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NMIT Arts & Media Building—Innovative structural design of a three storey post-tensioned timber building

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ABSTRACT

The NMIT Arts & Media Building in Nelson, New Zealand is the first in a new generation of multi-storey timber structures. It employs a number of innovative timber technologies including an advanced damage avoidance earthquake design that is a world first for a timber building. Aurecon structural engineers are the first to use this revolutionary Pres-Lam technology developed at the University of Canterbury.

This technology marks a fundamental change in design philosophy. Conventional seismic design of multi-storey structures typically depends on member ductility and the acceptance of a certain amount of damage to beams, columns or walls. The NMIT seismic system relies on pairs of coupled timber shear walls that incorporate high strength steel tendons post-tensioned through a central duct. The walls are centrally fixed allowing them to rock during a seismic event. A series of U-shaped steel plates placed between the walls form a coupling mechanism, and act as dissipaters to absorb seismic energy. The design allows the primary structure to remain essentially undamaged in a major earthquake while readily replaceable connections act as plastic fuses.

With a key focus on sustainability the extensive use of timber and engineered-wood products such as laminated veneer lumber (LVL) makes use of a local natural resource, all grown and manufactured within an 80 km radius of Nelson.

This IstructE award winning project demonstrates that there are now cost effective, sustainable and innovative solutions for multi-storey timber buildings with potential applications for building owners in seismic areas around the world.

1. Introduction

1.1. Project background

In an effort to promote the use of timber in multi-storey construction the New Zealand Ministry of Agriculture and Forestry agreed to invest $1 M into the design and construction of the Nelson-Marlborough Institute of Technology (NMIT)

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Fig. 1. 3D view of the NMIT Arts and Media Building Structure.

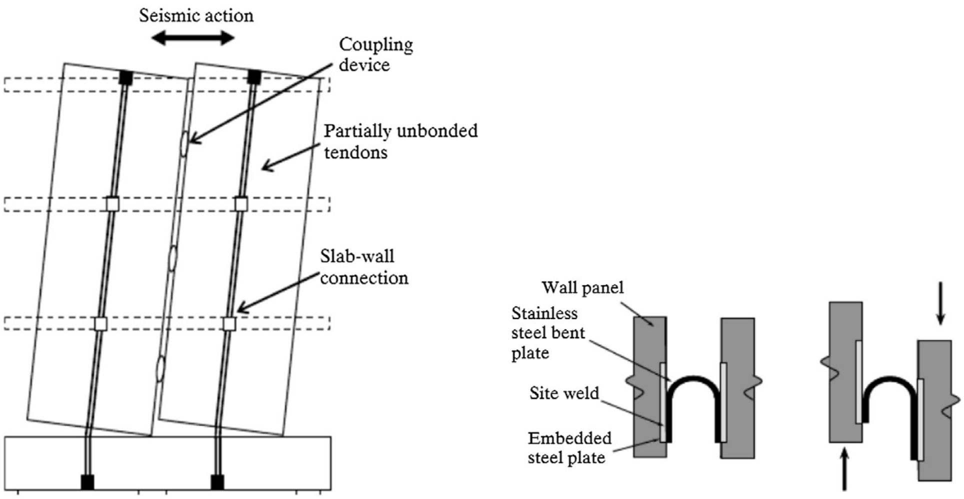

Fig. 2. Mechanism of coupled hybrid wall and UFP dissipaters.

Arts and Media building project. The completed building was required to demonstrate the innovative use of timber, and showcase to the construction industry the viability of multi-storey commercial construction in timber.

The NMIT project was awarded to Aurecon following a national design competition open to all consultants. Aurecon with Irving Smith Jack Architects won the competition against a number of New Zealand's top architects and engineers.

Fig. 1 shows a 3D rendering of the finished building structure. The main structural material is laminated veneer lumber (LVL), using radiata pine, manufactured by Nelson Pine Industries.

