Innovative use of timber as a seismic-resistant sustainable construction material in New Zealand

Figure 1
NMIT building, Nelson

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Introduction

Timber is almost unique as an organic mainstream construction material, which contains carbon derived from the removal of CO_2 from the atmosphere during its growth. The issue of how to deal with this sequestered carbon in the Life Cycle Assessment (LCA) of timber is one of great debate. If the sequestered carbon is included as a 'negative' carbon impact, it usually far outweighs the 'positive' carbon impacts from the timber product manufacturing processes. This makes the use of timber appear to be a way to not only reduce but reverse CO_2 emissions, and so it appears highly favourable when compared to other traditional structural materials such as concrete or steel.

Many innovative timber construction systems are being pioneered in New Zealand, driven by a strong domestic structural timber market but also the need for new seismic resistant buildings, following the devastating earthquakes in Christchurch in 2010-11. Timber has excellent inherent seismic properties, being lightweight and having a high strain to failure.

This paper examines the innovative use of timber in construction in New Zealand, as witnessed by the author on a study visit in 2013, supported by an Institution of Structural Engineers Educational Trust Pai Lin Li Travel Award. Descriptions of a number of buildings are presented which use innovative timber construction systems; the design of which have largely been driven by seismic resistance, but also demonstrate potential economic advantages for non-earthquake zones. The way in which the timber supply chain in New Zealand has developed in order to deliver these new systems and products has also been explored in visits to various manufacturing plants in the Nelson region of New Zealand, and is reported here.

Examples of innovative timber construction

Arts and Media Building, Nelson and Marlborough Institute of Technology

The Arts and Media building on the Nelson and Marlborough Institute of Technology (NMIT) campus in Nelson (Figure 1) was one of the Institution's 2011 Structural Awards winners. Designed by Irving Smith Jack architects and Aurecon engineers, it was completed in December 2010, and is a landmark building, widely regarded as the first post-tensioned timber building in the world. It came to be built using this system following a national design competition, for which the Ministry of Agriculture and Forestry (MAF) provided NZ$1M funding and stipulated that the building must be sustainable, local and substantially made of wood. The MAF also commissioned research to scrutinise aspects of the selected timber scheme, not only in construction but also how it was used by the occupiers post-completion. Funding was also made available for a detailed construction cost analysis, as well as a carbon LCA and life cycle cost analysis for the scheme as built, compared to alternative steel and concrete structural schemes.

The building is three storeys and

Figure 2
Post tensioned shear walls

Figure 3
Steel support structure to landing in atrium staircase

Figure 4
Merritt Building

Figure 5
Erection of portal frames, January 2013

comprises studios, galleries, workshops, teaching and office spaces, adjoining a full height atrium running the length of the building. The structure of the main block consists of a laminated veneer lumber (LVL) beam and column gravity frame with two pairs of 3m wide post tensioned LVL shear walls providing stability in both directions. The floors are a timber–concrete composite and the roof is formed of lightweight LVL purlins.

The post tensioned walls (Figure 2) are an example of a type of technology branded as EXPAN and developed by the Sustainable Timber Innovation Company (STIC), a New Zealand industrial/academic research consortium. In each wall, four Macalloy bars pass down a void within the wall section from the top storey to the foundations, providing the capacity to 'recentralise' the walls following an earthquake. Between each pair of walls at each floor are a number of U-shaped flexural steel plates, which act as energy dissipaters. They are designed to yield under seismic loads, limiting the shaking experienced by (and therefore damage to) the remainder of the building elements, hence why the system is known as a type of 'damage limiting design'. The plates themselves can be easily and cheaply replaced, reducing costs dramatically compared to a full structural frame repair; the expense of which has condemned many buildings in post-earthquake Christchurch to demolition.

The unique design has given rise to a number of interesting structural details in the building. The support to the atrium timber stair stringers at the landing is provided by a steel frame, designed to allow the stair to slide over it during the 'rocking' motion anticipated during an earthquake (Figure 3).

To allow the floors to remain horizontal but the shear walls to 'rock', the wall/floor connections are bolted through slotted holes and a single large pin, which transfers the lateral loads from the floor diaphragm into the wall.

