FEASIBILITY STUDY OF HYBRID WOOD STEEL STRUCTURES

by

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ABSTRACT

This thesis involves a detailed study of steel-wood hybrid structures and their applications in construction industry. Hybrid structures combine benefits of dissimilar materials to overcome their individual limitations. Various advantages and challenges of steel-timber hybrid structures are presented. Benefits include increase in tensile capacity, seismic performance, fire resistance of the structure, and cost savings. Challenges with this type of hybrid structures originate from the differences in the properties of the materials used. Connection design may be more difficult as temperature and humidity variations have different effects on steel and timber. The hybrid materials can be integrated at component levels (hybrid slab/diaphragms, hybrid beams, hybrid columns, hybrid diagonals, hybrid post-tensioned joints) and/or at the building system levels (hybrid frames, hybrid system of steel frames and wood diaphragms, vertical mixed system and hybrid trusses). To elaborate on these types of hybridization and their advantages and challenges, case studies of steel-timber, concrete-timber and steel-concrete structures are provided.

Despite the obvious advantages, today's applications of wood-steel hybrid structures have been limited. Currently there are no material and design standards for hybrid wood-steel structures. For light structures, NAHB Research Center has developed a builder's guide to hybrid wood and steel connection details. When combining steel and wood, designers should consider the advantages and limitation of each material and optimally utilize them. The literature review has highlighted the opportunity for wood-steel hybrid buildings and existing knowledge gaps.

Another aim of this thesis is to investigate technical software packages and identify the pros and cons of each software pachage for modeling hybrid structures. The considered software packages are ANSYS, SAPWood, SeismoStruct and OpenSees Navigator. Software packages are evaluated interms of their ability to model linear and non linear materials; orthotropic and isotropic materials and composite materials. Among the softwares ANSYS is found to be the most suitable for modelling hybrid wood and steel structures. A case study of a hybrid structure consisting of steel momet frame and wood shear wall is modeled with ANSYS. Static analysis is performed on the structure and it is observed that wood shear wall significantly reduce the lateral deflection of the system.

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1.0 INTRODUCTION

Hybrid construction combines the structural and architectural features of components made from different materials. In hybrid construction, various materials may work independently or act together homogeneously, but are always better than a single material.

During the last decade a lot of research has been done on applications of hybrid structures; however, the available information and details for steel and wood hybrid structures are dispersed and not readily accessible to builders. The major aim of this thesis is to perform a detailed literature study on existing hybrid steel and wood structures and identify current engineering techniques of hybridization along with the benefits and challenges associated with them. The literature review has highlighted the opportunity for wood-steel hybrid buildings and existing knowledge gaps. Moreover, technical software packages are investigated and their advantages and limitations in terms of predicting structural responses of hybrid systems are discussed.

The aim of all the hybridization techniques is to optimally utilize each material. Hybrid materials can be integrated at component levels and/or at the building system levels. Hybrid systems design is often considered for aesthetic purpose, sustainability, optimal use of different material properties, etc. Connection detail is the major challenge associated with hybrid structures. Possible innovative ways of connecting the two materials are discussed.

Despite the obvious advantages, today's applications of wood-steel hybrid structures have been limited. In Canada, hybrid structures have been used in several ways. In Quebec and Ontario, there are hundreds of steel-wood bridges, where steel is used as the main structural system and wood is used as the secondary structural system. This application is also common in buildings, where steel acts as the supporting frame and wood as the planar elements. Steel/timber hybrid structures have also become very popular in many other countries around the world such as USA, New Zealand, England and Japan.

Following is the overview of the thesis:

Chapter 1 provides a brief introduction of hybrid structures.

Chapter 2 provides material properties of steel, wood, and concrete. Monotonic loading and hysteretic properties of each material is then discussed. Finally advantage and disadvantage of each material property is highlighted.

Chapter 3 presents the possible ways of implementing steel and wood in a hybrid construction based on existing structures. The hybrid materials can be integrated at component levels and/or at the building system levels. Advantages and challenges of each type of hybridization are then discussed.

Chapter 4 highlights advances in hybrid wood steel structure. This section provides case studies of hybrid systems of “concrete-steel”, “concrete-wood” and “steel-wood.”

Chapter 5 investigates four software packages, namely, ANSYS, SAPWood, SeismoStruct and OpenSees. Special consideration is given to the types of analysis each software package can perform, and the capability of the software to model linear and non-linear materials; isotropic and orthotropic materials, laminated and composite sections. Based on the mentioned criteria the most suitable software for modelling hybrid wood steel structures is recommended.

Chapter 6 introduces a finite element model of a five storey hybrid steel building with Oriented Strand Board shear wall using ANSYS. The effect of shear wall on the lateral displacement of the steel frame is then observed.

2.0 PROPERTIES OF STEEL, WOOD AND CONCRETE

In-depth understanding of the properties of each material is essential for designing a hybrid structural system. Engineers and architect should remember the strengths of each material and know in what context each of them work best. Table 1 below shows the approximate material properties for concrete, steel and structural timber.

Table 1 –Approximate matrial properties for steel, concrete and structural timber

Source: Canadian Wood Council (2005), Introduction to Wood Design, Ontario, Canada,
Engineering Tool Box, Elastic Properties and Young Modulus for Structural Material, retrieved:Oct 15,2010
< http://www.engineeringtoolbox.com/young-modulus-d_417.html>

Approximate Material Properties for Steel, Wood and Concrete						
Material	Yield Strength (MPa)	Density (kg/m^3)	Poisson Ratio	Modulus Elasticity (MPa)	Compressive Strength (MPa)	Tensile Strength (MPa)
Steel	350	7800	0.3-0.31	200000	400-1000	400-1000
Concrete	N/A	2300	0.20-0.21	20000	20-40	2.0-5.0
Structural Timber	N/A	400-600		8000-11000	Parallel 30 Perpendicular 8	Parallel 6 Perpendicular 1

Wood can be very flexible under loads, keeping strength while bending, and is incredibly strong when compressed vertically. Wood is much weaker in compression perpendicular to the grain than in compression parallel to the grain. Wood exhibits its greatest strength in tension parallel to the grain. Cross grain of any kind materially reduces the tensile strength of wood, since the tensile strength perpendicular to the grain is only a small fraction of that parallel to the grain. In general, tensile strengths in tangential and radial directions are very low compared to the longitudinal strength, about 3% and 5%, respectively (Slavid, 2005). For concrete tensile strength is negligible compared to the compressive strength. As opposed to wood and concrete, steel excels in tension (Kulak, 2005).

Steel is considered isotropic, meaning that its properties are the same in any direction. However, wood has unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal, radial, and tangential. The longitudinal axis L is parallel to the grain; the radial axis R is perpendicular to the grain in the radial direction; and the tangential axis

T is perpendicular to the grain but tangent to the growth rings. These axes are shown in Figure 1. Since the differences in wood properties between the radial and tangential directions are minor compared to their mutual differences in the longitudinal direction, most wood properties for structural applications are given only for directions parallel to the grain (longitudinal) and perpendicular to the grain (radial and tangential) .

