic and international level. MAF's involvement in this project fits its goal of developing wood as a sustainable resource for commercial building construction, benefiting the NZ economy and environment.

Nelson Marlborough Institute of Technology

NMIT is the largest provider of quality Tertiary education in the top of the South Island of NZ. Art teaching has been a vital part of its history. The new Arts and Media building is a significant part of a long term vision for NMIT of developing their Nelson campus.

Irving Smith Jack Architects

ISJ Architects are project architects and lead design consultants for the NMIT Arts and Media project. ISJ have developed a niche NZ practice closely concerned with urban and environmental context, fostering a reputation for delivering innovative solutions within sensitive environments that has lead to its position of national standing. ISJ has an on-going interest in the use of locally sourced structural timber solutions integral with design and in addressing fundamental issues of sustainability within the building industry.

- Andrew Irving, ISJ Partner and senior architect.
- Gerard McDonnell, senior architect.

Aurecon Group

Aurecon is one of the largest engineering design teams in NZ with a particular emphasis and proven track record in education projects. Aurecon are leaders in both seismic and timber design. The structural design was carried out by Aurecon. A formal review of the design calculations was carried out by Dunning Thornton Consultants with a sub-contract to the University of Canterbury. Aurecon structural designers were:

- Carl Devereux, Technical Director.
- Shane Haydon, Senior Structural Engineer.
- Tony Holden, Senior Structural Engineer.

The design of building services and the fire engineering was also carried out by Aurecon;

- Simon Taylor, Technical Director.
- Paul Martini, Fire Engineer.

Arrow International

Arrow International is NMIT's project delivery partner and has worked with NMIT and the consultant team as Project and Construction Manager since the resolution of concept design. Arrow has a focus on the delivery of complex projects or projects with time, cost or quality requirements beyond that normally achieved in the NZ building industry.

- Graeme Jones, senior project manager.
- Colin Anderson, on-site project manager.
- Steve Kelso, project director.

Davis Langdon Ltd.

Davis Langdon's core business is providing the NZ construction industry with cost and project management. Davis Langdon was closely involved with NMIT and other project consultants in producing cost estimates and schedules of quantities for the building materials.

- Ross Davidson, senior partner.

Hunterbond Ltd.

Hunterbond produce engineered wood products for both commercial and residential structural projects. Hunerbond fabricated all the LVL elements at their workshop in Richmond, near Nelson.

- Jason Guiver, senior technical advisor.

ScionResearch

Scion is a Crown Research Institute dedicated to building the international competitiveness of the New Zealand forest industry and building a stronger bio-based economy. ScionResearch provided building life cycle assessment expertise to this project.

- Simon Love, LCA specialist.

BRANZ

BRANZ is an independent and impartial research, testing, consulting and information company providing services and resources for the building industry. Main areas of activity are to research and investigate the construction and design of buildings that impact the built environment in New Zealand and enable the transfer of knowledge from the research community into the commercial building and construction industry. BRANZ provided specialist expertise in the area of life cycle costing of buildings to this project.

- Ian Page, Manager Economics.

3.2 - Previous Research

In 2007, MAF identified an 'information gap' that existed around the use of timber in the construction and fit-out of commercial and large-scale residential buildings in New Zealand. Furthermore, there was a general lack of information concerning the environmental benefits of the use of wood to improve the long-term sustainability of buildings and around the use and benefit of life cycle assessment and its appropriate application to NZ buildings.

Over the past few decades, there has been little commercial and large-scale residential building utilising predominantly wood and wood products. Whilst MAF felt that there was no technical or financial reason for this lack of timber buildings, a major barrier appeared to be the conservatism of building owners and designers and a shortage of building design practitioners who are trained and experienced in the use of wood as a construction material for large buildings.

MAF proposed that the information gap existed because few have seen the need for this information until recently and there are few examples and few advocates.

In April 2007, the Civil and Natural Resources Engineering Department at the University of Canterbury was engaged by MAF (RFP POR/7811, 2007) to undertake research to help fill this information gap. A UC publication in May 2009, Research Report 2008-02, *Environmental impacts of multi-storey buildings using different construction materials* (John, et.al., 2009) investigated the life cycle energy use and global warming potential of the new six storey Biological Sciences building on the UC campus and compared this with similar designs in both timber and steel. A virtual design, called the *TimberPlus* building, maximised the use of timber throughout the building.

The research demonstrated that increasing the amount of timber in the building design led to a decrease in the initial embodied energy and global warming potential (GWP) of building materials and also decreased the total energy consumption and GWP over a 60 year lifetime.

The report also highlighted that the final destination of deconstruction waste at the end of the 60 year life cycle is extremely important. An end-of-life scenario which assumed permanent storage of carbon in wood materials showed that the net total GWP for the materials in the *TimberPlus* building is negative because the long-term storage of over 630 tonnes of carbon dioxide removed from the atmosphere and stored in the timber building's components more than cancels out all the greenhouse gases emitted in the manufacture of all the other building materials. In this scenario, the *TimberPlus* building could be considered to be 'carbon-neutral' for at least the first 12 years of its operation.

A construction time analysis for the Biological Sciences building reported little difference in time between the 'real' concrete building and the estimated time for construction of a similar timber building using post-tensioned technology.

Other UC research included, the report *Feasibility of multi-storey post-tensioned timber buildings* (Menendez Amigo, J.M. and Smith, T.J., 2011) which compares the cost and time of construction of two case study structures, based on a hotel in the seismically active region of Napier, New Zealand, one built in concrete and the other in post-tensioned timber.

The timber building was quicker to complete construction than the alternative design in concrete but was around 8% more expensive. The report identified significant cost savings that could be made in the timber construction from appropriate infrastructure and design changes.

The Civil and Natural Resources Engineering Department at the University of Canterbury presently has a number of students engaged in investigating the long-term use of energy in the operation of multi-storey commercial buildings, both in light weight timber buildings and in conventional concrete structures. In particular, the department is involved in the long-term monitoring of energy use in two multi-storey buildings on the NMIT campus in Nelson. These buildings, the new timber Arts and Media complex and the adjacent reinforced concrete Tourism building both have monitoring equipment installed to record ambient conditions, all energy inputs (electrical and hot water) and all information is being provided on a weekly basis to UC through NMIT's centralised building management system (BMS). The buildings are of similar size, aspect and occupancy and will allow comparisons to be made between the buildings.

3.3 - NMIT Arts and Media Project Background.

The new, landmark timber NMIT Arts and Media complex situated in Nile Street in Nelson, was opened on the 31st March 201, and is a significant part of a long-term vision for NMIT of developing their Nelson campus.

The concept behind the NMIT Arts and Media building project was to showcase to the construction industry that multi-storey timber buildings are a viable alternative to traditional forms of multi-storey construction.

In 2008 discussions were held around design concepts between NMIT managers, Arts and Media staff and the Ministry of Agriculture and Forestry. A competition for the design was created stipulating that the building must be sustainable, local and substantially made of wood. In partnership, MAF and NMIT offered a national design competition, with MAF providing $1,000,000 of contestable funding as the prize for the successful applicant to develop an innovative timber building design, and enable it to showcase this approach for commercial buildings.. MAF's involvement relates to their initiatives around how the forest industry can meet objectives for climate change mitigation as well as creating a sustainable resource for commercial building construction benefiting the climate and the New Zealand economy.

3.3.1 - The Arts and Media building as an educational and research tool.

The Arts and Media complex at NMIT has an obvious educational function, bringing students and staff together in a modern, stimulating environment. However, beyond this, it has a wider educational role.

Currently there are very few timber commercial buildings in New Zealand, a reflection of the fact that there are not many building companies and designers skilled in using wood for commercial buildings. The NMIT Arts and Media building is therefore a vital teaching tool for everyone in the construction industry. Engineers, architects, builders and the associated training providers will assess the construction process and the building to promote the use of timber in commercial construction. The Arts and Media building shows that timber can be successfully used in multi-storey commercial buildings. Timber is sustainable, renewable, locally available and requires less energy to manufacture than other building materials, like concrete and steel.

The building is fitted with advanced energy use measurement systems which will provide data on ambient environmental conditions, electrical supply and hot water heating to researchers at the School of Engineering at the University of Canterbury in Christchurch. This will enable the energy consumption of the new timber building to be compared to both the energy use computer models developed for the building prior to its construction and also to a recently constructed, adjacent concrete building. This research will identify how the two buildings react to local climate and promote a greater understanding of how timber buildings perform.

Furthermore, the School of Engineering at the University of Auckland and Geological and Nuclear Sciences (GNS) have combined to install instruments which will monitor seismicity, wind speed, temperature and humidity and compare movements in key structural and seismic components. Long-term deflections in primary structural timber members will also be observed.

3.3.2 - Environmentally sustainable design

ISJ Architects have provide a sustainable building design where the structural framework of the building utilises laminated veneer lumber (LVL) and other timber materials are used extensively in the internal linings and roof. All timber is sourced locally, being grown, milled, manufactured and erected within an eighty kilometre 'radius of resource' and acting as a carbon store.

ISJ Architects have noted the extensive and deliberate deployment and use of easily operated, relatively low technology energy saving devices in the Arts and Media building, including;

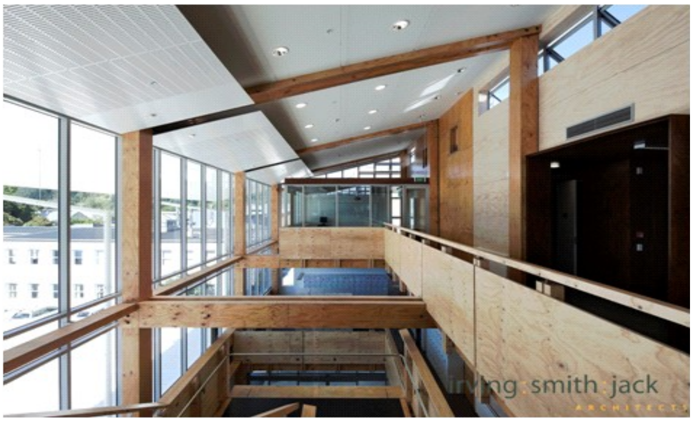
- Passive heating and cooling in the Atrium design.
- Natural ventilation.
- Shading provided by the extensive north elevation.
- Natural day-lighting through extensive glazing.
- High levels of insulation to floors, walls and ceilings and double glazing.
- Thermal mass through extensive use of exposed concrete floors.
- Utilising timber as a moisture buffer by exposing timberwork throughout the building.
- Recycling facilities throughout the building.
- Solar water heating and conserving water with low water use sanitary fixtures.

3.4 - References

- John, S.M., Nebel, B., Perez, N. and Buchanan, A. (2009). Environmental Impacts of Multi-Story Buildings Using Different Construction Materials. University of Canterbury, Research Report 2008-02.
- Menendez-Amigo, J.M. and Smith, T.J, (2011). Feasibility of Multi-Storey, Post-Tensioned Timber Buildings. University of Canterbury.

The following list includes references to material which will give the reader more background information.

- NMIT Arts & Media Building- Damage Mitigation Utilising Post-tensioned Laminated (Pres-Lam) Timber Walls. C.X.Devereux, T.J.Holden, A.H.Buchanan & S.Pampanin. Proceedings, Ninth Pacific Conf. on Earthquake Eng, April 2011, Auckland. Paper 90.
- Design of UFP-coupled post-tensioned timber shear walls. M.P.Newcombe, D.Marriott, W.Y.Kam, S.Pampanin & A.H.Buchanan. Proceedings, Ninth Pacific Conference on Earthquake Engineering, April 2011, Auckland. Paper 132.
- Demountability, Relocation and Re-use of a High Performance Timber Building. T.Smith, R.Wong, M.Newcombe, D.Carradine, S.Pampanin, and A.H.Buchanan. Proceedings, Ninth Pacific Conf. on Earthquake Eng, April 2011, Auckland. Paper 187.
- Experimental Testing of a Two-Storey Post-Tensioned Timber Building. M.P.Newcombe, S.Pampanin and A.H.Buchanan. Proceedings of the Ninth U.S. National and Tenth Canadian Conference on Earthquake Engineering, Toronto, July 2010.
- Simplified Design of Post-Tensioned Timber Buildings. M.Newcombe, M.Cusiel, S.Pampanin, A.Palermo, A.H.Buchanan. Proceedings, CIB W18 Workshop on Timber Structures, Nelson, New Zealand, August 2010.



Upper level atrium of the Arts and Media building. (Photo courtesy of Irving Smith Jack Architects.)

The new Arts and Media complex at Nelson Marlborough Institute of Technology. (Photo courtesy of Irving Smith Jack Architects.)

The main atrium in the Arts and Media complex at Nelson Marlborough Institute of Technology.(Photo courtesy of Irving Smith Jack Architects.)

Chapter 4 - The Buildings

4.1 - Introduction

This chapter presents;

- Design briefs (guiding principals and specific instructions) provided to Aurecon Group and ISJ Architects in Nelson for the scope of the alternative design solutions to the Arts and Media building at NMIT.
- A summary of the structural design of the *as-built* Arts and Media building at NMIT. The structural elements of this building are made of laminated veneer lumber (LVL) - the building is referred to as the Timber building.
- Alternative concept structural design solutions using either concrete or steel as the main structural material, in this report, known respectively as the Concrete and Steel buildings.
- An architectural review of both the Concrete and Steel alternative designs with reference to the Timber architecture.
- Brief notes on modifications made to the Timber building to reduce on-going (operational) energy consumption. This design is referred to as the TimberLow building.
- This chapter largely replicates the report contained in Appendix A, *NMIT Alternative Structural Design,* prepared for University of Canterbury by Aurecon Group (structural design) and ISJ Architects (architectural design).

4.2 - Summary

Aurecon Group and ISJ Architects worked together to produce alternative concept structural design solutions in both steel and concrete for the Arts and Media building. The scope of the alternative designs was based on the architectural scheme for the timber structural solution and required the alternative designs to match the building performance requirements of the timber solution.

This approach established equivalency between the three alternative structures to enable objective and in-depth comparison across a series of criteria including building methodology, energy use and cost.

4.3 - Background

The concept behind the NMIT Arts and Media building project was to showcase to the construction industry that large, multi-storey timber buildings are a viable alternative to traditional forms of multi-storey construction.

A Nelson based team of Irving Smith Jack Architects Ltd and multi-disciplinary engineers Aurecon Group, provided a design solution to meet the specific needs of NMIT as a creative learning institution, using state-of-the-art structural timber technology coupled with the use of locally produced materials and a design that expressed all the internal structural components. As the design developed, Arrow International, representing the client (NMIT), worked to value engineer the final design. The as-built Arts and Media building, opened in March 2011, is unique in the world as the first multi-storey, EXPAN timber building incorporating *Pres-Lam* technology developed at the University of Canterbury inChristchurch.

As an innovative design showcasing the use of structural timber, the Ministry of Agriculture and Forestry in NZ (MAF) commissioned research to scrutinise aspects of the construction and future usage of this new Arts and Media building in order to broaden the knowledge base and construction-industry understanding of the extensive use of engineered timber products as the main structural material in open-plan, multi-storey buildings. The research covered a detailed analysis of the cost of the various parts of the construction of the building, a review of the construction methodology and its effectiveness, the building's energy performance, its life cycle costing (LCC) and its carbon footprint using life cycle assessment (LCA).

Further, a most important part of this research was to determine the effectiveness and efficiency of using timber as the main structural material, compared with the more conventional structural materials, concrete and steel. To this end, the research commissioned the preparation of alternative concept structural design solutions to the *real* building, in both concrete and steel.

The beginning of this chapter sets out the '*rules'* which were put in place to offer a sound and scientific basis for deriving the alternative designs and following on, to be able to make these comparisons.

To this end, the same Nelson based team of Irving Smith Jack Architects Ltd and Aurecon Group engineers were engaged to provide the alternative building designs.

The difficulty of preparing alternative concept design solutions in different materials – and then making some *measureable* comparisons between different designs – is discussed briefly in Chapter 9.

4.3.1 - Design briefs for Arts and Media complex

The joint architectural/engineering team of Irving Smith Jack Architects Ltd and Aurecon Group devised a timber structural solution to match the architectural and performance requirements of the design brief issued by MAF in September 2008.

The key objectives established in the design brief were;

To create;

- *A new facility for NMIT School of Arts and Media.*
- *A new, generic teaching facility for NMIT.*
- *A building whose structural form uses and showcases its construction in timber.*
- *A demonstration and education project for the timber industry that encourages the future use of timber in the design and construction of multi level commercial buildings in New Zealand and overseas.* (This was interpreted to mean that the structure would be visible in the completed building to allow it to be used as the demonstration and education model).
- *A sustainable and environmentally-sound building within the available budget.*
- *A team approach to the design and construction of the facilities.*

The particular programmatic objectives were to;

- *Incorporate innovative design principles into the design of the building layout.*
- *Incorporate innovative design principles utilising timber as the primary structural component into the design of the building structure.*
- *Meet the project budget.*
- *Meet the project timeline.*

The following is extracted from the contract letter provided by Aurecon Group (working closely together with ISJ Architects) to the University of Canterbury (as Principal Investigator), accepting to undertake the design of alternative buildings for the Arts and Media building. This extract clearly sets out the agreed 'rules' for the design of alternative buildings.

Extract of contract letter from Carl Devereux, Executive, Aurecon Group, Nelson to Department of Civil and Natural Resources Engineering, University of Canterbury, dated 13 May 2010.

*We (*Aurecon Group*) understand that the aim of the project is to prepare alternative concept structural designs in both steel and concrete for the NMIT Arts and Media building. The concept designs are to be completed in sufficient detail to allow a preliminary cost estimate to be prepared by Ross Davidson of Davis Langdon Quantity Surveyors.*

Our understanding of the scope of the 'alternative' structural designs is that they are to be based on the architectural scheme complete for the Arts and Media building timber structural solution. We also understand that the scope only includes the three storey teaching building and does not include the workshop building or the media building.

We understand the 'alternative' structural solutions are also required to match the building performance requirements of the timber structural solution. In summary, the performance requirements of the alternative *structural solution will;*

- *Match the same floor plan and internal layout.*
- *Make use of the same column and beam layout to maintain the same floor spaces and room layout.*
- *Provide the same structural performance for seismic design. (The design will be based on a damage-resistant design similar to the design used for the timber solution).*
- *Provide the same structural performance for the gravity structure.*
- *Provide the same fire performance to meet the requirements of the fire report completed for the timber solution.*
- *Provide the same acoustic performance as provided in the timber solution.*

Notwithstanding meeting the above objectives for performance requirements, the alternative designs should;

- *Provide the same client expectation/s in terms of functionality as the Timber building – for instance, offer the same number of rooms, teaching and practical facilities, and cater for the same number of occupants including students and staff.*
- *Provide a similar quality of architectural features including interior and exterior surface finishes.*
- *Provide the same client expectation/s for comfort and internal environment as the Timber building.*

The alternative design will focus on the replacement of primary structural timber elements with appropriate steel and concrete alternatives. This will essentially involve a review of beams, columns, structural walls, floor systems, roof systems and foundation systems. The review of foundation systems will be limited to the change in size of footings and the change in the number of screw piles. It will not involve a review of alternative foundation systems.

What this review will not seek to provide is alternatives that change structural grids to maximise bean and floor spans for steel and concrete systems. The review will work with the existing structural grid so that the architectural design of the building is maintained.

4.3.2 - Alternative Concept Structural Design Solutions

4.3.2.1 - Project Scope

The aim of the *alternative concept structural design solutions* is to provide designs using alternative structural materials to those found in the Timber building, namely steel and concrete.

The concept designs were completed in sufficient detail to allow a preliminary cost estimate to be prepared by Davis Langdon, Quantity Surveyors.

The scope of the alternative structural design solutions was that they be based on the architectural scheme completed for the Arts and Media building timber structural solution. The scope only included the three storey teaching building and did not include the workshop building or the media building.

The alternative structural solutions were also required to match the building performance requirements of the timber structural solution. In summary the performance requirements of the alternative structural solutions (as set out in the Aurecon letter above):

- Matched the same floor plan and internal layout.
- Made use of the same column and beam layout to maintain the same floor spaces and room layout
- Provided the same structural performance for seismic design. (The design to be based on a damage-resistant design similar to the design used for the Timber solution)
- Provided the same structural performance for the gravity structure.
- Provided the same fire performance to meet the requirements of the fire report completed for the Timber solution

- Provided the same acoustic performance as provided in the Timber solution

Not withstanding meeting the above objectives for performance requirements, the alternative designs provided;

- The same client expectation/s in terms of functionality as the Timber building – for instance, offer the same number of rooms, teaching and practical facilities, and cater for the same number of occupants including students and staff.
- A similar quality of architectural features including interior and exterior surface finishes.
- The same client expectation/s for comfort and internal environment as the Timber building.

The alternative designs focused on the replacement of primary structural timber elements with appropriate steel and concrete elements. They essentially involve a review of beams, columns, structural walls, floor systems, roof systems and foundation systems. The review of foundation systems has been limited to the change in size of footings and the change in the number of screw piles. It has not involved a review of alternative foundation systems.

The alternative designs did not seek to provide alternatives that changed structural grids to maximise beam and floor spans for steel and concrete systems. The review worked with the existing structural grid so that the architectural design of the building was maintained.

4.3.2.2 - Fire and Acoustics

In addition to the structural review, a review of the fire rating and acoustic requirements of the alternative structural solutions was completed. A brief commentary on the appropriate treatment sufficient to allow cost estimates to be completed by the Quantity Surveyor was provided.

4.4 - The Timber building - the new Arts and Media Building

The new Arts and Media building, standing in Nile Street on the NMIT campus, was opened in March 2011. The background to the building is covered in Section 3.3.

The building was designed by Irving Smith Jack Architects of Nelson. The structural engineering was undertaken by Aurecon Group.

4.4.1 - Design and construction

4.4.1.1 - Overview

The new NMIT Arts and Media building is a "landmark" building – a world-first for innovative use of wood in the structure of a multi-storied building. The building was required to use and showcase its construction in timber, be environmentally sound and to demonstrate, educate and encourage the future use of timber in the design and construction of multi-level commercial buildings in NZ.

Irving Smith and Jack designed the building to highlight its timber construction. Timber components are visible, showcasing the innovative design approach and allowing this building to act as an exemplar for both the design and building industries. "*As architects, we see this as the first in a new generation of creative, sustainable, wooden structured multi-storied buildings.*" – Project Architect, Andrew Irving.

All structural beams, columns and floors are of engineered timber construction in locally sourced and manufactured laminated veneer lumber (LVL). It has excellent strength properties, is durable and fire resistant. This allowed the design of beams, columns and floor systems that are the equivalent of steel and concrete. The building's movement and regional seismicity are being measured by the University of Auckland to assess its structural performance over time.

The structural timber (LVL) 'skeleton' of the Arts and Media building. (Photo by Andy Buchanan)

Preparing for pouring the concrete topping on top of the Potius floor units.(Photo by Andy Buchanan)

Detailing of beam / column joint on Arts and Media building. (Photo by Andy Buchanan)

The massive timber (LVL) shear-walls of the Arts and Media building. (Photo by David Carradine)

Paired shear-walls showing the Macalloy tensioning bars running vertically and the U-shaped energy dissipaters. (Photo by David Carradine)

Aurecon structural engineers have achieved a 'world-first' timber seismic design for this building, incorporating technology developed at the University of Canterbury. Using pairs of rocking timber shear walls, joined with energy dissipaters, the structure is able to absorb seismic energy and reduce building damage during an earthquake. This is a new generation of seismic engineering known as damage resistant design. Aurecon's Lead project Engineer, Carl Devereux, says *"This NMIT building demonstrates that a high level of earthquake protection is achievable and affordable. The innovation in design will ensure this building is functional after a major earthquake event. It's important for building owners to know that this higher standard of earthquake protection is now available."*

4.4.1.2 - Timber Structural Solution

The timber structural solution for the main three storey Arts and Media building consists of:

- Lightweight timber roof structure using LVL timber purlins
- LVL timber beam and column gravity frame
- LVL timber stressed skin floor panels with concrete topping
- LVL timber post tensioned shear walls, ("rocking" timber walls)
- LVL timber lintels and secondary beams
- Concrete slab on grade ground floor

4.4.1.3 - Gravity Frame

The primary gravity frames consist of a continuous LVL column over three levels supporting a double LVL timber beam arrangement. The double LVL beams consist of two short spans and one long 9.6m span. The longer span has been designed for composite action with the concrete floor topping to control deflection. The double LVL beam is fabricated as two single beams and is supported on timber corbels incorporated into the timber column fabrication. A connection between the two beams is provided by the concrete topping.

The flooring system comprises of stressed skin timber floor panels, trade name "Potius Panels", spanning 6.0m between beams. These panels consist of a double 300x90 timber LVL joist fixed to a 36mm thick LVL slab. The connection provides a composite action between the LVL joist and the LVL slab. The panels support a 75mm concrete floor topping with mesh reinforcing. The concrete topping slab provides the robustness, stiffness and acoustic performance required for an educational or commercial building.

4.4.1.4 - Wind and Seismic Bracing

The lateral load resisting system for the building comprises of post-tensioned LVL timber shear walls. The design is based on PRESSS technology more commonly associated with precast concrete shear wall buildings which is now being applied to timber structures and has been researched and tested at the University of Canterbury. Similar systems have been developed by Aurecon for concrete and steel structures but this is the first time this technology has been used with timber walls.

The bracing system in the longitudinal direction is provided by pairs of 3.0m long shear walls adjacent to the stair and lift shaft. Bracing in the transverse direction is provided by pairs of 3.0m long shear walls at each end of the building. The transverse walls also provide resistance to the torsion loads due to mass eccentricities resulting from the open layout. The design is governed by the seismic loading due to the mass of the building and the high (approximately 4m) inter-storey heights. The wind loading is less than half that of the seismic loading and as such the bracing walls will also resist wind loads responding in an elastic manner.

Each pair of walls is a hybrid system with a wall thickness of 189mm. The walls are coupled to act integrally under lateral loading. The coupled walls are connected using U-shpaed flexural plates as energy dissipaters and each wall includes post-tensioning tendons through a central duct. These tendons act to minimize panel uplift and are sized to overcome the over strength forces of the energy dissipaters to ensure that the wall recentralises following lateral (typically seismic) loading. System ductility/energy absorption under seismic loading is provided by the coupling mechanism in the form of energy dissipaters fabricated from steel plate elements located in the vertical gap between each panel. Base shear is transferred to the foundations via a steel shoe at the base of the timber wall panels.

Lateral loads for both wind and seismic are transferred to the shear walls via the floor diaphragms which are assumed to be rigid. Diaphragm action is provided at roof level by timber purlins and a plywood lining, while the concrete floor topping provides a rigid floor diaphragm at the two suspended floor levels.

The damage-resistant design of this building is a unique and innovative solution. In a major seismic event the rocking timber walls will lift a maximum of 45mm at one end. This will result in very low inter-storey drifts, in the range of 1.0% - 1.5% of the storey height. The end result is that the primary and secondary structural elements will suffer only minimal damage and the building will remain fully functional following a major earthquake.

4.4.1.5 - Foundations

The geotechnical investigation highlighted the varied ground conditions across the site. In summary, the depth to good ground is 1m at the east side of the building up to six metres on the west side of the building. Based on this information a combination of shallow pad footings and screw piles up to six metres in depth has been designed to support gravity loads. Steel screw piles are also used locally to support vertical seismic loads from the shear walls where required. At the west end of the building where the existing site level falls away concrete foundation walls were used to allow backfilling for a slab on grade at the ground floor level.

4.4.1.6 - Fire Design

The fire design, to ensure the integrity of the building structure in a fire event and to comply with Ministry of Education requirements, involves the provision of an automatic fire sprinkler system. For an educational facility of this size sprinklers are mandatory to meet Ministry of Education requirements. The result of the use of sprinklers is that all primary structural elements supporting suspended floors are required to achieve a minimum 30 minute fire resistance rating. All timber members have been designed with a minimum 90mm thickness and charring rates have been used to calculate a reduced section size for the fire load case.

The design check was able to show that no additional treatment of timber members was required to achieve the required structural fire ratings.

4.4.1.7 - Preliminary Member Sizes

Details of preliminary member sizes can be found in the full Aurecon report in Appendix A.

4.5 - Alternative Buildings

4.5.1 - Concrete structural solution

The following is a summary of the Concrete structural solution. More details of the Concrete building can be found in the Aurecon report, Appendix A.

A discussion of the alternative Concrete solution appears after the structural summary.

The alternative Concrete structural solution for the main three storey Arts and Media building consists of:

- Lightweight roof structure using steel DHS purlins, steel rafters and a plywood diaphragm
- Precast concrete gravity frame comprising full height columns and precast half beams
- Stahlton / Interspan precast concrete floor system
- Precast concrete coupled shear walls with post tensioning (“rocking” concrete walls)
- Precast concrete secondary beams
- Structural steel wind beams and lintels.
- Concrete slab on grade ground floor

4.5.1.1 - Gravity Frame

The primary gravity frames consist of continuous precast concrete columns over three levels.

The primary floor beams consist of two short spans and one long span. The flooring system comprises of a Stahlton / Interspan precast floor offering a long span pre-tensioned flooring system with reduced concrete usage.

4.5.1.2 - Wind and seismic bracing

The lateral load resisting system for the building comprises of precast concrete, post tensioned shear walls. The design is based on the same PRESS technology as the timber solution with the concrete walls being a direct replacement for the timber walls. This allows the damage-resistant design to be utilised and offers a solution with a similar wall length and thickness to the post tensioned timber wall solution.

The total building weight of the Concrete solution is increased by 30% when compared to the Timber solution and therefore the seismic response is increased.

Lateral loads for both wind and seismic are transferred to the walls via rigid floor diaphragms.

The damage resistant modelling for the concrete solution has been based on achieving the same level of seismic performance as the Timber solution.

4.5.1.3 - Foundations

The foundation loads for the Concrete option are increased by 30% for gravity and 50% for earthquake when compared to the Timber option. Based on this the foundations sized and detailed for the concrete have increased.

4.5.1.4 - Fire design

The gravity frames and shear walls will be exposed in the building to meet the architectural design requirements. The design to achieve appropriate fire ratings is detailed in the Aurecon report.

4.5.1.5 - Preliminary Member Sizes

Details of preliminary member sizes can be found in the full Aurecon report in Appendix A.

4.5.1.6 - Discussion of Concrete structural solution

The Concrete solution is a structural solution that increases the overall weight of the building. The main effect that this has on the building structure is an increase in foundation loads for both the gravity load case and the seismic load case. Typically the size of foundation pads has increased 30% and the number of steel screw piles has increased by 30%. The increased weight of primary structural elements such as walls, beams and columns will require increased crane capacity and depending on the construction sequence may require crane access from more than one side of the building or the use of a tower crane.

Like the Timber and Steel solutions, the Concrete solution has been designed and detailed to allow for off-site fabrication and fast erection. Columns are to be precast full height with cast in shelf angles to allow quick erection and to also avoid unsightly in-situ pours of beam column joints.

All of the concrete members are to be exposed in the building and will require a high level of finish. To achieve this all members have been designed to allow them to be constructed as precast elements.

Connections for secondary wind beams and roof beams are to be cast into the columns to ensure well detailed and discreet connections.

Propping of the precast floor beams at mid-span is required to allow an efficient beam size to be used. Propping of the Stahlton/Interspan floor system at mid-span is also required to allow an efficient floor depth to be used. Propping for both of these elements will involve additional site time and cost.

The Stahlton/Interspan floor system will ensure a fast installation of the floor and with the use of 40mm timber sawn planks will provide a safe working platform for the floor construction. Large areas of the floor can then be poured as a single pour.

4.5.2 - Steel structural solution

The following is a summary of the Steel structural solution. More details of the Steel building can be found in the Aurecon report, Appendix A.

A discussion of the alternative Steel solution appears after the structural summary.

The alternative structural Steel solution for the main three storey Arts and Media building consists of:

- Lightweight roof structure using steel DHS purlins, steel rafters and a plywood diaphragm.
- Structural steel gravity frame using UB and UC steel sections.
- Steel floor deck using the Comfloor system.

- Structural steel K-Braced coupled frames with post tensioning (“rocking” steel frames).
- Structural steel lintels and secondary beams.
- Concrete slab on grade ground floor.

4.5.2.1 - Gravity Frame

The primary gravity frames consist of continuous steel columns over three levels supporting simply supported steel beams.

The flooring system comprises of a composite steel floor deck, trade name Comfloor 210.

4.5.2.2 - Wind and seismic bracing

The lateral load resisting system for the building comprises of Post-tensioned K-Braced steel frames.

The design is based on the same PRESSS technology as the timber solution with the K-Braced frame effectively forming an open but rigid steel wall to replace the solid timber wall. This allows the damage-resistant design to be utilised and offers a comparable steel solution to the post tensioned timber wall.

4.5.2.3 - Foundations

The foundation loads for the Steel option are very similar for the Timber option for both the gravity and seismic load cases. Based on this the foundations sized and detailed for the Steel option are identical to those sized and detailed for the Timber option.

4.5.2.4 - Fire design

The gravity frames and bracing frames will be exposed in the building to meet the architectural design requirements. The design to achieve appropriate fire ratings using intumescent paint is detailed in the Aurecon report.

4.5.2.5 - Preliminary Member Sizes

Details of preliminary member sizes can be found in the full Aurecon report in Appendix A.

4.5.2.6 - Discussion of Steel structural solution

Like the Timber solution the Steel solution is a lightweight structural solution. It has been designed and detailed to allow for off-site fabrication and fast erection. Structural elements are relatively lightweight and therefore it is expected that the building would be erected using mobile cranes similar to that used for erecting the Timber building.

Steel frame connections to be used in this solution are standard HERA type connections. All structural columns could be fabricated and erected as a single member avoiding the need for column splices.

All of the steel structure will be exposed in the completed building therefore a high level of finish is required to all welded and bolted connections. The use of intumescent paint systems will also require welds to be ground smooth and all bolts tidily installed to ensure a high quality paint finish.

Propping of floor beams during the concrete pours is required and propping of the steel floor deck system at mid-span is also required. The use of propping systems will ensure the use of efficient members and floor section depths. However, this is balanced by the additional site time and construction cost of the propping.

The Comfloor steel floor deck system will ensure a fast installation of the floor system. With a 6m floor span a single Comfloor sheet can be installed between beams allowing shear studs to be installed in the workshop. Large areas of the floor can then be poured in a single pour.

4.6 - Architectural Review

ISJ Architects were engaged to complete an architectural review of the proposed alternative structural solutions. A brief commentary on the appropriate architectural treatment was provided sufficient to allow cost estimates to be completed by the Quantity Surveyor. This included a mark up of relevant structural and architectural drawings to be used for comparison of costs between the alternatives.

The general architectural design parameters, that have been used for the Steel and Concrete alternative solutions are the same as those provided to the design team by NMIT for the design of the Timber building. In broad terms, this means that the functionality, performance and emphasis on structural elements and architectural design are similar for all three options – Timber, Steel and Concrete.

4.6.1 - Architectural Response

The architectural approach to the three structural options is constrained by the parameters noted in the Project Objectives (Section 4.3.1) and the Alternative Concept Structural Design Solutions - Project Scope (Section 4.3.2.1) provided at the beginning of the design stage for the Timber building.

Underlying the original Timber design is the premise that this approach should be industry leading. The sophistication of the lateral load resisting shear walls allows an elegant gravity resisting frame with simple rebated and bolted connections. This straight forward approach, where a simple gravity resisting frame can be coupled with a variety of lateral load resisting systems, could be applied to a variety of building typologies. To maintain this consistency, readily available steel or concrete componentry has been applied to each of the alternative designs, rather than pursuing a more 'custom-made' approach.

Internally, the Timber structure is exposed and its function expressed as far as practicable. This move is key to the design concept, and to the success of this project. A similar level of structural expression is proposed in both of the alternative (Steel and Concrete) designs.

The structure, in all three scenarios, is exposed as prescribed by the NMIT objectives. Each of the three materials will affect "the feel" of the building which, although very real, is impossible to quantify, as it is subjective. There is, however, no doubt that the steel or concrete will evoke a different emotional response from users and observers, to a building with an exposed timber structure.

The impact of a timber, steel or concrete structure on the external environment will be of lesser significance as the exterior appearance will be largely unchanged, as explained below.

Following are brief descriptions of all three design solutions - Timber, Steel and Concrete. These should be read in conjunction with the A3 architectural drawings (included in the full report in Appendix A) which incorporate the structural information provided by Aurecon. The layout and scale of spaces and the materials, except the primary structure, are based on the design originally developed with NMIT. Where possible these are replicated for the Steel and Concrete designs.

(Note; The drawings included in the report in Appendix A, showing the Steel and Concrete alternatives, show in red, the <u>differences</u> from the Timber solution in order to highlight the parts of the building that have by necessity been changed from the original Timber design. There has been a deliberate intent to leave the remainder unchanged.

4.6.2 - Timber

4.6.2.1 - Exposed Timber

It is not uncommon to have timber exposed to view within a building, but not so common for specifically engineered laminated veneer lumber (LVL). The inherent aesthetic qualities of the natural wood are enhanced by the laminations making it an interesting attractive option for an expressed primary structure. Due to its structural properties the LVL members outperform their natural timber counterparts although they are often larger in section than would be possible with the natural timber.

The selection of an exposed and expressed timber structure necessitated, at the outset of developed design, decision making regarding the quality of finish required to the timber components. At it's most basic level, fabricated LVL could be left in its factory made 'industrial state' with no attempt to mitigate fabrication tolerances, glue runs or surface damage. Instead, the architects elected, for this landmark project, to detail all timber elements with a high level of finish. This decision results in all timberwork being machine sanded, some components also being hand sanded and some production methods (Potius floor panels, as an example) being adapted to achieve acceptable visual appearance. Thereafter a higher level of attention has been paid to the subsequent protection of these finishes on site.

The LVL's natural fire resistant qualities negate any requirement for over-lining or intumescent painting.

4.6.2.2 - Shear Walls

The LVL rocking walls are a fundamental feature of the Timber building, as explained in the structural section of this chapter. These panels will be exposed to view from the interior as will the tops of the post-tensioning rods.

4.6.2.3 - Internal Spaces

The arrangement of spaces is primarily governed by the design brief requirements of NMIT and the desire to capitalise on the opportunity to provide ideal south light to studio and teaching spaces. The structural grid is in turn governed by this and the spanning capacity of the primary structural members. The atrium on the north side of the building provides a powerful contrast to the more intimate teaching spaces and also a means of creating natural air flow for passive ventilation and smoke purging.

4.6.2.4 - Atrium Stairs

The main public stairs in the atrium space will have LVL strings, treads, balustrade panels and posts supported on a slender steel frame. The stairs are a fundamental design element within the key architectural volume. Attention has been paid to highlight the expressive use of structural timber. Steel is used here to maximise circulation space at level 1.

4.6.2.5 - Services

The services duct (the longitudinal zone between grids 6 and 8) contains all major services to be run laterally through the building in a central location. Secondary services reticulation branches off this duct and these runs can be controlled to maintain a visual coherence.

Primary structural members will not be penetrated for services reticulation and many services components will be exposed to view, in an ordered fashion, to compliment the skeletal nature of the exposed structure. The lift is supported by a steel frame due to spatial constraints.

4.6.2.6 - Linings & Cladding

To compliment the timber building primary structure, many of the internal walls and ceilings will be lined with plywood or MDF.

All timberwork is expressed internally, none is featured externally. Instead, the architects have created an external skin from preassembled and or prefinished materials to reduce life cycle maintenance as far as possible. Exterior cladding and window systems will be lightweight and economical. Roofing will be profiled steel sheeting, while walls will also have steel sheeting with some fibre cement panelling.

Windows and main doors will be aluminium framed.

4.6.2.7 - Insulation

The thermal insulation to the building envelope will be to a higher level than required under the Building Code in order to maximise user comfort and energy efficiency. The thermal mass of the solid Timber structure will assist in maintaining temperature equilibrium within the building and assisting energy efficiency.

The degree of acoustic absorbency to the underside of the floor structure and degree of acoustic separation between spaces is determined by the use of the various spaces. Acoustic and fire separations will need to be created at the perimeter of each floor as required by the fire report.

4.6.2.8 - Surfaces, Finishes and Detail

Extra care is required when handling such large pieces of a relatively easily damaged product as all exposed LVL surfaces will have a clear finish and defects will be difficult to disguise. Wood based interior linings will be either clear finished or stained. The implications of electing an exposed and expressed timber structural system are discussed in more detail above.

4.6.3 - Steel Alternative Solution

4.6.3.1 - Exposed Steel

Historically exposing primary steel structure to view has been difficult due to fire rating requirements which usually resulted in encasing the steel in a fire rated lining or coating with unsightly intumescent paint. Due to recent advances in paint systems it is now possible to provide a fire rated coating which is indistinguishable from ordinary acrylic or enamel paint system. This has made acceptable the expression of the steel structure to the same degree as the timber. Other factors requiring careful consideration are the detailing of joints and achieving a high standard of workmanship in a structural system which is more commonly concealed behind linings and cladding. Steel to steel connections will be exposed. However all steel to concrete connections will be carefully detailed and concealed within the concrete element.

4.6.3.2 - Steel K-Braced Frames

The structure of the K-Braced steel frames will be exposed, including the post tensioning bars which extend full height. The open design of the steel rocking frames has required a different solution to vertical fire and smoke separations as noted below. In order to create separation between internal spaces, an additional layer of wall framing will be required behind the frames on grids 6 and 8.

4.6.3.3 - Internal Spaces

Rearrangement of wall framing around the K-Braced steel frames will have a direct impact on the amount of available floor area in the adjacent spaces. The inside face of the frames will encroach on the room by approximately 100mm which, in most spaces, is relatively insignificant. Additional wall framing on grids 6 and 8 may affect the internal layout of the Reception office as, because it has a shear wall on two sides, the width of the room will be reduced by 200mm.

4.6.3.4 - Atrium Stairs

Steel stairs could be similar in arrangement to the timber stairs but with RHS box section strings, steel mesh or grating open treads and balustrades with perforated steel sheeting and RHS posts. We would expect these to be expressive of the application of concrete construction and to be finished to a high level as with the timber option.

4.6.3.5 - Services

Positioning of services fixtures and reticulation of pipework and cabling will be identical to the Timber building. Primary structural members will not be penetrated for services reticulation and many services components will be exposed to view, in an ordered fashion, to compliment the skeletal nature of the exposed structure.

4.6.3.6 - Linings & Cladding

Internal linings and finishes are identical to the Timber building although, for aesthetic reasons, an alternative lining may be used in some of the areas which, for the timber building, were designated as plywood lined.

The approach to the external envelope, exterior cladding and windows remains unchanged from the Timber design.

The installation of lining material behind the exposed structure of the shear panels on grids E and L, will require special detailing and well planned execution as it will impact on the construction sequence.

4.6.3.7 - Insulation

In order to preserve the thermal insulation to the building envelope, external walls will be constructed outside the line of the shear walls on grids L and E. In other areas of the building the external insulating envelope is unaffected by the change to steel. The lack of thermal mass in the steel structure will not assist in maintaining temperature equilibrium within the building and will not assist energy efficiency.

The acoustic insulation remains unchanged from the timber solution. The same degree of acoustic absorbency to the underside of the floor structure and the same degree of acoustic separation between spaces and at roof level is required and will be provided in a similar manner.

At the shear walls the required acoustic and fire separations will need to be created at each floor level within the confines of the steel frame, which will be inherently difficult due to the spatial limitations and the profiles of the steel sections.

4.6.3.8 - Surfaces, Finishes and Detail

The exposed steel will require a very high level of finish to a similar standard and visual quality to that employed in the Timber building.

All exposed welds will be ground and all surfaces are to be brought up to smooth finish ready for highgloss paint – including intumescent paint.

4.6.4 - Concrete Alternative Solution

4.6.4.1 - Exposed Concrete

It is not uncommon for precast concrete to be exposed to view in contemporary buildings. However, it is very important, as with timber, to have good quality assurance checks in place during its production and installation as there are many factors that can affect the appearance of the final product.

4.6.4.2 - Fire Rating

Concrete has good inherent fire resisting properties. However, close attention to fire rated separations is still required at joints and junctions.

4.6.4.3 - Shear Walls

The shear walls in this instance are of similar physical size to the Timber design but, they have individual ducts for post tensioning rods. The flush exposed surface allows them to be integrated to the interior design – in particular the adjoining plasterboard-lined walls.

4.6.4.4 - Internal Spaces

Due to its sheer mass there are some obvious variations in the building resulting from the use of concrete as the primary structure, such as an increase in the size of footings. Its use, however, has little effect on the spatial attributes as the physical bulk of members is quite similar to timber.

4.6.4.5 - Atrium Stairs

Concrete stairs could be similar in arrangement to the timber stairs but with precast concrete strings, precast (perhaps coloured) concrete open treads and either timber balustrades, as for the Timber building, or with steel sheeting and RHS posts as for the Steel building. These would be expected to be expressive of the application of steel construction and to be finished to a high level as with the Timber option.

4.6.4.6 - Services

As with the Steel option, positioning of services fixtures and reticulation of pipework and cabling will be identical to the Timber building. Primary structural members will not be penetrated for services reticulation and many services components will be exposed to view, in an ordered fashion, to compliment the nature of the exposed structure.

4.6.4.7 - Linings & Cladding

Internal linings and finishes are similar to the Timber building except concrete elements will be clear finished, not painted out. As with the Steel option, alternative linings may be used in some of the areas which, for the timber building, were designated as plywood lined.

The approach to the external envelope, exterior cladding and windows remains unchanged from the Timber design.

4.6.4.8 - Insulation

The concrete shear panels provide less thermal insulation than their timber counterparts although, within the physical constraints of the structure, this can still be in excess of the requirements of the New Zealand Building Code. In other areas of the building, the external insulating envelope is unaffected by the change to concrete. The thermal mass of the concrete structure will assist in maintaining temperature equilibrium within the building and assisting energy efficiency.

The acoustic insulation remains unchanged from the timber solution. The same degree of acoustic absorbency is required to the underside of the floor structure and the same degree of acoustic and fire separation between spaces and at roof level is required and will be provided in a similar manner.

4.6.4.9 - Surfaces, Finishes and Detail

The exposed concrete will require a high level F5 finish. It is expected that a high level of attention will be paid to simplifying concrete detailing, and ensuring first class visual appearance of concrete work, infill timber and steel connections comparable to that achieved in the Timber building. An industrial level of construction would not be comparable or acceptable.

All exposed welds on steel connecting plates will be ground and all surfaces are to be smooth and ready for a clear finish. Steel connections, where required, will be exposed.

4.7 - The TimberLow Building

The TimberLow building design was derived to research the impact of making changes to the as-built Timber Arts and Media building in order to reduce the operational energy usage of the building, and to investigate whether the cost of such modifications would be offset by savings in the cost of energy usage over the life time of the building (see Chapter 5 - Building Energy). The structure and appearance of the TimberLow building are identical to the Timber building.

The building modifications were designed by Nicolas Perez, PhD candidate, at University of Canterbury, working closely with other experienced professionals, including services and design engineers from Aurecon Group in Christchurch. Perez's PhD thesis, which will be published in late 2011, will provide greater detail of the TimberLow building.

The major differences between the as-built Arts and Media building and the TimberLow design are the addition of more insulation and better glazing, as noted below:

- The addition of an extra insulation blanket (Pink batts Cosyfloor 450 R2.0) to all envelope walls (except for the shear walls), which has a nominal thickness of 70mm (but in the Arts and Media building was compressed to 60mm). This thermal insulation was added inside the existing wall which had an internal cavity of 150mm, so in the Timber building, 60mm was empty space with no insulation.
- The existing layer of 50mm of EPS was increased to 100mm EPS in all the externally-placed timber shear walls.
- To the roofs which had a thermal insulation blanket of 200mm thick R5.0 in the Timber building, an extra insulation blanket was added in the remaining 100mm empty space within the roof cavity. Thermal Insulation used was Pink Batt R2.2 Ceiling with a nominal thickness of 115mm compressed to 100mm to fit the available space.
- Modifications were made to the aluminium frames and the double glazing of all external windows, including the curtain wall in the North façade. The new frame is a PVC frame with double glazing with Argon gas inside the 10mm thick cavity between each of the glass panes of the double glazing kit. The glass used was a 4mm clear glass for the outside pane and a 4mm LowE glass for the inside pane.

Chapter 5 - Energy

5.1 - Introduction

This chapter covers the research to:

- Investigate the annual and (by extension) long-term energy use of the new NMIT Arts and Media building (1,980 m^2 gross floor area).
- Investigate the annual and long-term energy use of the alternative Concrete, Steel and TimberLow designs.
- Provide a thorough and soundly-based *estimate* for the yearly operational energy use of each building design (MWh) to input to the Life Cycle Costing study (Chapter 7) and Life Cycle Assessment analysis (Chapter 8).
- Assess the thermal comfort conditions within the four building designs using the Predicted Mean Vote index.
- Compare the energy use and 'comfort levels' of the different buildings year-on-year.

The research was carried out by Nicolas Perez, a Doctorate student in the Civil and Natural Resources Engineering department at University of Canterbury as part of his research on the influence of thermal mass on the space conditioning energy and indoor comfort conditions of buildings (Perez, pers. comm., 2011). Perez's thesis will be published in late 2011.

This chapter presents an outline of the research methodology used by Perez and an overview of the results.

Perez's thesis will include a Discussion and Conclusions section. However, this is not available for presentation in this document. The Discussion section that does appear at the end of this chapter contains points raised and debated between the authors, Perez and other co-researchers, in order to offer viewpoints on Perez's research prior to the publication of his thesis.

5.2 - Summary

Thorough and detailed investigation, coupled to extensive modelling using the Virtual Environment (VE) suite of performance and modelling software has provided detailed information on the predicted, on-going energy usage of the Arts and Media building, as well as that of three alternative building designs (Concrete, Steel and TimberLow buildings).

The research and modelling has been peer-reviewed by industry professionals, including leading building services engineers from Aurecon Group in New Zealand. Building performance models have been calibrated through the use of extensive energy and environmental monitoring data collected over the past 18 months in a building adjacent to the new Arts and Media building on the NMIT campus with similar size, aspect, use and occupancy.

Similar energy and environmental data will be available from monitoring equipment installed in the new Arts and Media building. This will be used in research work being undertaken through 2011 and 2012, to verify the validity and accuracy of energy performance models and energy predictions.

5.2.1 - Results

The research results show the annual energy use of the four building designs in Table 5.1.

Building	Total energy consumption (MWh/yr)
Timber (as-built Arts and Media building)	132.0
TimberLow	114.3
Concrete	133.1
Steel	134.7

Table 5.1: Total annual energy consumption (MWh/yr) for the Timber, TimberLow, Concrete and Steel buildings.

Differences in total annual energy consumption between the *as-built* Arts and Media building and the alternative Concrete and Steel designs are not significant. The TimberLow design could save around 15% of total annual energy consumption.

The Concrete building design offers the longest period of time within comfortable environmental conditions, whilst the TimberLow design offers the poorest environmental comfort conditions, with areas of the TimberLow building often predicted to be warm. (Note that the Arts and Media building, being an Educational facility has only low occupancy during the warmer summer months and hence does not have any form of air conditioning / cooling).

The results indicate that well-designed, timber multi-storey buildings can offer comparable total energy consumption and comfort conditions to conventional concrete and steel multi-storey buildings.

5.3 - Background

Operational energy cost – that is the monetary cost of using various forms of energy to occupy and run a building day-in, day-out, year after year - is extremely important, simply because energy is such a large part of the on-going cost associated with all buildings. With world-wide energy costs predicted to rise substantially in the future, the need to know - with a good degree of certainty - the cost of operating a building over a period of time is essential and, hence, is foremost in the minds of architects, engineers, building owners, tenants and business operators.

Highly sophisticated software modelling can provide the means to *predict* the energy use of a building before it is either built or commissioned. Alternative building designs can be compared. Design changes, such as the use of different building materials, to suit particular climates, different operations and desired indoor environments, etc. can be modelled. The level of 'confidence' in predicted energy use depends on the sophistication, flexibility and robustness of the modelling software, the model/s and the input data. Model calibration through the use of real operational data collected from similar buildings, preferably in a similar location can lead to a high degree of accuracy and certainty for predictions made on future energy usage

Closely monitoring energy use and the indoor environment of a building once it is built and operational enables energy use modelling to be checked, further calibrated and refined.

When calculating a building's life cycle energy consumption, the construction materials – both structural and finishing materials - have a direct effect on both the building's embodied energy and space conditioning (operational) energy, the latter depending, amongst other things, on the thermal characteristics of the materials. The combined thermal mass of all the building materials has an important influence on total energy consumption and comfort conditions.

The Virtual Environment (VE) suite of software from Integrated Environmental Solutions (IES)[1] is a world leading building performance and modelling tool and methodology used in this study to predict long-term energy use in the Arts and Media building and the alternative building designs. The analysis of each case study building includes the modelling of operational energy use with an emphasis on HVAC energy consumption and the assessment of indoor comfort conditions using Predicted Mean Vote (PMV).

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1 IES Virtual Environment performance analysis software is a first class suite of building simulation tools which allows architects/engineers to facilitate sustainable design throughout the entire process, particularly suited to creating understanding of the impact of different green design strategies.

The IES building performance modelling method enables an 'Integrated Design' approach, which helps enhance early stage analysis to quantify impact and ease the information exchange process. Physical, climatic and environmental factors and their interrelationships are taken into account, as is energy use, solar, lighting and material performance, allowing designers to 'virtually' test the feasibility of different energy saving strategies and new technologies.

Within VE-Pro, a variety of different interconnected modules and capabilities are available for use at any stage of the design process, so users can build the suite to meet their needs. Data can be easily shared amongst applications and the central model to integrate, inform and refine simulations. VE-Pro users can create a 3D model from scratch or from imported 2D DXF CAD data.

VE-Pro modules include Apache HVAC which performs the thermal analysis by simulating HVAC plant and control systems. Apache interacts with three modules which simulated different aspects of thermal performance (Solar shading and penetration [Suncast], HVAC systems and control [Apache HVAC] and natural ventilation and mixed mode systems [MacroFlo]). VE/Energy facilitates the design of low-impact energy systems.

Further information on VE software can be found at www.iesve.com

5.3.1 - How important is thermal mass in a building?

Perez's research (Perez, pers. comm., 2011) is aimed at determining the influence of thermal mass on space conditioning energy and indoor comfort levels in modern, multi-storey, commercial buildings. Such buildings have most of their thermal mass in primary structural elements. Based on common design practices, buildings which consider and introduce thermal mass in their HVAC design strategy, usually end up adding 'oversized' concrete structural elements. However, there are large environmental benefits in keeping structural systems light, as in the new Timber Arts and Media building (for instance, in term of greatly reduced foundations and lower embodied energy).

To achieve an optimum balance between the environmental impacts produced during a building's operations and the environmental impacts embodied in the building's materials, it is necessary to determine the most effective type and amount of thermal mass to incorporate in buildings.

Perez's research addresses the question of whether thermal mass in the form of massive timber structural components can provide effective thermal mass and the amount of thermal mass needed to influence thermal conditions in timber buildings, such as the new Arts and Media centre, in a way that this subsequently influences the performance of mechanical HVAC systems.

Perez's research will be available in the form of a University of Canterbury PhD thesis in the latter half of 2011.

5.4 - Modelling methodology

Modelling compares four designs, each of a three storey building providing generic space and facilities in the tertiary NMIT education institution – the *as-built* 1,980 m2 (gross floor area) Timber Arts and Media building, and three alternative virtual designs, the Concrete, Steel and TimberLow buildings. The latter was designed where insulation values of external walls and roof, as well as of glassing and window framing, were significantly increased to a level of best practice, to reduce the impact of heat losses.

5.4.1 - Notes on the Timber Arts and Media building design.

Detailed descriptions of the various building designs are given in Chapter 4 - The Buildings.

The following notes highlight features which are considered relevant to a consideration of energy use in the as-built Timber building.

The total gross floor area is 1,980 m^2, organised in three storeys occupied mostly by large studio rooms, performance spaces and administration offices, plus a large gallery and void spaces.

Large mass (by volume) LVL primary structural columns and beams and post-tensioned LVL shear walls have been used for earthquake resistance. The floor system includes a 75 mm concrete toping over an LVL board horizontally placed as permanent formwork and supported on LVL joists.

The building envelope is mostly light-weight insulated walls, although thick structural shear walls made of LVL are embedded in portions of the external walls in the East and West facades, reducing the external wall cavity space and subsequently the insulation values. There is a double glassed curtain wall on most of the North façade, and a large window area on the South façade; external glassing is double glassing on not-thermally-broken aluminium frame.

The Internal layout is largely consistent through all three storeys (there are some changes, mostly in room sizes) - see Figure 5.1.

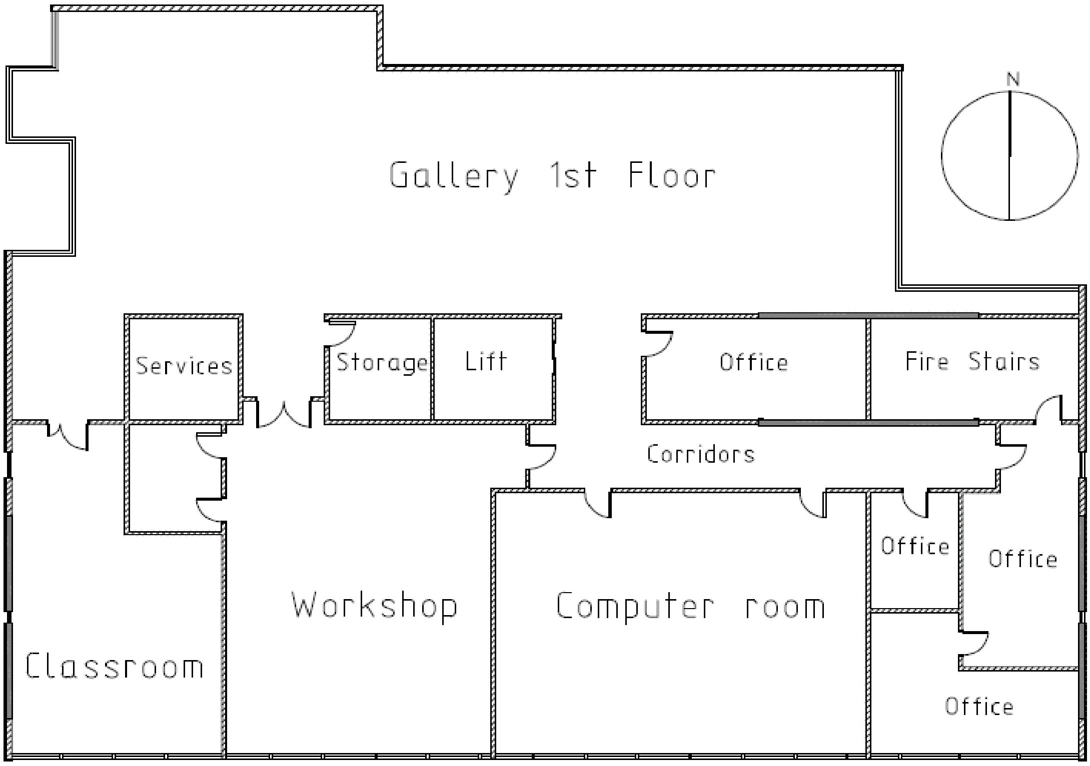


Figure 5.1: Plan section level 1 and level 2 of the Arts and Media building.

There is a long glazed area of the north wall (appropriately shaded by the roof overhang) that draws natural light into the main building through a full height gallery (see Figure 5.2). The gallery is three storeys tall and combines a series of enclosed rooms and open circulation spaces orientated and exposed to the gallery voids.

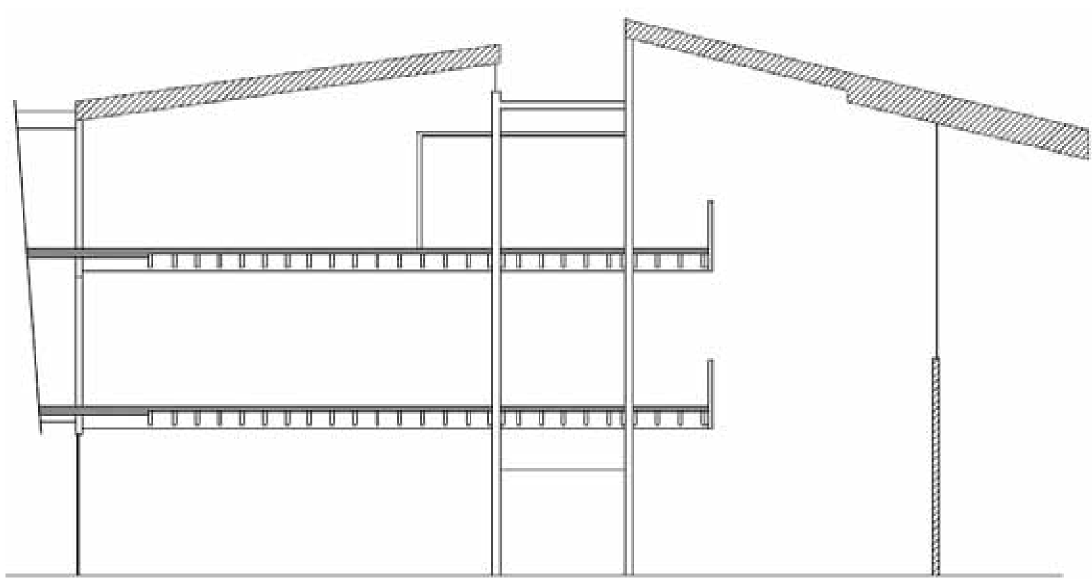


Figure 5.2: West elevation view and cross section of the Arts and media building.

The size of gallery space can be appreciated in Figure 5.2 where a transversal cross section of the Arts and Media building shows the full height of the gallery across the three floors. A large portion of the ground floor (Level 1) of the three storey building corresponds to the base of the North facing, three storey tall atrium/gallery space. The area occupied by the gallery void is less in the second and third floor than the area in the first floor.

The gallery is flanked by a narrow structural core containing relatively small rooms aligned together continuously from the East to the West façade of the building. This narrow service space is penetrated with linkages between the gallery and flexible multi-use seminar and studio spaces exposed to the South wall.

The building has a series of relatively large enclosed rooms exposed to the South façade normally occupied as studio or teaching areas and some offices especially in the first level. The south wall is conceived with large glass areas for drawing natural light into the studios. The upper level glazing leans out to become a "public gallery wall". The use of clear glass to maximise daylight also reveals a warm lively interior where the wooden multi-storey structure of floor/ceilings and walls is strongly apparent.

The particular design layout in the building is well integrated into the HVAC system where there is a well-planned integration of the gallery space to the air path of not only natural but also mechanical ventilation systems.

The extent of external glazing in the buildings is important and is summarised in Table 5.2.

Facade	External Wall Area (m^2)	External Glazed Area (m^2)	External Glazed to Wall Area Proportion (%)
North Facade	391	192	49
South Facade	475	323	68
East Facade	272	54	20
West Facade	284	58	21
High Level Roof Walls	97	16	17
Total	**1519**	**644**	**42**

Table 5.2: Arts and Media building area and external wall relevant data

There are large areas of glass in the envelope wall (42 %).

Due to a low R-Value, glassed areas have significant higher heat losses than those opaque areas of external walls which in the Arts and Media building are normally light weight insulated wall.

Due to large glazed area particularly on the South façade, the Arts and Media building does not have an optimized building envelope. There are large heat losses through the extensive glassed area in the South façade.

It is expected that the heat losses associated with glassed external wall areas of the Arts and Media building, particularly in the South façade, will penalize the energy performance of this building. It is also expected that when comparing the energy performance of the Timber, Concrete and Steel buildings, the influence of large glazed area will temper/moderate the difference in the energy comparison between these buildings.

In the TimberLow building, no structural or major architectural modifications were undertaken in comparison with the Timber building. However, the insulation values of the thermal envelope, in the existing external wall and including the roof were significantly increased to a level of best possible practice in New Zealand. As part of the upgrading of the thermal envelope, all external windows where changed from standard double gazing on not-thermally broken aluminium frame to double glazing windows with Argon gas in the cavity between the glass, and thermally broken PVC frames.

5.4.2 - Modelling - Construction Categories and Attributes

For the purposes of modelling, there are nine different constructions categories that are common to all four buildings, as follow:

- External wall
- Internal wall
- Suspended Ceilings
- Structural suspended floors
- Concrete suspended floor
- External overhang floor

- Roof
- Heated Slab
- Slab on ground

Windows have different thermal parameter sets than all nine other categories; all constructions categories except windows are considered opaque constructions where thermal capacitance, as defined by density, specific heat capacity, and thickness is a good representation of the capacity of the material to store heat and is used in the research as an approximation to a material's and subsequently a construction's thermal mass. Window constructions, by contrast, are to a good approximation mass-less, but they require properties characterising their solar transmission properties. The difference suggested between windows and opaque construction is predetermined by the Users Guides of the simulation tool used in this research (Integrated Environmental Solutions (IES) Ltd, 2009).

Each construction is characterized thermally by its resistance R and capacitance C. For all ten construction's categories previously introduced above, both resistance R and capacitance C were calculated. For materials with thermal conductivity of K, specific heat s, density ρ and thickness L, the thermal resistance R and capacitance C were calculated respectively according to the formulae:

$R = L/K$ and $C = \rho sL$

C unit is ($KJ/m^2.°K$) and R unit is (m^2K/W).

An external wall construction is a good example of how the total thermal resistance of a construction is handled in the modelling as an assembly of various different materials (see Figure 5.3) - the total capacitance is the result of the sum of all the individual capacitance values of each material in the construction assembly.

	R	C	R	C	R	C	R	C	R	C	R	C	R	C	∑R	∑C
External Light Wall	0.04	0.0	0.00	1.9	0.01	0.0	2.44	0.6	0.09	8.2	0.07	10.1	0.13	0.0	2.81	20.7
	Outside surface		Profiled Steel		Air Cavity		R2.8 Bridged Insulation		Timber (Pine)		Gypsum board		Inside surface			

Figure 5.3: Example of an external wall construction layer's and total R and C values

Table 5.3 offers a summary of the total R and C values of all constructions used in each building. Constructions are organized in each of the ten categories previously identified organised vertically by building. Some of the constructions are highlighted in grey - these are constructions that are unique for that particular building, whilst non-highlighted constructions are common to the four buildings. For instance, in 'Windows' constructions the same external glazing is used in the Timber, Concrete, and Steel buildings but an external glazing with a higher R-value is used in the TimberLow building (in grey).

TIMBER	∑R	∑C	CONCRETE	∑R	∑C	STEEL	∑R	∑C	TIMBER-LOW	∑R	∑C
Windows											
External glassing	0.25	15.0	External glazing	0.25	15.0	External glazing	0.25	15.0	PVC Frame Argon	0.50	15.0
Internal glassing	0.32	11.3	Internal glazing	0.32	11.3	Internal glazing	0.32	11.3	Internal glazing	0.32	11.3
External wall											
External light Wall	2.81	20.7	External light Wall	2.81	20.7	External light Wall	2.81	20.7	External light Wall - Low	4.55	21.2
External shear wall LVL	2.74	172.3	External shear wall Concrete	1.41	463.2				External shear wall LVL- Low	4.20	173.2
Internal wall											
Internal partitions light	2.70	26.0	Internal partitions light	2.70	26.0	Internal partitions light	2.70	26.0	Internal partitions light	2.70	26.0
Internal shear wall LVL	1.45	169.4	Internal shear wall Concrete	0.13	460.0				Internal shear wall LVL	1.45	169.4
Suspended celings											
Ceiling Gib	2.70	30.7	Ceiling Gib	2.70	30.7	Ceiling Gib	2.70	30.7	Ceiling Gib	2.70	30.7
Ceiling Acoustic	0.31	19.6	Ceiling Acoustic	0.31	19.6	Ceiling Acoustic	0.31	19.6	Ceiling Accoustic	0.31	19.6
Structural suspended floor											
Potius Carpet	1.12	248.3	Interspan Carpet	0.73	245.4	Comflor Carpet	0.42	284.4	Potius Carpet	1.12	248.3
Potius Vinyl	0.78	249.0	Interspa Vinyl	0.40	246.1	Comflor Vinyl	0.08	285.1	Potius Vinyl	0.78	249.0
Concrete suspended floor											
Suspended Concrete floor	0.13	428.4	Suspended Concrete floor	0.13	428.4	Suspended Concrete floor	0.13	428.4	Suspended Concrete floor	0.13	428.4
External overhang floor											
Floor Cantiliever Ligt	5.07	196.7	Floor Cantiliever Ligt	5.07	196.7	Floor Cantiliever Ligt	5.07	196.7	Floor Cantiliever Ligt	5.07	196.7
Floor Cantiliever Heavy	5.15	461.2	Floor Cantiliever Heavy	5.15	461.2	Floor Cantiliever Heavy	5.15	461.2	Floor Cantiliever Heavy	5.15	461.2
Roof											
Roof Timber	5.12	55.9	Roof Timber	5.12	55.9	Roof Timber	5.12	55.9	Roof Timber-Low	9.41	48.0
			Roof Steel	4.01	28.5	Roof Steel	4.01	28.5			
Heated slab											
Heated slab Vinyl	0.09	106.5	Heated slab Vinyl	0.09	106.5	Heated slab Vinyl	0.09	106.5	Heated slab Vinyl	0.09	106.5
Heated slab Clear	0.09	105.6	Heated slab Clear	0.09	105.6	Heated slab Clear	0.09	105.6	Heated slab Clear	0.09	105.6
Slab on gound											
Slab on Ground	3.44	1545.9	Slab on Ground	3.44	1545.9	Slab on Ground	3.44	1545.9	Slab on Ground	3.44	1545.9

Table 5.3: Timber, Concrete, Steel and TimberLow buildings, material's R and C values

- The materials quantities in all four case study buildings in this research were calculated. The structural and architectural design of the Timber, Concrete, Steel and TimberLow buildings were reviewed and analysed by a Quantity Surveyor consultant (QS), Davis Langdon.
- For each of the four buildings, a schedule was produced by the QS in which the quantities of eleven different construction materials were calculated. Every material in the schedule was then apportioned to the appropriate construction element where the material was present. The volume and weight (tonnes) of the material was given for each of the construction elements.
- The eleven construction materials were: concrete, reinforced steel, structural steel, other steel, glass, timber, aluminium, plasterboards, paints, particleboard/fibreboard, and insulation. In the case of the Timber and TimberLow buildings, LVL was added to the list.
- From the schedule of materials produced by the QS, the volume and weight of all structural elements in the primary structural system of the Timber and TimberLow, Concrete and Steel buildings was obtained. This is used for mass volume calculation of shear walls and in the floor systems.
- Note that there was an intentional architectural design decision to expose the main LVL structural elements. This same design concept – to expose structural elements - was applied to the alternative designs.
- Building's structural elements have the potential to become active sources of thermal mass, when these are exposed to habitable spaces. Exposed thermal mass has an effect on the performance of HVAC equipment and subsequently on space conditioning energy consumption.
- For each habitable and conditioned space in the Arts and Media Timber and Timber-Low, and Concrete buildings, the volume of exposed LVL and Concrete respectively from structural columns, beams, and rafters was calculated.
- In order to be able to include the volumes of materials in structural elements into the energy modelling, an interior stand-alone wall with a volume equal to that in exposed structural elements was added to each habitable and conditioned room in the model.

5.5 - Model parameters

5.5.1 - Location and weather data

The weather data used in energy performance simulation are typical meteorological values generated from a data bank collected historically over many years, known as a Typical Meteorological Year (TMY). As the Arts and Media building is located in Nelson, all comparisons were carried out using the TMY file for Nelson.

The Nelson region (Nelson Marlborough) is the sunniest region in New Zealand, with warm, dry and settled weather predominating during summer and usually mild winter days (NIWA National Institute of Water & Atmospheric Research, 2011). Nelson has less wind than many other urban centres in New Zealand and its temperatures are often moderated by sea breezes.

Typical summer daytime maximum air temperatures in Nelson range from 20°C to 26°C, but occasionally rise above 30°C. Typical winter daytime maximum air temperatures range from 10°C to 15°C. Mean annual temperature in Nelson is 12.6°C, with an annual highest temperature of 36.6 °C and a lowest of -6.6 °C.

5.5.2 - Occupancy and operation

The Arts and Media building is an educational building, so all four buildings were simulated using schedules of occupancy, lighting, equipments, and HVAC operation, based on schedules developed for School buildings recommended in NZS 4243:2007.

In VE, schedules are created as profile used as control switch, values greater than 50% are interpreted as "on" and other values as "off", values in schedules are either 100 or 0 % to represent "on" and "off" periods respectively.

Schedule 1: Building occupancy and HVAC plant operation					
	12am-8am	8am-11am	11am-6pm	6pm-10pm	10pm-12am
Week	0%	100%	0%	0%	0%
Saturday	0%	100%	0%	0%	0%
Sunday	0%	0%	0%	0%	0%
Schedule 2: Heated slab					
	12am-8am	8am-11am	11am-6pm	6pm-10pm	10pm-12am
Week	0%	100%	100%	0%	0%
Saturday	0%	100%	100%	0%	0%
Sunday	0%	0%	0%	0%	0%

Table 5.4: Schedules used in Virtual Environment to define Daily and Weekly operations.

Two main daily schedules were developed to be used in simulations. Table 5.4 shows Schedule 1 for building occupancy and HVAC plant operation and Schedule 2 which is produce for the HVAC heated slab operation. Schedule 1 is not only used to determine occupancy and HVAC plant operation, but also to determine daily lighting and office equipments operations. Schedule 2 is a variation of Schedule 1 and is used to turn on the heated slab one hour earlier than all applications in Schedule 1.

Daily profiles cover only a period of one day. Daily profiles are used as building blocks to create time variation patterns over longer periods. Table 5.4 shows the daily schedules for week days and also for Saturdays and Sundays. Occupancy and HVAC operations of buildings in this research include Saturday from 9am until 6pm, but on Sunday there is no occupancy or operations.

Educational buildings in New Zealand are not expected to operate during most of the summer period; because of no occupancy during summer period, cooling is normally not required for most of the teaching facilities and offices, and cooling is only made available in lecture theatres or computer laboratories because of large internal gains produced by high occupancy and/or equipment.

Annual Schedules	Start		End	
	Day	Month	Day	Month
Schedule 1: Building occupancy and HVAC plant operation	7th	Feb	25th	November
Schedule 2: Heated slab - heating in general	1st	May	31st	October

Table 5.5: Schedules used in Virtual Environment to define annual operations.

Table 5.5 shows the annual schedules produced when daily schedules in Table 5.4 are organized annually. It can be seen that, because of summer break, occupancy and HVAC plant operation are “off” from the 25th of November until the 7th of February of the following year; the total period where the buildings operates is approximately 10 months. Also in Table 5.5, heating only operates 6 months (1st of May until 31st of October); central boilers are “off” during the warmest six months of the year.

5.5.3 - Room thermal templates

Thermal modelling methodology combines room thermal conditions in all the spaces in the model and an HVAC system operating in conditioned spaces only. Thermal conditions were prearranged in thermal templates which were subsequently applied to all conditioned and unconditioned spaces in the building. Spaces inside the building’s thermal envelope where a thermal template has been assigned became thermal zones; thermal templates hold specific data for heat gains, lighting density and infiltration.

Building Thermal Templates	Internal Gains			
	People			Equipment
	Occupant Density (m^2/Person)	Sensible Gain (W/Person)	Latent Gain (W/Person)	Sensible Gain (W/M^2)
Classroom	6.5	63.0	54.0	0.0
Computer room	6.5	63.0	54.0	8.1
Gallery	23.3	63.0	54.0	0.0
Office	23.3	63.0	54.0	8.1
Storage & Circulation	0.0	0.0	0.0	0.0
Toilets	0.0	0.0	0.0	0.0
Unoccupied & Voids & Mass	0.0	0.0	0.0	0.0

Table 5.6: Internal gains assigned to thermal templates used in simulation

The HVAC system designed for the Arts and Media building was reproduced in Apache HVAC and was superimposed on conditioned spaces in the model (Mechanically ventilated spaces are included in the Conditioned spaces category). There are seven different thermal templates used in the modelling of all four buildings, as shown in Table 5.6, along with their respective internal gains associated with People and Equipment.

Internal gains are produced mainly by people and to a lesser extent by equipment and lighting. People's internal gains are either latent or sensible, sensible gains correspond to a 56 % and Latent gains to a 46 % of the People space gain component. Occupancy is approximately 170 people in total: 50 people in the first floor, 57 people in the second floor, and 63 people in the third floor. Regularly occupied space per person is 10 m^2 and average density corresponds to 0.1 people per m^2.

Storage and Circulation, and Toilet thermal zones have no internal gains apart from lighting. Only Unoccupied & Voids & Mass thermal zones have no internal gains at all (such thermal template is used in thermal zones where thermal conditions are completely derived from adjacent thermal zones and in some cases these act as thermal 'buffer', i.e. thermal zones between Suspended Ceiling and Structural suspended Floors).

Infiltration is set to be 0.25 air changes per hours (ac/hr) in all rooms located adjacent to the building thermal envelope, and is 0 ac/hr in fully internal rooms (Standards New Zealand, 2006b). Internal gains associated with equipment only exist in the computer room and in all office spaces.

5.5.4 - Lighting Data

Table 5.7 specifies luminance values (lux) per square meter of floor area assigned to each thermal template, where luminance values were set in accordance with NZS 4243: Part 2: Lighting (Standards New Zealand, 2007b). A dimming profile was created in VE to allow for external natural light to be equated into the luminance per square meter calculation. When enough natural light is available inside a thermal zone, VE will cap the total luminance value diming electric lighting (in such cases, electric consumption associated with lighting is not constant and fluctuates during the day).

The installed power density in Table 5.7 is used to calculate the total sensible gains. Total sensible gains are the result of the installed power density multiply by total illuminance.

5.5.5 - Conditioned and unconditioned thermal zones

All spaces in the VE models of all four buildings are set up as thermal zones with their respective thermal templates assigned. Thermal zones are then superimposed with an HVAC system which has been represented in an Apache HVAC model that defines the heating, ventilation and air conditioning system operating in all conditioned thermal zones.

Building Thermal Templates	Lighting	
	Total Illuminance Natural & Electric (Lux)	Sensible Gain (W/M^2)
Classroom	500	19
Computer room	500	19
Gallery	150	6
Office	500	19
Storage & Circulation	150	6
Toilets	150	6
Unoccupied & Voids & Mass	0	0
Installed Power Density		3.8 W/M^2/(Lux)

Table 5.7: Thermal template's luminance and lighting power density.

5.6 - Modelling of the HVAC system in VE Apache HVAC tool.

Operational energy use and the indoor comfort conditions were modelled using Virtual Environment Apache tool and particularly to model the HVAC system of the buildings in this research, the Apache HVAC tool was used. . As demonstrated above, a great level of detail and care was used to model the HVAC system of the actual Arts and Media building in order to examine – and predict - the expected performance of the building and the HVAC system when this was coupled together with the building model created.

The HVAC system in the actual building includes radiant heating systems, mechanical supply and extraction of air, and a heat recovery unit in the mechanical ventilation system. Only one computer room has mechanical cooling.

Simulations were produced for all building designs to assess the influence of thermal mass. For buildings using predominantly timber as the main structural component, the base scenario was where the insulation level of the envelope, roof, and windows, was sufficient to comply with the New Zealand Building Code. In the second scenario, TimberLow, insulation values were significantly increased to a level of best practice, to reduce the impact of heat losses on the comparison.

The following section outlines the main components of the modelling as carried out in the Apache HVAC tool.

5.6.1 - Overview HVAC system

The HVAC system in the actual Arts and Media building includes mechanical ventilation provided by a centralized Air Handling Unit (AHU), combining supply (2,060 lt/sec) and return of air (2,060 lt/sec). During the low temperature winter period, introduced external air can be warmed up to 27 °C by a hydronic heating coil (45 kW capacity). A heat exchange unit works in winter conditions recovering heat from warm return air.

Heating in Level 1 (ground-floor) is provided mostly by a hydronic heated slab (total capacity 26 kW). Heating in Level 2 and Level 3 is provided by hot water radiators (total heating capacity in Level 2 is 44 kW and in Level 3 43 kW). There is an Air Conditioning unit in the Computer room providing both convective heating and cooling (the computer room, 85 m^2 located in Level 1 is the only room with cooling). Heating coil capacity is 12.6 kW and cooling coil capacity is 10.3 kW.

Hot water is sourced from a Diesel boiler with a capacity to deliver up to 200 kW at 80% efficiency and cooling in the Computer room is sourced from an electric air cooled chiller with a cooling capacity of 30 kW.

Figure 5.4 shows the schematic of the HVAC system in the actual Arts and Media building, created in the VE Apache HVAC tool. It can be seen that the Air Handling Unit supplies air through a network integrated mainly by rooms and air connectors. Supply fans directly supply air to rooms in the south façade of Level 1, Level 2, and Level 3 respectively. Each individual Level is subdivided into segments representing the flow of air through each floor from air supplied via 'Segment A' through 'Segments B', and 'Segment C', to final air return via 'Segment D'.

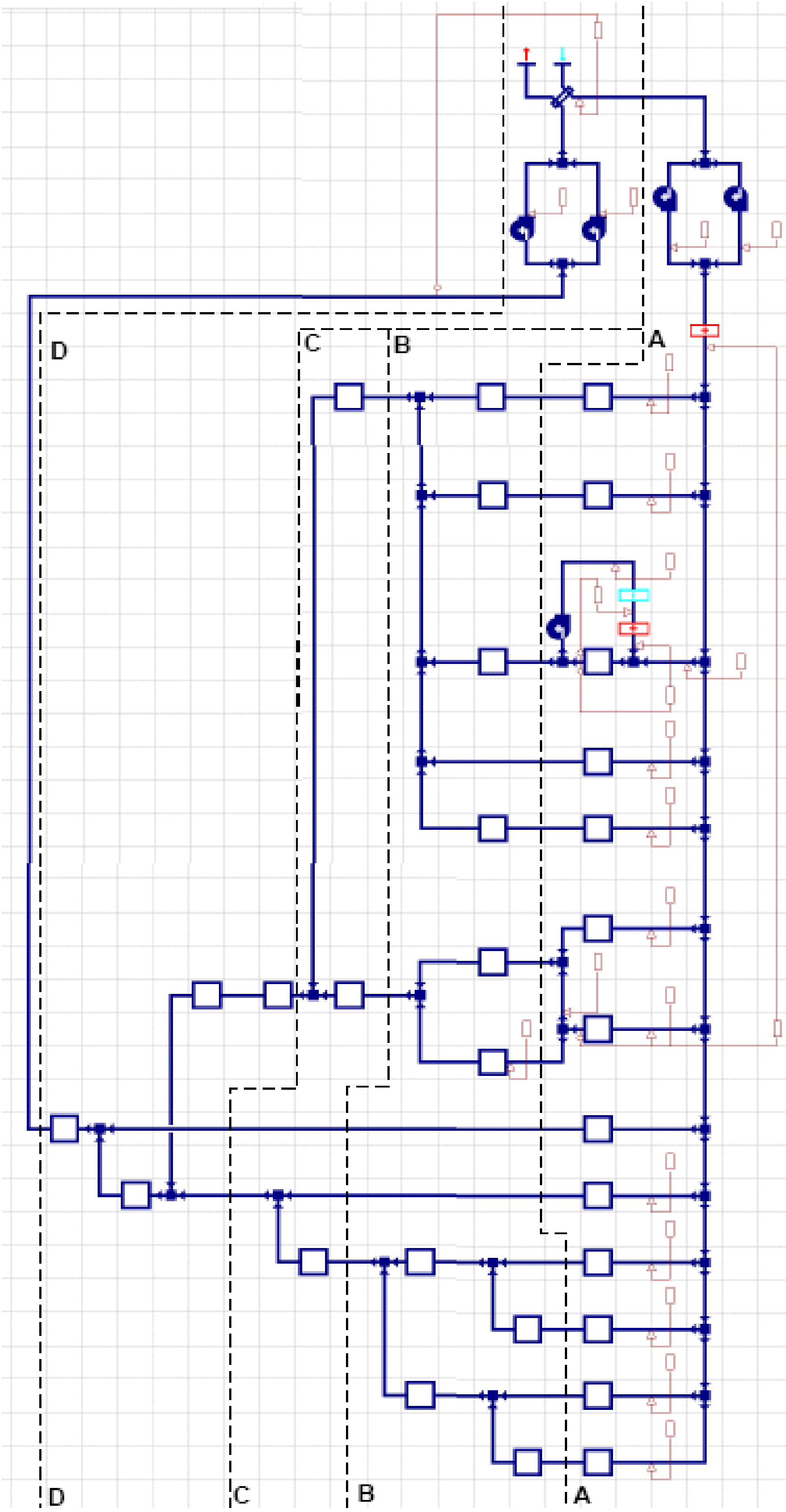


Figure 5.4: Schematic of the Mechanical ventilation system with heat recovery unit and underfloor heating network in Virtual Environment's Apache HVAC tool.

5.6.2 - Ventilation (Mechanical and Natural)

The building's internal layout can be simply subdivided into three areas; the full height gallery space adjacent to the North wall, the flexible multi-use seminar and studio spaces adjacent to the South wall, and the narrow structural core in between the gallery spaces and the spaces towards the South wall. The narrow structural core has a suspended ceiling above the occupied space that creates a built in 'plenum space' in between the suspended ceiling, below, and the structural floor, above. There are space linkages between the gallery space on the North and rooms in the South part of the building, and the plenum in that area is used as an air connector creating a path for mechanically supplied air to migrate from the rooms in the South part of the building to rooms in the North part of the building. The air finally flows through the gallery void up to the third floor of the galley where it is extracted. There is a single return air duct, extracting air from the top of the gallery and directing it through the heat recovery unit, placed in the central Air Handling Unit, before the air is exhausted to the exterior.

Together with mechanical ventilation, most of the rooms exposed to the South, East and West wall façades can incorporate natural ventilation for cooling purpose by opening specifically placed openable windows. Natural ventilation in the gallery space is limited to openable windows in Level 1 of the gallery in the East and West ends of it, and openable windows placed at the top of the gallery (abode the suspended ceilings of Level 3) not only in the East and West walls but also in a portion of external wall of the gallery that at that height, face South. The main entrance to the building is located in Level 1 at the West end of the gallery and there is a secondary entrance in the same level but at the East end of the gallery. Both entrances combine doors and openable windows. There are no openable windows in the North façade.

5.6.3 - Heating

Table 5.8 also shows radiant heating capacities for each conditioned room. Water systems are used for heating. Although hot water is used mostly for radiant heating systems such as heated slab, and radiators, there is also convective heating using hydronic heating coils to warm outdoor incoming air in the Air Handling Unit, or as heating coil into the Air Conditioning unit in the computer room(both convective heating sources are not reflected in Chapter 1 -).

There are two radiant heating systems:

- The hydronic heated slab in Level 1 (capacity of 26 kW), to heat spaces in Level 1, including the heated slab in the base of the full height gallery space.
- Hot water radiators in Level 2 and Level 3, used, not only in fully enclosed rooms in the South and North part of the building, but also in corridor spaces open to the gallery void.

There are two boilers supplying the Arts and Media building - one diesel boiler for heating of the building and one electric boiler for domestic hot water (DHW) production. The diesel boiler has a capacity to deliver up to 200 kW of heat at 80% efficiency; the total heating capacity of the system in place (including radiant and concoctive heating) is approximately 170 kW. The boiler for DHW is an electric boiler with a capacity of 50 kW at 80% efficiency.

(Note that both boilers in the Apache HVAC model are placed just outside the building thermal envelope).

5.6.4 - Cooling

The only cooling system in the Arts and Media building is supplied by the Air Conditioning unit in the Computer room. The hydronic cooling coil capacity is 10.3 kW and cooling is sourced from an electric air cooled chiller with a cooling capacity of 30 kW.

Due to very limited occupancy during summer, the cooling coil is designed mostly to overcome large internal gains produce by high occupancy, computers and other equipments such as printers and photocopiers during any occupied period.