The expected maximum horizontal inter-storey drift resulting from this design is 1.5% for a major seismic event - well below the 2.5% maximum stipulated by the New Zealand building codes.

Although the building is yet to be tested in a real seismic event, its success in raising the profile of timber engineering (and structural engineering in general) is not in doubt. The building is frequently toured by engineers, and on one such occasion a professor at the University of Canterbury found himself having the function of the energy dissipaters between the shear walls enthusiastically explained to him by the resident art students; a fine example of public engagement in the art of structural engineering.

The Merritt Building

The Merritt Building in Christchurch is situated in Victoria Street, a thriving community of boutique shops and cafés that was severely damaged during the February 2011 earthquake. Following the destruction of the existing building on the plot, the landowner wished to construct a new office building in timber (Figure 4), and approached architect Sheppard and Rout. Together with structural engineers Kirk Roberts, they developed a post tensioned LVL scheme, but unlike the NMIT building, there are no post-tensioned walls. Lateral stability is provided in the long direction by a precast concrete shear wall that extends the entire length of the building in the long direction

> "New Zealand has a history of developing successful home grown solutions and industries"

along the South East elevation (concrete was used for its acoustic performance as the building is close to the site boundary on this elevation), and seven post-tensioned portal frames in the short direction, which also take out the torsion due to the asymmetric layout (Figure 5).

Figure 6
Beam column junction showing post-tensioning cable termination

Figure 7
'Plug and play' connector energy dissipaters

Figure 8
Trimble Building under construction

Another example of EXPAN technology, steel tendons rather than Macalloy bars post tension both the primary beams and columns by passing through voids in the middle of the section (Figure 6). The energy dissipation is provided by so called 'plug and play' connections; necked steel bars at the top and bottom of the portal connections (Figure 7).

Under seismic loading, the building is again designed to 'self-centre' after rocking through the elastic behaviour of the post tensioned cables. During the rocking, rotation at the beam and column junction causes gaps to open, and the necked bars yield in a ductile manner, thus dissipating energy that would otherwise be transmitted throughout the structure. The portal connections are designed in such a way that 60% of the moment resistance is derived from the tendons and 40% from the dissipaters (a so-called 'magic ratio' to achieve self-centering and adequate rotation at the joint to activate the dissipaters).

The floors beams are designed to act compositely with the concrete topping, and the shear connection is provided by coach screws placed in the beams at notches to reduce rotation of the screw. The structural depth is not shallow: primary beams are 800mm deep, secondary beams 400mm deep.

The design was developed very soon after the February 2011 earthquake, when strong aftershocks were common in the city, so there was a desire to have the robust connections on show to emphasise that the building had been designed to resist significant seismic loading. The structural design is predicted to resist a 1 in 2,500 year event seismic event, with only a 1.5% storey drift in a 1 in 500 year event, well above the performance required of a typical new build structure. Timber may have been thought to be an expensive option, especially given the innovative system being used, but the base build cost for the three storey office and retail building, with a total area of 1,800m^2, was just NZ\$2,350/m^2; comparable with traditional building methods.

The Trimble Building

Trimble Navigation Systems employed around 240 people in New Zealand in its offices in Christchurch, which were damaged in the February 2011 earthquake and subsequently demolished.

The new building consists of two separate blocks with a total floor space of 6,000m^2 over two storeys (Figure 8). The construction of both blocks is a post-tensioned LVL frame incorporating EXPAN technology. Stability in the short direction is provided by coupled post-tensioned LVL shear walls connected by steel U-plate energy dissipaters, similar to those in the NMIT building, although these also have 'plug and play' dissipaters at the base (Figure 9). Stability in the long direction is provided by moment resistance at the beam–column connection, as in the Merritt Building, using a combination of the post tensioning Macalloy bars through the beams and columns and the 'plug and play' connectors at the top and bottom of the connection (Figure 10).

The upper floor is constructed using a timber-concrete composite system developed at the Sydney Institute of Technology. The timber joists are fixed to the plywood deck to form prefabricated units that are then easily lifted onto the

Figure 9
Two types of energy dissipater at base of shear walls

Figure 10
Face fixed 'plug and play' connectors to primary beams

frame and located onto bearers connected to the main longitudinal beams (Figure 11). The joists are notched to improve the shear connection of the coach screws to the 60mm concrete topping that is poured onto the deck. Shear connections are optimised for most beams, with more closely centred screws at the beam ends and widely centred screws in the mid-span.