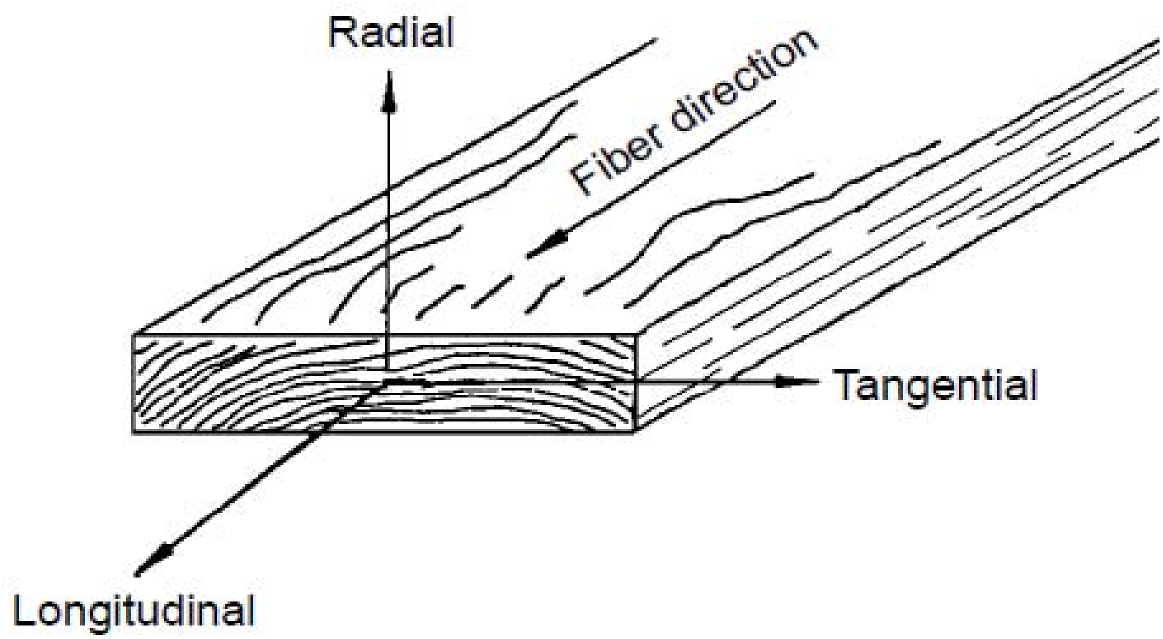


Figure 1 – Three principal axes of wood with respect to grain direction

Wood is a hygroscopic material. It gains and loses moisture depending on the environmental conditions to which it is exposed. The loss and gain of moisture effects dimentional stability and strength, and the presence of water in combination with other conditions can cause decay. The extend to which dimentional changes occurs depends upon the species and the orientation of the wood fibres (Slavid, 2005).

Figure 2 below shows the stress strain diagrams of wood, steel and concrete. Steel generally exhibits a very linear stress–strain relationship up to a well defined yield point as shown in Figure 2. The linear portion of the curve is the elastic region and the slope is the modulus of elasticity or Young's Modulus. As deformation continues, the stress increases on account of strain hardening until it reaches the ultimate strength (Kulak, 2005).

Figure 2 shows the stress strain diagrams of wood subjected to compression parallel and perpendicular to grain. The stress strain relation is nonlinear in compression. For compression parallel to grain, ultimate strength is the highest value of stress reached, shown by the ordinate at point A. Point B of the curve is at proportional limit, or also known as elastic limit. Proportional limit is the value of stress at the upper end of the straight-line portion of the curve, that is, the stress level above which stress is no longer proportional to strain. For compression perpendicular to grain, there is no true ultimate strength value for this type of loading, the failure criterion is not reaching an ultimate load, but rather reaching a limit beyond which the degree of distortion is considered unacceptable (Slavid, 2005).

Brittle materials such as concrete do not have a yield point, and do not strain-harden. Therefore the ultimate strength and breaking strength are the same. Figure 2 shows the stress-strain curve of concrete in uniaxial compression. One of the characteristics of a brittle failure is that the two broken parts can be reassembled to produce the same shape as the original component as there will not be a neck formation like in the case of ductile materials (McCormac, 2006).

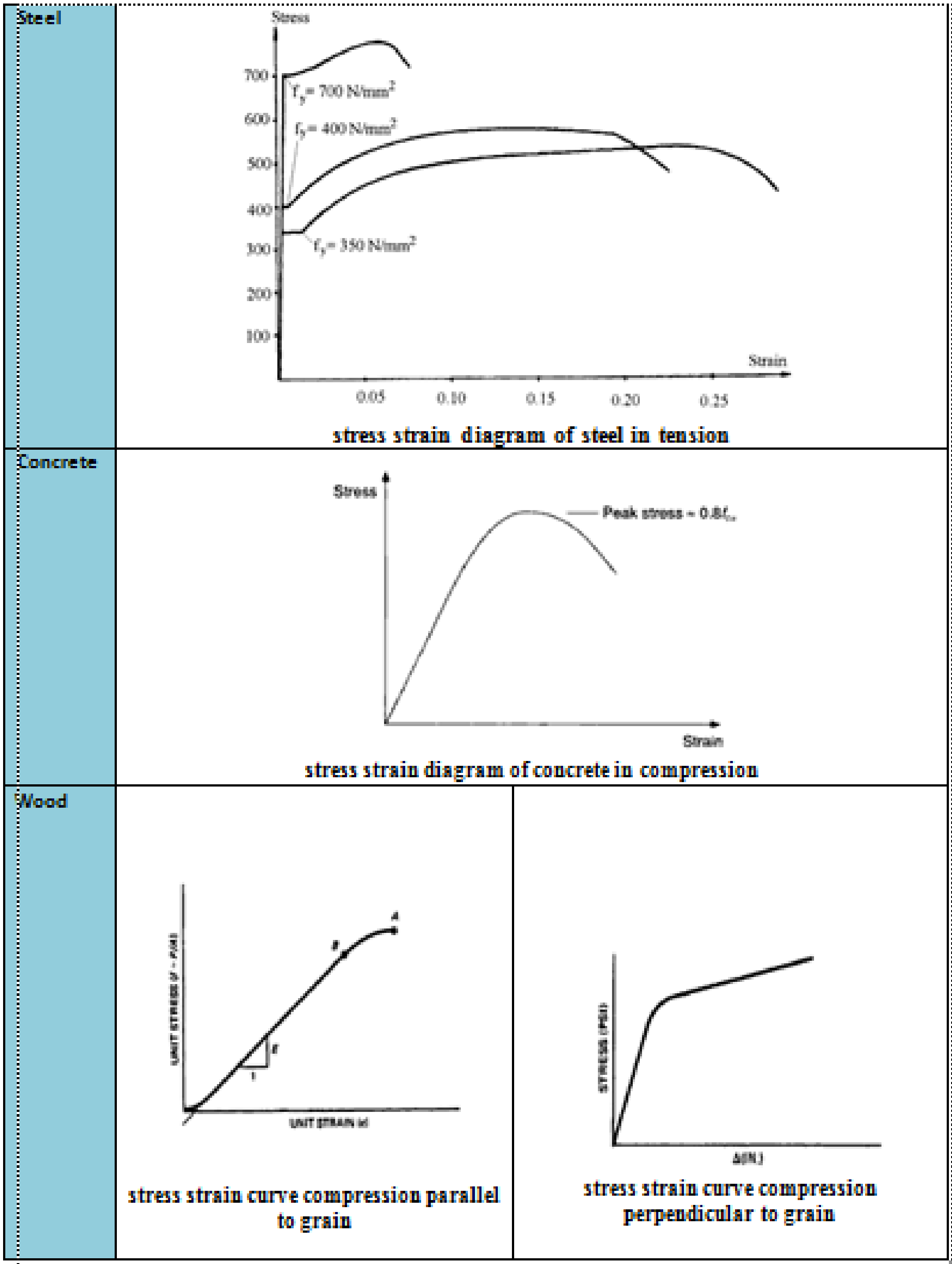


Figure 2 – Stess-strain diagrams of wood, steel, and concrete

The experimental results indicate that the cyclic force-deformation of a structure depends on the structural material and on the structural system. The force deformation plots show hysteresis loops under cyclic deformation because of inelastic behaviour. Figure 3 shows the hysteretic force deformation diagrams for steel, wood, and concrete.