Thermal template & Room name	Mechanical Ventilation			Radiant heating			
	Supply (L/s)		Return (L/s)	Radiators			Underfloor heating (kW)
	Direct	Indirect		R - 1 (4.6 kW)	R - 2 (3.8 kW)	R - 3 (2.7 kW)	
Level 1							
Computer room							
Computer	250						
Office_Core							
Interview	30						0.6
DB-Comms							
Reception-Mail	30						2.2
Office_Perimeter							
Staff-Program leader							1.3
Head of Sch-Prg led.							1.2
Classroom_Perimeter							
Textile	125						5.0
Seminar	125						3.4
Gallery							
Gallery 1st Floor		560	560				12.3
Σ	560	560	560	0.0	0.0	0.0	26.0
Level 2							
Gallery							
Gallery Void			750				
Landing-Gallery		750		4.6	3.8		
Office_Perimeter							
Staff	125			4.6			
Classroom_Perimeter							
Studio	625				23.0	8.1	
Toilets							
DB-Toilet							
Toilets-Storage							
Σ	750	750	750.0	9.2	26.9	8.1	0.0
Level 3							
Office_Perimeter							
Staff meet	125				3.8		
Staff	125			4.6			
Classroom_Perimeter							
Drawing Central	125				3.8	2.7	
Drawings West	125				3.8	2.7	
Studio seminar	125			4.6	3.8		
Drawings East	125			4.6	3.8		
Gallery							
Ceiling-Roof_Staff			2060				
Ceiling-Roof_Gallery							
Gallery		750		4.6			
L3_Void							
Toilets							
DB-Toilets							
Toilet-Storage							
Σ	750	750	2060	18.4	19.2	5.4	0.0

Table 5.8: Arts and Media building's mechanical ventilation and radiant heating data.

Table 5.8 shows the specific flow of mechanically supplied air into each conditioned space in the actual Arts and Media building (data is organized by levels).

5.6.5 - HVAC temperature control set points.

The conditions in the Level 2 Studio space determines the dry-bulb temperature of the air delivered to all other rooms with mechanical air supply from the AHU in the Arts and Media building. Temperature is controlled by a thermostat with a set-point of 20°C and a dead-band of 2°C - meaning that temperature in that room during winter conditions will fluctuate between 19°C and 21°C.

Dry-bulb temperature in rooms with under-floor heated slab in Level 1 is controlled by a thermostat with set-point of 22°C and a dead-band of 2°C.

Dry-bulb temperature in rooms with radiators (Level 2 and Level 3) is controlled by thermostatic radiator valves which control the flow of hot water through the radiator (set-point 22°C and dead-band 2°C).

There are both a heating (set-point 22°C, dead-band 2°C) and a cooling (set-point 23°C, dead-band 2°C) coil in the Computer room.

5.7 - Methodology for Assessment of building's thermal comfort conditions.

The assessment method used in this research is Predicted Mean Vote (PMV).

Comfort Parameters			
Clothing Levels:	0.61	clo	Trouser, long-sleeve shirt
Activity Levels:	80	W/M^2	Office activity: filing, standing
Air Speed:	0.1	M/s	

Table 5.9: Comfort parameters for PMV calculations –Default values.

PMV is defined in ANSI/ASHRAE Standard 55-2004: An index that predicts the mean value of the votes of a large group of persons on the seven-point thermal sensation scale, being: cold, cool, slightly cool, neutral, slightly warm, warm, and hot (American Society of Heating Refrigerating and Air-Conditioning Engineers Inc, 2004).

1 shows the comfort parameters for clothing levels, activity levels, and air speed. These parameters were taken by default from VE software.

- Activity levels describes the energy generated inside the body due to metabolic activity, defined as 58.2 W/m^2, which is equal to the energy produced per unit surface area of an average person, seated at rest. The surface area of an average person is 1.8 m^2.
- In the clothing levels the unit used is clo, which is a unit used to express the thermal insulation provided by clothing ensembles (1 clo =0.155m^2 °C/W).

Thermal Sensation Scale	
+ 3	hot
+ 2	warm
+ 1	slightly warm
0	neutral
- 1	slightly cool
- 2	cool
- 3	cold

Table 5.10: Comfort parameters for PMV calculations –Default values.

The ASHRAE thermal sensation scale, which was developed for use in quantifying people's thermal sensation, is defined in Table 5.10 (American Society of Heating Refrigerating and Air-Conditioning Engineers Inc, 2004). The

PMV model uses heat balance principles to relate metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity, to the average response of people on the scale in Table 5.10. The ANSI/ASHRAE Standard 55-2004 suggest a acceptable thermal environment for general comfort in the range of PMV from -0.5 PMV to +0.5 PMV (American Society of Heating Refrigerating and Air-Conditioning Engineers Inc, 2004).

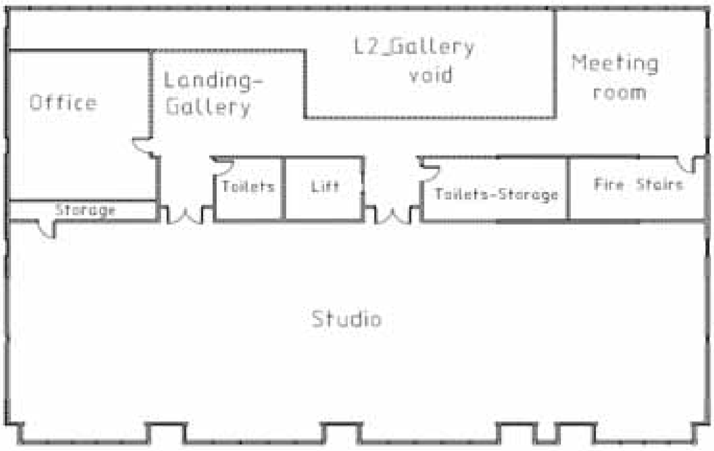


Figure 5.5: Plan section Level 2 of the Arts and Media building with the specified rooms where PMV has been assessed.

Assessment of PMV was carried out in only three rooms in the Arts and Media building (Figure 5.5). All three rooms are located in level 2 of the building. Landing-Gallery room (number 1) is a composite space interconnecting three zones/rooms in level 2, the rooms connected are: the stairs landing space, balcony/corridor between the landing space and the meeting room on the North West corner of the building, and the meeting room in the North East corner of the building. There is an office space in the North West corner called Staff, which has been also assessed using PMV and is tagged with a number 2. Assessment using PMV of a room located in the South façade of the building was undertaken in the Studio room.

5.8 - Results

5.8.1 - Assessment of building operational performance

Table 5.11 shows the total end-use energy consumption for the Timber, Concrete, Steel and TimberLow buildings (Mwh/yr).

	Timber		**Concrete**		**Steel**		**TimberLow**	
	Thermal	Electric	Thermal	Electric	Thermal	Electric	Thermal	Electric
Heating	75.6	-	76.7	-	78.3	-	57.3	-
DHW	-	20.1	-	20.1	-	20.1	-	20.1
Chillers	-	1.8	-	1.7	-	1.9	-	2.4
Fans	-	5.7	-	5.7	-	5.7	-	5.7
Lights	-	21.3	-	21.3	-	21.3	-	21.3
Equipment	-	7.5	-	7.5	-	7.5	-	7.5
Sub-total	75.6	56.4	76.7	56.3	78.3	56.5	57.3	57.0
Total (MWh/yr)	**132**		**133.1**		**134.7**		**114.3**	
Energy (kWh/M²/yr)	**78**		**78.6**		**79.6**		**67.5**	
(Gross floor area 1,980 M²; net lettable area 1,693 M²)								

Table 5.11: Total annual and end-use energy consumption for the Timber, Concrete, Steel and TimerLow buildings.

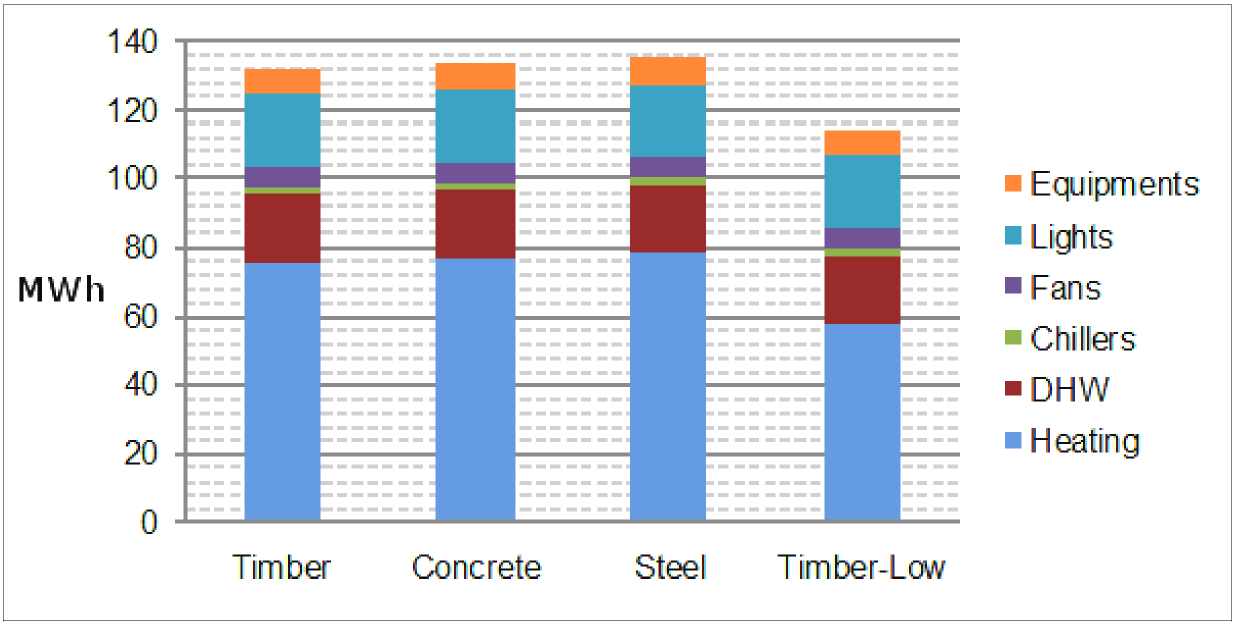


Figure 5.6: Total annual energy consumption broken down into end-use energy consumption for the Timber, Concrete, Steel and TimberLow buildings.

Figure 5.6 shows the total annual energy consumption for each building divided into end-uses.

Each of the energy end-uses in Figure 5.6 is a sum of different smaller components.

- Heating: Space conditioning boilers energy, and Distribution pumps energy.
- Domestic hot water (DHW): DHW boilers energy, and DHW auxiliary energy.
- Chillers: Chillers energy, and chillers auxiliary energy.
- Fans: Distribution fans energy.
- Lights: Lights electricity
- Equipments: Room equipments electricity

Table 5.11 shows that differences between total energy consumption between the Timber, Concrete and Steel buildings are not significant. Only the Timber-low building has a significant difference when compared with the Timber, or the Concrete, or the Steel buildings respectively.

The Timber building's total energy consumption is 1% lower than the total energy consumption of the Concrete building and 2% lower than in the Steel building. The TimberLow building's total energy consumption is 13% lower than the total energy consumption of the Timber building, this difference is 14% of the Concrete building and 15% of the Steel building.

It can be seen in Table 5.11 that DHW, Fans, Lights, and Equipments energy consumption is the same in all four case study buildings in. Differences are in Heating and less significantly in Chillers energy consumption.

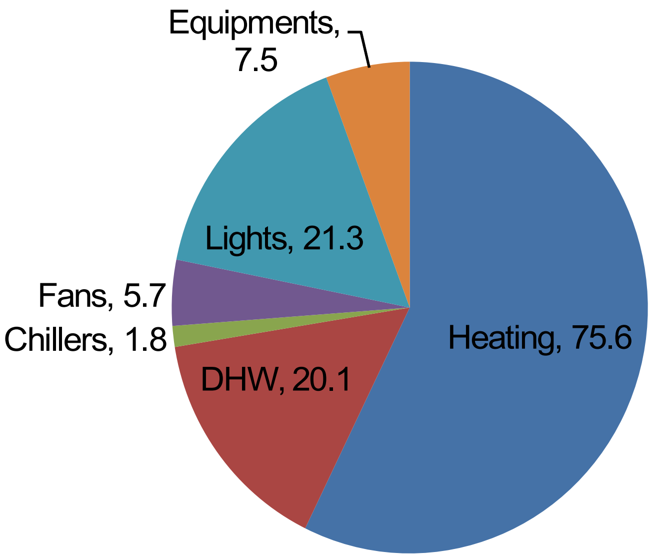


Figure 5.7: Timber building energy consumption by end-use (MWh/yr).

Figure 5.7 shows the relative proportion of each energy end-use in the Timber building. Heating is by far the largest energy consumer of all energy end-uses with an energy consumption of 75.6 MWh/year which is equivalent to a 57% of the total energy consumption of that particular building. Lighting and DHW contribute very similar energy consumption, being 21.3 and 20.1 MWh/year respectively and represent 16% and 15% of the total energy consumption in the Timber building respectively. Equipments represent a 7.5 %, Fans a 5.7 % and Chillers only a 1.8% of the total energy consumption in the Timber building.The Concrete and Steel buildings show a similar pattern, Figure 5.8 and Figure 5.9.

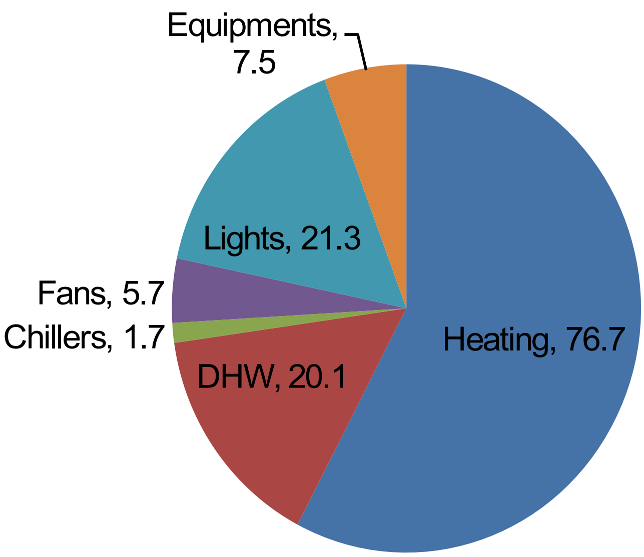


Figure 5.8: Concrete building energy consumption by end-use (MWh/yr).

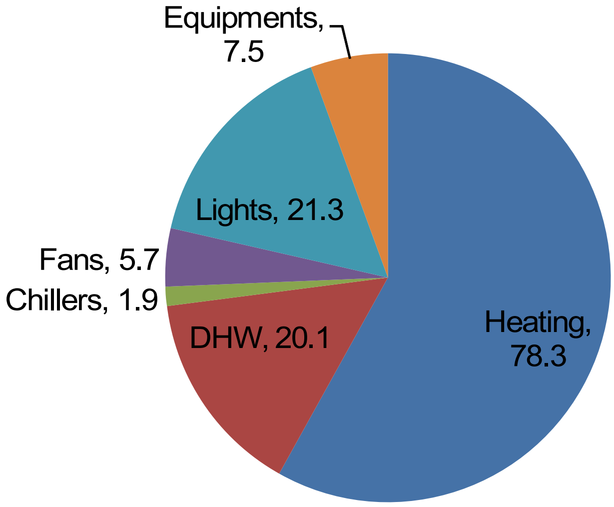


Figure 5.9: Steel building energy consumption by end-use (MWh/yr).

Figure 5.10 shows the relative proportion of each energy end-use in the TimberLow building. In this building, heating is the largest energy consumer of all energy end-uses with an energy consumption of 57.3 MWh/year, which is equivalent to 50% of the total energy consumption of that particular building. Lighting and DHW energy consumption are 21.3 and 20.1 MWh/year respectively and represent 19% and 17% of the total energy consumption. Equipment represents 7 %, Fans 5 % and Chillers only 2 % of the total energy consumption in the TimberLow building.

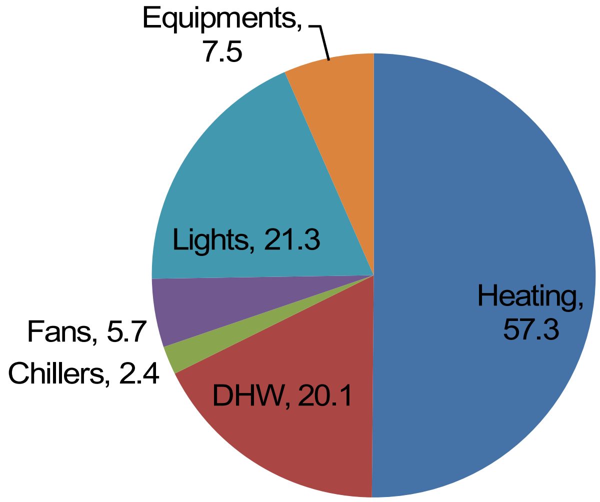


Figure 5.10: TimberLow building energy consumption by end-use (MWh/yr).

Heating only in the TimberLow building is 24 % lower than in the Timber building, 26% lower than in the Concrete building and 28% lower than in the Steel building. Conversely, in the TimberLow building, the Chillers energy consumption, although being at a very low level, is higher by 23 % compared with the Timber building, by 27% compared with the Concrete building, and by 21 % when compared with the Steel building.

All four buildings are considered to be low-energy consumption buildings with the predicted average energy consumption of the Timber, Concrete, Steel, and TimberLow buildings analysed all below 80 kWh/m^2/yr.

The New Zealand Green Building Council provides the newest energy use target in the New Zealand Green Star sustainability rating tool. Green Star was launched in 2007 and rates the 'sustainability' of new and refurbished office buildings in New Zealand. It is a conditional requirement for obtaining a NZ Green Star, that a base building design achieves an energy use figure of 120 kWh/m^2/yr or less using the modelling method in NZS 4243/4218 (NZ Green Building Council, 2008).

There is a tendency in simulations that the outcomes produced are lower than the audited energy consumption during occupancy. It is not the aim of this thesis to identify the reasons for the gap between the predicted and audited outcomes, however, a figure of 84-86 kWh/m^2.yr is well below the Standards New Zealand (NZS) 4220:1982, Property Council of New Zealand and the NZ Green Building Council benchmarks.

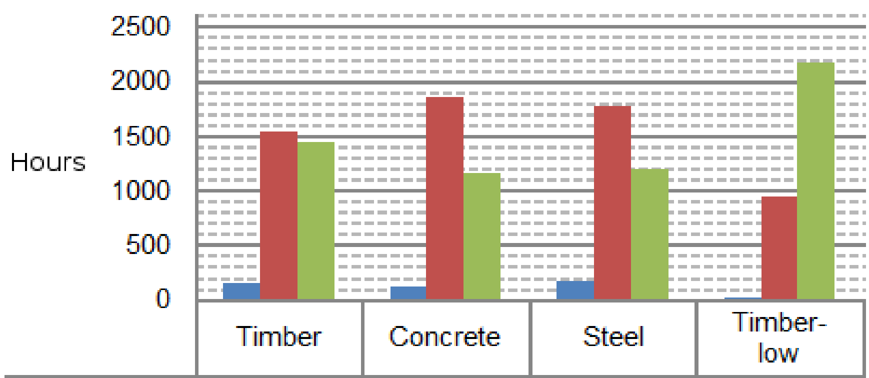
5.8.2 - Assessment of the building's thermal comfort conditions.

Figure 5.11, Figure 5.12 and Figure 5.13 show the PMV results for the three rooms specified in Figure 5.5; Level 2 Landing-Gallery space (number 1), Level 2 Staff room (number 2) and Level 2 Studio room (number 3) respectively. A PMV model has been undertaken for the same three rooms in the Timber, Concrete, Steel, and TimberLow buildings. Figure 5.11, Figure 5.12 and Figure 5.13 results are segregated in three categories:

- Hours of the building's occupied time throughout one year in which the specified space score -0.5 PMV or less (< -0.5). Thermal sensation of hours in this category range from slightly cool to cold.

- Hours of the building's occupied time throughout one year in which the specified space remind in a band of PMV between a comfortable range between -0.5 and 0.5 (-0.50 to 0.50). Thermal sensation of hours in this category is neutral, in other words comfortable.

- Hours of the building's occupied time throughout one year in which the specified space scores PMV +0.50 or more (> 0.50). Thermal sensation of hours in this category range from slightly warm, to hot.



	Timber	Concrete	Steel	Timber-low
< -0.50	152	124	170	14
-0.50 to 0.50	1534	1848	1776	942
> 0.50	1444	1159	1185	2175

Figure 5.11: PMV of Landing-Gallery room in level 2, North façade.

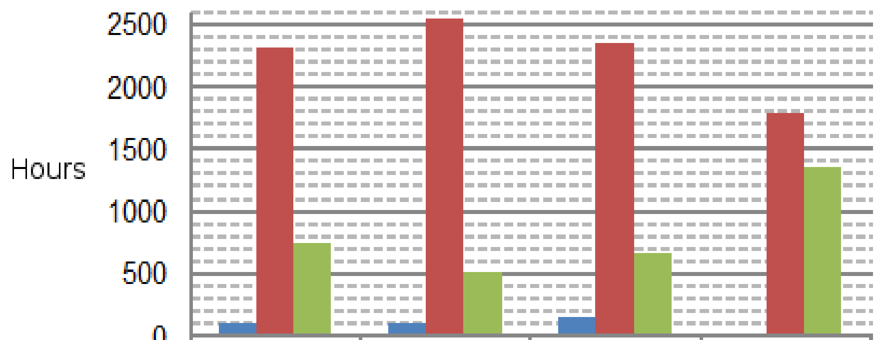
Figure 5.11 shows the results from the PMV modelling of the Landing-Gallery room in the Timber, Concrete, Steel, and TimberLow buildings. The Concrete building has the longest period of time within comfortable environmental conditions, followed closely by the Steel building with 4% fewer hours in the range of comfortable environmental conditions when compared with the Concrete building. The Timber is next with 12% fewer hours in the range of comfortable environmental conditions when compared to the Concrete building. Finally, the TimberLow building offers the poorest environmental comfort conditions, far lower than any of the other buildings in the comparison, with 49% less hours in the range of comfortable environmental conditions when compared to the Concrete building.

Figure 5.12 shows the results for the PMV modelling of the Staff room in the Timber, Concrete, Steel, and TimberLow buildings. In Figure 5.12, the Steel building has the longest period of time within comfortable environmental conditions, followed by the Concrete building with 11% fewer hours in the range of comfortable environmental conditions when compared with the Steel building. The Timber building has 23% fewer hours in the range of comfortable environmental conditions when compared to the Concrete building. Finally, the TimberLow building has 49% fewer hours in the range of comfortable environmental conditions when compared to the Concrete building.

Figure 5.13 shows the results for the PMV modelling of the Studio room in the Timber, Concrete, Steel, and TimberLow buildings. In Figure 5.13, the Concrete building has the longest period of time within comfortable environmental conditions, followed by the Steel building with 8% of fewer hours in the range of comfortable environmental conditions when compared with the Concrete building. The amount of hours within a range of environmental comfortable conditions in the Timber building is slightly lower than in the Steel building, and has 9% less hours in the range of comfortable environmental conditions when compared to the Concrete building. Finally, the TimberLow building is the building with the poorest environmental comfort conditions, far lower than any of the other buildings in the comparison, with 30% less hours in the range of comfortable environmental conditions when compared to the Concrete building.

	Timber	Concrete	Steel	Timber-low
< -0.50	24	5	48	0
-0.50 to 0.50	1535	1783	2002	1022
> 0.50	1571	1343	1080	2108

Figure 5.12: PMV of Staff room in level 2, North façade.



	Timber	Concrete	Steel	Timber-low
< -0.50	91	89	143	3
-0.50 to 0.50	2307	2541	2339	1776
> 0.50	733	500	649	1352

Figure 5.13: PMV of Studio room in level 2, South façade.

5.9 - Preliminary Conclusions

Perez draws the following preliminary conclusions from the results of his research work (a full analysis of results will be presented in Perez's PhD thesis).

- Regardless of whether the buildings are constructed mainly with concrete, steel or timber as the principal structural and non-structural materials, the influence of thermal mass has a relatively low impact on operational energy consumption for the weekly operating regime of the Arts and Media building of this study – at least in the temperate climate for which the modelling comparison was carried out.

- Because, as shown in several previous studies, the operational energy is by far the largest component of life-cycle energy use, this first conclusion suggests that the life-cycle energy usage of a building to be used for educational purposes in a temperate climate is relatively insensitive to the choice of primary structural material.
- While the variations in operational energy usage between buildings having different primary structural materials (timber, concrete and steel) may have been shown to be small, consideration of environmental comfort – as evidenced by PMV considerations – has shown that the concrete-based constructions consistently give the smallest number of hours outside the accepted comfort range.
- Nevertheless, the variation in the total hours of out-of-comfort-range conditions is comparatively small for the three building types within a given level of envelope insulative performance.

5.10 - Discussion

This Discussion section is compiled by the authors of this document from, as yet, unpublished information from Perez's research (which will be published as a PhD. thesis towards the end of 2011) and many discussions with Perez and other co-researchers over the last two years. As such, this Discussion represents the viewpoints of the authors and is presented in order to give the reader some 'pointers' to the validity and accuracy of the research, it's importance and its implications for the design of future multi-storey buildings.

5.10.1 - Comment on summary of results.

Perez's research indicates the following;

- Differences in total annual energy consumption between the *as-built* Arts and Media building and the alternative Concrete and Steel designs are not significant. The TimberLow design could save around 15% of total annual energy consumption.
- The Concrete building design offers the longest period of time within comfortable environmental conditions, whilst the TimberLow design offers the poorest environmental comfort conditions, with areas of the TimberLow building often predicted to be warm.

Models for total annual energy consumption for the Arts and Media building are based on the actual *as-built* design; this building incorporates energy efficient features and good insulation but is not specifically designed to minimise overall energy use. The comparative Concrete and Steel buildings were based on the same design criteria.

The results show that a 'light' timber building - with greatly reduced mass in comparison to the Concrete building – is able to employ massive timber structural components and concrete floors, together with carefully designed features to expose the timber surfaces to the internal environment, to substitute for conventional heavy thermal mass, typically provided in the form of structural concrete.

The thermal mass that is incorporated in the Arts and Media building is an important contributor to the building's energy performance, providing comparable total annual energy consumption results to the Concrete and Steel alternatives. In all the building designs, the floor slabs have the largest effect as sources of thermal mass. The thermal mass in the floor systems is roughly equivalent in each building design but different in the shear walls and other structural elements.

PMV results show that the Concrete building performs better than both the Arts and Media building and the Steel design. This is most probably due to the moderating influence of the greater thermal mass in the Concrete building (and is in line with conventional expectations for building design and materials).

All buildings exhibit a significant amount of time when the buildings are too warm. The reasons for this are likely to be complicated but at least, in part, attributable to the fact that none of the buildings employ conventional HVAC cooling (other than the computer room), which would be important for maintaining a comfortable environment during the warmer summer months (being an educational building – not normally occupied during summer – the designs did not need expensive cooling equipment). Further comment on PMV and design is given below.

The TimberLow design does reduce total annual energy consumption significantly. However, the additional cost of this design is not considered worthwhile from a purely financial, life cycle costing perspective (see Chapter 7). In addition, the TimberLow design has the poorest performance from a PMV perspective of all the buildings – an interesting result, where lower annual energy consumption would appear to have been 'traded-off' against building comfort levels. In reality, it is likely that the increased thermal efficiency of the TimberLow building – less heating is required during the colder winter months – mean that the building is unable to remain satisfactorily cool during the summer months, retaining heat within the building and unable to exchange the internal heat load with the outside of the building. Further comment on PMV of the TimberLow building is given below.

5.10.2 - Is energy use in buildings important?

In a world becoming increasingly constrained by easily available energy, particularly fossil fuels, and increasingly concerned about the environmental impacts of the use of energy, such as climate change, energy use in buildings is very important (with many global energy studies putting the proportion of total energy consumed by buildings over their full life cycle at around 40%). The life cycle assessment for the Arts and Media building (Chapter 8) considers both the impacts of overall energy use and the carbon footprint of the building.

All forms of energy are also becoming increasingly costly. The consideration of all energy costs over the full life time of a building, which may stretch to well over 100 years, can reveal compelling evidence for decisions regarding capital investment versus on-going operational costs. Chapter 7 covers the life cycle costing of the Arts and Media building and alternative designs. The cost of future energy supplies (seemingly only increasing) – and the changing global energy 'mix' – mean that cost / benefit predictions for energy use by buildings are complex and, at best, 'what-if' scenarios.

At present, typically, over the life time of a building, operational energy greatly outweighs embodied energy by a factor of around five or more. However, with a move to far greater operational energy efficiency for buildings, such as the 'passive house' movement in Europe, the initial (and maintenance) embodied energy of building materials will be increasingly important. The capital cost of implementing new technologies versus long-term energy cost savings – as well as shifting possible environmental impacts from one part of the life cycle or one location to another - will need to be mindfully scrutinised.

5.10.3 - How 'good' is the research providing the energy use predictions in this report?

The research conducted by Perez, providing the total annual energy use predictions for all the building designs covered by this report, is at the Doctorate level based at the Department of Civil and Natural Resources Engineering at the University of Canterbury.

The research has been guided and supervised by Dr. Alan Tucker and Dr. Larry Belamy and before publication will be scutinized, peer-reviewed and undergo the normal, rigorous academic processes. Experienced building services engineers from Aurecon Group have provide advice and reviewed the various building model which underpin the research.

The research is considered a comprehensive and detailed study, made possible by the open, full and willing participation of NMIT, involvement at an early stage in the building planning and design process and knowledge and data from studies conducted on another building adjacent to the Arts and Media building. The modelling used the latest Virtual Environment suite of software tools.

5.10.4 - How accurate are the building energy use predictions in this report?

The overall total energy use predictions for all the building designs are used by both the LCA (Chapter 8) and LCC (Chapter 7) studies and form a significant component of both. Hence, it is valid to ask 'How accurate are the predictions?'

The results, summarised in Section 5.8.1, are predictions derived from models using the sophisticated Virtual Environment suite of tools. At present, the predictions cannot be 'checked' against the real performance of the Arts and Media building.

A 'good' building energy model could be judged to be one that provides results which would closely mirror the actual 'real-life working' of such a building. Appropriate real-life data from monitoring of the energy consumption and environment of an operational building, collected over an extended period, and referenced to actual climate data, could be compared to predictions to provide some information on the level of accuracy of predictions.

In the case of this research, the only ‘real’, operational building is the timber-based Arts and Media building. The alternative designs will never be built and thus can never provide operational data.

From an energy use perspective, the Arts and Media building is probably the most ‘studied’ commercial-style, timber multi-storey building in the world. However, it is readily acknowledged that there are few such multi–storey timber buildings in the world and hence the research is breaking new ground. Rigorous, proven scientific methodology, and watchful supervision applied from experience in the modelling of multi-storey buildings, constructed in more conventional structural concrete and steel materials, has guided the research at all stages.

The Arts and Media complex has incorporated extensive energy monitoring and environmental metering equipment throughout the building. This equipment is currently providing data which will be able to be compared against the predicted energy use of the building, whilst using actual daily weather data for Nelson, and will form the basis of a final year student project at the University of Canterbury (due for completion by November 2011). This and other future research will report the accuracy of the predictions and allow calibration and refinement of models both for the Arts and Media building and also for other large timber buildings, even at the early design stage.

The modelling of the Arts and Media building has itself been refined – and benefited from other energy monitoring and modelling work conducted on the three-year old Tourism (T-block) building, situated immediately adjacent to Arts and Media. T-block, a conventional heavy-mass concrete design, has provided extensive data on energy consumption and environmental conditions. T-block is a similarly sized building, located with the same aspect and with a similar (educational-type) occupancy to the Arts and Media building. Analysis of this data will form part of Perez’s PhD thesis and report on the accuracy of the modelling.

In brief, initial modelling of T-block compared with actual metered data show that when considering the mean values of heating energy, total electricity, hot water energy and air temperatures in a number of locations within the building, the model was very good at predicting the total heating energy and room air temperatures. The initial model did not perform so well in considering total electricity consumption (lighting, computer equipment, etc.). The model was taking only a very simple approach to the energy audit of the building (a full energy audit would be very expensive and outside the scope of this project). Hence, the model was revised to allow for increased wattage for lighting and increased demand from equipment. This refinement or calibration of the model, allowed the model to consume electricity at the same mean rate as the actual building. The hot water consumption of the model was similarly increased.

All the Arts and Media building designs are comparable buildings – in location and use. The modelling of T-block allowed Perez to refine the model for the Arts and Media building in a similar way to the refinements of the initial T-block model. This form of calibration is expected to enhance the accuracy of the Arts and Median energy predictions, as well as the predictions for the alternative designs.

5.10.5 - Further modelling work by Perez

Perez provide the annual energy consumption predictions for all buildings early in 2011. Since this date, Perez has continued to refine the models with the result that there has been a decrease in the energy consumed by all building designs (around 10%). However, it is important to note that the relative changes to all designs are the same and hence the buildings maintain the same slight (probably not significant) differences. The authors are aware that this further refinement could be suggested to degrade the above claim that the models are working well (both predictions cannot be accurate) – but this is countered by noting that further work, in absolute terms, is improving the accuracy of predictions, whilst in relative terms makes little difference.

Perez is also conducting further work to investigate how the Arts and Media building – and its alternative designs – would operate if the building had a more conventional occupancy as a ‘commercial’ building, occupied throughout the whole year. Under this scenario, the building would be likely to have HVAC cooling operating during the warmer summer months. These results will be reported in Perez’s full PhD thesis.

Another scenario investigated by Perez is to look at PMV in alternative TimberLow, ConcreteLow and SteelLow designs (both of the latter follow the design criteria for the TimberLow building), again in a commercial building with cooling. Early results from this work suggest that all designs – in either structural timber, concrete or steel – can significantly improve their total annual energy consumption performance. When considering PMV without cooling of these low-energy buildings, the relative positioning of designs remains the same, with ConcreteLow performing the best (but with all buildings still having more than 50% of time when the buildings are considered too warm. When cooling is added to the models (to simulate a commercial building), the relative performance of the buildings remains the same but all buildings show improved PMV, with significantly more time when all buildings are within an agreeable comfort zone. This report is not able to comment on the financial cost or cost / benefit of providing cooling in commercial designs.

Perez will also investigate the effect of increasing the thermal mass in the Arts and Media building flooring system, as well as new technologies such as phase change materials, under floor air distribution and moveable louvres.

5.10.6 - What lessons can be learned and applied to the design of future large timber buildings?

It is difficult to draw lessons from research into one building, especially when the Arts and Media building is recognised to be a unique, 'landmark' design, certainly not optimised as a low-energy building.

However, whilst acknowledging the above, it is considered worthwhile to draw some broad conclusions which can be used as 'pointers' to aid in the design of future large / multi-storey timber buildings.

Firstly, the research shows that it is possible to design and build a low-energy, multi-storey timber building (by normal convention such a naturally ventilated building in NZ uses less than 100 KWh/m2/yr) and most importantly, when meeting specified design criteria, a timber building design matches the performance of alternative designs in concrete and steel. A building such as the new Arts and Media block, used for educational purposes in a temperate climate, is relatively insensitive to the choice of primary structural material.

The thermal comfort conditions within such a multi-storey timber building may not be as satisfactory as those provided within an alternative building. However, firstly it must be determined exactly on what features and criteria the occupants will make a judgement on comfort (so for the Arts and Media building, not normally occupied during the summer months, thermal comfort conditions for the occupants may well be entirely satisfactory). Secondly, it is considered that any indication of adverse thermal comfort conditions is a strong indicator to incorporating different levels and mechanisms for heating, cooling and ventilation. In other words, attaining the desired comfort levels will always be a case of optimising design to the local, ambient climate, whilst recognising that greater attention to ensuring thermal comfort conditions is most likely to be at a financial cost (and indeed, an environmental cost if more total energy is consumed).

The research indicates that there are alternatives to large thermal mass provided solely by concrete. Timber, when used in significant quantities, provides thermal mass and design features can ensure that the timber is exposed to maximise its effectiveness.

The Arts and Media building does incorporate a significant amount of concrete in the flooring systems and foundations. This provides conventional thermal mass and indicates that future designs would do well to consider combining various building materials, as appropriate to meet all design criteria.

The TimberLow design - which shows a significant increase in the number of hours of 'out-of-comfort-range' conditions - demonstrates that great care must be taken if superior envelope insulation is adopted without any compensating increase in thermal mass to absorb temperature spikes during periods of relatively high solar gain

Thermal mass is important in a building – be it provided by either concrete or timber – but alternative designs and new technologies may also contribute to the overall thermal and energy performance of large buildings. For instance, the replacement of the overhang in the north façade by louvers, so that heat gains from direct sun light would be avoided, would achieve lower indoor temperatures during summer – and even more improvement would be gained if the louvers were moveable. New technologies such as phase change materials, installed internally as room linings and under-floor air distribution are likely to feature more prominently in future building designs.

The research should be used carefully in drawing extrapolations to other large timber buildings. Is it wise – and fair – to extrapolate that any other multi-storey timber building would match the annual energy consumption of a similar concrete or steel building? The authors suggest that this research shows great potential for timber buildings to operate as low-energy buildings, particularly in temperate climates (such as the location of NMIT in Nelson) and to offer comparable performance to more conventional multi-storey buildings. Design features, such as the exposure of timber surfaces, utilisation of concrete in flooring system and the incorporation of new, alternative technologies should be carefully considered at the early design stage in order to maximise benefits. The authors firmly believe that the argument that only concrete can provide sufficient thermal mass in a building - for that building to be at both an affordable cost and comfortable - is incorrect.

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Chapter 6 - Cost and Timing of Construction

6.1 - Introduction

The new Arts and Media building at NMIT in Nelson is the only recent example of a large, multi-storey, commercial type (open-plan) building in New Zealand using timber as the main structural material. An 'information gap' exists around a number of aspects of constructing commercial, multi-storey timber buildings, including the cost and time for construction of such buildings.

A number of earlier studies have contributed to filling this information gap by comparing existing, '*real'* buildings with alternative timber designs. These real buildings have used either concrete or steel as the main structural material and similar, '*alternative'* designs have been modelled using timber as the main structural material (John et al, 2008). However, information on the commercial supply and fabrication of large timber elements and subsequent transport and erection of these elements has previously been sparse.

Multi-storey buildings in either concrete or steel are considered 'conventional' forms of construction, with many examples both in NZ and around the world – construction techniques and details, such as cost, are well understood. In comparison, the innovative use of timber as the primary construction material for large, commercial, open-plan buildings is not well documented, and only few such timber buildings exist around the world. In NZ, the design and costing of such buildings is breaking new ground. The Arts and Media building provides the first opportunity to investigate and analyse data from a '*real'* timber multi-storey building, and to make comparisons to alternative designs.

Thus, the main objectives of this research are to understand the construction process of the new Arts and Media building and then to disseminate information regarding the cost and construction of the building, using it as an example of modern, innovative timber engineering and design – in order to position timber as a viable alternative construction material to conventional concrete and steel for multi-storey buildings.

This chapter analyses and presents;

The cost of construction of the new Arts and Media building (the Timber building).

- The length of time for construction of the structural 'skeleton' of the Timber building.
- The cost and time for construction of alternative similar Concrete and Steel building designs.
- Comparisons between the as-built Timber building and alternative Concrete and Steel building designs, both for cost and time of construction.

A discussion section focuses on the 'lessons to be learned' from the construction of the Arts and Media building.

A series of photographs showing stages in the construction of the structural 'skeleton' of the Timber building is included in Appendix E.

6.2 - Summary

Table 6.1 presents a summary of the total cost of the new three storey Timber Arts and Media building at NMIT and compares this with similar building designs which use either concrete or steel as the main structural material. Table 6.1 also shows the time for construction of the structural part (*skeleton*) of the same three building designs (total working days from beginning fabrication of pre-fabricated elements through to installation of rafters and purlins).

The three buildings compare very closely in cost. The 'real' Timber and alternative Steel buildings can be considered the same cost, whereas the Concrete building is 4% cheaper than the other two options. This difference equates to approximately $200,000 in a total cost of $5.3 million and is largely due to the cheaper cost of the structural elements of the Concrete building, particularly the upper floors and the shear walls (even though the substructure cost for the Concrete building is relatively higher).

From the experience gained in working closely on this project, Davis Langdon, the quantity surveyors providing the cost estimates for the buildings expect that the construction of a multi-storey, open-plan building using timber as the main structural material, is no more costly than using either concrete or steel (as the main structural material). As the use of timber in such multi-storey buildings becomes more widespread and post-tensioning technology matures, it is anticipated that cost savings will be realised.

The structural part of the Timber and Steel buildings takes a similar time of between 11 - 12 weeks to construct (fabrication and on-site erection) and represents around 22% of the total time for construction of the entire building. The Concrete building takes nearly four weeks longer, with a much greater proportion of time (around 35%) required for on-site erection. From the recent extensive experience gained as Project and Construction Manager for the Arts and Media buidling, Arrow confidently predicts that future mulit-storey timber buildings will be at least as fast to construct as those in either steel or concrete.

Structural Material	Construction Cost (excluding consultant fees)	Time for construction of structural elements*
Timber	$5,352,000	58
Concrete	$5,140,000	74
Steel	$5,325,000	56

Table 6.1: Summary of the estimated cost of three alternative building designs and time to construct the structural parts of the buildings.

* Combined time for fabrication of structural elements, delivery and on-site construction ('hoist, erect and connect')

This research on the Arts and Media building has identified a number of design features, key points on the critical path of the construction process and construction techniques which could reduce both the cost and time for construction of future, similar timber multi-storey buildings. These are noted below and discussed in more detail in this Chapter.

- Communication.

  Open communication between all parties involved in construction of a multi-storey timber building is essential. Due to the lead-time required in fabricating the timber elements and the scope of possibilities in the fabrication options, the parties involved need to initiate effective communication channels early in the project and maintain these throughout. Points of note to enable efficient communication include:

  - Shared drawings.

    Common drawings, on compatible and integrated software platforms, would allow open and easy sharing between architects, engineers and fabricators for the structural elements of a building, which would reduce the double-up of work done by these parties and reduce the likelihood of fabrication errors.

  - Specification of requirements.

    Requirements for timber elements in terms of surface finish and treatment needs to be discussed early in the project and clearly identified for fabrication, so as to eliminate wasted time and effort (for instance, on high-quality finishing of timber elements which are later covered up). In addition, all connection components (parts that are required to fit the structural elements together) associated with the timber elements need to be specified and communicated during the costing process.

- Lead-time.

  Significant lead-time is required in both the supply and fabrication of the structural timber elements. The supply of LVL – in particular any non-standard sizes – can require several weeks lead-time. It is important that all lead-times be recognised and scheduled into the project.

- Delivery and storage.

  Due to the lead-time for the fabrication of many large LVL elements, suitable storage at the fabrication plant through the fabrication period needs to be available, so that all elements are available for immediate delivery once the construction process on-site reaches the stage of erection of LVL elements. Alternatively, storage of all necessary elements needs to be on-site. Either way, LVL elements would be available as required, to optimise the use of crane and labour.

- Design.

  The Timber Arts and Media building utilises new technology in the structural design. Implementation of this technology in a real building has highlighted some areas and points that are significant when using large, LVL elements as a structural material.

  - Using timber as the main structural material in multi-storey buildings – utilising large post-tensioned LVL elements and timber flooring systems (with drop-in installation) - presents the opportunity to significantly reduce and even eliminate wet trades on-site (after the concrete foundations have been completed). This can remove the need for the propping and curing of concrete in structural elements, such as flooring systems, allowing quicker construction and easier access within the construction site.

  - Design of timber floors as the structural diaphragm, instead of using a reinforced concrete topping, can greatly speed up construction, by avoiding the need to wait for pouring and curing of the concrete before removing lateral bracing.

  - Early stressing of the post-tensioning tendons can shorten or remove the need for lateral bracing of the structural frames and walls. Removal of bracing facilitates much easier - and earlier - access to the building during construction.

  - Significant savings in both cost and time of fabrication could be realised by reducing the number of structural elements visible in the completed building – thus allowing a much lower level of finish on some LVL elements – by using appropriate, conventional lining materials.

  - Suspended ceilings would remove the need to apply a high finish level to the underside of flooring elements, as well as offering significant savings in the fixing of services throughout the building (services would be hidden above the suspended ceilings).

  - The acoustic performance of the floors in the Timber building was increased by using a heavy concrete topping, as this was the most readily available option during the design phase. Other options for acoustic treatment, which also relate to the aesthetics of the building, are available including a raised service floor or suspended ceiling.

  - The use of a combination of different structural materials –timber, concrete and steel – in the most appropriate application could lead to a ‘hybrid’ design which could maximise the properties of all the structural materials in the most economic and least environmentally damaging way.

6.3 - Background

6.3.1 - The Buildings

The new Arts and Media complex at NMIT is comprised of three separate structures; a three storey Teaching block (also referred to as the Arts and Media building or the Timber building), a single level Workshop and an adjoining Media complex. The three storey Teaching block is intended to showcase timber as a structural building material. The research covered by this report – and the costs and timing in this chapter - only concerns the three storey Teaching block.

Details of the buildings are contained in Chapter 4.

6.3.2 - How the study was conducted

This study involved gathering and analysing information from a variety of sources, including but not limited to many senior people involved in the construction of the building. Site visits during the structural construction phase afforded both observation of the on-site processes and ‘live’ comments from site managers, overseers and construction workers. Structured and informal meetings during and following the construction phase with those widely involved in the construction project were utilised to gather retrospective and collaborative insight into the construction process. In addition, third-party, industry specialists from outside the scope of the project were consulted to provide a balanced perspective.

Those involved were:

- Irving Smith Jack Architects based in Nelson – designers for the real Timber building and the two alternative Concrete and Steel building designs.
- Aurecon Group, international engineering consultants, with offices in Nelson– structural engineering analysis, design and detailing of the real building and the alternative buildings. Design of building services, acoustics and fire engineering.
- Davis Langdon Ltd., international quantity surveyors with offices in Christchurch – detailed estimated pricing for the real building and the two alternative buildings.
- Arrow International Ltd., nationwide construction project managers – on-site project management and provision of construction programmes for the real building and the two alternative buildings
- Hunterbond Ltd. in Nelson – fabrication of LVL elements and detailed costing information for fabrication of LVL elements
- Nelson Pine Industries Ltd – supply of LVL
- Paremata Construction Ltd. – on-site erection of LVL elements and construction services.
- Other specialist sub-contractors were employed for various tasks.

A post-construction debrief meeting, chaired by an independent consultant with wide experience in the NZ construction industry and involving representatives of most of the above companies was held in Nelson in November, 2010. The meeting produced a risk analysis matrix covering many aspects of the construction process and is referenced a number of times in this chapter.

6.3.3 - Glossary of terms

LVL – Laminated veneer lumber[2]

LVL sheets – form of LVL as produced by manufacturers, typically 1.2 metres wide and a variety of thicknesses and lengths

Fabrication – the process of forming LVL sheets into elements (process can include cutting, gluing, drilling, finishing and timber treatment)

Elements – structural parts of a building, such as a column, beam or floor panel

Connection components –parts associated with the elements that are required to fit the structural elements together (often steel connectors)

Potius floors – an innovative flooring system from *Potius* Building Systems Ltd, Nelson which provides pre-fabricated LVL flooring panels that span up to 12 metres.

Finish –part of the fabrication process to create the desired surface aesthetic

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2 Structural Laminated Veneer Lumber (LVL) manufactured to AS/NZS 4357.0 Structural Laminated Veneer Lumber is an assembly of timber veneers laminated with a Type A phenolic resin. The grain direction of the outer veneers and of most or all of the inner veneers is in the longitudinal direction. LVL is suitable for use in all permanent structural applications and it has a wide variety of uses including beams and columns, truss chords, I-beam flanges, scaffold planks, concrete formwork supports and supports for structural decking.

LVL is manufactured under a rigorous product quality control and product certification scheme. This ensures an engineered product of known and consistent physical and mechanical properties. The veneer grades for LVL are controlled by the manufacturing specification of each individual LVL manufacturer. The design properties of structural LVL as well as product dimensions are published by the individual manufacturers. LVL dimensions vary between manufacturers, however manufactured billets are nominally 1200 mm wide and in standard thicknesses of 35 or 36, 39, 45, and 63 mm. Other thicknesses are available from some manufacturers. The 1200 mm wide billet is ripped into standard beam depths and includes beam depths of 1200 mm deep. In exposed applications, structural LVL must be preservative treated to ensure it lasts its full service life and surface finished to minimise surface checking.

6.3.4 - Cost information

6.3.4.1 - Where did the cost information come from?

All the cost information in this report is based on cost estimates provided by specialist Quantity Surveyors (QS)[3] employed by Davis Langdon in Christchurch.

Davis Langdon were engaged by NMIT at the commencement of the construction project to work closely with the client, ISJ architects, Aurecon engineers, Arrow International and others, to provide both a cost estimate and a schedule of quantities of materials, labour and services for the construction of the entire Arts and Media complex.

The cost estimates presented by Davis Langdon represent all costs directly associated with the construction of the building – the 'construction cost' – including all margins, P & G (preliminary and general costs), and all labour and materials.

The cost estimates do not include consultant input – that is the 'construction cost' does not account for consultant's time and materials related to:

- Architectural designs provided by Irving Smith Jack (including the initial project set-up and management costs and any costs related to the 'competition' (see section 3.3)).
- Consulting engineering provided by Aurecon Group including specialist structural, electrical, mechanical, hydraulic and fire design engineering.
- Geotechnical investigation.
- Site surveying.
- Project management provided by Arrow International (as opposed to construction management).
- Quantity surveying provided by Davis Langdon.

The process of producing a schedule of quantities is refined over time, as more details of the building and the construction process are better defined and made available, working from initial estimates towards detailed estimates and finally tender documents, which are used to tender for the building's construction. The QS will often remain with the project through to the final commissioning of the building to record and monitor costs.

Davis Langdon's close involvement with the Arts and Media building was from the initial, pre-build phases of the construction, through to providing final cost estimates. These cost estimates, produced in September 2010, form the basis of all cost information in this report. The cost estimates were used by NMIT to establish contractual agreements for the construction process.

Arrow International was engaged by NMIT to undertake project and construction management duties during the building of the new Arts and Media complex. Arrow International was responsible for monitoring and controlling costs. Davis Langdon received feedback from Arrow International on construction progress during the project.

6.3.4.2 - Determination of cost estimates.

Davis Langdon provided experienced staff to produce a schedule of quantities and a cost estimate for the Arts and Media building. These staff draw on a wide understanding of the construction industry, construction techniques and materials both locally, within NZ and internationally and previous documented schedules for buildings already constructed. Both concrete and steel buildings are widespread throughout NZ and, for these buildings, a QS is able to provide very accurate and detailed cost estimates and material schedules.

However, to provide schedules for large, multi-storey timber buildings – and in particular, a building employing the new *Expan*[4] technology - there was a paucity of information, as there were no such buildings recently completed within NZ. The challenge to the QS is to provide accurate cost estimates and schedules for such

3 A Quantity Surveyor identifies and collates the costs involved in a construction project, in order to develop an overall budget for that project. The QS undertakes cost planning which aims to help all members of the design team to arrive at practical solutions and stay within the project budget. It is the final detailed cost estimate prepared by the Quantity Surveyor, in consultation with a project architect, which forms a basis on which subsequent tenders can be evaluated. The QS prepares schedules of quantities to translate the drawing, plans and specifications produced by the design team into a standard form to enable each contractor to calculate tender prices fairly, on exactly the same basis for all competitors.

buildings. This is achieved through working closely with all those actually involved from the early stages of design, through supplying the timber materials, to fabrication, and on-site erection (rather than being able to reference previously built constructions).

For the cost estimate, Davis Langdon used an LVL cost of $1,200 per m^3, the market rate at that time for LVL supplied from Nelson Pine Ltd.

Fabrication of all LVL components was undertaken by Hunterbond Ltd. in Richmond, 12 km outside Nelson. Costs for all LVL elements contained in the cost estimates were calculated and agreed by Davis Langdon and Hunterbond representatives working closely together. The costs for LVL elements in the Timber building are detailed in Section 6.4 (and further discussed in Section 6.6). Due to commercial sensitivity, detailed costs, per element are not able to be presented.

Note that the Davis Langdon cost estimates provided for the Timber Arts and Media building are all working with (the then) *present* commercial rates – of course, the latter will vary from time-to-time depending on market factors, etc. The schedules do not include any allowance for the $1,000,000 design prize money provided by MAF, nor any contributions made by local companies. However, cost estimates do account for local construction industry conditions and availability, at that time.

Davis Langdon are confident that the cost estimates provided for the Arts and Media building establish a good reference and valuable related information for the accurate costing of the construction of future similar timber buildings.

Davis Langdon were easily able to estimate cost and material schedules for the alternative Concrete and Steel buildings drawing on their knowledge and experience of similar, recent multi-storey buildings in NZ. Davis Langdon is confident that these alternative estimates are accurate (within any limitations imposed by the structural and architectural drawings provided to them by Aurecon and ISJ Architects).

6.3.5 - Time for construction

6.3.5.1 - What does time for construction mean?

All times in this chapter (unless specifically noted) refer only to the structural part of the Arts and Media building (and the alternative designs) and the various activities around directly providing the structural part of the building. Times are all the accumulated working days passing between the start of an activity and its completion (5 days per week, excluding weekends), including any 'down' days not spent directly on structural activities, for instance if there is a halt to construction because structural elements are not available to continue construction, for whatever reason.

Overall time for construction of the structural elements of the building encompasses all the steps from the start of producing shop drawings necessary for the fabrication of elements, through to the completion of the building's structure on-site (referred to as the *total time for construction*). Total time for construction is considered because in the normal course of events for the construction of a large building, a critical point is reached at which both architectural and structural design and documentation has been completed and the final 'go-ahead' is given for construction. It is at this point that the various architectural and structural drawings are translated into shop drawings, which provide the very detailed and precise information necessary for fabrication of structural elements and on-site construction.

In order to clearly demonstrate which parts of the construction process take significant time, and in order to be able to make a 'fair' comparison, it is useful to sub-divide this total time for construction into the time for off-site fabrication of construction elements, through to include all on-site structurally related activities ('hoist, erect and connect' including the pouring and curing of any concrete structural elements, in foundations, beams, columns and floors), including delivery of elements to the site and then further, to highlight only the on-site construction time, from when the first structural elements are available on-site to commence construction.

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4 *Expan* is a range of pre-stressed, pre-fabricated timber products offering designers and developers all the aesthetic and structural advantages of wood – with the strength and endurance of concrete and steel. At the core of the *Expan* system is a range of building technologies based on the latest LVL and glulam products. Multi-storey *Expan* buildings incorporating *Pres-Lam* technology use post-tensioned tendons, embedded in the timber, to lock the system together. The system allows the creation of very open-plan, very flexible building lay-outs without the need for closely spaced columns and walls (see http://www.expan.co.nz and http://www.stic.co.nz/products).

Within these times, there are various 'activities', for instance, the manufacture of *Potius* floors, which are discrete activities and time here refers to the length of time from initiation of an activity (the discrete manufacture of floors units) to the completion of that activity (this is referred to as the *time for element construction*).

Some activities, such as the supply of LVL material from the manufacturer, are not considered within the above times, as it is considered that judicial planning will ensure that sufficient LVL is available to the fabricator '*just-in-time'*. However, it is recognised that the availability of LVL is on the critical path for the construction of the building - meaning that if LVL was not available, then almost none of the subsequent processes could proceed. If such an activity, as the supply of LVL was restricted, and LVL had to be specifically manufactured, then this would need to be very clearly accounted for in any timing schedules.

Figure 6.1is a simple schematic of the basic supply chain and on-site construction process.

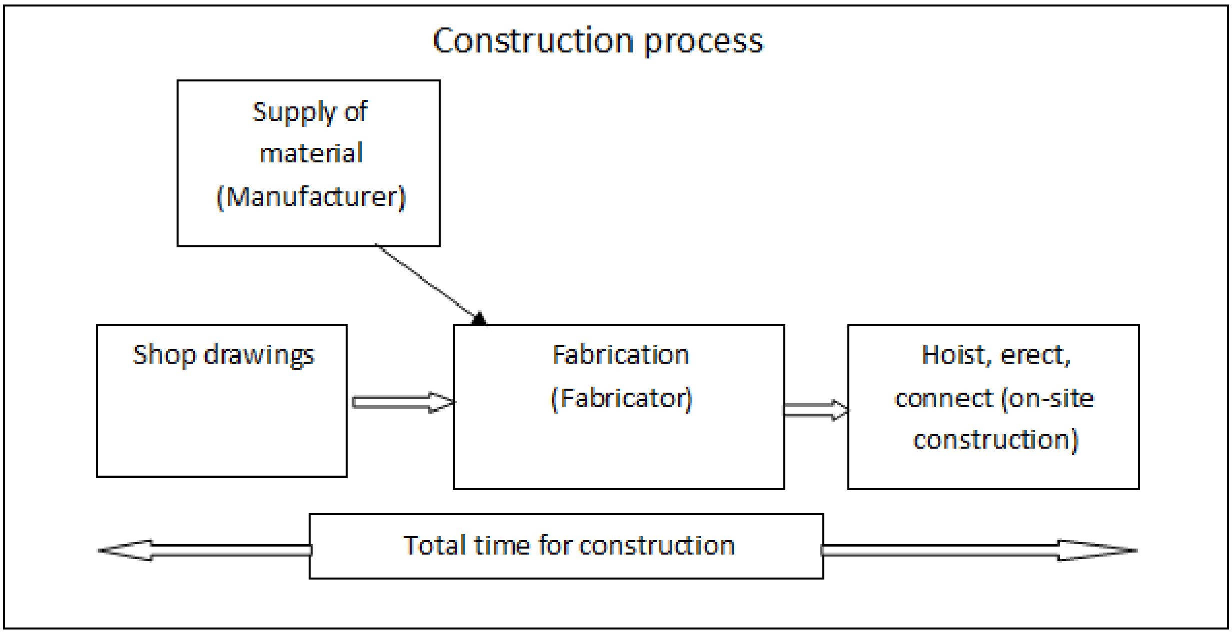


Figure 6.1: The basic supply chain

6.3.6 - Where did the time information come from?

All the time information was provided by Arrow International, the project and construction managers.

Working with all the various groups involved in the construction project, Arrow produced detailed Gantt[5] charts in Microsoft Project software (Appendix B) for the predicted construction of the Arts and Media building – these detail the length of time of various construction activities and as such, predicted a total time for construction of the building – this is referred to as the *Original* building schedule.

Arrow monitored progress against these predictions throughout the whole construction project to produce a record of actual times for various activities – referred to as the *Actual* building schedule.

Arrow was separately engaged by University of Canterbury to complete predicted building schedules for the alternative Concrete and Steel buildings.

5 Construction projects such as the new Arts and Media building use a Gantt chart (a type of bar chart) that illustrates a project schedule, breaking down a complex activity into a number of elements. Gantt charts illustrate the start and finish dates of the terminal elements and summary elements of a project. Terminal elements and summary elements comprise the work breakdown structure of the project. Gantt charts also show the dependency (i.e. precedence network) relationships between activities. Gantt charts can be used to show current schedule status using percent-complete shadings and a vertical "today" line. Gantt charts have become a common technique for representing the phases and activities of a project work breakdown schedule, so they can be understood by a wide audience.

Care needs to be taken in interpreting Gantt charts. While it is necessary that for each structural element, certain steps are followed sequentially, these processes will most likely be running concurrently for different elements. For example, while the columns are being erected on-site, the upper floors may still be being fabricated (concurrent processes).

In contrast, the initiation of some processes will be dependent on other process being completed – for instance, it is impossible for erection of columns on-site to be undertaken before the columns are actually fabricated and transported to the site (sequential processes). Thus some processes are on the 'critical path' and any delays in such processes will cause an overall delay in the total construction time.

6.4 - The Timber Building

The entire Arts and Media complex on the NMIT site, including the Teaching block, Workshop and Media Centre had a total construction cost of $8,850,000. This equates to $3,080 per m^2 (ISJ Architects communicated to the authors that at the outset of the design phase in 2008, initial budget benchmarking for similar educational buildings (against recently completed multi-level Polytechnic buildings both in Wellington and the regions) suggested that a suitable range for Tertiary Arts and Media facilities would be in the range of $3,000 to $3,400 per m^2. As design progressed and the initially simple workshop facility developed to include specialist spaces, music practice spaces and editing suites, this range seemed applicable to the project as a whole).

This report is concerned only with the three storey Teaching block - hence further costs, unless otherwise specified, refer only to the Teaching block. Furthermore, the costing analysis of the building is primarily concerned with the structural elements of the building, specifically the laminated veneer lumber (LVL) elements, structural concrete and associated connection components. The focus is on the structural part of the building. The remainder of the building - cladding, exterior and interior fit out – would be similar should the building be constructed from another structural material.

6.4.1 - Cost of construction analysis

6.4.1.1 - Construction cost for the Timber building

Costs for the Timber Arts and Media building are clustered into eight groups, as shown in Figure 6.2, each group aggregating much more detailed costs and presented as percentages of the total construction cost in Figure 6.3. These groups were discussed and agreed with the QS and allow the research to be presented in a manageable format (the full, highly detailed cost estimate runs to many pages). Table 6.9, at the end of this chapter presents more detailed cost information to the greatest level of detail allowable.

The structure of the building amounts to approximately 21% of the overall construction cost and the substructure around 11% of the construction cost. The structural cost can be further broken down into the elements that make up the structure, as shown in Figure 6.4. This shows that the frame amounts to half the structural cost (50%), the upper floors approximately a third of the cost (31%), and the shear walls the remaining amount (19%).

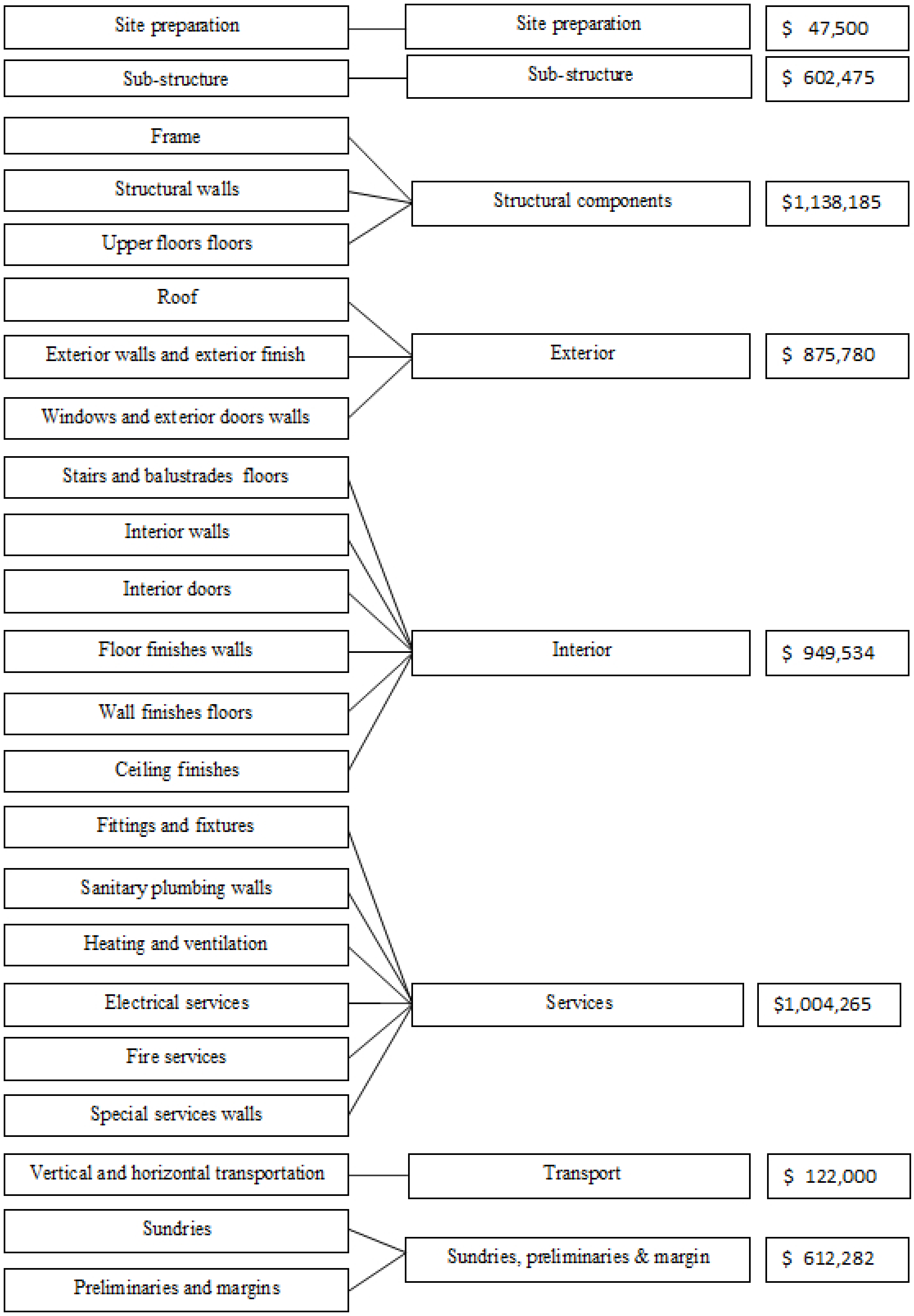
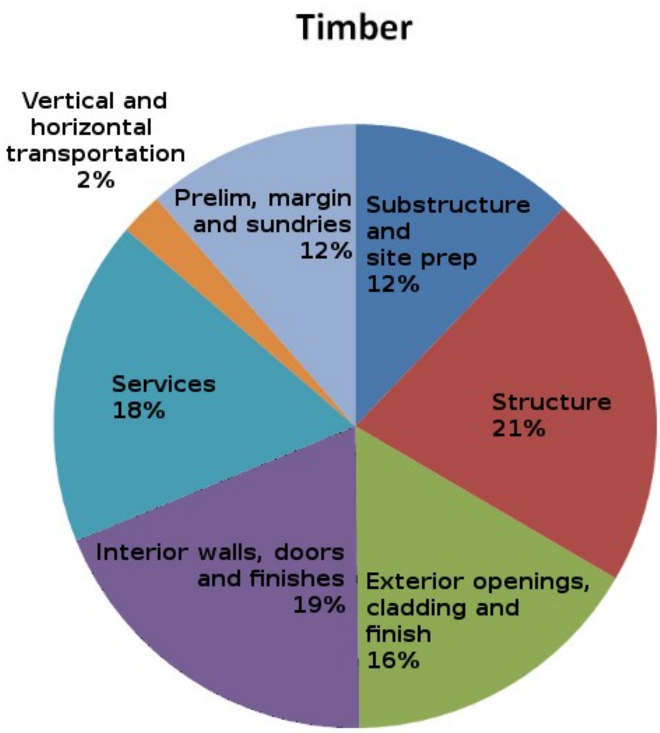


Figure 6.2: Building sections clustered into groups for costing analysis.



Structure; 21% of total building cost

Figure 6.3: Building clusters for three storey Timber Arts and Media building (percentage of total cost)

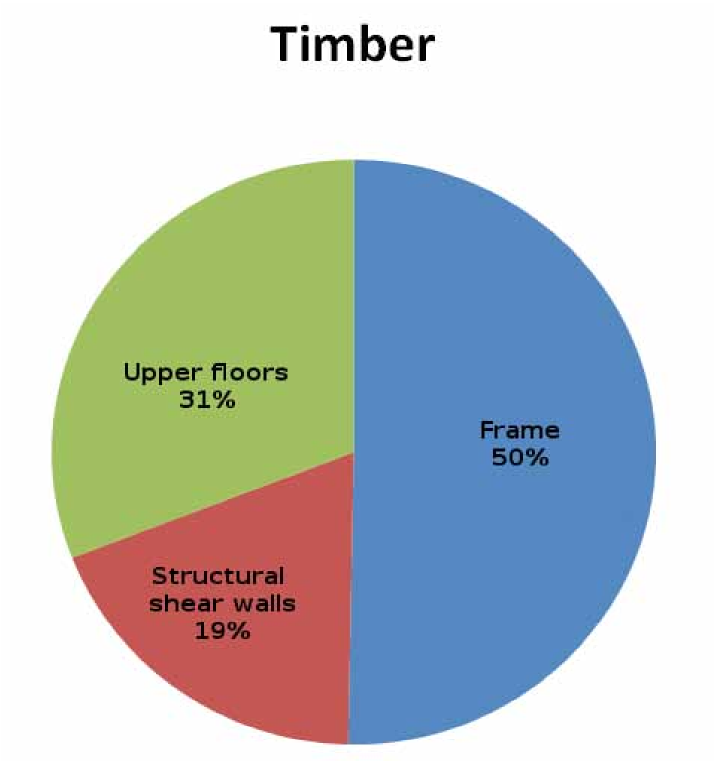


Figure 6.4: Percentage cost of structural components comprising the structure of Timber Arts and Media building

6.4.1.2 - Cost of structural elements of the Timber Arts and Media building.

Costs for the structural elements comprise the cost of supply of material[6], the cost of fabrication[7] and the cost to hoist and fix on-site. The processes to produce the structure, as well as the variables influencing the cost at each stage, are shown in Figure 6.5. Variables influencing fabrication costs are discussed in more detail in Section 6.

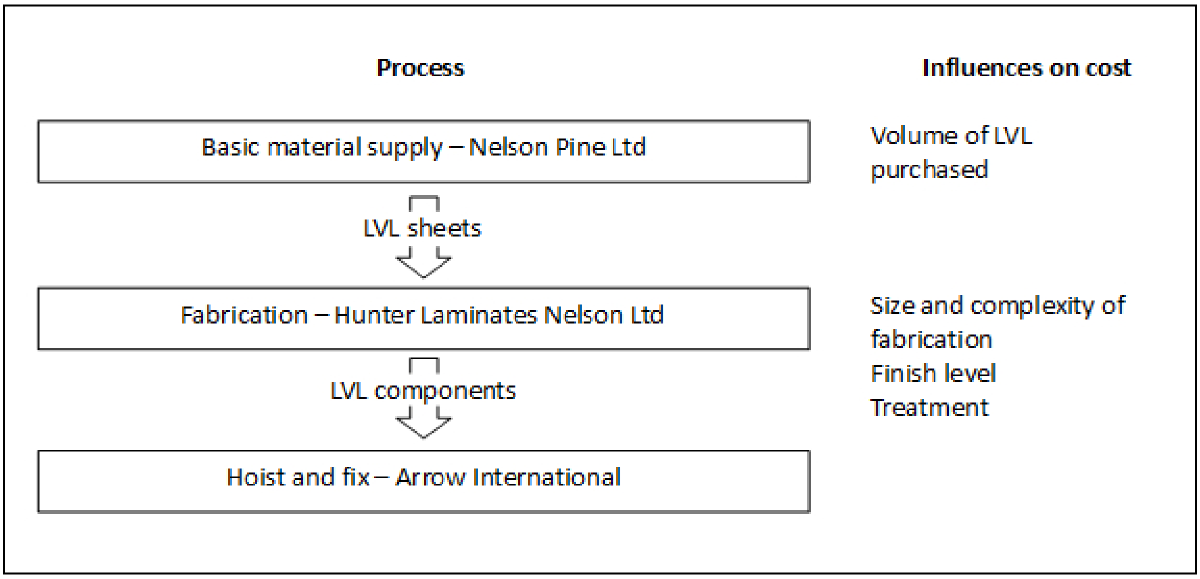


Figure 6.5: Diagrammatic representation of the main processes that resulted in the completion of the structure of the Timber Arts and Media building, showing important influences on cost.

LVL elements are the parts that are put together to create the structure of the building through the use of connection components. The total cost of the structural parts of the building includes the total process, from the supply of the LVL sheets from Nelson Pine, through to the completion of the structure of the building on-site.

Figures 6.6, 6.7 and 6.8 show the costs as a percentage for each type of structural element, namely frame, structural shear walls, and upper floors. Generally, for standard fabricated LVL elements, such as frame elements (columns and beams), the cost of material and fabrication combined are roughly equal, with the on-site hoist and erect work making up the remaining percentage (Figure 6.6).

These ratios vary both for more complex and simpler elements, in terms of fabrication, as shown by the structural walls and upper floors respectively. The structural walls are large elements that have a relatively large amount of fabrication compared to the volume of LVL used. Consequently, the fabrication costs outweigh the supply costs. Conversely, the upper-floor *Potius* panels have a small amount of fabrication compared to the volume of LVL used.

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6 The cost estimates in this study are based on the cost of LVL being $1,200 per cubic meter supplied. The amount supplied is the total volume supplied by the LVL manufacturer to the fabricator, not the aggregated final volume of all the LVL elements.

7 The cost of fabrication includes the cost of manufacturing associated connection components, such as the steel work to connect elements.

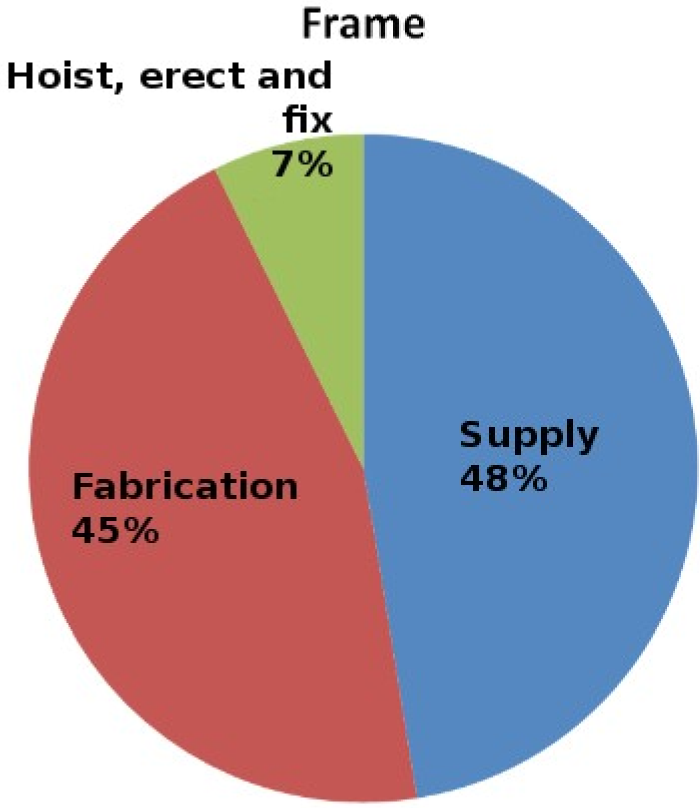


Figure 6.6: Percentage cost of frame elements for material, fabrication, and hoist and fix.

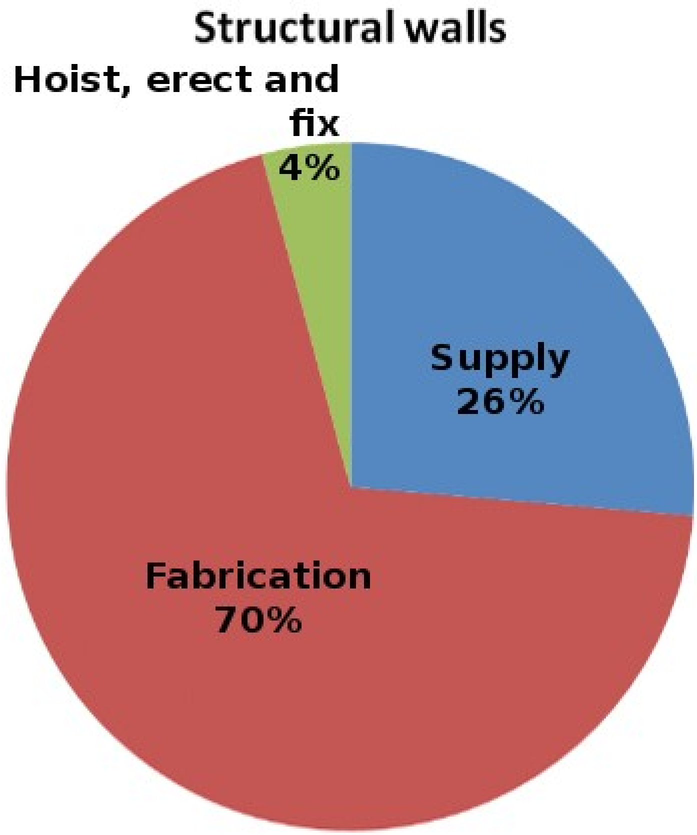


Figure 6.7: Percentage cost of structural wall elements for material, fabrication, and hoist and fix.

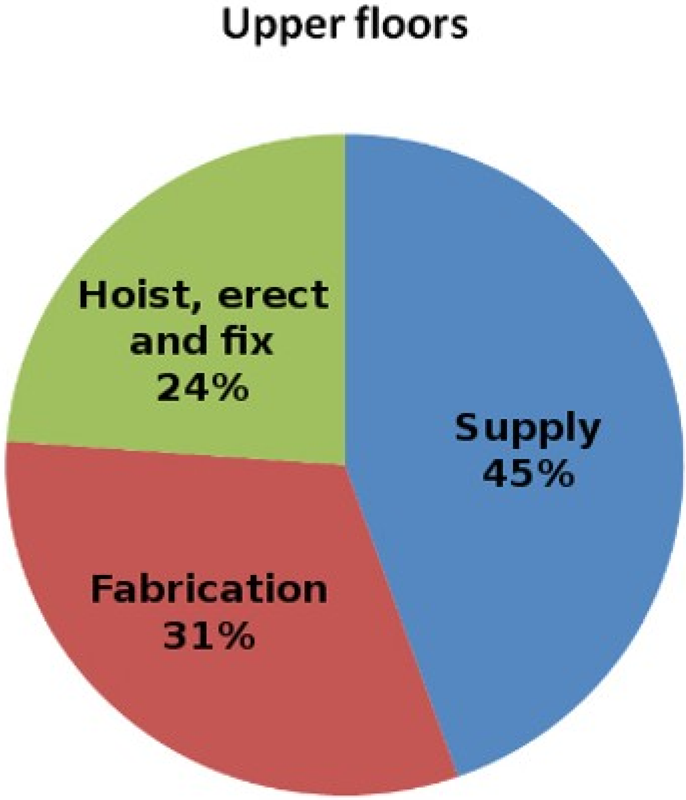


Figure 6.8: Percentage cost of upper floor elements for material, fabrication, and hoist and fix.

6.4.2 - Time of construction analysis

Total time for construction of the structural elements of the Arts and Media (Teaching) building was 123 days (that is the number of working days passing between the date of starting work on the shop drawings at Hunterbond Ltd. through to the date of completion of the installation of rafters and purlins).

The time from the commencement of fabrication at Hunterbond, after approval of shop drawings, through to completion of the on-site structurally related activities was 58 days (estimated 60 days), whilst the time for on-site erection alone was 35 days (estimated 27 days).

Some temorary bracing of the framework of the building remained in place beyond completion of the rafters and purlins. The Arrow project manager stated that the temporary bracing did not impede in any way or delay any subsequent construction activities.

Note that there are some activities which fall outside these timeframe – such as the manufacture of LVL at Nelson Pine Ltd. (LVL was assumed to be available 'just-in-time') and the manufacture and installation of the main stairs in the Arts and Media building (which was considered to be a specialist, architectural feature, not a standard component in the structural framework of a normal multi-storey building).

This actual time of 123 days compared to Arrow's predicted time of 100 days prior to construction commencing. While the total time taken to construct the structure was longer than predicted, there were parts of the process that were closely estimated, whilst some parts were quicker and others took longer than predicted. The increases in time were in the preparation of the shop drawings, time for fabrication and delivery of the LVL elements and erection of the LVL elements. Decreases in time were noted in the fabrication of the *Potius* floor panels, and some placement of LVL elements. In order to keep to the overall construction schedule, the erection process was altered, on-site, to allow work on-site to continue while the remainder of the LVL elements were fabricated.

The Gantt chart for the Timber Arts and Media building is included in Appendix B. Table 6.2 summarizes the key activities of the construction of the structural framework of the building.

Timber Building Schedule	Original building schedule (days)	Actual building schedule (days)
Total time for construction of structural elements	100	123
Itemised activities contributing to construction of the structural framework; (Note that summing the individual activities is not appropriate as some activities are sequential and some are concurrent)		
Shop Drawings	33	55
Approval of Shop Drawings	10	10
Fabrication of LVL components for Teaching (beams, columns, shear-walls)	30	47
Fabrication of *Potius* Floor	30	21
Delivery of LVL	3	26
Delivery of *Potius*	3	28
Erect LVL	17	25
Erect Shear-walls	10	10
Erect *Potius* Flooring to L1	3	10
Erect *Potius* Flooring to L2	3	10
Install Rafters and Purlins	10	10
(Fabrication of Main Stairs)	20	
(Installation of Main Stairs)	5	

Table 6.2: Time for key activities during construction of the structural part of the Timber building. (The original building schedule was programmed prior to construction commencing, while the actual building schedule gives the times that each process took in reality).

A significant increase in the number of days, from 33 to 55, to produce shop drawings for all the LVL components is evident in the comparison between the original, predicted LVL programme schedule and the actual building schedule. This 66% increase in time was due to the drawings having to be redrawn for the fabrication workshop, reviewed and re-submitted, as opposed to using and further developing those directly produced and used by the architects and engineers on the building project. Full integration of drawings between all parties involved in the project would reduce the time required to produce drawings suitable for fabrication, and further, could reduce the incidence of errors in sizing, tolerance and placement of connections between elements.

Deliveries of the LVL elements and *Potius* floor panels to the site were originally scheduled to take three days each. In reality, however, delivery of these structural elements was spread over 26 and 28 days respectively. The original schedule predicted that all LVL structural elements would be available for collection and subsequent transport from Hunterbond Ltd. to the Arts and Media building site during a three day period, before the commencement of any on-site construction. A similar expectation was applied to delivery of the *Potius* floors.

The extended delivery times are a reflection of the times for fabrication at both Hunterbond and *Potius* being spread over many days, with delivery being piece-meal. At Hunterbond, it was not possible to fabricate LVL elements and store these for subsequent delivery – the original schedule assumed that this would be the case and all LVL elements would be stored at Hunterbond, until such time as all elements could be transported to site. Thus, fabrication at Hunterbond proceeded, element by element, with individual or groups of elements (beams and columns) being transported from Hunterbond to site, as and when ready. This fabrication process meant that an optimised erection of LVL elements – beams, columns and shear-walls – was not possible on-site and the erection process itself proceeded somewhat piece-meal. However, on-site construction was able to commence almost immediately after the delivery of the first of the structural elements and without having to wait for delivery of all structural elements.

Indeed, this significant increase in delivery spread over many days resulted in the need to alter the construction sequence for the whole complex (including the Workshop and Media Centre), and hence the crane used to lift the components onto and around the site, as well as lifting each component into position for fixing, was at times not fully utilised. It should be noted that this report examines only part of the overall building on the NMIT site, specifically that of the three storey Teaching block. The Workshop and Media Centre were being constructed concurrently with the Teaching block, so resources in personnel and equipment could be diverted to where there was the most work to be done, thus reducing overall delays in construction of the Teaching block.

Fabrication of the LVL elements, not including the floor panels, increased by seventeen days, from a predicted 30 days to 47 days. Fabrication of the *Potius* floor panels was significantly shorter than predicted, 21 days as opposed to 30 days. The availability at the site of LVL elements, the main structural components for the building, is quite plainly on the critical path for the construction process and the extended time for fabrication over the predicted time highlights the need to accurately estimate the fabrication time and build sufficient lead times into the construction schedules, so that all fabrication is completed before LVL elements are needed on-site.

On-site erection of shear-walls took 10 days (as predicted) and installation of *Potius* floor units took a total of 10 days for each of two levels due to the extended, spread out delivery of the floor units. If all *Potius* floor units had been available to the construction team, as required, then installation of these units would probably all have been completed within 2 to 3 days (pers. comm., Arrow project manager.)

Erection of the main structural beams and columns took 25 days compared to a predicted time of 17 days – this largely reflects the delays in delivery of LVL elements to the site. Erection of the timber structural framework was '*stop-start'*. Again, it was noted by Arrow staff on-site, that the erection of LVL beams and columns would have proceeded much more quickly, if these elements had been available, when required on-site.

The actual time to manufacture and install the main staircase in the atrium is not shown as the stairs is not considered a normal structural component of the building, although they are fabricated from LVL.

6.5 - The alternative Concrete and Steel building designs – a comparison of cost and time of construction.

This section compares the cost and time of construction of both the Concrete and the Steel multi-storey buildings, which are largely similar in design, size and usage to the Timber building but which differ primarily in the use of either pre-fabricated concrete or steel respectively, as the main structural material. (Note that the Concrete alternative design utilises pre-fabricated panels, columns and beams – this was deemed necessary by Aurecon and ISJ Architects in order to achieve the equivalent level of finish on the internally-exposed structural elements to those in the Timber building).

This study focuses on the cost and timing of the structural phase of the buildings, as the ensuing construction stages, cladding and fit-out are very similar in all the alternative designs, regardless of the structural material used. While there is a 'real' Timber building, it is not possible to actually build three (similar) buildings. Therefore, the comparison is made using information on the real Timber building but virtual Concrete and Steel buildings.

Chapter 4 provides details on the design of the alternative buildings (the main structural components are constructed from the structural material being examined). While each design is labelled by a specific material, the alternative designs (as is also the case with the 'real' Timber building) use a mix of many other materials.

It is recognised that as each material has different strengths and weaknesses for structural purposes, there is inherent difficulty in trying to make an absolute comparison between the alternative buildings. A trade-off exists between creating a suitable alternative design (use of a particular structural material) to allow comparison and optimising the use of a particular structural material in each situation.

The Buildings Chapter 4 sets out the design guidelines which were created to ensure that changes between the alternative building designs were limited to only structural (and directly related) parts of the buildings, whilst maintaining as many similar features as possible. It is recognised, that if the structural materials were used to the optimum each time, the alternative building designs could become quite different and hence, comparison could not so easily be made.

As described in Section 6.3.4, cost estimates for the alternative buildings were provided by Davis Langdon, Quantity Surveyors, based on drawings supplied by Aurecon Group and Irvine Smith Jack Architects. Arrow International provided the timing schedules for all buildings (see Section 6.3.5).

6.5.1 - Construction process

All three buildings (Timber, Concrete and Steel) follow a similar construction process, with the frame being erected, firstly with columns and then beams, followed by the shear walls, and floors. Each material has slightly different requirements, for example the heavier materials necessitating a larger crane, or the fabricated timber elements requiring weather protection. Overall, however, the procedures are similar regardless of the structural material - placing a pre-cast concrete beam is similar to placing a fabricated timber beam.

6.5.2 - Cost of construction comparison

Overall, the three buildings compare very closely in cost. The Timber and Steel buildings are considered to be the same cost, whereas the Concrete building is 4% cheaper than the other two options – see Table 6.3. This percentage difference equates to approximately $200,000 in a total cost of around $5 million for the three storey Teaching block of the Arts and Media complex. For the Timber building, a significant part of the difference in cost is due to the cost of the upper floors, whilst for the Steel building, a significant part of the difference in cost is due to the cost of the shear walls.

Structural material	Total cost for three storey building – Teaching block
Timber	$5,352,000
Concrete	$5,140,000
Steel	$5,325,000

Table 6.3: Total cost of the alternative designs of the three storey Arts and Media building at NMIT

Table 6.4 gives a more detailed breakdown of the grouped costs for the three buildings and allows comparison across the three buildings. The grouping of building parts is very similar to that illustrated in Figure 6.2 – however, note that the substructure (the foundation and associated works) is included in the structure grouping for the purposes of the comparison between the structural materials to explicitly compare the three designs using the total structural cost including foundations. (In the cost analysis of the Timber building, section 6.4.1 and Figures 6.2 and 6.3, the substructure was shown separately from the other structural building elements).