1.2. Innovation in timber design

A number of innovative timber solutions were implemented as part of the overall project. NMIT represents a "world first" in terms of innovative timber technology and seismic design. Seismic lateral bracing is provided through pairs of LVL coupled shear walls that incorporate high strength steel tendons post-tensioned through a central duct. The walls are centrally fixed which allows them to rock, rather than sustaining damaged to the plastic hinge region, during a seismic event. Pairs of U-shaped Flexural Steel Plates (UFPs) are placed between the panels to provide additional moment-resisting coupling, as well as, act as energy dissipaters/fuses absorbing seismic energy. Fig. 2 adapted from Buchanan et al. [1] illustrates the shear wall rocking mechanism and action of the UFP dissipaters.

These concepts are part of a new philosophy in Performance-Based Engineering. The use of rocking/dissipative jointed ductile connections relying upon the use of post-tensioning techniques (typically referred to as PRESSS-technology) was originally developed in the US during the late 1990s for precast concrete structures [6–7,9].

The system minimises damage to the structure by focusing plastic deformations on readily replaceable connections, allowing the building to remain operational after a major earthquake event. The structural solution adopted has embraced this emerging new design philosophy providing a landmark timber building. The design is based on the latest and extensive research carried out by the University of Canterbury to develop Prestressed Laminated timber solutions (Pres-Lam) for multi-storey timber buildings described by Pampanin et al. [8], Iqbal et al. [2], Smith et al. [11], and Buchanan et al. [1]. Such patented technology, owned by a spin-off company of the University of Canterbury (Prestressed Timber limited) is now being promoted through New Zealand and Australia by the R&D Research Consortium STIC Ltd (Structural Timber Innovation Company) as the "EXPAN building system incorporating Pres-Lam technology".

Essential to the delivery of any new technology is the ability to meet local and international standards and regulations. With this in mind the assistance of University of Canterbury researchers was enlisted. A University design team, including Dr Andy Buchanan (now of PTL), Dr Stefano Pampanin and then PhD students Michael Newcombe and Kam Weng, provided valuable comments and feedback throughout the structural design phase. This team assisted Alistair Cattanach of Dunning Thornton Consultants to peer review critical aspects of the design to ensure a robust solution. Non-linear time-history analyses, using lumped plasticity models implemented in Ruaumoko (Carr, 2008), and based on the latest procedures developed and extensively validated for Pres-Lam connections were carried out as part of the seismic design verification.

2. Structural systems

2.1. Building description

The new NMIT Arts and Media facility is divided into three blocks: The three storey studio/gallery/teaching wing, the workshop wing and the music and drama wing. The main focus of this paper is on the structural system incorporated in the three storey wing where much of the timber design innovation has been applied. The building footprint for the main three storey wing covers an area of approximately 500 m^2 per floor.

2.2. LVL (laminated veneer lumber)

The use of Nelson Pine LVL was a natural choice given the proximity of their LVL plant to the building site. The LVL timber product has strength properties (in the range of 30–40 MPa) that allow for the fabrication of beams, columns and walls at sizes similar to those used in concrete and steel design. The LVL structural system enabled the use of traditional structural grids that allowed long clear spans and large floor plates free of columns. A particular challenge for the structural designers is the low elastic modulus of LVL, typically in the range of 11 GPa. Innovative design was required in the use of composite timber and concrete sections to ensure that deflections were effectively controlled.

All LVL timber beams, columns and walls were fabricated off-site in a manner similar to pre-cast concrete. With the ability to transport large sections to site and its lower weight by volume, the use of LVL allowed for simpler craneage, fewer site connections and considerable speed of erection.

A main feature of the NMIT project was the minimisation of its 'carbon footprint'. Using timber as the predominant structural system takes advantage of wood's inherent carbon storage. The building structure itself acts as an effective carbon sink resulting in a negative 'carbon footprint'. This project reduced embodied energy within the structural components and energy use associated with transport.