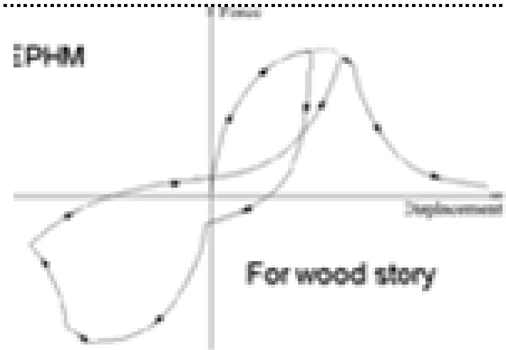
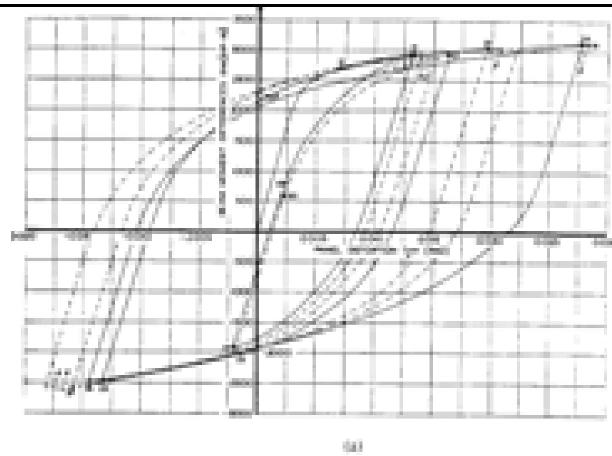
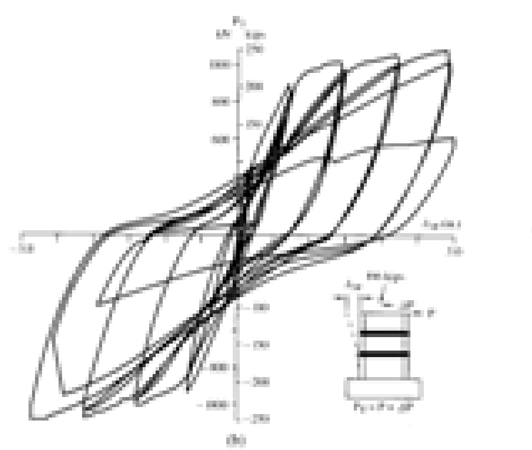
Wood	
steel	
Reinforced concrete	

Figure 3 – Force-deformation relation of steel, wood, and concrete

The area within each cycle of hysteresis loop gives the dissipated energy. As shown for steel the absorbed energy is greatest for each cycle, and full cycles are being repeated hence greatest amount of energy is being dissipated. Therefore, in case of earthquake steel behaves with much more ductility. As apposed to steel, for wood no cyclic behavior is observed. Finally, for concrete the cycles gets smaller and smaller and the dissipated energy becomes lower (Chopra, 2007).

2.1. Advantages of Hybrid Wood Steel Structure

Even though, material properties of steel and wood different by combing them in a hybrid structure one can take advantage of the inherent benefits of each material and overcome their limitations. Steel excels in tension while wood reacts much better to compression. The compression strength of timber ranges from about 20 MPa through to 40 MPa. These figures are in the range of concrete compressive strengths. Timber is brittle in tension, much like concrete. Many of the principals of reinforced concrete design could be applicable to reinforced timber design. In general terms, this equates to using the timber components to resist compressive forces, and using steel, or other materials, to resist tensile forces. Of course, timber has a significant tensile strength, which can be utilised, as long as the principals of capacity design are applied, to ensure that a brittle failure mechanism will not occur. Therefore, when constructing a hybrid wood/steel truss, the wood should be placed up on top of the truss in compression and steel should be placed at the bottom chord to be in tension (*Leckie,* 2008).

Combining steel and wood will increase the seismic performance of the structure. Wood has a high strength to weight ratio therefore wood buildings tend to be lighter than other building types (Slavid, 2005). Table 2 shows a comparison of strength/density ratios for some structural materials. For clear wood this ratio is significantly higher than other building materials

Table 2 – Strength/density ratios for some structural materials

Source: Slavid.R., (2005) Wood Architecture, London Laurence King Publishing Ltd, pp 239

Material	Density (kg/m^3)	Strength (MPa)	Strength/Density (10^{-3} $MPa.m^3/kg$)
Structural Steel	7800	400-1000	50-130
Aluminium	2700	100-300	40-110
Concrete,compression	2300	30-120	13-50
Clear softwood, tension	400-600	40-200	100-300
Clear softwood, compression	400-600	30-90	70-150
Structural timber, tension	400-600	15-40	30-80
Glass fibre in epoxy, tension			500
Carbon fibre in epoxi, tension			1000

Lightness is an advantage in an earthquake. Since forces in an earthquake are proportional to the weight of the structure, lightweight wood-frame buildings that are properly designed and built can be expected to perform very well in earthquakes.

On the other hand, steel will add ductility to the timber structure. Ductility is the ability of the structure to yield and to deform without collapse. It is desirable for a building to have some flexing capability when subjected to the sudden loads of an earthquake because the flexing allows the building to dissipate energy.

Wood as a resource has numerous advantages over other materials from a global impact standpoint. Wood is environmentally friendly due to its reduced carbon footprint. In this era of global warming, sustainable development strategies are not only essential, but are increasingly mandated by most governments. Wood, as the most sustainable, natural, and renewable building material, needs to be more widely used in the building industry. However, products such as glulam and structural composite lumber are considered engineered products because of the manufacturing process. While the gluing and lamination increases the strength and reduces the moisture content of the wood, it makes the products unsuitable for recycling and, as with many wood products, generates up to 30 per cent wasted wood, which counters some of the positive marks for green building that wood receives for being a renewable resource (Slavid, 2005).

On the other hand, steel has high level of recycle content and can be used to reinforce the timber members (AISC, 2006). Therefore, combining steel and wood would result in increase in sustainability.

In Canada and most other countries around the world, building codes have height and area limitations on wood construction due to fire safety considerations. But there is no limitation if wood is used with a non-combustible material such as steel. (Cheung, 2000). Although wood is combustible, but buildings constructed with large structural timbers have excellent fire-resistive qualities. Fire resistance is the length of time a structural member can support its load before collapsing. Timber members of chunky section sizes have an inherent fire rating by means of the charring rate of the outer layers. This is a distinct advantage over steel structures which may require additional fire proofing.

Steel is a non-combustible material, but the mechanical properties of structural steel are affected by heat (Gehri, 1985). However, in fire, timber members char on faces exposed to fire but still retain strength and stiffness by virtue of the much cooler core within the charred surfaces and thus their performance is predictable and collapse is unlikely (Cheung, 2000). Hence, hybrid steel and timber structures perform better in fire.

3.0 TYPES OF HYBRIDIZATION

The following section describes the possible ways of implementing steel and wood in a hybrid construction based on existing structures. The hybrid materials can be integrated at component levels and/or at the building system levels. Advantages and challenges of each type of hybridization are discussed.

3.1 Component Level Hybridization

Component level hybridization exists when a mix of steel and timber is employed within a structural element. This is similar to a composite construction where two different materials are bound together so that they act together as a single unit from a structural point of view. Examples of such hybridization includes: hybrid bridge decks, hybrid slabs/diaphragms, hybrid beams, hybrid columns and hybrid braces. Another possible way of having component level hybridization is to post-tension the timber member with steel rods and creates ductile joint connections.

3.1.1 Hybrid bridge decks and slabs

Hybrid steel concrete bridge decks and slabs are very common. Buildings and bridges frequently use concrete slabs supported by steel beams. Slabs transfer floor and deck loads to steel beams and these beams bear the entire structure loading. The beams and the slabs deflect together and the concrete slabs are usually adjacent to the compression side of the beam cross-section. Same principle can be applied to hybrid timber steel bridge deck and slab. The timber-steel composite bridge deck is a new type of bridge superstructure. As shown in Figure 4, the system utilizes a stress-laminated timber deck with inverted steel T-beams for added stiffness.