Each part of the building is grouped into a cluster of similar items, such as all the structural elements (including substructure), exterior items, interior items, services, etc.. A more detailed costing is shown in Table 6.9 the end of this chapter. Items cannot be shown in any greater detail due to commercial sensitivity of certain information.

Building cluster	Concrete	Steel	Timber
Site preparation	$47,500	$47,500	$47,500
Structure, including substructure	$1,568,000	$1,734,000	$1,741,000
Exterior openings cladding and finish	$876,000	$876,000	$876,000
Interior walls, doors, finish	$931,000	$911,000	$950,000
Services	$1,004,000	$1,004,000	$1,004,000
Vertical and horizontal transportation	$122,000	$122,000	$122,000
Preliminaries, margin and sundries	$591,000	$610,000	$612,000

Table 6.4: Cost of building clusters for the different structural materials

Care must always be exercised in making comparisons between buildings and making predictions about estimated costs of any future building/s. The costs above apply to the particular buildings in this study and due to the nature of these buildings – each alternative design being a showcase building for the material used - the numbers do not necessarily reflect the cost of constructing any other building. Therefore, it was considered appropriate to make comparisons between the three buildings using percentage of costs related to each building group in relation to the total building cost, rather than absolute costs.

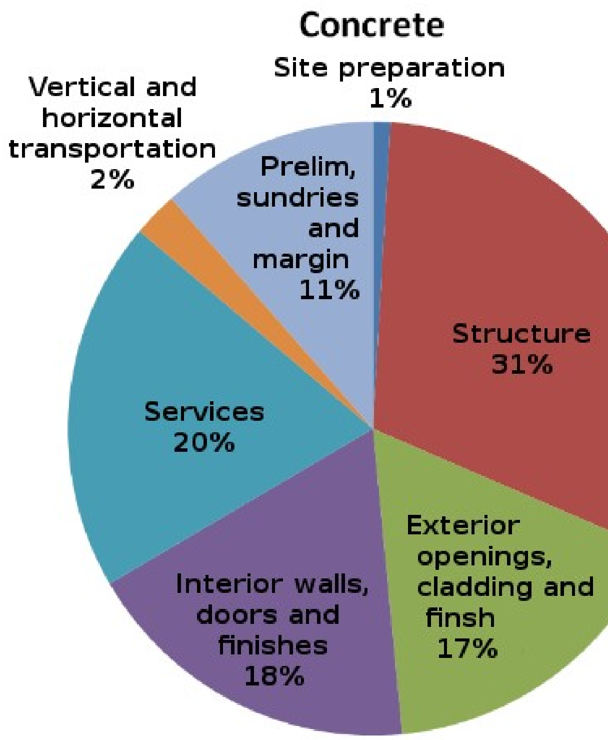


Figure 6.9: Cost (percentage of total cost) of building using concrete for structure, grouped into building areas.

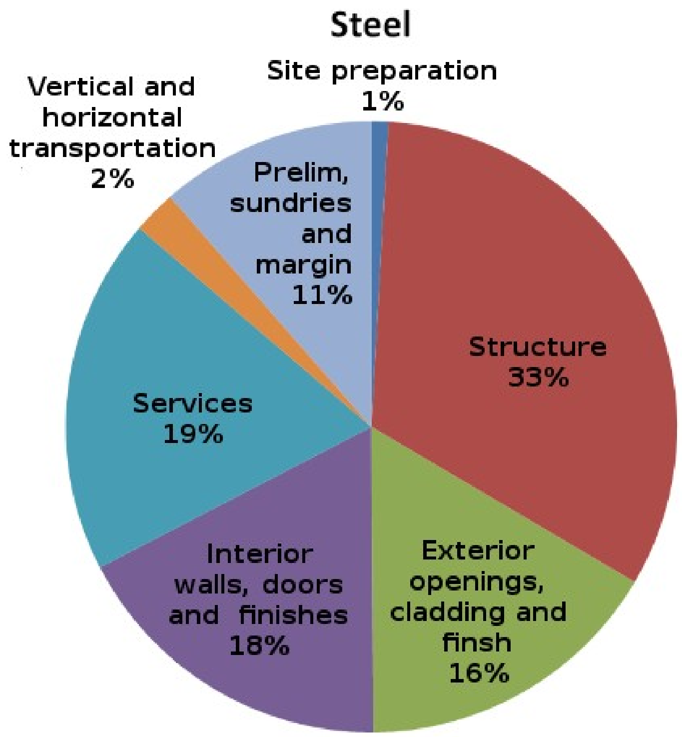


Figure 6.10: Cost (percentage of total cost) of building using steel for structure grouped into building areas.

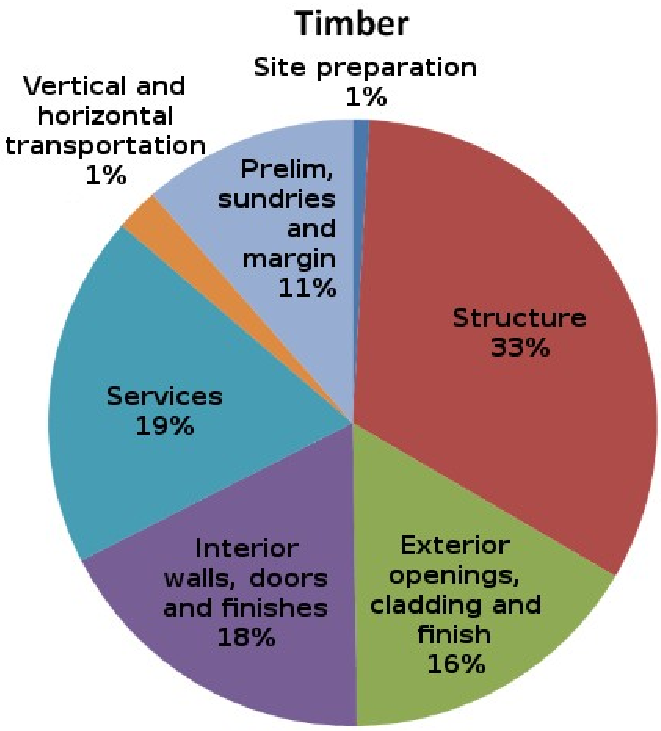


Figure 6.11: Cost (percentage of total cost) of building using timber for structure grouped into building areas.

Figures 6.9, 6.10 and 6.11 present a breakdown of the total costs for the Concrete, Steel and Timber buildings. The structure, including substructure, comprises 33% of the total building cost for Steel and Timber, and 31% for Concrete. The costs of other building groupings are also very similar between the three buildings. Preparation of the site is the same for all three alternative designs, and this would likely be the case on most sites. An exception may be on a difficult site where the larger foundations required for a concrete building may require extra site work.

The most significant difference between the three buildings is the main structural material used. Hence, it is the different cost of the structural components, including the different substructure required to support the building, that largely determines the overall difference in cost between the buildings. All other parts of the buildings, except the structure, are very similar or the same cost (whilst there are small differences between parts of the construction between the alternative designs as a result of using different structural materials, other than those related to the structure, these are not significant in the overall costing of the buildings).

Figure 6.12, 6.13 and 6.14 show the percentage cost of the structural components, including the substructure, for Concrete, Steel and Timber.

The frame of all three buildings amounts to around 33% of the structural cost. For the Steel and Timber buildings, the frame cost is approximately equal to that of the substructure (35%), whereas for Concrete the substructure is significantly more of the structural cost. Overall, Steel and Timber compare very closely in the cost for the structure, including the substructure due to the similar mass of these building's materials. Concrete, has larger substructure requirements, hence the cost of the substructure is greater than for the other two alternative designs. In terms of percentage, almost half (48%) of the structural costs for the Concrete building are for the substructure.

The cost of the upper floors (which includes any necessary form work, steel, structural concrete and/or concrete topping) is significantly greater for the Timber building than the other structural materials, being 20% as opposed to 11% and 12% for Concrete and Steel respectively. This may be due to the experimental nature of the Timber design where the upper floors have not yet been optimised, as have the conventional Steel and Concrete flooring solutions. Potential for reduction in the cost of the upper floors in a Timber building is discussed in Section 6.6.

The cost of the shear walls is least for Concrete (8%) and significantly greater for Steel (19%), with Timber in between (12%). This cost difference is largely due to the different methods of fabrication for each of the materials. Large concrete elements can be cast using a (relatively) simple form, whereas the fabrication required in manufacturing large timber and, in particular, large steel elements is more complex. Together with the difference in substructure cost, this cost difference in the shear walls is a large contributing factor to the difference in total structural costs between the three buildings.

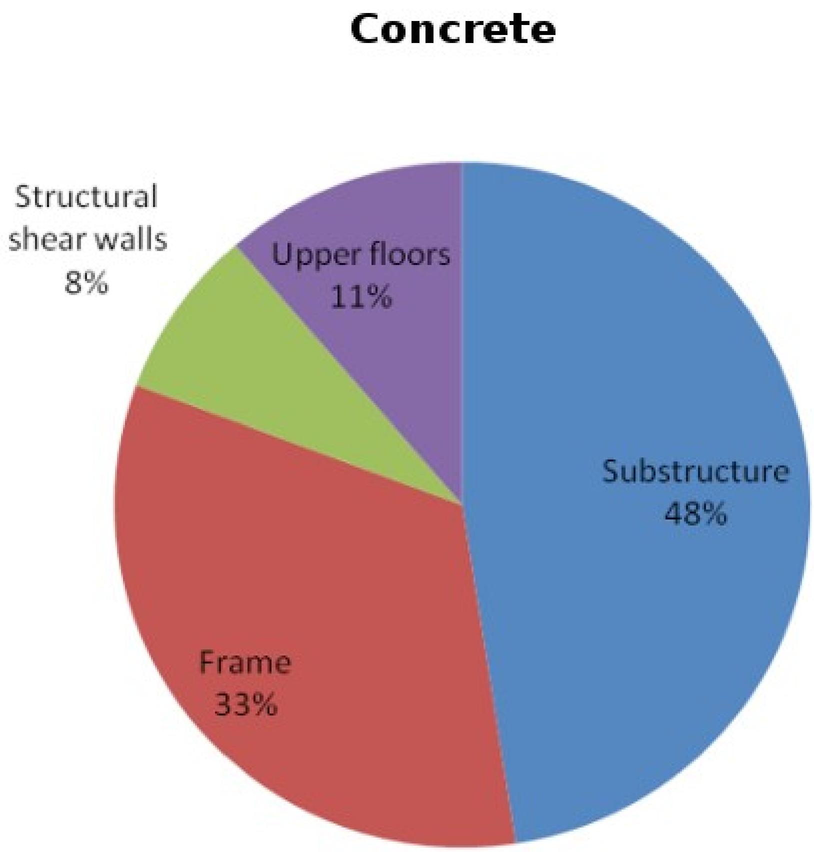


Figure 6.12: Cost (percentage) of the structural components of the Concrete building.

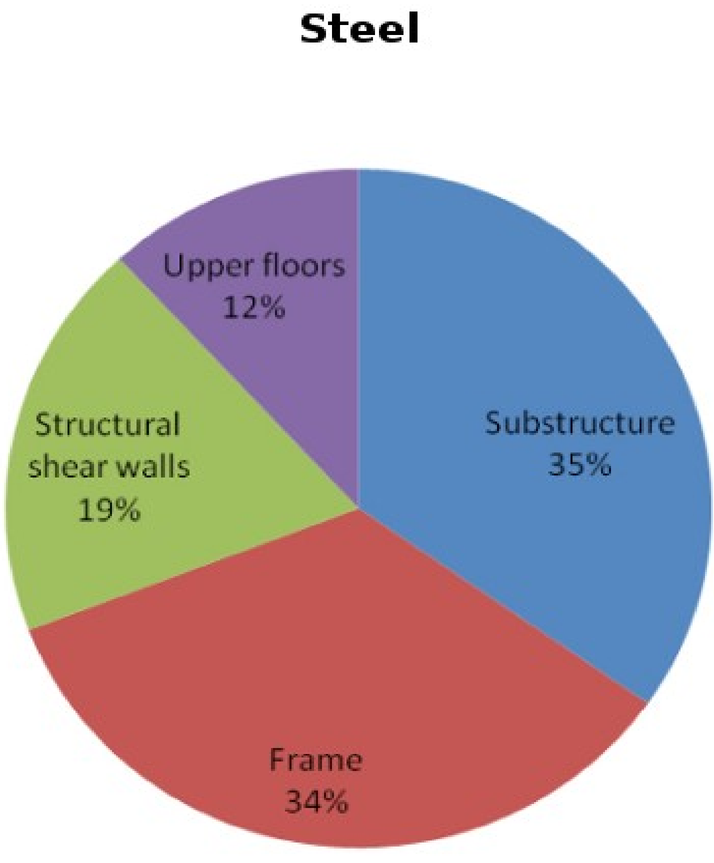


Figure 6.13: Cost (percentage) of the structural components of the Steel building.

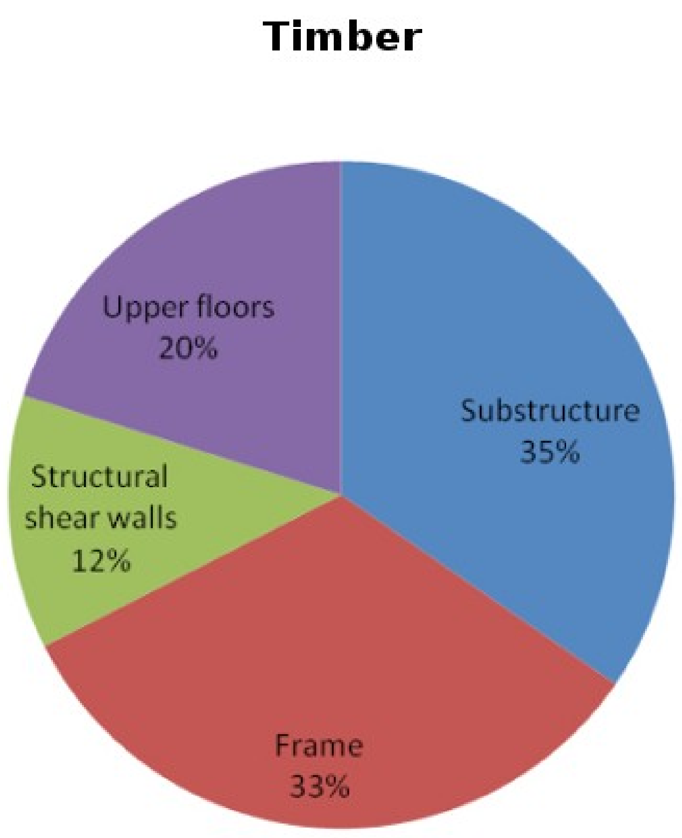


Figure 6.14: Cost (percentage) of the structural components of the timber building.

6.5.3 - Time of construction comparison

The time of construction discussed in this section covers the structural components of the building but not the site preparation, exterior work/cladding, internal work, services and finishing. These other parts of the construction are expected to take the same amount of time regardless of the structural building material. (See Section 3.5 for more on what is meant by time of construction). The actual times from the construction of the Arts and Media building is given, whilst times for the Concrete and Steel buildings are estimated by Arrow International.

	Timber building [actual] (days)	Concrete building [estimated] (days)	Steel building [estimated] (days)
Total time for construction of structural part of building (including shop drawings)	123	117	99
Time for fabrication of structural elements including delivery and on-site construction ('hoist, erect and connect' including the pouring and curing of any structural concrete)	58	74	56
On-site erection of structural elements ('hoist, erect and connect' including the pouring and curing of any structural concrete)	35	45	30

Table 6.5: Comparative construction times for the Timber, Concrete and Steel buildings (days)

The total time for construction of the structural parts of the three designs is 123 days for Timber, 117 days for Concrete, and 99 days for Steel – see Table 6.5. (Note that a Concrete design combining some pre-fabricated elements (eg. beams and panels) with cast in-situ elements (eg. all columns) is estimated to reduce the total time of construction to 108 days but would not be able to provide the required level of finish to interior structural elements).

The principal reason for the extended time for the Timber building is that there were delays in completing the shop drawings (an additional 22 days beyond the predicted time) – this delay is not related to the building being made specifically of timber, nor to any on-site construction delays but rather to communication, sharing of information and integration of drawings between various parties involved in the project. A comparison of the combined time for fabrication and on-site erection clearly shows that the manufacture of pre-cast concrete elements (45 days) is very time consuming.

When considering only the on-site construction process, the comparative times are 35 days for Timber, 45 days for Concrete and 30 days for Steel.

The whole complex (Teaching block, Workshop and Media Centre) took just over 12 months, from site establishment to occupation of the building. Therefore, the construction of the structural part of the building represents a relatively small portion (around 22%) of the overall project. However, any saving in time at the 'structural stage' would present an opportunity to move onto the next phase/s of the project sooner.

Whilst the cost schedules – for instance in terms of labour or crane time, etc. - should at least in part reflect any differences in time of construction, this isn't necessarily true when considering the total cost (so the Concrete building, despite taking longer to construct, does not incur an overall cost penalty). However, the cost schedules alone do not account for or illustrate the benefit/s which could accrue from completing a building in a shorter period of time when, for example, the building could be occupied at an earlier date, resulting in earlier returns of rental income for a commercial building.

Tables 6.6, 6.7 and 6.8 show greater details of the schedules for each building. It is clear that anticipating lead-times prior to on-site construction is very important and an area where time can be 'won or lost' - priority should be given to good communications between all parties and careful, detailed, and integrated planning.

Timber	**Days**
Total	**123**
Shop drawings	55
Approval of shop drawings	10
Fabricate LVL elements	47
Fabricate *Potius* floor panels	21
Delivery of LVL elements	26
Delivery of Potius floor panels	28
Erect LVL elements	25
Erect shear walls	10
Erect Potius floor panels – level 1	10
Erect Potius floor panels – level 2	10
Install rafters and purlins	10

Table 6.6: Schedule for Timber building

Concrete	Days
Total	**117**
Shop drawings	33
Approval of shop drawings	10
Manufacture of Precast panels, columns & beams	45
Delivery and erect precast panels Grd-L1-2	4
Delivery and erect Precast Columns	4
Delivery and erect precast beams L1	4
Propping for Stalton ribs	3
Stalton ribs to L1	3
Install timber infills to L1	4
Form edges & Resteel to L1 floorslab	3
Pour floorslab L1	1
Delivery and erect precast panels L1-2 to roof	3
Delivery and erect precast beams to L2	3
Propping for Stalton ribs	3
Stalton ribs to L2	3
Install timber infills to L2	4
Form edges & Resteel to floorslab L2	3
Pour floorslab L2	1
Install rafters and purlins to Teaching	7

Table 6.7: Schedule for Concrete building

6.6 - Discussion

Much discussion has resulted from the innovative building design, use of large LVL elements and the overall construction process of the Timber Arts and Media building –involving not only those directly involved in the project but many other construction industry experts and consultants. It is important that relevant *points of learning* from as many of these discussions as possible are recorded and wisely used to improve designs in future projects.

It is important to note that while, retrospectively, there are many ideas as to what could potentially be done differently, not all suggestions would have been feasible for the Arts and Media building. A main goal of the Arts and Media building is to showcase modern timber construction - therefore some of the discussion ideas put forward, even had they been investigated during the design stage, could not have been implemented as they would have compromised the desired outcomes of this particular building.

Steel	Days
Total	**99**
Shop drawings	33
Approval of shop drawings	10
Fabricate structural steel members	26
Deliver and erect steel members	20
Install Traydek to L1	3
Resteel, form and pour slab L1	4
Install Traydek to L2	3
Resteel, form and pour slab L2	4
Propping to Traydek L1	2
Propping to Traydek L2	3
Metal purlins	10

Table 6.8: Schedule for Steel building

This discussion will examine

- some of the opportunities and issues around using timber, particularly LVL, as a structural building material,
- some of the lessons that have been learned from the construction of the new Arts and Media building,
- and, where possible, make recommendations about what could be done differently with regard to the design and the construction process of similar commercial, open-plan multi-storey timber buildings in NZ in the future.

Some points arose from discussion between the authors and personnel involved at different levels of the construction of the Arts and Media building – where appropriate, reference to a person or organisation is noted. The post-construction debrief meeting held at NMIT in November 2010, also gave rise to important points – however, some of these were '*in general discussion'* and not able to be referenced to a particular individual.

6.6.1 - Timber as construction material

Timber has some properties not typically associated with other structural materials. Being a natural based product, timber can absorb moisture which results in dimensional changes, perpendicular to grain. The natural composition of wood results in very small movements along the length of elements. Note that after closing-in of a building, any movement in timber is very small, in the order of millimetres, and does not result in observable movement by occupants of the building.

Small dimensional swelling due to increased moisture content of the timber elements was expected and measured during construction. While the dimensional swelling did not affect the overall building dimensions, there were cases when connections were slightly problematic to construct. Specifically, reduction in size of a checkout in a column, and increased size of a beam resulted in connections that required some force to construct. The required tolerance in the connections was discussed during construction between the erection crew and the engineers. For future buildings, further investigation of the allowable tolerance on the finished connection may be required to reduce this issue.

There was more 'forgiving' movement in the timber LVL elements than originally expected, often resulting in easy alignment of connections along the length and height of elements. This compares to other more rigid construction materials where any error in fabrication can result in the component being unable to fit in with other already constructed components. Furthermore, small changes to timber elements could be readily made on-site with commonly available carpentry tools.

Localised ingress of water to any LVL elements that were exposed to the weather during the construction process was restricted by the application of a waterproofing weather shield with special care being taken with the exposed end grain of the LVL. Once elements were in place, extra precaution was taken by capping the uppermost section of the columns and shear walls with plastic covers, as shown in Figure 6.15. The storage of timber on-site and limiting exposure of timber elements to any adverse weather during construction (and before *closing-in* the building) always needs to be carefully considered in the construction planning process and monitored during construction.

Overall, timber is considered to be a clean product to work with, creating less on-site mess, which in turn required less clean-up and provided a pleasant working environment for the construction crew. A pleasant worksite and the capability to make small changes on-site, when required, thereby reducing delays, increases motivation in the construction crew which leads to faster construction times (pers. comm., Arrow project manager).

Figure 6.15: Protective weather capping on top of columns and walls.

The vast experience of personnel in New Zealand in the extensive use of timber materials in the construction industry - in design, engineering, fabrication and site construction of timber buildings - should not be underestimated in terms of return to the country. Expertise in these areas could allow exports in not only value added products but whole building packages exported around the world (pers. comm. with Arrow Site Manager).

A small construction crew, of around 4 to 5 people appears to be an ideal number to have on-site for the construction of a large, multi-storey timber building, such as the Arts and Media building. The three storey Teaching block benefited from being constructed in conjunction with two other buildings on the same site, the Workshop and Media Centre. This allowed diversion of labour and kept all members of the construction crews occupied when there were delays on the critical path of the Teaching block.

6.6.2 - Supply of LVL from the manufacturer

The LVL sheets for the Arts and Media building were manufactured and supplied by Nelson Pine Industries Ltd. The cost of LVL product from the LVL manufacturer will normally depend on the volume being purchased, with larger orders offering an economy of scale and a lower price. Very large orders of LVL from a manufacturer may require some lead-time for supply and typically, also, lead-time depends on existing orders of LVL from the manufacturer. There is very likely to be a lead-time on supply of specialised, non-standard LVL sheets, which may be in the order of some weeks.

Lead-time must be clearly understood, communicated and recognised in the project schedule from an early stage in the planning process and for large or non-standard orders, good, early communication with the LVL supplier will be essential.

The cost of supply of LVL sheets from the manufacturer – which are used to fabricate the LVL elements – relates to the sizes which are able to be supplied from the manufacturer (both standard and non-standard). LVL sheets are normally able to be supplied by NZ manufacturers in a variety of different thicknesses and lengths and, in order to minimise wastage, these need to match the sizes/requirements of the elements being fabricated. This should be noted by the fabricator when costing the supply of LVL from the factory, as costing to the finished length/size of the elements may not accurately represent the total amount of LVL required by the fabricator and hence the real cost. Some wastage of LVL (off-cuts) should always be expected but good communication and co-ordination at both an early stage and during fabrication between the design team, the engineers, the manufacturer, the fabricator and the on-site construction team would help to reduce this wastage and hence reduce total cost for LVL material (pers. comm. Hunterbond and Arrow, project manager).

Local supply of the LVL for the Arts and Media building was beneficial in terms of the sustainability values held by NMIT and the design team. Local supply also resulted in low transport costs of the LVL sheets to the fabricator and the LVL elements from the fabricator to the site. Supplying the same volume of LVL to another, more distant, location could potentially increase the cost of supply of the LVL components by 5 to 10% (pers. comms. at post-construction debrief meeting, November 2010).

6.6.3 - Fabrication of LVL Elements

6.6.3.1 - General

The cost of both the supply of LVL material and fabrication of LVL elements was provided by Hunterbond to Davis Langdon who completed the cost estimate for the whole project. The process of costing the LVL elements requires explanation as different companies may approach the process in different ways. Hunterbond took the approach of costing groupings of elements – which included the supply of LVL material and delivery to the fabricator, together with all the costs of fabrication[8] and - and aggregating these costs across all elements of the building to provide a single cubic metre cost. Thus, the cost calculated represents the cost for this particular building and may not be indicative of a generic timber building, particularly a simpler, *non-showcase* building. However, the relative cost for each form of element (for example, columns and beams), in terms of supply, fabrication, and hoist and fix, as discussed in Section 4.1 above and shown in Figures 6.6, 6.7 and 6.8 will apply to a wide range of typical building types.

As seen in Figures 6.6, 6.7 and 6.8 , the cost of fabrication of an element depends on the complexity of fabrication, and the level of surface finish and any chemical treatment required. Obviously, the cost of an element also depends on the volume of LVL sheet required to manufacture the element. However, this is influenced by the base cost of LVL, given present market rates, and the total volume of LVL supplied for the project.

6.6.3.2 - Size and complexity of fabrication

Fabrication complexity influences the cost of an element. Some LVL elements of the Arts and Media building were costly to produce, specifically the shear walls due to their large size and complex fabrication and the stairs due to the complexity of the design. Large elements fabricated at Hunterbond involve a significant amount of hand fabrication as opposed to machinery-based fabrication - hence the time and cost to produce these items is higher than would likely be the case with increased machinery based fabrication (however, it may be that most machinery simply could not handle elements of the size of the shear walls and the only option for fabrication is manually).

6.6.3.3 - Finish level

The finish level on LVL elements can vary from an 'industrial finish' where basic finishing is done to remove the majority of glue marks, through to a 'high finish level' where each surface is sanded to a smooth finish and no marks are apparent. The finish required for the Arts and Media building was a high finish level due to the showcase nature of the building, as well as the use of the building as studios, teaching and exhibitions spaces. Obviously the higher the finish level, the more work is required and hence, a much greater cost is associated with a high finish level.

In future buildings, it will not always be necessary to expose the LVL structure, as in the Arts and Media building. The LVL structural elements can be covered with internal linings similar to many other buildings. In this case, the finish level on the LVL would not be important as it will not be exposed in the occupied building. There is also the option to partially cover the LVL structural elements, selectively exposing some LVL elements to view. Selective

8 Fabrication included pre-cutting, gluing, finish cutting to tight tolerances, drilling holes and rebates, planing, sanding and other surface finishing, application of weather proofing sealant and any chemical treatments where necessary.

exposure of LVL elements presents the opportunity to potentially reduce costs, while still maintaining some of the aesthetics offered by timber. Reduction in costs for finish level should be compared to the cost of internal lining material, before a design decision is made on the amount of exposure.

The finish level of each LVL element must be specified in the design documents, so as to avoid unnecessary fabrication costs. In some cases in the Arts and Media building, LVL elements were finished to a high level and subsequently covered by internal linings.

Achieving a high level of surface finish on the LVL elements requires that the LVL supplied should have little, or minimal surface marking or obvious grain defects. For those elements whose finish is critical, this requirement needs to be clearly communicated to the manufacturer / supplier of the LVL sheets.

Cupping defect of wide LVL elements can occur, which will affect the surface finish. Removing high points created by cupping requires extra finish sanding. Wide LVL elements should be designed and ordered as "cross-banded LVL" which has much greater dimensional stability if it gets wet.

Finishing of large elements at Hunterbond required a lot of manual work due to the nature of the fabrication facilities. Small elements were able to be finished at the same time as basic fabrication using machinery, so the time required for finishing was much less, per volume of LVL, than the larger elements. Note, however, that many of the smaller elements were those covered by internal linings, so the high finish level was not required in any case.

Figure 6.16: Attachment of temporary fixings to exposed structural elements, which damages the timber finish.

Extra finishing, beyond that which was done to achieve the high surface finish, was required on-site to remove marks created by the collars around the LVL elements to attach the temporary bracing (finishing on-site is even more expensive than factory finishing). While every effort was made to not damage the surface of the LVL elements, some staining occurred. In addition, a few surface marks were made by attachment of temporary fixing during construction – see Figure 6.16. While the small team of core construction crew were fully aware of the requirements of the surface finish required, other personnel were perhaps less familiar with the intended outcome of the building and therefore did not take as much care as was necessary.

Clear communication about the level of finish required for each element or element type, both prior to the project commencing and during construction could decrease the fabrication time and reduce unnecessary work.

6.6.3.4 - Chemical treatment of LVL elements

Any requirements for chemical treatment, to increase the durability of LVL elements exposed to long-term moisture, needs to be communicated to the fabricator, in order to accurately determine the fabrication costs of the components. There are maximum levels of treatment possible on LVL, as well as maximum sizes that can be treated given the current treatment facilities (pers. comms. Hunterbond and Arrow). The exposure and hence treatment required will depend on whether the elements are permanently exposed to the weather or only exposed during construction, and for internal elements the treatment type will depend on the desired surface finish. In the

Arts and Media building, no LVL elements are exposed to the weather in the completed building, so the only items requiring chemical treatment were small sections of the external walls.

6.6.3.5 - Recommendations for fabrication, finish and treatment

Future investment in fabrication machinery capable of producing and finishing large LVL elements may be a way to reduce the cost and time of fabrication and increase the volume output of the fabrication facility. In addition, supplying elements for a structure in a short, clearly defined time period and specifically in the order required for erection, will improve the time of the critical path for construction of a building. This would be particularly important if only a single building was being constructed on a site, where diversion of personnel to other tasks and areas on the site, during slower times, is not possible.

In order to provide accurate costs for supply and fabrication of LVL structural elements, precise information is required at an early stage of the project. The initial costing by the fabricator for the LVL components for the Arts and Media building were deemed not as accurate as required for the final cost estimate, due to insufficient design information being available to the fabricator. Close collaboration between the design team (architects and engineers) and the supply team (LVL manufacturers and fabricators) during the design stage (from the very beginning of the project) is essential to minimise costs, fabrication requirements and delays in supply of fabricated elements.

6.6.3.6 - Time for fabrication and supply of LVL elements

Generally fabrication of the LVL components took longer than originally estimated (+55%). Delays were due to indecision over final designs, limited capacity at the fabrication premises, and increased demands on the fabricators, beyond those originally planned and agreed, especially in terms of supply and use of components - the parts associated with the elements required to fit the structural elements together - and the increased expectation for quality of surface finish required on a large majority of elements. These issues could have been reduced with better communication between all parties involved, use of the same fully integrated drawings, available to all parties, increased fabrication capacity, and, ultimately, greater experience, for all parties in this type of building and fabrication of large LVL elements.

Supply of LVL elements to the construction site required a longer lead-time than originally expected and scheduled for the project. Storage of fabricated LVL components was a problem and presented scheduling difficulties, as without adequate storage on-site, items needed to be fabricated to be delivered as close to the time of erection as possible. There were times during the construction of the building when a lot of LVL elements were required in a short time period to ensure the most efficient hoist and fix schedule, including effective use of the crane. Due to the (limited) capabilities of the fabrication plant, some LVL elements were not supplied as promptly as required.

Timely delivery of the LVL components on the critical path is crucial to enable the fastest erection time possible. The post-construction debrief meeting reasoned that there could have been up to 30% reduction in the on-site construction time of the building's structure, if the LVL elements had been delivered on time and in the order specified in the building schedule (from 35 down to 23 days). Any lead-time needed at a fabrication facility needs to be recognised so that sufficient lead-time is allowed, as well as early decisions and direct communication made to ensure the components can be manufactured in time to allow the most efficient building construction schedule.

6.6.4 - Delivery of the LVL elements to the construction site

Delivery of the LVL components to the site from the fabrication facility was by truck. Once at the site, the components were lifted off the truck by the mobile crane and either erected directly or placed at the site for storage. Ideally all components would be lifted from the truck and directly into position, or very close to where they are to be erected. This method requires the components to be ordered and delivered in stacking order on the truck. As not all the components were supplied at exactly the time required, some components were necessarily stored on-site for some time while other components were delivered and erected. Organisation in delivery presents opportunities for cost and time savings.

6.6.5 - Erection/construction

Erection and fixing of the LVL elements on-site was faster and easier than expected due to the nature of the material, as discussed in Section 6.6.1 (pers. comm., Arrow project manager).

Timber being a light weight material (lighter than steel and concrete for the same size element) meant that handling the components on-site was easily managed by a small construction team. Timber was also noted to be forgiving (pers. comm., Arrow), resulting in small alterations to components readily done on-site with simple tools, and components fitting together easily, with greater allowance for length tolerances than other less flexible materials, such as steel or concrete.

As already noted in Section 6.6.1, the ease with which the building was constructed was a great motivator for the construction team (pers. comm., Arrow project manager). Timber was seen as a clean product that was a pleasure to work with. Indeed, without exception, the researchers found that all those involved with the building commented that they would readily be involved in future similar timber construction projects.

Again, as already noted in Sections 6.6.3.6 and 6.6.4, the erection sequence of the LVL structural elements was altered from the original plan during the on-site construction phase. Fabrication and the order of delivery of elements, and limited capacity to store elements, either on-site or at another location, resulted in periods when there were insufficient LVL elements to proceed with the erection of the structure as rapidly as the crane and construction team were capable of.

Erection of the LVL required a crane to lift elements on to the site and into position. When required on-site, the Arts and Media building used a mobile crane. The size of the elements and the height and distance to which they had to be lifted influenced the size of the crane required, and hence the cost associated with this aspect of the construction. Efficient use of any crane is essential to keep costs to a minimum. The construction sequence of the LVL erection is important when determining the crane requirements. As discussed in section 6.3.6, the construction sequence depends on the LVL elements being delivered to site when required ('just-in-time' when storage is not optimal). Increased crane capacity was required in the Arts and Media building due to the construction sequence being altered during the construction phase due to the order of LVL components being delivered to the site.

The type and size of crane used in construction has an influence on the ease and speed of construction. Obviously a larger crane can lift heavier components a greater height and distance. The crane size required is closely linked to the construction sequence and dependent on the location of the crane relative to the building foundations. If a building is constructed from the furthest point back towards where the crane is situated, the height and reach of the crane will be less critical. The cost associated with a larger crane should be balanced against the speed of moving components around the site, and hence the speed of construction (pers. comm., Arrow project manager).

The engineering specification required that each frame of the building be (individually) braced until the concrete topping on each suspended floor level had reached sufficient strength (to become a rigid diaphragm). Hence the bracing on the building remained beyond the completion of the rafters and purlins (but as noted earlier, the Arrow project manager confirmed that the bracing remaining in place did not in any way impede or delay construction activities). Subsequent analysis has concluded that for similar future buildings, temporary bracing would not be required to remain once rapid post-tensioning of the timber structural elements is completed immediately following all the structural elements and connections being in place.

Whilst there was temporary bracing required for the framing and shear walls of the Arts and Media building, the *Potius* floors did not require propping during the concrete pouring and curing. This allowed easy and unrestricted access to areas of the building that would otherwise not have been possible, resulting in fewer delays, compared to a situation where conventional floor propping is required.

The post-construction debrief meeting agreed that pre-designing the temporary bracing for the Arts and Media building, along with an un-interrupted supply of those LVL elements required, could have reduced the erection time for the frame elements by up to 20% (the Arrow construction crew manager reasoned that a saving on the erection time for the LVL structural elements and components as great as 42% or 15 days could have been achieved for this building if the temporary bracing had not been required). In addition, reducing the extra material and associated labour (including hire of deadmen, props, and craning in manufacturing bracing and collars) to create and attach the temporary bracing has the potential to save up to $80,000 (Arrow project manager).

Eliminating wet trades on-site, involved in the concrete topping for the floors, offers the potential to reduce overall construction time by around 5-6 days for the Arts and Media building (post-construction debrief meeting). In such a case, the building could be enclosed at an earlier date.

Using a suitably designed timber flooring system, which could act as a structural diaphragm without waiting for the concrete topping, has been put forward as a method to reduce the critical path timing.

As with many custom-designed buildings, there were occasions when relatively minor changes had to be made on-site. These changes included, re-drilling holes for bolted connections and needing to pack under a column to raise the height of the support, due to the foundation on this external column being lower than that of the rest of the foundations. The foundation was necessarily lower as the column is permanently outside the external envelope of the building and hence the ground surface has a slope. The packing underneath the column is not visible at building completion as the column and foundation bracket is clad.

6.6.6 - Design discussion

The Arts and Media Teaching block is the first large scale, multi-storey, post-tensioned structural timber building in New Zealand, meeting a design level which embraces damage resistant design through the use of timber shear walls. Not surprisingly, therefore, there has been much discussion around the building's design. Some of the points which have arisen follow below.

6.6.6.1 - Sizes and tolerances.

- An element that uses standard sizes of LVL or multiples of standard LVL sizes will result in less wastage of the raw material (LVL sheets) than an element that uses non- standard sizes. Some off-cuts of LVL were used in the manufacture of smaller elements to reduce wastage, and the building did benefit from being part of a larger project, where some of the LVL was used in the smaller elements required for the Workshop and Media complex. Using multiples of standard size of the LVL sheets reduces the amount of pre-fabrication required, as well as reducing waste. Close communication and understanding between the design team, the LVL manufacturer and the fabrication team should result in the best outcomes, as each team can inform the other of requirements and capabilities.

6.6.6.2 - Foundations and structural framework.

- Design, fabrication and installation of the steel shoes for the shear walls was intricate and created some issues. The purpose of the base of the shear wall is to allow the wall to rock during seismic motion - hence a hard base is required onto which the walls can rock. The link between the shear walls and the foundations needs to be designed carefully so as to provide the required support, and also to reduce the possibility of moisture ingress into the timber. Attachment of the steel shoes to house the LVL rocking shear walls did create some areas for potential moisture infiltration into the LVL. The Macalloy bars that run the height of the shear walls and provide the anchoring for each wall are tied into the ground using separate foundations from the surrounding building to ensure uplift during seismic events does not occur. The steel shoes allowed water to pool at a point of contact with end-grain of the LVL shear walls – this could have been easily solved by providing water drainage holes in the shoes at negligible extra cost.

  Some delay in construction occurred due to the concrete surface supporting the shoes for the walls having to be correctly levelled after the concrete had been poured.

  Reducing the complexity of the steel shoes has potential to reduce the fabrication cost and installation time (post-construction debrief meeting). The erection of the shear walls is on the critical path for the whole building, so savings in the installation of these walls will contribute to overall time savings.

- Supplying the large shear walls in more than one piece has been discussed as a method to reduce the difficulty of fabrication - and thus the cost - of such large elements, to reduce any problems associated with transportation to site and for faster, easier erection on-site. However, the difficulty of splicing the wall elements together on-site was generally considered to outweigh the other potential benefits. Creating shear walls in single 1.2 metre widths, standard LVL sheet size, (and thus increasing the number of shear walls) could potentially provide a saving on fabrication and erection. However, the number and size of walls impacts on the architecture and engineering design of the building and any proposed change here would need to be thoroughly examined and understood. It was not felt that the large length of the fabricated elements presented any problem during fabrication - rather, the complexity in shear wall fabrication resulted from the cross-layup of the individual LVL sheets, which was necessary to increase dimensional stability, and the large width of the walls (pers. comm., Hunterbond). The cost of fabricating the LVL walls was much greater than the cost of equivalent precast concrete, but new developments such as the introduction of Cross-Laminated Timber (CLT) may be able to greatly reduce the difference.

- Some tolerance problems were encountered on connections where a threaded rod was epoxy-fixed into an element that had to fit into a pre-drilled hole on another element. Any small out-of-alignment on the threaded rod resulted in difficulties of connection, even given the small movements afforded by timber. This requires more attention to site tolerances by the designers. A recommendation is to have through bolted connections wherever possible (pers. comm., Arrow project manager).

- Foundation types and the quantity of foundation material were widely discussed during construction. Due to the different ground conditions over the area of the site, and the seismic design criteria, the foundations had to be designed to ensure certainty that the building's foundations would have sufficient strength to prevent uplift during a seismic event. Reducing the overall weight of the building by reducing the amount of, or eliminating altogether, the concrete in the flooring could potentially reduce the size of the foundations required, thus fully realising one of the major benefits of building in timber, the light weight.

In other words, timber is a lighter product than concrete, so the foundations can be made smaller, but, the concrete required for acoustic performance of the floors added weight, so the foundations had to be able to handle this.

6.6.6.3 - Floors and ceilings.

- The combination of *Potius* floors and concrete topping selected for this building was not optimum The *Potius* floors had sufficient strength and stiffness on their own to carry gravity loads, and they could have been used as a structural diaphragm with no topping concrete. However some of the supporting LVL beams required composite action with the concrete, and this required a large volume of structural concrete for minor benefit and significant additional time and cost. This is one reason for the high cost of the structural floors in the timber building, shown in Table 6.9.

- The timber *Potius* flooring panels were topped with in-situ poured concrete in order to achieve the desired top wearing surface finish and to meet acoustic requirements in the building. A floor system where the structural parts are separate from the acoustic solution – perhaps with a suspended acoustic ceiling - would have the benefit of reducing the level of finishing on the LVL elements (if appearance was not as great a determining factor as in the Arts and Media building) creating the potential for a significant saving on fabrication finishing cost (post-construction debrief meeting) Over all the floors, this saving in labour to achieve the high finish could save 10% or more of the total cost of the floors.

  However, if a suspended ceiling is chosen as an alternative to a high quality exposed timber ceiling, the cost of this should be compared to the cost of finishing the LVL.

  In addition, a suspended ceiling would reduce the complexity and cost of services connections. Most services in the Arts and Media building are exposed, resulting in the need for very costly, close attention to be paid to the services layout and method of attachment. Placing the services behind a suspended ceiling would remove this extra complexity.

  Another possibility is to use a different material in the floor system, such as a concrete, pre-cast T floor system. A further suggestion is to incorporate pre-cast light-weight concrete panels with the timber *Potius* panels, thus achieving the same high durability floor surface and the same acoustic outcome, whilst removing the necessity of having wet trades on-site.

6.6.6.4 - Finishes.

- If the large, internally-exposed shear walls were lined as an alternative to the high quality sanded finish, potential savingscould be up to 75% of the finishing cost component of the fabrication (post-construction debrief meeting). Again, however, further investigation as to any cost savings would need to be investigated as lining, for example in plaster board, could be more costly overall.

- If a lower level of surface finish on the LVL elements of the building was acceptable, or the LVL elements were covered in some other finish, the amount of fabrication and the subsequent attention to protection of the elements on-site would be significantly reduced. Once fabricated to a high finish, the LVL elements have to remain in that condition throughout the whole construction process, from transport, to delivery, to erection and fixing and closing-in the building around the LVL structure. While it is comparatively easy to ensure team members directly involved in the construction of the LVL structure treat the surface as a finished product, increasing the number and type of workers on-site inevitably means team members have a lower vested interest in the building and subsequently, are not aware, or do not treat the LVL as a finished product.

6.6.6.5 - Mixed materials.

- It is very rare for any building to be constructed from just a single material, including the Timber Arts and Media building, which utilises other materials (concrete and steel) in its construction. However, had the timber building's design criteria allowed use of a larger proportion of other materials, significant cost savings may have been possible. In future timber projects, it may be that the majority of the structural components of the building are constructed from timber, but with greater inclusion of other materials where these make the most structural and economic sense. (ISJ Architects undertook a quick assessment of a hybrid Arts and Media building which utilised the design features for the sub-structure, the frame, the stairs and balustrade and the interior walls from the Timber design and the structural walls (still maintaining damage resisting design), the upper floors and ceiling finishes from the Concrete building and calculated a possible cost saving of around 6 - 7% ($315,000) over the total construction cost of the Timber building.

6.7 - References

- John, S.M., Nebel, B., Perez, N. and Buchanan, A. (2009). Environmental Impacts of Multi-Story Buildings Using Different Construction Materials. University of Canterbury, Research Report 2008-02.

	Concrete	Steel	Timber
Total	**$5,140,382**	**$5,325,024**	**$5,352,041**
Site Preparation	$47,520	$47,520	$47,520
Substructure	$745,575	$602,475	$602,475
Frame	$519,576	$597,236	$572,535
Structural shear walls	$125,460	$329,244	$214,285
Upper floors	$177,590	$205,450	$351,365
Roof	$166,560	$166,560	$166,560
Exterior walls and exterior finish	$140,320	$140,320	$140,320
Windows and exterior doors	$568,900	$568,900	$568,900
Stairs and balustrades	$72,600	$76,050	$77,600
Interior walls	$386,365	$395,495	$380,770
Interior doors	$79,000	$79,000	$79,000
Floor finishes	$169,465	$169,465	$169,465
Wall finishes	$1,760	$1,760	$1,760
Ceiling finishes	$222,119	$209,679	$240,939
Fittings and fixtures	$68,850	$68,850	$68,850
Sanitary plumbing	$63,800	$63,800	$63,800
Heating and ventilation services	$257,305	$257,305	$257,305
Electrical services	$326,695	$326,695	$326,695
Fire services	$177,115	$177,115	$177,115
Vertical and horizontal transportation	$122,000	$122,000	$122,000
Special services	$110,500	$110,500	$110,500
Sundries	$81,900	$81,900	$81,900
Preliminaries and margin	$509,407	$527,705	$530,382

Table 6.9: Estimated costs for the three alternative building designs (Davis Langdon)

Chapter 7 - Life Cycle Costing

7.1 - Introduction

This chapter examines and compares the life cycle costs (LCC) of four alternative designs for the new Arts and Media building erected at the Nelson-Marlborough Institute of Technology (NMIT).

LCC (also known as whole-life cost) analysis is often used for option evaluation when procuring new assets and for decision-making to minimise whole-life costs throughout the life of an asset. It is also applied to comparisons of actual costs for similar asset types and as feedback into future design and acquisition decisions.

Three of the designs differ in the main structural materials used, namely Timber, Concrete and Steel and a low-energy timber design (TimberLow) is also included. The basic floor plan and exterior of the four buildings are the same, so each design provides the same level of amenity.

The aim of the LCC analysis is to determine if any particular design has a significant cost advantage over the other materials.

The LCC analysis was undertaken by BRANZ and the full report is presented in Appendix C

This LCC uses;

- The information from the detailed analysis by Davis Langdon, Quantity Surveyors, of the quantities of building materials and associated costs of the four alternative building designs.
- The life cycle energy assessment results determined from the Life Cycle Assessment (LCA) undertaken by ScionResearch on the four alternative building designs. This in turn includes the results of the extensive energy modelling and analysis of the on-going operational energy of all four designs (see Chapter 5).

The LCC considers a 60 year building lifetime and offers a sensitivity analysis to;

- Discount rate used
- Building lifetime (alternative analysis period 100 years) and
- Future energy price escalation.

7.2 - Summary

The results for a 60 year building lifetime and a 100 year building lifetime are summarised in Table 7.1 and Table 7.2 below, showing the life cycle costs for the four alternative designs.

For both a 60 year and 100 year building lifetime, the results are dominated by the initial cost, and the on-going costs of the four alternative buildings are similar, as the future cash-flows add only another 20% to the lifetime costs in present value terms.

A 100 year analysis period, gives similar results to a 60 period because after 60 years, future costs are increasingly heavily discounted and the design rankings are unchanged.

The Concrete building has the overall lowest lifetime cost followed by the Steel building and then the Timber and the low-energy TimberLow design. The spread between the first three is less than 3.5%.

Over 60 years, the TimberLow design is 5.5% more expensive than the Concrete design mainly because the PVC frames it uses are not cost effective compared to the reduced thermal bridging energy savings. Even when savings are counted over a 100 year period, TimberLow is still about 5.4% more expensive than the Concrete design.

To some extent the cost differences reflect the aesthetics of the interior finished surfaces. In the timber designs the LVL shear wall and ceiling beams were featured as a clear seal finish, adding to costs, whereas for the two other materials less attention was paid in finishing these components.

Life cycle for four designs NMIT Arts Building				
	Timber	**Concrete**	**Steel**	**TimberLow**
Initial cost	$5,352,041	$5,140,382	$5,325,024	$5,489,461
Energy costs - present value	$490,997	$494,973	$500,292	$432,141
Other costs - present value	$612,409	$616,575	$611,951	$675,118
	$6,455,447	$6,251,930	$6,437,268	$6,596,720
Other costs includes mainenance, replacements and operation costs.				
Analysis over a period of 60 years and discount rate is 5%				

Table 7.1: Summary results for 60 year building lifetime.

Life cycle for four designs NMIT Arts Building				
	Timber	**Concrete**	**Steel**	**TimberLow**
Initial cost	$5,352,041	$5,140,382	$5,325,024	$5,489,461
Energy costs - present value	$548,902	$553,347	$559,293	$483,105
Other costs - present value	$692,382	$695,986	$691,258	$759,844
	$6,593,326	$6,389,715	$6,575,576	$6,732,410
Other costs includes mainenance, replacements and operation costs.				
Analysis over a period of 100 years and discount rate is 5%				

Table 7.2: Summary results for 100 year building lifetime.

7.3 - Life Cycle Cost.

Life-cycle cost (LCC) refers to the total cost of ownership over the life of an asset, such as a building (also commonly referred to as "cradle to grave” costs). In this analysis, costs considered include only the financial cost of the four alternative building designs (environmental and social costs are often more difficult to quantify and assign numerical values; Chapter 8 - Carbon and Energy Footprinting examines some of the major environmental impacts of the buildings).

LCC analysis is often used for option evaluation when procuring new assets and for decision-making to minimise whole-life costs throughout the life of an asset. It is also applied to comparisons of actual costs for similar asset types and as feedback into future design and acquisition decisions.

The primary benefit is that costs which occur after an asset has been constructed or acquired, such as maintenance, operation and disposal, become an important consideration in decision-making. If focus is only on the short-term, up-front capital costs of building acquisition, this may fail to take into account the longer-term costs of occupying (and eventually deconstructing) a building over its lifetime – for instance, low initial development costs could lead to high maintenance costs in the future. The longer-term maintenance and operation costs for a poorly designed building, particularly the energy costs associated with operating (heating and cooling) a building can be a significant proportion of the total lifetime costs. Conversely, high initial expenditure on innovative technology may not provide the anticipated longer-term cost savings benefits over time.

LCC of each building design are considered and converted using nominated discount rates into present-value costs.

7.4 - Method

7.4.1 - Financial analysis method and assumptions

A present value method was used because it enables consistent comparisons to be made between the different cost streams over time (Lu, 1969).

Present value PV = Initial cost $+ \sum H/(1 + r)^h + C_1/(1+ r) + C_2/(1 + r)^2 + C_3/(1 + r)^3 + \ldots + C_n/(1 + r)^n$

Where:

H is the cost of maintenance or replacements at year h

$C_1, C_2, C_3, \ldots + C_N$ are annual energy costs in year 1, 2, 3 ….N.

r= discount rate.

N = period of analysis, years.

The base case parameters were:

- 60 years analysis period.
- 5% discount rate.

Energy prices were assumed to escalate at 1.6% pa above the general inflation rate (Ministry of Economic Development, 2009). Energy costs include electricity volume kWh, daily peak kVA and line charges, plus diesel costs. These were obtained from Trustpower Ltd., Tauranga and the rates are applicable to the Nelson area. Operation costs such as cleaning and services routine maintenance charges were obtained from the Property Council of NZ (Property Council of NZ, 2009).

7.4.2 - Energy modelling

Summarised energy modelling results were provided to BRANZ from research conducted by the Civil and Natural Resources Engineering Department at the University of Canterbury. Chapter 5 provides details of this energy modelling and extensive data and details will be included in Nicolas Perez's PhD thesis due for publication in late 2011.

The modelling included boiler consumption (diesel fired) separately from electric plant and machinery consumption. Peak loads at hour intervals for the year were also provided enabling peak electricity charges to be estimated.

7.5 - Results

Table 7.3 presents LCC results for a 60 year building lifetime.

7.5.1 - Initial costs

Details of initial construction costs for all four buildings are shown in Chapter 6 Cost and Timing of Construction.

These costs were compiled by Davis Langdon, Quantity Surveyors, who were closely involved from an early stage in the new Timber Arts and Media building and were also engaged to provide detailed information on the three alternative building designs, working with details provided by the same architectes and structural engineers .

7.5.2 - Maintenance and replacements (60 year lifetime)

Maintenance / replacement regimes over the building's full lifetime are summarised in Table 7.3 above. Details of these regimes are shown in Table 7.4 and Table 7.5 below. In Table 7.4, the exterior wall, windows and roof components are the same for the three designs. For the other components, there are some differences in maintenance costs between the designs relating to surface finishes.

Life Cycle Costs for Four Designs NMIT Arts and Media Building Discount rate 5%. Analysis period 60 years					
		Timber	**Concrete**	**Steel**	**TimberLow**
Initial cost		$5,352,041	$5,140,382	$5,325,024	$5,489,461
Energy costs					
Electricit use	MWh/yr	38.26	38.29	38.32	38.48
Total daily peaks	kVA/yyr	6,129	6,350	6,175	6,194
Diesel use	MWh/yr	93.74	94.81	96.42	75.84
Energy cost per year	$/yr	$19,078	$19,233	$19,439	$16,791
Total energy cost	$PV	$490,997	$494,973	$500,292	$432,141
Major maintenance/replace					
Exterior walls	$PV	$13,758	$13,758	$13,758	$13,758
Windows	$PV	$82,394	$82,394	$82,394	$145,103
Roof	$PV	$26,954	$26,954	$26,954	$26,954
Interior walls	$PV	$50,950	$54,212	$46,160	$50,940
Ceiling	$PV	$30,955	$28,318	$24,445	$30,955
Frame	$PV	-	$3,531	$10,832	-
		$205,011	**$209,167**	**$204,543**	**$267,710**
Other costs common to all designs					
Other replacements	$PV	$125,184	$125,184	$125,184	$125,184
Cleaning services/maint.	$PV	$282,224	$282,224	$282,224	$282,224
Total Present Value		$6,455,447	$6,251,930	$6,437,268	$6,596,720
% difference from minimum		3.3%		3.0%	5.5%
Discount rate =		5%	PV = present value		
Analysis period =		60	years		
Electricity price per kWh		16.84	cents/kWh		
per kVA		4.30	cents/peak kVA per day		
Diesel price per kWh		13	cents/kWh		
Fixed line charge		51	cents per day		
Energy price escalation rate		1.6%	per annum		
Rates, insurance not inluded					

Table 7.3: Detailed cost summary – 60 year analyisis period

MAJOR MAINTENANCE OR REPLACEMENTS						Discount rate 5%, Analysis period 60 years										
							Unit rates	All designs					Present value of maintenance or replacement.			Low e
Component					Low e	Maintenance/ replacement regime	$/unit	Replace/ re-paint cost $				PV factor	Timber	Concrete	Steel	Timber
Exterior walls	Units	All designs except low e timber			Timber						Low e					
Dimondek 400	sqm	401			401	Repaint at year 15 then every 10 years	22.5	9,023			Timber	1.137	10,261	10,261	10,261	10,261
Hardipanel	sqm	205			205	Repaint at year 15 then every 10 years	15	3,075				1.137	3,497	3,497	3,497	3,497
Windows													13,758	13,758	13,758	13,758
Curtain wall glazing	sqm	555			555	Replace DG units every 30 years.	500	277,500			277,500	0.231	64,207	64,207	64,207	64,207
Shopfront glazing	sqm	114			114	Replace DG units every 30 years.	400	45,600			45,600	0.231	10,551	10,551	10,551	10,551
Comm section glazing	sqm	75			75	Replace DG units every 30 years.	400	30,000			30,000	0.231	6,941	6,941	6,941	6,941
Commercial doors	No	1			1	Replace Doors every 30 yrs	3000	3,000			3,500	0.231	694	694	694	810
Curtain wall frame	sqm	555			555	Replace support frame every 60 years. (1)	250	138,750			208,125	0.000	-	-	-	48,155
Shopfront frame	sqm	114			114	Replace support frame every 60 years. (1)	250	28,500			39,900	0.000	-	-	-	9,232
Comm section frame	sqm	75			75	Replace support frame every 60 years. (1)	200	15,000			22,500	0.000	-	-	-	5,206
Roof													82,394	82,394	82,394	145,103
Dimondek 400	sqm	759			759	Repaint at year 15 then every 10 years	19.5	14,801				1.137	16,832	16,832	16,832	16,832
Membrane(bitum 2 coat)	sqm	158			158	Replace every 30 years	90	14,220				0.231	3,290	3,290	3,290	3,290
Box gutter	m	49			49	Replace every 30 years	60	2,940				0.231	680	680	680	680
Downpipes	m	112			112	Replace every 30 years	50	5,600				0.231	1,296	1,296	1,296	1,296
Rainhead	No	6			6	Replace every 30 years	500	3,000				0.231	694	694	694	694
Dimondek soffits	sqm	36			36	Repaint at year 15 then every 10 years	15	540				1.137	614	614	614	614
Villaboard soffits	sqm	208			208	Repaint at year 15 then every 10 years	15	3,120				1.137	3,548	3,548	3,548	3,548
					Low e						Low e		26,954	26,954	26,954	26,954
Interior walls		Timber	Concrete	Steel	Timber			Timber	Concrete	Steel	Timber					
Gibbboard	sqm	710	710	1026	710	Repaint at year 15 then every 10 years	12	8,520	8,520	12,312	8,520	1.137	9,689	9,689	14,002	9,689
MDF	sqm	307	307	307	307	Repaint at year 15 then every 10 years	12	3,684	3,684	3,684	3,684	1.137	4,190	4,190	4,190	4,190
Grooved MDF	sqm	44	44	44	44	Repaint at year 15 then every 10 years	14	616	616	616	616	1.137	701	701	701	701
Clear seal concrete			906			Repaint at year 15 then every 10 years	12	-	10,872	-	-	1.137	-	12,364	-	-
Clear seal LVL	sqm	533			533	Repaint at year 15 then every 10 years	15	7,995	-	-	7,995	1.137	9,092	-	-	9,092
Clear seal plywood	sqm	682	682	682	682	Repaint at year 15 then every 10 years	15	10,230	10,230	10,230	10,230	1.137	11,634	11,634	11,634	11,634
Stain finish plywood	sqm	410	410	410	410	Repaint at year 20 then every 20 years	12	4,920	4,920	4,920	4,920	0.519	2,553	2,553	2,553	2,553
Seratone	sqm	116	116	116	116	Replace every 30 years	80	9,280	9,280	9,280	9,280	0.231	2,147	2,147	2,147	2,147
Timber skirting	m	641	641	641	641	Repaint at year 15 then every 10 years	15	9,615	9,615	9,615	9,615	1.137	10,934	10,934	10,934	10,934
Ceiling													50,940	54,212	46,160	50,940
Clear fin. LVL floor	sqm	1563			1563	Repaint at year 30 then every 30 years	18	28,134	-	-	28,134	0.231	6,510	-	-	6,510
Clear fin. Exposed conc	sqm		622			Repaint at year 30 then every 30 years	12	-	7,464	-	-	0.519	-	3,873	-	-
Stain fin plywood	sqm	215	215	215	215	Repaint at year 20 then every 20 years	12	2,580	2,580	2,580	2,580	0.519	1,339	1,339	1,339	1,339
Clear fin plywood	sqm	73	73	73	73	Repaint at year 15 then every 10 years	14	1,022	1,022	1,022	1,022	1.137	1,162	1,162	1,162	1,162
MDF susp grid	sqm	418	418	418	418	Repaint at year 15 then every 10 years	12	5,016	5,016	5,016	5,016	1.137	5,704	5,704	5,704	5,704
Gibboard suppended	sqm	182	182	182	182	Repaint at year 15 then every 10 years	12	2,184	2,184	2,184	2,184	1.137	2,484	2,484	2,484	2,484
Gibboard timber frame	sqm	101	101	101	101	Repaint at year 15 then every 10 years	12	1,212	1,212	1,212	1,212	1.137	1,378	1,378	1,378	1,378
Gibboard skillion frame	sqm	551	551	551	551	Repaint at year 15 then every 10 years	12	6,612	6,612	6,612	6,612	1.137	7,519	7,519	7,519	7,519
Gibboard timb frame	sqm	66	66	66	66	Repaint at year 15 then every 10 years	12	792	792	792	792	1.137	901	901	901	901
MDF bulkhead	sqm	108	108	108	108	Repaint at year 15 then every 10 years	12	1,296	1,296	1,296	1,296	1.137	1,474	1,474	1,474	1,474
Suspend ceiling	sqm	182	182	182	182	Repaint at year 15 then every 10 years	12	2,184	2,184	2,184	2,184	1.137	2,484	2,484	2,484	2,484
Frame													30,955	28,318	24,445	30,955
Paint to steelwork	sqm	0	486	1491	0	Repaint at year 20 then every 20 years	14	-	6,804	20,874	-	0.519	-	3,531	10,832	-
TOTAL													205,000	209,167	204,543	267,709

Quantities of components and replacement costs are from the Davis Langdon worksheet Repaint is **2 coat acyrlic**. (1) For PVC frame replace the frame every 30 years.

Table 7.4: Major maintenance items which vary between designs

Replacement Details Other Components				
Comment			Same costs for all designs	Present value of replacements all designs
Exterior aluminium fins	Replace 8 fins	Replace every 40 years	$15,300	$2,173
Exterior doors	Replace 3 doors	Replace every 35 years	$16,500	$3,818
Interior doors	Replace all doors and closets	Replace every 40 years	$79,000	$11,222
Floor finishes	Mainly carpet tiles, vinyl and repolish concrete floors	Replace every 30 years	$169,465	$39,210
Fixtures and fittings		Replace every 30 years	$68,850	$15,930
Sanitary plumbing	All except HWC and Solar	Replace every 40 years	$56,800	$8,068
	HWC and Solar	Replace every 20 years	$7,000	$3,633
HVAC services	Fan coil unit	Replace every 20 years	$4,400	$2,283
	Air handling unit	Replace every 40 years	$7,500	$1,065
	Transfer fans	Replace every 20 years	$9,350	$4,852
Electrical services	Lighting only	Replace every 40 years	$92,650	$13,161
Special services	Access control only	Replace every 15 years	$24,000	$19,769
		Total	**$550,815**	**$125,184**

Table 7.5: Replacement items common to all designs

Table 7.6 shows non-energy operational costs, common to all designs.

Cleaning, Services Maintenance, Water, WOF		
Same costs for all three designs		
	Unit rate \$/lettable M^2	Annual cost \$
WOF	0.4	$602
Cleaning	3.0	$4,518
HVAC	3.5	$5,271
Lifts	2.0	$3,012
Water	1.0	$1,506
		$14,909
		PV $282,224
These costs from NZ Property Council "Operating Expenses Benchmark", 2008 Edition		
Net floor area 1,506 m^2 (excludes service areas)		

Table 7.6: Operations costs common to all designs

7.5.3 - Energy use

Energy use and peak energy for the four designs are shown in Figure 7.1 to Figure 7.3. Electrical energy use is almost the same for all three designs, but diesel consumption (for the space heating boiler), differs somewhat between the materials. Electricity for non-residential buildings is charged by overall volume and also the daily peak demand, so the latter was also modelled, as shown in Figure 7.3 . The energy use volumes and peak charges are included in Table 7.3.

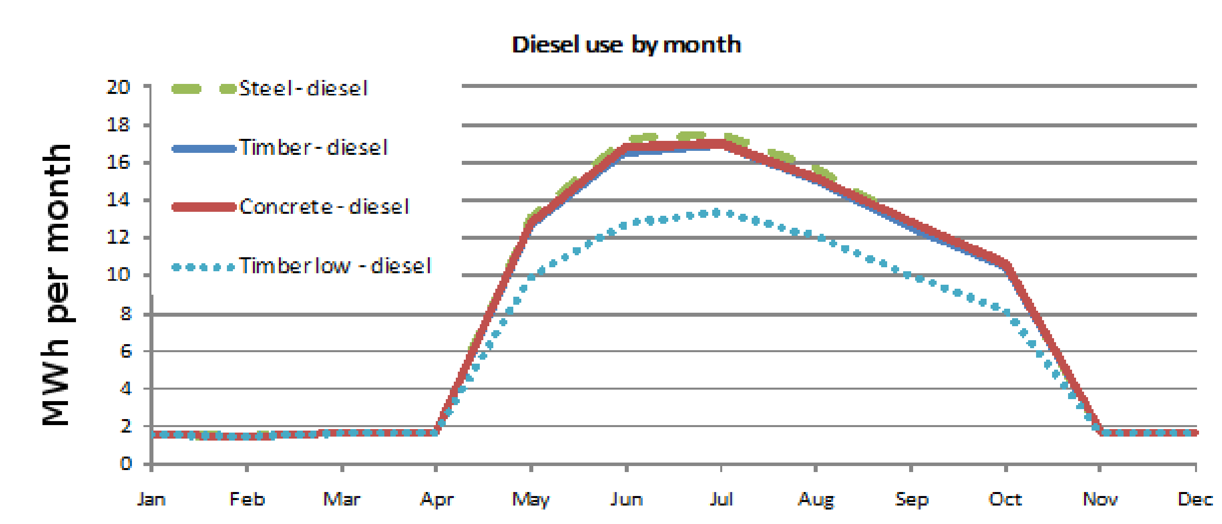


Figure 7.1: Diesel energy use for the four designs

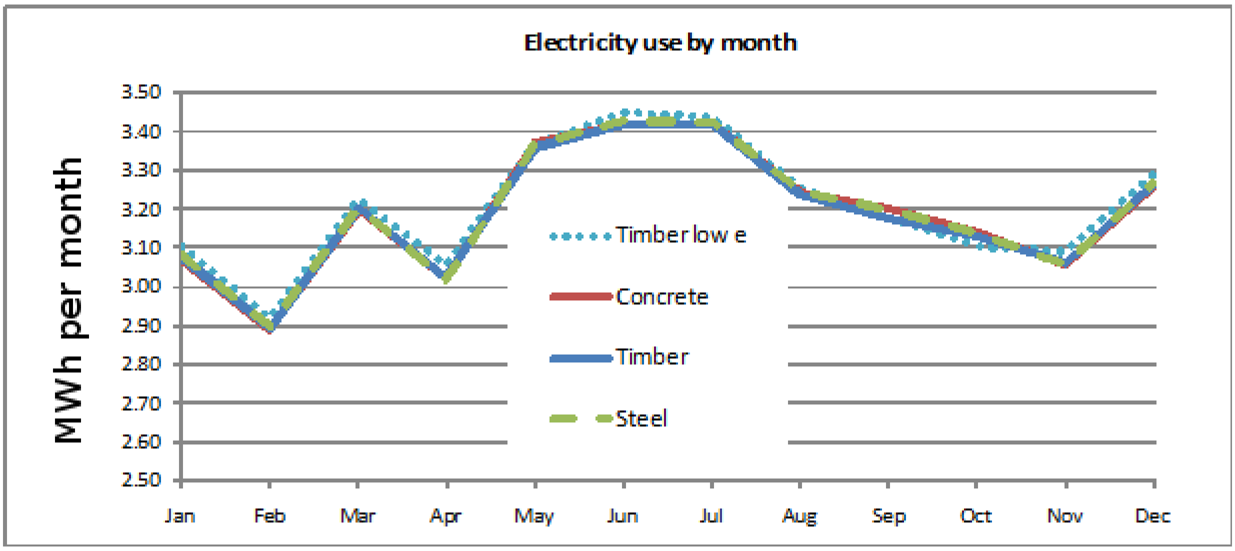


Figure 7.2: Electricity energy use for the four designs

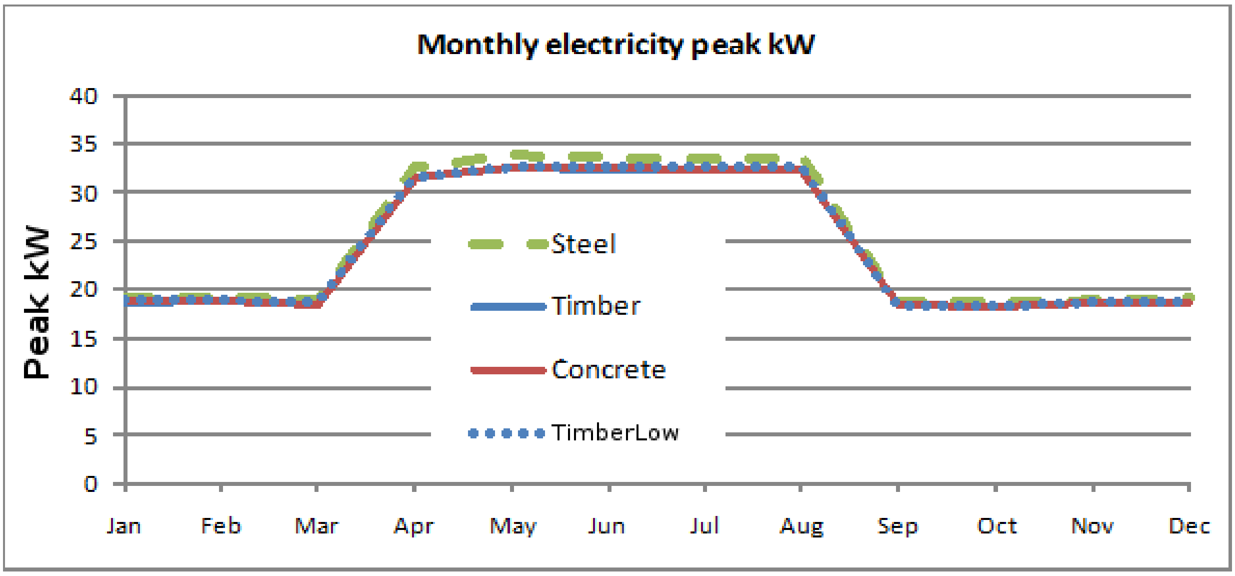


Figure 7.3: Peak electricity use for the four designs

7.5.4 - Lifetime costs

The results of adding up initial, energy and maintenance, and other operational costs over a 60 year period are in Table 7.3 above. Future costs have been discounted back to the present, and the discount rate and analysis period are at the bottom.

7.5.5 - Sensitivity to assumptions

The analysis factors were changed to assess whether the ranking of the design would change.

7.5.5.1 - Sensitivity to discount rate.

The results in Figure 7.4 indicate that with higher discount rate the future costs are heavily discounted and the present value numbers are reduced. However the relative rankings are unchanged with the Concrete building being the lowest in lifetime costs.

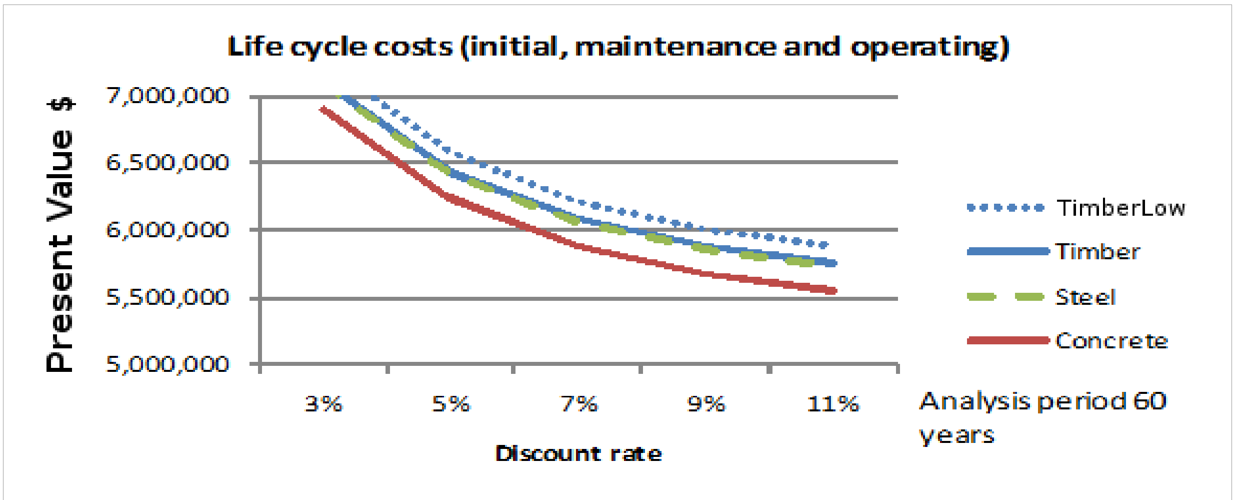


Figure 7.4: Discount rate changes v lifetime costs.

7.5.5.2 - Sensitivity to building lifetime (analysis period).

A similar result occurs with changes in the analysis period, where the Concrete building remains the lowest cost option, see Figure 7.5. After about 60 years, the lifetime costs flatten out and do not increase very much due to the heavy discounting of distant events.

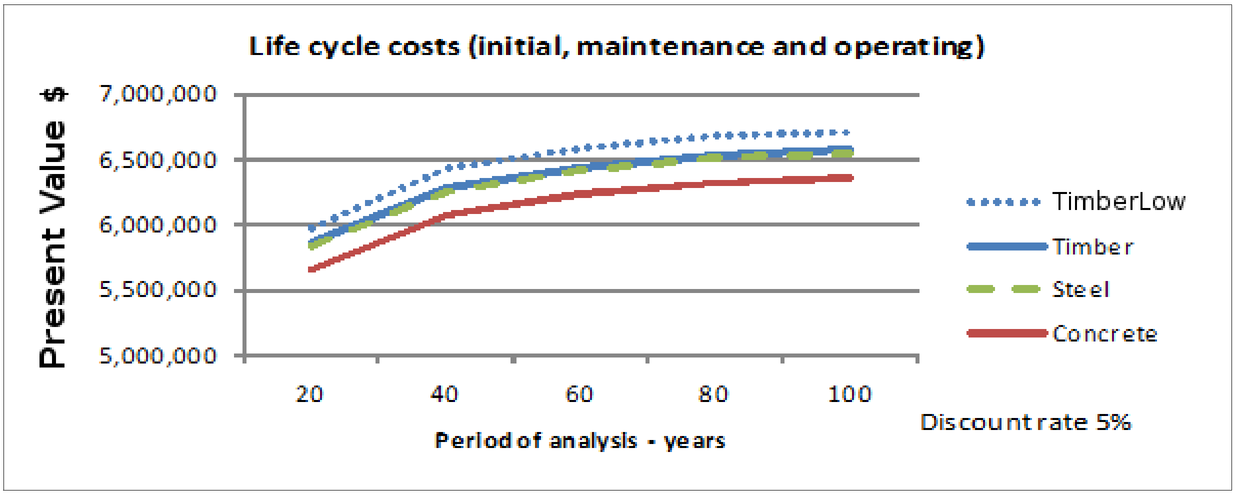


Figure 7.5: Analysis period changes v lifetime costs

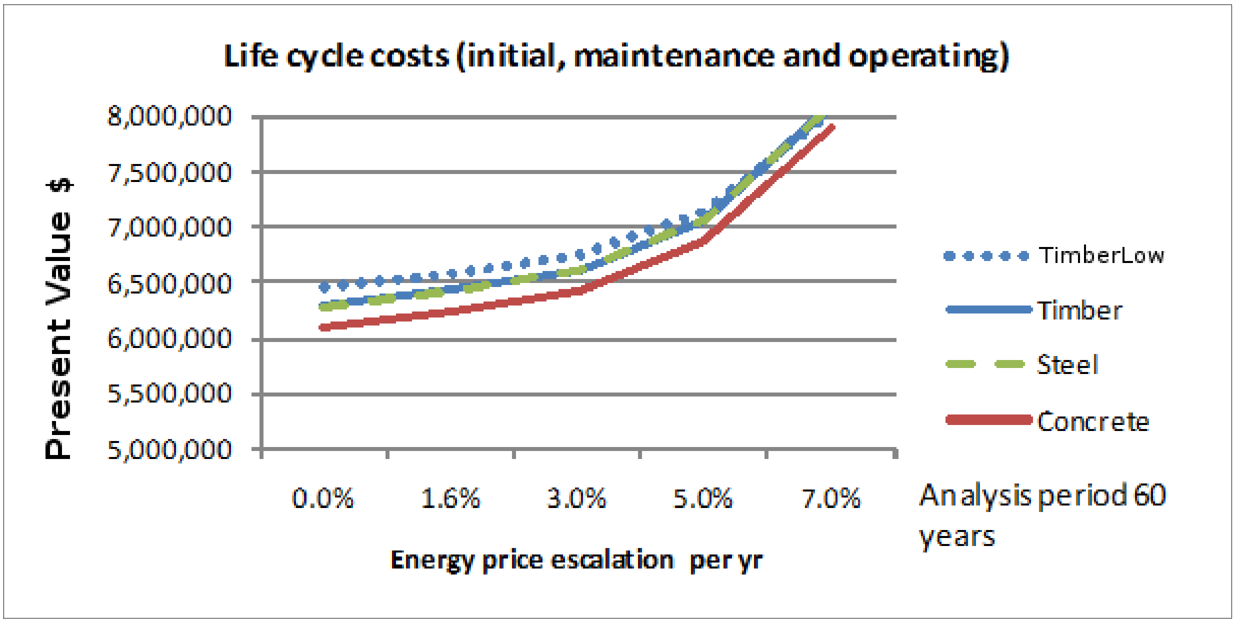


Figure 7.6: Energy price escalation rate changes v lifetime costs.

7.5.5.3 - Sensitivity to energy price escalation

Figure 7.6 shows the effect of changes in energy price escalation of lifetime costs. Again the rankings are the same as before. Note however, total costs rise quite rapidly as energy prices increase. The current Ministry of Economic development (MED, 2009) projections have electricity rising on average about 1.6% per year above the general inflation level, and this is used as the base case.

Table 7.7gives a summary of life-cycle costs for a building life time of 100 years.

Life Cycle Costs for Four Designs NMIT Arts Building Discount rate 5%. Analysis period 100 years					
		Timber	**Concrete**	**Steel**	**TimberLow**
Initial cost		$5,352,041	$5,140,382	$5,325,024	$5,489,461
Energy costs					
Electricit use	MWh/yr	38.26	38.29	38.32	38.48
Total daily peaks	kVA/yyr	6,129	6,350	6,175	6,194
Diesel use	MWh/yr	93.74	94.81	96.42	75.84
Energy cost per year	$/yr	$19,078	$19,233	$19,439	$16,791
Total energy cost	$PV	$548,902	$553,347	$559,293	$483,105
Major maintenance/replace					
Exterior walls	$PV	$14,768	$14,768	$14,768	$14,768
Windows	$PV	$111,214	$111,214	$111,214	$178,676
Roof	$PV	$30,194	$30,194	$30,194	$30,194
Interior walls	$PV	$55,310	$58,822	$50,179	$55,310
Ceiling	$PV	$34,696	$30,756	$26,332	$34,696
Frame	$PV	-	$4,032	$12,371	-
		$246,182	**$249,786**	**$245,058**	**$313,644**
Other costs common to all designs					
Other replacements	$PV	$150,279	$150,279	$150,279	$150,279
Cleaning services/maint.	$PV	$295,920	$295,920	$295,920	$295,920
Total Present Value		$6,593,326	$6,389,715	$6,575,576	$6,732,410
% difference from minimum		3.2%		2.9%	5.4%
Discount rate =		5%	PV = present value		
Analysis period =		60	years		
Electricity price per kWh		16.84	cents/kWh		
per kVA		4.30	cents/peak kVA per day		
Diesel price per kWh		13	cents/kWh		
Fixed line charge		51	cents per day		
Energy price escalation rate		1.6%	per annum		
Rates, insurance not inluded					

Table 7.7: Detailed cost summary – 100 year analyisis period

7.6 - Discussion

The main results are shown in Table 7.3 above. The maintenance for the roof, and the exterior walls are the same for four designs. There are also other common costs (cleaning, routine maintenance of plant, water charges, etc) for the four options, at the bottom of the table. The main differences arise in the windows, energy use, and interior surfaces.

The windows are aluminium framed except in the TimberLow design where PVC frames are used to reduce thermal bridging. Anodised aluminium window frames have been in New Zealand for over 40 years and they are expected to last about 60 years, assuming regular window cleaning washing. PVC frames have a short history locally and overseas experience suggests a shorter life than for aluminium. A replacement period of 30 years has been assumed for PVC frames (which is the main reason for the high maintenance cost for the TimberLow building). Double glazing units need replacing when the cavity seals fail allowing vapour between the glazing panes. Commercial double glazing units are also expected to last about 30 years.

(Note that the alternatives of timber window frames or thermally broken aluminium window frames have not been included, although they may have led to a lower lifetime cost).

Diesel energy use, for the space heating boilers is fairly similar between the Timber, Concrete and Steel designs, varying by about 2% between highest and lowest. This reflects the slightly different heat sink properties of the various structural materials.

The TimberLow design has extra insulation and PVC window frames which reduce window heat losses, and its energy use is significantly less than for the other designs. However the savings over the life of the building are more than off-set by the higher cost of the extra insulation and the PVC windows and their replacements.

Interior surface maintenance costs have some differences. In the Timber design the LVL shear walls, and the LVL ceiling beams were featured and enhanced with a clear seal finish, requiring some maintenance. Similarly, the concrete shear walls had a clear seal finish. The painted wall linings area for the Steel structure is larger than the other two because the steel frame stands in front of the linings, the latter continuing behind the K-frames.

Insurance and local council rates costs have been excluded but are likely to be the same for all designs.

7.7 - References

Lu, F. P. S. (1969). Economic decision-making for engineers and managers. Whitcombe and Tombes Ltd, Christchurch.

MED (2009). New Zealand's Energy Outlook 2009. Ministry of Economic Development, Wellington.

Property Council New Zealand (2009). Operating expenses benchmark - Office buildings and shopping centres. 2008 Edition. PCNZ, Auckland.

Chapter 8 - Carbon and Energy Footprinting

8.1 - Introduction

This chapter investigates the primary energy consumption and global warming potential (GWP) of the new Timber Arts and Media building at Nelson Marlborough Institute of Technology (NMIT), and makes comparisons with three alternative building designs (the Concrete, Steel and TimberLow buildings) through the use of life cycle assessment (LCA).

This work was carried out by the Life Cycle Group at ScionResearch Limited, a New Zealand Government Crown Research Institute (CRI). This chapter is largely an abbreviation of the full report produced by ScionResearch, which is reproduced in Appendix D.

8.2 - Summary of results

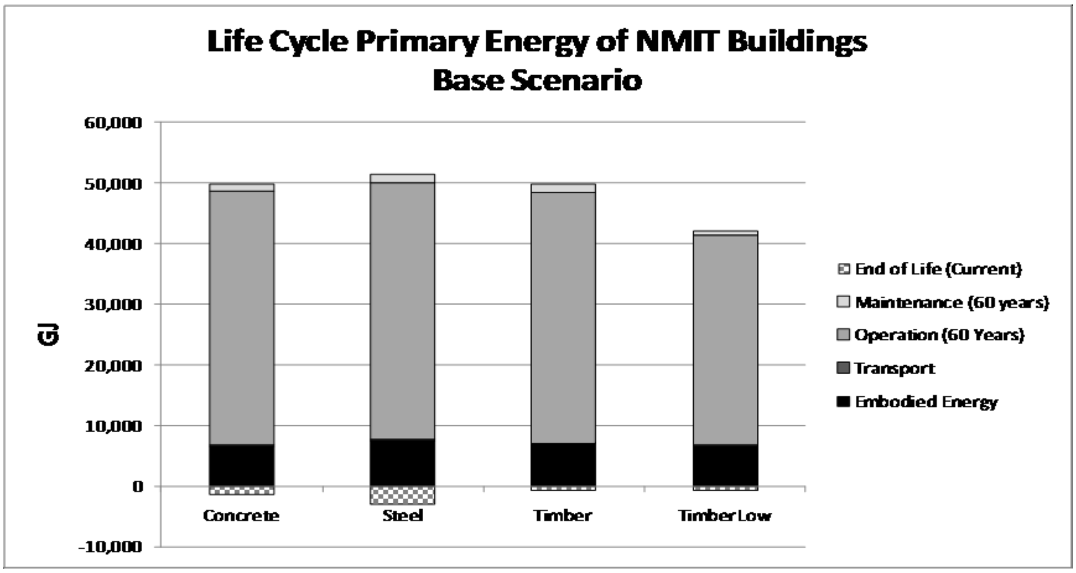


Figure 8.1: Primary Energy for each NMIT building variant, by life cycle stage

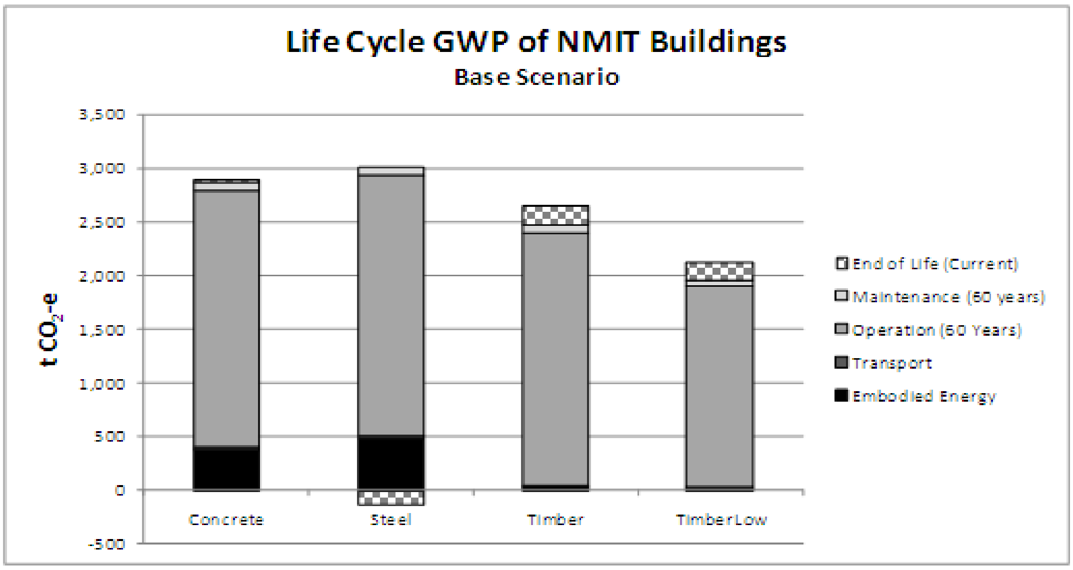


Figure 8.2: Global warming potential for each NMIT building variant, by life cycle stage

The base scenario for this study assumes current waste disposal practices in New Zealand where all timber would be sent to landfill at the end of each building's life, 85% of steel would be recycled and all concrete would go to clean-fill.

Figure 8.1 and Figure 8.2 demonstrate that;

- The operation of the buildings is the dominant contributor to both lifetime energy consumption and global warming potential (GWP).
- The three conventional buildings have very similar total energy consumption.
- The TimberLow building has the lowest total energy consumption.
- The Timber building has an 8% lower life time GWP than the Concrete and Steel buildings.
- The TimberLow building has more than 25% lower life time GWP than the Steel and Concrete buildings.
- Embodied GWP emissions from manufacturing the materials for the Timber and TimberLow buildings are very low – that is, the production of all the materials for these two buildings is nearly *carbon neutral*.

Figure 8.3 shows that;

- Whilst the embodied energy of the materials in all the buildings is similar (Fig. 8.1), the production of materials for the Timber and TimberLow buildings uses a significantly large proportion (> 40%) of renewable, "*clean*" energy.
- The materials in the Concrete and Steel building use more than 85% non-renewable, carbon-intensive fossil-based energy.