With sustainability being a key focus, the full timber design makes use of a natural resource grown and manufactured within an 80 km radius of Nelson. All of the structural timber supplied for the project was locally grown, with each individual panel of LVL traceable to a specific forest plantation.

2.3. Post-tensioned LVL shear walls

The lateral load resisting system promotes the very latest in damage avoidance technology for timber structures. As this is a world first commercial application of a post-tensioned hybrid rocking wall system in timber, precautions were taken to ensure that the system would not be too highly stressed at the design limits considered. Tests and numerical analysis performed at the University of Canterbury have shown that this system can be easily used for buildings up to six storeys in height [2,11].

The bracing system in both the longitudinal and transverse directions is provided by two sets of post-tensioned coupled shear walls. To meet the NMIT and architects brief the design had to allow for open plan floor spaces at each storey while also providing for large uninterrupted external wall elevations. The use of the LVL shear walls provides this, and future proofs the building for possible re-developments. Each shear wall is a hybrid system (e.g. self-centering and dissipative) comprising of two 3.0 m long LVL post-tensioned and coupled shear wall panels, constructed from 3 × 63 mm wide LVL sections. Fig. 3 shows details of the panel construction, post-tensioning rods, and energy dissipation devices.

Each panel is vertically post-tensioned to the foundation through a central opening using 4–32 mm diameter Macalloy rods. Starter (post-tensioning) bars are cast into the foundation ground beams and coupled to the main bars though an opening left at the bottom of the panel. An additional opening was provided at the top of the wall to accommodate stressing jacks. Strain gauges have been placed on the bars for ongoing monitoring and maintenance to ensure that relaxing of the

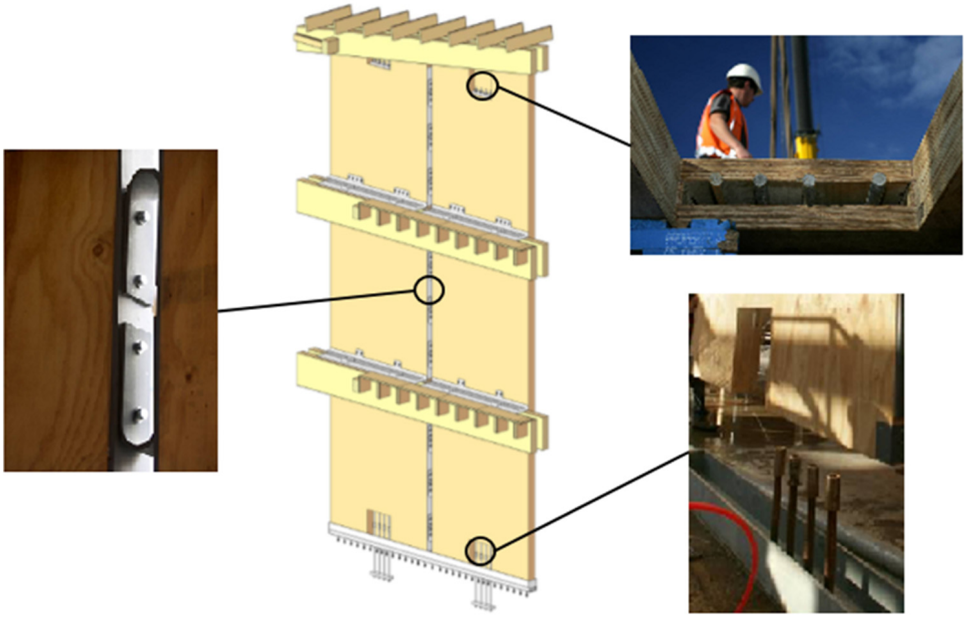

Fig. 3. LVL Coupled Shear Walls showing Post-Tensioning Rods and U-Shape Flexural Plates (UFP) Energy Dissipating Devices.

bars, creep, and shrinkage of the timber donot compromise the initial design post-tensioning. The initial design stress in this case is approximately 60% of yield (e.g. 350 kN per rod for a total of 1400 kN axial load). At the design level drift, elongation of the rods due to wall uplift increases the tensile stress, which was checked to remain under 90% of yield. It is important for the re-centring behaviour of the structure that the post-tensioning rods are not overstressed beyond their elastic yield limit.