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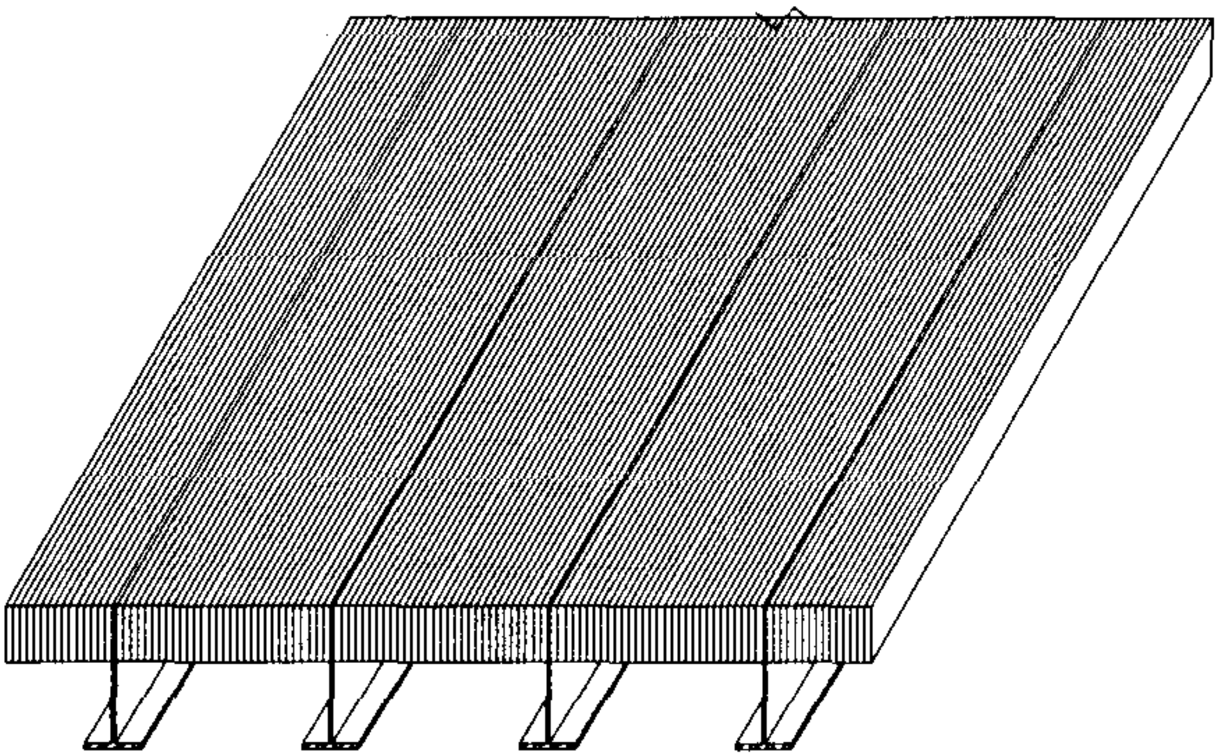


Figure 4 – Stress-laminated timber deck with inverted steel T-beams

There are numerous advantages associated with such hybridization. The overload capacity of a composite system is better than that of a non-composite system of the same size because the former system is stiffer. The added stiffness provided by the T-beams will allow longer spans than those possible with the conventional stress-laminated deck. Assuming that adequate interconnections are provided between the timber deck and the steel beam, as load applies, both the steel beam and the timber deck act together to carry the load so that the size of the required steel beam will be less than that for the non-composite section. This reduction in steel weight, not only directly saves cost, but also reduces the overall depth of the beam and the deck. Deflections of a composite system will also be reduced under superimposed load. Although a composite cross section has lots of benefits, additional cost of providing connection between the deck and the beam arises. As shown in Figure 5, one possible way of connecting the deck and the beam is using shear bulkheads. This technique is implemented in the bridges in northern Ontario (Krisciunas, 1996).

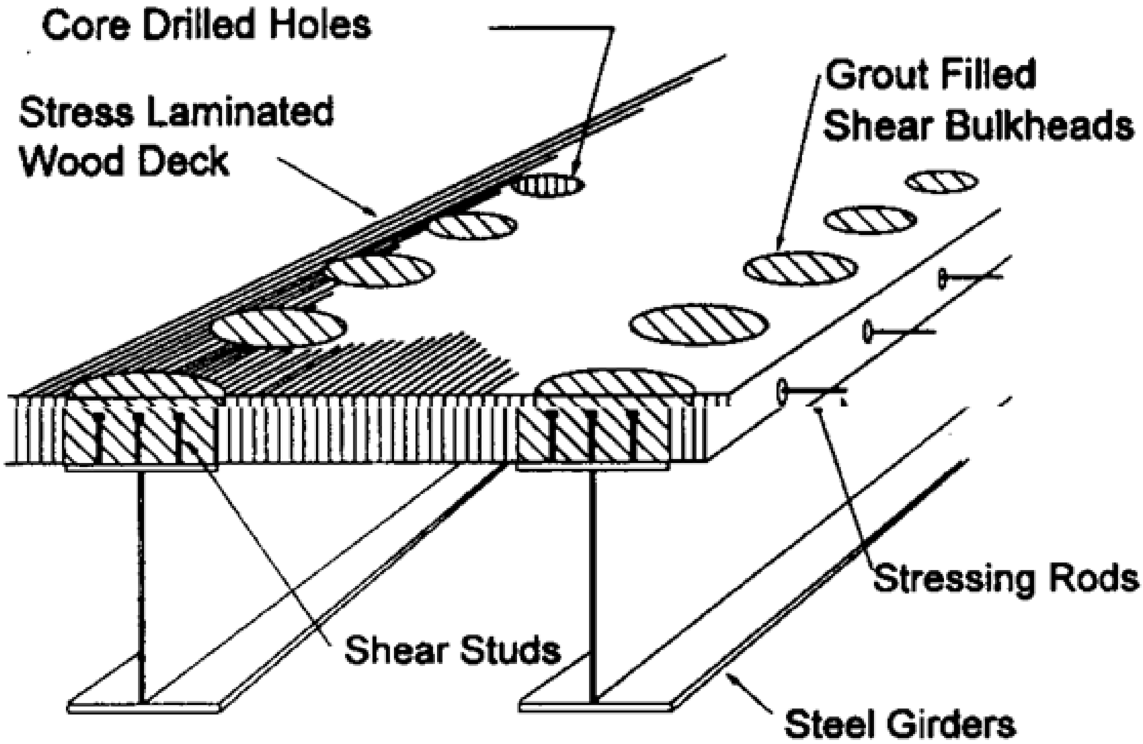


Figure 5 – Conceptual design of hybrid steel timber bridge in Northern Ontario

Conversely, hybrid bridge decks can consist of an orthotropic steel deck attached to a double glulam beam having rectangular cross sections. This method is used in Bochu Bridge in Japan. Major Challenege is the connection between the glulam beams and the steel deck. The beams are stiffened by two vertically inserted glued-in steel plates having different sizes at upper and lower surface. The deck is connected to the beams through the upper inserted steel plates which also act as shear connector. Figure 6 is a picture of Bochu Bridge. Prior to building this bridge, similar bridge model was tested to investigate the bending capacity of such hybrid structure and validate the composite beam theory used to design it (Kiss, Usuki and Gotou, 2004).