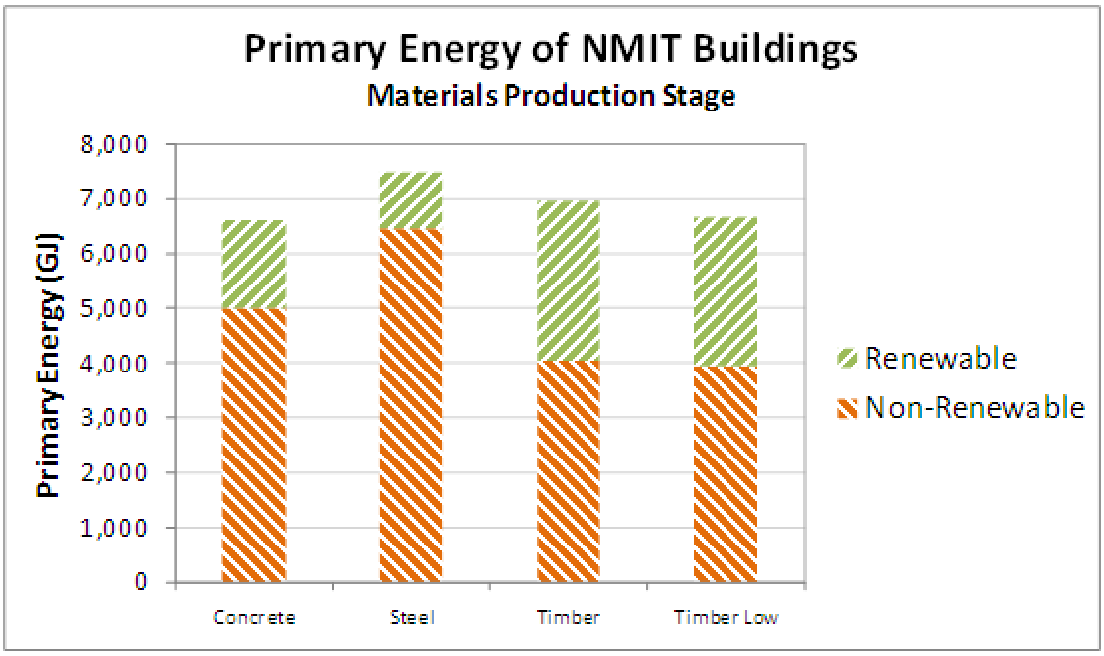


Figure 8.3: Renewable and non-renewable energy balance of NMIT materials production stage

At end-of-life stage, steel recycling has the largest impact reduction benefiting both the Steel and Concrete buildings. For the Timber and TimberLow buildings, possible landfill emissions from decomposition of timber are greater than any offset heat or electricity generated from landfill gas burning.

For a realistic scenario in 60 years time – when the buildings would actually be deconstructed - which assumes total recycling and energy recovery, the end-of-life results for GWP and primary energy improve noticeably in all cases and mean that the end of life stage results in energy output (or avoidance of impact).

Whilst the end of life energy avoidance of the Steel building doubles, the Concrete building energy avoidance trebles and the energy output of the Timber buildings improves almost tenfold.

8.3 - Background

Principles and guidelines of Life Cycle Assessment (LCA), defined by ISO 14040 and 14044, are used to calculate a 'carbon and energy footprint' for the Timber Arts and Media building and the alternative Concrete, Steel and TimberLow buildings.

Research and results obtained from other parts of the overall project are used during this 'footprinting' work, as follows;

1. The design and construction of the Arts and Media building.
2. The design of three alternative buildings – Concrete, Steel, and TimberLow.
3. The quantification of the construction materials used in each building.
4. Operational energy modelling and results for each design.
5. The calculation of transport distances for building materials.
6. The completion of estimated maintenance schedules for each building.
7. Background research on the lifespan of various building materials and end of life disposal and/or recycling options after building deconstruction in New Zealand.

Building on the above research, this study compares the lifetime primary energy consumption and the global warming potential (GWP) of the buildings, and investigates the environmental hotspots of each building.

8.3.1 - LCA Overview

Life Cycle Assessment is based on the concept of Life Cycle Thinking which integrates consumption and production strategies over a whole life cycle, so preventing a piece-meal approach to systems analysis. Life cycle approaches avoid problem-shifting from one life cycle stage to another, from one geographic area to another, and from one environmental medium to another.

LCA is an analytical tool for the systematic evaluation of the environmental impacts of a product or service system through all stages of its life.

ISO 14040 (ISO, 2006b) defines LCA as:

"… a technique for assessing the environmental aspects and potential impacts associated with a product, by

> *compiling an inventory of relevant inputs and outputs of a product system;*
>
> *evaluating the potential environmental impacts associated with those inputs and outputs;*
>
> *interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.*

LCA studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences."

8.3.2 - Elements of an LCA

An internationally accepted framework for LCA methodology is defined in AS/NZS ISO 14040 and 14044 (ISO, 2006a, 2006b). These standards define the generic steps which have to be taken when conducting an LCA. The following section will explain these steps and give examples on how they can be applied to the building industry.

Details of the different elements of LCA (Goal and scope definition; Inventory analysis; Impact assessment and Interpretation) are shown in the ScionResearch report in Appendix D. The LCA framework is summarized in Figure 8.4 below.

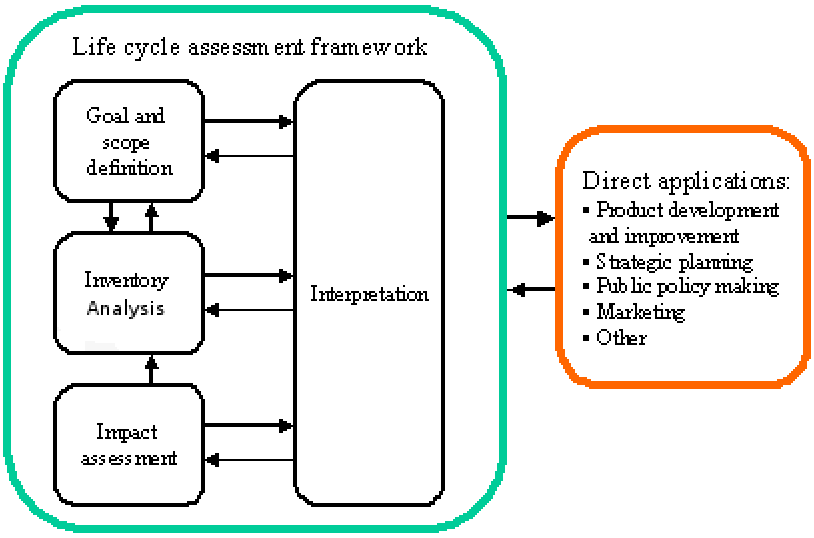


Figure 8.4: LCA framework (ISO 14040)

8.4 - Goal and scope definitions for the four buildings.

8.4.1 - Goal

The goal of this study is to calculate two specific environmental impacts - primary energy consumption and global warming potential (GWP) - of the 3-storey NMIT Arts and Media building and the alternative Steel, Concrete and TimberLow designs, covering production of all materials (cradle-to-gate) and beyond to include the full life-time of the buildings (established at 60 years, with an additional 100-year scenario also investigated). A base end-of-life scenario and an alternative realisitic end-of-life scenario, including recycling of building components have been considered.

The different designs are composed of different structural materials: concrete, steel and timber. The TimberLow variant is a low-energy building based on a timber structure.

8.4.2 - Scope

The scope of the study includes a clear description of the system under analysis, the functional unit, system boundaries and data quality as well as the intended audience and application of the results. These are described for this project below.

8.4.2.1 - Functional Unit

The results of the study are related to the NMIT Arts and Media building (the funtional unit) located in Nelson, and used over a period of 60 or 100 years. Four designs of the building have been considered: the actual (Timber) building, alternative designs using concrete and steel as the structural basis respectively (the Concrete and Steel buildings) and a TimberLow design which is a low-energy variant of the existing building.

8.4.2.2 - System Boundaries

The system boundaries applied in this study were “cradle to grave”.

System expansion has been employed to take into account the benefits of any recycling of metals and concrete, and energy from wood. Upstream processes such as the production of diesel used in transport, as well as the emissions of the transport vehicles have been taken into account, including all related environmental impacts. This also applies to the provision of natural gas for heating and electricity.

The actual construction and demolition of the building are not taken into account because they are considered to be negligible (Kellenberger and Althaus, 2009).

The results of the study are shown for the following stages of the life cycle:

- Production of building materials
- Transport to building site in Nelson
- Use of building over 60 years (and an alternative scenario, 100 years).
- Building maintenance both internal and external
- Electricity for lighting, hot water, appliances and cooling
- Diesel for heating
- End-of-life
    - Current (Base) scenario - all timber materials to average NZ landfill, steel recycled at 85%, and concrete to clean-fill.
    - Alternative realistic scenario – combustion of all timber in a high-efficiency cogeneration plant to produce heat and electricity, as well as recycling of all concrete, aluminium and steel.

All stages of the life cycle as well as the scenarios are described in detail in Section 4, Inventory Analysis in the full report in Appendix D.

8.4.2.3 - Data Quality

Two aspects with regard to data quality need to be considered:

- Input-output data, i.e. quantities of materials used and transport distances.
- Life cycle inventory data, i.e. emissions and energy required for the production of the materials or generation of electricity.

The data quality for both aspects of this research report can generally be described as high quality data and the majority of life cycle inventory data was based on New Zealand-specific figures.

The input-output data for the timber NMIT building is based on actual quantities, as the building has been completed and materials quantified by professional Quantity Surveyors. The input-output data for the alternative designs is based on calculations – because they are theoretical buildings, the material consumption could not be measured on site.

The life cycle inventory data used in this study is from three key sources:

- The data for most building materials is based on a recent dataset developed as part of the project “Life Cycle Assessment: Adopting and adapting overseas LCA data and methodologies for building materials in New Zealand” (Nebel et al., 2009). Global warming potentials for New Zealand energy sources (primarily electricity, natural gas and diesel) are based on recent life-cycle calculations from AgriLink (Barber, 2009).
- The recent detailed study on laminated veneer lumber (LVL) in New Zealand, “Carbon Footprint of New Zealand Laminated Veneer Lumber” (Love, 2010) provides a comprehensive dataset for LVL used in the Arts and Media building.
- Data for the few materials that are not included in this dataset are based on data that is part of a LCA software package (GaBi 4.3) and is based on European industry data (PE International, 2010). The data has been amended and checked for consistency with literature data and is compliant with the ISO Standards 14040 and 14044. The documentation of the data describes the production process, applied boundary conditions, allocation rules etc. for each product. The data covers resource extraction, transport, and processing, i.e., “cradle to gate”. Included are material inputs, energy inputs, transport, outputs and as well as the emissions related to energy use and production. Capital equipment is excluded as it is not expected to be a significant impact in a study of this type (Frischknecht et al., 2007).

8.4.2.4 - Intended Audience and Application of the Results

The study was conducted under contract to the University of Canterbury with the end-client being the Ministry for Agriculture and Forestry (MAF). It is anticipated that the results will be used to inform policy making. The results can also be used to demonstrate the benefits of a life cycle approach when comparing different building designs.

8.4.2.5 - Impact Categories

Primary energy, as an indicator for resource consumption, and greenhouse gas emissions (GWP) are the two impact categories that have been considered.

Primary Energy

Primary energy is energy contained in raw fuels and any other forms of energy that has not been subjected to any conversion or transformation process. Primary energies are transformed in energy conversion processes to more convenient forms of energy, such as electrical energy and cleaner fuels. The transformation includes losses that occur in the generation, transmission, and distribution of energy.

Embodied energy is the energy consumed by all processes from extraction of raw materials through to the production of a product - “cradle to gate”.

Embodied energy usually includes energy from fossil fuels as well as energy from renewable fuels, based on the assumption that there is a limit to how much renewable energy can be harnessed.

In currently available commercial databases, including the widely used Ecoinvent database as well as the GaBi database, non-harnessed solar energy for photosynthesis is also included. This is done to keep the energy balance intact because a calorific value is assigned to all timber products. This means the output of energy (calorific value of timber) is balanced by an equivalent input of energy, (solar). However, this can be seen as distorting the overall use of renewable energy, because the solar energy for timber production cannot be utilised in any other way. In the LCA data for building materials in New Zealand (Nebel et al., 2009) non-harnessed energy has therefore been excluded. However, as the NZ data does not cover all materials, it needs also to be consistent with available databases in order to be able to mix NZ data with data from those to provide a full range of materials and this option has therefore been provided too. Not all materials used in the four buildings analysed in this report are available in the new New Zealand dataset, e.g. PVC and glass data are not available and the data had therefore to be sourced from the GaBi database.

Global Warming Potential (GWP)

GWP is an expression of the contribution of a product or service to potential warming of the atmosphere, possibly leading to climate change.

An internationally agreed characterisation model exists for the calculation of Global Warming Potential. This has been published by the IPCC. This report uses the most recent figures for CO_2 equivalents for greenhouse gas emissions published by the Intergovernmental Panel for Climate Change (IPCC, 2007).

8.5 - Life Cycle Assessment – Inventory Analysis

8.5.1 - Material Quantities

The material quantities for each building type and building component are presented in tonnes in Appendix A of the ScionResearch report (Appendix D). The material quantities, for each building type, were estimated by a quantity surveyor, Davis Langdon in Christchurch. The total quantities, in tonnes, of the main building materials are summarised and presented in Table 8.1

Material (tonnes)	Concrete	Steel	Timber	TimberLow
Concrete	1,633.49	995.82	961.42	961.42
Reinforcing Steel (NZ)	135.99	77.89	77.89	77.89
Structural Steel (Imported)	39.41	123.31	2.64	2.64
Sheet Steel (NZ)	9.34	23.88	9.34	9.34
Glass	27.47	27.47	27.47	27.47
Timber	72.32	38.53	37.04	37.04
LVL	0.00	0.00	163.46	163.46
Plywood/MDF	29.84	28.96	29.84	29.84
Aluminium	3.69	3.69	3.69	1.13
Plasterboard	14.01	16.76	14.01	14.01
Paint	0.75	0.82	0.76	0.76
Glass Wool Insulation	16.22	16.22	16.22	17.58
Expanded Polystyrene	0.00	0.00	0.15	0.30
PVC	0.00	0.00	0.00	1.33
Building Paper	0.00	0.12	0.12	0.12
Total	**1,982.53**	**1,353.47**	**1,344.05**	**1,344.33**

Table 8.1: Total building material quantities for each building design.

8.5.2 - Maintenance

A maintenance schedule for each building design was developed based on life cycle costing data from BRANZ (Page, 2010). The replacement or refurbishment lifetimes of specific building materials are presented in Appendix B of the ScionResearch report (Appendix D).

It was assumed that structural components and insulation would last the entire lifespan of the building. It was also assumed that any replacements required would be with an identical material to the original.

The quantities of materials needed for maintenance over both 60 and 100 years are shown in Table 8.2 and Table 8.3 below.

Total Replacements (kg) over 60 years	Timber	Concrete	Steel	TimberLow
Paint	7,334	7,745	7,406	7,357
MDF	510	510	510	510
Steel (sheet)	360	360	360	400
Glass	23,530	23,530	23,530	23,530
Aluminium	2,700	2,700	2,700	140
Timber	1,580	1,580	1,580	1,580
PVC	0	0	0	1,333

Table 8.2: Mass of building replacements over 60 years

Total Replacements (kg) over 100 years	Timber	Concrete	Steel	TimberLow
Paint	13,661	14,198	13,514	13,685
MDF	1,531	1,531	1,531	1,531
Steel (sheet)	1,080	1,080	1,080	3,359
Glass	47,060	47,060	47,060	47,060
Aluminium	5,260	5,260	5,260	140
Timber	3,160	3,160	3,160	3,160
PVC	0	0	0	3,976

Table 8.3: Mass of building replacements over 100 years

8.5.3 - End-of-Life Inventory

8.5.3.1 - Current (Base) Scenario

The base scenario assumes that all wooden building materials, including wood-based materials installed in each building, such as timber, LVL, plywood, and MDF, would be sent to landfill following deconstruction at the end of each building's life. Plastics, glass and concrete are sent to clean-fill. For the landfill scenarios, the transport to the landfill as well as all emissions associated with the operation of the landfill (e.g. use of bulldozers) are included (PE International, 2010).

Recycling rates for metals and glass have been estimated to represent the New Zealand situation. These estimates are given in Table 8.4 below. Some limited data exists for steel recycling rates, but glass and aluminium are not known. At present, concrete recycling does happen on a small scale, by individual contractors (Kirby and Gaimster, 2010). Despite this, the actual recycling rate is unknown, and this in the Base scenario has been excluded. Concrete recycling is addressed further in the Future scenario section.

Process	Assumption	Source/Explanation
Recycling rate of steel:	85%	NZ Steel [9]
Recycled steel results in:	Avoided production of virgin steel 1:1	Common assumption from ISO and the International Life Cycle Data system (ICLD, 2010).
Recycling of aluminium window frames	0%	No data found
Recycling of glass windows	0%	O-I New Zealand[10]
Recycling of Concrete	0% (unknown)	No accurate figures, but expected to be minimal. Expected to increase in the future.(Kirby and Gaimster, 2010)

Table 8.4: Base end-of-life assumptions for metals, glass and concrete

Behaviour of wood in landfill is a complex issue. The recent study of New Zealand LVL (Love, 2010) has been used for the GWP and energy values of LVL, including for the end of life stage. Further details, including all assumptions, are presented in the full ScionResearch report (Appendix D).

For modelling of incineration, it is assumed that complete combustion occurs, releasing all stored $CO_2$and assumes the energy produced from burning the wood waste is used for cogeneration of heat and electricity. This heat could be used for industrial uses, displacing heat from natural gas, and the electricity could replace electricity from the national grid. The GWP impacts of these displacements (using current New Zealand environmental data) have been taken into account (Barber, 2009). All assumptions for end of life processes for wood are detailed in Section 4 of the ScionResearch report (Appendix D).

9 http://www.nzsteel.co.nz/go/news/sustainability-new-zealand-steel-has-been-working-on-it-for-years/

10 http://www.recycleglass.co.nz/recycling.htm

The total mass of all the structural timber, architectural finishes and each wooden component for each building is presented in Table 8.5. The total carbon within the wooden materials (i) in the building was calculated for each building based on this proportion (Table 8.4). This is then converted to CO_2-e (ii). Using the 18% decomposition figure given above, carbon emissions have been calculated and shown as total CO_2-e released (iii). Line (iv) shows the remaining CO_2-e left after emissions have been subtracted from the stored carbon.

		Building Designs			
		Concrete	Steel	Timber	TimberLow
Timber in building	tonnes	72.32	38.53	37.04	37.04
LVL in building	tonnes	0.00	0.00	163.46	163.46
Plywood/MDF in building	tonnes	29.84	28.96	29.84	29.84
(i) Total Carbon content of building*	tonnes	49.43	32.15	104.53	104.53
(ii) Total CO_2-e sequestered for building lifespan	tonnes	181.27	117.89	383.30	383.30
iii) Total CO_2-e released from landfill**	tonnes	90.85	59.08	192.10	192.10
iv) Net CO_2-e sequestered in landfill	tonnes	90.42	58.80	191.20	191.2

Table 8.5: Net tonnes CO_2 equivalent stored in landfill including total GHG emissions released from decomposition

* This does not equal 50% of the mass, as some of the mass of wood products is made up by resins and additives. Calculations were based on data from Love (2010) and used as an approximation for plywood and MDF

** This figure includes CO_2 emissions from methane flaring and energy generation, but not from any offset electricity/heat

8.5.3.2 - A future realistic 'reutilisation' scenario

Life cycle assessment, by its very nature, often considers what will happen in the future. In the case of large buildings, constructed to have a long life time, deconstruction is many years beyond the time of construction – in this research, the building life time is considered to be either 60 or 100 years.

Therefore, it can be logically argued that LCA should consider a scenario which will actually take place at the time of deconstruction, in 60 or more years time. With the rapidly advancing pace of technology in this area of science and an increasing demand internationally from both Governments and the world's population, it is entirely realistic to assume that material disposal will be much more efficient, maximising the recovery of energy and minimising harm to the environment.

Thus, as a future 'reutilisation' scenario, instead of sending waste materials to landfill, all timber from all four building designs are used as fuel to generate energy and all structural steel and concrete is recycled.

The amount of recycled steel was then assumed to replace virgin steel and credited to the building. Energy and emissions from the recycling process were taken into account. For the Concrete building, all concrete was assumed to be recycled as aggregate (if this aggregate was used again to make concrete, this would require the use of new cement). Due to the unknown energy input for the crushing, sorting and reuse of concrete as aggregate, it is assumed that the energy needed for these steps would be similar to that of producing virgin aggregate, therefore cancelling each other out. However, this scenario does avoid the impacts of disposal of such a large amount of concrete in clean-fill.

The total mass of wooden materials was the same as in the land-filling scenario which includes timber, LVL, plywood, and MDF. It was assumed that all these materials would be burnt in a cogeneration plant with an energy conversion efficiency of 98%. This figure is an estimate of a high-performance cogeneration plant, and is based on previous estimates of plants using cardboard and paper waste as inputs, which showed efficiencies up to 98% (Merrild et al., 2008). An efficiency of 98% means that 98% of the calorific value of the wood ((i) in Table 8.7 below) is recovered as useful energy (ii) through combustion with a ratio of electricity to heat of approximately 1:3 (Merrild et al., 2008, Connell Wagner, 2007). It was assumed that this electricity (iii) and heat (iv) are used, and replace electricity from the national grid and heat from burning natural gas. This displaces GWP emissions (0.061 kg CO_2e per MJ heat from natural gas and 0.066 kg CO_2 e per MJ electricity) and primary energy (1.13 MJ per MJ heat from natural gas and 2.36 MJ per MJ electricity) (Barber, 2009). These assumptions are summarised in Table 8.6 below.

Process	Assumption	Source
Calorific value of wood waste	15.68 GJ/tonne	Energy Efficiency and Conservation Authority[11]
Efficiency of wood cogeneration plant (best case)	98%	(Merrild et al., 2008)
% of energy output as electricity	29%	
% of energy output as heat	71%	
CO_2-e associated with 1 MJ New Zealand electricity (for offsetting)	0.066 kg CO2-e	(Barber, 2009)
CO_2-e associated with 1 MJ New Zealand heat from natural gas (for offsetting)	0.061 kg CO2-e	

Table 8.6: Assumptions for incineration of wood waste

	Concrete	Steel	Timber	TimberLow
Wood Waste (t)	98.9	64.3	209.1	209.1
Energy (GJ)				
(i) Calorific Value	1,550.4	1,008.3	3,278.3	3,278.3
(ii) at 98% efficiency	1,519.4	978.0	3,180.0	3,180.0
(iii) Metered Electricity	440.6	283.6	922.2	922.2
(iv) Metered Heat	1,078.8	694.4	2,257.8	2,257.8
CO_2 Displacement (t)				
Electricity	29.1	18.7	60.9	60.9
Natural Gas	65.8	42.3	137.6	137.6
Total	94.8	61.1	198.5	198.5
CO_2 Storage	0.0	0.0	0.0	0.0
Total GWP Impact (t CO_2-e)	-94.8	-61.1	-198.5	-198.5
Total Renewable Energy (GJ)	-753.9	-485.3	-1,557.9	-1,577.9
Total Non-Renewable Energy (GJ)	-1,505.0	-968.8	-3,149.8	-3,149.8

Table 8.7: Energy recovered from wood combustion and CO_2 displaced from avoiding the use of traditional energy sources (natural gas and electricity)

Energy from combusting wood is recovered, which can replace conventional energy from fossil fuels (and in a future, 'best case' scenario, all of this energy is assumed to be used). The avoided fossil CO_2 can be subtracted from the GWP of the end-of-life phase in which the wood is being combusted. This is known in LCA as 'system expansion'.

The total displacement of fossil fuels for each building is shown in Table 8.7 above.

8.5.4 - Transport

Sources of building materials for the actual NMIT building have been documented, and therefore the actual distances (or the nearest estimate) have been used. For other buildings, some assumptions have been made, for

11http://www.eecabusiness.govt.nz/renewable-energy/wood-energy-knowledge-centre/tools-and-calculators example that structural steel would be imported from Australia or Asia.

Emission factors for truck transport are taken from Love (2010). Emission factors for ocean transport come from UK figures (DEFRA, 2008), and are converted into energy figures using data from Barber (2009).

8.5.5 - Operational Energy

Total energy consumed (electricity and diesel) during the 60 year operation period for each building type was supplied by Perez (Table 8.8) as metered consumption (Perez, 2010) – for further details see Chapter 5, Building Energy. To demonstrate total energy consumption this has been converted to primary energy and the respective GWP has also been calculated.

A life cycle inventory dataset for New Zealand has been used to calculate the primary energy content and the GWP for electricity. The dataset takes the New Zealand electricity mix as well as New Zealand specific emissions into account (Barber, 2009).

The results for metered energy consumption, as well as primary energy and GWP are shown in Table 8.8. The figures for metered energy consumption have then been multiplied with the respective numbers for CO_2 equiv./kWh and MJ primary energy/kWh for heat from diesel and electricity.

Total Operational Impacts (60 years)				
	Non-renewable Energy (GJ)	**Renewable Energy (GJ)**	**Total Primary Energy (GJ)**	**Total GWP (t CO_2-e)**
Concrete	72,151	9,000	81,151	5,077
Steel	73,608	9,006	82,614	5,177
Timber	71,167	8,995	80,162	5,009
TimberLow	54,915	9,029	63,944	3,892

Table 8.8: Operational energy (GJ) and GWP (t CO2-e) over 60 years

The primary energy consumption associated with the operation stage was determined and used instead of using the consumed MWh in the building because the system boundaries include all energy use associated with each stage of the life cycle. Therefore it was imperative to include all energy consumed in the process of delivering the useable energy to the buildings. Table 8.9 shows the operational energy required if the building was to be used for 100 years.

Total Operational Impacts (100 years)				
	Non-renewable Energy (GJ)	**Renewable Energy (GJ)**	**Total Primary Energy (GJ)**	**Total GWP (t CO_2-e)**
Concrete	120,251	15,000	135,251	8,462
Steel	122,680	15,010	137,690	8,629
Timber	118,612	14,992	133,604	8,349
TimberLow	91,525	15,049	106,574	6,486

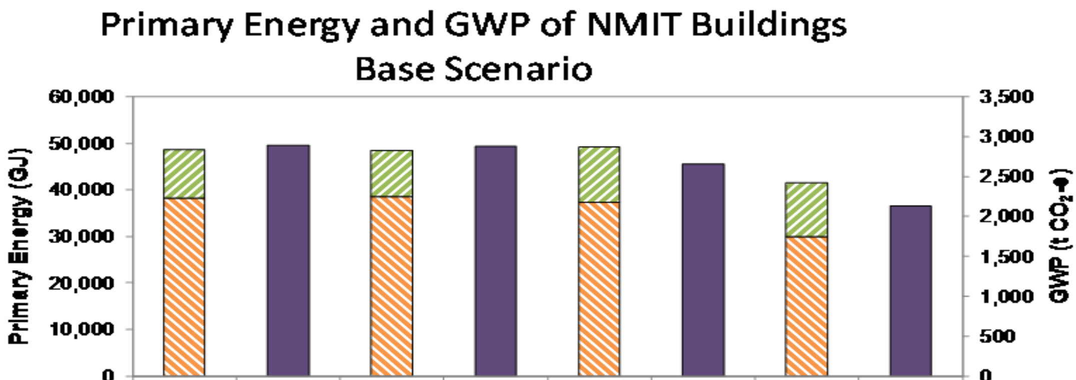
Table 8.9: Operational energy (GJ) and GWP (t CO2-e) over 100 years

8.6 - Life Cycle Assessment – Impact Assessment

Total primary energy and GWP were the two impact categories calculated for each building type. The results for each building are presented for the following life cycle stages: initial material production, maintenance, transport, operation over the 60 (or 100) year lifetime of the buildings, maintenance, and end of life.

8.6.1 - Base end-of-life scenario

The total primary energy and GWP contributions from each building can be seen in Figure 8.5 below. The three conventional buildings have very similar total energy consumption, with the TimberLow building showing the lowest total consumption. Renewable energy makes up 21%, 22%, 24% and 28% of the Steel, Concrete, Timber and TimberLow buildings, respectively. In terms of GWP, the Concrete and Steel results are very similar, though the Timber building has an 8% lower GWP result, and the TimberLow building has a GWP result over 25% lower than the Steel and Concrete buildings.



	Concrete		Steel		Timber		TimberLow	
Total Primary Energy	48,516		48,356		49,103		41,453	
Ren. Energy	10,492		9,949		11,872		11,531	
Non Ren. Energy	38,024		38,408		37,231		29,922	
Total GWP		2,894		2,878		2,651		2,129

Figure 8.5: Total life cycle primary energy and GWP of each NMIT building variant over 60 years

The contribution of each stage to the primary energy consumption is shown in Table 8.10 below, and graphically in Figure 8.6. The use phase of the buildings is the dominant contributor, making up 85 - 88% of the respective totals. Production of materials makes up approximately 14%, building maintenance 2%, and transport of materials well under 1%. In all cases, the end of life processes result in negative impacts.

	Concrete	Steel	Timber	TimberLow
Materials	6,599	7,468	6,950	6,657
Transport	201	161	124	124
Operation	41,887	42,520	41,460	34,529
Maintenance	1,239	1,224	1,220	793
End of Life	-1,410	-3,016	-650	-651
Total	**48,516**	**48,356**	**49,103**	**41,453**

Table 8.10: Primary Energy (GJ) for each NMIT building variant, by life cycle stage

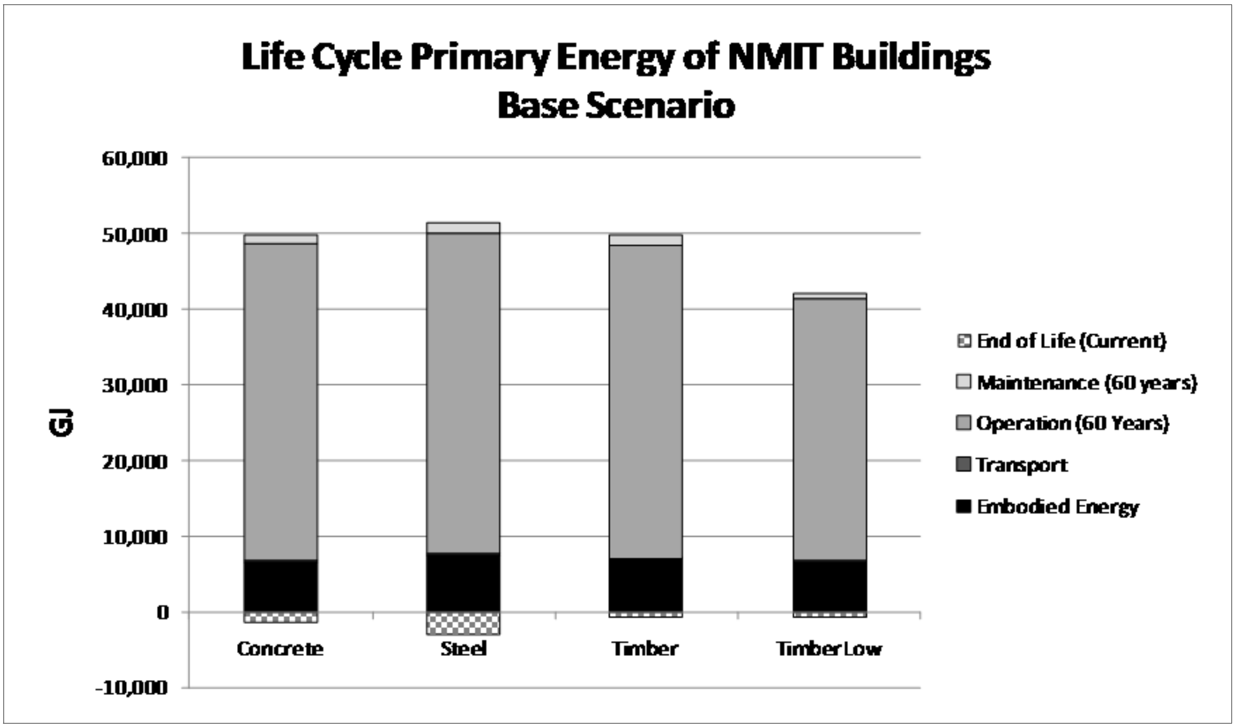


Figure 8.6: Primary Energy for each NMIT building variant, by life cycle stage

The two life cycle stages where the Timber buildings differ from Concrete and Steel the greatest are in materials production and end of life. The Timber buildings show relatively similar magnitude primary energy use in the material production stage to the other buildings. However, the wood products used in the Timber buildings use a significantly higher proportion of renewable energy than the other building materials. When split into non-renewable and renewable energy, this can be seen clearly (Figure 8.7). In the end of life stage, steel recycling has the largest impact reduction, due to the offset of energy-intensive virgin steel production – this benefits both the Steel and Concrete buildings. Energy from timber decomposition in landfill is relatively small in comparison, though still results in output of energy.

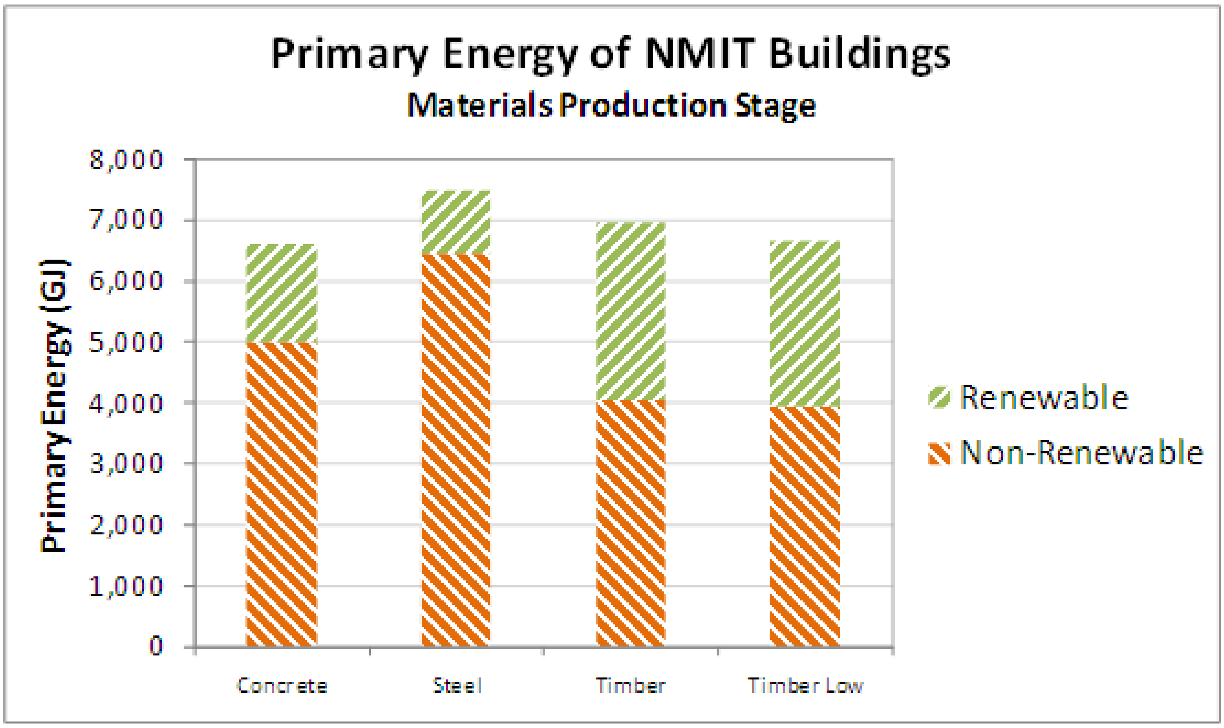


Figure 8.7: Renewable and non-renewable energy balance of NMIT materials production stage

The GWP results for the different building variants are shown below in Table 8.11 and Figure 8.8. Again, the dominant stage is the operation of the building, due to the heating needed over 60 years. Focus on energy efficiency in the TimberLow building means that its operational emissions are approximately 20% lower than the other buildings. Emissions from the production of materials for the buildings are very low in the Timber and TimberLow buildings, due to CO_2 uptake in the tree growth stage of wood products.

End of life emissions vary, and are again mostly influenced by steel. Recycling of the steel from the Steel and Concrete buildings (and subsequent replacement of virgin steel) is the reason for low figures in this stage. For the Timber and TimberLow buildings, the landfill emissions from decomposition of timber are greater than any offset heat or electricity from landfill gas burning. As with primary energy, the transport stage has minimal impact over the life cycle.

	Concrete	Steel	Timber	TimberLow
Materials	382	496	33	16
Transport	27	20	17	17
Operation	2,376	2,419	2,347	1,868
Maintenance	77	76	76	51
End of Life	33	-128	178	178
Total	**2,895**	**2,844**	**2,651**	**2,129**

Table 8.11: GWP (t CO2 eq.) for each NMIT building variant, by life cycle stage

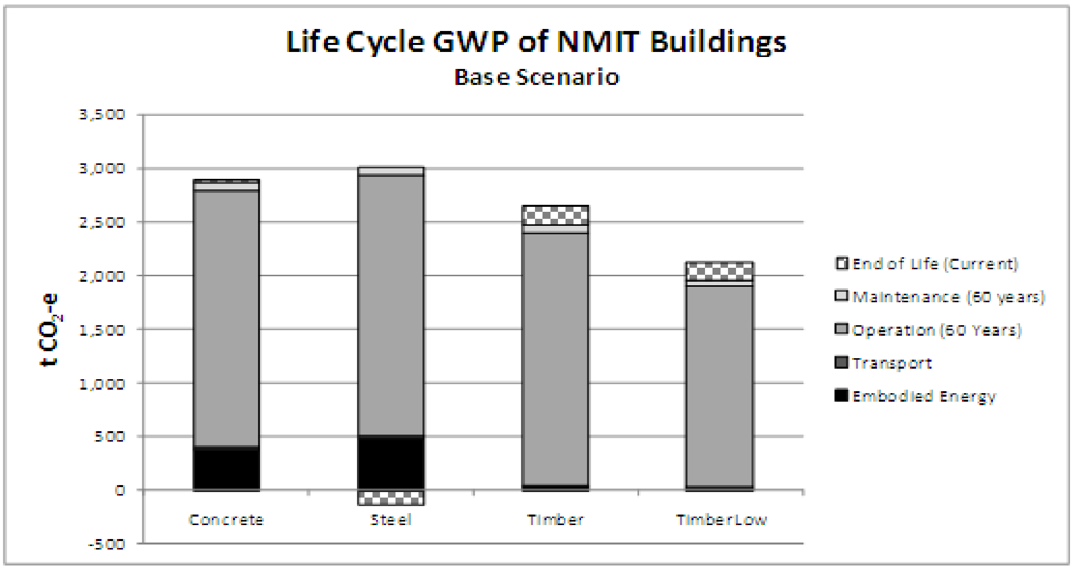


Figure 8.8: GWP for each NMIT variant by life cycle stage

8.6.2 - Alternative future reutilisation scenario

An alternative scenario investigates the impact of 'best case' end of life processes in the future and involves recycling of high levels of steel, concrete (into aggregate substitute) and aluminium. Wood is burned in a high-efficiency cogeneration plant, and is used to offset other sources of energy. The results for the future disposal and recycling scenarios, as well as comparing 60- and 100-year building life spans are shown in Figure 8.9 and Figure 8.10 below.

The results of the different scenarios show clear trends that follow on from the base case. A 66% increase in lifespan (from 60 to 100 years) increases the operational and maintenance impacts by a similar amount. Due to the operation stage being the dominant stage in the building's life cycle the total impacts increase by approximately 60% in the 100-year scenario. The materials, transport and end of life are unchanged in this comparison.

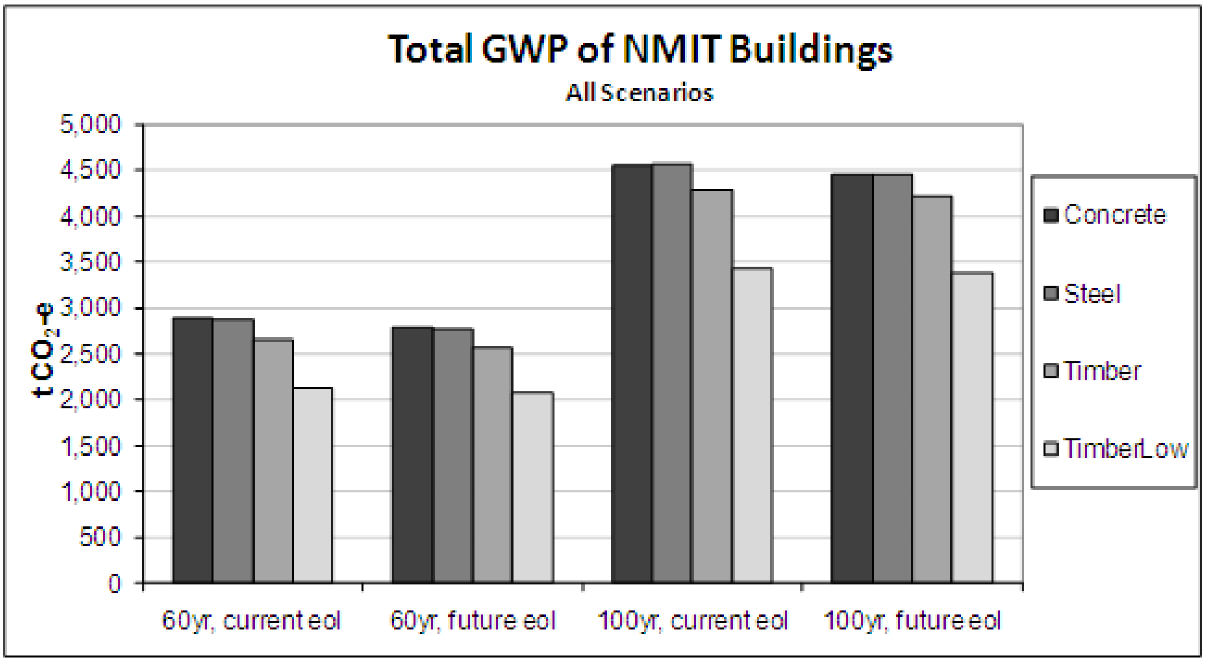


Figure 8.9: Comparison of total GWP of NMIT building variants over 60- and 100-year time frames, and current and future end of life processes. (eol = end of life)

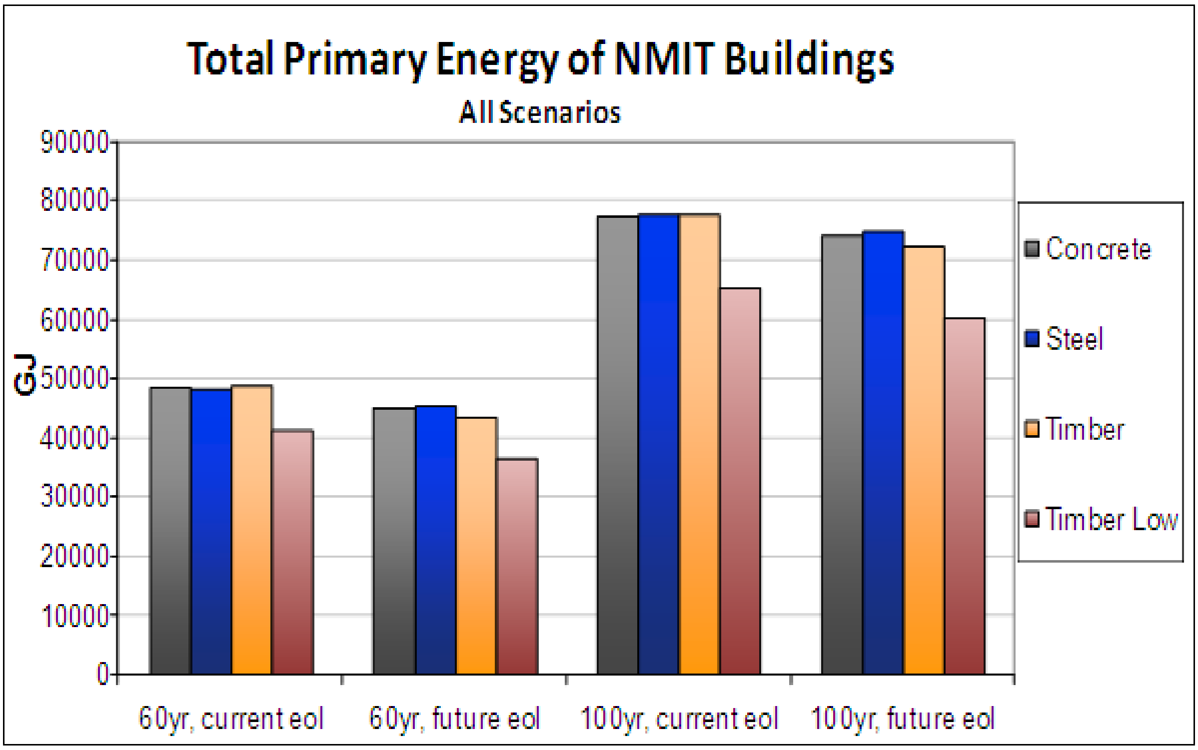


Figure 8.10: Comparison of total primary energy consumption of NMIT building variants over 60- and 100-year time frames, and current and future end of life processes. (eol = end of life)

When investigating the different end of life options (base scenario versus future total recycling and energy recovery scenario), the end of life results for GWP and primary energy improve noticeably with future waste options. In Figure 8.11, the end of life primary energy use is shown, and in all cases it is negative, meaning that the end of life stage results in an energy output (or avoidance of impact). The end of life energy avoidance of the Steel building doubles, Concrete energy avoidance trebles, and the energy output of the Timber building improves almost tenfold. These changes are driven mainly by steel recycling, energy recovery from timber products, and recycling of aluminium-framed windows.

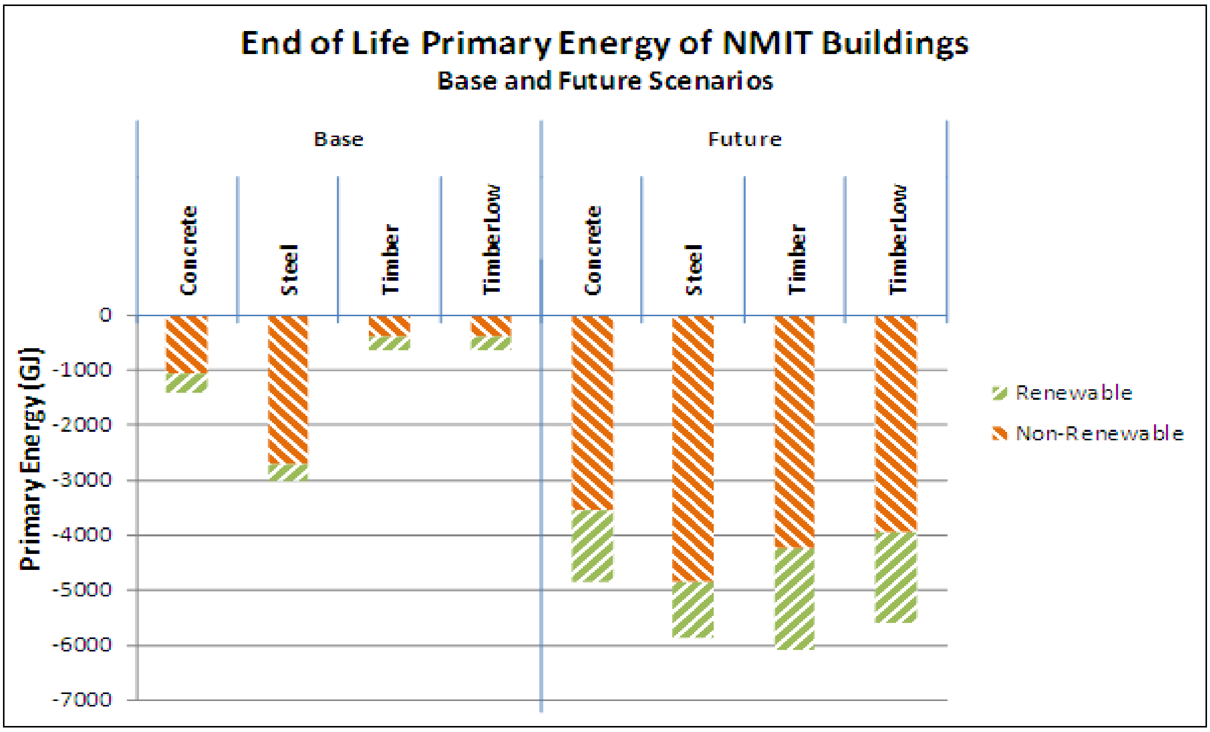


Figure 8.11: Base and future end of life primary energy consumption for each NMIT building variant

8.7 - Discussion and Conclusions

In this project, the new Arts and Media building built with massive LVL structural beams, columns and shear walls (the Timber building) was compared with theoretical alternatives, using steel and concrete structural components. In addition, an energy-efficient building was considered (the TimberLow building). The global warming potential and energy consumption of each building was investigated, starting from material production and continuing through use and maintenance, and including disposal and recycling processes after life spans of 60 and 100 years.

The dominant stage in the life cycle of every building was the use phase. Electricity from lighting, cooling and other uses, in addition to diesel used in the main boiler, contributed 80-90% of the GWP impacts of the main three buildings, and up to 92% of the TimberLow building's life cycle GWP impacts. For energy, the use phase contributed from 83% to 95% of the life cycle impacts, depending on the building and scenario. These results indicate that a large impact could be made by minimising energy use in this phase; this would be applicable to all buildings.

At the other end of the scale, transport made a very small (<0.5%) impact on the energy use of each building, and was responsible for less than 1% of GWP emissions. Maintenance made up approximately 2.5% to 3.5% of energy use and GWP emissions for each building. The remaining impacts were from material production and end of life processes.

The Timber and TimberLow buildings differ from the Steel and Concrete buildings in that their GWP emissions begin with an uptake of CO_2, in the form of tree growth. This means that in a cradle to gate analysis, the Timber and TimberLow buildings have negative GWP values due to carbon stored in the materials. The Steel and Concrete buildings generally have larger GWP emissions and energy usage in this style of analysis, as production of the raw materials is an energy-intensive process, and uses a large proportion of fossil fuels. Conversely, the Timber and TimberLow buildings emit CO_2 when disposed of in present-day landfill, while much steel is recycled, avoiding emissions from virgin steel production.

When the base scenario is considered, the TimberLow building shows considerably lower energy use and GWP emissions than the other buildings. This is not unexpected as it has been designed as a low energy building. Of the three conventional building designs, the total energy use is effectively the same for all buildings. When split into energy types, the Timber building has a higher renewable energy figure than the other buildings, but a lower non-renewable energy figure, thus reducing its reliance on fossil fuels. Much of this can be attributed to the materials production stage. The Timber building has a GWP figure approximately 8% lower than the Steel and Concrete buildings.

A future end of life scenario is considered in this study, where wood waste is incinerated in a high-efficiency plant[12], and steel, concrete and aluminium are recycled. In this case, the only noticeable change in relative impacts is that the energy use of the Timber building drops slightly below that of the Steel and Concrete buildings. This difference is not large, and thus it is not conclusive which of the conventional buildings would have the lowest overall energy use in this scenario. Again, the Timber building uses a much higher proportion of renewable energy, which indicates that the Timber building incorporates more energy from electricity and wood waste than the other buildings (which tend to use more fossil fuels in their production).

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12 The report “ *Environmental impacts of multi-storey buildings using different construction materials”* (John et al., 2009) and the conference paper “*Extended Producer Responsibility of Treated Timber Waste”* (Love, 2007) provide a good overview of the current options for the recycling and disposal of treated timber waste in NZ.

Modern timber preservation techniques do not need to employ CCA treatments. Future timber buildings will not need to use CCA treated timber. Research, technology advances and strong market drivers particularly in Europe are developing methods for the removal of treatments from timber products, thus rendering them safe for recycling, landfill disposal or incineration without the use of complex filtration systems.

Whilst there are no facilities currently available in NZ for burning treated timber for energy production, advances in gasification and pyrolysis are considered very likely to provide a number of thermal treatment options in the future.

At present, treated timber products can be recycled as particleboard, chipboard and orientated strand board or incorporated into wood-plastic and wood-cement composites.

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Chapter 9 - Discussion

Discussion of many points covered by this research has been included in the separate chapters, often presenting viewpoints and conclusions from the independent industry consultants engaged to investigate and report on their own 'field of expertise' .

This chapter briefly presents some points around the science of making comparisons between buildings and ensuring a 'fair and level playing field'.

9.1 - Comparing buildings – what is the purpose and is it '*fair'*?

This research document not only reports on the '*facts'* of cost and time of construction of the new timber Arts and Media building at NMIT but extends beyond this to make a comparison between this new building and similar buildings constructed in concrete and steel.

It is appropriate to discuss the reason and soundness of making this comparison by posing the question "*Comparing building – what is the purpose and is it fair?"* This is important because many people in the building industry need to know what are the different options for constructing a building and what will be the effects, financially, environmentally and otherwise – both long and short term - of making an important decision about the different construction materials that can be used.

As noted in Chapter 3, there is a lack of information around some aspects of commercial-type, multi-storey buildings constructed mainly of timber, if only because few, modern buildings exist and hence there has been little opportunity for research and understanding. The research covered by this report is intended to provide just some of the answers – or indeed, maybe only parts of the answers - and, like all research, builds on previous knowledge and, then in turn, will itself be extended by future investigations.

The research recognises certain limitations in the methodology and information available. The research covered by the Research Report 2008-02, *Environmental impacts of multi-storey buildings using different construction materials* (John, et.al., 2009) was reviewed by a number of industry bodies and peers. Comments have been acknowledged in the design of this current research.

The authors believe that recognising limitations and working to minimise their effects, makes the research more credible, rigorous and robust and allows objective and scientifically-based comparisons to be made between the building designs. Three areas that are noteworthy concern the actual design of alternative buildings, the end-of-life scenario/s adopted for life cycle assessment and the estimation of operational energy usage.

9.1.1 - Alternative building designs - comparing apples with apples.

The purpose of comparing two (or more) *things* (for instance inanimate objects, such as building) is firstly to discover whether a difference exists between the two objects –if it doesn't then this may be an entirely satisfactory result – and then, if it does, exactly what that difference is. It is necessary to define that difference/s, and then, to go a further step to discover what the consequential effect of that difference/s is on some measurable quality.

For this study, a deliberate difference between buildings has been *introduced* (the main construction material) and the research attempts to quantify the consequences on such aspects as cost (including long-term life cycle cost), time of construction, operational energy usage and environmental impacts.

It is common, when comparing two things, to hear the phrase "apples for apples". Of course, by definition once a difference exists, then the two apples are different! The skill in good research is to minimise and carefully control the variables between the things being compared, in order to be able to identify and highlight the consequences of introducing those differences. In other words, the 'apples' are different, in clearly defined ways, but they are both still recognisable as apples – as opposed to oranges.

Put simply, this study changes the main construction material and measures the change in cost of construction materials (or time of construction, etc.).

It is an obvious truism that there can only be one 'real' building. The design of alternative buildings to the 'real' Arts and Media building generated considerable debate and much effort was expended in this research at the 'front-end' to '*minimise and carefully control the variables between the things being compared, in order to be able to identify and highlight the consequences of introducing those differences'*.

The design process is amply covered in Section 4.3.1 and 4.3.2 of Chapter 4, including a copy of the contract letter that passed between UC and Aurecon/ISJ. The latter two consultant companies were employed to provide the alternative designs because it was felt that, together, they had firstly, the expertise, secondly, the experience and understanding of the 'real' Arts and Media building, and thirdly, that they were independent of UC. In the previous report (John et al., 2008), the alternative building designs were completed by UC staff and research students (although the designs did have independent review from industry consultants).

The *deliberately introduced* differences between the Timber, Concrete and Steel buildings are restricted to the structural elements of the buildings. (As stated in the contract letter, "*The alternative design will focus on the replacement of primary structural timber elements with appropriate steel and concrete alternatives"* and further *"The review will work with the existing structural grid so that the architectural design of the building is maintained").*

This report acknowledges that if the architects and engineers were given a 'clean slate' to develop a landmark building, meeting all the objectives and design criteria specified by NMIT, then a Concrete or a Steel building could look different to what has been produced for this report.

Furthermore, it is considered valid that the design of the 'real' Arts and Media building, is centred around those criteria which 'display' timber - the 'real' building, then acting as the template for the Concrete and Steel buildings, 'forces' certain, perhaps less than optimal design criteria on to these alternative structures. However, neither is the 'real' building considered to be optimised in all aspects of its design – for instance, the TimberLow alternative design demonstrates that changes can be made to reduce energy consumption.

ISJ Architects and Aurecon state that in their opinion equivalency is established between the building designs, allowing objective and in-depth comparison to be made across a series of criteria.

At the end of the day, with all the various constraints including budget and time, the alternative designs, and the changes that they incorporate, provide the basis for a 'fair' comparison between buildings which employ different structural materials.

9.1.2 - End-of-life scenario – what happens to building materials after deconstruction?

The purpose of the detailed life cycle assessment (LCA) in Chapter 8 – covering the full life cycle of the alternative buildings and all their building materials – is to determine whether there is a discernable difference in some specific environmental impacts through utilising different structural building materials over the whole building life time.

The LCA assumes a base scenario where all materials are dealt with in a way which is presently possible and practicable in New Zealand (all wooden materials sent to landfill, concrete to clean-fill and 85% recycling of steel). What happens to building materials at the stage of building deconstruction – considered to be the end-of-life of the building, if not the absolute end-of-life of the materials – can have a profound effect on the environmental impacts of the building being investigated.

However, all the alternative buildings are designed for a lifetime which exceeds 60 years (the base scenario for the LCA), and the reality is that a substantial building such as the Arts and Media complex will exist well beyond 60 or even 100 or 200 years. Is it not then 'fair' to consider what would be a 'realistic' end-of-life disposal scenario 60 years hence from now (or 100 years, etc.)?

The Research Report 2008-02, *Environmental impacts of multi-storey buildings using different construction materials* (John, et.al., 2009) was criticised for being '*futuristic'*. This report presented the results of a full LCA study on the new Biological Sciences building at the University of Canterbury, as carried out by ScionResearch. The report also considered how environmental impacts would differ if all carbon was prevented from being released back into the atmosphere after deconstruction (a permanent carbon storage scenario), being particularly relevant to global warming potential (GWP). The report compared alternative designs for the Biological Sciences building utilising either concrete or steel or timber as the main structural material. The permanent storage scenario demonstrated that a building employing more timber in its structure would create less adverse energy usage and GWP environmental impacts.

In this present study, ScionResearch present an alternative 'future' end-of-life scenario, considered wholly realistic for 60 years hence, which maximises recovery of energy and minimises harm to the environment (all wooden material is used as fuel to generate energy and all structural steel and concrete is recycled). The results are detailed in Chapter 8.

ScionResearch considers that the comparison made between materials and the alternatives considered for end-of-life of each material – timber, concrete and steel – is ‘fair’. The base scenario offers 85% recycling of all steel (a figure provided by NZ Steel), although it is not specified whether steel can be recycled repeatedly into a form which would allow the same use and structural performance.

In the base scenario, all timber is sent to landfill and ScionResearch state that the behaviour of wood in landfill is complex. Unfortunately, presently, it is also poorly researched and this has resulted in a position being taken in modelling future deconstruction which is considered very conservative – that is, the decomposition of timber in landfill and the resultant emissions are a ‘worst case scenario’ (pers. comm., Simon Love, ScionResearch). Research[13] presently being conducted in Australia by Fabiano Ximenes at Industry and Investment NSW in Australia may offer more realistic information about decomposition rates and long-term carbon storage for timber in modern landfills, including composite wood products, such as particleboard and medium-density fibreboard, which have not been studied in depth before.

Future disposal of concrete proposes that all concrete is recycled into aggregate for new concrete, although ScionResearch were unable to quantify the energy input for this to happen.

The future, realistic utilisation scenario (section 8.6.2) shows that all materials benefit from anticipated improvements in disposal, reuse and recovery of energy in the future. Whilst for all buildings, *“GWP and primary energy improve noticeably”*, it is only the Timber building which shows any relative improvement in energy use.

If the comment of ‘futuristic’ is made about the end-of-life scenarios covered by this report, with the implication that ‘nobody knows what the future holds’ then this is acknowledged but reasonably countered by the points made above, which show that the LCA utilised both current, up-to-date and best practice information for all materials, as well as proposing a realistic scenario for material disposal in 60 years or more.

9.1.3 - Building operational energy use.

As shown in Section 8.6.1, the operational energy use phase of a building dominates the full building life cycle. As such, the absolute cost of providing this energy both in financial terms (life cycle costing) and environmental impacts (LCA) is very important and any relative cost differential between buildings made of different structural materials could – and indeed, should - be a significant consideration for the long-term financial viability of occupying and running a building.

This research provides the results of energy modelling for four alternative building designs (Timber, Concrete, Steel and TimberLow) and makes a comparison between the amount of energy used each year in each building. The new Arts and Media building was only occupied for the first time in February, 2011. Therefore, no ‘real’ data was available on energy usage and, quite obviously, there was no ‘real’ data available for the alternative designs – so, operational energy usage, in all building designs is estimated. Because of its importance, the authors considered that the estimation of operational energy use should be thoroughly investigated, well understood and carefully peer reviewed.

A considerable amount of time and effort has been expended on the energy use estimations by Nicolas Perez, PhD student in the Department of Civil and Natural Resources Engineering at UC. His work is reported in Chapter 5. Perez has received advice and peer review from colleagues, supervisors and specialist industry consultants and his full work will be presented in his PhD thesis towards the end of 2011.

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13 The fraction of carbon released as carbon dioxide and methane from both wood and landfill has been identified as a research priority for the National Carbon Accounting System in Australia. The project involves excavations of both closed and operational landfills in Cairns, Brisbane and Sydney, and placement of a range of wood and paper products in laboratory anaerobic reactors under optimal conditions. Laboratory simulations will determine the maximum extent of decomposition theoretically possible in landfill. Release of carbon dioxide and methane will be measured using gas chromatography.

Perez has used information and insight gained from research on the Tourism building at NMIT, a multi-storey concrete building, similar in size, orientation and use to the Arts and Media building. Perez's models for all the alternative designs are based on the initial findings and calibration from data available over more than a year from this building. This enabled Perez to have a clear understanding of the local environmental conditions, the siting and aspect of both the Tourism building and the new Arts and Media complex and the typical occupancy of such educational buildings.

In order to be able to make a fair comparison between the alternative Timber, Concrete and Steel buildings, all have been designed with the same HVAC systems and same level of insulation. Only the TimberLow building has been partially optimised to reduce operational energy use. It is acknowledged that the Timber, Concrete and Steel designs could all be designed for improved energy consumption but within the limits of the imposed budget and other design criteria, all are considered to be designed to the same level.

9.2 - References

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APPENDIX A

NMIT Alternative Structural Design

by

Aurecon Group and ISJ Architects.

NMIT Alternative Structural Design

Report ref:
210688 001
Revision 2

Prepared for University of Canterbury

Structural Design by AURECON

Architectural Review by ISJ Architects

irving : smith : jack

aurecon

Document prepared by:

AURECON New Zealand Limited
1st Floor, 62 Bridge Street
Nelson 7040 New Zealand

T: +64 3 539 0190
F: +64 3 539 0191
E: nelson@ap.aurecongroup.com
W: aurecongroup.com

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aurecon

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Contents

1. Executive Summary

1.1 Aim of Report

This report compares the recently completed NMIT Arts & Media building, New Zealand's landmark timber design project, with similar structural concept steel and concrete alternative designs.

AURECON has been commissioned by the University of Canterbury to prepare this report.

1.2 Concept

The NMIT Arts & Media building showcases to the design and construction industry that a multi-storey timber building is a viable alternative to traditional forms of multi-storey construction.

1.3 Design

The commission to design and construct the NMIT Arts and Media building was secured by a Nelson based team of Irving Smith Jack Architects and multi-disciplinary engineers AURECON. The successful design meets the specific needs of NMIT as a learning institution; using state of the art structural timber technology coupled with the use of locally produced and fabricated Laminated Veneer Lumber (LVL).

The scheme, as completed, responds to the Ministry of Agriculture and Forestry's aspiration for *'a building whose structural form uses and showcases its construction in timber'* and which could '*act as a demonstration and education project…to allow it to be used as a demonstration and education model'.* The design deliberately reveals and expresses all internal timber components as a legible whole, making the structural system, materiality and construction approach apparent.

The structural scheme is notable for a simple bolted gravity resisting frame system coupled with a sophisticated damage avoidance design approach utilising pairs of coupled post tensioned shear walls; the first use of this approach in timber internationally.

1.4 Alternate Structural Design Solutions

To further this report, AURECON have provided concept designs for two further, equivalent structures, one in steel and one in concrete. Design parameters were applied to these alternatives that matched the functionality, performance and emphasis on structural elements required of the original timber design to ensure equivalence in terms of:

- Floor plan and internal layout

- Column and beam layout
- Spaces and room layout
- ‘Damage Avoidance’ structural performance for seismic design.
- Structural performance for the gravity structure
- Fire performance stipulated in the fire report
- Acoustic performance

1.5 Equivalency and Discussion on Structural Design Solutions

Irving Smith Jack Architects and AURECON, as independent consultants, have produced the alternative designs described in detail in the body of this report.

Both organisations have been involved from the earliest stages of design, throughout documentation and construction in the realisation of the NMIT Arts and Media building. By adhering to the design intent of the original brief, and the design parameters defined above, the alternative structures involve changes to only essential components; from timber to either steel or concrete.

Both the timber and structural steel design solutions provide a building of equivalent weight whilst the concrete design solution gives an increase in building weight by approximately 30% requiring an increase in the lateral load resisting system and the foundation system.

This approach establishes equivalency between the three alternative structures, to enable objective and in depth comparison across a series of criteria including building methodology, energy use and cost.

1.6 Architectural Review

The three buildings have been reviewed by Irving Smith Jack Architects to identify comparative design implications regarding eight key aspects of the building;

- Visual exposure of the structure,
- Seismic bracing systems,
- Internal spatial planning,
- The main stair,
- Accommodation of building services,
- Internal linings and external cladding,
- Thermal insulation requirements,
- Surface finishes and detail design.

The purpose of this exercise is to quantify the design effect of utilising either steel or concrete over timber as the primary structural material, to assist with subsequent comparison and analysis by other parties to this process.

1.7 Limitations

This report has been prepared using available information and with the standard of care typical of this scope of work. The assumptions listed throughout the report should be reviewed carefully as these represent limitations and areas of potential risk with regard to cost and comparability between the reviewed options.

The Aurecon design assumptions for purpose of this exercise is to quantify the design effect of utilising either steel or concrete over timber as the primary structural material, to assist with subsequent comparison and analysis by other parties to this process. Not all alternative solutions have been reviewed when considering steel and concrete options but rather a like for like substitution has been carried out to enable cost and comparability between the reviewed options.

Aurecon takes no responsibility and disclaims all liability whatsoever for any loss or damage that the client may suffer as a result of using or relying on any such information or recommendations contained in our report, except to the extent that Aurecon expressly indicates in this report that it has verified the information to its satisfaction. The report is limited to the scope defined herein. Should further information become available, or the scope of the report change, Aurecon reserves the right to review the report in the context of the additional information and revise this report accordingly.

2. NMIT Arts and Media Project Background

2.1 The Concept

The concept behind the NMIT Arts and Media building project is to showcase to the construction industry that multi storey timber buildings are a viable alternative to traditional forms of multi storey construction.

The Arts and Media building was selected by the Ministry of Agriculture and Forestry as a suitable timber demonstration project at the early concept design stage. MAF then provided access of up to $1 million for the project through a contestable fund, which provided funding for the successful applicant to develop an innovative timber building design, and enable it to showcase this approach for commercial buildings.

In 2008 discussions were held around design concepts between NMIT managers, Arts and Media staff and the Ministry of Agriculture and Forestry. A competition for the design was created stipulating that the building must be sustainable, local and substantially made of wood. In partnership, the Ministry of Agriculture and Forestry (MAF) and NMIT offered a national design competition, with MAF providing $1m towards construction costs as the prize. MAF's involvement relates to their initiatives around how the forest industry can meet objectives for climate change mitigation as well as creating a sustainable resource for commercial building construction benefiting the climate and our economy. Planting more trees creates a carbon 'sink' , MAF research has shown that well-managed sustainable forests mitigate erosion and improve water quality and wood buildings also store carbon emissions. Currently there are very few wooden commercial buildings in New Zealand, a reflection of the fact that there are not many building companies and designers skilled in using wood for commercial buildings.

The NMIT Arts and Media building is therefore a vital teaching tool. Engineers, architects, builders and the associated training providers will be invited to assess the construction process and the building to promote the use of wood in commercial construction. This building shows that timber can be successfully used in multi-storey commercial buildings. Timber is sustainable, renewable, locally available and requires less energy to manufacture than other building materials, like concrete and steel.

2.2 The Design

A Nelson based team of Irving Smith Jack Architects and multi-disciplinary engineers AURECON, won the design competition against a formidable array of top design teams from throughout New Zealand. The judges comments said the design solution meets the specific needs of NMIT as a creative learning institution, using state-of-the-art structural timber technology coupled with the use of locally produced materials including Laminated Veneer Lumber (LVL) and a design that expresses all the internal structural components. It is unique in the world in terms of wooden building design.

The NMIT Arts and Media building construction has been completed. The building now provides an excellent learning tool for many aspects of timber construction. Numerous studies are underway that include review of the design performance, the energy performance, the construction methodology and the building costs.

3. Project Scope

3.1 Alternative Structural Design Solutions

The aim of the project is to prepare alternative concept structural design solutions in both steel and concrete for the NMIT Arts and Media building. The concept designs have been completed in sufficient detail to allow a preliminary cost estimate to be prepared by Davis Langdon Quantity Surveyors.

The scope of the "alternative" structural design solutions is that they are to be based on the architectural scheme completed for the Arts and Media building timber structural solution. The scope only includes the three storey teaching building and does not include the workshop building or the media building.

The "alternative" structural solutions are also required to match the building performance requirements of the timber structural solution. In summary the performance requirements of the alternative structural solutions will:

- Match the same floor plan and internal layout
- Make use of the same column and beam layout to maintain the same floor spaces and room layout
- Provide the same structural performance for seismic design. (The design will be based on a damage avoidance design similar to the design used for the timber solution)
- Provide the same structural performance for the gravity structure.
- Provide the same fire performance to meet the requirements of the fire report completed for the timber solution
- Provide the same acoustic performance as provided in the timber solution

Notwithstanding meeting the above objectives for performance requirements, the alternative designs will;

- Provide the same client expectation/s in terms of functionality as the Timber building – for instance, offer the same number of rooms, teaching and practical facilities, and cater for the same number of occupants including students and staff.
- Provide a similar quality of architectural features including interior and exterior surface finishes.
- Provide the same client expectation/s for comfort and internal environment as the Timber building.

The alternative designs focus on the replacement of primary structural timber elements with appropriate steel and concrete elements. They essentially involve a review of beams, columns, structural walls, floor systems, roof systems and foundation systems. The review of foundation systems has been limited to the change in size of footings and the change in the number of screw piles. It has not involved a review of alternative foundation systems.

What this review will not seek to provide is alternatives that change structural grids to maximise beam and floor spans for steel and concrete systems. The review will work with the existing structural grid so that the architectural design of the building is maintained.

3.2 Fire and Acoustics

In addition to the structural review, a review of the fire rating and acoustic requirements of the alternative structural solutions is to be completed. A brief commentary on the appropriate treatment sufficient to allow cost estimates to be completed by the Quantity Surveyor has been provided.

3.3 Architectural Review

To complete the review ISJ Architects were engaged to complete an architectural review of the proposed alternative structural solutions. A brief commentary on the appropriate architectural treatment has been provided sufficient to allow cost estimates to be completed by the Quantity Surveyor. This includes a mark up of relevant structural and architectural drawings to be used for comparison of costs between the alternatives.

4. Timber Structural Solution

The timber structural solution for the main three storey arts building consists of:

- Lightweight timber roof structure using LVL timber purlins and a plywood diaphragm also utilised for insulation and acoustic purposes
- LVL timber beam and column gravity frame
- LVL timber stressed skin floor panels and reinforced concrete diaphragm topping
- LVL timber post tensioned shear walls, (“rocking” timber walls)
- LVL timber lintels and secondary beams
- Concrete slab on grade ground floor with a mixture of foundation pads and screw piles for uplift resistance under the rocking shear walls.

4.1 Gravity Frame

The primary gravity frames consist of a continuous LVL column over three levels supporting a double LVL timber beam arrangement. The double LVL beams consist of two short spans and one long 9.6m span. The longer span has been designed for composite action with the concrete floor topping to control deflection. The double LVL beam is fabricated as two single beams and is supported on timber corbels incorporated into the timber column fabrication. A connection between the two beams is provided by the concrete topping.

The flooring system comprises of stressed skin timber floor panels, trade name “Potius Panels”, spanning 6.0m between beams. These panels consist of a double 300x90 timber LVL joist fixed to a 36mm thick LVL slab. The connection provides a composite action between the LVL joist and the LVL slab. The panels support a 75mm concrete floor topping with mesh reinforcing and acts as a diaphragm to transfer horizontal floor loads to the LVL shearwalls. The concrete topping slab provides the robustness, stiffness and durability required for an educational or commercial building.

4.2 Wind and Seismic Bracing

The lateral load resisting system for the building comprises of floor level reinforced concrete floor diaphragms transferring horizontal loads to the post-tensioned LVL timber shear walls. The design is based on PRESSS technology more commonly associated with precast concrete shear wall buildings which is now being applied to timber structures and has been researched and tested at the University of Canterbury. Similar systems have been developed by AURECON for concrete and steel structures but this is the first time this technology has been used with timber walls.

The bracing system in the longitudinal direction is provided by pairs of 3.0m long shear walls adjacent to the stair and lift shaft. Bracing in the transverse direction is provided by pairs of 3.0m long shear walls at each end of the building. The transverse walls also provide resistance to the torsion loads due to mass eccentricities resulting from the open layout. The design is governed by the seismic loading due to the mass of the building and the high (approximately 4m) inter-storey heights. The wind loading is less than half that of the seismic loading and as such the bracing walls will also resist wind loads responding in an elastic manner.

Each pair of walls is a hybrid system with a wall thickness of 189mm. The walls are coupled to act integrally under lateral loading. The coupled walls are connected using energy dissipators and each wall includes post-tensioning tendons through a central core. These tendons act to minimize panel uplift and are sized to overcome the over strength forces of the energy dissipators to ensure that the wall recentralises following lateral (typically seismic) loading. System energy absorption (equivalent to ductility 4) under seismic loading is provided by the coupling mechanism in the form of energy dissipaters fabricated from steel plate elements located in the vertical gap between each panel. Base shear is transferred to the foundations via a steel shoe encapsulating the base of the timber wall panels.

Lateral loads for both wind and seismic are transferred to the shear walls via rigid diaphragms. Diaphragms are provided at roof level by timber purlins and a plywood lining, while the concrete floor topping provides a rigid floor diaphragm at the two suspended floor levels.

The damage avoidance modelling design of this building is a unique and innovative solution. In a 500 year design earthquake seismic event the rocking timber walls will lift a maximum of 45mm at one end. This will result in very low inter-storey drifts, in the range of 1.0% - 1.2%. The end result is that the primary and secondary structural elements such as internal partitions, facade and building services will suffer only minimal damage and the building structure will remain fully functional following the earthquake allowing the occupation of the building within hours rather than months.

4.3 Foundations

The geotechnical investigation highlighted the varied ground conditions across the site. In summary the depth to good ground is 1m at the east side of the building and found at depths of 6m on the west side of the building. Based on this information a combination of shallow pad footings and screw piles up to 6m in depth has been designed to support gravity loads. Steel screw piles are also used locally to support vertical seismic loads from the shear walls where required. At the west end of the building where the existing site level falls away concrete block-work foundation walls have been used to allow backfilling for a slab on grade construction at the ground floor level. Base shear has been taken out by a combination of passive bearing from foundation beams and under floor slab friction.

4.4 Fire Design

The fire design, to ensure the integrity of the building structure in a fire event and to comply with Ministry of Education requirements, involves the use of sprinklers. For an educational facility of this size sprinklers are mandatory to meet Ministry of Education requirements. The result of the use of sprinklers is that all primary structural elements supporting suspended floors are required to achieve a minimum 30 minute structural rating. All timber members have been designed with a minimum 90mm thickness and charring rates have been used to calculate a reduced section size for the fire load case. The design check was able to show that no additional treatment of timber members was required to achieve the required structural fire ratings.

4.5 Designed Member Sizes

The designed member sizes are referenced on the drawings in Appendix A and have been sized as follows:

- Purlins: 300x45 LVL and 150x45 LVL
- Roof beam span 1: 2-400x171 LVL
- Roof beam span 2: 2-550x171 LVL
- Roof Diaphragm: 16mm plywood, blocking at plywood joints
- Floor beam span 1: 2-750x171 LVL
- Floor beam span 2: 2-460 x 171 LVL
- Columns: 400x405 LVL and 300x405 LVL

- Secondary wind beams to north façade: 300x135 LVL and 400x171 LVL
- Secondary beams at south facade: 660x189 LVL and 396 x 189 LVL
- Suspended Floor: 396mm depth Potius panel LVL floor system, 75mm concrete floor topping with MDT–430-240 mesh and diaphragm reinforcing
- Shear Walls: 189mm thick 3.0 metre long LVL coupled shear walls with post-tensioned steel Macalloy bar tendons
- Ground Floor: 150mm concrete slab on 100mm EPS polystyrene on 2 layers DPM on grade
- Foundations: 5 pad type concrete foundations and 55 steel screw piles and associated pile caps and foundation beams

4.6 Timber Solution Discussion

The timber solution provides is a lightweight structural solution. It has been designed and detailed to allow for off-site fabrication and fast erection. Structural elements are relatively lightweight and the building was be erected using mobile cranes.

The timber frame connections developed used simple beams sitting in notches in the columns acting as corbels allowing a simple pin bolted connection to be used between the beams and the columns. All structural beams and columns were off-site fabricated and erected as single members avoiding the need for on-site column splices.

All of the timber structure is exposed in the completed building therefore a high level of finish is required to all the timberwork and exposed bolted connections. The use minimum member thickness enabled the inherent fire resistance of the timber members to be utilised.

No propping of floor beams or Potius flooring was required during the concrete pours. This eliminated the loss of additional site time and construction cost of the propping.

The use of the Potius flooring system will ensure a fast installation of the floor system. With a 6m floor span the flange hung Potius panels were landed on the floor beams. This provided an immediate working platform allowing shear stud coach screws to be installed on site and the floor diaphragm reinforcing to be placed without the need to prop the floor.

5. Steel Structural Solution

The alternative structural steel solution for the main three storey arts building consists of:

- Lightweight roof structure using steel DHS purlins, steel rafters and a plywood diaphragm also utilised for insulation and acoustic purposes
- Structural steel gravity frame using UB and UC steel sections
- Steel floor deck using the Comfloor system
- Structural steel post tensioned K-Braced coupled frames ("rocking" steel frames)
- Structural steel lintels and secondary beams
- Concrete slab on grade ground floor with a mixture of foundation pads and screw piles for uplift resistance under the rocking shear walls

5.1 Gravity Frame

The primary gravity frames consist of continuous steel columns over three levels supporting simply supported steel beams. The steel beams consist of two short spans and one long 9.6m span. The longer span floor beams have been designed for composite action with welded shear studs connecting the beams into the concrete floor topping. All floor beams will require full propping during construction until the composite action of the beam to floor slab has been achieved.

The flooring system comprises of a composite steel floor deck, trade name Comfloor 210. The steel floor deck offers a long span flooring system with reduced concrete usage and a reduced amount of temporary propping. The composite floor system has an overall depth of 300mm and will require one row of temporary props at mid-span during construction.

5.2 Wind and Seismic Bracing

The lateral load resisting system for the building comprises of Post-tensioned K-Braced steel frames. The design is based on the same PRESSS technology as the timber solution with the K-Braced frame effectively forming an open but rigid steel wall to replace the solid timber wall. This allows the damage avoidance design to be utilised and offers a comparable steel solution to the post tensioned timber wall.

The bracing system in the longitudinal direction is provided by pairs of 3.0m long steel frames adjacent to the stair and lift shaft. Bracing in the transverse direction is provided by pairs of 3.0m long steel frames at each end of the building. The transverse walls also provide resistance to the torsion loads due to mass eccentricities resulting from the open layout. Like the timber solution the steel solution is also governed by the seismic loading due to the mass of the building and the high (approximately 4m) inter-storey heights. The total building weight of the steel solution is within 10% of the timber solution and therefore the seismic response is very similar. The wind loading is again less than half that of the seismic loading and as such the bracing walls will resist wind loads, responding in an elastic manner.

Like the timber solution each pair of K-braced frames with dissipators is a hybrid system with an overall frame thickness of 250mm. The frames are coupled to act integrally under lateral loading using an identical steel energy dissipaters to those used for the timber solution. Each steel frame also includes post-tensioning tendons threaded between a double beam arrangement at each floor level. Base shear is transferred to the foundations via a steel shoe encapsulating the base of the steel frames.

Lateral loads for both wind and seismic are transferred to the steel frames via rigid diaphragms. Diaphragms are provided at roof level by the plywood acoustic lining, while the Comfloor concrete floor provides a rigid floor diaphragm at the two suspended floor levels.

The damage avoidance modelling for the steel solution has been based on achieving the same level of seismic performance as the timber solution. Modelling of the K-Braced frame has been completed to ensure an appropriate frame stiffness is achieved that results in the same very low inter-storey drifts, in the range of 1.0% - 1.2%.

5.3 Foundations

The foundation loads for the steel option are very similar for the timber option for both the gravity and seismic load cases. Based on this the foundations sized and detailed for the steel option are identical to those sized and detailed for the timber option.

5.4 Fire Design

The gravity beams and columns and bracing frames will be exposed in the building to meet the architectural design requirements. To achieve appropriate fire ratings intumescent coatings are to be used on the simply supported beams and columns to achieve a 30minute fire rating. Fire rating of the steel deck floors is achieved by providing additional trough reinforcing in the concrete floor for the fire load case. No fire rating is required to steel members at the roof level and therefore protection systems are not provided to the structural steel columns and steel roof beams above level 3.

5.5 Preliminary Member Sizes

Preliminary steel member sizes can be referenced on the drawings in Appendix A and have been sized as follows:

- Purlins: 250DHS13 and 150DHS12 with one row of braces per bay
- Roof beams: 460UB67 and 310UB46
- Roof diaphragm: 16mm plywood with blocking at plywood joints
- Floor beam span 1: 530UB92 with shear studs at 300mm centres
- Floor beam span 2: 460UB82 with shear studs at 300mm centres
- Columns: 250UC89 and 250UC72
- Secondary wind beams to north façade: 200UB30 and 250UB39 with shear studs at 300mm centres
- Secondary floor beams at south façade: 250UB38 with shear studs at 300mm centres and 460UB 67
- Suspended Floor: Comfloor 210 composite steel floor deck system, 300mm overall floor depth with additional trough reinforcing.
- Braced Frames: Steel K-braced frames with post-tensioned steel Macalloy bar tendons, using 250UC73 and 380 PFC sections
- Ground Floor: 150mm concrete slab on 100mm EPS polystyrene on 2 layers DPM on grade
- Foundations: 5 pad type concrete foundations and 55 steel screw piles and associated pile caps and foundation beams

5.6 Steel Solution Discussion

Like the timber solution the steel solution is a lightweight structural solution. It has been designed and detailed to allow for off-site fabrication and fast erection. Structural elements are relatively lightweight and we would therefore expect that the building would be erected using mobile cranes similar to that used for erecting the timber building.

Steel frame connections to be used in this solution are standard HERA pin or cleat type connections. All structural columns could be fabricated and erected as a single member avoiding the need for on-site column splices if this was chosen.

All of the steel structure will be exposed in the completed building therefore a high level of finish is required to all welded and bolted connections. The use of intumescent paint systems will also require welds to be ground smooth and all bolts tidily installed to ensure a high quality paint finish.

Propping of floor beams during the concrete pours is required and propping of the steel floor deck system at mid-span is also required. The use of propping systems will ensure the use of efficient members and floor section depths, this is however balanced by the additional site time and construction cost of the propping.

The Comfloor steel floor deck system will ensure a fast installation of the floor system. With a 6m floor span a single Comfloor sheet can be installed between beams allowing shear studs to be installed in the workshop. Large areas of the floor can then be poured as a single pour.

6. Concrete Structural Solution

The alternative concrete structural solution for the main three storey arts building consists of:

- Lightweight roof structure using steel DHS purlins, steel rafters and a plywood diaphragm also utilised for insulation and acoustic purposes
- Precast concrete gravity frame comprising full height columns and precast half beams
- Stahlton / Interspan precast concrete floor system
- Precast concrete coupled shear walls with post tensioning (“rocking” concrete walls)
- Precast concrete secondary beams
- Structural steel wind beams and lintels.
- Concrete slab on grade ground floor

6.1 Gravity Frame

The primary gravity frames consist of continuous precast concrete columns over three levels. The precast columns are formed with cast in steel shelf angles to support precast concrete floor beams. The precast columns are also formed with cast in sleeves that allow the beam top reinforcing to pass through the column.

Like the timber and steel solutions the primary floor beams consist of two short spans and one long 9.6m span. The beams are to be precast half height to allow the placement of top reinforcing through the column and also to provide seating for the precast floor system. All floor beams will require propping at mid-span during construction.

The flooring system comprises of a Stahlton / Interspan precast floor. The floor system offers a long span pre-tensioned flooring system with reduced concrete usage. The floor system has an overall depth of 240mm and will require one row of temporary props at mid-span during construction.

6.2 Wind and Seismic Bracing

The lateral load resisting system for the building comprises of precast concrete, post tensioned shear walls. The design is based on the same PRESSS technology as the timber solution with the concrete walls being a direct replacement for the timber walls. This allows the damage avoidance design to be utilised and offers a solution with a similar wall length and thickness to the post tensioned timber wall solution.

The bracing system in the longitudinal direction is provided by pairs of 200mm thick by 3.0m long concrete walls adjacent to the stair and lift shaft. Bracing in the transverse direction is provided by pairs of 3.0m long concrete walls at each end of the building. The transverse walls also provide resistance to the torsion loads due to mass eccentricities resulting from the open layout. Like the timber solution the concrete solution is also governed by the seismic loading due to the mass of the building and the high (approximately 4m) inter-storey heights. The total building weight of the concrete solution is however increased by 30% when compared to the timber solution and therefore the seismic response is increased. Despite the increase in seismic load the increased stiffness of the concrete shear walls and the ability to increase the compressive strength, the design wall length for the concrete shear walls is able to be maintained at 3.0m. The wind loading is less than one third that of the seismic loading and as such the bracing walls will resist wind loads, responding in an elastic manner.

Like the timber solution each pair of walls with dissipators is a hybrid system with an overall wall thickness of 200mm. The walls are coupled to act integrally under lateral loading using identical steel energy dissipaters to those used for the timber solution. Each wall also includes post-tensioning tendons threaded through ducts cast full length through the walls. Base shear is transferred to the foundations via a steel shoe encapsulating the base of the concrete walls.

Lateral loads for both wind and seismic are transferred to the walls via rigid diaphragms. Diaphragms are provided at roof level by steel purlins and a plywood lining, while the concrete floor topping provides a rigid floor diaphragm at the two suspended floor levels.

The damage avoidance modelling for the concrete solution has been based on achieving the same level of seismic performance as the timber solution. Modelling of the concrete system has been completed to ensure an appropriate frame stiffness is achieved that results in the same very low inter-storey drifts, in the range of 1.0% - 1.2%.

6.3 Foundations

The foundation loads for the concrete option are increased by 30% for gravity and 50% for earthquake when compared to the timber option. Based on this the foundations sized and detailed for the concrete have increased. The total number of screw piles required has increased from 55 to 71 with larger pile caps, and the foundation pads increasing in plan area by 30%.