U-shaped flexural plates (UFPs) act as energy dissipation devices between the timber panels. 6 sets of UFPs, (2 pairs per storey) couple together the wall units. 140×16 Grade 300 MPa mild steel plates were machined and connected to the panels via friction grip bolts screwed into pre-installed epoxied glued couplers. Oversized holes in the UFP plates provided a building tolerance of +/−5 mm, which was sufficient given the accuracy inherent in the prefabricated construction. This arrangement allowed the UFP's to be installed following placement of the LVL panels aiding construction, as well as, providing a means in which to replace them if required following a major seismic event. The use of UFPs is not a recent technological development having been first researched by Kelly et al. [3] and extensively and successfully tested for both precast concrete and timber solutions [2,9].

Energy dissipation comes in the form of uniform bending of the UFP's as the walls rock. Relative movement along the inside edges of the walls cause the plates to roll, inducing a uniform flexure. The gap between the panels is approximately 200 mm, which strongly influences the amount of energy dissipation and moment capacity provided to the system. The larger the gap, the less tight the radius of the plate, the smaller the flexural demand and thus energy absorbed. A 20 mm steel plate is epoxy dowelled to the inside ends of the walls providing a continuous tie to evenly transfer loads from the UFP's into the panels. The post-tensioning and energy dissipation devices provide moment resistance based on the level of displacement at the joint. As is typically employed with post-tensioned hybrid (rocking-dissipative) systems and connections, the initial post-tensioning force applied was made great enough to overcome the resistance of the energy dissipaters thus allowing the system to re-centre itself following a seismic event. The initial post-tensioning stress is also set so that the bars remain in their elastic range when the walls are at their design displacement and the bars are stretched to their maximum tension levels.

The panels are connected to timber drag beams via 200 mm steel dowels, which in turn, transfer shears forces into the concrete floor diaphragms through multiple sets of coach screws. The dowels allow the panels to rock whilst minimising the curvature and deformations introduced in the floor beams and slab. Lateral restraint is provided by 4 bolts in vertical slots positioned at each end of the panels.

The bottom corners of the LVL panels are armoured with a folded steel plate, and set into a fabricated steel shoe epoxy dowelled into the top of the foundation ground beams. The dowelled connections have Teflon washers which both reduce friction, as well as, prevent the wall from "catching" while rocking. Shear from the LVL coupled panels is transferred to the ground beams through friction and direct bearing. Screw piles cast into each end of the shear wall ground beams carry the design uplift and bearing loads, with reinforced concrete bored piles providing shear transfer into the ground. Fig. 4 shows the installation process and construction method used in erecting the LVL panels.

Fig. 4. Photos taken during construction and installation of LVL post-tensioned and coupled shear panels.