The construction manager on site noted that a key benefit of this type of construction was the simple site management, as only a single gang of workers were on site, dedicated to the erection of the timber frame, avoiding the need to coordinate multiple gangs that are required for other construction types, e.g. formwork erectors, steel fixers and concrete gangs for *in situ* concrete frames.

Timber portal frame connections: Quick Connect

The Quick Connect system, developed at the University of Auckland, is an innovative connection design used for pitched LVL roof beams in portal frame construction. Pre-fabricated, pre-installed LVL sleeves are screwed to the main portal frame LVL members and grooved to allow the insertion of threaded rods that are fastened to the receiving columns or rafters. The system allows for offsite assembly, saving time and money as well as an element of damage limiting design, because in the event of high loads (e.g. during an earthquake) the steel tendons will yield. Like the other EXPAN products, they act like 'structural fuses', saving the rest of the structure from significant damage and can be replaced cheaply and easily. The expedient installation of LVL rafters to any type of column reduces the use of a crane and labour required during erection. Quick Connect portal frames have found a niche

> "The system won the Timber Innovation in Business category in the 2012 New Zealand Wood Awards"

in the industrial/agricultural sector in New Zealand, where they are being used to replace traditional steel construction. For basic 'tin shed' buildings such as these, cost is more than ever the key design driver. Portal framed warehouses that were delivered at a cost of NZ$350/m^2 using traditional steel construction could be delivered using Quick Connect connections between LVL roof beams and steel columns for only 15% additional cost, but this was more than offset by the savings in programme. The system won the Timber Innovation in Business category in the 2012 New Zealand Wood awards.

The system is also used in other types of building. One of the first known domestic applications was designed by Batchelar McDougall Consulting for a house in Wanaka. Situated in a mountainous environment, the two-storey home, built predominantly of timber structural insulated panels (SIPs), was subject to high wind loads. The design made the most of the vistas by having a highly glazed envelope at first floor level which required an additional brace frame to provide lateral stability in the absence of structural walls. The client

Figure 11
Pre-fabricated timber concrete composite floor units

and architect wished to maintain the timber structure of the house, so rather than a steel moment connection, a Quick Connect portal frame was used to stabilise the gable end of the building where the walls could not be used for restraint. The 6m span, flat roof was supported by a 360mm x 90mm LVL beam with end moment connections formed with the Quick Connect system (Figure 12).

Further development and opportunities for timber construction

Although the STIC research consortium funding expired in 2013, there is still ongoing research to continue to optimise EXPAN technology, particularly with respect to the cost of the connections. It is hoped that the momentum gained in timber construction will continue to increase following Forte in Australia and NMIT and other successful post-tensioned buildings in New Zealand. It is clear that in Christchurch, timber has the potential to be put to widespread use in commercial and residential post-earthquake construction. As work gradually moves from demolition to rebuild, it is interesting to note that many of the first new buildings to appear in the city are constructed from timber. Many so-called 'pop up' buildings (constructed very quickly because of their high economic importance) are timber framed – including the student union bar at the University of Canterbury (Figure 13).

Timber supply chain

New Zealand has a history of developing successful home grown solutions and industries, given its geographical isolation.