6.4 Fire Design

The gravity frames and shear walls will be exposed in the building to meet the architectural design requirements. With appropriate detailing of reinforcing covers the concrete structural elements will achieve the required fire rating of 30 minutes with no additional protection being required. Floor beam shelf angles will require fire protection and this is to be provided with intumescent paint coatings.

6.5 Preliminary Member Sizes

Preliminary member sizes can be referenced on the drawings in Appendix A and have been sized as follows:

- Purlins: 250DHS13 and 150DHS12 with one row of braces per bay
- Roof beams: 460UB67 and 310UB46
- Roof diaphragm: 16mm plywood with blocking at plywood joints
- Floor beam span 1: 850d x 450w reinforced concrete beam
- Floor beam span 2: 600d x 450w reinforced concrete beam
- Columns: 300mm square reinforced concrete column
- Secondary wind beams to north façade: 200UB30 and 250UB39
- Secondary floor beams at south façade: 600d x 450w and 450d x 350w reinforced concrete beams
- Suspended Floor: Stahlton / Interspan 125mm deep pre-stressed ribs with 40mm thick dry dressed timber infill planks and 75mm reinforced concrete topping
- Ground Floor: 150mm concrete slab on 100mm EPS polystyrene on 2 layers DPM on grade
- Shear Walls: 200mm thick reinforced concrete walls with steel post tensioned tendons
- Foundations: 5 pad type concrete foundations and 71 steel screw piles and associated pile caps and foundation beams.

6.6 Concrete Solution Discussion

The concrete solution is a structural solution that increases the overall weight of the building. The main effect that this has on the building structure is an increase in foundation loads for both the gravity load case and the seismic load case for loads on the walls, post tensioning and foundations. Typically the size of foundation pads has increased 30% and the number of steel screw piles has increased by 30%. The increased weight of primary structural elements such as walls, beams and columns will require increased crane capacity and depending on the construction sequence may require crane access from more than one side of the building or the use of a tower crane.

Like the timber and steel solutions the concrete solution has been designed and detailed to allow for off site fabrication and fast erection. Columns are to be precast full height with cast in shelf angles to allow quick erection and to also avoid unsightly beam column joint insitu pours. It is also possible to do single level precast columns, but this has not been adopted here inorder to maintain the speed of construction.

Precast and wall splices could be introduced at floor levels to decrease carnage however the grout tube patches could be unsightly if exposed on the inside of the building.

All of the concrete members are to be exposed in the building and will require a high level of finish. To achieve this all members have been designed to allow them to be constructed as precast elements.

Connections for secondary wind beams and roof beams are to be cast into the columns to ensure well detailed and discreet connections.

Propping of the precast floor beams at mid-span is required to allow an efficient beam size to be used. Propping of the Stahlton / Interspan floor system at mid-span is also required to allow an efficient floor depth to be used. Propping for both of these elements will involve additional site time and cost.

The Stahlton / Interspan floor system will ensure a fast installation of the floor and with the use of 40mm timber sawn planks will provide a safe working platform for the floor construction. Large areas of the floor can then be poured as a single pour.

7. Architectural Review

Irving Smith Jack Architects have completed an architectural review of the steel and concrete alternatives.

7.1 Design Parameters

The general architectural design parameters (project description and objectives), that have been used for the steel and concrete alternative solutions are the same as those provided to the design team by the NMIT for the design of the timber building. In broad terms this means that the functionality, performance and emphasis on structural elements are similar for all three options – timber, steel and concrete. These are described below.

7.1.1 Project Description

Design and construct a new and innovative multi level generic teaching facility for NMIT, initially to be used for their Arts and Media programme, using timber as the prime structural components.

7.1.2 Objectives

The key NMIT architectural objectives for this project are:

- A new facility for the NMIT School of Arts and Media
- A new generic teaching facility for NMIT
- A building whose structural form uses and showcases its construction in timber/steel/concrete
- A demonstration and education project. It would be expected that the structure would be visible in the completed building to allow it to be used as the demonstration and education model
- A sustainable and environmentally sound building within the available budget
- A team approach to the final design solution

The particular programmatic objectives are to:

- Incorporate innovative design principles into the design of the building layout.
- Incorporate innovative design principles utilising timber/steel/concrete as the primary structural component into the design of the building structure.

- Meet the project budget
- Meet the project timeline

7.2 Engineering Response

In accordance with the briefing document, Aurecon engineers have developed designs for timber, concrete and steel structures, details of which are included in this report. In general terms each of these designs incorporate the objectives described above within the physical performance and layout parameters of the timber building design - that is the floor plans, grid layout, fire protection, internal environment and structural performance are identical to the timber building.

7.3 Architectural Response

The architectural approach to the three structural options is constrained by the parameters listed above, provided at the beginning of the design stage for the timber building. Underlying the original timber design is the premise that this approach could be industry leading. The sophistication of the lateral load resisting shear walls allows an elegant gravity resisting frame with simple rebated and bolted connections. This straight forward approach, where a simple gravity resisting frame can be coupled with a variety of lateral load resisting systems, we believe could be applied to a variety of building typologies. To maintain this consistency, readily available steel or concrete componentry has been applied to each of the alternative designs, rather than pursuing a more ‘custom-made’ approach.

Internally, the timber structure is exposed and its function expressed as far as practicable. This move is key to the design concept, and to the success of this project from a MAF perspective. A similar level of structural expression is proposed in both of the alternative (steel and concrete) designs.

The structure, in all three scenarios, is exposed as prescribed by the NMIT objectives. Each of the three materials will affect “the feel” of the building which, although very real, is impossible to quantify, as it is subjective. There is, however, no doubt that the steel or concrete will evoke a different emotional response from users and observers, to a building with an exposed timber structure.

The impact of a timber, steel or concrete structure on the external environment will be of lesser significance as the exterior appearance will be largely unchanged, as explained below.

Following are brief descriptions of all three design solutions - timber, steel and concrete. These should be read in conjunction with the attached A3 architectural drawings which incorporate the structural information provided by Aurecon. The layout and scale of spaces and the materials, except the primary structure, are based on the design originally developed with NMIT. Where possible these are replicated for the steel and concrete designs.

The drawings showing the steel and concrete alternatives show in red, the differences from the timber solution in order to highlight the parts of the building that have by necessity been changed from the original timber design. There has been a deliberate intent to leave the remainder unchanged.

7.4 Timber

7.4.1 Exposed Timber

It is not uncommon to have timber exposed to view within a building, but not so common for the specifically engineered laminated veneer lumber (LVL). The inherent aesthetic qualities of the natural wood are enhanced by the laminations making it an interesting attractive option for an expressed primary structure. Due to its structural properties the LVL members outperform their natural timber counterparts. Engineered lumber sections can often be manufactured larger in section than would typically be possible with the natural timber.

The selection of an exposed and expressed timber structure necessitated, at the outset of developed design, decision making regarding the quality of finish required to the timber components. At it's most basic level, fabricated LVL could be left in its factory made 'industrial state' with no attempt to mitigate fabrication tolerances, glue runs or surface damage. Instead we have elected, for this landmark project, to detail all timber elements with a high level of finish. This decision results in all timberwork being machine sanded, some components also being hand sanded and some production methods (potius floor panels as an example) being adapted to achieve acceptable visual appearance. Thereafter a higher level of attention has been paid to the subsequent protection of these finishes on site.

The LVL's natural fire resistant qualities negate any requirement for over-lining or intumescent painting.

7.4.2 Shear Walls

The LVL rocking walls are a fundamental feature of the timber building, as explained in the structural section of this report. These panels will be exposed to view from the interior as will the tops of the post tensioning rods.

7.4.3 Internal Spaces

The arrangement of spaces is primarily governed by the design brief requirements of the NMIT and the desire to capitalise on the opportunity to provide ideal south light to studio and teaching spaces. The structural grid is in turn governed by this and the spanning capacity of the primary structural members. The atrium on the north side of the building provides a powerful contrast to the more intimate teaching spaces and also a means of creating natural air flow for passive ventilation and smoke purging.

7.4.4 Atrium Stairs

The main public stairs in the atrium space will have LVL strings, treads, balustrade panels and posts supported on a slender steel frame. The stairs are a fundamental design element within the key architectural volume. Attention has been paid to highlight the expressive use of structural timber. Steel is used here to maximise circulation space at level 1.

7.4.5 Services

The services duct (the longitudinal zone between grids 6 and 8) contains all major services to be run laterally through the building in a central location. Secondary services reticulation branches off this duct and these runs can be controlled to maintain a visual coherence.

Primary structural members will not be penetrated for services reticulation and many services components will be exposed to view, in an ordered fashion, to compliment the skeletal nature of the exposed structure. The lift is supported by a steel frame due to spatial constraints..

7.4.6 Linings & Cladding

To compliment the timber building primary structure, many of the internal walls and ceilings will be lined with plywood or MDF.

All timberwork is expressed internally, none is featured externally. Instead we have created an external skin from preassembled and or prefinished materials to reduce life cycle maintenance as far as possible. Exterior cladding and window systems will be lightweight and economical. Roofing will be profiled steel sheeting, while walls will also have steel sheeting with some fibre cement panelling. Windows and main doors will be aluminium framed.

7.4.7 Insulation

The thermal insulation to the building envelope will be to a higher level than required under the Building Code in order to maximise user comfort and energy efficiency. The thermal mass of the solid timber structure will assist in maintaining temperature equilibrium within the building and assisting energy efficiency.

The degree of acoustic absorbency to the underside of the floor structure and degree of acoustic separation between spaces is determined by the use of the various spaces.

Acoustic and fire separations will need to be created at the perimeter of each floor as required by the fire report.

7.4.8 Surfaces, Finishes and Detail

Extra care is required when handling such large pieces of a relatively easily damaged product as all exposed LVL surfaces will have a clear finish and defects will be difficult to disguise. Wood based interior linings will be either clear finished or stained. The implications of electing an exposed and expressed timber structural system are discussed in more detail above.

7.5 Steel Alternative Solution

7.5.1 Exposed Steel

Historically exposing primary steel structure to view has been difficult due to fire rating requirements which usually resulted in encasing the steel in a fire rated lining or coating with unsightly intumescent paint. Due to recent advances in paint systems it is now possible to provide a fire rated coating which is indistinguishable from ordinary acrylic or enamel paint system. This has made acceptable the expression of the steel structure to the same degree as the timber. Other factors requiring careful consideration are the detailing of joints and achieving a high standard of workmanship in a structural system which is more commonly concealed behind linings and cladding. Steel to steel connections will be exposed, however all steel to concrete connections will be carefully detailed and concealed within the concrete element.

7.5.2 Steel K-Braced Frames

The structure of the K-Braced steel frames will be exposed, including the post tensioning bars which extend full height. The open design of the steel rocking frames has required a different solution to vertical fire and smoke separations as noted below. In order to create separation between internal spaces an additional layer of wall framing will be required behind the frames on grids 6 and 8.

7.5.3 Internal Spaces

Rearrangement of wall framing around the K-Braced steel frames will have a direct impact on the amount of available floor area in the adjacent spaces. The inside face of the frames will encroach on the room by approximately 100mm which, in most spaces, is relatively insignificant. Additional wall framing on grids 6 and 8 may affect the internal layout of the Reception office as, because it has a shear wall on two sides, the width of the room will be reduced by 200mm.

7.5.4 Atrium Stairs

Steel stairs could be similar in arrangement to the timber stairs but with RHS box section strings, steel mesh or grating open treads and balustrades with perforated steel sheeting and RHS posts. We would expect these to be expressive of the application of concrete construction and to be finished to a high level as with the timber option.

7.5.5 Services

Positioning of services fixtures and reticulation of pipework and cabling will be identical to the timber building. Primary structural members will not be penetrated for services reticulation and many services components will be exposed to view, in an ordered fashion, to compliment the skeletal nature of the exposed structure.

7.5.6 Linings & Cladding

Internal linings and finishes are identical to the timber building although, for aesthetic reasons, an alternative lining may be used in some of the areas which, for the timber building, were designated as plywood lined.

The approach to the external envelope, exterior cladding and windows remains unchanged from the timber design.

The installation of lining material behind the exposed structure of the shear panels on grids E and L, will require special detailing and well planned execution as it will impact on the construction sequence.

7.5.7 Insulation

In order to preserve the thermal insulation to the building envelope, external walls will be constructed outside the line of the shear walls on grids L and E. In other areas of the building the external insulating envelope is unaffected by the change to steel. The lack of thermal mass in the steel structure will not assist in maintaining temperature equilibrium within the building and will not assist energy efficiency.

The acoustic insulation remains unchanged from the timber solution. The same degree of acoustic absorbency to the underside of the floor structure and the same degree of acoustic separation between spaces and at roof level is required and will be provided in a similar manner.

At the shear walls the required acoustic and fire separations will need to be created at each floor level within the confines of the steel frame, which will be inherently difficult due to the spatial limitations and the profiles of the steel sections.

7.5.8 Surfaces, Finishes and Detail

The exposed steel will require a very high level of finish to a similar standard and visual quality to that employed in the timber building.

All exposed welds will be ground and all surfaces are to be brought up to smooth finish ready for high gloss paint – including intumescent paint.

7.6 Concrete

7.6.1 Exposed Concrete

It is not uncommon for precast concrete to be exposed to view in contemporary buildings, however it is very important, as with timber, to have good quality assurance checks in place during its production and installation as there are many factors that can affect the final product.

7.6.2 Fire Rating

Concrete has good inherent fire resisting properties, however close attention to fire rated separations is still required at joints and junctions.

7.6.3 Shear Walls

The shear walls in this instance are of similar physical size to the timber design but, they have individual ducts for post tensioning rods. The flush exposed surface allows them to be integrated to the interior design – in particular the adjoining plasterboard-lined walls.

7.6.4 Internal Spaces

Due to its sheer mass there are some obvious variations in the building resulting from the use of concrete as the primary structure, such as and increase in the size of footings. Its use, however, has little effect on the spatial attributes as the physical bulk of members is quite similar to timber.

7.6.5 Atrium Stairs

Concrete stairs could be similar in arrangement to the timber stairs but with precast concrete strings, precast (perhaps coloured) concrete open treads and either timber balustrades, as for the timber building, or with steel sheeting and RHS posts as for the steel building. We would expect these to be expressive of the application of steel construction and to be finished to a high level as with the timber option.

7.6.6 Services

As with the steel option positioning of services fixtures and reticulation of pipework and cabling will be identical to the timber building. Primary structural members will not be penetrated for services reticulation and many services components will be exposed to view, in an ordered fashion, to compliment the nature of the exposed structure.

7.6.7 Linings & Cladding

Internal linings and finishes are similar to the timber building except concrete elements will be clear-finished, not painted out. As with the steel option, alternative linings may be used in some of the areas which, for the timber building, were designated as plywood lined.

The approach to the external envelope, exterior cladding and windows remains unchanged from the timber design.

7.6.8 Insulation

The concrete shear panels provide less thermal insulation than their timber counterparts although, within the physical constraints of the structure, this can still be in excess of the requirements of the New Zealand Building Code. In other areas of the building the external insulating envelope is unaffected by the change to concrete. The thermal mass of the concrete structure will assist in maintaining temperature equilibrium within the building and assisting energy efficiency.

The acoustic insulation remains unchanged from the timber solution. The same degree of acoustic absorbency is required to the underside of the floor structure and the same degree of acoustic and fire separation between spaces and at roof level is required and will be provided in a similar manner.

7.6.9 Surfaces, Finishes and Detail

The exposed concrete will require a high level F5 finish. We will expect a high level of attention to be paid to simplifying concrete detailing, and ensuring first class visual appearance of concrete work, infill timber and steel connections comparable to that achieved in the timber building. An industrial level of construction would not be comparable or acceptable.

All exposed welds on steel connecting plates will be ground and all surfaces are to be smooth and ready for a clear finish. Steel connections, where required, will be exposed.

7.7 Life Cycle Assessment

In addition to the perhaps more obvious, physical differences we have reviewed in this report there is a more complex dimension to the comparison of the alternative structural systems which would require a much more in depth review of the designs – that is the assessment of the life cycle and the embodied energy for each system.

The energy used in production, transportation, speed of erection, material, emissions from fabrication and finishing, and all environmental effects directly or indirectly attributable to the use of the three structural systems over the entire life of the building would need to be quantified in order to evaluate its true environmental impact. Once this is done, relative costs can also be estimated.

For example, in contrast to concrete and timber, a steel structure may have more volatile organic compound (VOC) and heavy metal emissions due to the painting, gas cutting, and welding of the steel members. However the energy use and the environmental emissions of steel and concrete framed buildings may be comparable if the total impacts from materials, manufacturing, construction, transportation, use, maintenance, and demolition are considered.

7.8 Combined Structural Systems

This comparison of timber, steel and concrete has not addressed the possibility of also using a combination of these materials in a building – a scenario that may prove to be appropriate for the majority of commercial building applications. This approach obviously increases the number of possible design solutions which could be explored.

Any possible advantages to utilising a combination of structural systems may become more evident once an elemental cost analysis is carried out.

Appendix A
Structural Drawings

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Te Whare Wananga o Te Tau Ihu o Te Waka a Maui

ARTS AND MEDIA BUILDING

DRAWING INDEX

DRG No.	TITLE
TIMBER	
SKK-T-001	PLAN FOUNDATIONS TIMBER OPTION
SKK-T-002	PLAN LEVEL 2 TIMBER OPTION
SKK-T-003	PLAN LEVEL 4 / ROOF TIMBER OPTION
SKK-T-004	ARTS ELEVATION GRID F TIMBER OPTION
SKK-T-005	ARTS ELEVATIONS SHEAR WALLS TIMBER OPTION
STEEL	
SSK-S-001	PLAN FOUNDATIONS STEEL OPTION
SSK-S-002	PLAN LEVEL 2 STEEL OPTION
SSK-S-003	PLAN LEVEL 4 / ROOF STEEL OPTION
SSK-S-004	ARTS ELEVATION GRID F STEEL OPTION
SSK-S-005	ARTS ELEVATIONS SHEAR WALLS STEEL OPTION
CONCRETE	
SSK-C-001	PLAN FOUNDATIONS CONCRETE OPTION
SSK-C-002	PLAN LEVEL 2 CONCRETE OPTION
SSK-C-003	PLAN LEVEL 4 / ROOF CONCRETE OPTION
SSK-C-004	ARTS ELEVATION GRID F CONCRETE OPTION
SSK-C-005	ARTS ELEVATIONS SHEAR WALLS CONCRETE OPTION

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INFORMATION
NOT FOR CONSTRUCTION

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Drawing No.	Rev.
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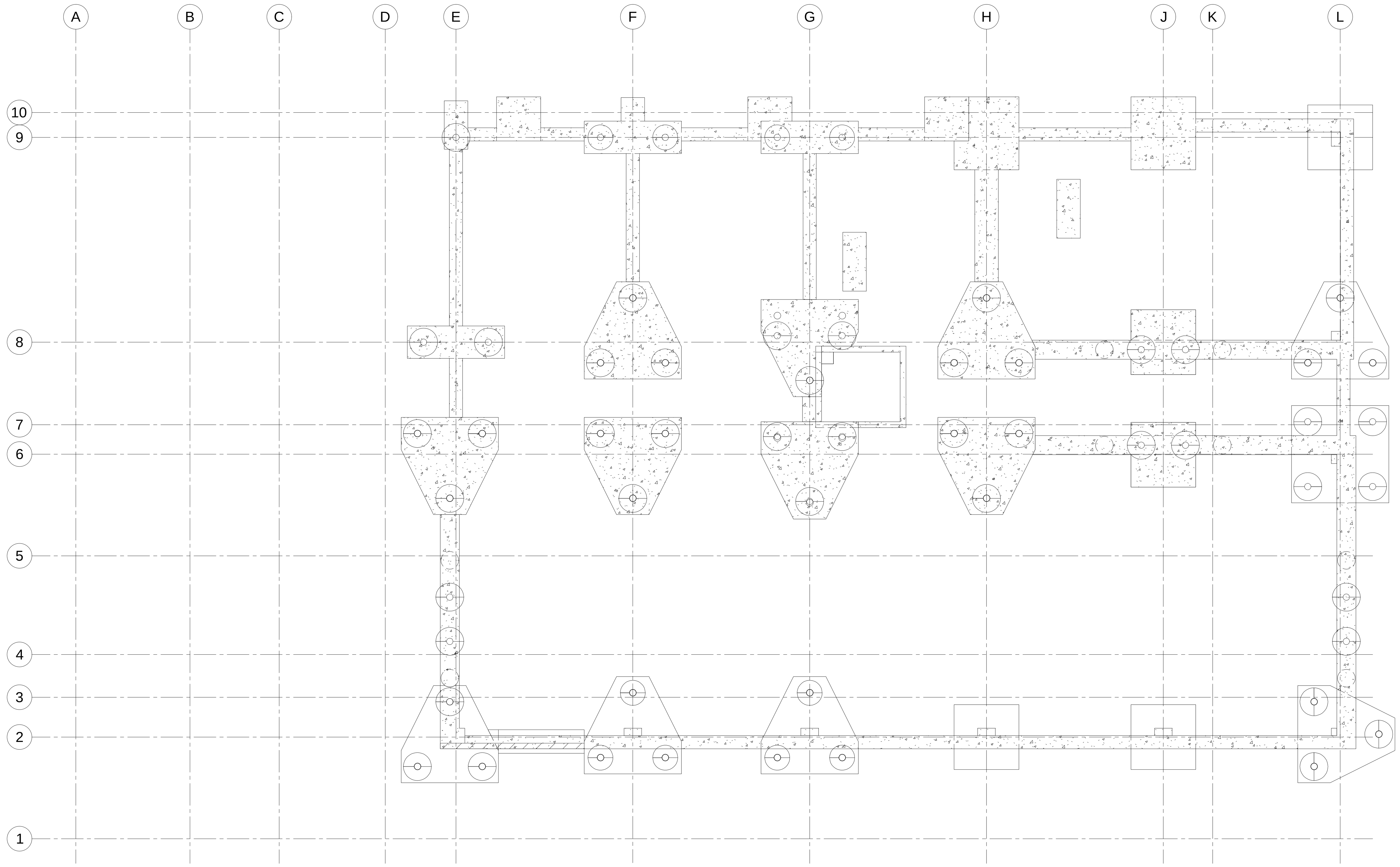

NOTE:
FOUNDATIONS AS PER EXISTING TIMBER DESIGN FOUNDATIONS

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01	06.08.10	ISSUED FOR INFORMATION	PW	CPD	AF

Aurecon New Zealand Limited
1st Floor, 62 Bridge Street (PO Box 1545)
Nelson New Zealand
Telephone: +64 3 573 0190
Facsimile: +64 3 573 0191
Email: nelson@ap.aurecongroup.com

Client:

Nelson Marlborough Institute of Technology
Te Whare Wananga o Te Tau Ihu o Te Waka a Maui

Project:

ARTS AND MEDIA BUILDING

Drawing Title:

PLAN
FOUNDATIONS
TIMBER OPTION

Drawn	Signed	Date	Verified	Signed	Date
PW	PW	06.08.10	CPD	CPD	06.08.10
Designed	Signed	Date	Approved	Signed	Date
SLH	SLH	06.08.10	AF	AF	06.08.10

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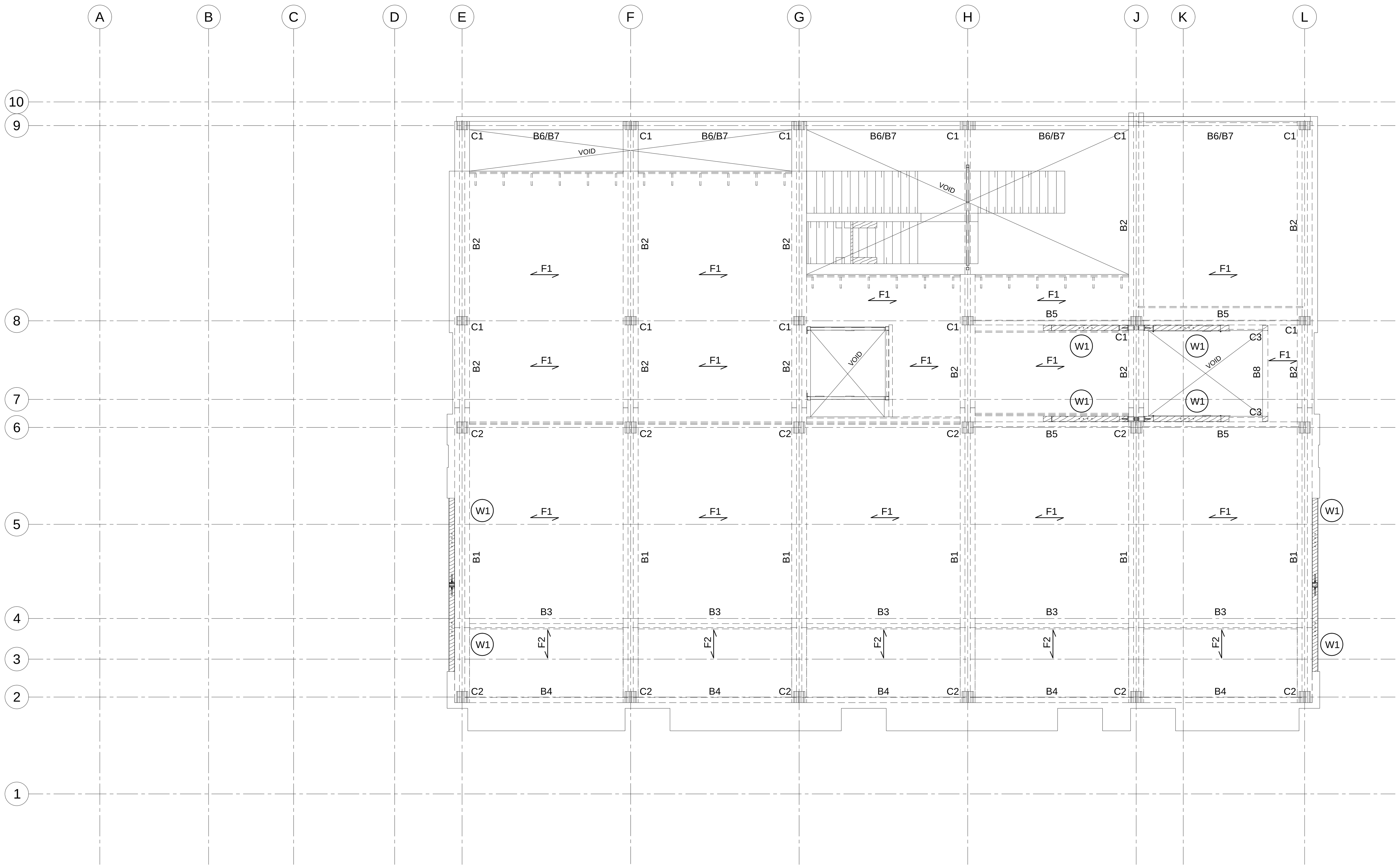

MEMBER	SIZE	SHEAR STUDS	FIRE RATING
BEAMS			
B1	2 - 750x171 LVL	YES	-
B2	2 - 460x171 LVL	YES	-
B3	396x189 LVL	YES	-
B4	660x189 LVL	-	-
B5	460x171 LVL	-	-
B6	300x171 LVL	-	-
B7	400x171 LVL	-	-
B8	200x189 LVL	-	-
COLUMNS			
C1	405 x 300	-	-
C2	405 x 400	-	-
WALLS			
W1	3m x 0.189m LVL	-	-

FLOORING:
F1 396mm DEEP POTIUS PANEL
75mm TOPPING
F2 200mm THICK INSITU SLAB

CONCRETE STRENGTHS:
f'c = 30 MPa TOPPING
f'c = 25 MPa FOUNDATIONS

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INFORMATION
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01	06.08.10	ISSUED FOR INFORMATION	PW	CPD	AF

aurecon

Aurecon New Zealand Limited
1st Floor, 62 Bridge Street (PO Box 1545)
Nelson New Zealand
Telephone: +64 3 573 0190
Facsimile: +64 3 573 0191
Email: nelson@ap.aurecongroup.com

Client:

nmit
Nelson Marlborough Institute of Technology
Te Whare Wananga o Te Tau Ihu o Te Waka a Maui

Project:

ARTS AND MEDIA BUILDING

Drawing Title:

PLAN
LEVEL 2
TIMBER OPTION

Drawn	Signed	Date	Verified	Signed	Date
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Designed	Signed	Date	Approved	Signed	Date
SLH	SLH	06.08.10	AF	AF	06.08.10

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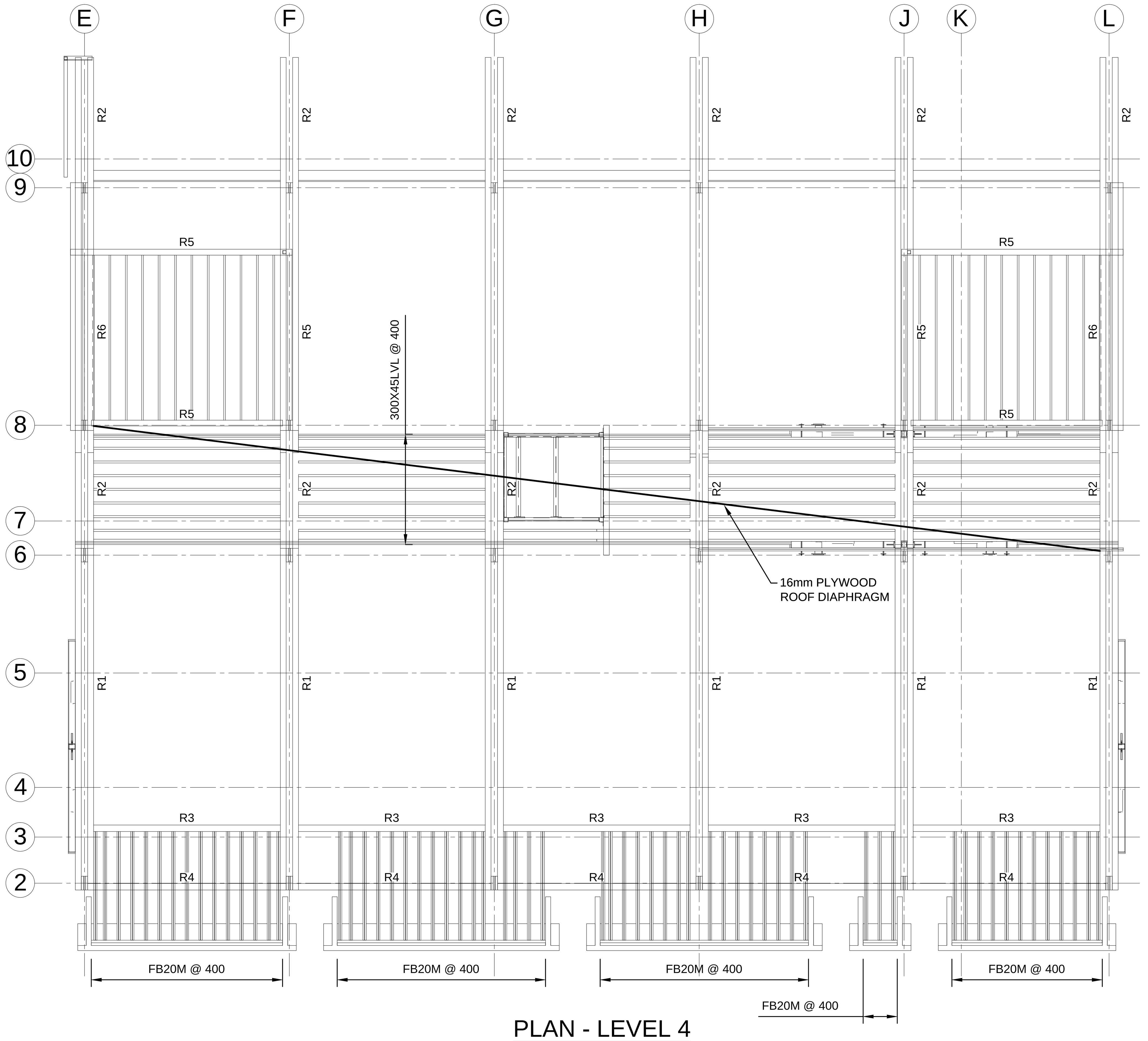

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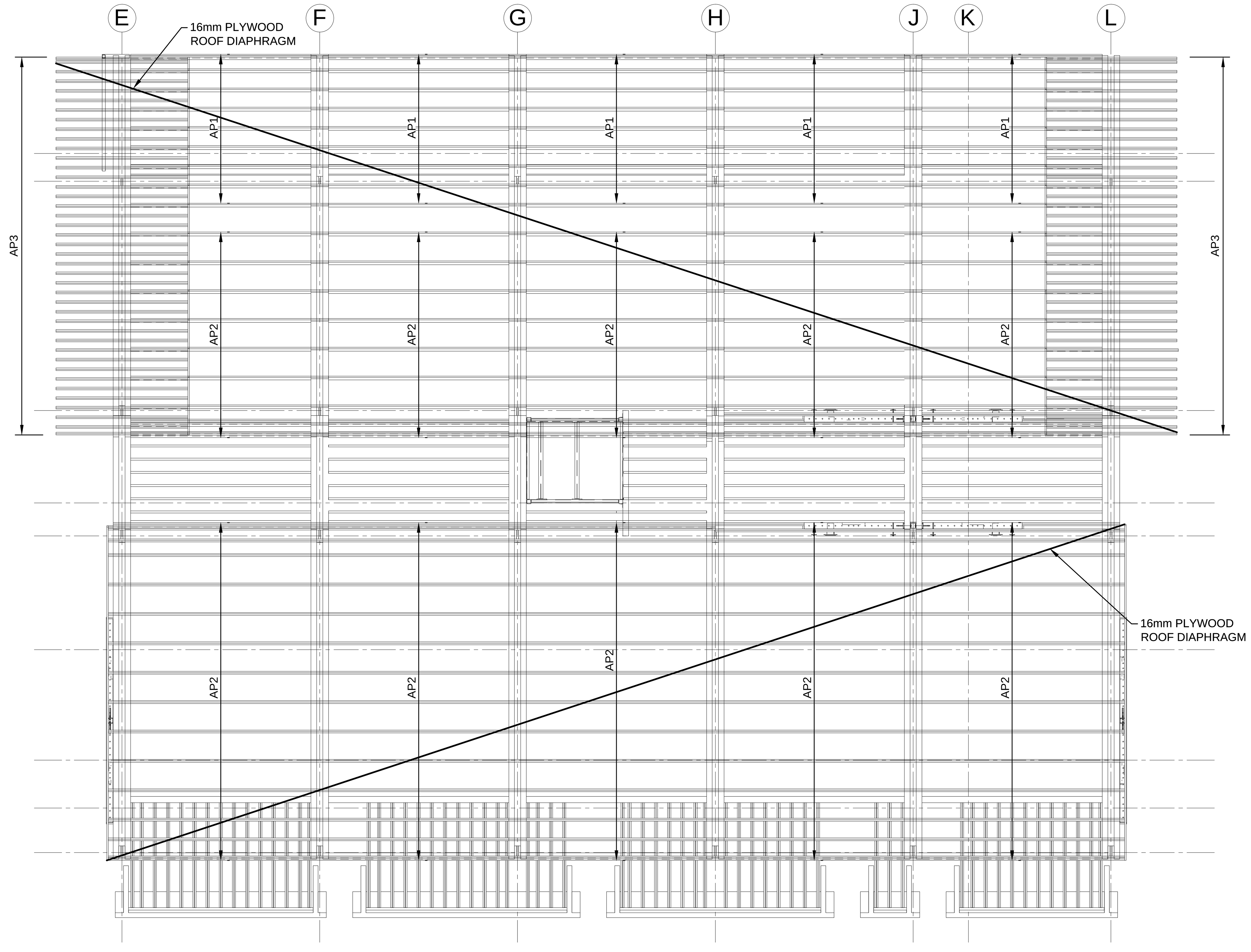
(FRAMING)



PLAN - LEVEL 4
(PURLINS)

FRAMING:

R1	2 - 550 X 171 LVL
R2	2 - 400 X 171 LVL
R3	400 X 189 LVL
R4	400 X 189 LVL
R5	230 X 171 LVL
R6	230 X 126 LVL

PURLINS:

AP1	300X45LVL @ 600 C/C
AP2	300X45LVL @ 900 C/C
AP3	150X45LVL @ 300 C/C

SCALE 1:100

INFORMATION
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Rev.	Date	Revision Details	Des.	Ver.	App.
02	17.08.11	ISSUED FOR INFORMATION	PW	CPD	AF
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aurecon
Aurecon New Zealand Limited
1st Floor, 62 Bridge Street (PO Box 1545)
Nelson New Zealand
Telephone: +64 3 573 0190
Facsimile: +64 3 573 0191
Email: nelson@ap.aurecongroup.com

Client: nmit Nelson Marlborough Institute of Technology
Te Whare Wananga o Te Tau Ihu o Te Waka a Maui

Project: ARTS AND MEDIA BUILDING

	Signed	Date
Drawn PW	PW	06.08.10
Designed SLH	SLH	06.08.10
Verified CPD	CPD	06.0810
Approved AF	AF	06.08.10

Drawing Title: PLAN
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TIMBER OPTION

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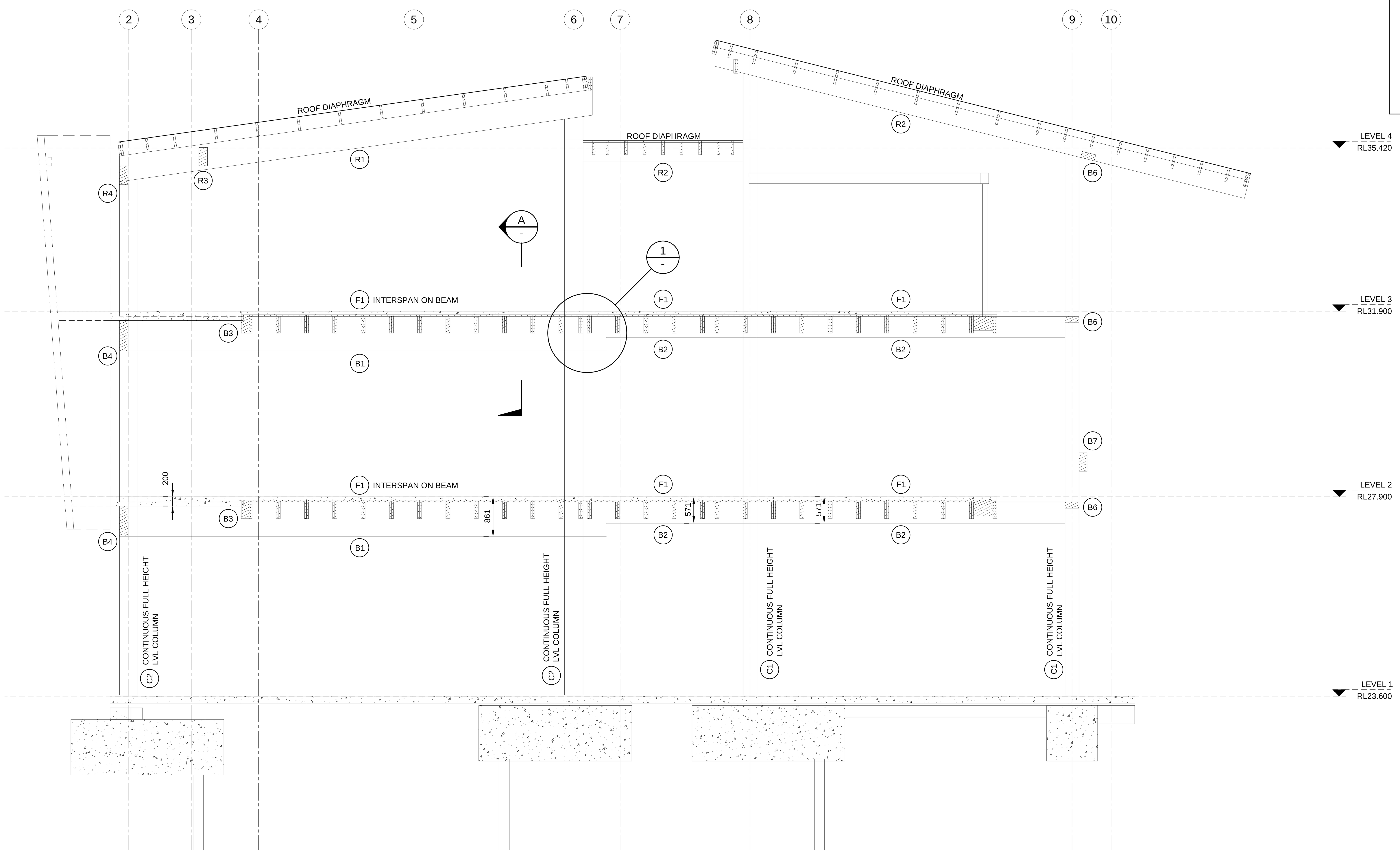
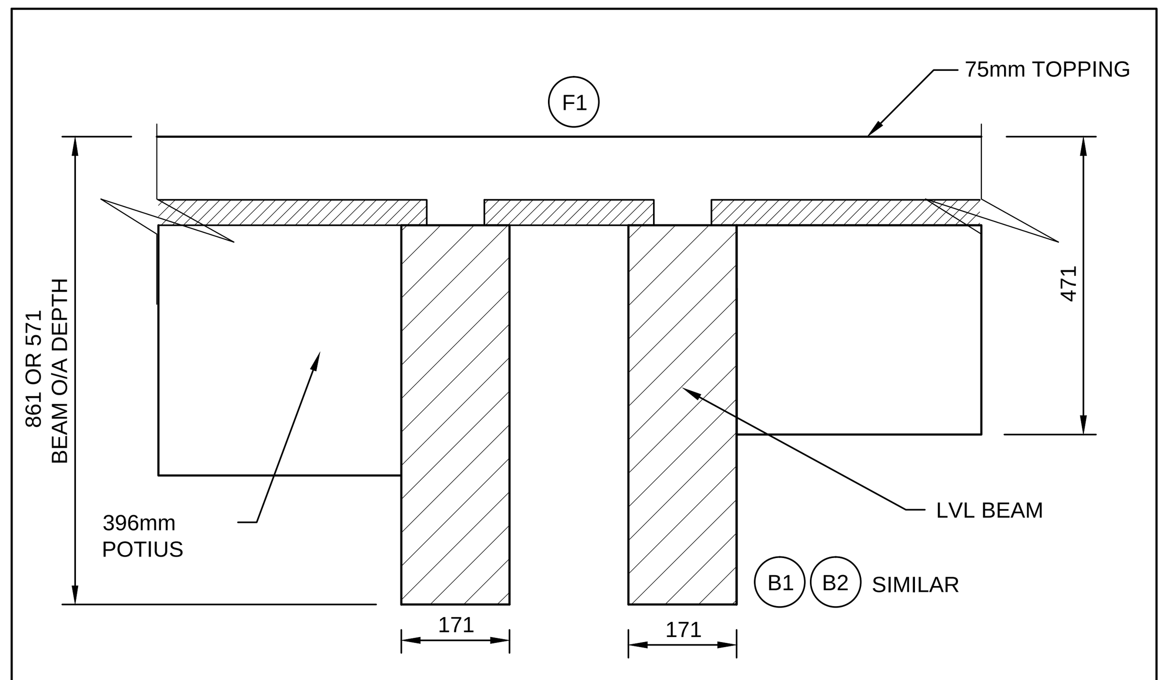
Rev. 02





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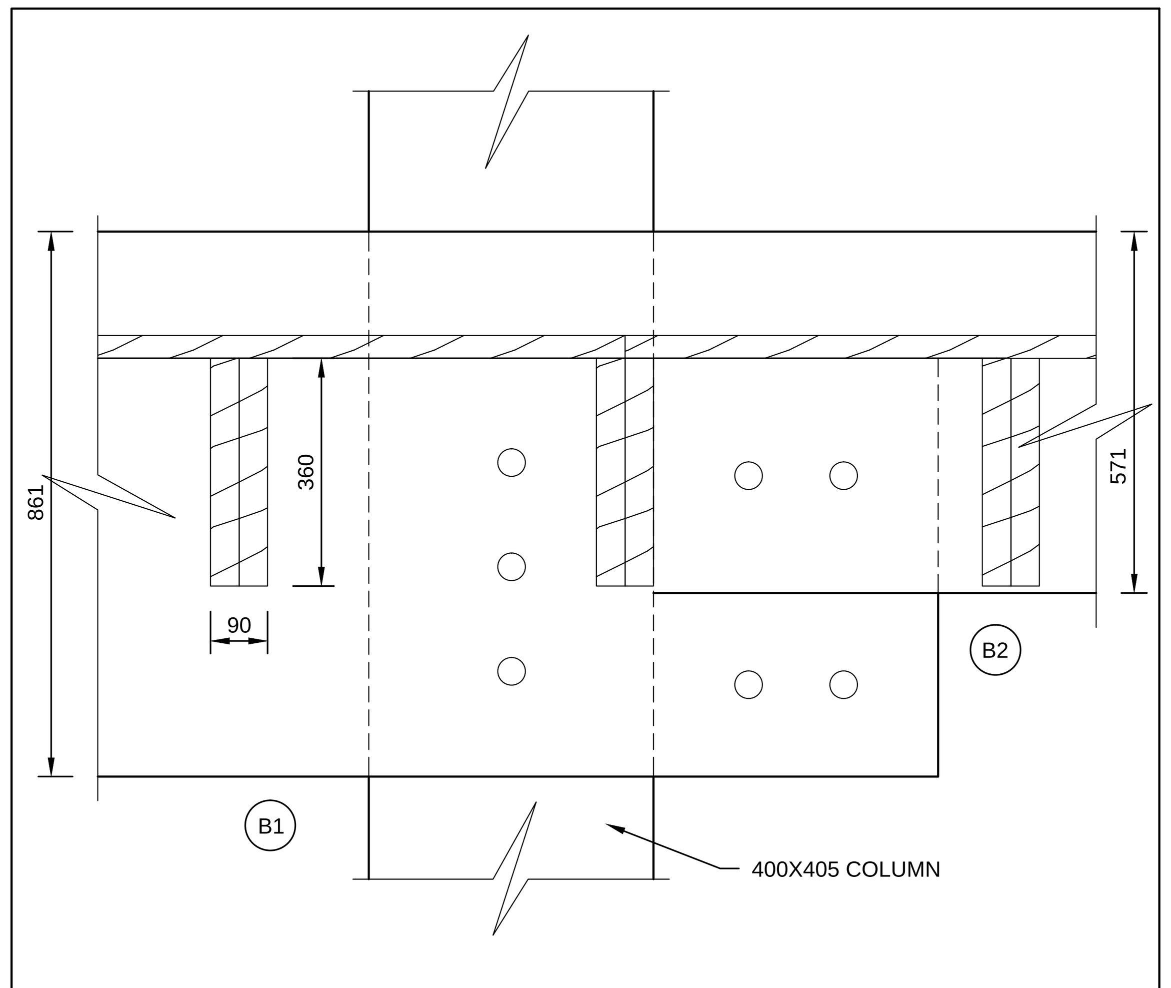

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aurecon
Aurecon New Zealand Limited
1st Floor, 62 Bridge Street (PO Box 1545)
Nelson New Zealand
Telephone: +64 3 573 0190
Facsimile: +64 3 573 0191
Email: nelson@ap.aurecongroup.com

Client:
nmit
Nelson Marlborough Institute of Technology
Te Whare Wananga o Te Tau Ihu o Te Waka a Maui

Project:
ARTS AND MEDIA BUILDING

	Signed	Date
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Designed SLH	SLH	06.08.10
Verified CPD	CPD	06.08.10
Approved AF	AF	06.08.10

Drawing Title:
ARTS
ELEVATION
GRID F
TIMBER OPTION

INFORMATION
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Project No. 210688.001
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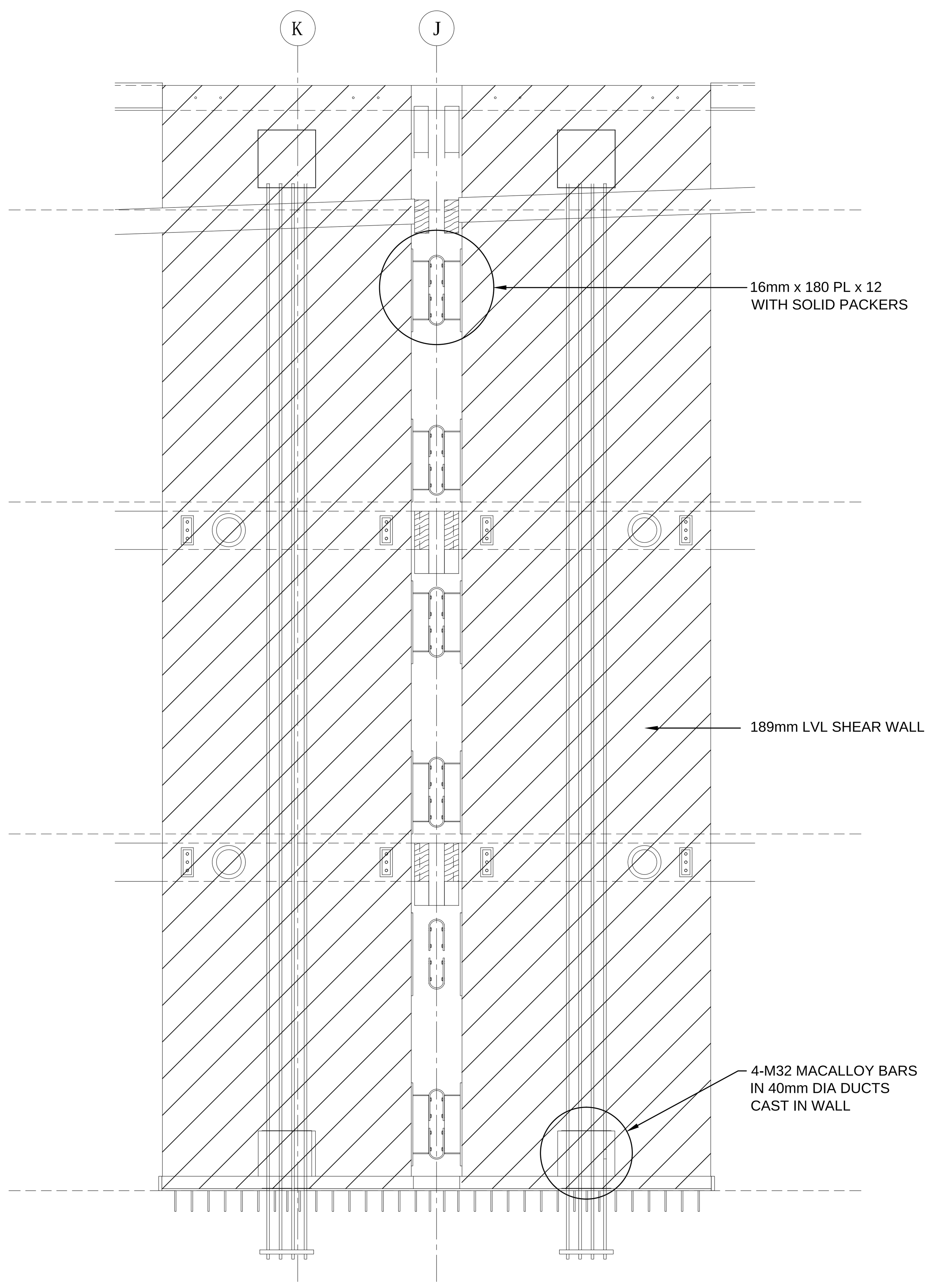
Drawing No. SSK-T-004
Rev. 02



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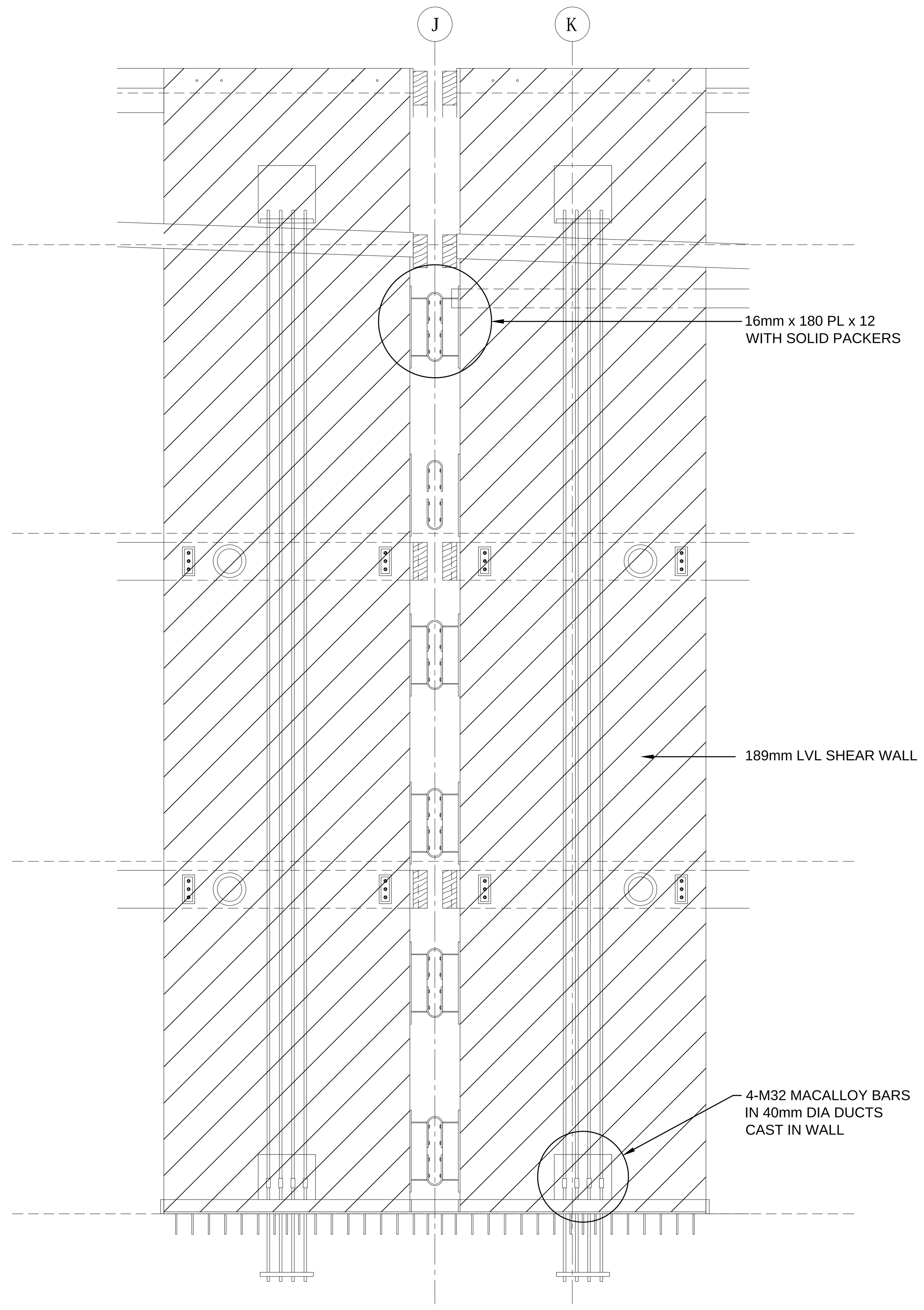

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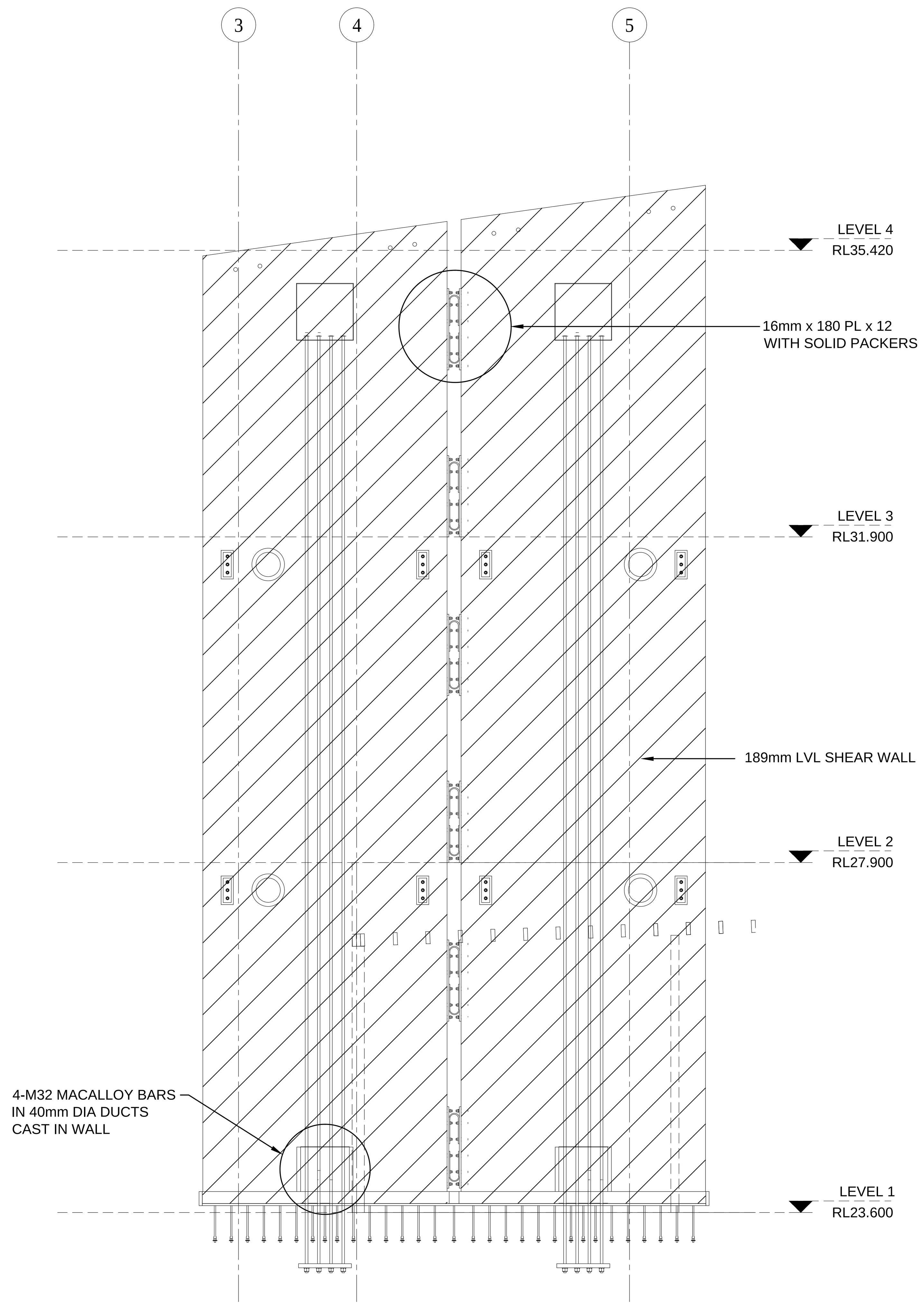

ELEVATION GRID E & L
SHEAR WALL

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INFORMATION
NOT FOR CONSTRUCTION

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aurecon
Aurecon New Zealand Limited
1st Floor, 62 Bridge Street (PO Box 1545)
Nelson New Zealand
Telephone: +64 3 573 0190
Facsimile: +64 3 573 0191
Email: nelson@ap.aurecongroup.com

Client: nmit Nelson Marlborough Institute of Technology
Te Whare Wananga o Te Tau Ihu o Te Waka a Maui

Project: ARTS AND MEDIA BUILDING

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Designed	SLH	SLH	06.08.10
Verified	CPD	CPD	06.08.10
Approved	AF	AF	06.08.10

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ARTS
ELEVATIONS
SHEAR WALLS
TIMBER OPTION

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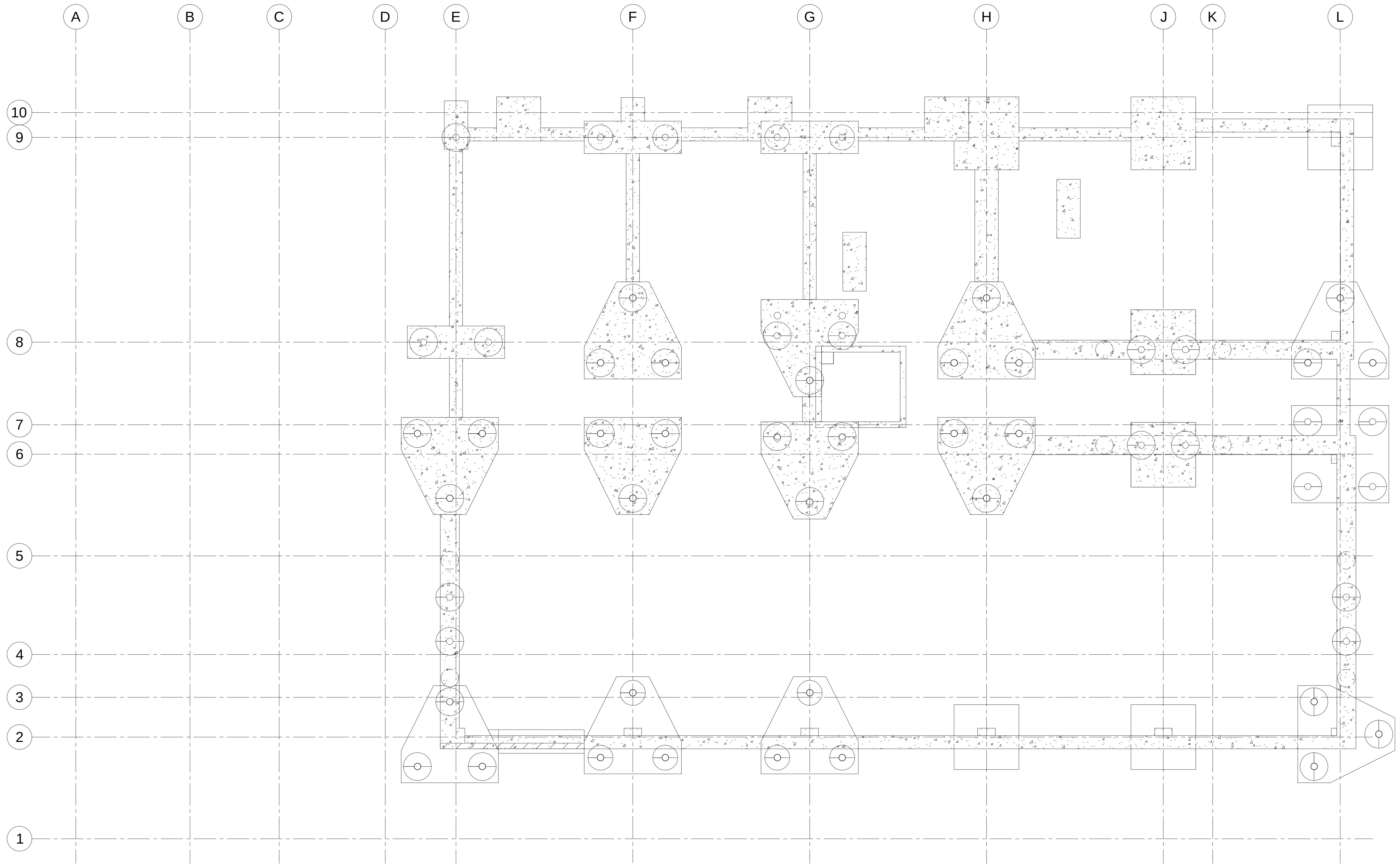
Rev. 02



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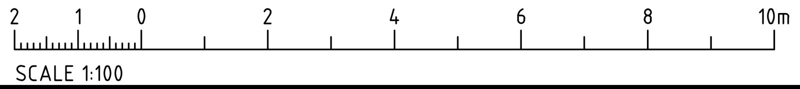

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Aurecon New Zealand Limited
1st Floor, 62 Bridge Street (PO Box 1545)
Nelson New Zealand
Telephone: +64 3 573 0190
Facsimile: +64 3 573 0191
Email: nelson@ap.aurecongroup.com

Client:

Nelson Marlborough Institute of Technology
Te Whare Wananga o Te Tau Ihu o Te Waka a Maui

Project:

ARTS AND MEDIA BUILDING

Drawing Title:

PLAN
FOUNDATIONS
STEEL OPTION

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Designed	Signed	Date	Approved	Signed	Date
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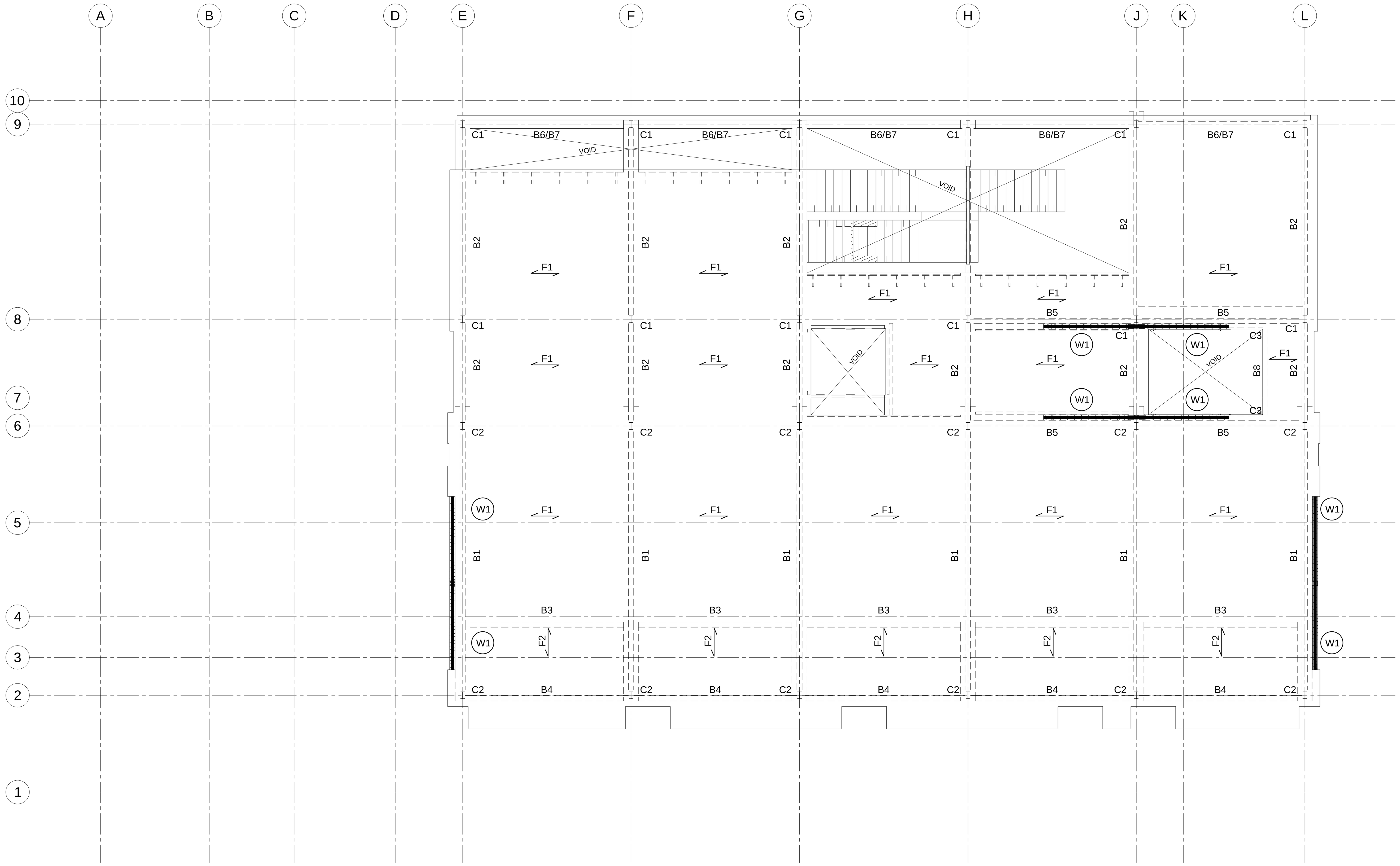

MEMBER	SIZE	SHEAR STUDS	PROPPING	FIRE RATING
BEAMS				
B1	530 UB 92	19mm dia @ 300c/c	YES	YES
B2	460 UB 82	19mm dia @ 300c/c	YES	YES
B3	250 UB 38	19mm dia @ 300c/c	YES	YES
B4	460 UB 67	19mm dia @ 300c/c	YES	YES
B5	380 PFC	19mm dia @ 300c/c	-	YES
B6	200 UB 30	19mm dia @ 300c/c	-	YES
B7	250 UB 39	19mm dia @ 300c/c	-	YES
B8	200 PFC	19mm dia @ 300c/c	-	YES
COLUMNS				
C1	250 UC 72	-	-	YES
C2	250 UC 89	-	-	YES
C3	100 SHS 9	-	-	YES
WALLS				
W1	250 UC FRAME	-	-	YES

FLOORING:
F1 COMFLOR 210
300mm OVERALL
HD16 PER TROUGH
MDT430-400 MESH
1-ROW PROPS MIDSPAN
F2 200mm THICK INSITU SLAB

CONCRETE STRENGTHS:
f'c = 30 MPa BEAMS, COMFLOR AND INSITU SLAB

FIRE RATING:
30 MINUTE INTUMESENT PAINT BY AUTEX SPECIFY THIS FIRE RATING UP TO LEVEL 3

SCALE 1:100

INFORMATION
NOT FOR CONSTRUCTION

Rev	Date	Revision Details	Des.	Ver.	App.
02	17.08.11	ISSUED FOR INFORMATION	PW	CPD	AF
01	06.08.10	ISSUED FOR INFORMATION	L.K.	CPD	AF

aurecon
Aurecon New Zealand Limited
1st Floor, 62 Bridge Street (PO Box 1545)
Nelson New Zealand
Telephone: +64 3 573 0190
Facsimile: +64 3 573 0191
Email: nelson@ap.aurecongroup.com

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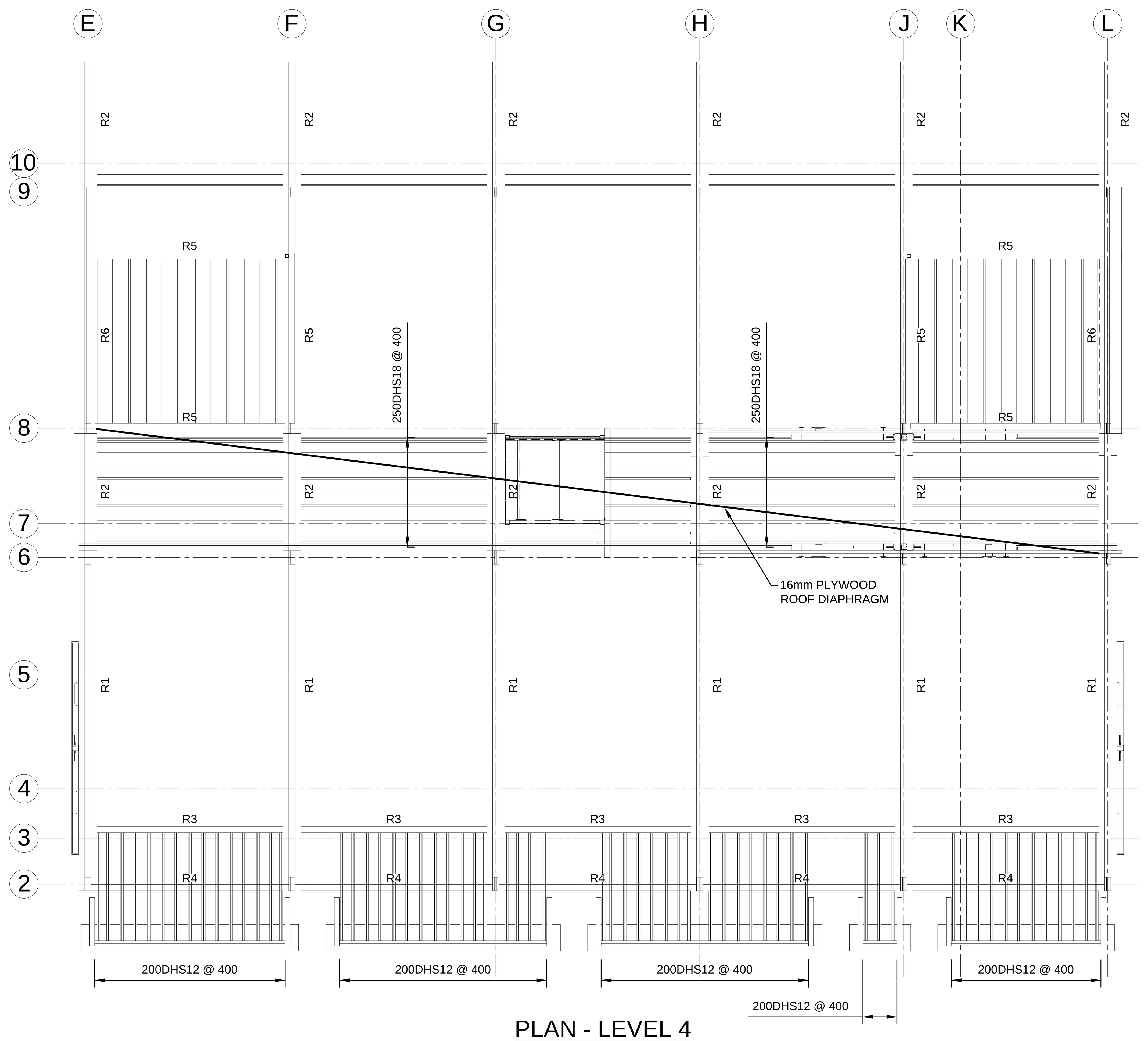
Te Whare Wananga o Te Tau Ihu o Te Waka a Maui

Project:
ARTS AND MEDIA BUILDING

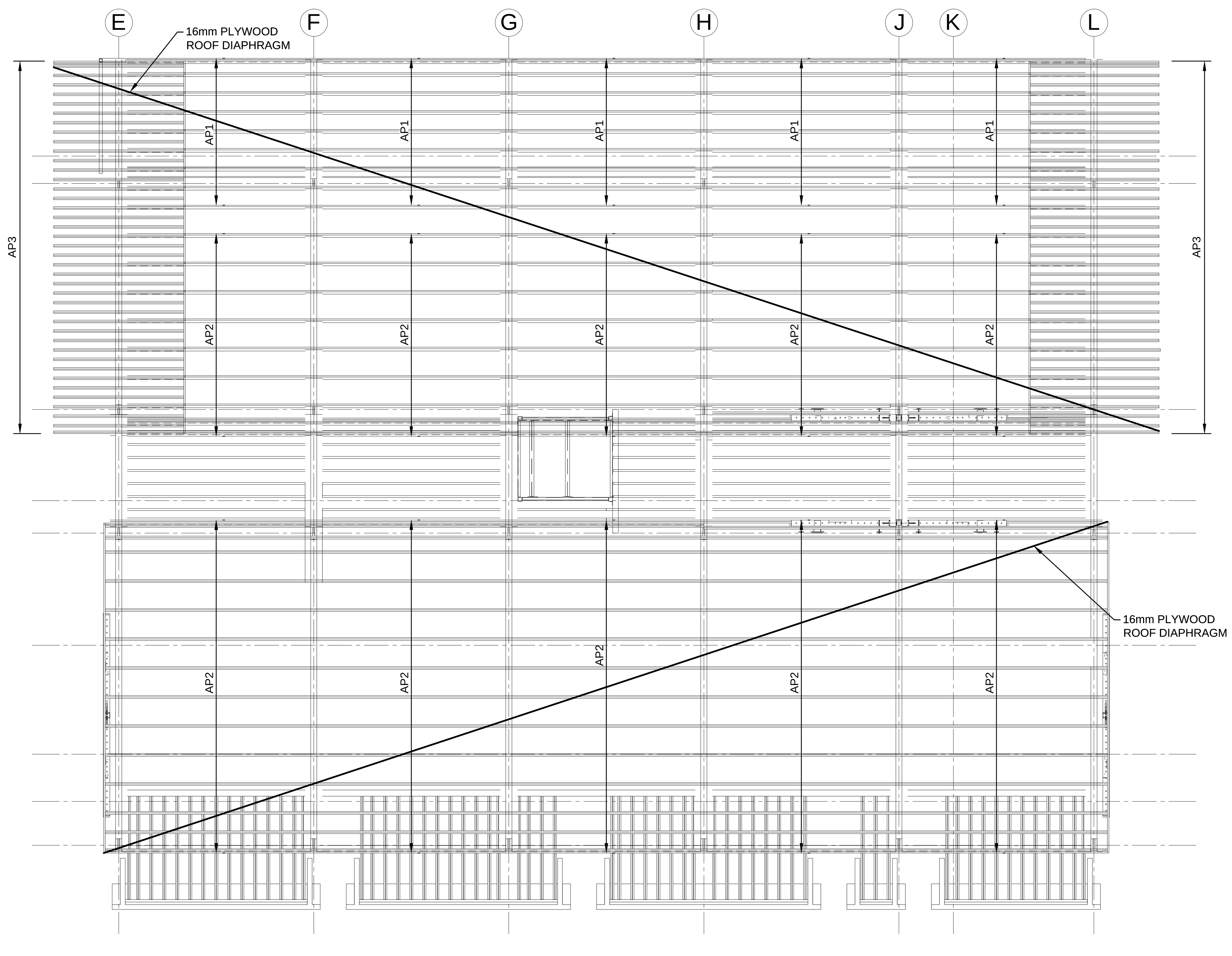
Drawing Title:
PLAN
LEVEL 2
STEEL OPTION

Drawn	Signed	Date	Verified	Signed	Date
LK	LK	06.08.10	CPD	CPD	06.08.10
Designed	Signed	Date	Approved	Signed	Date
SLH	SLH	06.08.10	AF	AF	06.08.10

Project No. 210688.001
Scale: 1:100 (A1) 1:200 (A3)
Sheet Size A1
Drawing No. SSK-S-002
Revision: 02



PLAN - LEVEL 4
(FRAMING)



PLAN - LEVEL 4
(PURLINS)

FRAMING:

R1	460UB67
R2	310UB46
R3	250UB37.3
R4	250UB37.3
R5	180UB18
R6	250UB31.4

PURLINS:

AP1	250DHS13 @ 600 C/C
AP2	250DHS13 @ 900 C/C
AP3	150DHS12 @ 300 C/C

ALL ONE ROW OF BRACES

2 1 0 2 4 6 8 10m
SCALE 1:100

AMENDMENT 00 NOT ISSUED YET!!! 00/00/00

Rev.	Date	Revision Details	Des.	Ver.	App.
02		TITLE UPDATED			
01	06.08.10	ISSUED FOR INFORMATION	PW	CPD	AF

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Nelson New Zealand
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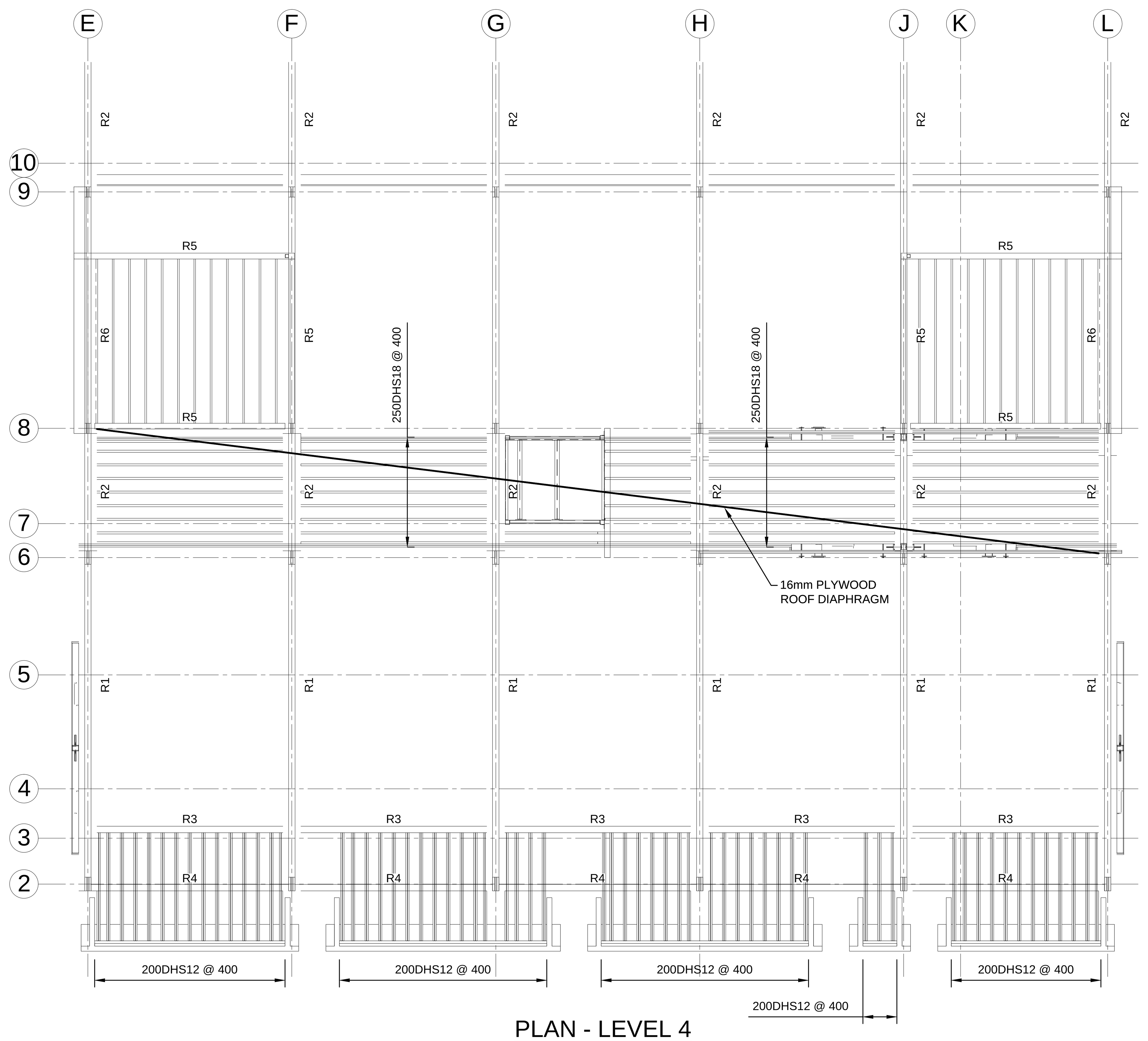
Project: ARTS AND MEDIA BUILDING

		Signed		Date
Drawn	LK		LK	06.08.10
Designed	SLH		SLH	06.08.10
Verified	CPD		CPD	06.08.10
Approved	AF		AF	06.08.10

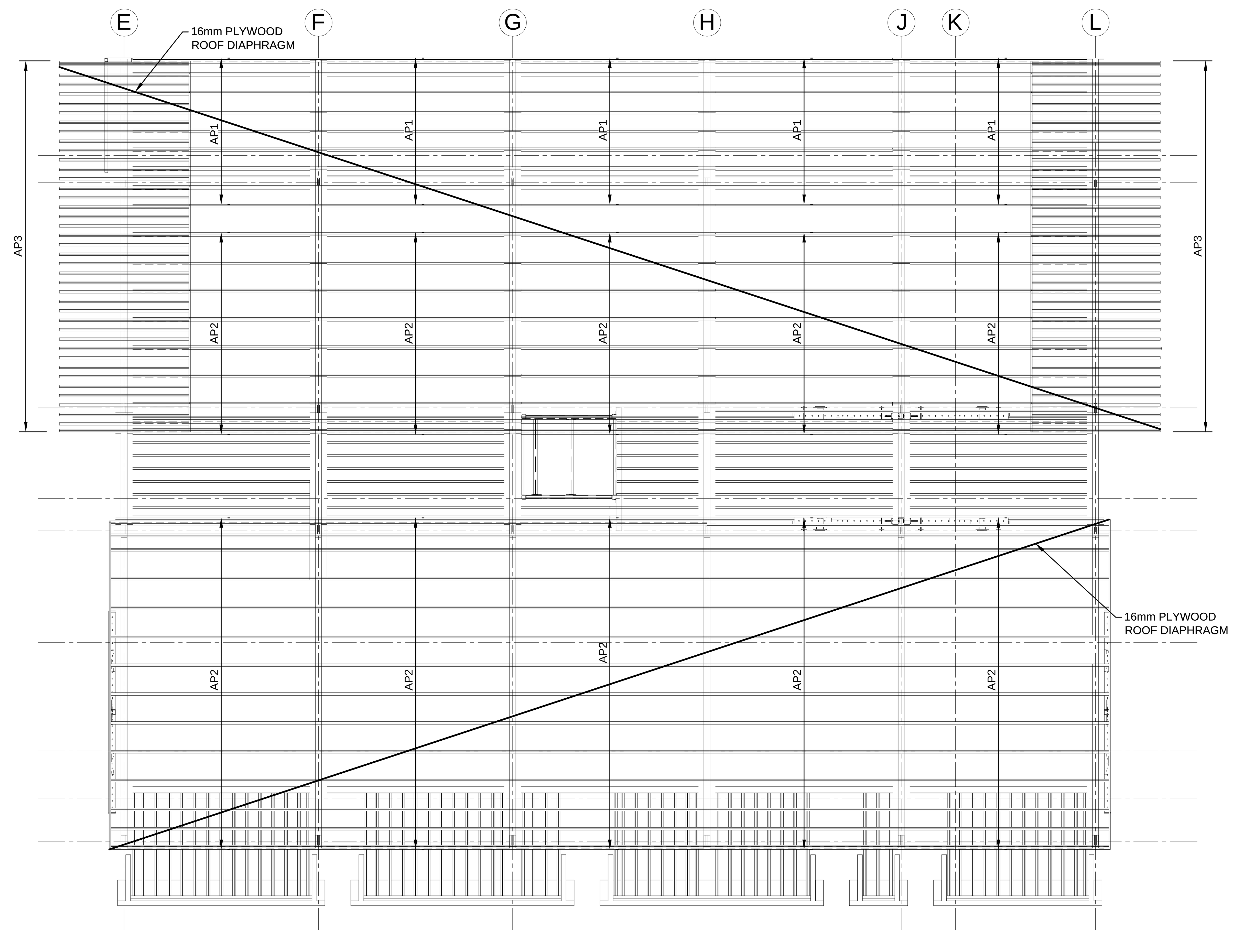
Drawing Title: PLAN
LEVEL 4 / ROOF
STEEL OPTION

INFORMATION
NOT FOR CONSTRUCTION

Project No. 210688.001
Scale 1:100 (A1) 1:200 (A3)
Sheet Size A1
Drawing No. SSK-S-003
Rev. 02



PLAN - LEVEL 4
(FRAMING)



PLAN - LEVEL 4
(PURLINS)