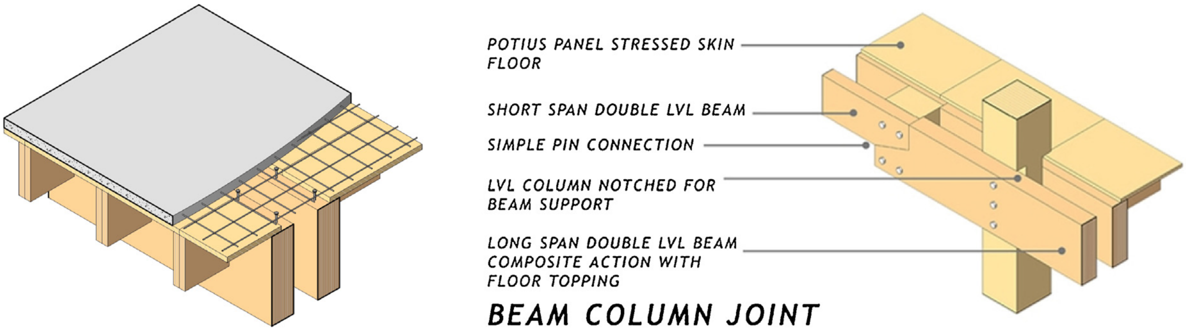

Fig. 5. Details showing Concrete Topping over Potius Panel Stressed Skin Timber Floor.

The facade and glazing systems have been specially detailed to allow for the design deformations and lateral drifts between floors in accordance with the low damage philosophy followed.

2.4. Stressed skin floor panels

The flooring system itself makes use of pre-fabricated stressed skin panels (Potius Panels). These units have been in production for several years in Nelson and have been used on a number of long span residential projects. Each panel acts much like a concrete precast double-T, and essentially provides an alternative to a traditional rib and infill or Unispan concrete floor. Each panel unit consists of two 360 × 90 timber LVL joists fixed to a 36 mm thick LVL slab, and were selected for their long span capability along with the ability to support a concrete floor topping. Fig. 5 shows the build up of a typical floor section. This technology is not new, as stressed skin panels have been used with timber and plywood sheets previously. What is new however is the use of LVL, as this provides the ability to have continuous joists and sheets avoiding the cost of complex splices and joints. Composite action was avoided in order to allow for concrete shrinkage in the topping. The panels were all fabricated off-site and transported to site in 5.4 m lengths. They were then lifted into place using a small mobile crane and flange hung. Given that the panels were not required to be propped this ensured speed of erection.

A 75 mm reinforced concrete floor topping provides acoustic rating to the floor, fire rating between floors, a rigid diaphragm and a significant thermal mass to the building. Structurally the concrete topping was essential in the transfer of lateral loads to shear walls, as well as, provided composite action with the main floor beams and general stiffness and restriction of building movement.

2.5. LVL column and double beam

The LVL columns were detailed such that they could be fabricated from standard available Nelson Pine sections, avoiding expensive runs of timber. The columns were fabricated and transported to site as a single member requiring no on-site splices. Full height corbels assisted with the quick installation of the beams and allowed for simple bolted connections.

The double beam system selected allows for simple beam/column connections and a straightforward erection procedure. Columns were erected full height with the beams then able to be placed alongside each column as continuous spans. A single beam splice is provided in the central span and modelled as a pin connection. As shown in Fig. 5 the splice is located away from the columns in order to allow for beam continuity.

The beam to column connections were detailed as simple pin joints which, when added to timbers inherent resilience and ability to deform elastically, allows them to accommodate the design lateral movements of the building.

2.6. Constructability

The ability to construct the timber solution was a central focus during the initial design phase. From the outset the design steered away from complex moment resisting or post tensioned timber frames that would have been both difficult to build and unlikely to be cost effective. Wherever possible components were standardised to promote efficiency of manufacture, and encourage efficient site erection. Member sizes were also based on readily available sections, the ability to fabricate these simply into larger sections, and simple connection detailing. It was the view that simplicity reduces the construction risk, and maximises building efficiency. To test this theory a local builder was engaged to build a scale model of a typical beam column joint and floor panel. These were built in only a few hours from hand sketch details with not a single query from the builder.

3. Lateral load analysis

3.1. Direct displacement based design

A Direct Displacement Based Design (DDBD) philosophy [10] was used in the lateral load analysis of the superstructure. The design techniques used are similar and in cases adapted from the design of PRESSS-technology (Precast Seismic Structural Systems), developed during the late 1990s in the US under the coordination of the University of San Diego [7,9], and has been previously utilised by Aurecon and others in a number of overseas, as well as, New Zealand based projects [6]. Significant variation can occur between lateral forces calculated using a traditional Force Based Design (FBD) and DDBD. Often inelastic displacements for a structure designed using FBD will be much larger than predicted. In addition the elastic deformations in timber structures may also be much higher than predicted, thus the assumed ductility used (often up to 4 in some case), can be unrealistic [4,5].