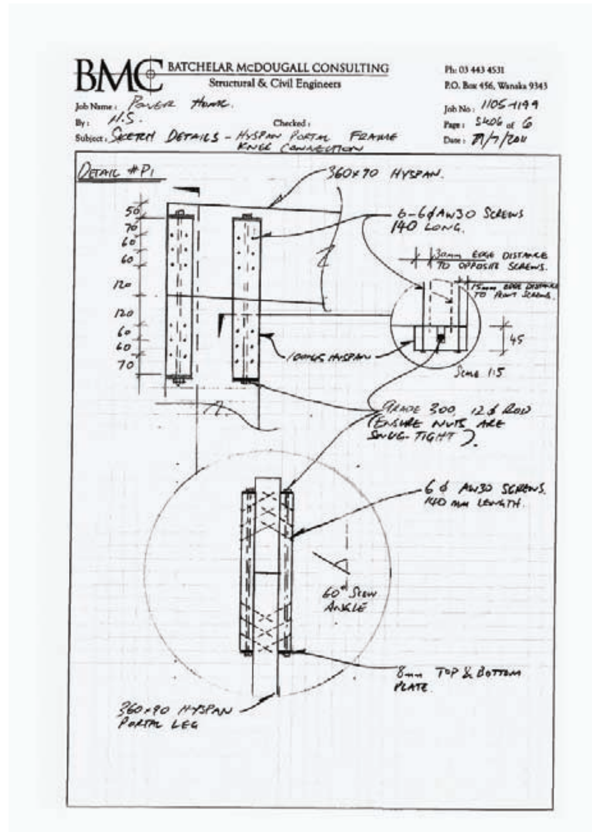

Figure 12 Sketch showing Quick Connect details

Figure 13 'The Foundry' student union bar, University of Canterbury

The theory and technology behind the EXPAN timber systems developed primarily in the New Zealand universities of Canterbury and Auckland require a completely new way of engineering timber, which has been provided by the existing domestic timber supply chain.

Nelson Pine

Nelson Pine Industries has been operating since 1986 but only started making LVL in 2002. Situated on a coastal plain overlooking Tasman Bay, the factory covers nearly 8ha (Figure 14). Alongside the largest single site medium density fibreboard (MDF) plant in the world, Nelson Pine Industries has the capacity to produce approximately 80,000m^3 of LVL per year, much of which is exported to Asia, the Middle East and Australia for a variety of uses, including scaffold planks and formwork in addition to high strength structural applications. But as its investment in the STIC consortium indicates, Nelson Pine Industries recognises the potential of engineered timber in new construction techniques, including post-tensioned timber, and is clearly keen to promote this new application of its product.

The Nelson region has around 175,000ha of plantation forests; approximately 16% of the productive land area, making it one of New Zealand's most important forestry areas. About 2Mm^3 of timber (mostly Radiata Pine) is produced here every year and Nelson Pine has the capacity to process around 50% of this for the manufacturing of MDF and LVL.