FRAMING:	
R1	460UB67
R2	310UB46
R3	250UB37.3
R4	250UB37.3
R5	180UB18
R6	250UB31.4

PURLINS:	
AP1	250DHS13 @ 600 C/C
AP2	250DHS13 @ 900 C/C
AP3	150DHS12 @ 300 C/C
ALL ONE ROW OF BRACES	

2 1 0 2 4 6 8 10m
SCALE 1:100

INFORMATION
NOT FOR CONSTRUCTION

Rev.	Date	Revision Details	Des.	Ver.	App.
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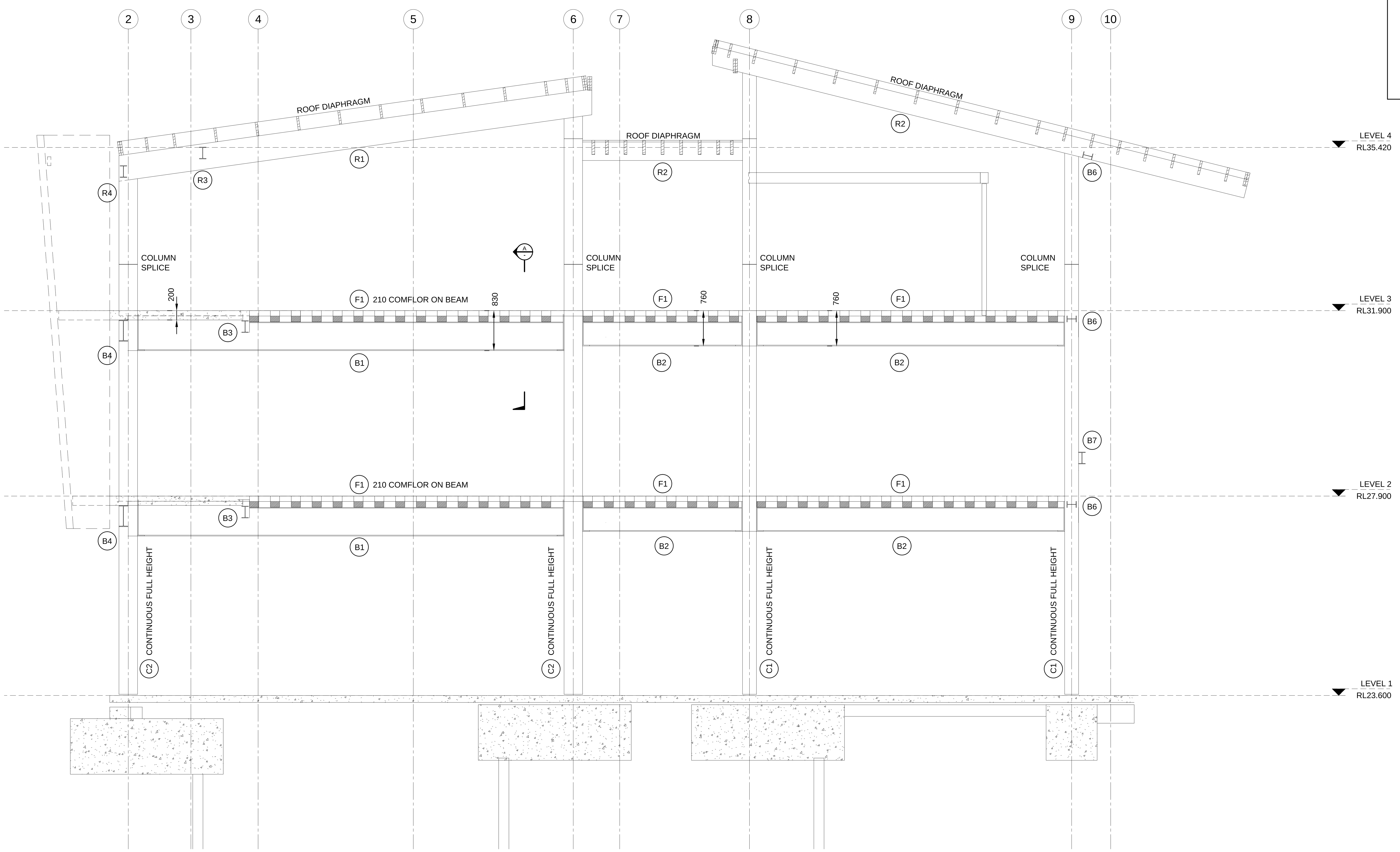
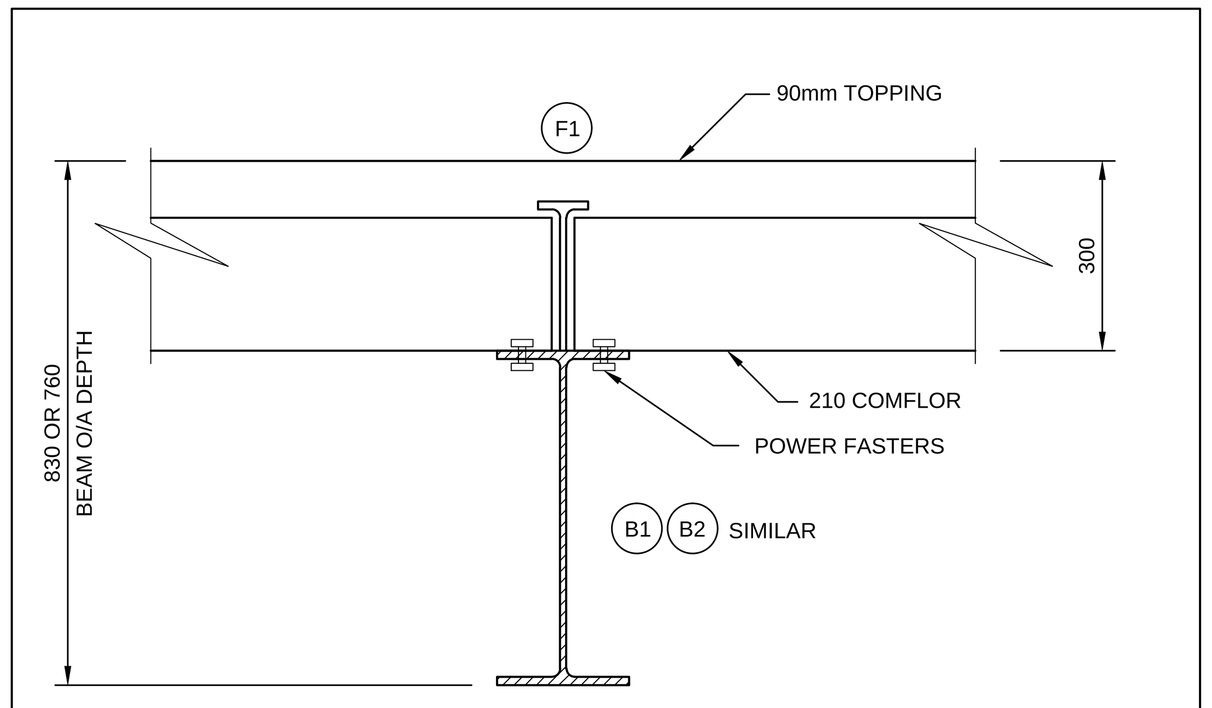
Project: ARTS AND MEDIA BUILDING

Drawn	Signed	Date
LK	LK	06.08.10
Designed SLH	Signed SLH	Date 06.08.10
Verified CPD	Signed CPD	Date 06.08.10
Approved AF	Signed AF	Date 06.08.10

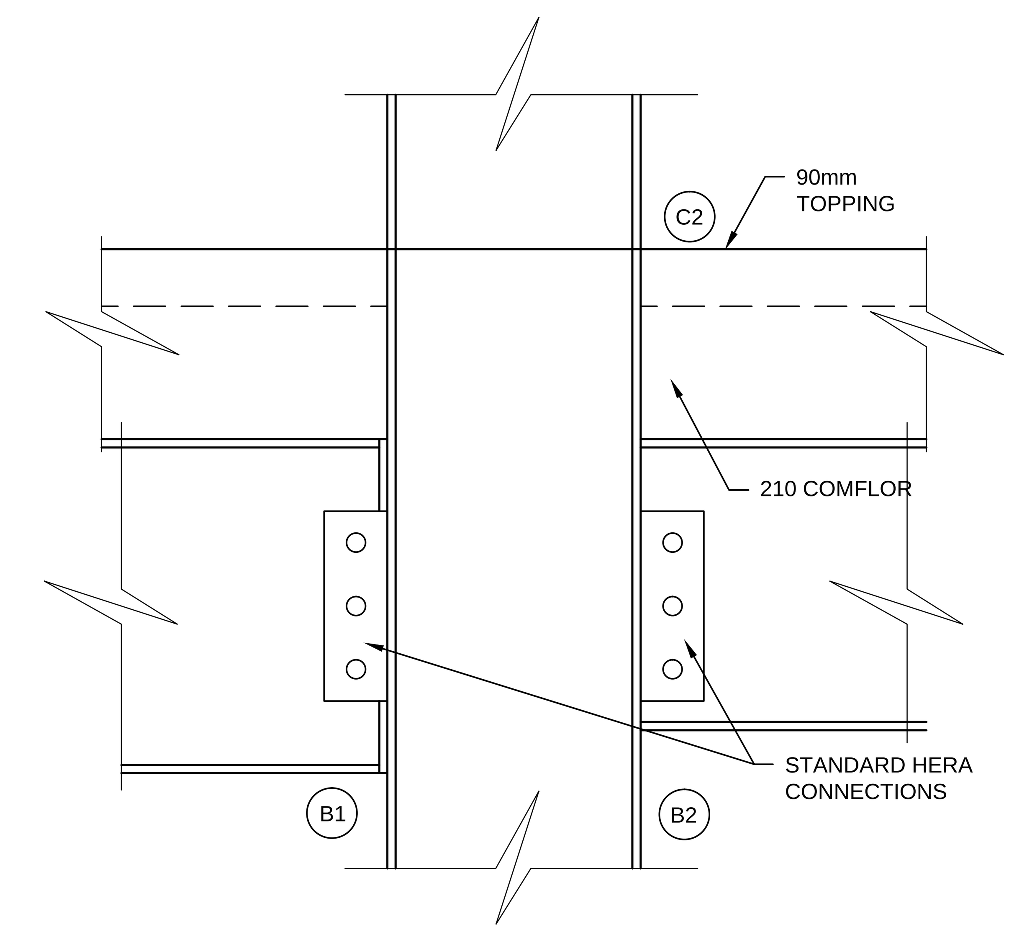
Drawing Title:
PLAN
LEVEL 4 / ROOF
STEEL OPTION

Project No. 210688.001
Scale 1:100 (A1) 1:200 (A3)
Sheet Size A1
Drawing No. SSK-S-003
Rev. 02





SECTION A-A
SCALE 1:20 (@A3)



DETAIL 1
SCALE 1:20 (@A3)

1000 0 1000 2000 3000 4000 5000mm
SCALE 1:50

INFORMATION
NOT FOR CONSTRUCTION

Rev.	Date	Revision Details	Des.	Ver.	App.
02	17.08.11	ISSUED FOR INFORMATION	PW	CPD	AF
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aurecon
Aurecon New Zealand Limited
1st Floor, 62 Bridge Street (PO Box 1545)
Nelson New Zealand
Telephone: +64 3 573 0190
Facsimile: +64 3 573 0191
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Project: ARTS AND MEDIA BUILDING

		Signed		Date
Drawn	LK	Signed	LK	06.08.10
Designed	SLH	Signed	SLH	06.08.10
Verified	CPD	Signed	CPD	06.08.10
Approved	AF	Signed	AF	06.08.10

Drawing Title: ARTS ELEVATION GRID F STEEL OPTION

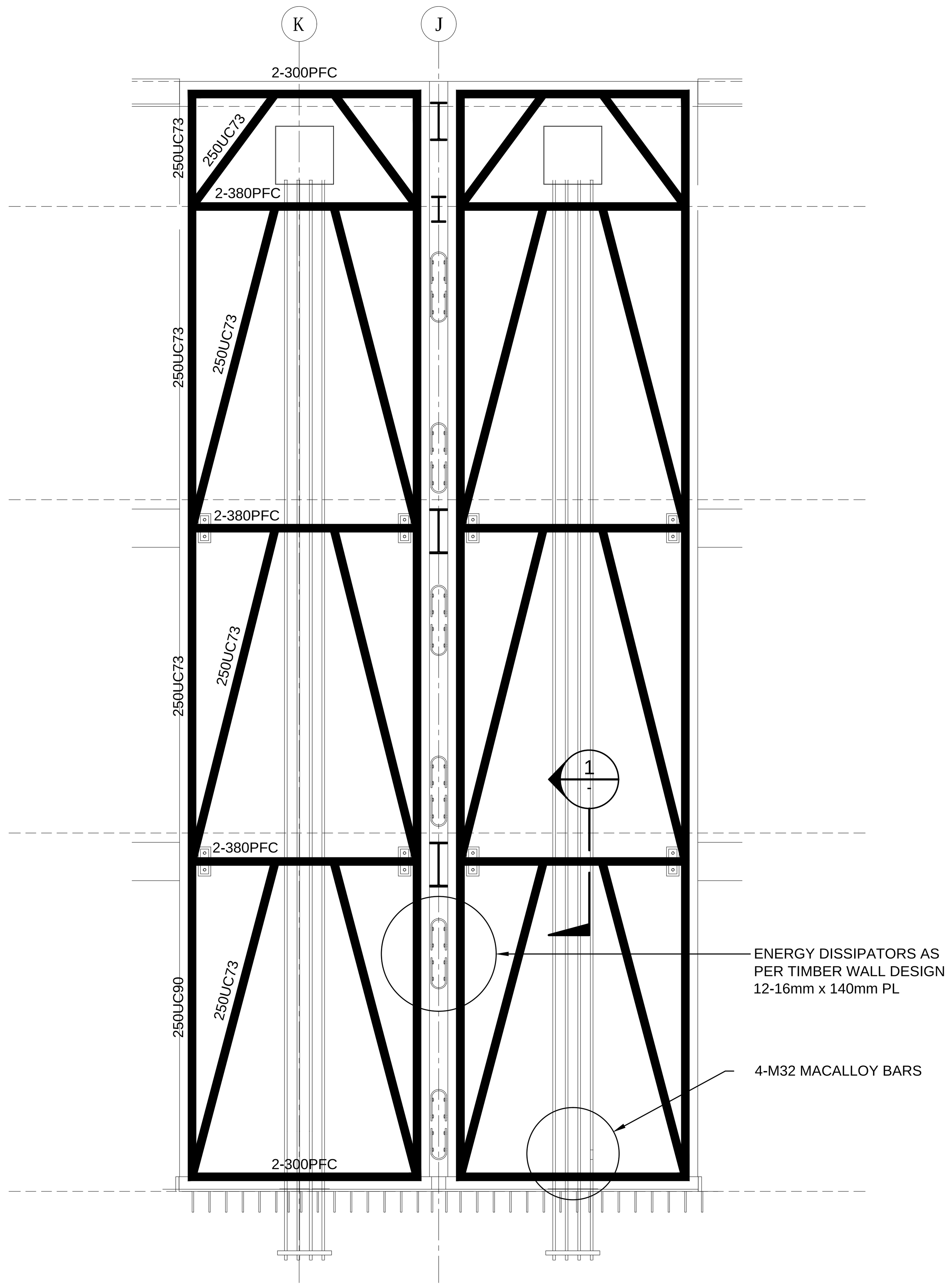
Project No. 210688.001

Scale 1:50 (A1) 1:100 (A3)

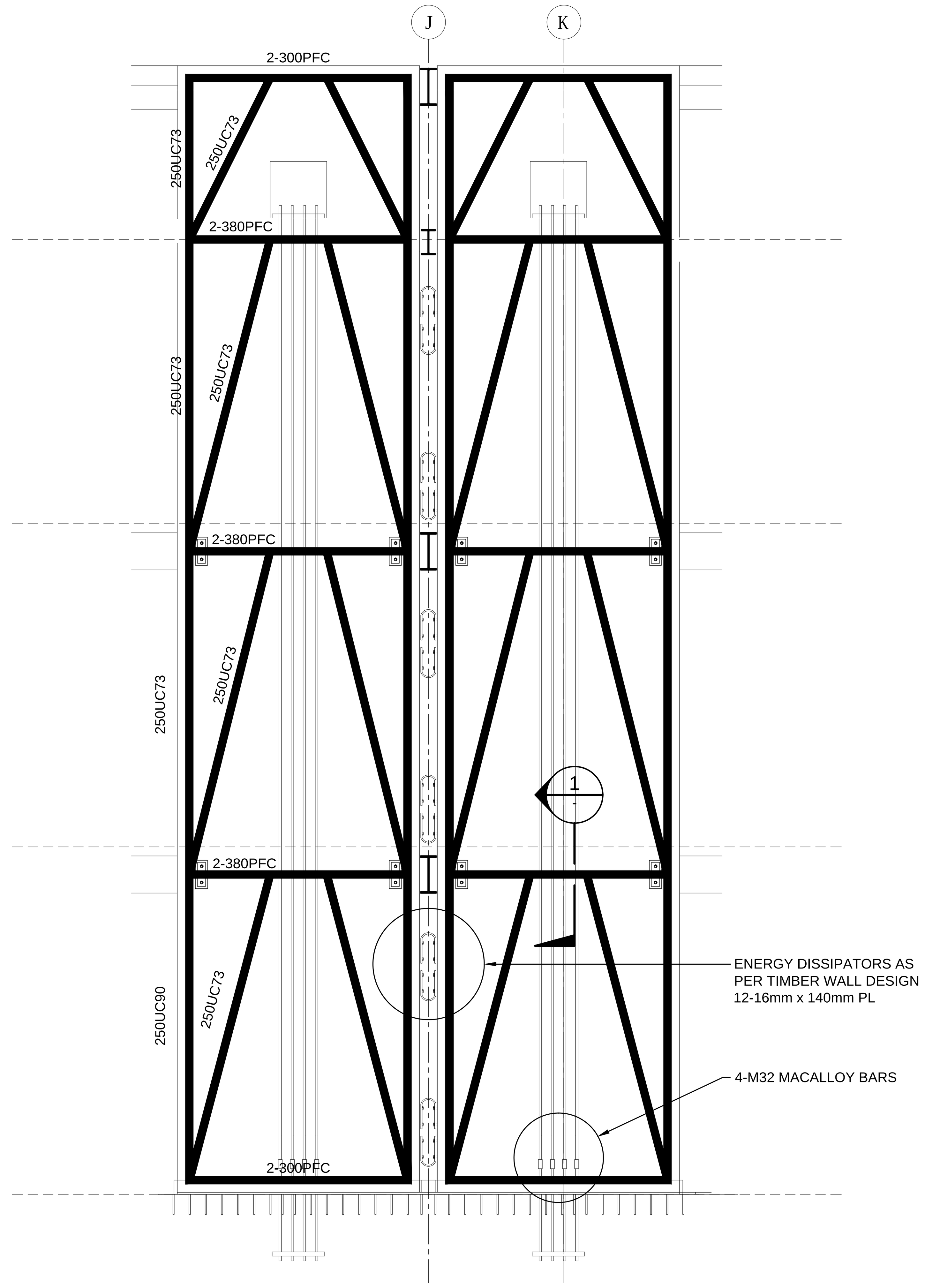
Sheet Size A1

Drawing No. SSK-S-004

Rev. 02

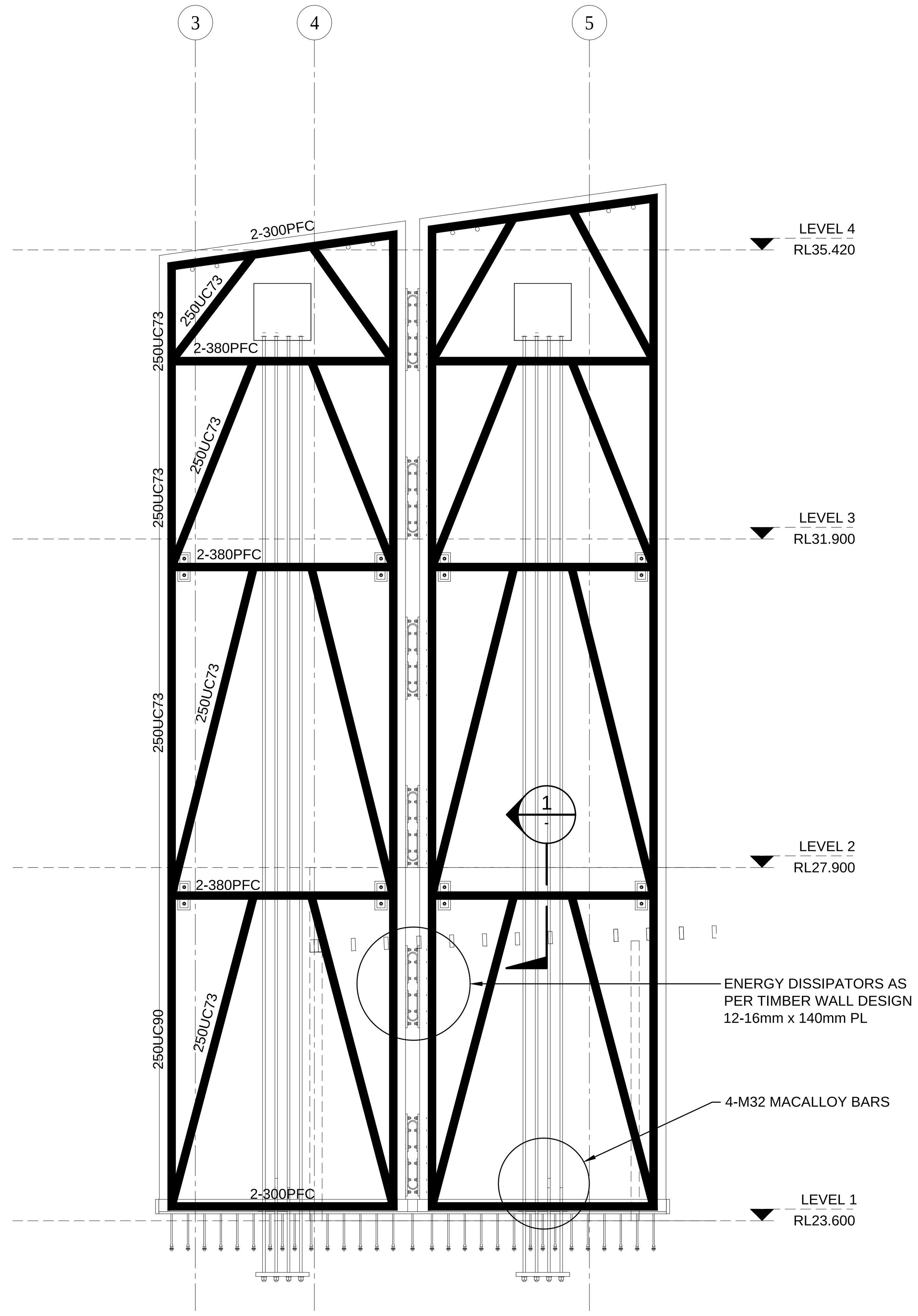


ELEVATION GRID 6
SHEAR WALL

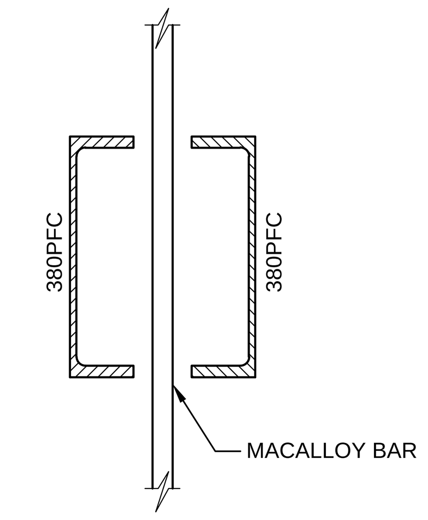


STEEL GRADE = 350MPa

ELEVATION GRID 8
SHEAR WALL



ELEVATION GRID E & L
SHEAR WALL



SECTION 1
SCALE 1:10

1000 0 1000 2000 3000 4000 5000mm
SCALE 1:50

INFORMATION
NOT FOR CONSTRUCTION

Rev.	Date	Revision Details	Des.	Ver.	App.
02	17.08.11	ISSUED FOR INFORMATION	PW	CPD	AF
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aurecon
Aurecon New Zealand Limited
1st Floor, 62 Bridge Street (PO Box 1545)
Nelson New Zealand
Telephone: +64 3 573 0190
Facsimile: +64 3 573 0191
Email: nelson@ap.aurecongroup.com

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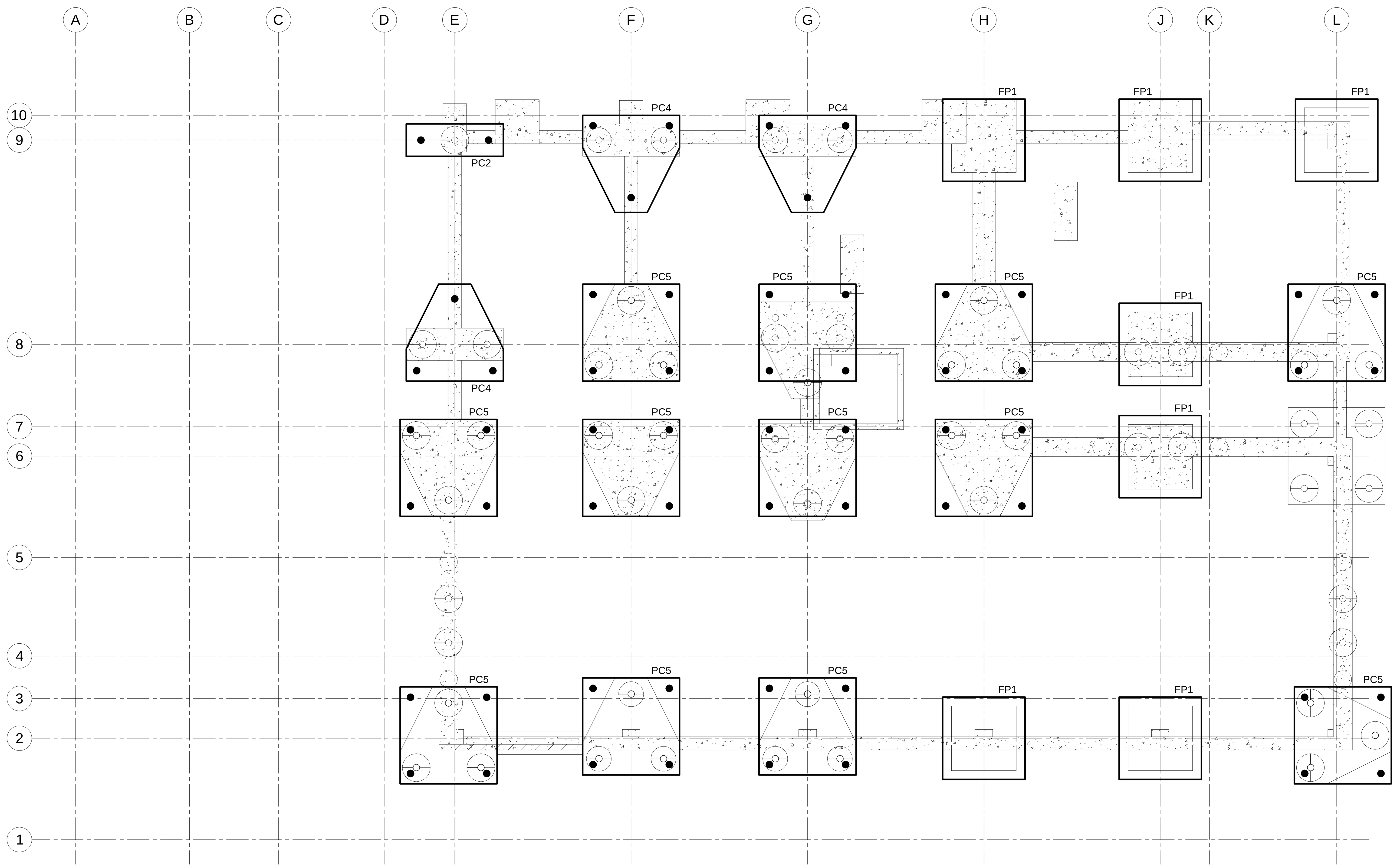
Drawn	Signed	Date
LK	LK	06.08.10
Designed SLH	SLH	06.08.10
Verified CPD	CPD	06.08.10
Approved AF	AF	06.08.10

Drawing Title: ARTS ELEVATIONS SHEAR WALLS STEEL OPTION

Project No. 210688.001
Scale 1:50 (A1) 1:100 (A3)
Sheet Size A1
Drawing No. SSK-S-005
Rev. 02



FOUNDATION:	NOTE:	CONCRETE STRENGTH
FP1 INCREASE IN PLAN AREA FROM 2.2m x 2.2m TO 2.8m x 2.8m	NEW PILE CAPS AND PADS OVERLAIN TIMBER DESIGN PILE CAPS AND PADS	f'c = 25 MPa FOUNDATIONS

2 1 0 2 4 6 8 10m
SCALE 1:100

Rev	Date	Revision Details	Des.	Ver.	App.
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1st Floor, 62 Bridge Street (PO Box 1545)
Nelson New Zealand
Telephone: +64 3 573 0190
Facsimile: +64 3 573 0191
Email: nelson@ap.aurecongroup.com

Client:
nmit
Nelson Marlborough Institute of Technology
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Project:

ARTS AND MEDIA BUILDING

Drawing Title:

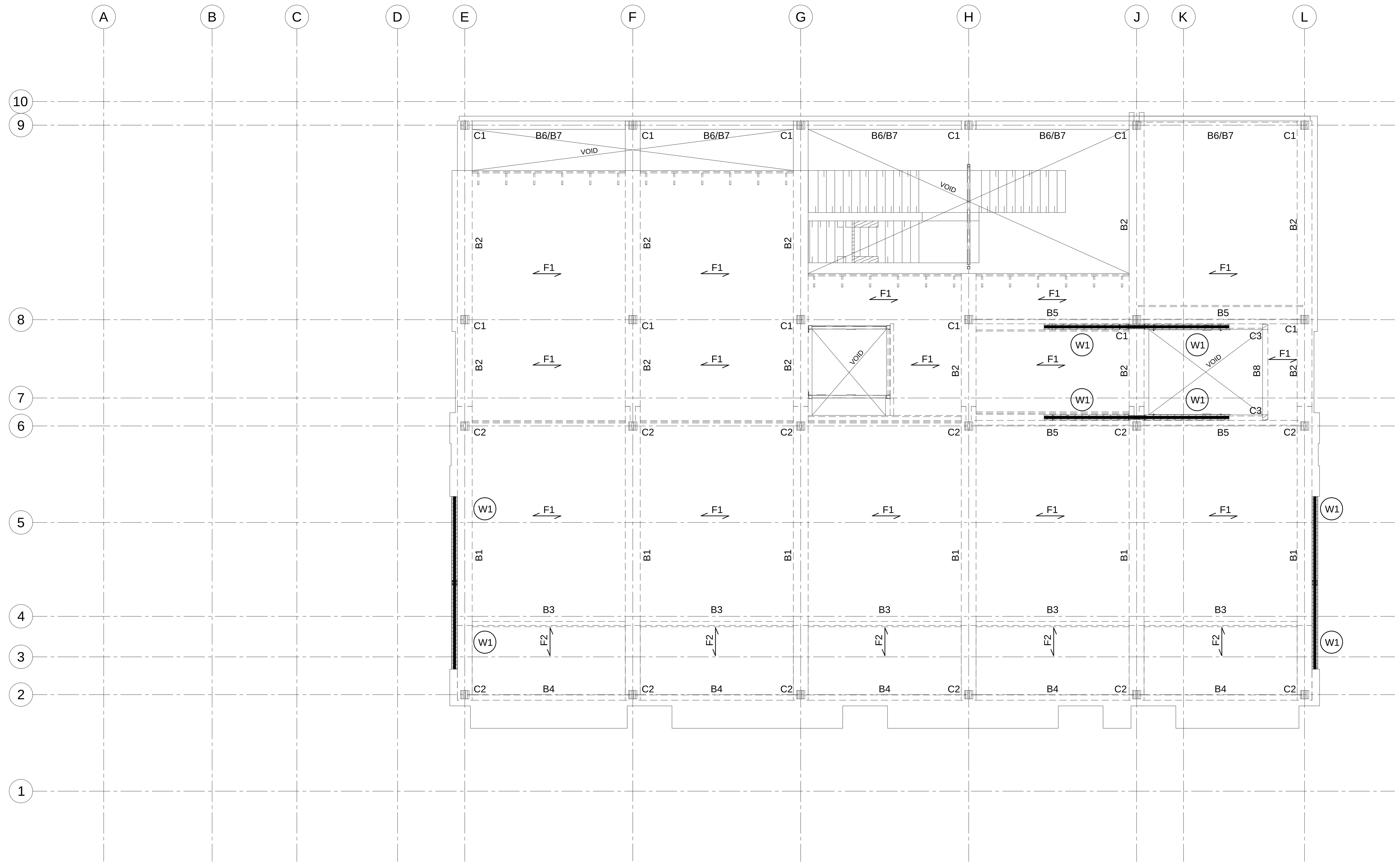
PLAN
FOUNDATIONS
CONCRETE OPTION

Drawn	Signed	Date	Verified	Signed	Date
LK	LK	06.08.10	CPD	CPD	06.08.10
Designed	Signed	Date	Approved	Signed	Date
SLH	SLH	06.08.10	AF	AF	06.08.10

Project No. 210688.001
Scale: 1:100 (A1) 1:200 (A3)
Sheet Size A1

INFORMATION
NOT FOR CONSTRUCTION

Drawing No. SSK-C-001
Revision: 02



MEMBER	SIZE	REINFORCING	PROPING	FIRE RATING
BEAMS				
B1	850d x 450w	200kg/m³	YES	-
B2	600d x 450w	200kg/m³	YES	-
B3	450d x 350w	200kg/m³	YES	-
B4	600d x 450w	200kg/m³	YES	-
B5	380 PFC	-	-	YES
B6	200 UB 30	-	-	YES
B7	250 UB 39	-	-	YES
B8	200 PFC	-	-	YES
COLUMNS				
C1	300 x 300	150kg/m³	-	-
C2	300 x 300	150kg/m³	-	-
WALLS				
W1	3.0m x 0.2m	100kg/m³	-	-

FLOORING:
F1 125mm INTERSPAN
RIB 40mm TIMBER INFILL
75mm TOPPING (240mm DEPTH)
1-ROW PROPS
F2 200mm THICK INSITU SLAB

CONCRETE STRENGTHS:
f'c = 30 MPa BEAMS, COLUMNS AND TOPPING
f'c = 25 MPa FOUNDATIONS

FIRE RATING
NOT REQUIRED

2 1 0 2 4 6 8 10m
SCALE 1:100

INFORMATION
NOT FOR CONSTRUCTION

Rev	Date	Revision Details	Des.	Ver.	App.
02	17.08.11	ISSUED FOR INFORMATION	PW	CPD	AF
01	06.08.10	ISSUED FOR INFORMATION	PW	CPD	AF

aurecon
Aurecon New Zealand Limited
1st Floor, 62 Bridge Street (PO Box 1545)
Nelson New Zealand
Telephone: +64 3 573 0190
Facsimile: +64 3 573 0191
Email: nelson@ap.aurecongroup.com

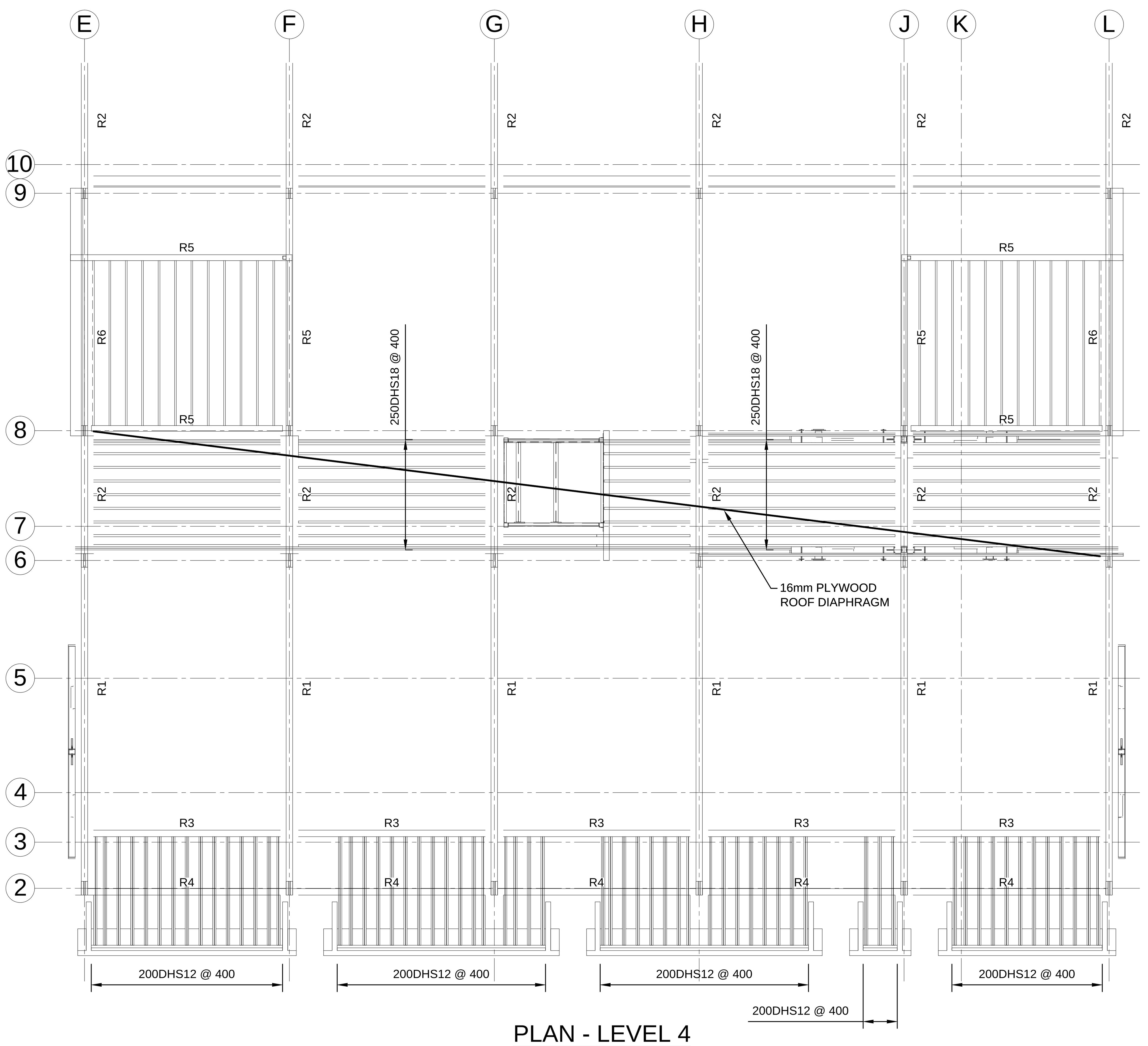
Client:
nmit
Nelson Marlborough Institute of Technology
Te Whare Wananga o Te Tau Ihu o Te Waka a Maui

Project:
ARTS AND MEDIA BUILDING

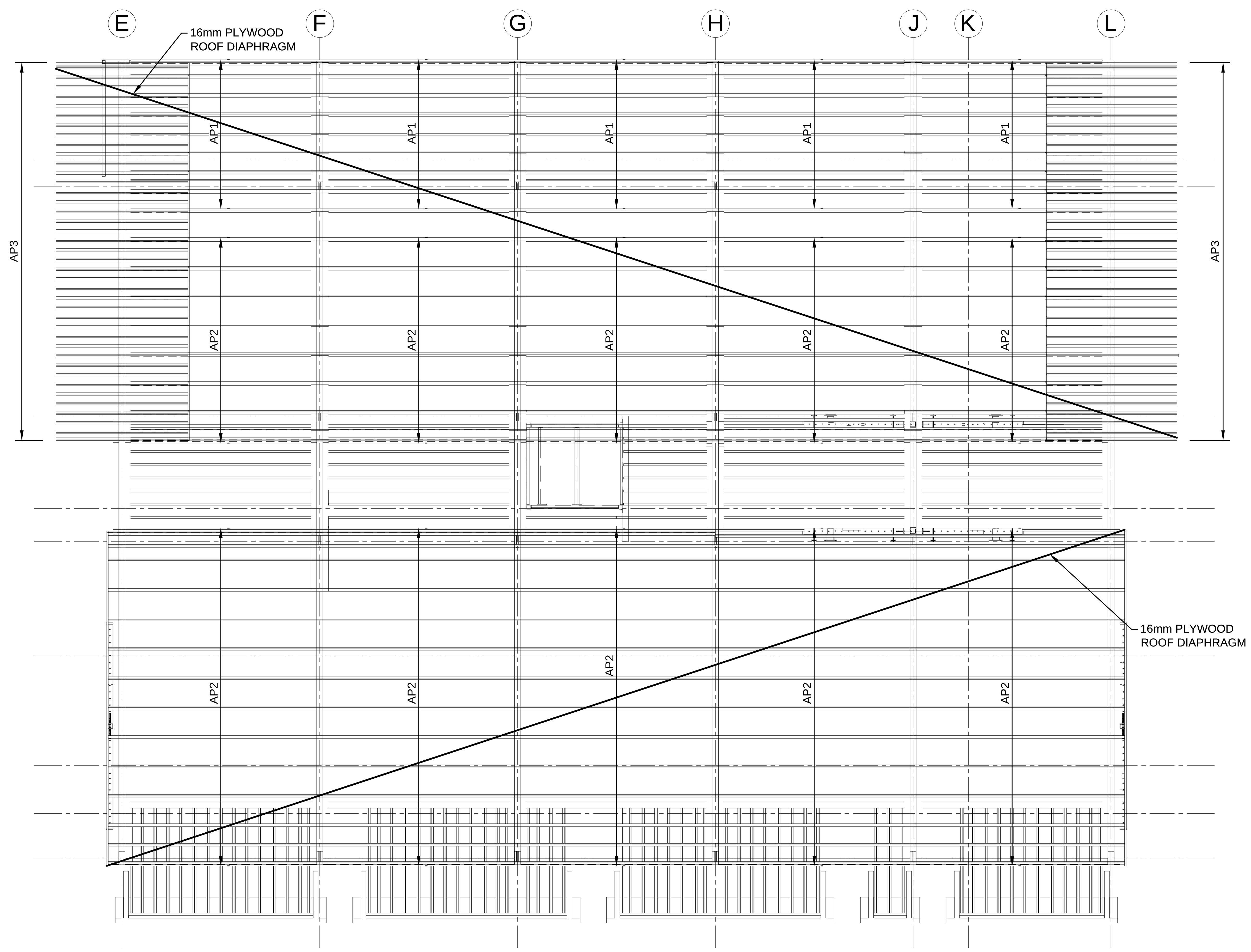
Drawing Title:
PLAN
LEVEL 2
CONCRETE OPTION

Drawn	Signed	Date	Verified	Signed	Date
LK	LK	06.08.10	CPD	CPD	06.08.10
Designed	Signed	Date	Approved	Signed	Date
SLH	SLH	06.08.10	AF	AF	06.08.10

Project No.: 210688.001
Scale: 1:100 (A1) 1:200 (A3)
Sheet Size: A1
Drawing No.: SSK-C-002
Revision: 02



PLAN - LEVEL 4
(FRAMING)



PLAN - LEVEL 4
(PURLINS)

FRAMING:	
R1	460UB67
R2	310UB46
R3	250UB37.3
R4	250UB37.3
R5	180UB18
R6	250UB31.4

PURLINS:	
AP1	250DHS13 @ 600 C/C
AP2	250DHS13 @ 900 C/C
AP3	150DHS12 @ 300 C/C
ALL ONE ROW OF BRACES	

2 1 0 2 4 6 8 10m
SCALE 1:100

Rev.	Date	Revision Details	Des.	Ver.	App.
02	17.08.11	ISSUED FOR INFORMATION	PW	CPD	AF
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aurecon
Aurecon New Zealand Limited
1st Floor, 62 Bridge Street (PO Box 1545)
Nelson New Zealand
Telephone: +64 3 573 0190
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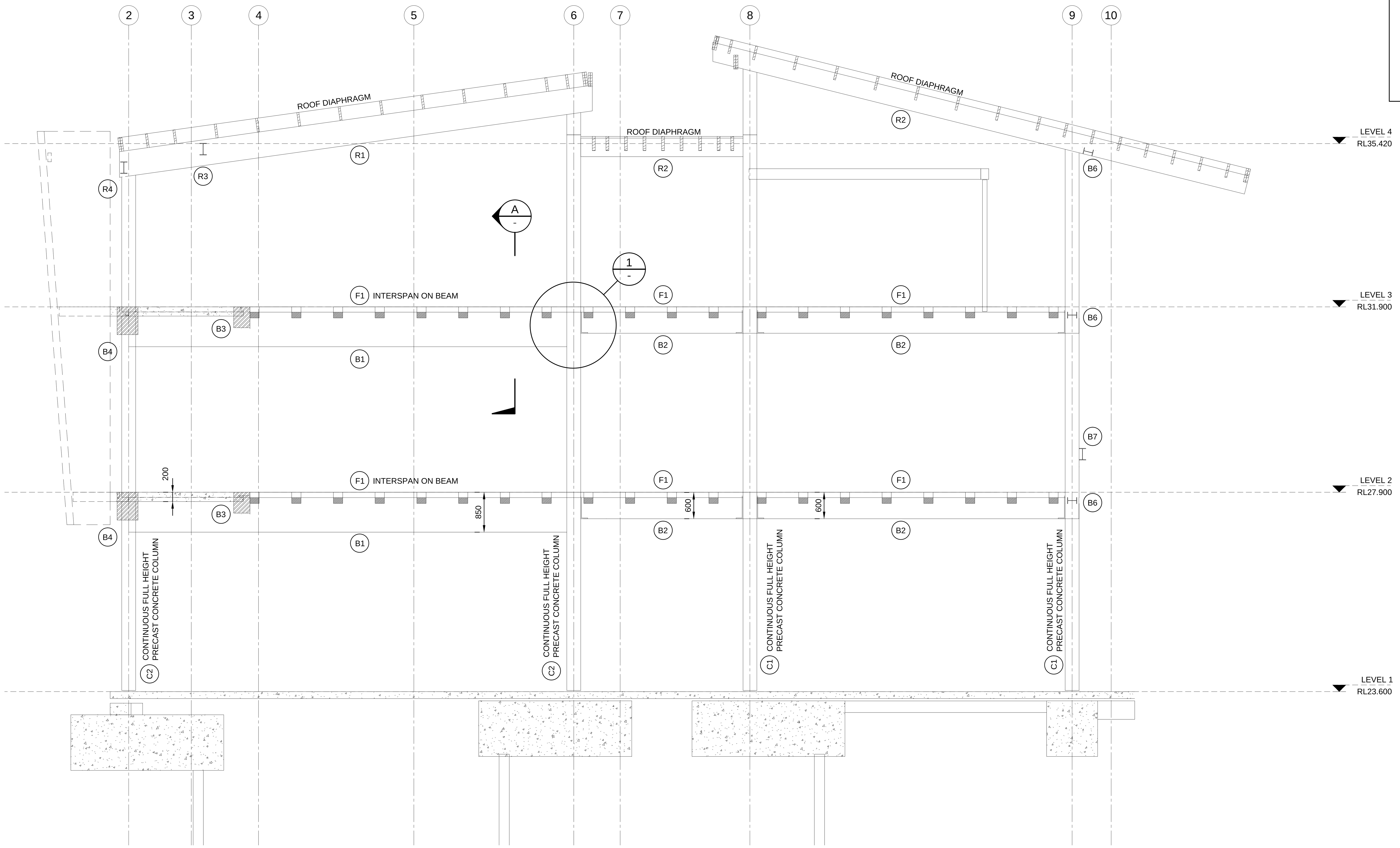
Project: ARTS AND MEDIA BUILDING

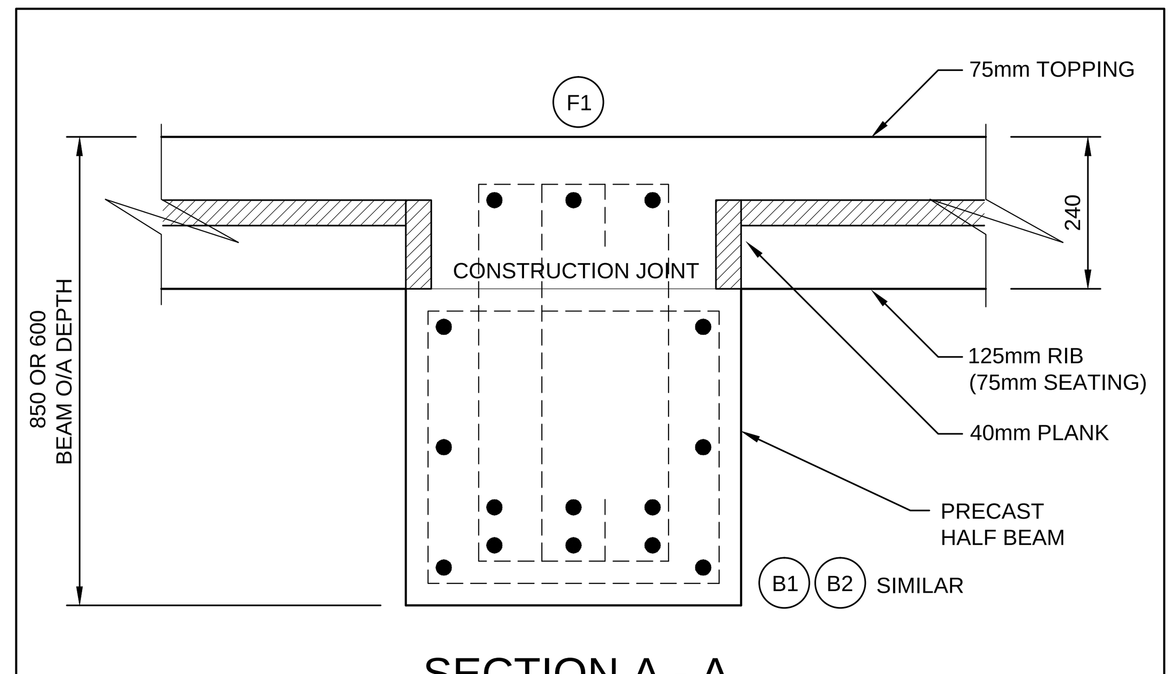
		Signed		Date
Drawn	LK	Signed	LK	06.08.10
Designed	SLH	Signed	SLH	06.08.10
Verified	CPD	Signed	CPD	06.0810
Approved	AF	Signed	AF	06.08.10

Drawing Title: PLAN LEVEL 4 / ROOF CONCRETE OPTION

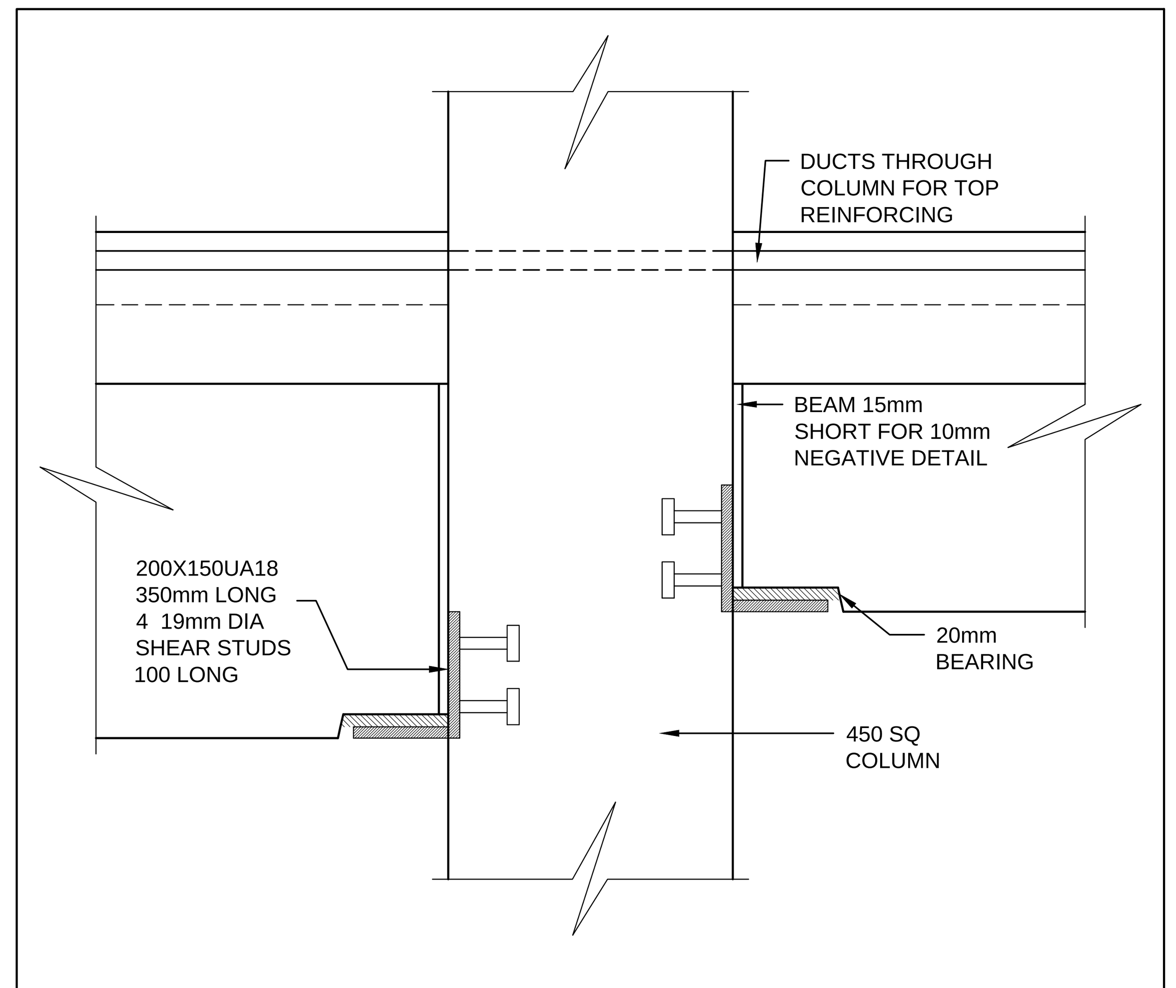
INFORMATION
NOT FOR CONSTRUCTION

Project No. 210688.001
Scale 1:100 (A1) 1:200 (A3)
Sheet Size A1
Drawing No. SSK-C-003
Rev. 02





SECTION A - A
SCALE 1:10



DETAIL 1
SCALE 1:10

1000 0 1000 2000 3000 4000 5000mm
SCALE 1:50

Rev.	Date	Revision Details	Des.	Ver.	App.
02	17.08.11	ISSUED FOR INFORMATION	PW	CPD	AF
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nmit
Nelson Marlborough Institute of Technology
Te Whare Wananga o Te Tau Ihu o Te Waka a Maui

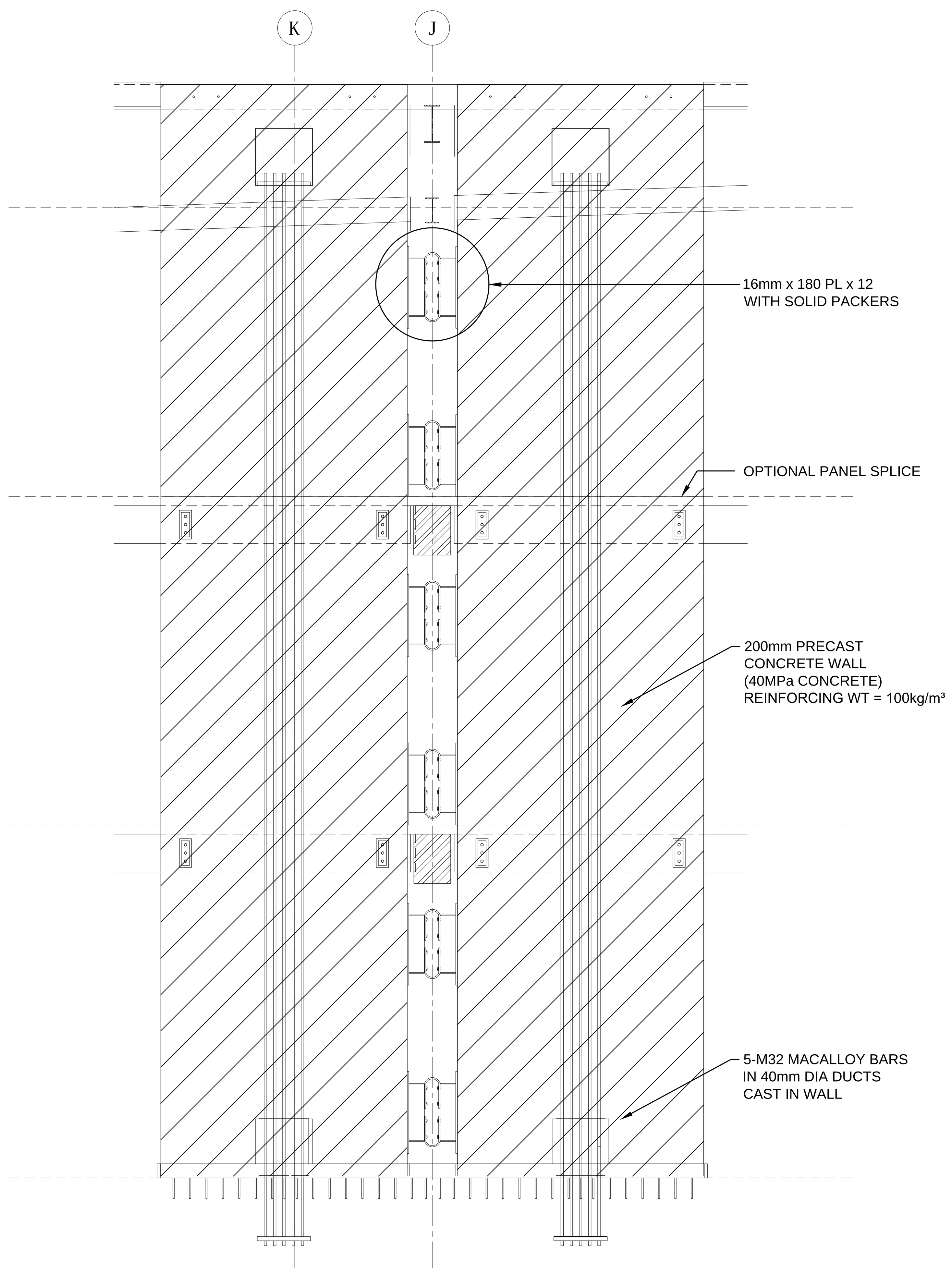
Project:
ARTS AND MEDIA BUILDING

Drawn LK	Signed LK	Date 06.08.10	
Designed SLH	Signed SLH	Date 06.08.10	
Verified CPD	Signed CPD	Date 06.08.10	
Approved AF	Signed AF	Date 06.08.10	

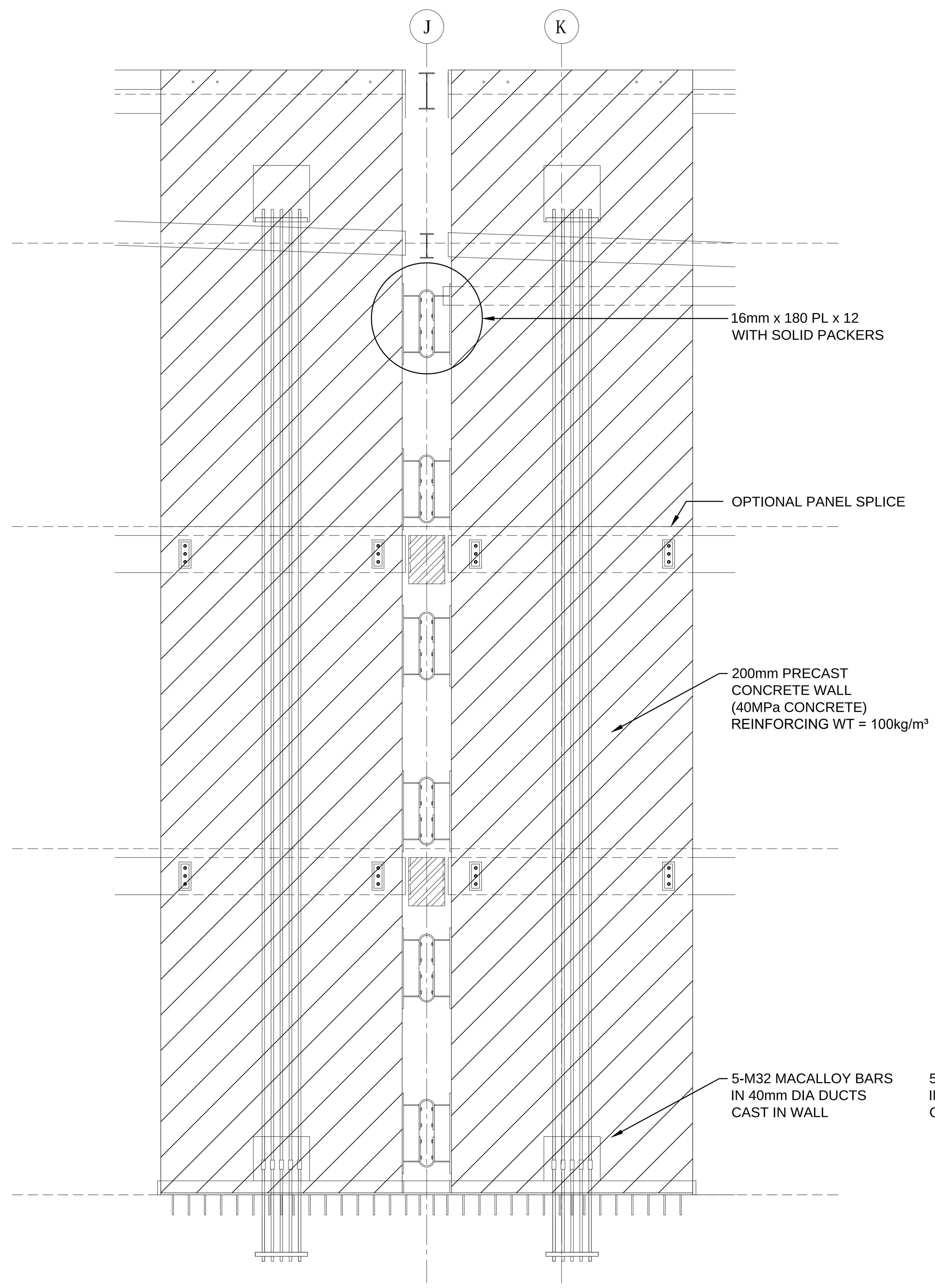
Drawing Title:
ARTS
ELEVATION
GRID F
CONCRETE OPTION

INFORMATION
NOT FOR CONSTRUCTION

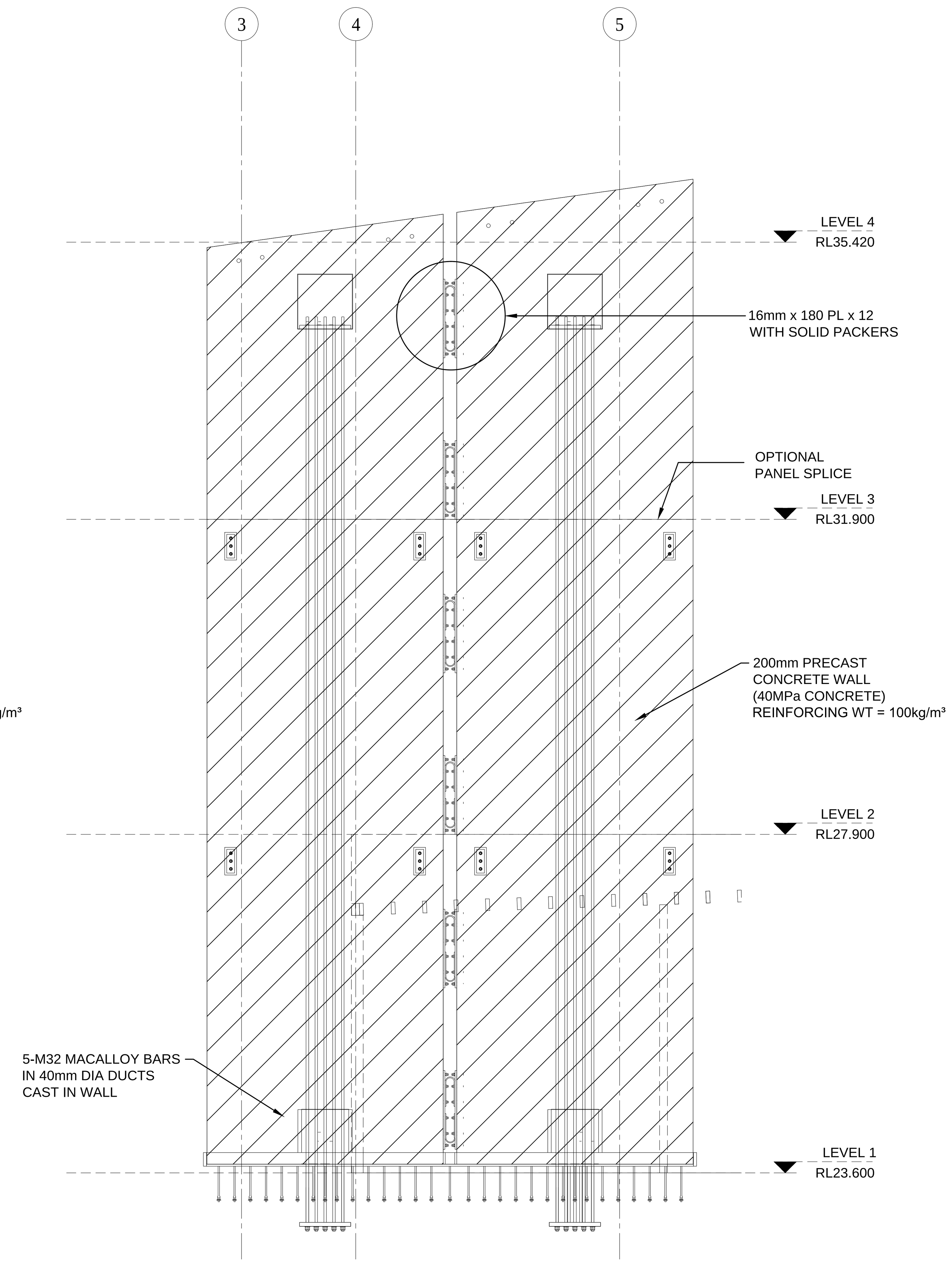
Project No. 210688.001
Scale 1:50 (A1) 1:100 (A3)
Sheet Size A1
Drawing No. SSK-C-004
Rev. 02



ELEVATION GRID 6
SHEAR WALL



ELEVATION GRID 8
SHEAR WALL



ELEVATION GRID E & L
SHEAR WALL

1000 0 1000 2000 3000 4000 5000mm
SCALE 1:50

INFORMATION
NOT FOR CONSTRUCTION

Rev.	Date	Revision Details	Des.	Ver.	App.
02	17.08.11	ISSUED FOR INFORMATION	PW	CPD	AF
01	06.08.10	ISSUED FOR INFORMATION	PW	CPD	AF

aurecon

Aurecon New Zealand Limited
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Nelson New Zealand
Telephone: +64 3 573 0190
Facsimile: +64 3 573 0191
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Client:
nmit
Nelson Marlborough Institute of Technology
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Project:
ARTS AND MEDIA BUILDING

		Signed	Date
Drawn	LK	LK	06.08.10
Designed	SLH	SLH	06.08.10
Verified	CPD	CPD	06.08.10
Approved	AF	AF	06.08.10

Drawing Title:
ARTS
ELEVATIONS
SHEAR WALLS
CONCRETE OPTION

Project No. 210688.001
Scale 1:50 (A1) 1:100 (A3)
Sheet Size A1
Drawing No. SSK-C-005
Rev. 02

Appendix B
Architectural Review Drawings

Exposed clear finished LVL columns

Exposed clear finished LVL columns

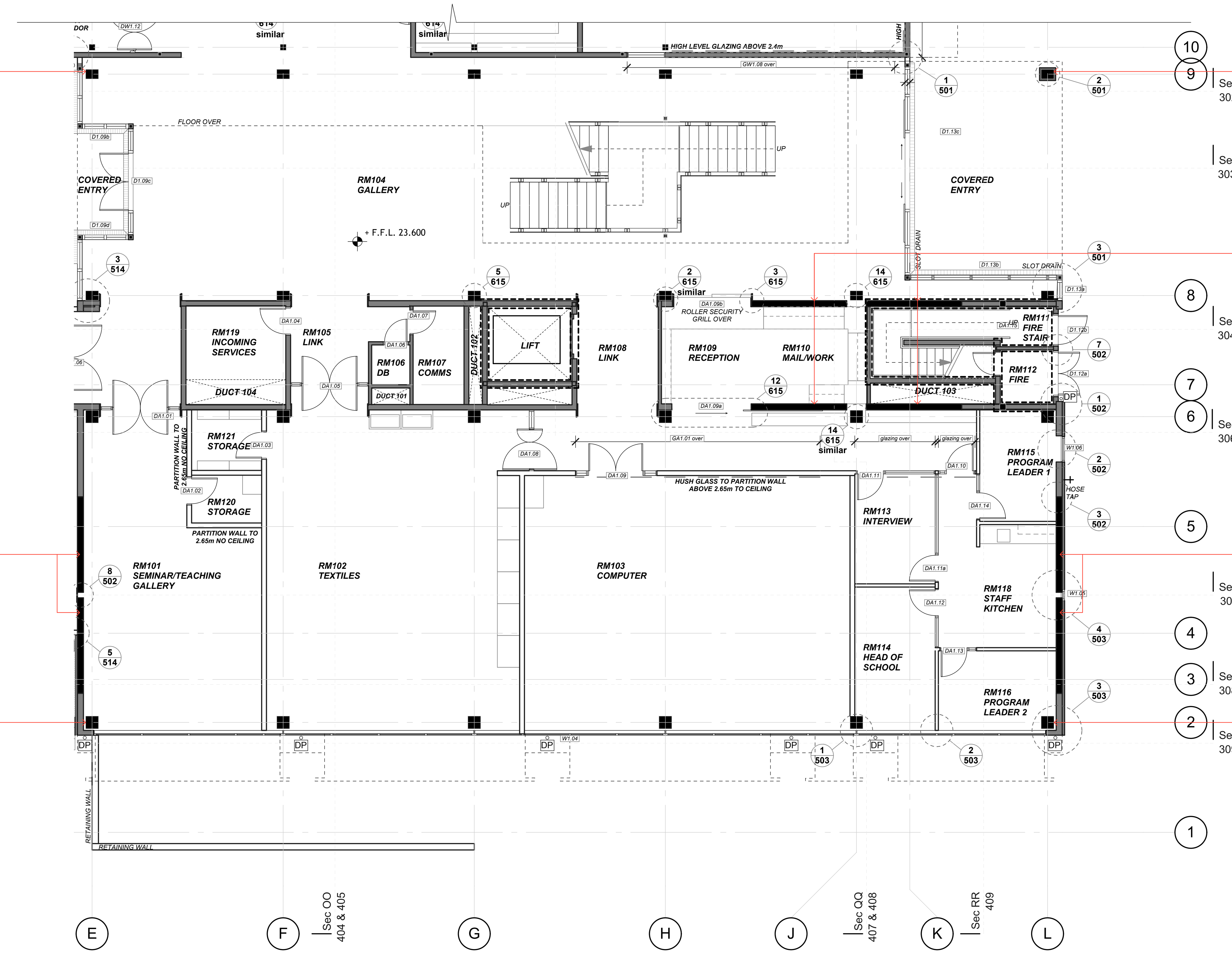
Pairs of clear finished LVL shear walls, exposed both sides

Pair of clear finished LVL shear walls with strapping and cladding to outside face

Pair of clear finished LVL shear walls with strapping and cladding to outside face

Exposed clear finished LVL columns

Exposed clear finished LVL columns



TIMBER OPTION - 06/08/10	REVISION: 0 - Report for UOC	DATE: 06-08-10	N M I T A R T S A N D M E D I A B U I L D I N G S
			N M I T C A M P U S
			L E V E L 1 - P L A N

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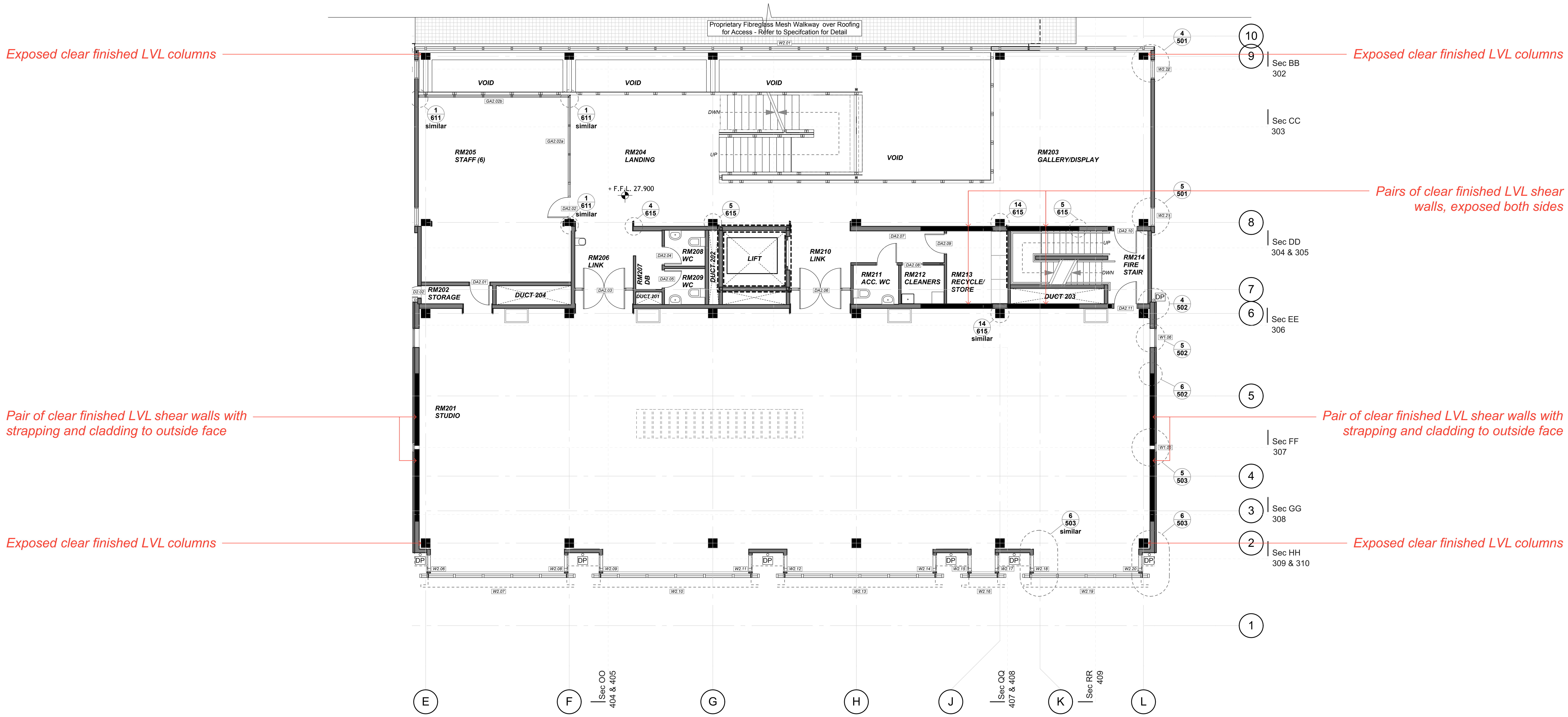
irving : smith : jack ARCHITECTS

SHEET NO. 1



TIMBER OPTION - 06/08/10

REVISION	DATE	
0 - Report for UOC	06-08-10	NMIT ARTS AND MEDIA BUILDINGS
		NMIT CAMPUS
		LEVEL 2 - PLAN

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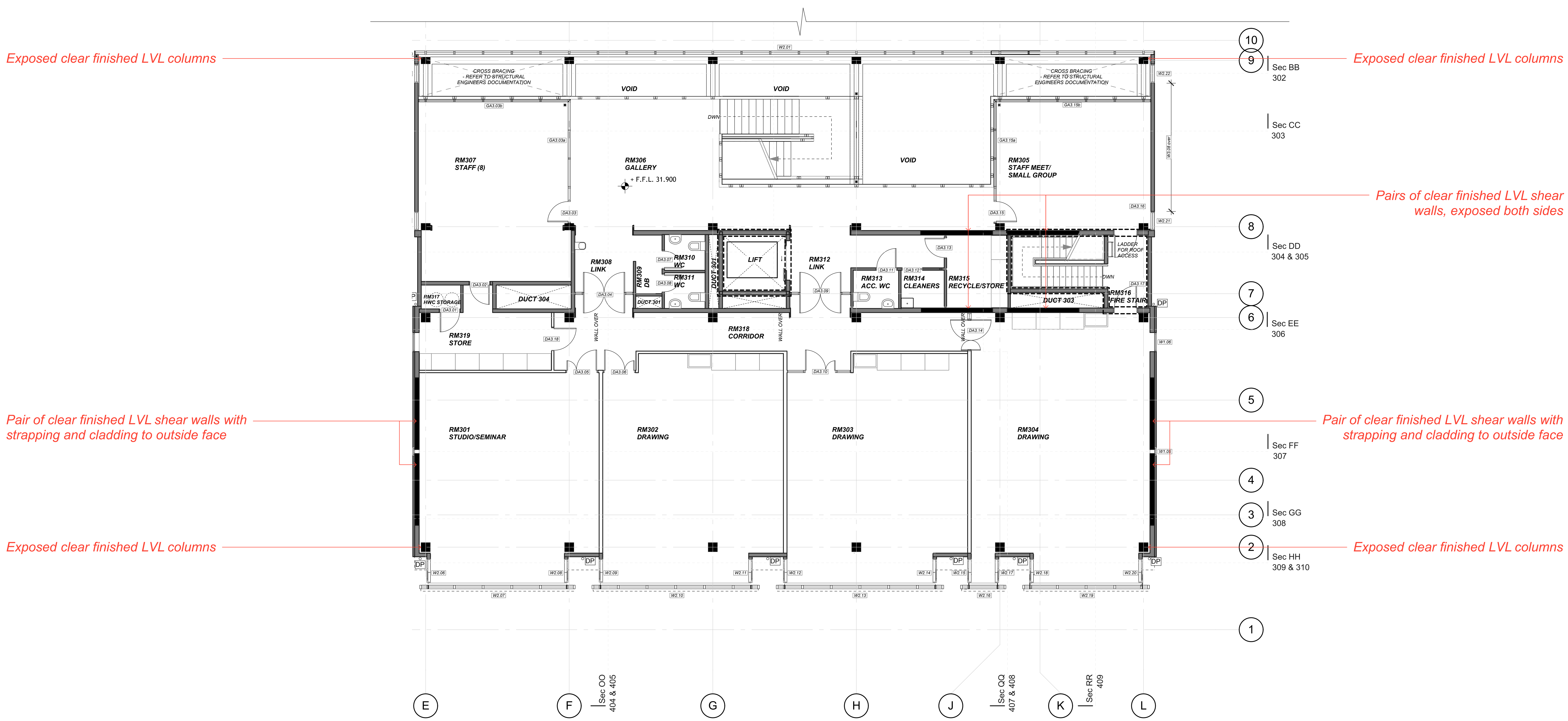
SHEET NO. 2



TIMBER OPTION - 06/08/10

REVISION	DATE	
0 - Report for UOC	06-08-10	NMIT ARTS AND MEDIA BUILDINGS
		NMIT CAMPUS
		LEVEL 3 - PLAN

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SHEET NO. 3
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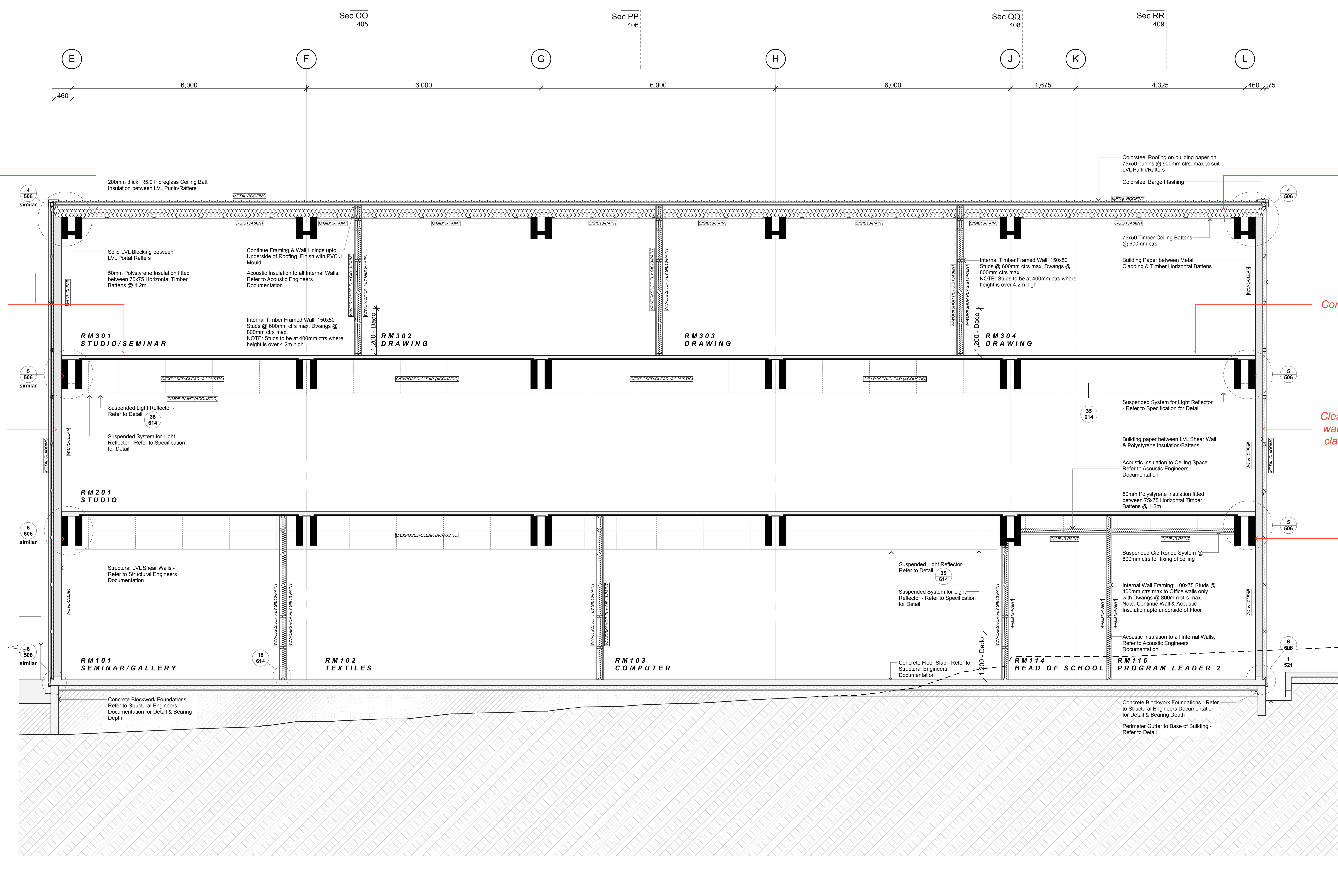

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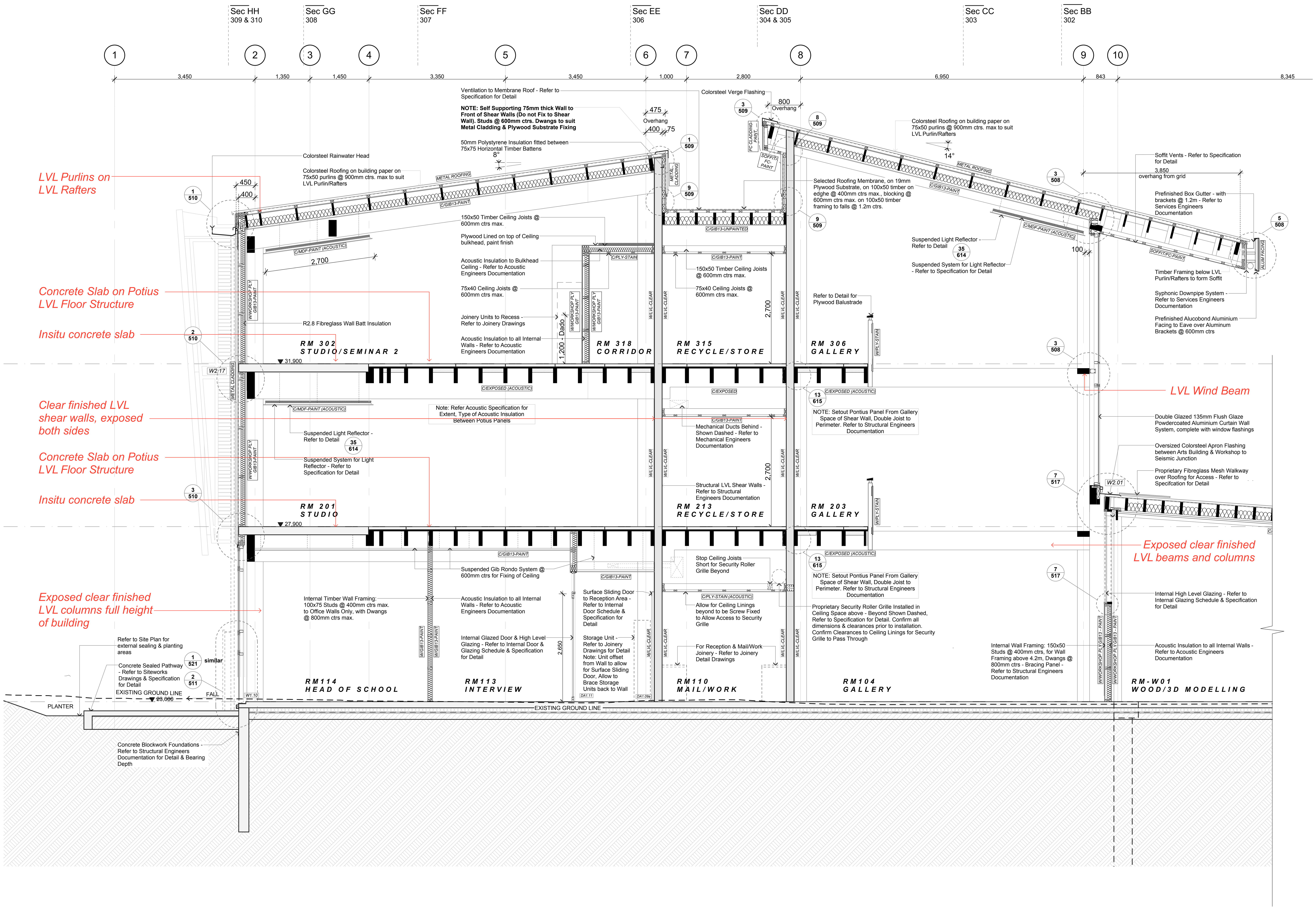
SHEET NO. 4



TIMBER OPTION - 06/08/10

REVISION	DATE
0 - Report for UOC	06-08-10

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SECTION QQ

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SHEET NO. 5

LEGEND

- Steel structure in lieu of LVL
- Additional Framed Walls
- Elements unaffected by change in steel structure