The building was designed according to the NZS1170.5 displacement spectra for a 1/500yr return period earthquake, soil type C, in Nelson. A design drift of 1.0% was targeted as an appropriate limit, following a Performance-Based Engineering damage avoidance philosophy. This limit is increased to 1.5% when considering additional torsional effects and possible pile settlements, which is still significantly less than the allowable design code limit of 2.5%. Careful design and detailing consideration was given to non-structural items, such as the façade, windows, services, and internal linings, as their performance is critically important when ensuring operational functionality following the design level event.

The lateral design is governed by seismic loading due to the mass of the building and the large (approximately 4 m) inter-storey heights. The calculated design wind loads were found to be less than half that of the seismic loading, and as such the bracing walls were designed to respond in an elastic manner without rocking. Given the building is largely constructed in timber, it is much lighter than an equivalent structure built in steel or concrete. As such the seismic loads are largely reduced, which in particular provided significant savings in terms of the foundation construction.

During the design phase close reference was made to Priestley et al. [10] in regards to the DDBD procedure, and more recent developments for timber jointed ductile connections in determining an appropriate flag shaped hysteresis loop model and associated area based equivalent viscous damping, as well as, estimating the appropriate timber yield displacement behaviour of the LVL panels [4,5]. Fig. 6 illustrates the basic DDBD approach used in the lateral system design. The structure is initially converted into an equivalent single degree of freedom system, where an effective mass is found to act at an effective height. Based on the initial design drift chosen and the length of the LVL panels a displacement profile is calculated. The expected deflected profile of the building was found to be largely linear with the majority of rotation occurring at the base of the shear panels. An effective ductility is obtained from the calculated yield and design (target) displacements. It is assumed that at yield all deformations are due to elastic deformations of the wall panel itself, though the UFP's theoretically yield under any small displacement [3].

An important point of difference in the design of timber coupled walls is that yield displacement is not independent of strength as is generally assumed in Priestley et al. [10] for other structural materials. Newcombe et al. [5] provides expressions on estimating the correct yield displacement, and also provides expressions for the total equivalent viscous damping based on previously conducted research. Damping is in part related to the re-centring ratio, or the ratio of the self-righting moments to the resisting moment due to energy dissipation (typically referred to as moment ratio λ, [8]). A λ ratio of approximately 1.5 is suggested in order to ensure that the wall will re-centre itself after a seismic event, but also provide meaningful energy dissipation.

The 5% damped pseudo-displacement spectrum, derived from the NZS1170.5 acceleration spectrum, is scaled for the estimated equivalent viscous damping, and in conjunction with the effective design displacement previously established the required system period is obtained. From this period and the calculated mass, the stiffness and thus lateral loads on