The first stage in the LVL production

Figure 14
Nelson Pine factory

Figure 15
Logs awaiting 'peeling' on LVL production line

Figure 16
Automated laying up of veneers after application of glue

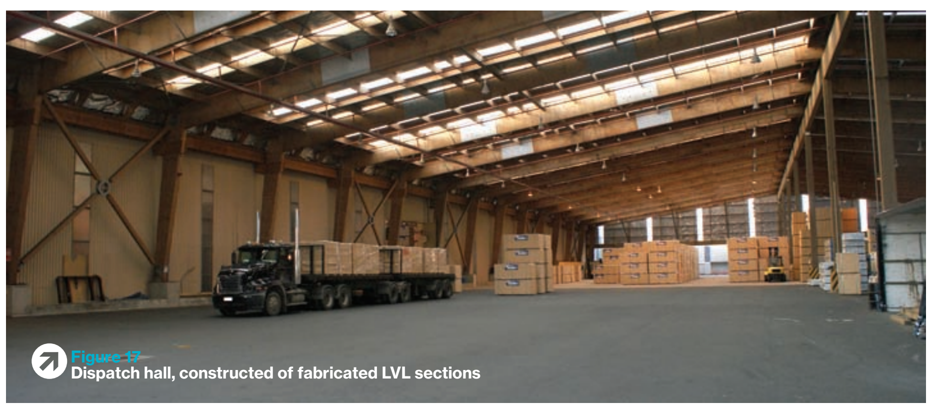

Figure 17
Dispatch hall, constructed of fabricated LVL sections

process is debarking, after which logs are placed in hot water baths, where they are heated to 80°C for 24hrs, bringing the core temperature up to improve the performance of the 'peeling' process. Here, the logs are held at each end and rotated about their axis at high speed. A high precision lathe slices off a continuous veneer, approximately 3.5mm thick, reducing the diameter of the log from around 450mm to 78mm (Figure 15). The veneers are cut to 1.3m x 2.7m sheets and automated scanners check for the presence of imperfections such as knots or bark, removing them as necessary. The veneers are then dried in a steam powered, six deck drier to a target moisture content of 6-8%. Once dry, they are visually graded, as well as graded for strength using sonic methods. All sheet edges are scarfed, to enhance strength as well as to achieve uniform thickness when the sheets are laid up. An automated production line arranges the laying up of face sheets and core sheets, all with parallel grain direction, and phenol formaldehyde glue is applied through a curtain coating machine to ensure uniform covering. The sheets are then laid up into a mat of the required thickness in a continuous process over a moving conveyor (Figure 16). They are then put through the 45m long hot press where, under 10bar pressure and 120°C heat, the glue is cured in only a few minutes to produce the billets of LVL. Sanding is an option for products which require a smoother finish. Finally the billets are cut to size, wrapped and packed, ready for distribution.

The company is keen to showcase the uses of LVL in buildings such as NMIT, that are fast becoming landmarks. It also uses its own product for its own buildings. Many of the huge warehouses that form the factory are constructed from LVL beams and columns. The roof and walls for the 64m span, 14m high dispatch hall are all framed with LVL sections, demonstrating the structural performance of the material on an impressively large scale (Figure 17).

Nelson Pine Industries is also keen to highlight the environmental credentials of its product. All the offcuts and timber waste from the factory are either used to make MDF or burned in the boilers on site to provide renewable heat for the MDF and LVL manufacturing lines. Together with the other two LVL manufacturers in New Zealand (Carter Holt Harvey and Juken New Zealand) it contributed primary data on energy and material use to a study by SCION, the New Zealand forest and wood products research institute, to produce a carbon footprint report[1] for LVL made in New Zealand. Freely available online, the report is refreshing in its clarity and open discussion of the major factors contributing to the product's emissions, including the sequestration of carbon in growing timber and the impact of different end-of-life scenarios. The study was carried out in accordance with the *Guidelines for GHG footprinting for engineered wood products*[2], developed by New Zealand's Ministry for Agriculture and Forestry. These were produced as part of MAF's GHG footprinting strategy to enable land based primary sectors to respond to the increasing pressures from export markets for product specific environmental impact data, especially GHG emissions. Although it clearly has a narrower scope than the European Standards which cover carbon footprinting of construction products (CEN TC 350 suite), it is much more readable, directly addressing the key issues of carbon sequestration and landfilling timber within a robust LCA methodology that is in accordance with ISO standards. An example perhaps of how the geographic isolation of New Zealand (and the importance of exports to its economy) allows progress to be made in addressing the technicalities of environmental impacts quickly in response to market demand for information. In contrast, the European standard addressing LCA of timber products, EN 16485[3], ended its consultation period on the draft version in November 2012 and is not due for publication until August 2014.

Hunter Laminates

Hunter Laminates is traditionally a glulam manufacturer, based in Richmond, 10km from Nelson. It is now diversifying, finding that it has the tools and skills to produce the fabricated LVL sections used in EXPAN post-tensioned frames, and is investing in new plant to make the process more efficient.

Layers of LVL are glued together into fabricated sections in much the same way that laminates of plain timber are glued together to make glulam sections. Once the glue is applied, the sections are placed in presses that can be adjusted to suit any length of section, including curved members. It is then gently heated to around 70°C and left to cure for around 24hrs, after which the section is ready for treatment, if required. A light organic solvent preservative (LOSP) treatment is typically used for internal exposed applications. The finished sections are loaded into a pressurised bath where the preservative is applied by vacuum impregnation, ensuring a uniform penetration into the timber.

Hunter Laminates has manufactured LVL members for the new Nelson Pine dispatch hall extension (Figure 18) and a post-tensioned office building in Nelson but is also working further afield. Other projects include LVL sections for post tensioning for the new 9,000m² campus buildings for Tate Electronics in Christchurch and portal frame members which use the EXPAN Quick Connect system for the new Netball City stadium on the Olympic Park in Sydney.