Exposed steel UC columns

Exposed steel UC columns

Exposed steel stair & balustrade

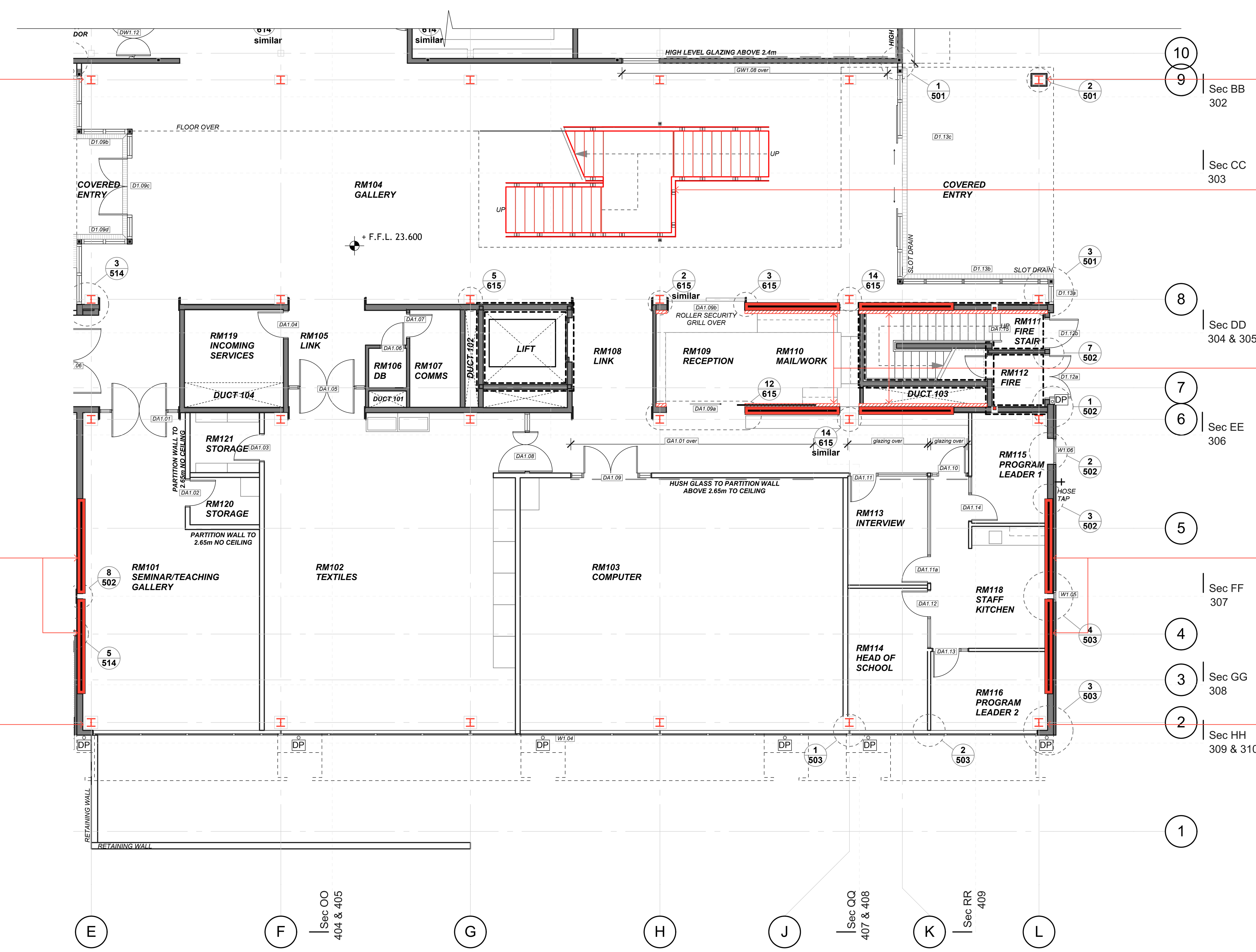
Pairs of exposed K-braced frames with lined timber framed walls to one side (hatched)

Pair of exposed K braced frames with lined and clad timber framed walls to outside face

Pair of exposed K-braced frames with lined and clad timber framed walls to outside face

Exposed steel UC columns and UB's supporting Comflor floor system

Exposed steel UC columns and UB's supporting Comflor floor system



STEEL OPTION - 06/08/10

REVISION	DATE
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NMIT CAMPUS
LEVEL 1 - PLAN

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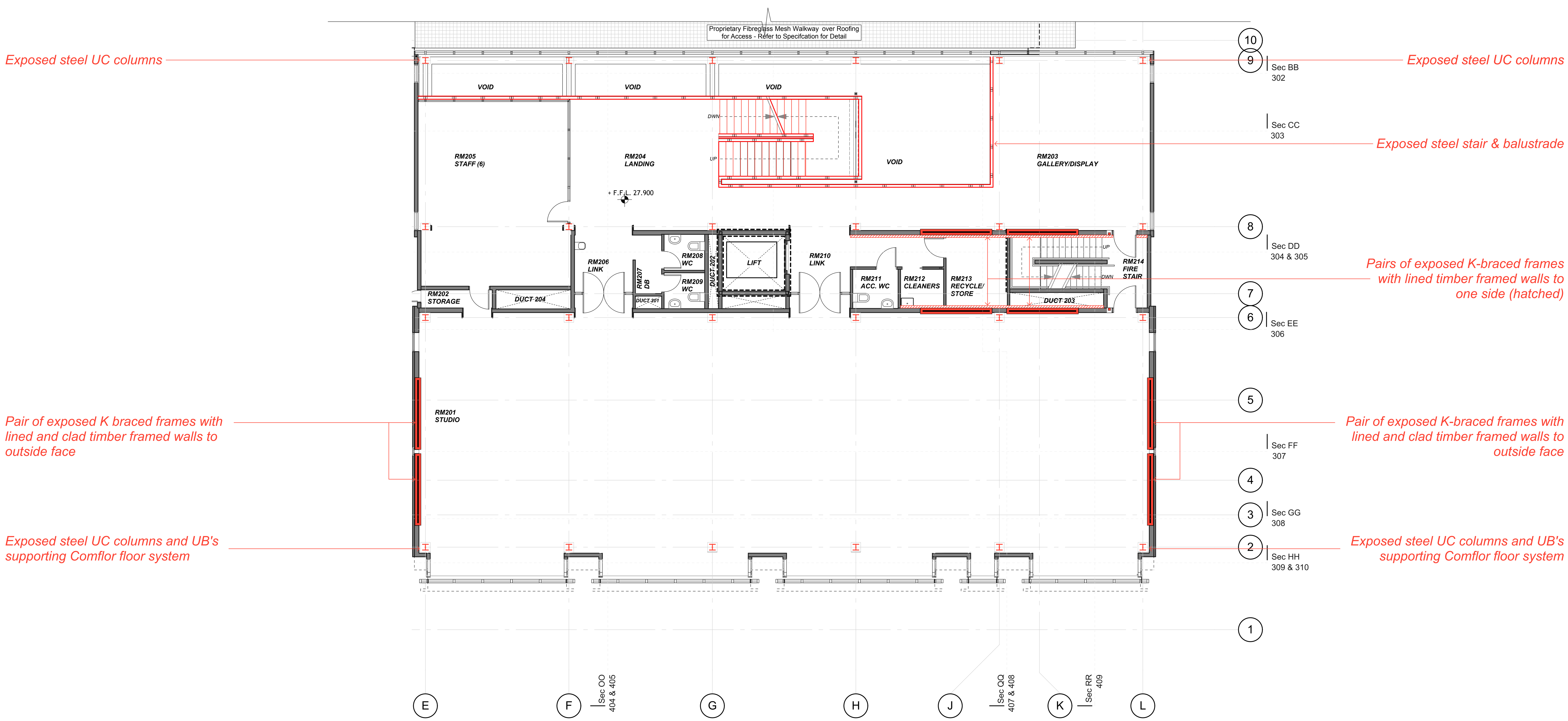
SHEET NO. 6
REVISION

LEGEND

- Steel structure in lieu of LVL
- Additional Framed Walls
- Elements unaffected by change in steel structure



STEEL OPTION - 06/08/10

REVISION	DATE
0 - Report for UOC	06-08-10

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LEVEL 2 - PLAN

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SHEET NO. 7

STEEL OPTION - 06/08/10	0 - Report for UOC	06-08-10	NMIT ARTS AND MEDIA BUILDINGS NMIT CAMPUS LEVEL 3 - PLAN	

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STEEL OPTION - 06/08/10

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NMIT ARTS AND MEDIA BUILDINGS
NMIT CAMPUS
SECTION GG

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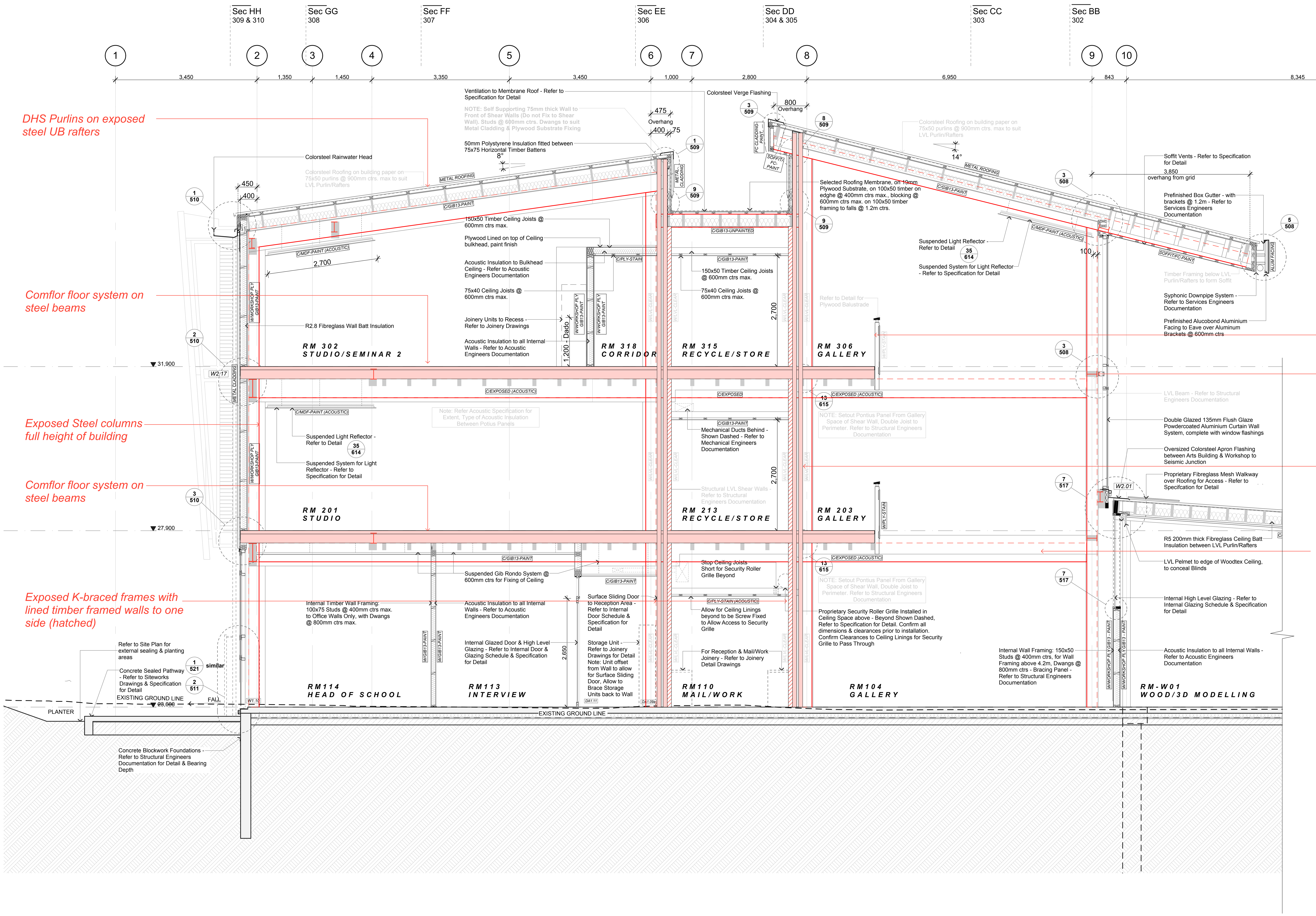
9

LEGEND

- Steel structure in lieu of LVL
- Additional Framed Walls
- Elements unaffected by change in steel structure
- Comparable LVL structure (beams)



STEEL OPTION - 06/08/10

REVISION	DATE
0 - Report for UOC	06-08-10

NMIT ARTS AND MEDIA BUILDINGS
NMIT CAMPUS
SECTION QQ

DRAWN
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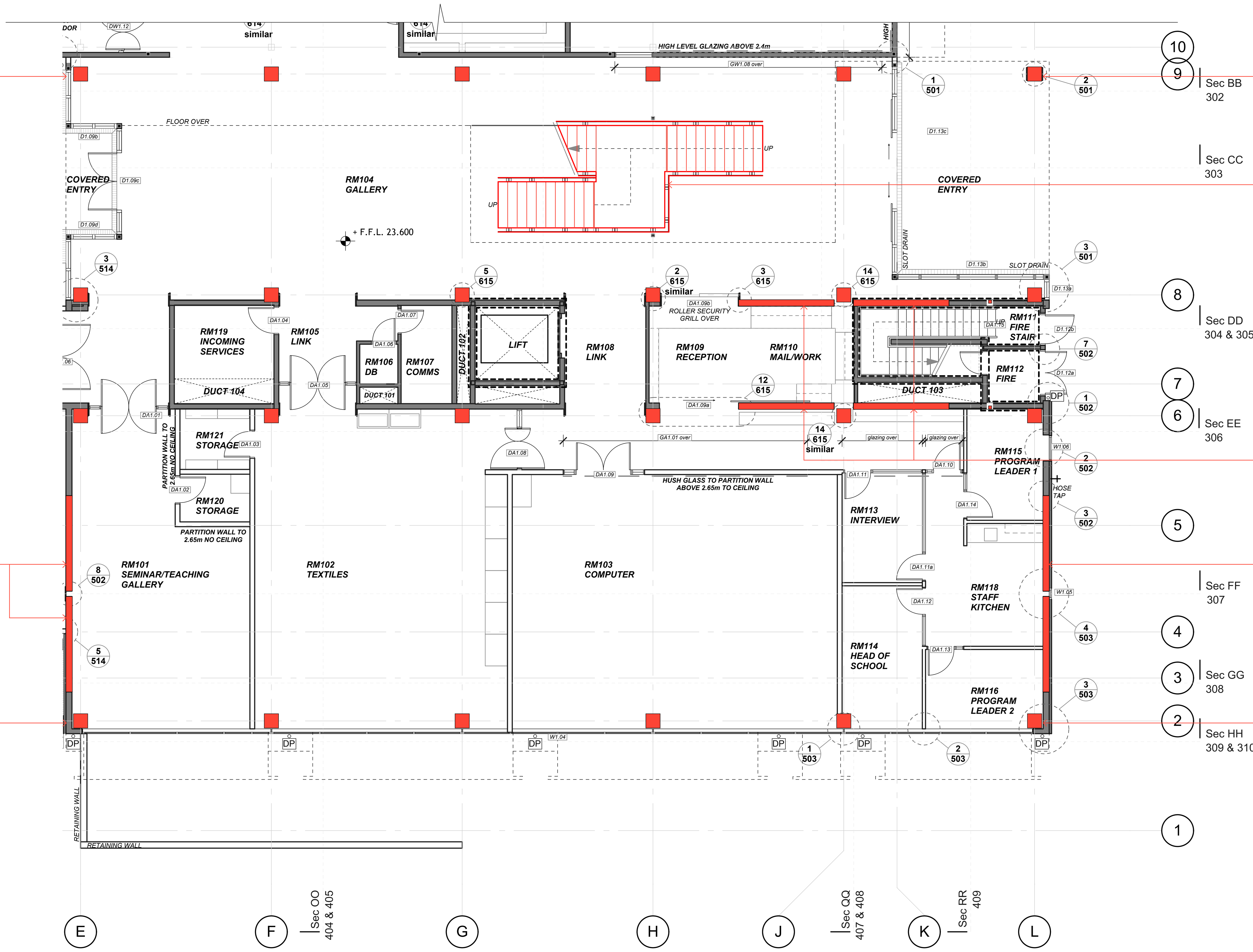
SHEET NO. 10
REVISION

LEGEND

Conc. structure in lieu of LVL

Elements unaffected by change in concrete structure



CONCRETE OPTION - 06/08/10

REVISION	DATE
0 - Report for UOC	06-08-10

NMIT ARTS AND MEDIA BUILDINGS
NMIT CAMPUS
LEVEL 1 - PLAN

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SHEET NO. 11

LEGEND

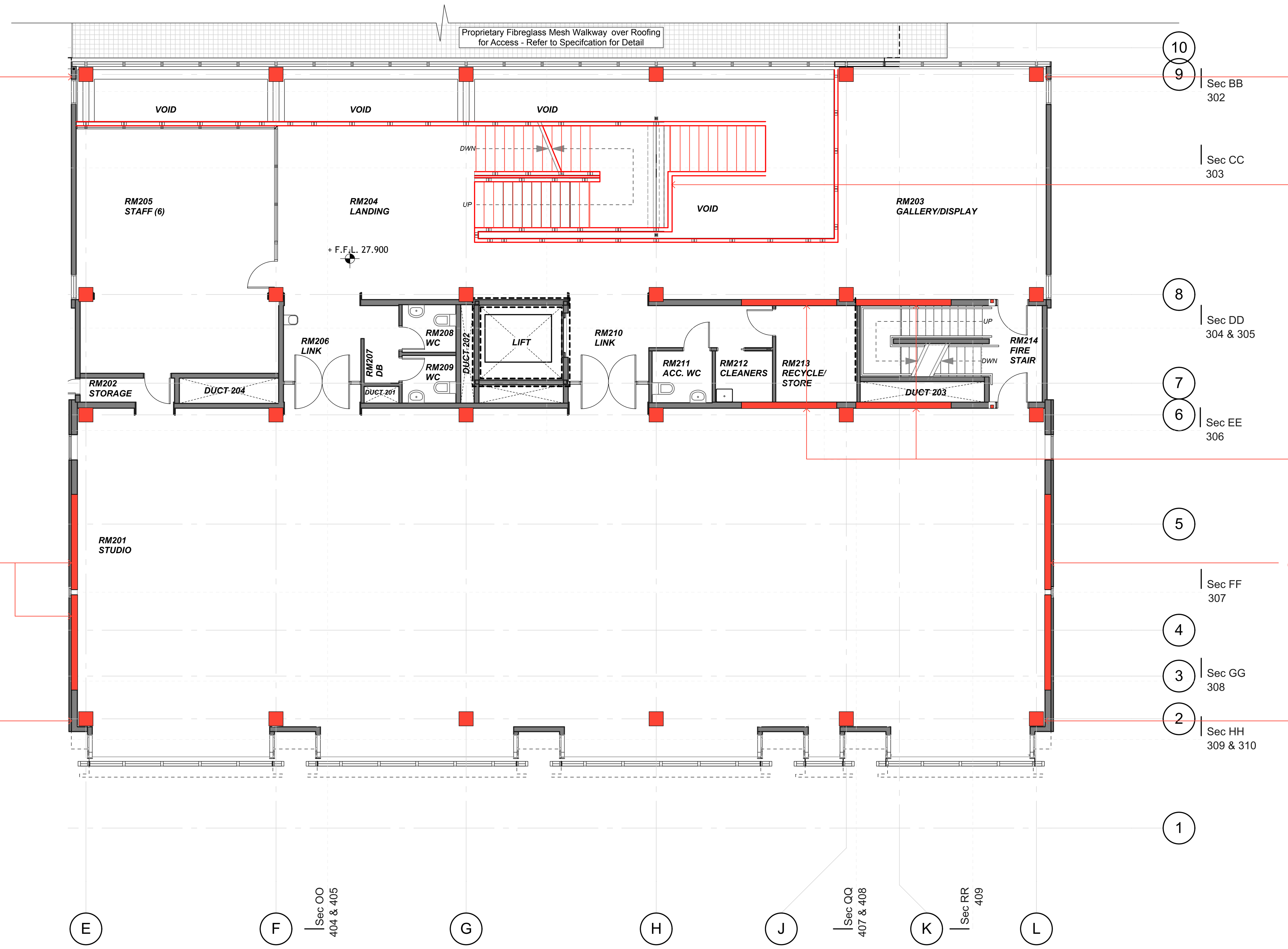
Conc. structure in lieu of LVL

Elements unaffected by change in concrete structure

Exposed clear finished precast concrete columns

Pair of exposed clear finished precast concrete shear walls with strapping and cladding to outside face

Exposed clear finished precast concrete columns



Exposed clear finished precast concrete columns

Exposed Concrete stairs

Pairs of clear finished precast concrete shear walls, exposed both sides

Pair of exposed clear finished precast concrete shear walls with strapping and cladding to outside face

Exposed clear finished precast concrete columns

CONCRETE OPTION - 06/08/10

REVISION	DATE	
0 - Report for UOC	06-08-10	NMIT ARTS AND MEDIA BUILDINGS
		NMIT CAMPUS
		LEVEL 2 - PLAN

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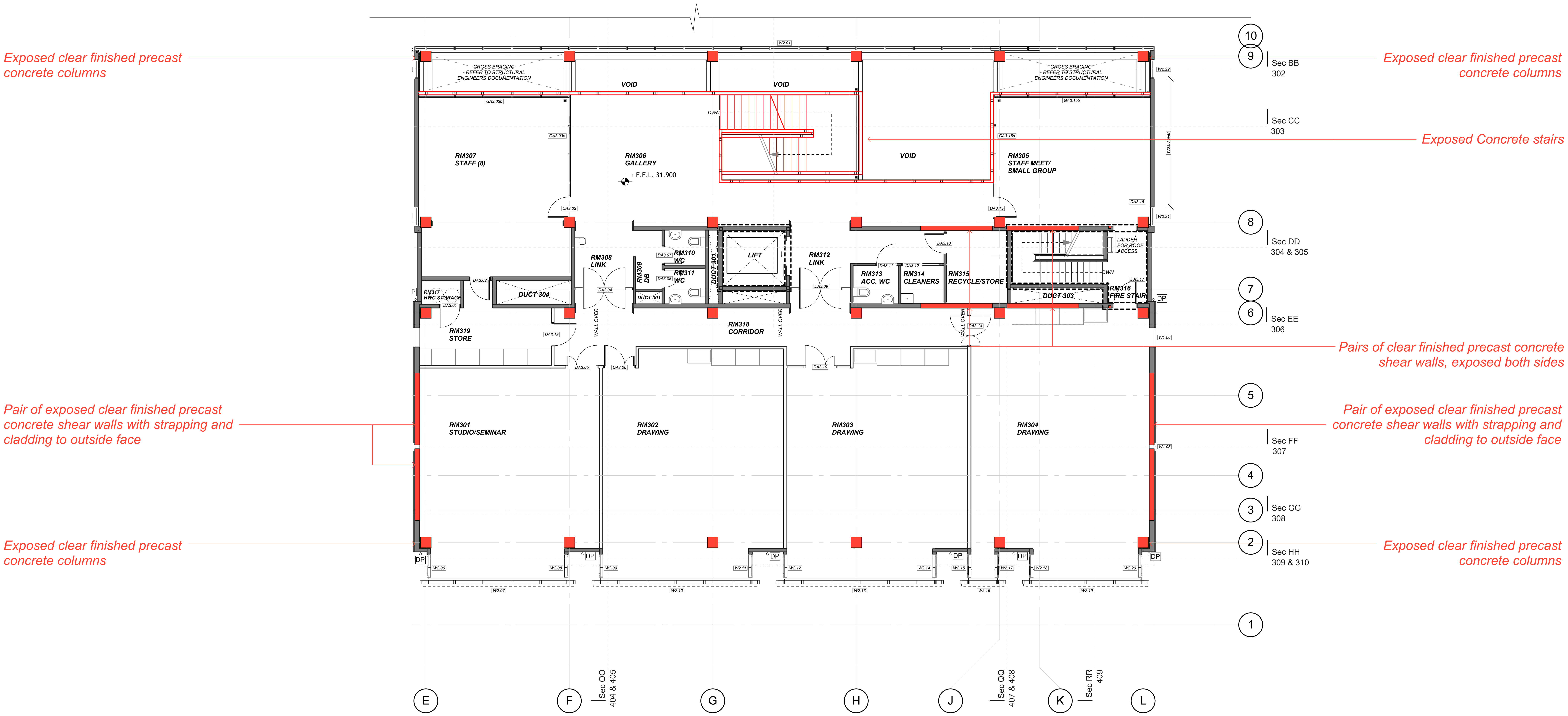
SHEET NO. 12

REVISION

LEGEND

Conc. structure in lieu of LVL

Elements unaffected by change in concrete structure



CONCRETE OPTION - 06/08/10

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		NMIT CAMPUS	DATE
		LEVEL 3 - PLAN	JOB NO.

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NMIT ARTS AND MEDIA BUILDINGS
NMIT CAMPUS
SECTION GG

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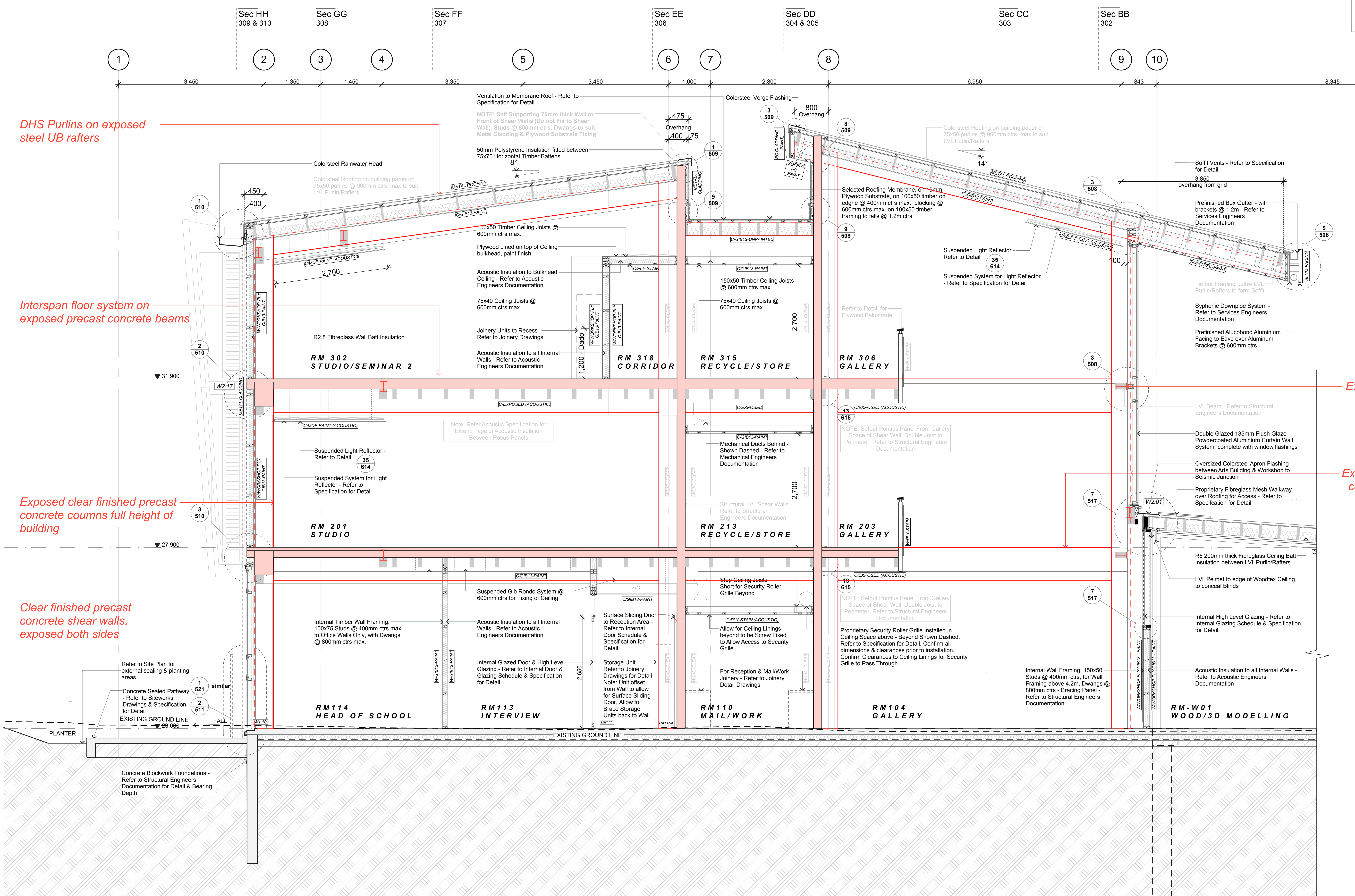
SHEET NO. 14



LEGEND

- Conc. structure in lieu of LVL
- Elements unaffected by change in concrete structure
- Comparable LVL structure (beams)

CONCRETE OPTION - 06/08/10

REVISION	DATE
0 - Report for UOC	06-08-10

NMIT ARTS AND MEDIA BUILDINGS
NMIT CAMPUS
SECTION QQ

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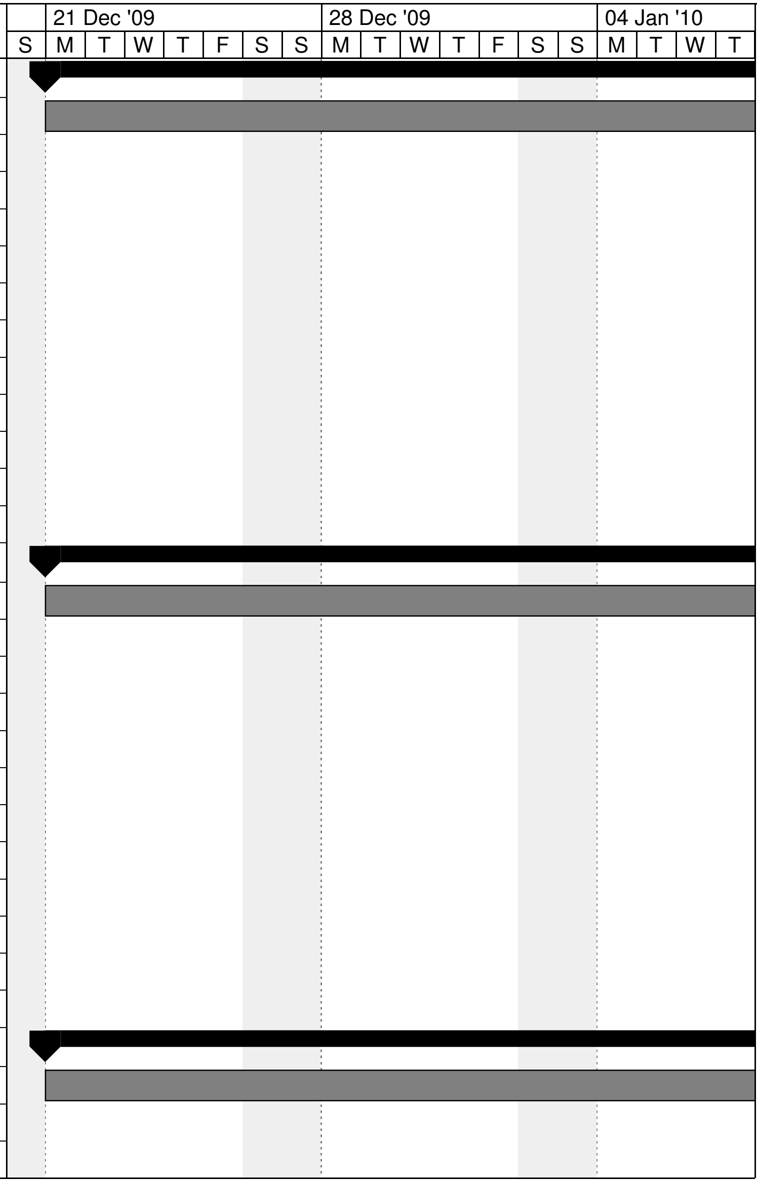
APPENDIX B

Gantt Charts – Building Schedules

by
Arrow International

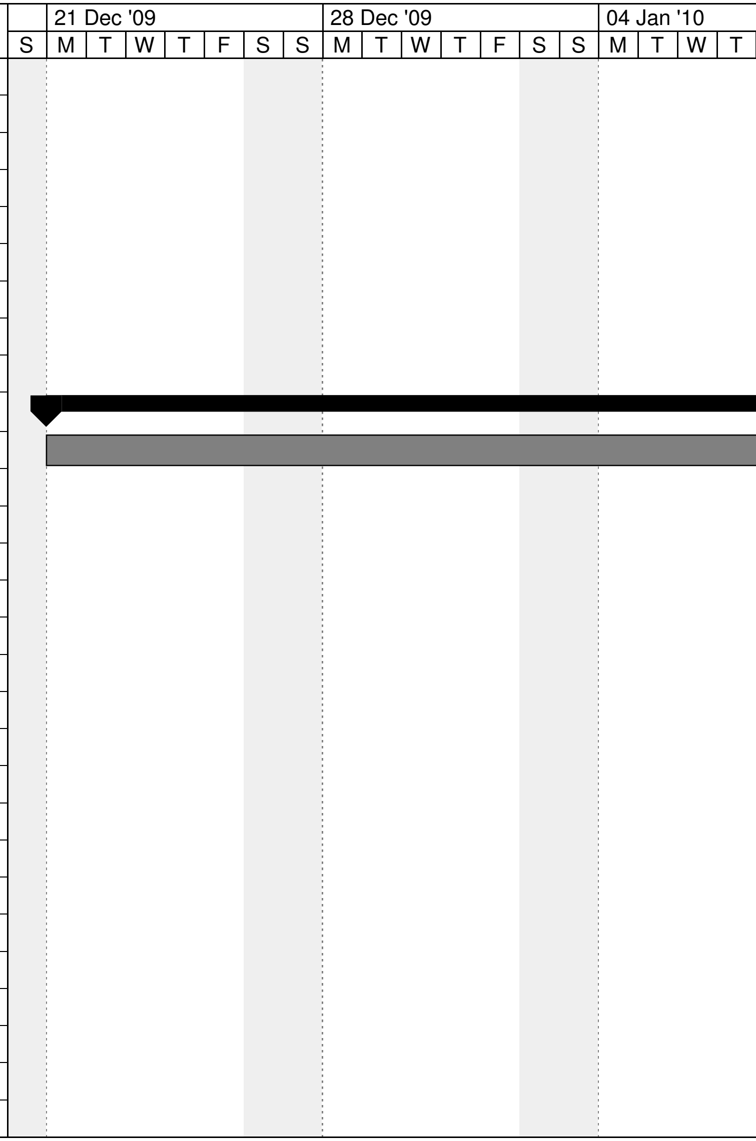
ID		Task Name	Duration	Start	Finish
1		**Original LVL Programme**	**100 days**	**Mon 21/12/09**	**Fri 07/05/10**
2		Shop Drawings	33 days	Mon 21/12/09	Wed 03/02/10
3		Approval of Shop Drawings	10 days	Thu 04/02/10	Wed 17/02/10
4		Manufacture of LVL components for Teaching	30 days	Thu 18/02/10	Wed 31/03/10
5		Manufacture of Potius Floor for Teaching	30 days	Thu 18/02/10	Wed 31/03/10
6		Delivery of LVL for Teaching	3 days	Thu 25/03/10	Mon 29/03/10
7		Delivery of Potius for Teaching	3 days	Thu 01/04/10	Mon 05/04/10
8		Erect LVL to Teaching	17 days	Thu 01/04/10	Fri 23/04/10
9		Erect Shearwalls to Teaching	10 days	Thu 01/04/10	Wed 14/04/10
10		Erect Potius Flooring to Teaching L1	3 days	Mon 26/04/10	Wed 28/04/10
11		Erect Potius Flooring to Teaching L2	3 days	Thu 29/04/10	Mon 03/05/10
12		Install Rafters and Purlins to Teaching	10 days	Mon 26/04/10	Fri 07/05/10
13					
14		**Actual LVL Programme**	**123 days**	**Mon 21/12/09**	**Wed 09/06/10**
15		Shop Drawings	55 days	Mon 21/12/09	Fri 05/03/10
16		Approval of Shop drawings	10 days	Mon 08/03/10	Fri 19/03/10
17		Manufacture of LVL components for Teaching	47 days	Mon 22/03/10	Tue 25/05/10
18		Manufacture of Potius floor for Teaching	21 days	Mon 19/04/10	Mon 17/05/10
19		Delivery of LVL for Teaching	26 days	Mon 19/04/10	Mon 24/05/10
20		Delivery of Potius for Teaching	28 days	Wed 21/04/10	Fri 28/05/10
21		Erect LVL to Teaching	25 days	Thu 22/04/10	Wed 26/05/10
22		Erect Shearwalls to Teaching	10 days	Tue 20/04/10	Mon 03/05/10
23		Erect Potius Flooring to Teaching L1	10 days	Tue 11/05/10	Mon 24/05/10
24		Erect Potius Flooring to Teaching L2	10 days	Tue 11/05/10	Mon 24/05/10
25		Install Rafters and Purlins to Teaching	10 days	Thu 27/05/10	Wed 09/06/10
26					
27		**Structural Steel Erection Programme**	**99 days**	**Mon 21/12/09**	**Thu 06/05/10**
28		Shop Drawing	33 days	Mon 21/12/09	Wed 03/02/10
29		Approval Of Shop Drawings	10 days	Thu 04/02/10	Wed 17/02/10
30		Fabricate Structural Steel Members for Teaching	26 days	Thu 18/02/10	Thu 25/03/10



Project: LVL Programmes
Date: Mon 11/07/11

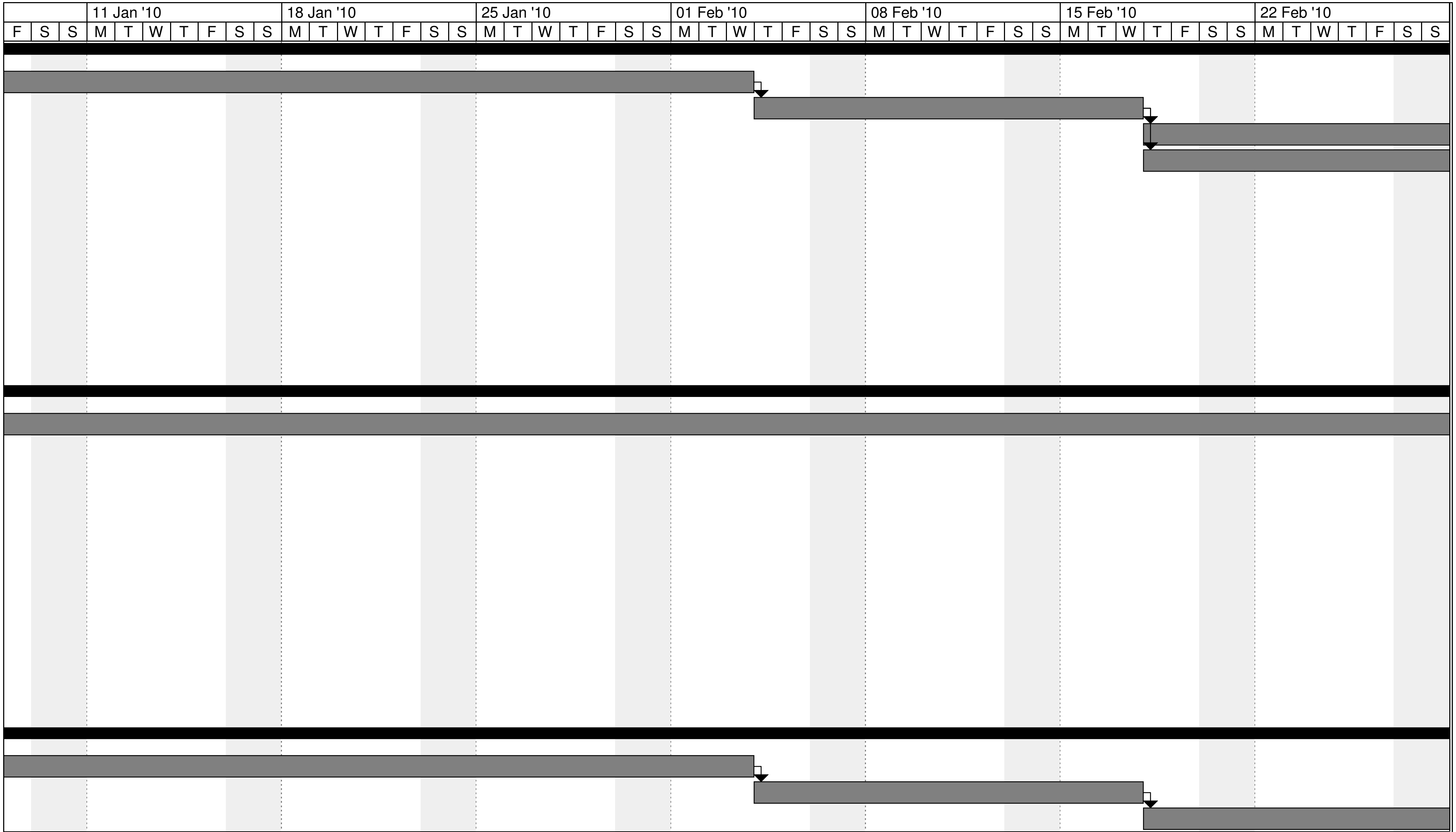
Task		Milestone		External Tasks	
Split		Summary		External Milestone	
Progress		Project Summary		Deadline	

ID		Task Name	Duration	Start	Finish
31		Deliver and erect steel to Teaching	20 days	Fri 26/03/10	Thu 22/04/10
32		Install Traydek to Teaching L1	3 days	Wed 07/04/10	Fri 09/04/10
33		Resteel, form and pour slab Teaching L1	4 days	Mon 12/04/10	Thu 15/04/10
34		Install Traydek To Teaching L2	3 days	Wed 21/04/10	Fri 23/04/10
35		Resteel, form and pour slab Teaching L2	4 days	Mon 26/04/10	Thu 29/04/10
36		Propping to Traydek L1	2 days	Mon 05/04/10	Tue 06/04/10
37		Propping to Traydek L2	2 days	Mon 19/04/10	Tue 20/04/10
38		Metal Purlins to Teaching	10 days	Fri 23/04/10	Thu 06/05/10
39					
40		**Precast Concrete Programme**	**117 days**	**Mon 21/12/09**	**Tue 01/06/10**
41		Shop drawings for Precast panels, columns & beams	33 days	Mon 21/12/09	Wed 03/02/10
42		Approval of Shop Drawings	10 days	Thu 04/02/10	Wed 17/02/10
43		Manufacture of Precast panels, columns & beams	45 days	Thu 18/02/10	Wed 21/04/10
44		Delivery and erect precast panels Grd-L1-2	4 days	Wed 31/03/10	Mon 05/04/10
45		Delivery and erect Precast Columns	4 days	Tue 06/04/10	Fri 09/04/10
46		Delivery and erect precast beams L1	4 days	Mon 12/04/10	Thu 15/04/10
47		Propping for Stalton ribs	3 days	Thu 15/04/10	Mon 19/04/10
48		Stalton ribs to L1	3 days	Mon 19/04/10	Wed 21/04/10
49		Install timber infills to L1	4 days	Tue 20/04/10	Fri 23/04/10
50		Form edges & Resteel to L1 floorslab	3 days	Mon 26/04/10	Wed 28/04/10
51		Pour floorslab L1	1 day	Thu 29/04/10	Thu 29/04/10
52		Delivery and erect precast panels L1-2 to roof	3 days	Fri 30/04/10	Tue 04/05/10
53		Delivery and erect precast beams to L2	3 days	Wed 05/05/10	Fri 07/05/10
54		Propping for Stalton ribs	3 days	Fri 07/05/10	Tue 11/05/10
55		Stalton ribs to L2	3 days	Tue 11/05/10	Thu 13/05/10
56		Install timber infills to L2	4 days	Wed 12/05/10	Mon 17/05/10
57		Form edges & Resteel to floorslab L2	3 days	Tue 18/05/10	Thu 20/05/10
58		Pour floorslab L2	1 day	Fri 21/05/10	Fri 21/05/10
59		Install rafters and purlins to Teaching	7 days	Mon 24/05/10	Tue 01/06/10



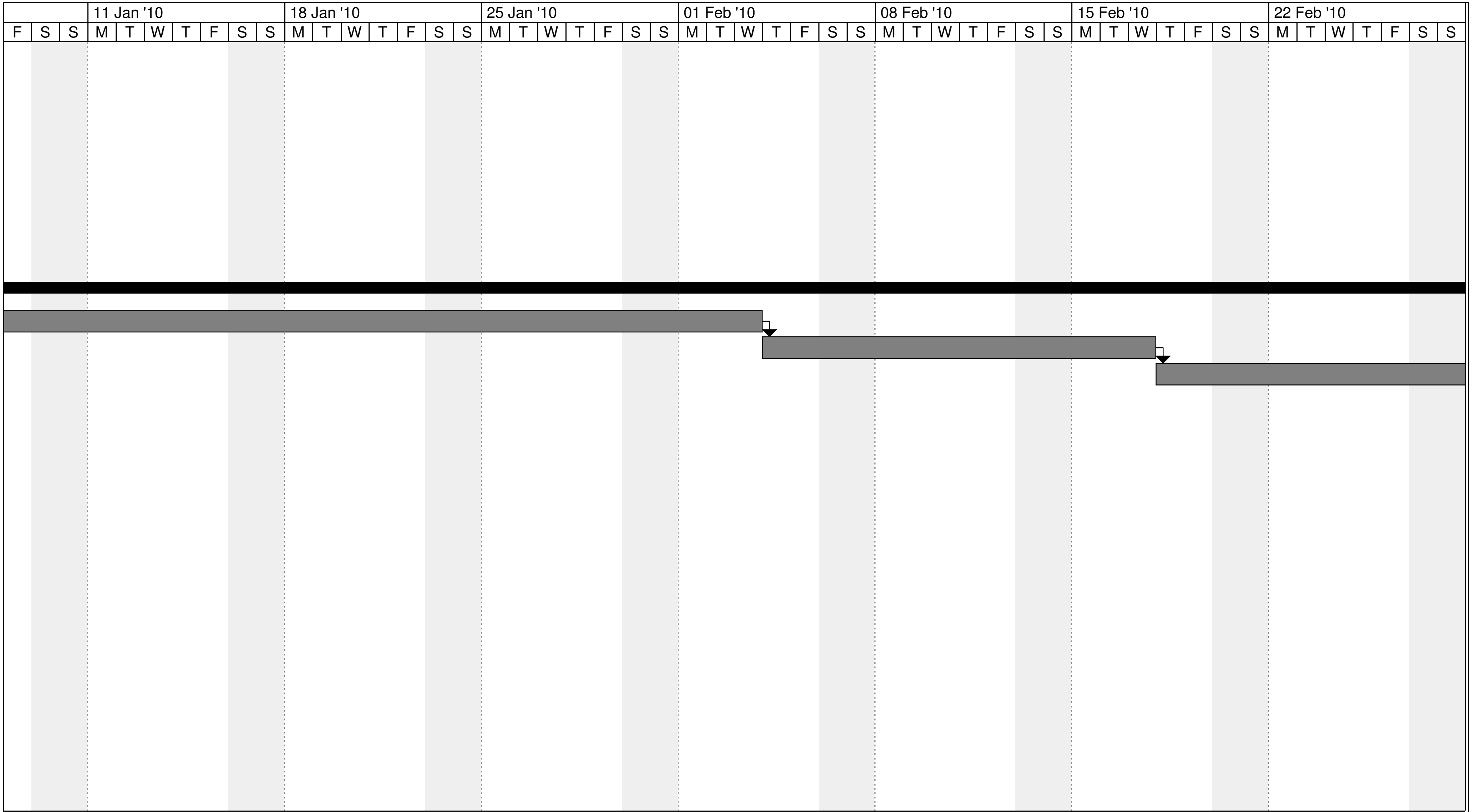
Project: LVL Programmes
Date: Mon 11/07/11

Task		Milestone		External Tasks	
Split		Summary		External Milestone	
Progress		Project Summary		Deadline	



Project: LVL Programmes
Date: Mon 11/07/11

Task	Milestone	External Tasks
Split	Summary	External Milestone
Progress	Project Summary	Deadline



Project: LVL Programmes
Date: Mon 11/07/11

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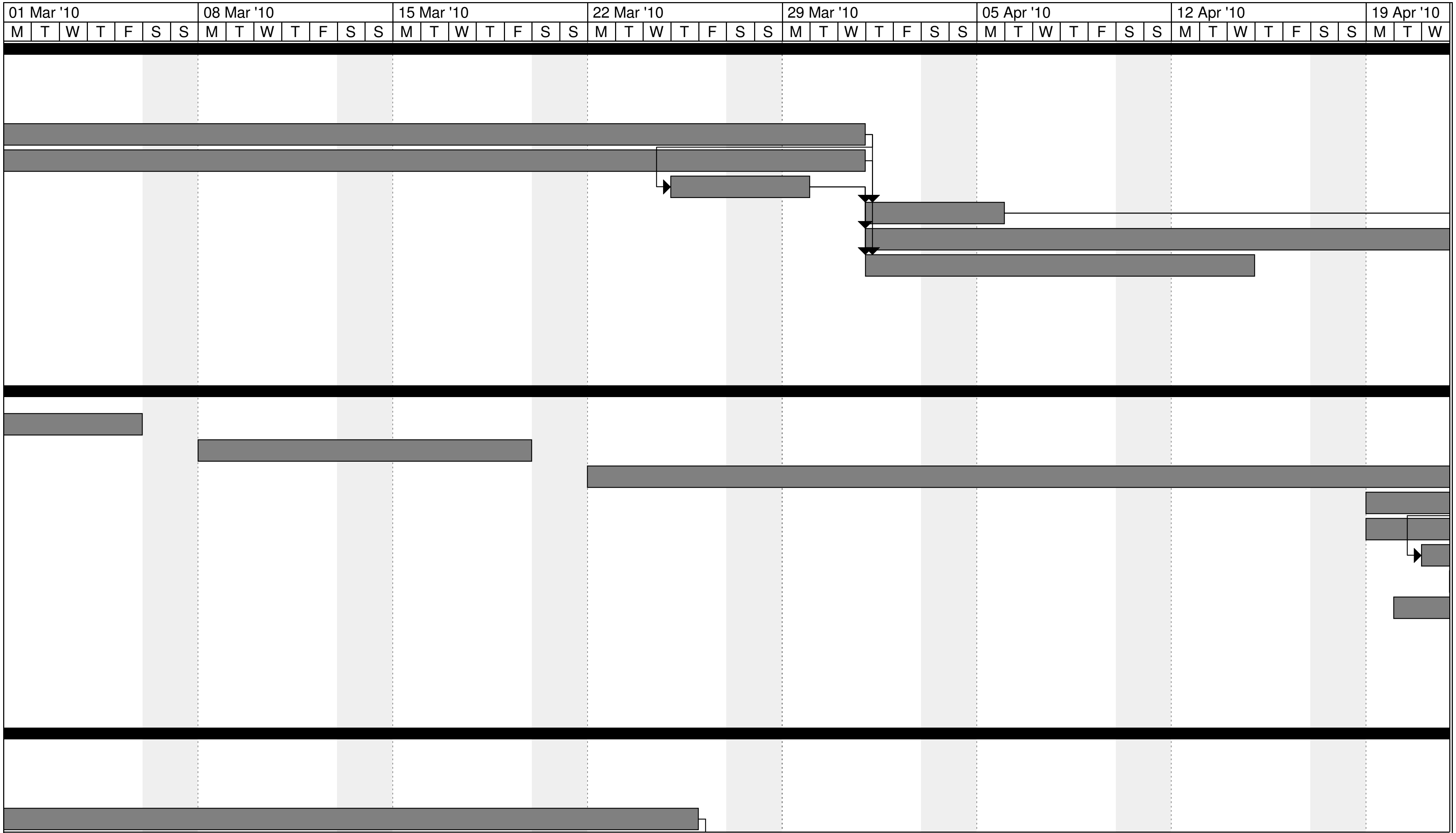
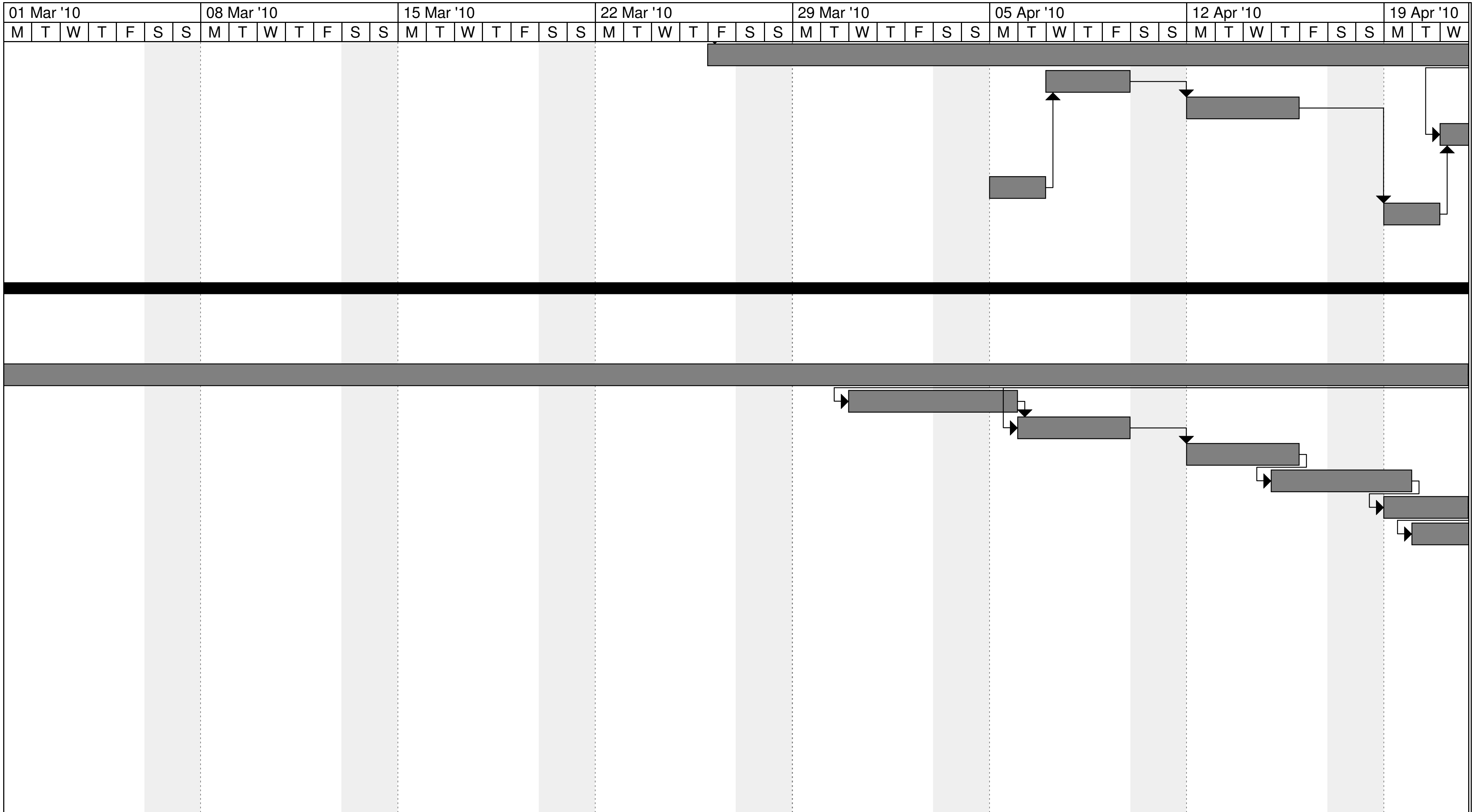
Split		Summary		External Milestone	
Progress		Project Summary		Deadline	



Project: LVL Programmes
Date: Mon 11/07/11

Task	Milestone	External Tasks
Split	Summary	External Milestone
Progress	Project Summary	Deadline



Project: LVL Programmes
Date: Mon 11/07/11

Task
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Progress
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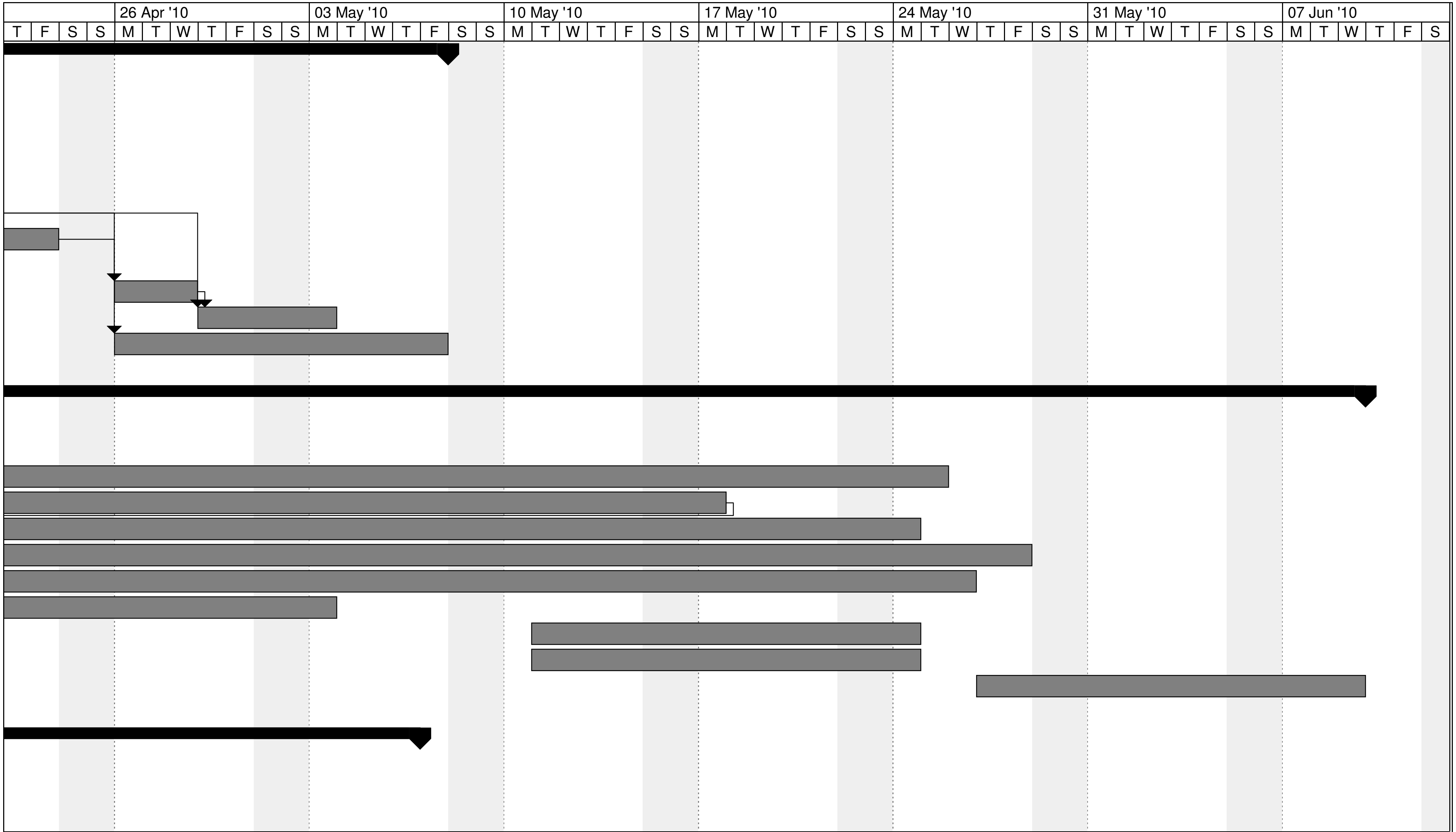
Summary
Project Summary
External Tasks
External Milestone
Deadline



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Date: Mon 11/07/11

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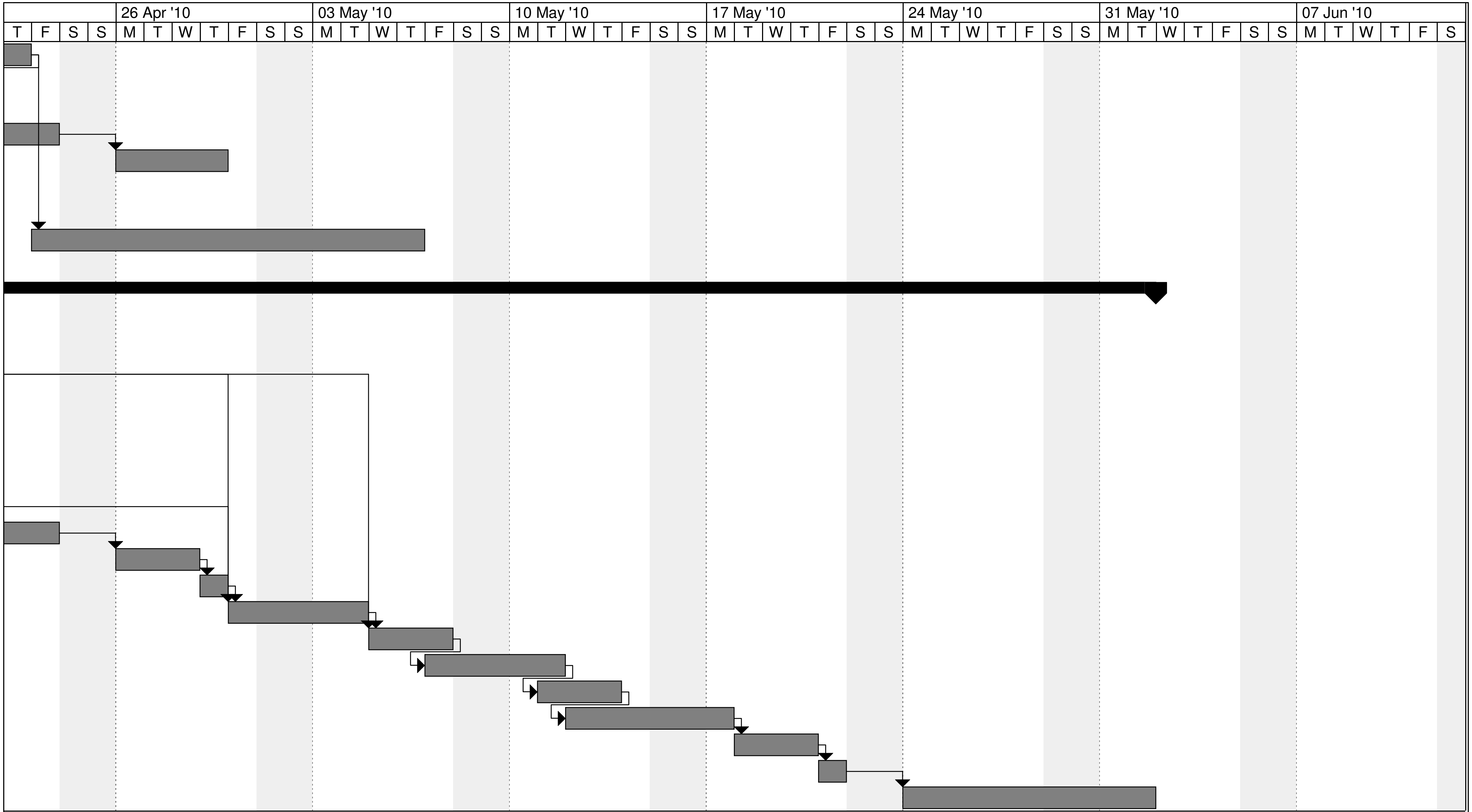
Split		Summary		External Milestone	
Progress		Project Summary		Deadline	



Project: LVL Programmes
Date: Mon 11/07/11

Task
Split
Progress
Milestone
Summary
Project Summary
External Tasks
External Milestone
Deadline

APPENDIX C

NMIT Arts and Media building - An assessment of life cycle costs for alternative designs

by
BRANZ

E568

Nelson-Marlborough Institute of Technology Arts Building - An assessment of life cycle costs for alternative designs.

Author: Ian Page
Manager Economics

Reviewer: Joe Fung
Economist

Contact: BRANZ Limited
Moonshine Road
Judgeford
Private Bag 50908
Porirua City
New Zealand
Tel: +64 4 237 1170
Fax: +64 4 237 1171
www.branz.co.nz

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 iii. any defects in the Products the subject of the Services; or

 iv. any changes, modifications or alterations to the Products the subject of the Services.

Contents

Nelson-Marlborough Institute of Technology Arts Building - An assessment of life cycle costs for alternative designs.

1. CLIENT

University of Canterbury
Private Bag 4800
Christchurch Mail Centre
Christchurch 8140
New Zealand

2. INTRODUCTION

This report examines the life cycle costs of four alternative designs for a new Arts building erected at the Nelson-Marlborough Institute of Technology (NMIT). Three of the designs differ in the main structural materials used, namely timber, concrete and steel and a low energy timber design is also included. The basic floor plan and exterior of the four buildings are the same, so each design provides the same level of amenity. The aim of this analysis is to determine if any particular design has a significant cost advantage over the other materials.

3. SUMMARY

The results are summarise in Table 1 showing the life cycle costs for the four alternative designs. The results are dominated by the initial cost, and the on-going costs of the four alternatives is similar. Concrete has the overall lowest life time cost followed by steel then timber and the low energy timber design. The spread between the first three is less than 3.5%. However the low energy timber design (Timber low-e) is 5.5% more expensive than the concrete design mainly because the PVC frames it uses are not cost effective compared to the reduced thermal bridging energy savings.

Table 1 Cost summary

Life cycle costs for four designs NMIT Arts Building				
	Timber	Concrete	Steel	Timber low-e
Initial cost $	5,352,041	5,140,382	5,325,024	5,489,461
Energy costs - $ present value	490,997	494,973	500,292	432,141
Other costs - $ present value	612,409	616,575	611,951	675,118
	6,455,447	6,251,930	6,437,268	6,596,720
Other costs includes maintenance, replacements and operation costs				
Analysis over a period of 60	years and discount rate	5%		

A 100 year analysis period gives similar results to Table 1 because after 60 years future costs are heavily discounted and the design rankings are unchanged. The results for the 100 year analysis period are in the appendix.

4. METHOD

4.1 Financial analysis method and assumptions

A present value method was used because it enables consistent comparisons to be made between the different cost streams over time. (Lu 1969).

Present value PV = Initial cost $+ \sum H/(1+r)^h + C_1/(1+r) + C_2/(1+r)^2 + C_3/(1+r)^3 + \ldots + C_n/(1+r)^n$
Where:
H is the cost of maintenance or replacements at year h
C_1, C_2, C_3, … + C_N are annual energy costs in year 1, 2, 3 ….N.
r= discount rate.
N = period of analysis, years.

The base case parameters were:
60 years analysis period.
5% discount rate.

Energy prices were assumed to escalate at 1.6% pa above the general inflation rate. (Ministry of Economic Development, 2009). Energy costs include electricity volume kWh, daily peak kVA and line charges, plus diesel costs. These were obtained from Trustpower Ltd, Tauranga and the rates are applicable to the Nelson area. Operation costs such as cleaning and services routine maintenance charges were obtained from the NZ Property Council (2009).

4.2 Energy modelling

Energy modelling results were provided by the Civil and Natural Resources Engineering Department at the University of Canterbury[1]. The modelling included boiler consumption (diesel fired) separately from electric plant and machinery consumption. Peak loads at hour intervals for the year were also provided enabling peak electricity charges to be estimated.

5. MAIN RESULTS

5.1 Initial costs, maintenance and replacements

Details of initial costs and the maintenance / replacement regimes are included in the appendix. The results are summarised in Table 2.

[1] Personal communication Nicolas Perez.

Table 2 Detailed cost summary

Life cycle costs for four designs NMIT Arts Building Discount rate 5%, Analysis period 60 years					
		Timber	**Concrete**	**Steel**	**Timber low-e**
Initial cost $		5,352,041	5,140,382	5,325,024	5,489,461
Energy costs					
Electricity use	MWh/yr	38.26	38.29	38.32	38.48
Total daily peaks	kVA/yr	6129	6350	6175	6194
Diesel use	MWh/yr	93.74	94.81	96.42	75.84
Energy cost per year	$/yr	19,078	19,233	19,439	16,791
Total Energy cost	$PV	490,997	494,973	500,292	432,141
Major maintenance /replace					
Exterior walls	PV $	13,758	13,758	13,758	13,758
Windows	PV $	82,394	82,394	82,394	145,103
Roof	PV $	26,954	26,954	26,954	26,954
Interior walls	PV $	50,940	54,212	46,160	50,940
Ceiling	PV $	30,955	28,318	24,445	30,955
Frame	PV $	-	3,531	10,832	-
		205,000	209,167	204,543	267,709
Other costs (common to all designs)					
Other replacements	$PV	125,184	125,184	125,184	125,184
Cleaning,services maint	$PV	282,224	282,224	282,224	282,224
Total Present Value $		6,455,447	6,251,930	6,437,268	6,596,720
% difference from minimum		3.3%		3.0%	5.5%
Discount rate =		5%		PV = present value.	
Analysis period =		60	yrs		
Electricity price	per kWh	16.84	cents/kWh		
	per kVA	4.3	cents/peak kVA per day		
Diesel price	per kWh	13	cents/kWh		
Fixed line charge		51	cents per day		
Energy price escalation rate		1.6%	per annum		
Rates, insurance not included.					

5.2 Energy use

Energy use and peak energy for the four designs are shown in Figure 1 to Figure 3. Electrical energy use is almost the same for all three designs, but diesel consumption (for the space heating boiler), differs somewhat between the materials. Electricity for non-residential buildings is charged by overall volume and also the daily peak demand, so the latter was also modelled, as shown in Figure 3. The energy use volumes and peak charges are included in Table 2.

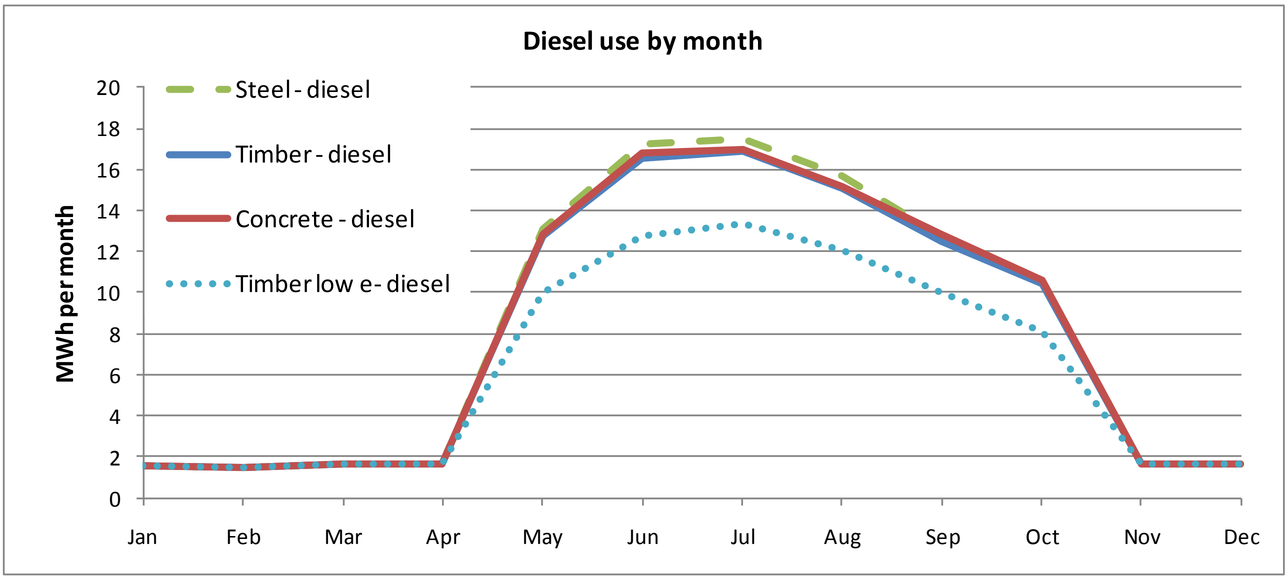

Figure 1 Diesel energy use for the four designs

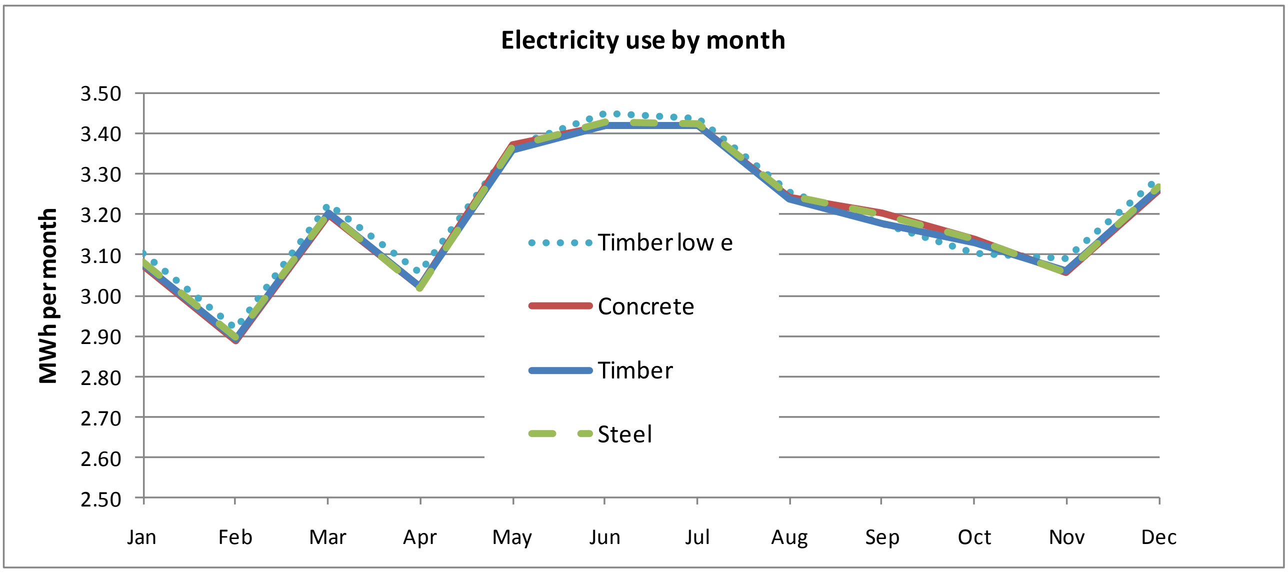

Figure 2 Electricity energy use for the four designs

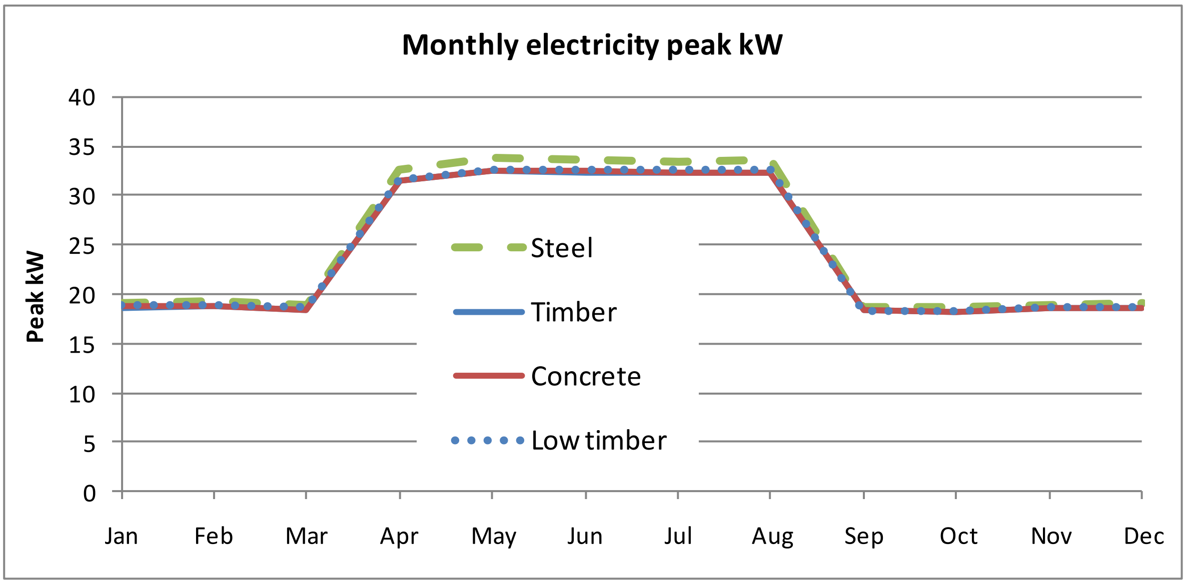

Figure 3 Peak electricity use for the four designs

5.3 Life time costs

The results of adding up initial, energy and maintenance, and other operational costs are in Table 2 above. Future costs have been discounted back to the present, and the discount rate and analysis period are at the bottom.

5.4 Sensitivity to assumptions

The financial factors were changed to assess whether the ranking of the design would change. The results are in Figure 4 and indicate that with higher discount rate the future costs are heavily discounted and the present value numbers are reduced. However the relative rankings are unchanged with concrete being the lowest in life time costs.

A similar results occurs with changes in the analysis period, where concrete remains the lowest cost option, see Figure 5. After about 60 years the lifetime costs flatten out and do not increase very much due to the heavy discounting of distant events.

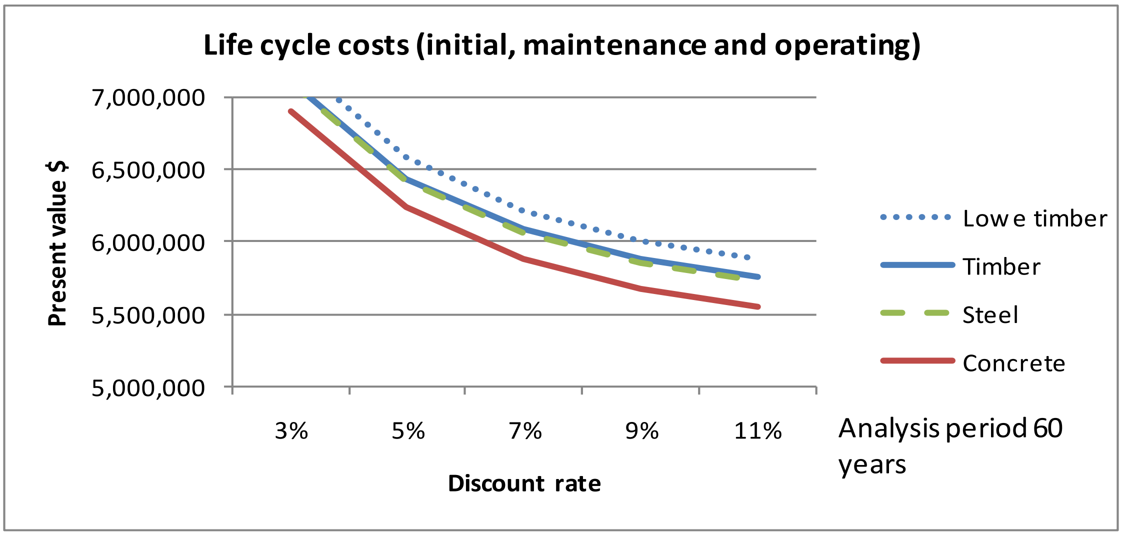

Figure 4 Discount rate changes v lifetime costs.

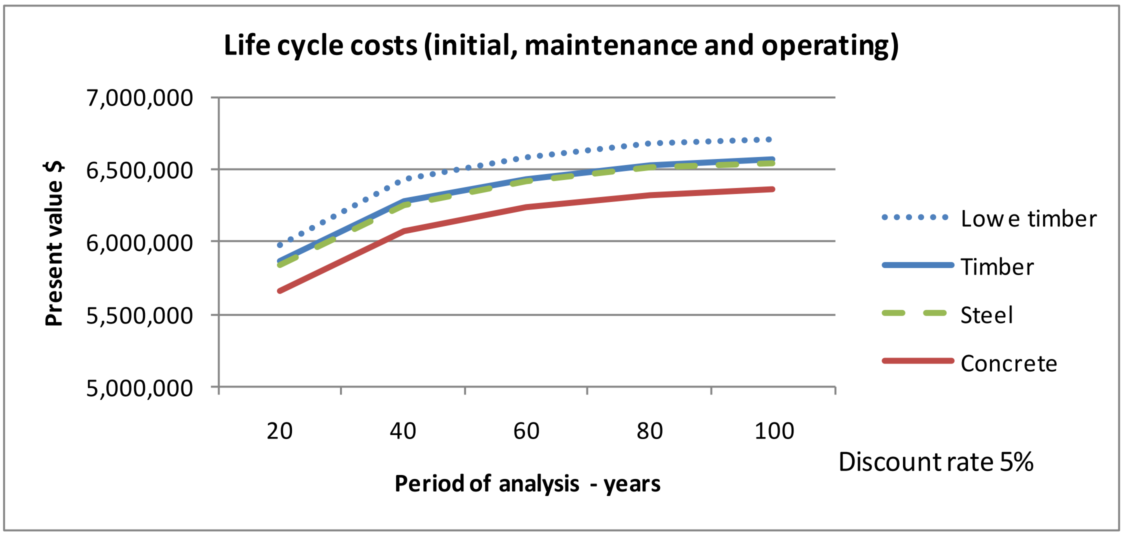

Figure 5 Analysis period changes v lifetime costs

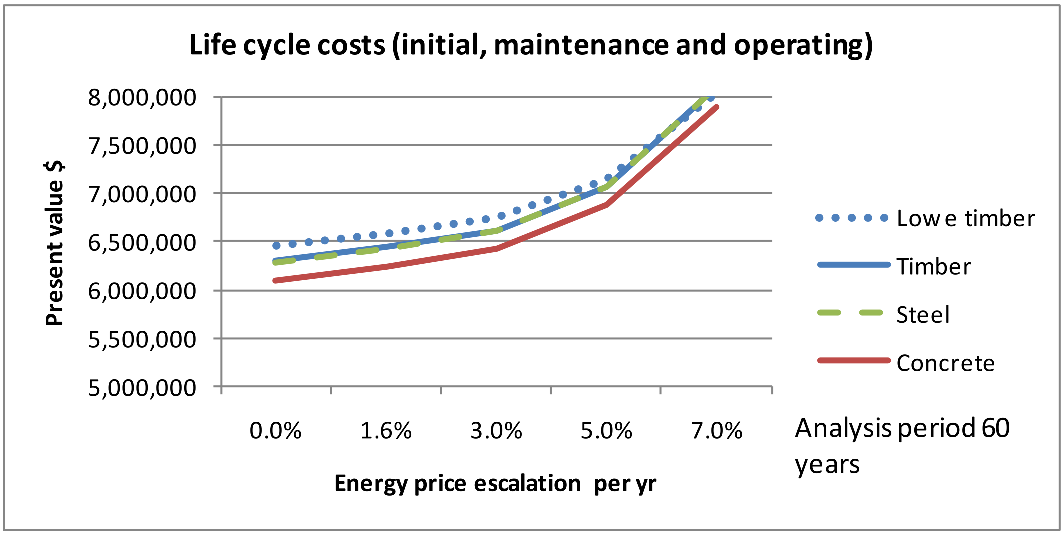

Figure 6 Energy price escalation rate changes v lifetime costs.

Figure 6 shows the effect of changes in energy price escalation of lifetime costs. Again the rankings are the same as before. Note however, total costs rise quite rapidly as energy prices increase. The current Ministry of Economic development (MED, 2009) projections have electricity rising on average about 1.6% per year above the general inflation level, and this is used as the base case.

6. DISCUSSION

The main results are shown in Table 2 above. The maintenance for roof, and the exterior walls are the same for four designs. There are also other common costs (cleaning, routine maintenance of plant, water charges, etc) for the four options, at the bottom of the table. The main differences arise in the windows, energy use, and interior surfaces.

The windows are aluminum framed except in the low energy timber design where PVC frames are used to reduce thermal bridging. Anodised aluminum window frames have been in New Zealand for over 40 years and they are expected to last about 60 years, assuming regular window cleaning washing. PVC frames have a short history locally and overseas experience suggests a shorter life than for aluminum. A replacement period of 30 years has been assumed for PVC frames. Double glazing units need replacing when the cavity seals fail allowing vapour between the glazing panes. Commercial double glazing units are also expected to last about 30 years.

Diesel energy use, for the space heating boilers is fairly similar between the first three designs, varying by about 2% between highest and lowest. This reflects the slightly different heat sink properties of the various structural materials.

The low-e timber design has extra insulation and PVC window frames which reduce window heat losses, and its energy use is significantly less than for the other designs. However the savings over the life of the building are more than off-set by the higher cost of the extra insulation and the PVC windows and their replacements.

Interior surface maintenance costs have some differences. In the timber design the LVL shear walls, and the LVL ceiling beams were featured and enhanced with a clear seal finish, requiring some maintenance. Similarly, the concrete shear walls had a clear seal finish. The painted wall linings area for the steel structure is larger than the other two because the steel frame stands in front of the linings, the latter continuing behind the K-frames.

Insurance and local council rates costs have been excluded but are likely to be the same for all designs.

7. CONCLUSIONS

The first three options had similar life time costs, within a range of less than 3.5% from each other. The low-e timber design was about 5.5% more expensive than the concrete design, and even when savings are counted over a 100 year period the low-e design is still about 5.4% more expensive than the concrete design.

The analysis is dominated by the initial cost amount as the future cashflows add only another 20% to the lifetime costs in present value terms. To some extent the cost differences reflect the aesthetics of the interior finished surfaces. In the timber designs the LVL shear wall and ceiling beams were featured as a clear seal finish, adding to costs, whereas for the two other materials less attention was paid in finishing these components.

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Property Council New Zealand (2009). Operating expenses benchmark - Office buildings and shopping centres. 2008 Edition. PCNZ, Auckland.

9. APPENDIX

The appendix has two main parts:

- Detailed data for 100 analysis period.
- Maintenance cost details, and costs common to all designs.

9.1 Analysis period 100 years results

Table 3 Summary results 100 year analysis period

Life cycle costs for four designs NMIT Arts Building					
		Timber	Concrete	Steel	Timber low-e
Initial cost $		5,352,041	5,140,382	5,325,024	5,489,461
Energy costs - $ present value		548,902	553,347	559,293	483,105
Other costs - $ present value		692,382	695,986	691,258	759,844
		6,593,326	6,389,715	6,575,576	6,732,410
Other costs includes maintenance, replacements and operation costs					
Analysis over a period of	100	years and discount rate is		5%	

Table 4 Detailed results 100 year analysis period

Life cycle costs for four designs NMIT Arts Building						
Discount rate 5%, Analysis period 100 years						
			Timber	Concrete	Steel	Timber low-e
Initial cost $			5,352,041	5,140,382	5,325,024	5,489,461
Energy costs						
	Electricity use	MWh/yr	38.26	38.29	38.32	38.48
	Total daily peaks	kVA/yr	6129	6350	6175	6194
	Diesel use	MWh/yr	93.74	94.81	96.42	75.84
	Energy cost per year	$/yr	19,078	19,233	19,439	16,791
	Total Energy cost	$PV	548,902	553,347	559,293	483,105
Major maintenance /replace						
	Exterior walls	PV $	14,768	14,768	14,768	14,768
	Windows	PV $	111,214	111,214	111,214	178,676
	Roof	PV $	30,194	30,194	30,194	30,194
	Interior walls	PV $	55,310	58,822	50,179	55,310
	Ceiling	PV $	34,696	30,756	26,332	34,696
	Frame	PV $	-	4,032	12,371	-
			246,183	249,786	245,058	313,644
Other costs (common to all designs)						
	Other replacements	$PV	150,279	150,279	150,279	150,279
	Cleaning,services maint	$PV	295,920	295,920	295,920	295,920
	Total Present Value $		6,593,326	6,389,715	6,575,576	6,732,410
	% difference from minimum		3.2%		2.9%	5.4%
	Discount rate =		5%		PV = present value.	
	Analysis period =		100	yrs		
	Electricity price	per kWh	16.84	cents/kWh		
		per kVA	4.3	cents/peak kVA per day		
	Diesel price	per kWh	13	cents/kWh		
	Fixed line charge		51	cents per day		
	Energy price escalation rate		1.6%	per annum		
Rates, insurance not included.						

9.2 Maintenance cost details

The maintenance regime cost details and frequency are shown in Table 5 and Table 6. Non-energy operational costs are shown in Table 7.

In Table 5 the exterior wall, windows and roof components are the same for the three designs. For the other components there are some differences in maintenance costs between the designs relating to surface finishes.