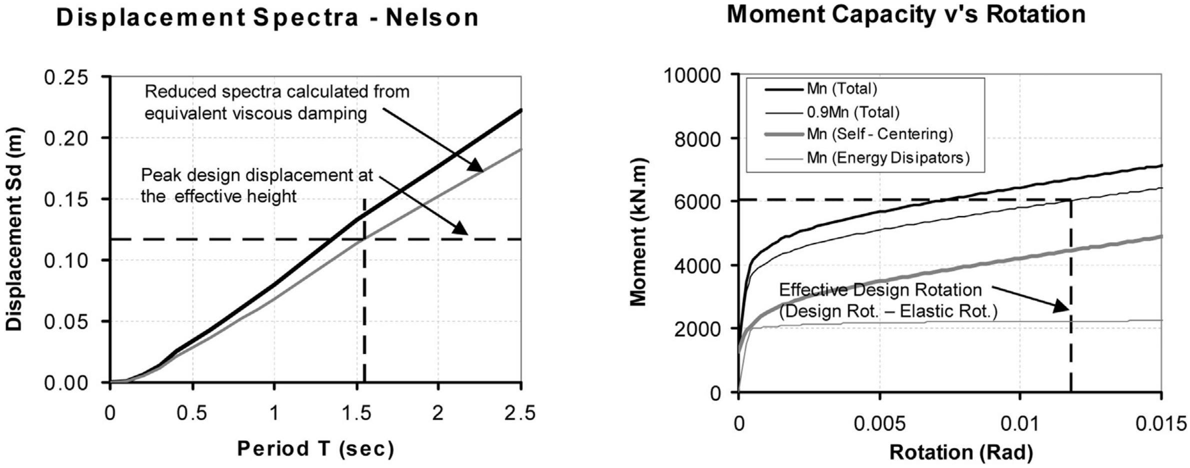

Fig. 6. DDBD demand aligning with Design Capacity of Coupled Shear Wall.

Fig. 7. Interior and Exterior View of Completed 3- Storey NMIT Arts and Media Building.

the system can be found. The lateral loads are distributed up the structure per the DDBD method, with 8% of the total base shear redistributed to the roof to account for higher modes. An iterative process was used to calculate the strength of the coupled system, in order to match the design actions required at the design displacement. As can be seen in Fig. 6 the system illustrates a robust behaviour in that if a larger than expected event does occur the walls will simply displace further, thus increasing the period and reducing the applied loads, as well as, increasing the moment capacity of the system. Given that the design drift has been limited to well below the NZS1170 code drift limit of 2.5%, there is significant reserve capacity in the system to perform well even under a larger than expected design event.

Sensitivity studies were conducted including consideration of additional torsion, and pile settlement. It was found that the system could readily accommodate these variations in displacement terms, where as, in a conventional strength type approach performance would not necessarily be as reliable. Capacity design principles including the use of material over-strength factors, were applied in the design of the shear connections, LVL panels, diaphragms, and ground beams. Dynamic Amplification Factors per NZS1170 were also used in order to protect against potential actions relating to higher modes effects. Subsequent non-linear time history analyses confirmed the appropriate conservatisms of adopting these values.

3.2. Structural monitoring programme

A structural monitoring programme has been initiated as part of a collaborative project between the University of Auckland School of Engineering (UA) and Geological and Nuclear Sciences (GNS). This programme will monitor seismicity, wind speed, temperature and humidity, and compare movements in key structural and seismic components. This 10 year project will provide valuable information for both researchers and designers, which will assist in making this new construction technology more widespread.

4. Conclusions

To date few commercial multi-storey timber buildings in New Zealand have been designed or built that would compete with a similar concrete or steel building. This is not necessarily due to lack of capability of timber products, but rather through lack of opportunity and industry misconceptions. The latest trends in building design, especially in the European Union, are seeing a rapid growth in multi-storey timber buildings. This is primarily for reasons of sustainability, where timber is used as a carbon sink but more recently because of improving design techniques and knowledge. Timber is now promoted for its affordability and speed of construction.

The success of the NMIT Arts & Media project (Fig. 7) has proven that with innovative design multi-storey timber construction is a viable option which can compete with traditional steel and concrete options. The engineered structural system has been evaluated as being very cost competitive, and has subsequently been adopted in a number commercial building developments.

The NMIT building project offered a unique opportunity for Aurecon structural designers. The first commercial use of the Pres-Lam post-tensioned rocking-dissipative timber system marks a fundamental change in timber design. The Performance-Based Engineering philosophy ensures that the building will continue to function after the design level seismic event. In the wake of the 2011 Canterbury Earthquakes this project demonstrates to building owners that a fully functioning building post-earthquake can be achieved in a cost effective manner.

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