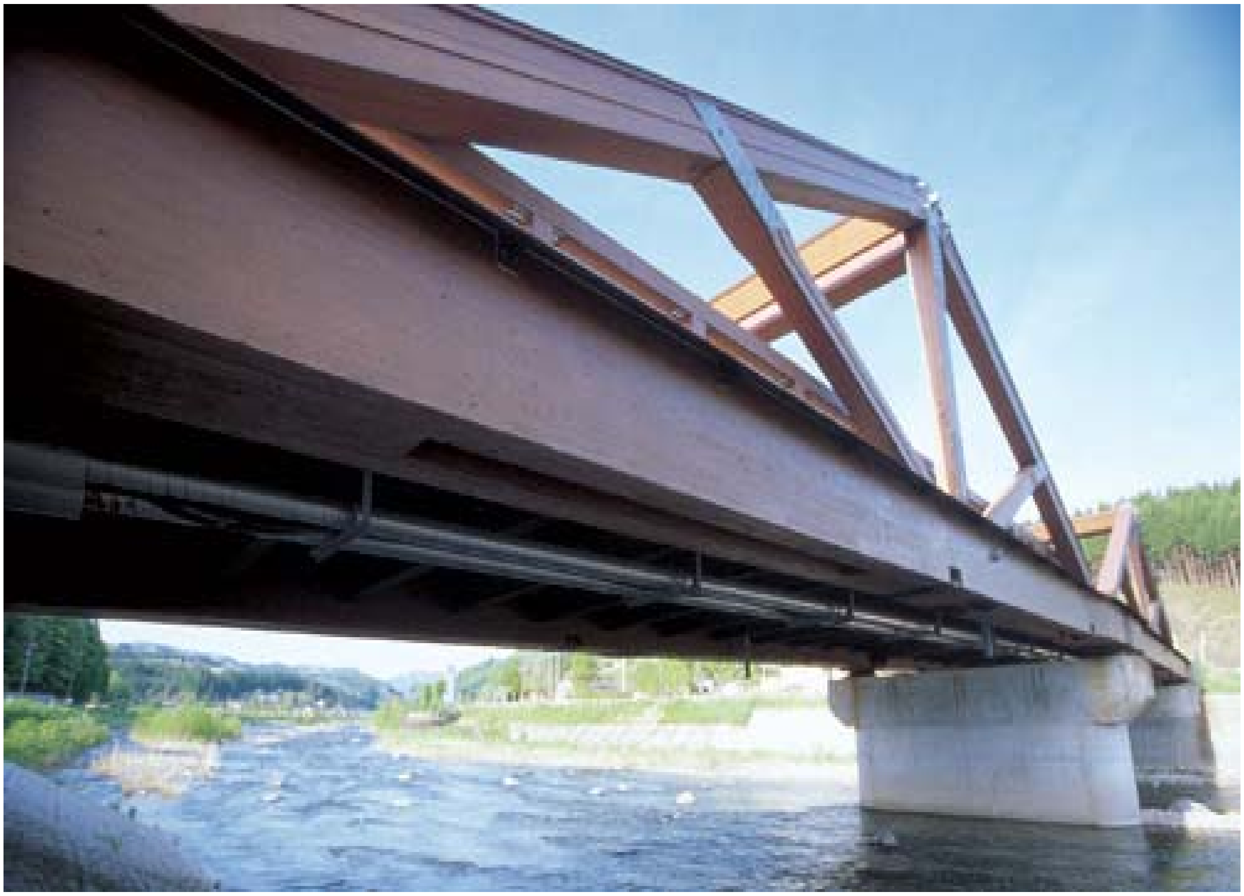


Figure 6 – Bochu Bridge in Japan

3.1.2 Hybrid beams, columns and braces

Hybrid timber steel members include steel plate reinforced with wood members; wood member reinforced with steel plates; and wood member with inserted steel member.

A "flitch beam" as shown in Figure 7, is typically comprised of a steel plate placed between wood members. This hybrid beam is usually used in the construction of houses, decks, and other primarily wood-frame structures. With a flitch plate beam, the structural load is shared between the steel plate and the wood side pieces proportionally to their relative stiffness. In order to structurally analyze a flitch plate beam, transformed section properties are used that treat the composite section as an equivalent wood member. Connection between the steel plate and wood side pieces is done using bolts. Bolt size and spacing in the construction of flitch beams is crucial so that all the materials act as one solid member.

Advantages of flitch beam include increased load capacity, increased buckling capacity, no shrinkage distortion and cost saving. Flitch beams are used where a solid wood member is not practical, such as depth limitations or heavy loads or where an existing wood beam needs to be strengthened to resist higher loads. A flitch beam can typically support heavier loads over a longer span than an all-wood beam of the same cross section. Unlike engineered wood beams, flitch plate beams can be flush framed with dimension lumber joists without causing shrinkage related distortions to the structure. Moreover, the wood side pieces provide lateral support to the slender steel flitch plate and brace the steel against lateral buckling. Finally, flitch beams can be used as an economical alternative to higher strength pre-engineered wood members (Bulleit, 1984).

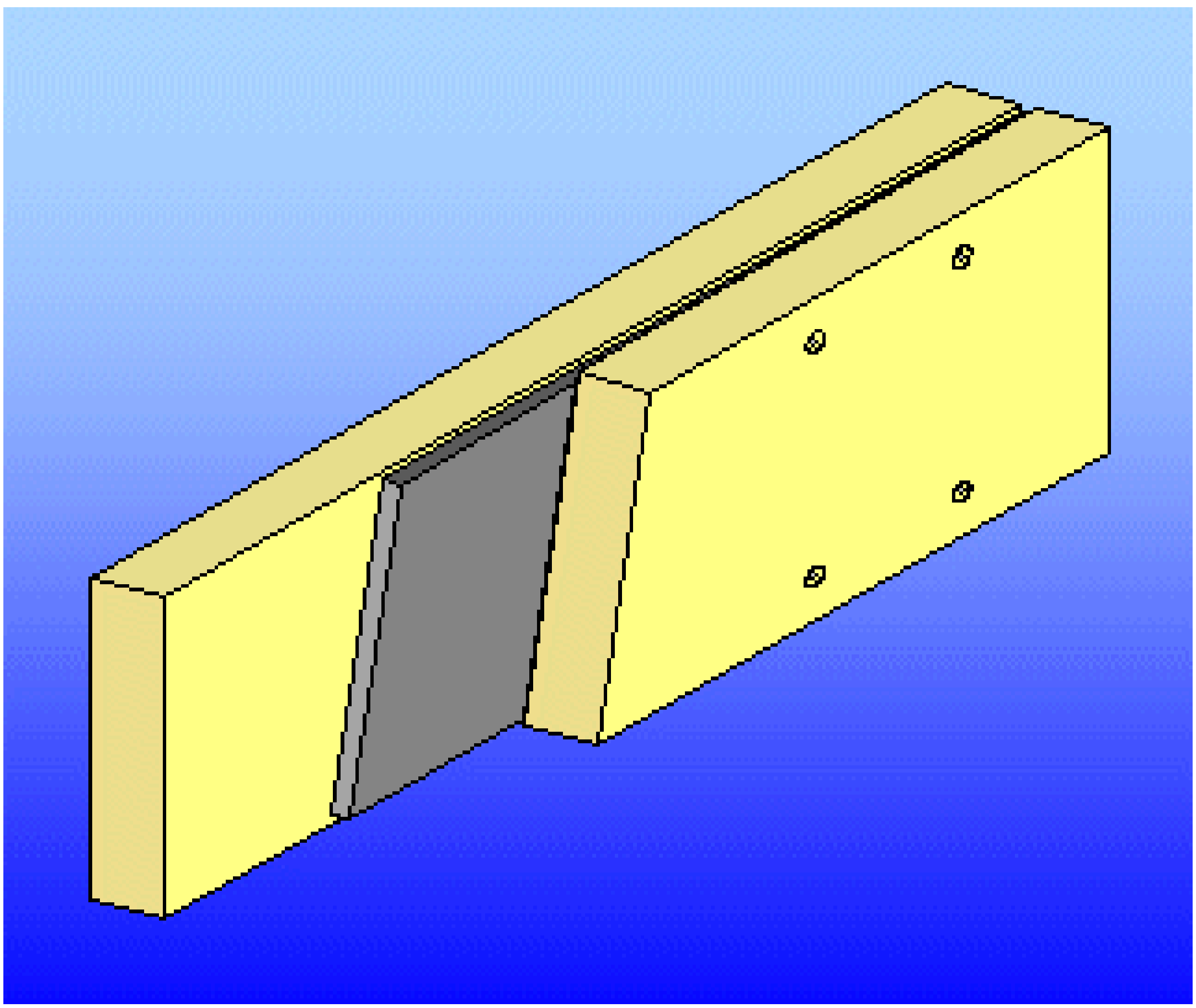


Figure 7 – Typical flitch beams

Wood member reinforced with steel plates are another type of hybrid steel timber beams. Figure 8 shows this type of wood member reinforced by steel plates on top and bottom or reinforced with steel plate in between. Alternatively the wood member can be reinforced by attaching channels to opposite sides of an existing wood beam. Advantages of such members include increased in fire resistance, improved buckling capacity, and increased in bending strength (Bulleit, Sandberg, and Woods, 1989).