Table 5 Major maintenance items which vary between designs

MAJOR MAINTENANCE OR REPLACEMENTS						Discount rate 5%, Analysis period 60 years										
							Unit	All designs					Present value of maintenance			
							rates						or replacement.			Low e
Component					Low e	**Maintenance/ replacement regime**	$/unit	Replace/ re-paint cost $				PV factor	Timber	Concrete	Steel	Timber
Exterior walls	Units	All designs except low e timbe			Timber						Low e					
Dimondek 400	sqm	401			401	Repaint at year 15 then every 10 years	22.5	9,023			Timber	1.137	10,261	10,261	10,261	10,261
Hardipanel	sqm	205			205	Repaint at year 15 then every 10 years	15	3,075				1.137	3,497	3,497	3,497	3,497
Windows													13,758	13,758	13,758	13,758
Curtain wall glazing	sqm	555			555	Replace DG units every 30 years.	500	277,500			277,500	0.231	64,207	64,207	64,207	64,207
Shopfront glazing	sqm	114			114	Replace DG units every 30 years.	400	45,600			45,600	0.231	10,551	10,551	10,551	10,551
Comm section glazing	sqm	75			75	Replace DG units every 30 years.	400	30,000			30,000	0.231	6,941	6,941	6,941	6,941
Commercial doors	No	1			1	Replace Doors every 30 yrs	3000	3,000			3,500	0.231	694	694	694	810
Curtain wall frame	sqm	555			555	Replace support frame every 60 years. (1)	250	138,750			208,125	0.000	-	-	-	48,155
Shopfront frame	sqm	114			114	Replace support frame every 60 years. (1)	250	28,500			39,900	0.000	-	-	-	9,232
Comm section frame	sqm	75			75	Replace support frame every 60 years. (1)	200	15,000			22,500	0.000	-	-	-	5,206
Roof													82,394	82,394	82,394	145,103
Dimondek 400	sqm	759			759	Repaint at year 15 then every 10 years	19.5	14,801				1.137	16,832	16,832	16,832	16,832
Membrane(bitum 2 coat)	sqm	158			158	Replace every 30 years	90	14,220				0.231	3,290	3,290	3,290	3,290
Box gutter	m	49			49	Replace every 30 years	60	2,940				0.231	680	680	680	680
Downpipes	m	112			112	Replace every 30 years	50	5,600				0.231	1,296	1,296	1,296	1,296
Rainhead	No	6			6	Replace every 30 years	500	3,000				0.231	694	694	694	694
Dimondek soffits	sqm	36			36	Repaint at year 15 then every 10 years	15	540				1.137	614	614	614	614
Villaboard soffits	sqm	208			208	Repaint at year 15 then every 10 years	15	3,120				1.137	3,548	3,548	3,548	3,548
					Low e						Low e		26,954	26,954	26,954	26,954
Interior walls		Timber	Concrete	Steel	Timber			Timber	Concrete	Steel	Timber					
Gibboard	sqm	710	710	1026	710	Repaint at year 15 then every 10 years	12	8,520	8,520	12,312	8,520	1.137	9,689	9,689	14,002	9,689
MDF	sqm	307	307	307	307	Repaint at year 15 then every 10 years	12	3,684	3,684	3,684	3,684	1.137	4,190	4,190	4,190	4,190
Grooved MDF	sqm	44	44	44	44	Repaint at year 15 then every 10 years	14	616	616	616	616	1.137	701	701	701	701
Clear seal concrete			906			Repaint at year 15 then every 10 years	12	-	10,872	-	-	1.137	-	12,364	-	-
Clear seal LVL	sqm	533			533	Repaint at year 15 then every 10 years	15	7,995	-	-	7,995	1.137	9,092	-	-	9,092
Clear seal plywood	sqm	682	682	682	682	Repaint at year 15 then every 10 years	15	10,230	10,230	10,230	10,230	1.137	11,634	11,634	11,634	11,634
Stain finish plywood	sqm	410	410	410	410	Repaint at year 20 then every 20 years	12	4,920	4,920	4,920	4,920	0.519	2,553	2,553	2,553	2,553
Seratone	sqm	116	116	116	116	Replace every 30 years	80	9,280	9,280	9,280	9,280	0.231	2,147	2,147	2,147	2,147
Timber skirting	m	641	641	641	641	Repaint at year 15 then every 10 years	15	9,615	9,615	9,615	9,615	1.137	10,934	10,934	10,934	10,934
Ceiling													50,940	54,212	46,160	50,940
Clear fin. LVL floor	sqm	1563			1563	Repaint at year 30 then every 30 years	18	28,134	-	-	28,134	0.231	6,510	-	-	6,510
Clear fin. Exposed conc	sqm		622			Repaint at year 30 then every 30 years	12	-	7,464	-	-	0.519	-	3,873	-	-
Stain fin plywood	sqm	215	215	215	215	Repaint at year 20 then every 20 years	12	2,580	2,580	2,580	2,580	0.519	1,339	1,339	1,339	1,339
Clear fin plywood	sqm	73	73	73	73	Repaint at year 15 then every 10 years	14	1,022	1,022	1,022	1,022	1.137	1,162	1,162	1,162	1,162
MDF susp grid	sqm	418	418	418	418	Repaint at year 15 then every 10 years	12	5,016	5,016	5,016	5,016	1.137	5,704	5,704	5,704	5,704
Gibboard suppended	sqm	182	182	182	182	Repaint at year 15 then every 10 years	12	2,184	2,184	2,184	2,184	1.137	2,484	2,484	2,484	2,484
Gibboard timber frame	sqm	101	101	101	101	Repaint at year 15 then every 10 years	12	1,212	1,212	1,212	1,212	1.137	1,378	1,378	1,378	1,378
Gibboard skillion frame	sqm	551	551	551	551	Repaint at year 15 then every 10 years	12	6,612	6,612	6,612	6,612	1.137	7,519	7,519	7,519	7,519
Gibboard timb frame	sqm	66	66	66	66	Repaint at year 15 then every 10 years	12	792	792	792	792	1.137	901	901	901	901
MDF bulkhead	sqm	108	108	108	108	Repaint at year 15 then every 10 years	12	1,296	1,296	1,296	1,296	1.137	1,474	1,474	1,474	1,474
Suspend ceiling	sqm	182	182	182	182	Repaint at year 15 then every 10 years	12	2,184	2,184	2,184	2,184	1.137	2,484	2,484	2,484	2,484
Frame													30,955	28,318	24,445	30,955
Paint to steelwork	sqm	0	486	1491	0	Repaint at year 20 then every 20 years	14	-	6,804	20,874	-	0.519	-	3,531	10,832	-
TOTAL													**205,000**	**209,167**	**204,543**	**267,709**

Quantities of components and replacement costs are from the Davis Langdon worksheet Repaint is 2 coat acrylic. (1) For PVC frame replace the frame every 30 years.

Table 6 Replacement items common to all designs

REPLACEMENT DETAILS OTHER COMPONENTS				
			Same costs for all 4 designs	**Present value**
	Comment		Replace $	of replacements
Exterior finish and doors				All designs
Alumium fins	Replace 8 fins	Replace every 40 years	15,300	2,173
Doors	Replace 3 doors	Replace every 35 years	16,500	3,818
Interior doors	Replace all doors & closers	Replace every 40 years	79,000	11,222
Floor finishes	Mainly carpet tiles, vinyl & repolish conc floors.	Replace every 30 years	169,465	39,210
Fixtures and fittings		Replace every 30 years	68,850	15,930
Sanitary plumbing	All excl HWC & solar	Replace every 40 years	56,800	8,068
	HWC & Solar	Replace every 20 years	7,000	3,633
HVAC services	Fan coil unit	Replace every 20 years	4,400	2,283
	Air handling unit	Replace every 40 years	7,500	1,065
	Transfer fans	Replace every 20 years	9,350	4,852
Electrical services	Lighting only	Replace every 40 years	92,650	13,161
Special Services	Access control only	Replace every 15 years	24,000	19,769
			550,815	125,184

Table 7 Operations costs common to all designs

CLEANING, SERVICES MAINTENANCE, WATER, WOF		
	Same costs for all 3 designs	
	Unit rate $/lettable sqm	Annual cost $
WOF	0.4	602
Cleaning	3.0	4,518
HVAC	3.5	5,271
Lifts	2.0	3,012
Water	1.0	1,506
		14,909
	$PV	282,224

Theses costs from NZ Property Council "Operating Expenses Benchmark" 2008 Edition.
Net floor area 1,506 sqm (excludes service areas)

APPENDIX D

Carbon and Energy Footprint of a New Three-Storey Building at Nelson Marlborough Institute of Technology (NMIT)

by

ScionResearch

Carbon and Energy Footprint of a New Three-Storey Building at Nelson Marlborough Institute of Technology (NMIT)

A report written under contract to
the University of Canterbury

By Simon Love

Scion
Private Bag 3020, Rotorua
New Zealand
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Table of Contents

1. Introduction

This report investigates some of the environmental impacts of the new Arts and Media building at Nelson Marlborough Institute of Technology (NMIT), and makes the comparison with three alternative building designs through the use of Life Cycle Assessment (LCA).

This work was carried out by Scion, a New Zealand Government Crown Research Institute (CRI).

2. Background

Principles and guidelines of Life Cycle Assessment (LCA) are used to calculate a „carbon and energy footprint' in this Ministry of Agriculture and Forestry (MAF) funded research project (MAF Pol.# 0910-11809). However, the study is dependent on research and results obtained from other parts of the overall project, undertaken prior to the footprinting work. The necessary steps before being able to undertake the study are summarised below;

1. The design and construction of the Arts and Media building.
2. The design of three alternative buildings – Concrete, Steel, and TimberLow.
3. The quantification of the construction materials used in each building.
4. Operational energy modelling and results for each design.
5. The calculation of transport distances for building materials.
6. The completion of estimated maintenance schedules for each building.
7. Background research on lifespan and end of life options in New Zealand.

Building on the above research, this study compares the lifetime energy consumption and the global warming potential (GWP) of the buildings, and investigates the environmental hotspots of each building.

LCA Overview

Life Cycle Assessment is based on the concept of Life Cycle Thinking which integrates consumption and production strategies over a whole life cycle, so preventing a piece-meal approach to systems analysis. Life cycle approaches avoid problem-shifting from one life cycle stage to another, from one geographic area to another, and from one environmental medium to another.

Life Cycle Assessment is an analytical tool for the systematic evaluation of the environmental impacts of a product or service system through all stages of its life. It extends from extraction and processing of raw materials through to manufacture, delivery, use, and finally on to end of life. This is often referred to as "cradle to grave". A number of other environmental assessment tools are restricted to the production process, which is sometimes called "gate to gate", or in the case of embodied energy covers the life cycle from "cradle to gate" without taking the end-of-life into account.

Definition of LCA

ISO 14040 (ISO, 2006b) defines LCA as:
"... a technique for assessing the environmental aspects and potential impacts associated with a product, by

- *compiling an inventory of relevant inputs and outputs of a product system;*
- *evaluating the potential environmental impacts associated with those inputs and outputs;*
- *interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.*

LCA studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences."

Elements of an LCA

An internationally accepted framework for LCA methodology is defined in AS/NZS ISO 14040 and 14044 (ISO, 2006a, ISO, 2006b). These standards define the generic steps which have to be taken when conducting an LCA. The following section will explain these steps and give examples on how they can be applied to the building industry.

Four different phases of LCA can be distinguished:

Goal and Scope Definition

The goal and scope of the LCA study are clearly defined in relation to the intended application. This includes a detailed description of the reasons for undertaking the study, as well as the intended audience and the intended application of the results.

Having defined the goal of the study, scoping involves defining the functional unit, system boundaries and other requirements for the study, such as data quality, and choice of environmental impacts to be analysed in the "impact assessment".

Inventory Analysis

The inventory analysis involves the actual collection of data and the calculation procedures. The relevant inputs and outputs of the analysed product system are quantified and produced as a table. These are the material and energy inputs, and product and emission outputs to air, water and land.

In an LCA, the material and energy flows should be "*drawn from the environment ... or discarded into the environment without ... human transformation*" (ISO, 2006a). Thus the overall product system should extend upstream to primary resources, and downstream to the point where material is emitted into the environment.

The initial phase is to develop an "input-output" table of the product systems. This would, for example, show kg of concrete used, kWh of electricity consumed and diesel consumed for transport. A detailed inventory is then compiled.

At the end of the life cycle, treatment of solid waste should be considered as part of the product system. This means that „waste' does not leave the product system analysis but is dealt with within the system boundaries.

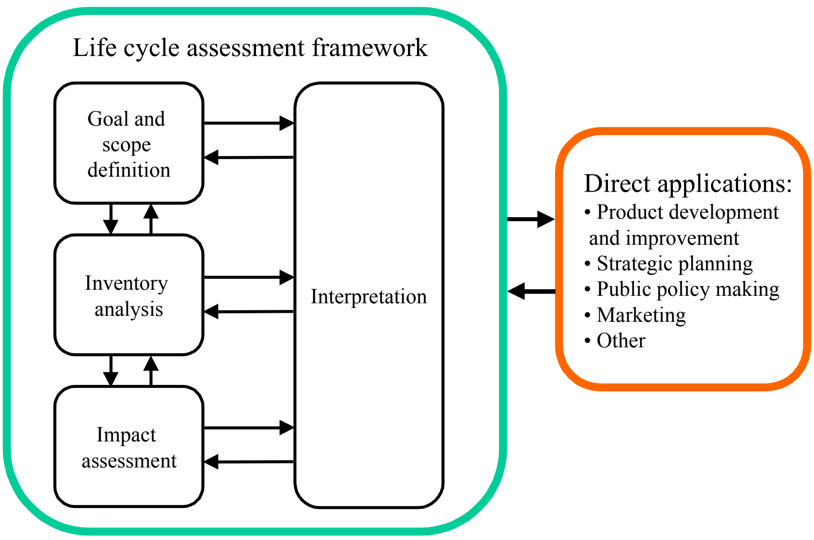
Impact Assessment

The impact assessment translates the results of the inventory analysis into environmental impacts (e.g. climate change, ozone depletion). The aim of this phase is to evaluate the significance of potential environmental impacts. The international standard defining guidelines for LCA work states that "the selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied…" (ISO, 2006b). For this reason, this project cannot be considered a „full LCA', and thus is referred to as a „carbon and energy footprint'.

The contribution to climate change is, for example, expressed as the Global Warming Potential (GWP). GWP is defined over a certain time period to reflect the relative life spans of each greenhouse gas in the atmosphere - in this project the time period used is 100 years. In order to calculate the GWP, all emissions contributing to climate change that are listed in the inventory table, e.g. carbon dioxide and methane, are converted into kg CO_2 equivalents. The following methodology is applied: CO_2 has a weighting of 1 kg CO_2 equivalent whereas the more potent greenhouse gas methane has a value of 25 kg CO_2 equivalents (IPCC, 2007). In other words 1 kg of methane contributes 25 times as much to global warming as 1 kg CO_2. In this way it is possible to add up the results of all emissions which contribute to the same environmental impact category.

Interpretation

In this phase conclusions and recommendations for decision-makers are drawn from the inventory analysis and the impact assessment. These can be represented as shown in Figure 2.1. In practice, LCA involves a series of iterations as its scope is redefined on the basis of insights gained throughout the study.



3. Life Cycle Assessment – Goal & Scope Definition

Goal

The goal of this study is to calculate (using LCA methodology) specific environmental impacts (energy consumption and Global Warming Potential) of the 3-storey NMIT Arts and Media building and the alternative Steel, Concrete and „TimberLow' designs. This covers production of all materials (including associated upstream processes, e.g. resource extraction and energy generation) and transport to site (known as „cradle-to-gate') and beyond to include the full life-time of the buildings (established at 60 years, with a 100-year scenario also investigated). A base end-of-life scenario and an alternative future end-of-life scenario, including recycling of building components have been considered.

The different designs are composed of different structural materials: concrete, steel and timber. The TimberLow variant has been examined, in which a low-energy building based on a timber structure has been designed.

Scope

The scope of the study includes a clear description of the system under analysis, the functional unit, system boundaries and data quality as well as the intended audience and application of the results. These are described for this project below:

Functional Unit

The results of the study are in relation to the NMIT Arts and Media building located in Nelson, and used over a period of 60 or 100 years. Four designs of the building have been considered: the actual building, alternative designs using concrete and steel as the structural basis respectively, and a TimberLow design which is a low-energy variant of the existing building.

System Boundaries

The system boundaries applied in this study were "cradle to grave", which means that all impacts of manufacturing the building products, their transport, the use phase of the building, maintenance of building components and the disposal of materials after the building's useful life were considered. System expansion has been employed to take into account the benefits of any recycling of metals and concrete, and energy from wood. Upstream processes such as the production of diesel used in transport as well as the emissions of the truck have been taken into account, including all related environmental impacts. This also applies to the provision of natural gas for heating and electricity.

The actual construction and demolition of the building are not taken into account because they are likely to be negligible (Kellenberger and Althaus, 2009).

The results of the study are shown for the following stages of the life cycle:

- production of building materials
- transport to building site in Nelson
- use of building over 60 years and, as an alternative scenario, 100 years.
    - maintenance

    - electricity for lighting, hot water, appliances and cooling
    - diesel for heating
- end-of-life
    - Current (base) scenario:
        - all timber materials to average NZ landfill, steel recycled at 85%, and concrete to cleanfill.
    - Future (optimistic) scenario – combustion of all timber in a high-efficiency cogeneration plant to produce heat and electricity, as well as recycling of all concrete, all aluminium and steel.

It should be noted that the „base' scenario considers current disposal techniques – yet the building materials will not be available for disposal for at least 60-100 years. Rapid advances are being made in recycling, reuse and energy generation from waste, and so the „base' scenario is unlikely to represent the actual situation in 60-100 years.

Whilst the „future' scenario estimates likely future disposal options - and, as such, proposed future practices are not „set-in-stone' – it is considered to be a more realistic end-of-life scenario than the „base' scenario. However, it could be that even more efficient end-of-life options will become available in the future. For pragmatic reasons and being able to use currently-available data, the „base' scenario is the chosen default scenario.

All stages of the life cycle as well as the scenarios are described in detail in the inventory analysis.

Data Quality

Two aspects with regard to data quality need to be considered:

- input-output data, i.e. quantities of materials used and transport distances
- life cycle inventory data, i.e. emissions and energy required for the production of the materials or generation of electricity

Input-output data was for the project was either measured directly or calculated by professional Quantity Surveyors. Data for the three alternative designs was calculated, because these designs represent theoretical buildings, and therefore material consumption could not be measured directly.

The life cycle inventory data used in this study is from two key sources:

The data for most building materials is based on a recent dataset that has been developed as part of the project "Life Cycle Assessment: Adopting and adapting overseas LCA data and methodologies for building materials in New Zealand" (Nebel et al., 2009). In this project European-based industry data was combined with New Zealand specific data, compiled and calculated by Andrew Alcorn at the Centre for Building Performance Research at Victoria University (Alcorn, 2003). Global warming potentials for New Zealand energy sources (primarily electricity, natural gas and diesel) are based on recent life-cycle calculations from AgriLink (Barber, 2009).

The recent detailed study on laminated veneer lumber (LVL) in New Zealand, „Carbon Footprint of New Zealand Laminated Veneer Lumber' (Love, 2010) provides a comprehensive dataset for LVL used in the Arts and Media building. 30 MPa concrete was modelled on the closest-available NZ dataset, which was for 40 MPa concrete.

Data for the few materials that are not included in these datasets are based on data that is part of a LCA software package (GaBi 4.3) and is based on European industry data (PE International, 2010). The data has been amended and checked for consistency with literature data and is compliant with the ISO Standards 14040 and 14044. The documentation of the data describes the production process, applied boundary conditions, allocation rules etc. for each product. The data covers resource extraction, transport, and processing, i.e., “cradle to gate”. Included are material inputs, energy inputs, transport, outputs and as well as the emissions related to energy use and production. Capital equipment is excluded as it is not expected to be a significant impact in a study of this type (Frischknecht et al., 2007).

Intended Audience and Application of the Results

The study was undertaken for the Ministry for Agriculture and Forestry (MAF), subcontracted through the University of Canterbury. It is anticipated that the results will be used to inform policy making. The results can also be used to demonstrate the benefits of a life cycle approach when comparing different building designs. The project also can identify further research opportunities in the built environment field.

Impact Categories

The two impact categories that have been considered are primary energy, as an indicator for resource consumption, and greenhouse gas emissions (Global Warming Potential) .

Primary Energy

Primary energy is energy contained in raw fuels and any other forms of energy that has not been subjected to any conversion or transformation process. Primary energies are transformed in energy conversion processes to more convenient forms of energy, such as electrical energy and cleaner fuels. The transformation includes losses that occur in the generation, transmission, and distribution of energy. For example, the provision of 1 MJ of electricity from natural gas requires 1.13 MJ of primary energy (Barber, 2009). Primary energy consumption for “cradle to gate” or “cradle to site” is often referred to as “embodied energy”.

Embodied energy is the energy consumed by all processes from extraction of raw materials through to the production of a product. The definition of the system boundaries vary for different assessments and sometimes include the delivery to the building site, energy requirements for installation, and transport of workers to the site (“cradle to site”). However, data for these processes is often hard to quantify. Published figures for embodied energy are therefore often based on a “cradle to gate” concept.

Embodied energy usually includes energy from fossil fuels as well as energy from renewable fuels, based on the assumption that there is a limit to how much renewable energy can be harnessed. The supply of electricity from hydro or wind is for example restricted and should therefore also be used efficiently in order to minimise fossil fuel use. In order to address this issue only harnessed renewable energy should be considered, e.g. electricity generated from hydro energy, or thermal energy from combustion of biomass. In this case, for example, the calorific value of biomass is included. The solar energy required for the photosynthesis to grow timber is excluded since it is captured within a product, but not used for energy production (harnessed renewable energy).

In currently available commercial databases, including the widely used Ecoinvent database as well as the GaBi database non-harnessed solar energy for photosynthesis is also included. This is done to keep the energy balance intact because a calorific value is assigned to all timber products. This means the output of energy (calorific value of timber) is balanced by an equivalent input of energy, (solar). However, this can be seen as distorting the overall use of renewable energy, because the solar energy for timber production cannot be utilised in any other way. In the LCA data for building materials in New Zealand (Nebel et al., 2009) non-harnessed energy has therefore been excluded. However, as the NZ data does not cover all materials, it needs also to be consistent with available databases in order to be able to mix NZ with data from those to provide a full range of materials and this option has therefore been provided too. Not all materials used in the four buildings analysed in this report are available in the new New Zealand dataset, e.g. PVC and glass data are not available and the data had therefore to be sourced from the GaBi database.

Global Warming Potential (GWP)

Increasing amounts of greenhouse gases (such as carbon dioxide and methane) enhance the natural greenhouse effect and are possibly leading to an increase in global temperature. During the 20th century, the average global temperature increased by about 0.6°C (IPCC, 2001). Climate change is therefore often referred to as 'global warming'. Since the effects may also include storms or regional cooling, the term 'climate change' is more suitable. The natural greenhouse effect is an important factor in heating the atmosphere: short wavelength solar radiation entering the Earth's atmosphere is re-radiated from the Earth's surface in longer infrared wavelengths and then reabsorbed by components of the atmosphere. Without the natural greenhouse effect the average global temperature would be about -18°C. Due to the greenhouse effect the average global temperature is 15°C (IPCC, 2001).

The general recommendation is to use the most recent figures for CO_2 equivalents for greenhouse gas emissions published by the Intergovernmental Panel for Climate Change (IPCC). In 2007, the IPCC updated its estimates of Global Warming Potentials (GWP) for key greenhouse gases from 1996 (IPCC, 2007).

The global warming potential is an expression of the contribution of a product or service to climate change. An internationally agreed characterisation model exists for the calculation of the Global Warming Potential. This has been published by the IPCC.

4. Life Cycle Assessment – Inventory Analysis

Material Quantities

The material quantities for each building type and building component are presented in tonnes in Appendix A: Material Quantities. The material quantities for each building type were estimated by a quantity surveyor, Davis Langdon in Christchurch. The total quantities, in tonnes, of the main building materials are summarised and presented in Table 4.1.

Table 4.1: Total building material quantities for each building design.

Material (tonnes)	Concrete	Steel	Timber	TimberLow
Concrete	1,633.49	995.82	961.42	961.42
Reinforcing Steel (NZ)	135.99	77.89	77.89	77.89
Structural Steel (Imported)	39.41	123.31	2.64	2.64
Sheet Steel (NZ)	9.34	23.88	9.34	9.34
Glass	27.47	27.47	27.47	27.47
Timber	72.32	38.53	37.04	37.04
LVL	0.00	0.00	163.46	163.46
Plywood/MDF	29.84	28.96	29.84	29.84
Aluminium	3.69	3.69	3.69	1.13
Plasterboard	14.01	16.76	14.01	14.01
Paint	0.75	0.82	0.76	0.76
Glass Wool Insulation	16.22	16.22	16.22	17.58
Expanded Polystyrene	0.00	0.00	0.15	0.30
PVC	0.00	0.00	0.00	1.33
Building Paper	0.12	0.12	0.12	0.12
Total	**1,982.65**	**1,353.46**	**1,344.05**	**1,344.33**

Maintenance

A maintenance schedule for each building design was developed based on life cycle costing data from BRANZ (Page, 2010). The replacement or refurbishment lifetimes of specific building materials are presented in Appendix B: Maintenance Schedules. It was assumed that structural components and insulation would last the entire lifespan of the building. It was also assumed that any replacements required would be with an identical material to the original.

Table 4.2: Mass of building replacements over 60 years

Total Replacements (kg) over 60 years	Timber	Concrete	Steel	TimberLow
Paint	7,334	7,745	7,406	7,357
MDF	510	510	510	510
Steel (sheet)	360	360	360	400
Glass	23,530	23,530	23,530	23,530
Aluminium	2,700	2,700	2,700	140
Timber	1,580	1,580	1,580	1,580
PVC	0	0	0	1,333

Table 4.3: Mass of building replacements over 100 years

Total Replacements (kg) over 100 years	Timber	Concrete	Steel	TimberLow
Paint	13,661	14,198	13,514	13,685
MDF	1,531	1,531	1,531	1,531
Steel (sheet)	1,080	1,080	1,080	3,359
Glass	47,060	47,060	47,060	47,060
Aluminium	5,260	5,260	5,260	140
Timber	3,160	3,160	3,160	3,160
PVC	0	0	0	3,976

End-of-Life Inventory

Current (Base) Scenario

The base scenario assumes that all wooden building materials, including wood-based materials installed in each building, such as timber, LVL, plywood, and MDF, would be sent to landfill following deconstruction at the end of each building's life. Plastics, glass and concrete are sent to cleanfill. For the landfill scenarios the transport to the landfill as well as all emissions associated with the operation of the landfill (e.g. use of bulldozers) are included (PE International, 2010).

Recycling rates for metals and glass have been estimated to represent the New Zealand situation. These estimates are given in Table 4.4 below. It can be seen that some data exists for steel recycling rates, but glass and aluminium are not known. In addition, it should be noted that reinforcing steel can only be recycled after concrete is crushed, and data for this is scarce. It was assumed that the NZ Steel figure below includes reinforcing steel. At present, concrete recycling does happen on a small scale, by individual contractors (Kirby and Gaimster, 2010). Despite this, the actual recycling rate is unknown, and this in the base scenario has been excluded. Concrete recycling is addressed further in the future scenario section.

Table 4.4: Base end of life assumptions for metals, glass and concrete

Process	Assumption	Source/Explanation
Recycling rate of steel:	85%	NZ Steel [1]
Recycled steel replaces:	Virgin steel 1:1	Common assumption from ISO and the International Life Cycle Data system (ICLD, 2010).
Recycling of aluminium window frames	0%	No data found
Recycling of glass windows	0%	O-I New Zealand[2]
Recycling of Concrete	0% (unknown)	No accurate figures, but expected to be minimal. Expected to increase in the future.(Kirby and Gaimster, 2010)

[1] http://www.nzsteel.co.nz/go/news/sustainability-new-zealand-steel-has-been-working-on-it-for-years/
[2] http://www.recycleglass.co.nz/recycling.htm

The behaviour of wood in landfill is a complex issue. The 2006 IPCC National Greenhouse Gas Inventory Guidelines stated:

"The reported degradabilities especially for wood, vary over a wide range and is yet quite inconclusive. They may also vary with tree species. Separate DOCf [fraction of organic carbon that decomposes] values for specific waste types imply the assumption that degradation of different types of waste is independent of each other…scientific knowledge at the moment of writing these guidelines is not yet conclusive on this aspect". (IPCC, 2006)

As reported in a recent study of LVL, there are a range of scientific papers which present vastly different decomposition rates for wood. (Love, 2010) Engineered wood products present a further challenge, as they include fillers and resins, and may be treated. The recent study of New Zealand LVL has been used for the GWP and energy values of LVL, including for the end of life stage (Love, 2010). This study excluded decomposition of the resin component, and this assumption has been carried through for plywood, MDF and particleboard in this project.

From the proportion of carbon released, 50% of that will be released as carbon dioxide (CO_2) and 50% as methane (CH_4) (IPCC, 2006). A 42 % capture of methane has been taken into account (MfE, 2008). It is anticipated that the amount of landfill gas captured from New Zealand landfills will increase in the future; however to avoid additional uncertainties, the latest figure based on physical data has been used. Of this methane, not all will be used for energy generation – some is flared. In 2007, 6 out of 11 NZ landfills with methane capture technology generated energy (MfE, 2007). Using these figures, a rough assumption has been made that 43% of captured methane is used for energy generation, and 57% is flared.

Another assumption was that 10% of the non-captured methane underwent microbial oxidation to CO_2 in the landfill (IPCC, 2006). Based on this information the total release of Greenhouse Gas (GHG) from decomposition was calculated. The total release of GHG from decomposition was then converted into respective GWP by multiplying each GHG by its GWP coefficient, CO_2 being 1 and CH_4, 25 (IPCC, 2007).

For the modelling of incineration, it is assumed that complete combustion occurs, releasing all stored CO_2. This scenario is therefore an assumption of no permanent carbon storage (i.e. all carbon is oxidised). In the future, it is unlikely that wood products would be incinerated without energy recovery. Therefore, this scenario assumes the energy produced from burning the wood waste is used for cogeneration of heat and electricity. This heat could be used for industrial uses, displacing heat from natural gas, and the electricity could replace electricity from the national grid. The GWP impacts of these displacements (using current New Zealand environmental data) have been taken into account (Barber, 2009). All assumptions for end of life processes for wood are detailed in Table 4.5.

Table 4.5: End of life assumptions for wood products

Process	Assumption	Source
% of dry wood that is carbon	50%	(Sandilands et al., 2008)
Decomposition of carbon in wood in landfills*	18%	(Ximenes et al., 2008)
% of carbon converted to methane	50%	(IPCC, 2006)
% of carbon converted to CO2	50%	

Methane captured (average current NZ landfill)	51%	(MfE, 2008)
% of non-captured methane that oxidises in landfill	10%	(IPCC, 2006)
% of captured methane used for energy (current NZ landfill)	43%,	(MfE, 2007)
Electricity produced per kg methane (in methane cogeneration plant)	16.65 MJ	Ecoinvent (Frischknecht et al., 2005)
Heat produced per kg methane (in methane cogeneration plant)	30.525 MJ	Ecoinvent (Frischknecht et al., 2005)

* after 46 years

The total mass of all the structural timber, architectural finishes and each wooden component for each building is presented in Table 4.6. The total carbon within the wooden materials (i) in the building was calculated for each building based on the proportion in Table 4.5 above. This is then converted to CO_2-e (ii). Using the 18% decomposition figure given above, carbon emissions have been calculated and shown as total CO_2-e released (iii). Line (iv) shows the remaining CO_2-e left after emissions have been subtracted from the stored carbon.

Table 4.6: Net tonnes CO_2 equivalent stored in landfill including total GHG emissions released from decomposition

		Building Designs			
		Concrete	**Steel**	**Timber**	**Timber-Low**
Timber in building	tonnes	72.32	38.53	37.04	37.04
LVL in Building	tonnes	0.00	0.00	163.46	163.46
Plywood/MDF in Building	tonnes	29.84	28.96	29.84	29.84
i) Total Carbon content of building*	tonnes	49.43	32.15	104.53	104.53
ii) Total CO_2-e sequestered for building lifespan	tonnes	181.27	117.89	383.30	383.30
iii) Total CO_2-e released from landfill**	tonnes	90.85	59.08	192.10	192.10
iv) Net CO_2e sequestered in landfill	tonnes	90.42	58.80	191.20	191.20

* This does not equal 50% of the mass, as some of the mass of wood products is made up of resins and additives. Calculations were based on data from Love (2010) and used as an approximation for plywood and MDF

** This figure includes CO_2 emissions from methane flaring and energy generation, but not from any offset electricity/heat

Future Scenario

In the material reutilisation scenario, instead of sending waste materials to landfill, all wooden materials from all four building designs were used as fuel to generate energy and all structural steel and concrete was recycled.

In the future scenario, all recoverable steel was assumed to be recycled – though it should be noted that recycling of reinforcing steel involves crushing of large concrete components, which may not always be feasible. The amount of recycled steel was assumed to replace virgin steel and credited to the building. Energy and emissions from the recycling process were taken into account. For the Concrete building, all concrete was assumed to be recycled. Due to the unknown energy input for the crushing, sorting and reuse of concrete as aggregate, it is assumed that the energy needed for these steps would be similar to that of producing virgin aggregate, therefore effectively cancelling each other out. This scenario does however avoid the impacts of disposal of such a large amount of concrete in cleanfill.

The total mass of wooden materials was the same as in the landfilling scenario which includes timber, LVL, plywood, and MDF. It was assumed that all these materials would be burnt in a cogeneration plant with an energy conversion efficiency of 98%. This figure is an estimate of a high-performance cogeneration plant, and is based on previous estimates of plants using cardboard and paper waste as inputs, which showed efficiencies up to this level (Merrild et al., 2008). An efficiency of 98% means that 98% of the calorific value of the wood (i in Table 4.8 below) is recovered as useful energy (ii) through combustion with a ratio of electricity to heat of approximately 1:3 (Merrild et al., 2008, Connell Wagner, 2007). It was assumed that this electricity and heat is used, and replaces electricity from the national grid and heat from burning natural gas. The current electricity mix was used as a proxy for the future New Zealand mix. This displaces GWP emissions (0.061 kg CO_2e per MJ heat from natural gas and 0.066 kg CO_2 e per MJ electricity) and primary energy (1.13 MJ per MJ heat from natural gas and 2.36 MJ per MJ electricity) (Barber, 2009). These assumptions are summarised in Table 4.7 below.

Table 4.7: Assumptions for incineration of wood waste

Process	Assumption	Source
Calorific value of wood waste	15.68 GJ/tonne	Energy Efficiency and Conservation Authority[3]
Efficiency of wood cogeneration plant (best case)	98%	(Merrild et al., 2008)
% of energy output as electricity	29%	
% of energy output as heat	71%	
CO2-e associated with 1 MJ New Zealand electricity (for offsetting)	0.066 kg CO2-e	(Barber, 2009)
CO2-e associated with 1 MJ New Zealand heat from natural gas (for offsetting)	0.061 kg CO2-e	

[3] http://www.eecabusiness.govt.nz/renewable-energy/wood-energy-knowledge-centre/tools-and-calculators

Table 4.8: Energy recovered from wood combustion and CO_2 displaced from avoiding the use of traditional energy sources (natural gas and electricity)

	Concrete	Steel	Timber	TimberLow
Wood Waste (t)	98.9	64.3	209.1	209.1
Energy (GJ)				
(i) Calorific Value	1,550.4	1,008.3	3,278.3	3,278.3
(ii) at 98% efficiency	1,519.4	978.0	3,180.0	3,180.0
(iii) Metered Electricity	440.6	283.6	922.2	922.2
(iv) Metered Heat	1,078.8	694.4	2,257.8	2,257.8
CO2 displacement (t)				
Electricity	29.1	18.7	60.9	60.9
Natural gas	65.8	42.3	137.6	137.6
Total	94.8	61.1	198.5	198.5
CO2 Storage	0.0	0.0	0.0	0.0
Total GWP Impact (t CO2-e):	-94.8	-61.1	-198.5	-198.5
Total Renewable Energy (GJ)	-753.9	-485.3	-1,577.9	-1,577.9
Total Non-Renewable Energy (GJ)	-1,505.0	-968.8	-3,149.8	-3,149.8

This displacement can be explained more clearly by tracking the path of the carbon, within the wooden products, from cradle to grave.

Growing timber takes up CO_2 from the atmosphere and stores it as carbon. When the wood is harvested from the forest the carbon continues to be stored within the wood. The wood is then used in various forms in construction of buildings, exists over the full lifetime of the buildings and carbon continues to be stored up to the point of deconstruction.

When the waste timber is combusted, CO_2 is released back into the atmosphere, which brings the balance back to approximately zero. However, energy is recovered, which can replace conventional energy from fossil fuels (and in a future scenario, all of this energy is assumed to be used). Therefore, the avoided fossil CO_2 can be subtracted from the GWP of the end-of-life phase in which the wood is being combusted. This is known in LCA as „system expansion'.

The total displacement of fossil fuels for each building is shown in Table 4.8 above, based on the above explanation.

Transport

Sources of building materials for the actual NMIT building have been documented, and therefore the actual distances (or the nearest estimate) have been used. For other buildings, some assumptions have been made. It was assumed that structural steel would be imported from Australia or Asia, and therefore an average shipping distance has been used. It is assumed that PVC would be made in Auckland, and that the EPS insulation would be made in Blenheim. Transport distances for the different materials are presented in Table 4.9 below.

Table 4.9: Transport of materials to NMIT Buildings

Transport of Materials to NMIT Buildings (t km)				
	Concrete	Steel	Timber	Timber Low
Transport by Truck	172,874	157,546	102,994	103,085
Transport by Cook Strait Ferry	16,996	20,707	8,268	8,268
Transport by International Ship	9,225	9,225	9,225	2,825

Emission factors for truck transport are taken from Love (2010). Emission factors for ocean transport come from UK figures (DEFRA, 2008), and are converted into energy figures using data from Barber (2009). Emission factors used in this project are shown below in Table 4.10. No renewable energy is used in the transportation stage.

Table 4.10: Emission factors and energy use factors for transport

	Emission Factor (kg CO2-e per t km)	Non-Renewable Energy (MJ per t km)
Truck Transport	0.1	0.7232
Ferry Transport	0.011	0.15339
International Shipping	0.007	0.0976

Operational Energy

Total energy consumed (electricity and diesel) during the 60 and 100 year operation periods for each building type was supplied by Nicolas Perez as metered consumption (Perez, 2010). To demonstrate the total energy consumption this has been converted to primary energy, and the respective GWP values have also been calculated.

A life cycle inventory dataset for New Zealand has been used to calculate the primary energy content and the GWP for electricity. The dataset takes the New Zealand electricity mix as well as New Zealand specific emissions into account (Barber, 2009).

The following factors have been used:

Electricity:
Global Warming potential: 0.238 kg CO_2 equiv. / kWh
Primary energy: 8.500 MJ/kWh

Heat from diesel:
GWP: 0.219 kg CO_2 equiv. / kWh (3.108 kg/ litre, and)
Primary energy: 4.068 MJ/kWh (diesel's higher heating value is 44.8 MJ/kg, and density is 0.832 kg/l)

The results for metered energy consumption, as well as primary energy and GWP over 60 and 100 years are shown in Table 4.11 and Table 4.12 below. The figures for metered energy consumption have then been multiplied with the respective numbers for CO_2 equiv./kWh and MJ primary energy/kWh for heat from diesel and electricity.

Table 4.11: Operational energy (GJ) and GWP (t CO_2-e) over 60 years

Total Operational Impacts (60 years)				
	Non-Renewable Energy (GJ)	Renewable Energy (GJ)	**Total Primary Energy (GJ)**	**Total GWP (t CO_2-e)**
Concrete	32,888	9,000	**41,887**	**2,376**
Steel	33,514	9,006	**42,520**	**2,419**
Timber	32,465	8,995	**41,460**	**2,347**
TimberLow	25,500	9,029	**34,529**	**1,868**

The primary energy consumption associated with the operation stage was determined and used instead of using the consumed MWh in the building because the system boundaries include all energy use associated with each stage of the life cycle. Therefore it was imperative to include all energy consumed in the process of delivering the useable energy to the buildings. Shown below in Table 4.12 is the operation energy required if the building was to be used for 100 years.

Table 4.12: Operational energy (GJ) and GWP (t CO_2-e) over 100 years

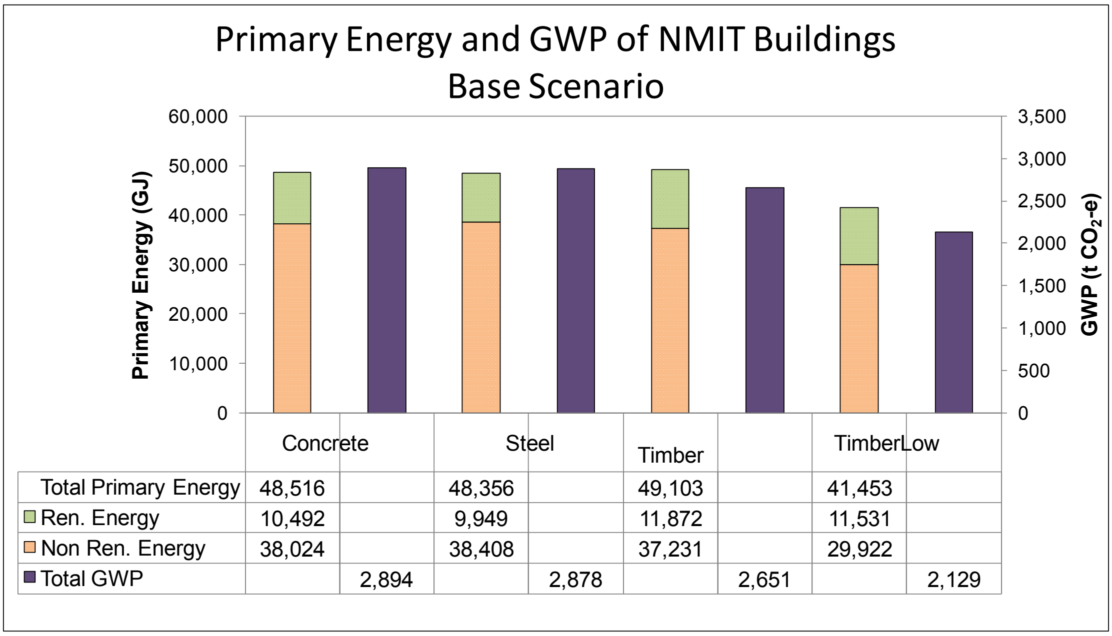
Total Operational Impacts (100 years)				
	Non-Renewable Energy (GJ)	Renewable Energy (GJ)	**Total Energy (GJ)**	**GWP (t CO_2-e)**
Concrete	54,813	15,000	**69,812**	**3,960**
Steel	55,857	15,010	**70,867**	**4,032**
Timber	54,108	14,992	**69,100**	**3,912**
TimberLow	42,500	15,049	**57,549**	**3,114**

5. Life Cycle Assessment – Impact Assessment

Total primary energy and GWP were the two impact categories calculated for each building type. The results for each building are presented for the following life cycle stages: initial material production, maintenance, transport, operation over the 60 (or 100) year lifetime of the buildings, maintenance, and end of life.

Base Scenario

The total primary energy and GWP contributions from each building can be seen in Figure 5.1 below. The three conventional buildings have very similar total energy consumption, with the TimberLow building showing the lowest total consumption. Renewable energy makes up 21%, 22%, 24% and 28% of the Steel, Concrete, Timber and TimberLow buildings, respectively. In terms of GWP, the Concrete and Steel results are very similar, though the Timber building has an 8% lower GWP result, and the TimberLow building has a GWP result over 25% lower than the Steel and Concrete buildings.



	Concrete		Steel		Timber		TimberLow	
Total Primary Energy	48,516		48,356		49,103		41,453	
Ren. Energy	10,492		9,949		11,872		11,531	
Non Ren. Energy	38,024		38,408		37,231		29,922	
Total GWP		2,894		2,878		2,651		2,129

Figure 5.1: Total life cycle primary energy and GWP of each NMIT building variant over 60 years

To investigate these results further, the total impacts must be broken down into life cycle stages. The contribution of each stage to the primary energy consumption is shown in Table 5.1 below, and graphically in Figure 5.2. It is clear from these results that the use phase of the buildings is the dominant contributor, making up 85-88% of the respective totals. Production of materials makes up approximately 14%, building maintenance 2%, and transport of materials well under 1%. In all cases, the end of life processes result in negative impacts.

Table 5.1: Primary Energy (GJ) for each NMIT building variant, by life cycle stage

	Concrete	Steel	Timber	Timber Low
Materials	6,599	7,468	6,950	6,657
Transport	201	161	124	124
Operation	41,887	42,520	41,460	34,529
Maintenance	1,239	1,224	1,220	793
End of Life	-1,410	-3,016	-650	-651
Total	48,516	48,356	49,103	41,453

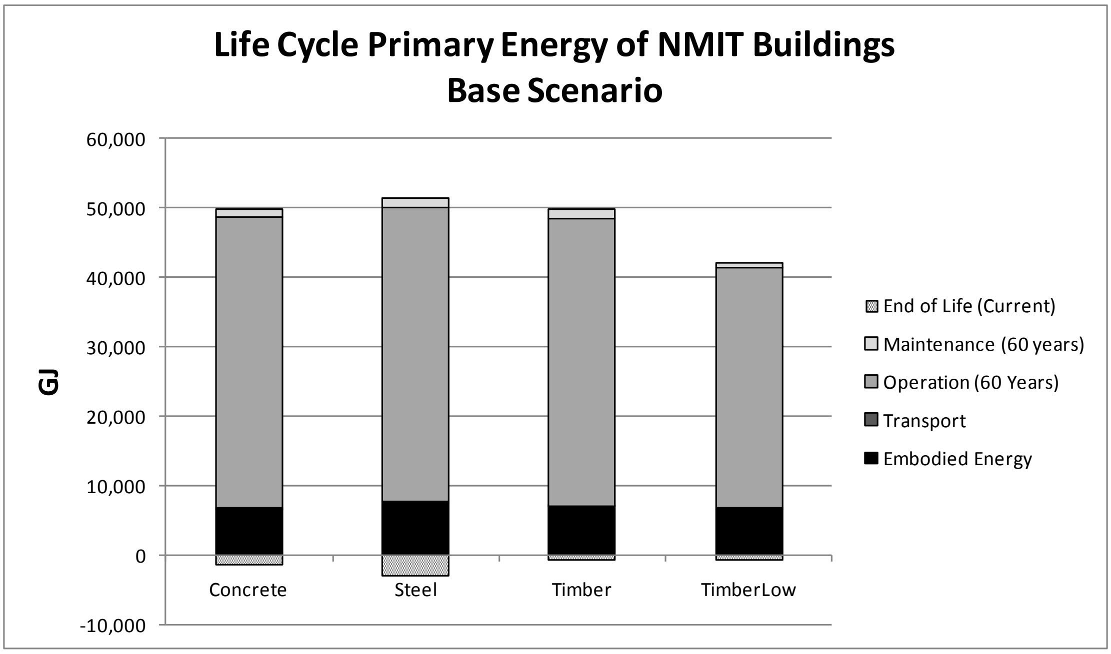


Figure 5.2: Primary Energy for each NMIT building variant, by life cycle stage

The two life cycle stages where the timber buildings differ from concrete and steel the greatest are in materials production and end of life. The timber buildings show lower primary energy use in the material production stage, but still of a relatively similar magnitude to the other buildings. The wood products used in the timber buildings do however use a significantly higher proportion of renewable energy than the other building materials. When split into non-renewable and renewable energy, this can be seen clearly (Figure 5.3). In the end of life stage, steel recycling has the largest impact reduction, due to the offset of energy-intensive virgin steel production – this benefits both the steel and concrete buildings. Energy from timber decomposition in landfill is relatively small in comparison, though still results in output of energy.

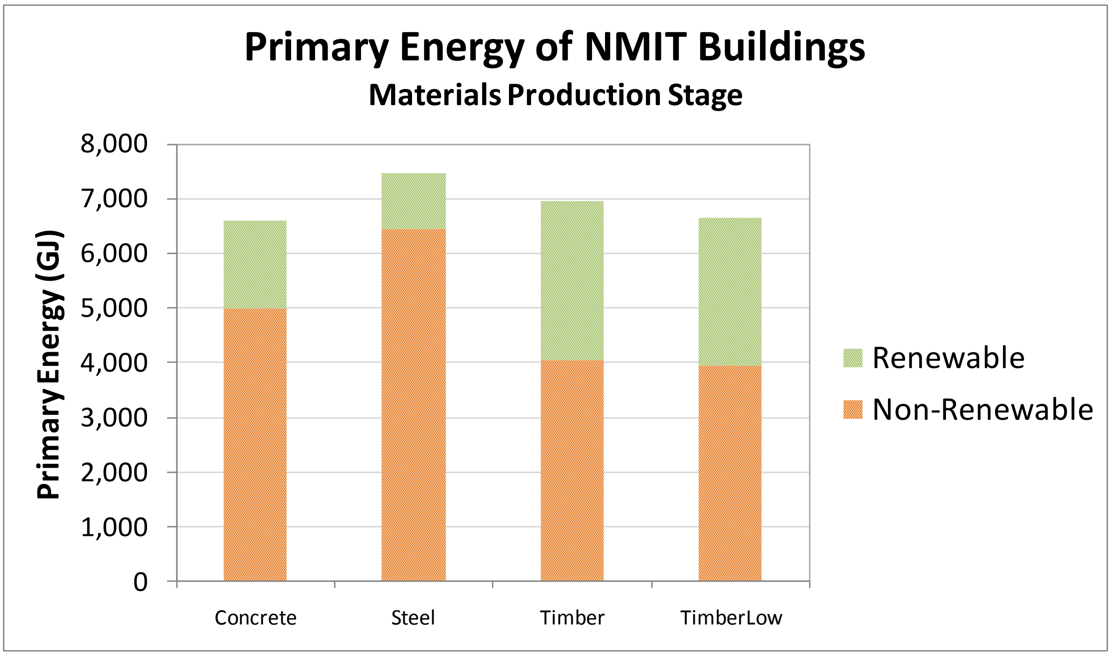


Figure 5.3: Renewable and non-renewable energy balance of NMIT materials production stage

The GWP results for the different building variants are shown below in Table 5.2 and Figure 5.4. Again, the dominant stage is the operation of the building, which is unsurprising due to the heating needed over 60 years. Because of the focus on energy efficiency in the TimberLow building, its operational emissions are approximately 20% lower than the other buildings. Emissions from the production of materials for the buildings are very low in the Timber and TimberLow buildings, due to CO_2 uptake in the tree growth stage of wood products.

End of life emissions vary, and are again mostly influenced by steel. Recycling of the steel from the Steel and Concrete buildings (and subsequent replacement of virgin steel) was the reason for low figures in this stage. For the Timber and TimberLow buildings, the landfill emissions from decomposition of timber are greater than any offset heat or electricity from landfill gas burning. As with primary energy, the transport stage has minimal impact over the life cycle.

Table 5.2: GWP (t CO_2 eq.) for each NMIT building variant, by life cycle stage

	Concrete	Steel	Timber	TimberLow
Materials	381	490	33	16
Transport	27	20	17	17
Operation	2,376	2,419	2,347	1,868
Maintenance	77	76	76	51
End of Life	33	-128	178	178
Total	2,894	2,878	2,651	2,129

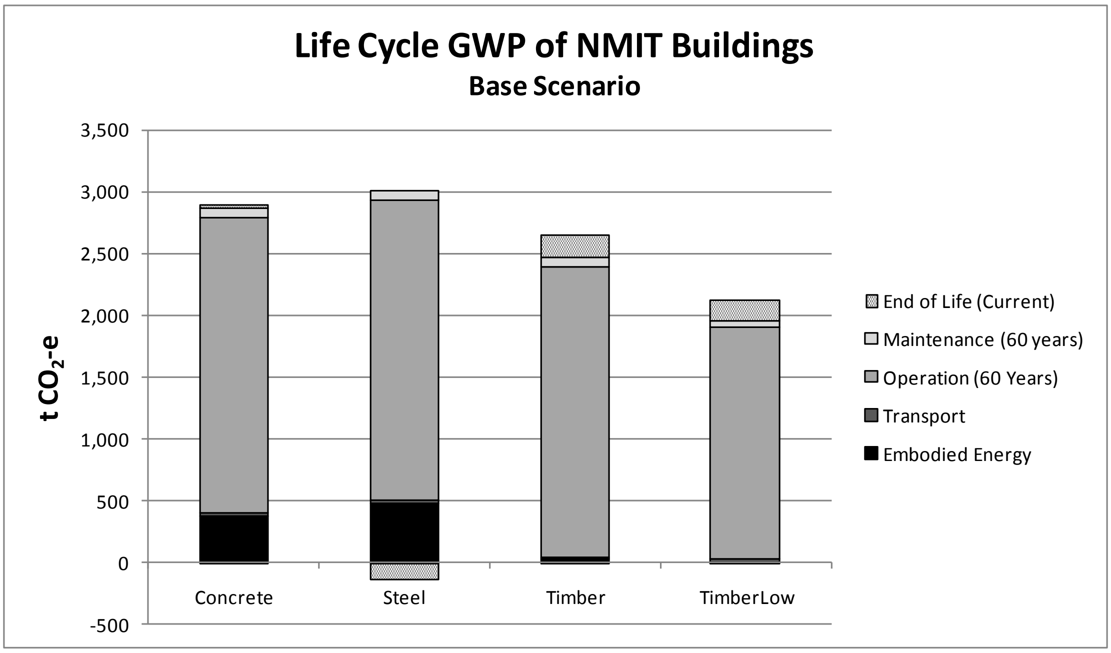


Figure 5.4 GWP for each NMIT building variant, by life cycle stage

6. Scenarios

As described in the section entitled „Life Cycle Assessment – Inventory Analysis', there is an additional scenario taken into account in this project. This scenario investigates the impact of predicted end of life processes in the future. This scenario involves recycling of high levels of steel, concrete (into aggregate substitute) and aluminium. Wood is burned in a high-efficiency cogeneration plant, and is used to offset other sources of energy. The results for the future disposal and recycling scenarios, as well as comparing 60- and 100-year building life spans are shown in Figure 6.1and Figure 6.2 below.

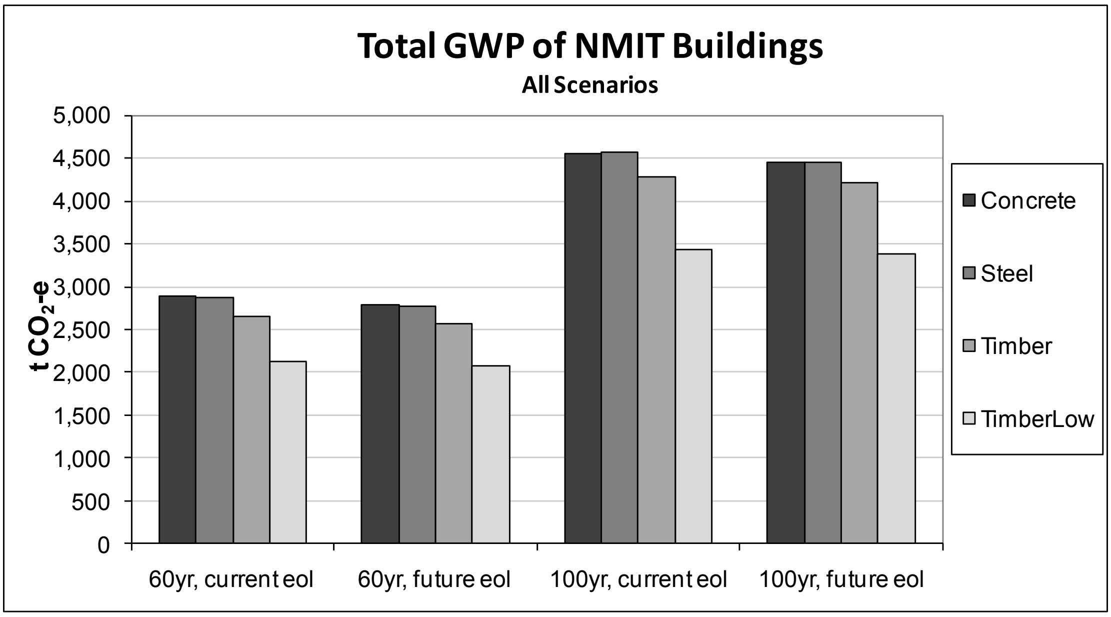


Figure 6.1: Comparison of total GWP of NMIT building variants over 60- and 100-year time frames, and current and future end of life processes. (eol = end of life)

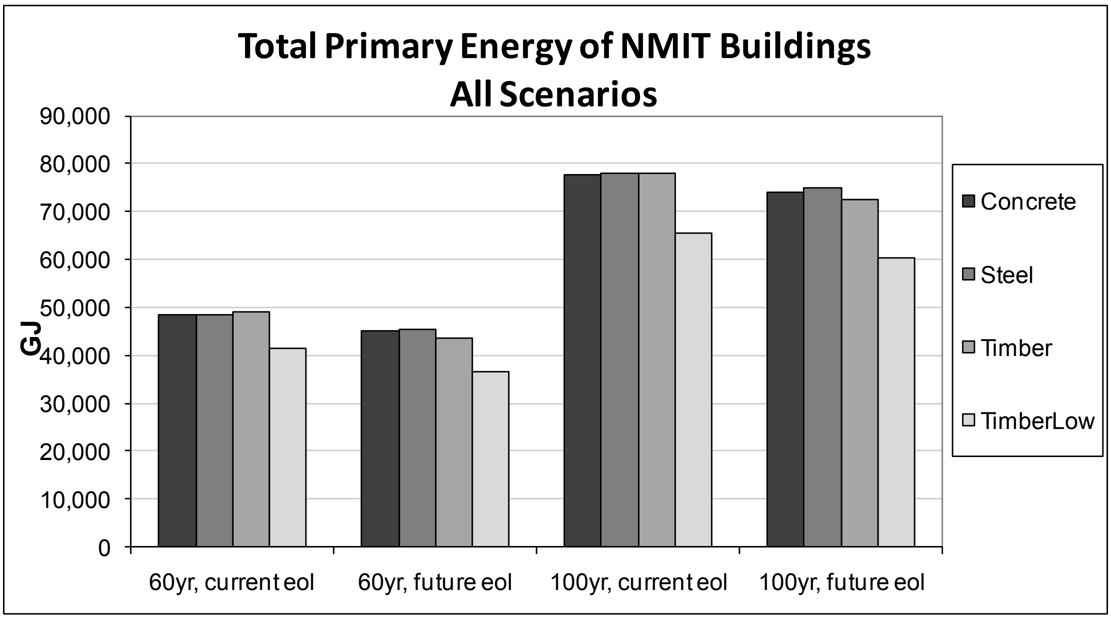


Figure 6.2: Comparison of total primary energy consumption of NMIT building variants over 60- and 100-year time frames, and current and future end of life processes. (eol = end of life)

The results of the different scenarios show clear trends that follow on from the base case. A 66% increase in lifespan (from 60 to 100 years) increases the operational and maintenance impacts by a similar amount. Due to the operation stage being the dominant stage in the building's life cycle the total impacts increase by approximately 60% in the 100-year scenario. The materials, transport and end of life are unchanged in this comparison.

When investigating the different end of life options (base scenario versus future total recycling and energy recovery scenario), the end of life results for GWP and primary energy improve noticeably with future waste options. In Figure 6.3, the end of life primary energy use is shown, and in all cases it is negative, meaning that the end of life stage results in an energy output (or avoidance of impact). The end of life energy avoidance of the Steel building doubles, Concrete energy avoidance trebles, and the energy output of the Timber building improves almost tenfold. These changes are driven mainly by steel recycling, energy recovery from timber products, and aluminium recycling of aluminium-framed windows.

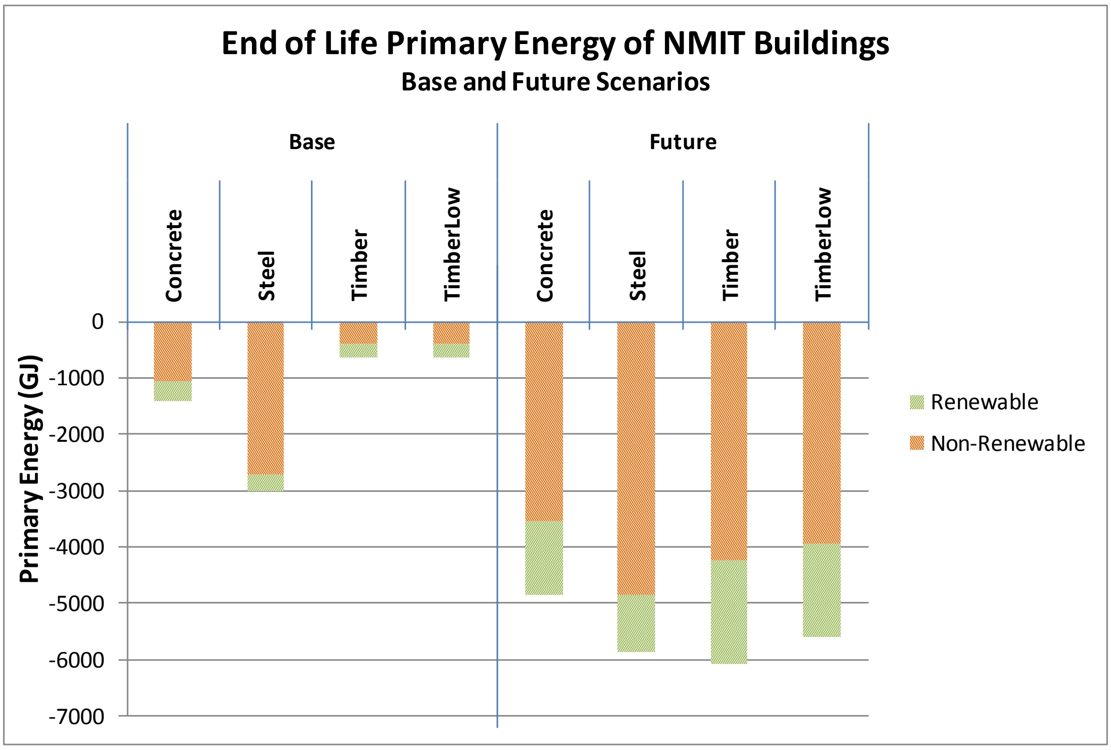


Figure 6.3: Base and future end of life primary energy consumption for each NMIT building variant

7. Discussion and Conclusions

In this project, the new Arts and Media building built with massive LVL structural beams, columns and shear walls (the „Timber' building) was compared with theoretical alternatives, using steel and concrete structural components. In addition, an energy-efficient building was considered (the „TimberLow' building). The global warming potential and energy consumption of each building was investigated, starting from material production and continuing through use and maintenance, and including disposal and recycling processes after life spans of 60 and 100 years.

The dominant stage in the life cycle of every building was the use phase. Electricity from lighting, cooling and other uses, in addition to diesel used in the main boiler, contributed 80-90% of the GWP impacts of the main three buildings, and up to 92% of the TimberLow building's life cycle GWP impacts. Looking at energy use, the use phase contributed from 83% to 95% of the life cycle impacts, depending on the building and scenario. These results indicate that a large impact could be made by minimising energy use in this phase; this would be applicable to all buildings.

At the other end of the scale, transport made a very small (<0.5%) impact on the energy use of each building, and was responsible for less than 1% of GWP emissions. Maintenance made up approximately 2.5% to 3.5% of energy use and GWP emissions for each building. The remaining impacts were from material production and end of life processes.

The Timber and TimberLow buildings differ from the Steel and Concrete buildings in that their GWP emissions begin with an uptake of CO_2, in the form of tree growth. This means that in a cradle to gate analysis, the Timber and TimberLow buildings have negative GWP values due to carbon stored in the materials. The Steel and Concrete buildings generally have larger GWP emissions and energy usage in this style of analysis, as production of the raw materials is an energy-intensive process, and uses a large proportion of fossil fuels. Conversely, the Timber and TimberLow buildings emit CO_2 when disposed of in present-day landfill, while much steel is recycled, avoiding emissions from virgin steel production.

When the base scenario is considered, the TimberLow building shows considerably lower energy use and GWP emissions than the other buildings. This is not unexpected as it has been designed as a low energy building; it should also be noted that this analysis does not include economics. Of the three conventional building designs, the total energy use is effectively the same for all buildings. When split into energy types, the Timber building has a higher renewable energy figure (24% in the base scenario) than the other buildings (21-22%), and therefore a lower non-renewable energy figure, thus reducing its reliance on fossil fuels. Most of this can be attributed to the materials production stage. The Timber building has a GWP figure approximately 8% lower than the Steel and Concrete buildings.

A future end of life scenario is considered in this study, where wood waste is incinerated in a high-efficiency plant, and steel, concrete and aluminium are recycled. In this case, the only noticeable change in relative impacts is that the energy use of the Timber building drops slightly below that of the Steel and Concrete buildings. This difference is not large, and thus it is not conclusive which of the conventional buildings would have the lowest overall energy use in this scenario. Again, the Timber building uses a higher proportion of renewable energy, which indicates that the building incorporates more energy from electricity and wood waste than the other buildings (which tend to use more fossil fuels in their production).

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Appendix A: Material Quantities

CONCRETE BUILDING							
	m	m2	workings		m3	density	**tonnes**
Concrete in;							
Beam Foundations					35.69		**82.44**
Pile Caps					204.73		**472.93**
Pad Foundations					21.95		**50.70**
Ground Floor Slabs					100.95		**233.19**
Suspended Floor Slabs					113.28	2.31	**261.68**
Beams					102.62		**237.05**
Columns					58.52		**135.18**
Walls					61.00		**140.91**
Stairs					8.40		**19.40**
Reinforcing Steel in;							
Beam Foundations					35.69	0.3	**10.71**
Pile Caps					204.73	0.35	**71.66**
Pad Foundations					21.95	0.3	**6.59**
Ground Floor Slabs				667.00		0.003211	**2.14**
Suspended Floor Slabs				1187.00		0.006939	**8.24**
Beams					102.62	0.2	**20.52**
Columns					58.52	0.15	**8.78**
Walls					61.00	0.1	**6.10**
Stairs				8.40		0.15	**1.26**
Structural Steel in;							
Rafters							**10.61**
Beams							**7.54**
Purlins							**9.28**
Dissipator							**0.07**
Macalloy Post Tensioners							**2.57**
Other Steel in;							
Wall Cladding							**3.01**
Roof Cladding							**5.70**
Soffits							**0.27**
Spouting							**0.16**
Downpipes							**0.20**
Glass in;							
Windows							**23.03**
Doors							**0.50**
Borrowed Lights							**3.94**
Timber in;							
Interspan Flooring							**35.28**
Rainscreen Cavity Battens							**0.69**
External Wall Framing							**5.71**
Roof Framing							**3.99**
Soffit Framing							**1.76**
Internal wall framing							**18.46**
ceiling framing							**3.69**
ceiling battens							**0.97**
Plywood roofs							**1.58**
Plywood diaphragm							**7.43**
Plywood Walls							**7.32**
Plywood ceilings							**1.93**
Plywood balustrading							**0.88**
Doors							**1.58**
Skirtings							**0.19**

Aluminium in:							
Windows							**2.51**
Doors							**0.05**
Borrowed lights							**0.79**
Facings							**0.07**
Fins							**0.14**
Louvres							**0.13**
Plasterboard to:							
Walls - 13 Standard							**6.18**
Ceilings - 13 Standard							**7.83**
Paint to:				Total m2		Density	
Exterior Walls				205.00		0.000108	**0.02**
Exterior Soffits				208.00			**0.02**
Interior Walls				2153.00			**0.23**
Ceilings				1540.00			**0.17**
Concrete				1528.00			**0.17**
Steelwork				486.00			**0.05**
Doors				175.20			**0.02**
Skirtings				641.00			**0.07**
Particleboard/fibreboard to:							
Hardpanel Walls							**2.77**
Villaboard soffits							**1.77**
MDF Walls							**3.79**
MDF Ceilings/Bulkheads							**2.37**
Insulation to:		m2					
Walls - R3.6		495				0.0015	**0.74**
Walls - acoustic		623				0.014	**8.72**
Walls - Fire		256				0.00045	**0.12**
Ceilings - R5.0		786				0.002952	**2.32**
Ceilings - Acoustic		317				0.014	**4.44**

S T E E L   B U I L D I N G

	m	m2	workings		m3	density	tonnes
Concrete in;							
Beam Foundations					35.69		**82.44**
Pile Caps					149.13		**344.49**
Pad Foundations					13.55	2.31	**31.30**
Ground Floor Slabs					100.95		**233.19**
Suspended Floor Slabs					128.17		**296.07**
Stairs				3.60			**8.32**
Reinforcing Steel in;							
Beam Foundations					35.69	0.3	**10.71**
Pile Caps					149.13	0.35	**52.20**
Pad Foundations					13.55	0.3	**4.07**
Ground Floor Slabs				667.00		0.003211	**2.14**
Suspended Floor Slabs				1187.00		0.006939	**8.24**
Stairs				3.60		0.15	**0.54**
Structural Steel in;							
Rafters							**10.61**
Columns							**39.51**
Beams							**45.05**
Braces							**14.76**
Purlins							**9.28**
Stairs							**1.46**
Dissipator							**0.07**
Macalloy Post Tensioners							**2.57**
Other Steel in;							
Comflor							**11.42**
Wall Cladding							**3.01**
Roof Cladding							**5.70**
Soffits							**0.27**
Spouting							**0.16**
Downpipes							**0.20**
Balustrading							**3.12**
Glass in;							
Windows							**23.03**
Doors							**0.50**
Borrowed Lights							**3.94**
Timber in;							
Rainscreen Cavity Battens							**0.69**
External Wall Framing							**5.71**
Roof Framing							**3.99**
Soffit Framing							**1.76**
Internal wall framing							**19.95**
ceiling framing							**3.69**
ceiling battens							**0.97**
Plywood roofs							**1.58**
Plywood diaphragm							**7.43**
Plywood Walls							**7.32**
Plywood ceilings							**1.93**
Doors							**1.58**
Skirtings							**0.19**

Aluminium in;							
Windows							**2.51**
Doors							**0.05**
Borrowed lights							**0.79**
Facings							**0.07**
Fins							**0.14**
Louvres							**0.13**
Plasterboard to;							
Walls - 13 Standard							**8.93**
Ceilings - 13 Standard							**7.83**
Paint to;				Total m2		Density	
Exterior Walls				205.00			**0.02**
Exterior Soffits				208.00			**0.02**
Interior Walls				2469.00			**0.27**
Ceilings				1540.00		0.000108	**0.17**
Steelwork				2328.00			**0.25**
Doors				175.20			**0.02**
Skirtings				641.00			**0.07**
Particleboard/fibreboard to;							
Hardpanel Walls							**2.77**
Villaboard soffits							**1.77**
MDF Walls							**3.79**
MDF Ceilings/Bulkheads							**2.37**
Insulation to;		m2					
Walls - R3.6		495				0.0015	**0.74**
Walls - acoustic		623				0.014	**8.72**
Walls - Fire		256				0.00045	**0.12**
Ceilings - R5.0		786				0.002952	**2.32**
Ceilings - Acoustic		317				0.014	**4.44**

T I M B E R   B U I L D I N G

	m	m2	workings		m3	density	tonnes
Concrete in;							
Beam Foundations					35.69		**82.44**
Pile Caps					149.13		**344.49**
Pad Foundations				13.55		2.31	**31.30**
Ground Floor Slabs					100.95		**233.19**
Suspended Floor Slabs					113.28		**261.68**
Stairs				3.60			**8.32**
Reinforcing Steel in;							
Beam Foundations					35.69	0.3	**10.71**
Pile Caps					149.13	0.35	**52.20**
Pad Foundations				13.55		0.3	**4.07**
Ground Floor Slabs				667.00		0.003211	**2.14**
Suspended Floor Slabs				1187.00		0.006939	**8.24**
Stairs				3.60		0.15	**0.54**
Structural Steel in;							
Dissipator							**0.07**
Macalloy Post Tensioners							**2.57**
Other Steel in;							
Wall Cladding							**3.01**
Roof Cladding							**5.70**
Soffits							**0.27**
Spouting							**0.16**
Downpipes							**0.20**
Glass in;							
Windows							**23.03**
Doors							**0.50**
Borrowed Lights							**3.94**
Timber in;							
Rainscreen Cavity Battens							**0.69**
External Wall Framing							**5.71**
Roof Framing							**3.99**
Soffit Framing							**1.76**
Internal wall framing							**18.46**
ceiling framing							**3.69**
ceiling battens							**0.97**
Plywood roofs							**1.58**
Plywood diaphragm							**7.43**
Plywood Walls							**7.32**
Plywood ceilings							**1.93**
Plywood balustrading							**0.88**
Doors							**1.58**
Skirtings							**0.19**
LVL in;							
Columns							**20.64**
Beams							**37.04**
Rafters							**15.35**
Purlins							**10.30**
Walls							**29.17**
Stairs							**4.35**
Potius Flooring							**46.61**

Aluminium in;							
Windows							**2.51**
Doors							**0.05**
Borrowed lights							**0.79**
Facings							**0.07**
Fins							**0.14**
Louvres							**0.13**
Plasterboard to;							
Walls - 13 Standard							**6.18**
Ceilings - 13 Standard							**7.83**
Paint to;				Total m2		Density	
Exterior Walls				205.00			**0.02**
Exterior Soffits				208.00			**0.02**
Interior Walls				2153.00			**0.23**
Ceilings				1540.00		0.000108	**0.17**
LVL				2096.00			**0.23**
Doors				175.20			**0.02**
Skirtings				641.00			**0.07**
Particleboard/fibreboard to;							
Hardpanel Walls							**2.77**
Villaboard soffits							**1.77**
MDF Walls							**3.79**
MDF Ceilings/Bulkheads							**2.37**
Insulation to;		m2					
Walls - R3.6		495				0.0015	**0.74**
Walls - acoustic		623				0.014	**8.72**
Walls - Fire		256				0.00045	**0.12**
Walls - 100 EPS		144				0.00105	**0.15**
Ceilings - R5.0		786				0.002952	**2.32**
Ceilings - Acoustic		317				0.014	**4.44**

TIMBER LOW BUILDING

	m	m2	workings	m3	density	tonnes
Concrete in;						
Beam Foundations				35.69		**82.44**
Pile Caps				149.13		**344.49**
Pad Foundations			13.55		2.31	**31.30**
Ground Floor Slabs				100.95		**233.19**
Suspended Floor Slabs				113.28		**261.68**
Stairs			3.60			**8.32**
Reinforcing Steel in;						
Beam Foundations				35.69	0.3	**10.71**
Pile Caps				149.13	0.35	**52.20**
Pad Foundations			13.55		0.3	**4.07**
Ground Floor Slabs			667.00		0.003211	**2.14**
Suspended Floor Slabs			1187.00		0.006939	**8.24**
Stairs			3.60		0.15	**0.54**
Structural Steel in;						
Dissipator						**0.07**
Macalloy Post Tensioners						**2.57**
Other Steel in;						
Wall Cladding						**3.01**
Roof Cladding						**5.70**
Soffits						**0.27**
Spouting						**0.16**
Downpipes						**0.20**
Windows						**2.20**
Doors						**0.04**
Glass in;						
Windows						**23.03**
Doors						**0.50**
Borrowed Lights						**3.94**
Timber in;						
Rainscreen Cavity Battens						**0.69**
External Wall Framing						**5.71**
Roof Framing						**3.99**
Soffit Framing						**1.76**
Internal wall framing						**18.46**
ceiling framing						**3.69**
ceiling battens						**0.97**
Plywood roofs						**1.58**
Plywood diaphragm						**7.43**
Plywood Walls						**7.32**
Plywood ceilings						**1.93**
Plywood balustrading						**0.88**
Doors						**1.58**
Skirtings						**0.19**

LVL in;							
Columns							**20.64**
Beams							**37.04**
Rafters							**15.35**
Purlins							**10.30**
Walls							**29.17**
Stairs							**4.35**
Potius Flooring							**46.61**
Aluminium in;							
Borrowed lights							**0.79**
Facings							**0.07**
Fins							**0.14**
Louvres							**0.13**
PVC in;							
Windows	1.1 1.6 1.9	555 114 75			0.9354000		**1.31**
Doors	2.1	8			0.0168	1.4	**0.02**
Plasterboard to;							
Walls - 13 Standard							**6.18**
Ceilings - 13 Standard							**7.83**
Paint to;				Total m2		Density	
Exterior Walls				205.00			**0.02**
Exterior Soffits				208.00			**0.02**
Interior Walls				2153.00			**0.23**
Ceilings				1540.00		0.000108	**0.17**
LVL				2096.00			**0.23**
Doors				175.20			**0.02**
Skirtings				641.00			**0.07**
Particleboard/fibreboard to;							
Hardpanel Walls							**2.77**
Villaboard soffits							**1.77**
MDF Walls							**3.79**
MDF Ceilings/Bulkheads							**2.37**
Insulation to;		m2					
Walls - R3.6		495				0.0015	**0.74**
Walls - R2.0 Cosyfloor		495				0.001239	**0.61**
Walls - 100 EPS		144				0.0021	**0.30**
Walls - acoustic		623				0.014	**8.72**
Walls - Fire		256				0.00045	**0.12**
Ceilings - R5.0		786				0.002952	**2.32**
Ceilings - R2.2		786				0.000944	**0.74**
Ceilings - Acoustic		317				0.014	**4.44**

Appendix B: Maintenance Schedules

Paint					times repainted (2 coats)	
	Square Metres				60 years	100 years
	Timber	Concrete	Steel	Timber Low		
Paint - Repaint at yr 15 then every 10 yrs	6207	6580	5990	6207	5	9
Paint - Repaint at yr 20 then every 20 yrs	625	1111	2116	625	2	4
Paint - Repaint at yr 30 then every 30 yrs	1563	622	0	1563	1	3
Spouting/Downpipes					# Replacements in timeframe	
	Amount of Material in Building (kg)				60 years	100 years
	Timber	Concrete	Steel	Timber Low		
Steel in spouting downpipes	360	360	360	360	1	3
Windows						
Glass in windows	23030	23030	23030	23030	1	2
Aluminium in windows	2510	2510	2510	0	1	2
PVC in Windows	0	0	0	1310	1	3
Steel in windows	0	0	0	2200	0	1
Membrane						
Bitum membrane - ignored due to lack of data						
Seratone						
MDF (used as approximation)	510	510	510	510	1	3
Doors & Fins						
All aluminium fins replaced once	140	140	140	140	1	1
Doors - glass	500	500	500	500	1	2
Doors - timber	1580	1580	1580	1580	1	2
Doors - aluminium	50	50	50	0	1	2
Doors - PVC	0	0	0	24	1	2
Doors - Steel	0	0	0	40	1	2

APPENDIX E

Photos of construction sequence

by
K. Mulligan

Appendix E. Series of photographs showing stages in construction sequence of the three storey Arts and Media building at NMIT. (Courtesy of K. Mulligan).

Figure E.1. Main fabricating area at HunterBond Ltd., near Nelson. LVL elements for the NMIT three storey Arts and Media Teaching block can be seen. Column – foreground left, Beam – foreground

Figure E.2. Laminated LVL sheets glued into larger blocks to fabricate LVL elements. Recently glued – lower. Fabricated – upper.

Figure E.3 LVL column showing check out to fit beams.

Figure E.4 NMIT Arts and Media building site. The three storey Teaching block is in the foreground with the Workshop area to the right, and the Media complex at the back (Nile Street, to the left).

Figure E.5 Foundation for shear wall with steel shoe to seat shear wall and attachment points for Macalloy bars.

Figure E.6 Foundation and attachment for column. Note the elevation to allow floor slab to be poured.

Figure E.7 LVL elements arriving at the site by truck. The elements are hoisted off the truck by crane – seen in background.

Figure E.8 Column being hoisted into place by crane. The elements are hoisted from one end and manoeuvred into position at the other end by hand.

Figure E.9 LVL elements being moved around the site by crane. The increased height of the crane allowed elements to be lifted over the existing structure.

Figure E.10 Shear wall lifted from horizontal position into place. The walls are raised using two strops, tilted to vertical and lifted into place via the top strop.

Figure E.11 Shear wall being placed into steel shoe.

Figure E.12 Manoeuvring the base of the shear wall into the steel shoe.

Figure E.13 Connection between column and beams. There is one more bay to be constructed to the right, the beam of which will be connected to the rods epoxied into the existing right side beam.

Figure E.14 Shear wall in position but not attached to corresponding beam.

Figure E.15 Temporary bracing to right side of rear bay frame and shear walls. The temporary bracing stays in position until the floors have been constructed.

Figure E.16 Interior temporary bracing to frame. The collars to attach the bracing have to be carefully fitted to ensure minimal marking of the timber surface.


Figure E.17 Top of the shear wall showing top anchoring of Macalloy bars and instrumentation to measure movement in the Macalloy bars

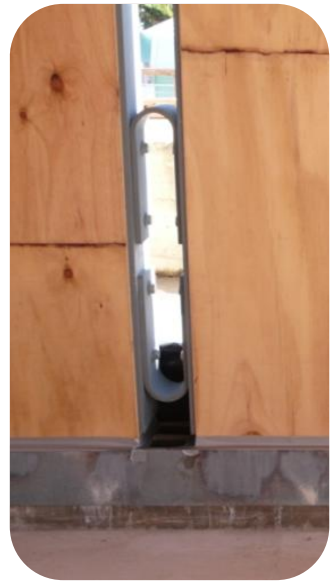


Figure E.18 U-shaped dissipaters in-between shear walls.


Figure E.19 Bottom of a shear wall showing the Macalloy bars attached into the anchoring points.

Figure E.20 Structure taking shape, shear walls in position and final columns being lifted into position. The Workshop structure is in the foreground.

Figure E.21 Shear walls showing pivot and sliding connections to beams and steel blocks for U-shaped dissipaters.

Figure E.22 *Potius* floor panels hoisted as a stack up to second floor level.

Figure E.23 *Potius* floor panels in position and others stacked ready to be placed.

Figure E.24 Second floor level with plastic laid ready to pour concrete topping.

Figure E.25 Coach screws into beams in-between frame bays.

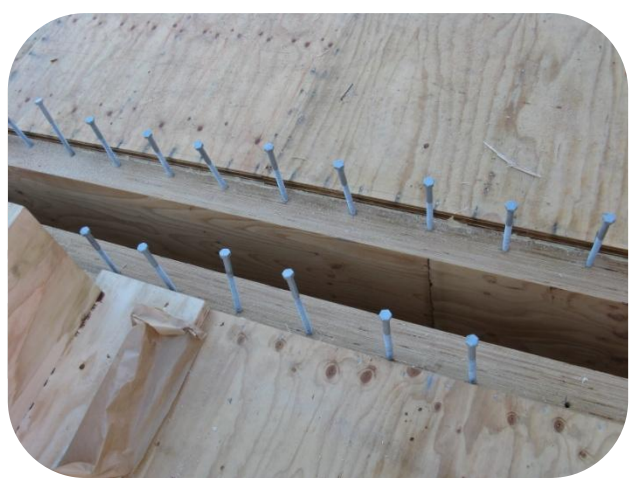


Figure E.26 Underside of second floor showing flanges of I floor panels.

Figure E.27 Underside of second floor showing forming for cantilevered concrete section of floor to the south of the building.

Figure E.28 Underside of concrete cantilevered floor section.

Figure E.29 Collars for temporary bracing to a column and protection to limit marking on timber surface.

Figure E.30 Plastic covering on exposed end grain of columns to increase moisture protection over and above weather shield sealant.

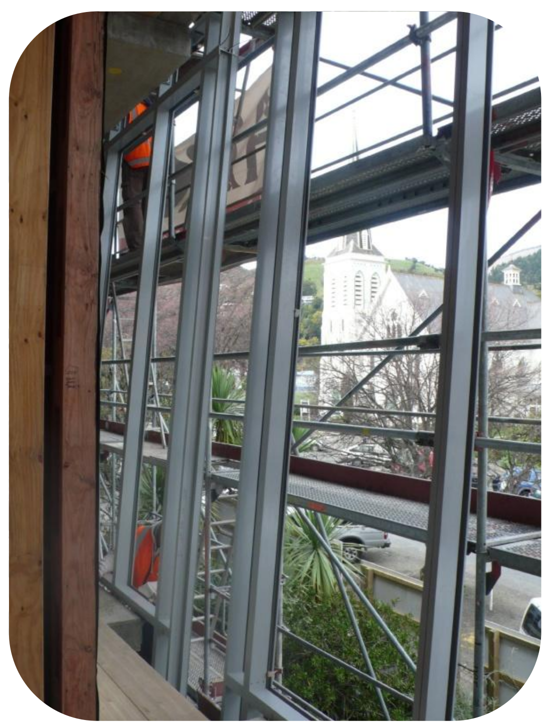
Figure E.31 Plastic capping to exposed ends of shear walls.

Figure E.32 Third floor level with *Potius* floor panels in place. View is looking along southern bay towards the east.

Figure E.33 Reinforcing for concrete floor topping.

Figure E.34 Front elevation of three storey building showing glazing and timber structure behind.

Figure E.35 Rear elevation sloped glazed panels.



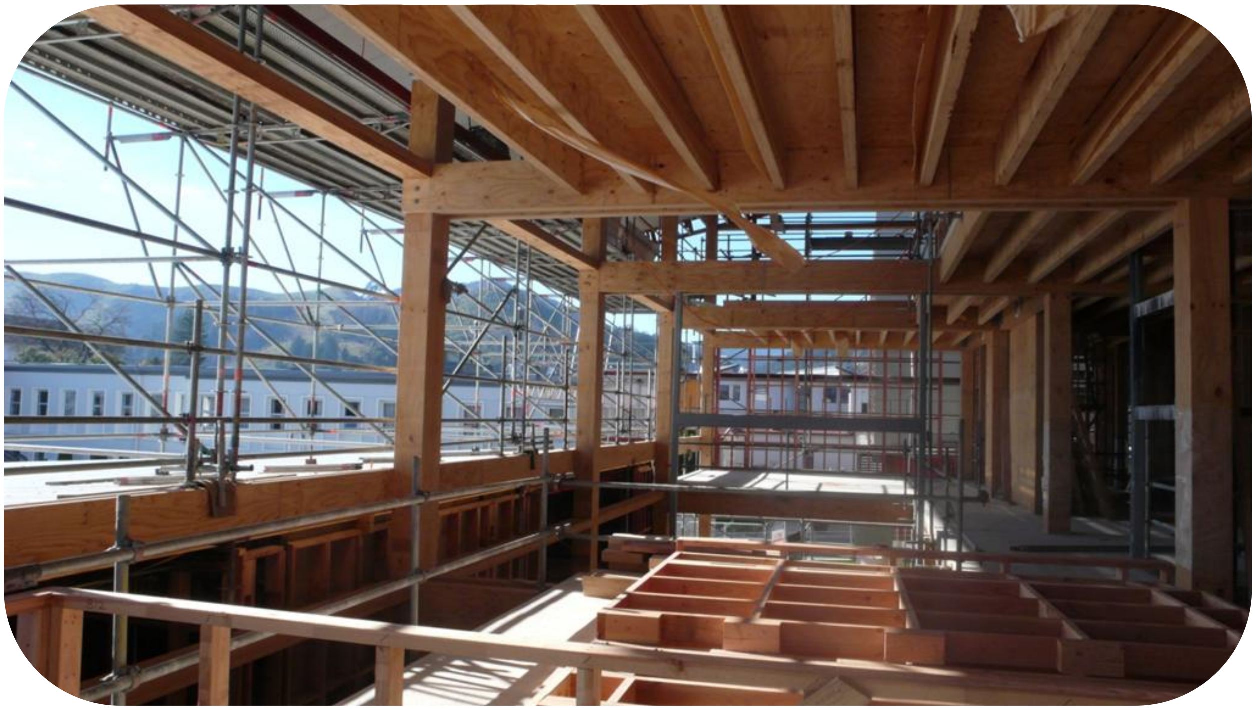


Figure E.36 Interior view of second floor with interior wall frames ready for installation.

Figure E.37 Connection of column and beams and underside of *Potius* floor panels. Exposed services add to the aesthetic of the building.

Figure E.38 Instrumentation to measure relative movement between LVL elements.