XLam

Another example of New Zealand's entrepreneurial activity in the timber industry is XLam NZ Ltd, the only Cross Laminated Timber (CLT) panel manufacturer in the Southern hemisphere. In little over a year of operation, it has successfully delivered CLT panels for a number of residential buildings in New Zealand and is moving into the commercial building sector. Its factory contains a 15m x 3.4m press with capacity for an output of 8,000m³ CLT per annum (Figure 19). Situated in the heart the Nelson–Marlborough region, it has good access to both Radiata Pine and Douglas Fir, offering a choice in aesthetic appearance.

XLam has faced the significant challenge of being the first to introduce a new product into the New Zealand market, which offers many benefits but is also a radically new way of building and designing, which architects, engineers and clients can be reluctant to adopt before seeing proven examples. Quantity surveyors can also be notoriously conservative when pricing new building systems without experience to base their estimates on, and no client wants to be the first. Nevertheless, XLam has invested heavily in its equipment, initially making use of the fully operational production facility to make demonstration panels for a variety of different applications, including many of the plant items in the factory itself. It is confident that the boom in the use of CLT in Europe will soon spread to the Australasian region, as its benefits become more widely recognised.

Figure 18
Fabricated LVL column for installation at new Nelson Pine dispatch hall

Almost every stage of timber processing is carried out in-house, so XLam can oversee all aspects of quality control; vital when introducing a new product to the construction industry. Timber, direct from sawmills is graded on site, both for visual appearance and stiffness. Imperfections are removed and the boards go through the fully automated finger jointing machine. They are then planed to remove 5mm of thickness before being put into the press and laid up in layers of alternating grain direction (Figure 20). The quality of the final product is determined by the thickness of the glue line, which must be maintained between 0.1mm and 0.3mm. Before the glue is applied to the boards in the press, the flow rate and viscosity of the glue is tested to ensure uniformity during application. The boards are face glued only; XLam's own testing has shown that gluing the edges of boards does not improve their performance significantly, and leaving the edges free may also offer the timber a chance to expand and contract with changes in moisture content. The press is sealed with a membrane and a vacuum pressure of around 90kPa is applied for 2.5hrs. Panels can be laid up with openings incorporated for windows or doors, and smaller openings can be cut after the panel is cured. Layer

Figure 19
Cross Laminated Timber press, XLam factory

thicknesses are 20mm and 35mm (with 45mm expected to be available in the near future) while panel thicknesses range from 60-130mm, with the potential to increase to 500mm.

While XLam is currently not at a comparable scale to the established CLT producers in Europe, it is growing strongly and pushing the boundaries of its product with its own testing programmes. It is experimenting with ideas such as cast-in conduits to panels for service runs, and 'TwinSkin' cassette panels for long span floor and roof applications.

In July 2013, work was being undertaken to manufacture wall panels for the new Kaikoura District Council building, a museum, library and office building to be made entirely from timber. In this building, the shear walls that would incorporate EXPAN post-tensioning tendons will be made from CLT rather than LVL. This will be the first of its kind in the world, but seeing the ambition of XLam, it is not likely to be the last.

Conclusions

The examples of innovative timber design in New Zealand are world-leading, and have great potential to be used abroad, especially in areas requiring specialist seismic design. However, there are other lessons that can be learned, even in non-earthquake regions. The co-operation between the local timber supply chain and the design and academic community is an excellent example of maximising the value of a domestic resource, which could provide a useful example to those involved in the 'Grown in Britain' campaign[4]. The fact that direct government funding led to the post-tensioned timber frame of the NMIT building, which has now spawned a number of buildings using the same system (and not required subsidies to be commercially viable), should be taken on board by those looking to increase the use of timber as a mainstream structural material.

With the growth of timber construction in New Zealand mirroring similar growth in Europe, scrutiny into the embodied carbon of timber as a material, and how to account for the sequestration of carbon in LCA studies, in such a way that it provides a fair comparison of its impacts against other mainstream materials, will only intensify. Although the most developed standards describing LCA methodologies are still those from Europe, the example of the New Zealand government publishing transparent carbon footprinting methodologies, and the subsequent publication of embodied carbon data for LVL by industry, is one that other governments should look to emulate.

Figure 20 Boards come out of finger jointing machine onto this storage platform, itself constructed from CLT

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