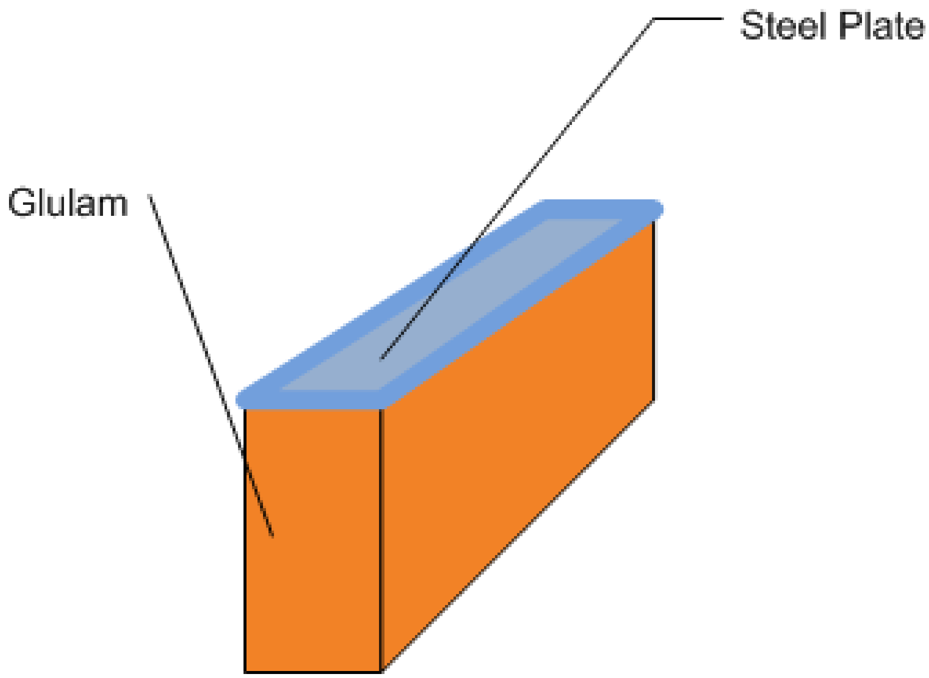


Figure 8 –Wooden member reinforced with steel plate(s)

Wooden members with built-in steel materials are another type of hybrid members. The built in steel materials can be H-shape steel member, square steel bar or steel plates as shown in Figure 9.

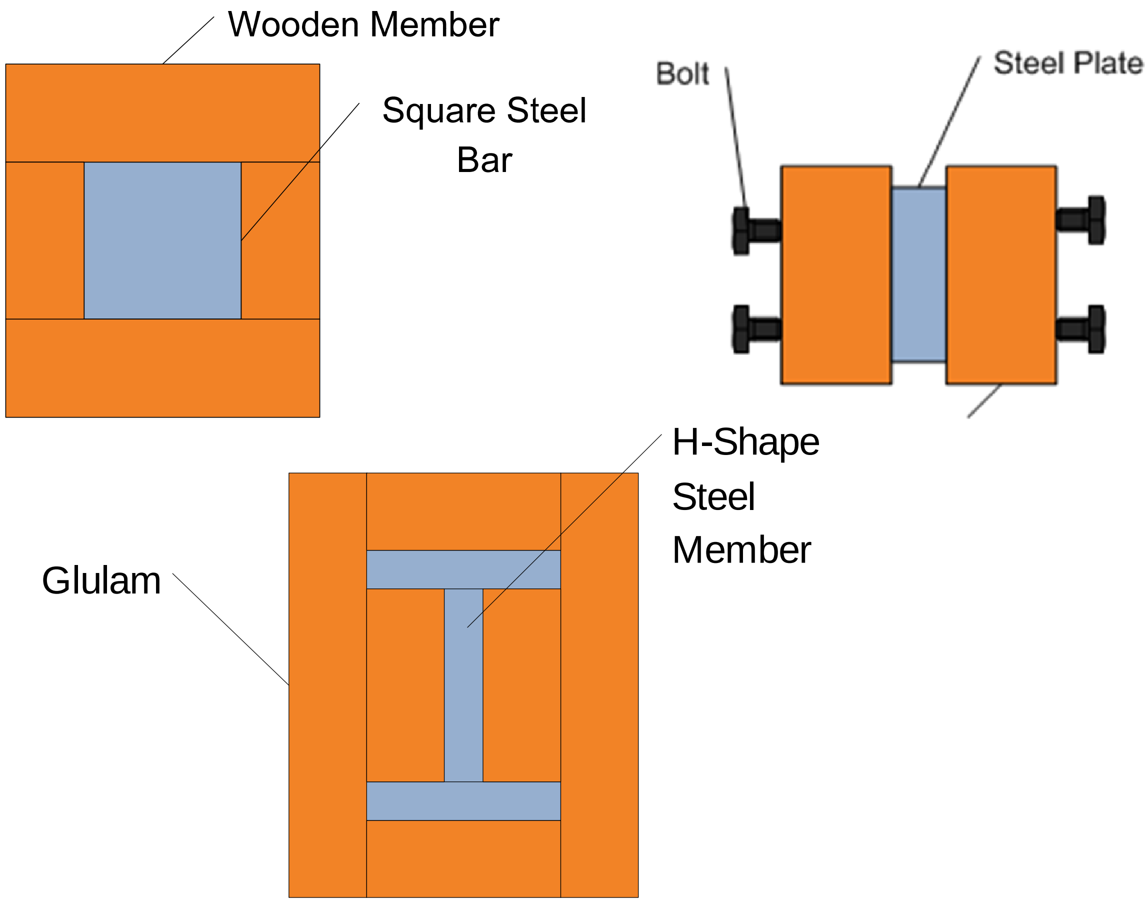


Figure 9 - Glulam member with inserted steel members

The deformation is equal between wood and steel of the hybrid member. Therefore, the loading is shared depending on the ratio of flexural rigidity (EI) of timber and steel. Since this ratio is much higher in steel, steel bears almost the entire load. The function of wood side pieces is to provide lateral support and prevent buckling.

When combining the wood with the inserted steel it is essential to have clearance to allow for possible dimension change of steel and timber due to expansion of steel or shrinkage of timber (Koshihara M., and Isoda H, 2005).

3.1.3 Hybrid joints

Another example of component hybridization involves material assemblies to create joints. These connection systems are conceptually similar to post-tensioned precast concrete building systems. The connections join prefabricated structural timber elements using unbonded post-tensioned steel tendons. Grouted longitudinal mild steel bars are also combined in the joint system as a form of dissipation device in order to enhance the seismic performance of the connection system.Figure 10 shows a conceptual hybrid solution for LVL beam-column connections based on the combination of post-tensioning and internal dissipaters (e.g. epoxied mild steel bars). While the post-tensioning provides a desirable recentering characteristic, the dissipation devices allow adequate energy absorption by the system. The researchers have compared the response of these innovative systems with the response of solutions using “monolithic” construction such as cast-in-place reinforced concrete, welded or bolted steel construction, or fully bolted, nailed or glued timber construction. It is observed that these innovative systems have many benefits over monolithic structural systems (Smith, Pampanin, Buchanan and Fragiacomo, 2008).

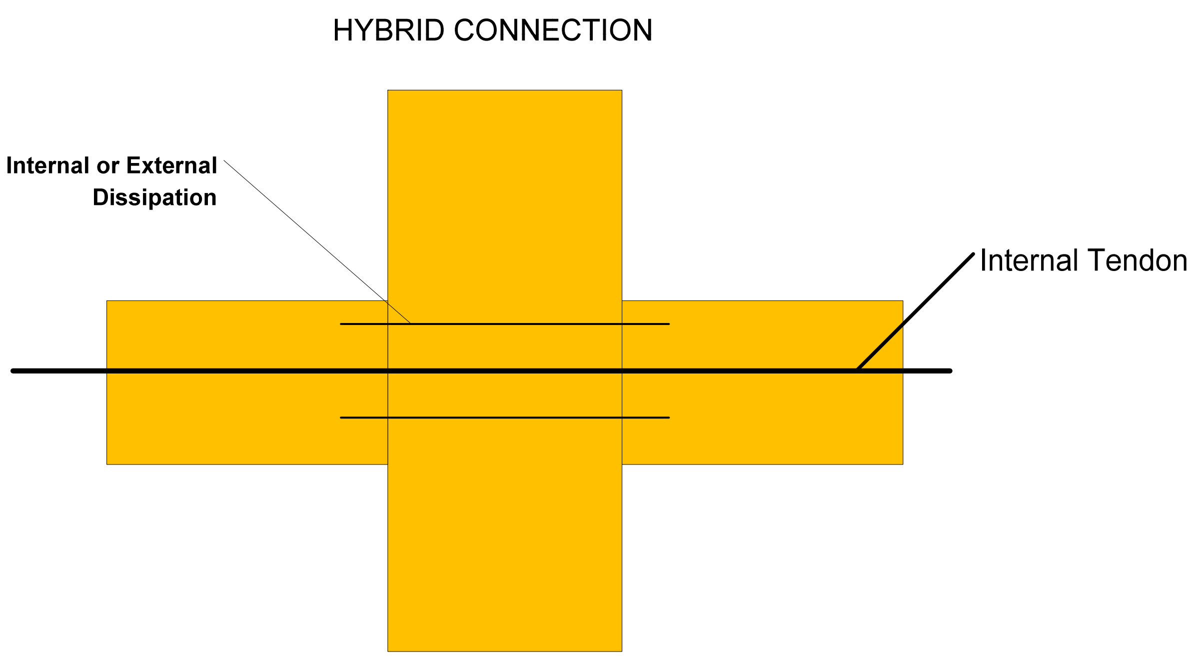


Figure 10 – Basic concept of hybrid jointed ductile connections for LVL frame systems

This connection system can be used for beam to column, wall to foundation and column to foundation. As shown in Figure 11 below, the beams and walls are pre fabricated with full-length internal duct openings for placing the post tensioning tendons.

Figure 11 - Test building members

The major benefit of post-tensioning is that a large number of strong, whilst ductile, moment-resisting connections can be made in one stressing operation at each level of each frame, avoiding the need for hundreds of nails or screws in traditional timber connections. In frames, the full-length horizontal tendons pass through ducts along the beams, and through holes in the columns, providing moment-resistance at each beam column connection. In timber walls, the tendons or threaded bars are placed vertically from the foundation to an anchor plate at the top of the multi-storey wall panels. Vertical post tensioning in columns is also possible to improve the overall system re-centering capacity as well as to act as hold-down systems. Therefore, the post-tensioning in construction provides for rapid erection and simple and economical connections between the large timber elements (Smith, Pampanin, Buchanan, and Fragiacomo, 2008).

3.2 The Building System Hybridization

In a building system hybridization a structure is simply constructed using both timber and steel members and the structural work is being shared between the two structural members. There are numerous ways of employing building system hybridization**.** Examples include vertical mixed system, hybrid roof trusses, hybrid frames and steel moment resisting frame with timber floor joist and diaphragm. With such hybrid structures, consideration of joint details is of focal importance. The joint details and challenges are discussed.

3.2.1 Vertical mixed system

A vertical mixed system is a type of building system where the first few storeys are constructed from different material than the upper storeys. In hybrid timber steel vertical system, the first floors are usually constructed from steel, and the top storeys are constructed from timber or hybrid steel timber. Major reason for having such hybrid system is that in Canada and most other countries around the world, building codes have height and area limitations on wood construction due to fire safety considerations. But there is no limitation if wood is used with a non-combustible material such as steel or concrete. (Cheung, 2000). Major challenge in design of such hybrid structure is the large difference in lateral stiffness between the “flexible” wood frame building and the “rigid” ground-story concrete structure. Shake table test on concrete-wood specimen suggests that seismic responses are greater for specimens with smaller stiffness ratio than that with larger stiffness ratio (Xiong and Jia G, 2008).

3.2.2 Hybrid trusses

The combination of timber and steel materials can produce most aesthetic designs; timber for compression members and steel for tension members, can permit a variey of timber truss styles to be achieved. Where steel rods or cables can be incorporated in a truss design, they can contribute to simplicity in the joint design and give openness in the appearance to the framework of trusses. Timber trusses can have distinct advantages for use in buildings where the stored materials may give rise to environments that could be corrosive to steel. In such situation, the amount of steelwork can be kept to a minimum so that expensive anti-corrosion costs are minimized.

Hybrid roof trusses are another way of employing structural hybridization. The combination of timber and steel materials can produce most aesthetic designs; timber for compression members and steel for tension members, can permit a variey of timber truss styles to be achieved.Though timber trusses tend to appear solid and heavy, they can take on a more delicate look when steel cables or rods are substituted for tension members. Where steel rods or cables can be incorporated in a truss design, they can contribute to simplicity in the joint design and give openness in the appearance to the framework of trusses. While adding steel creates a pleasing mix of materials, it adversely affects the fire resistance of the truss. Also, because steel expands and contracts with temperature changes, architects must look carefully at the connections to wood members. This is especially important when a hybrid truss is part of a building's exterior. Timber trusses can have distinct advantages for use in buildings where the stored materials may give rise to environments that could be corrosive to steel. In such situation, the amount of steelwork can be kept to a minimum so that expensive anti-corrosion costs are minimised (Leckie, 2008). Figure 12 below is a picture of a hybrid roof truss used in Southridge School in Surrey.

Figure 12 - Southridge School, Surrey

3.2.3 Steel frame and timber floor joist and plywood diaphragm

Building structure consisting of steel moment resisting frame and composite timber long span floor joist and plywood diaphragm has many advantages. Figure 13, shows a 14 storey building which utilizes a perimeter moment resisting frame of structural steel with a structural steel internal gravity post and beam system. The flooring system which supports gravity loads and acts as a diaphragm to transfer lateral loads to the steel frames is constructed from timber “HYBEAM” joists and plywood flooring. “HYBEAM” is an all wood I-beam with a number of advantages over sawn timber joists. It is optimised to conserve wood resources; it is available in long lengths for long or multiple span floor and floor-ceiling systems; it has a uniform height with no shrinkage; and it is light weight.

The lightweight nature of the floor construction has benefits in reducing the overall weight of the building which has a positive spin off with regards to seismic design and foundation sizes.
There are also construction benefits with respect to the possibility of prefabricating lightweight sections of floor panels which could be lifted into place with less cranage than would be required

for heavier materials. A building may only require a mobile crane rather than a tower crane, as a result. Other possibilities exist whereby the floor system may be built on top of the previous floor and hoisted into place by a series of screw jacks placed at strategic locations. This system is similar to that already utilised in some countries with post tensioned concrete slabs, however the weight of construction is once again, far less than concrete (Banks, 2006).

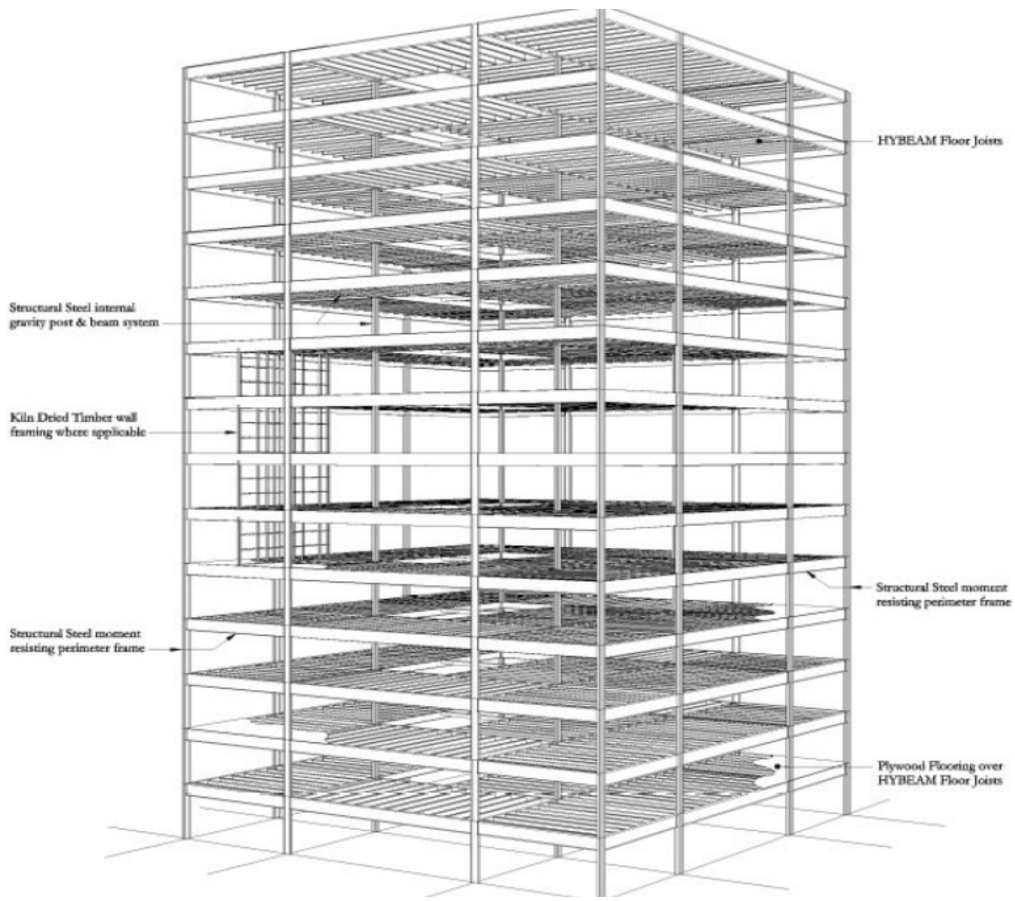


Figure 13 - 14 storey hybrid timber steel building

3.2.4 Hybrid frame

Another way of employing structural system hybridization is hybrid frames where wood and steel share gravity and lateral load. Hybrid frames are typically formed by having steel columns connected to a timber beam. These composite systems resemble conventional steel frame construction except that the steel beam is replaced by timber. Compared to an all timber frame, steel column increase the load bearing capacity and without them deeper timber sections would be required to carry the same load. Hence, hybrid steel timber frames provide economical and aesthetic advantage (B & K Timber Structures, 2008).

With hybrid structures, consideration of joint details is of focal importance. Limited amount of research results are available on the performance of hybrid steel-wood system response and performance. For light structures, NAHB Research Center has developed a builder's guide to hybrid wood and steel connection details (NAHB Research Center, 2003). Because of the differences in properties of steel and wood, connections between wood and steel can be difficult. The big problem from a structural point of view is the different expansion/contraction coefficients when you have dissimilar materials, especially on a column-beam- wall type interface. A temperature differential cause steel to expand and contract but has little effect on wood. Moreover, changes in humidity, which have little effect on steel, can cause wood to shrink and permanently change its dimensions. Strain compatibility must exist, not only under design action forces, but also simultaneously with temperature and moisture change induced forces (Leckie, 2008).

One method to achieve this is to post tension the timber members, ensuring that the member always remains under compression after being subjected to a combination of tensile and compression forces arising from the applied external forces and the internal forces arising from temperature and moisture content change. Figure 14 is the strain diagram of a post tension timber member subjected to applied forces.

It may not always be possible to maintain a net compressive strain on the member once the external forces are applied. This is very much dependent on the individual structure, its geometry and the economies of having members' sizes large enough to achieve this. A resultant tensile strain is not an insurmountable problem. All that is required is to ensure that the tensile steel members (tie rods for example) are sized so that the tensile strain is not so large as to overstress the timber component or to pull apart the timber joints in the system (Banks, 2006).

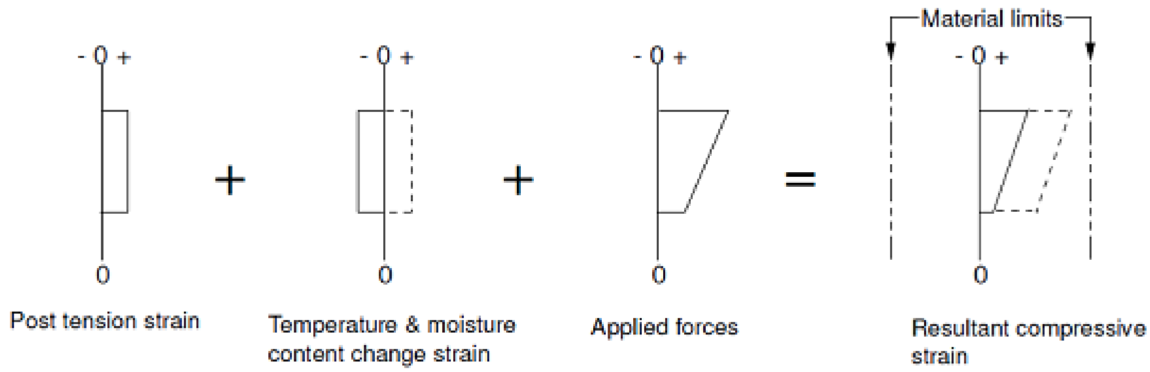


Figure 14 – Strain diagram of a post tension wood member

Another way to overcome the strain compatibility is to have slotted holes in the steel member which can allow for some movement. Because it is important to limit the restraint that the steel connecting elements impose, a bolted steel connection should not span the full depth of a wood element (B & K Timber Structures, 2008).

4.0 CASE STUDIES OF HYBRID STRUCTURES

This section provides case studies of “concrete-steel”, “concrete-wood” and “steel-wood”. Previous section described possible ways of employing timber and steel in a hybrid structure. Many of these ways have already been implemented using steel and concrete, or timber and concrete. Eventhough the major focus of this report is on hybrid timber steel structures; but, it is also beneficial to investigate lesson learnt from steel-concrete and timber-concrete hybrid structures and explore the techniques used to construct these hybrid systems. A brief summary of the case studies are provided below.

Post tensioning is a common way of hybridization. Case studies of post tensioned concrete and timber members are provided. Post tensioning is originally developed for use with pre-cast concrete. It combines the use of high-strength steel strands or bars, typically referred to as tendons with additional sources of energy dissipation. Same concept is applied for reinforcing timber. In both cases, post tenstioning helps to eliminate residual displacement, and greatly reduces the damage to structural members during a significant seismic event.

Hybrid frames are another way of hybridization of two materials. Case studies of hybrid steel-timber frame and hybrid steel-concrete frame are provided. These case studies indicate that hybrid frames have economical and structural benefits. Having concrete as the column would provide material cost saving; and having steel as the beam permits long span floor framing and minimize field labor. Similarly, compared to all timber frames, using steel as the column would increase load carrying capacity of the frame. Major challenge associated with such hybridization is the beam column connection. Techniques used to accommodate possible dimension changes of the two materials due to difference in expansion/contraction coefficients and possible shrinkage in wood and concrete are discussed.

Finally two case studies of vertical mixed system of concrete-timber, and concrete-timber and steel member are provided. In the first case study, dynamic characteristics and the seismic performances of the vertical concrete timber system is investigated and the effect of stiffness ratio between concrete and timber on the seidmic performance of the building is discussed. The focus of the second case study is on the advantages of the composite steel timber members used in the building.

4.1 Hybrid Steel-Concrete Structure Case Studies

Following sections discusses the advantages and challenges of two types of hybridization of steel and concrete, namely, hybrid frames and post-tensioned concrete walls.

4.1.1 Overview of U.S.–Japan research on the seismic design of composite reinforced concrete and steel moment frame structures

Following section is the summary of the paper "Guidelines: seismic design of composite reinforced concrete and steel buildings" by Nishiyama, Kuramoto, and Noguchi. As discussed previously hybrid frames are one way of employing building system hybridization. A brief summary of the result of the U.S.–Japan Cooperative Research Program on the seismic design of moment frames consisting of reinforced concrete (RC) columns and steel (S) beams—the so-called composite RCS frames is provided.

These RCS composite systems are similar to conventional steel frame construction except that the steel columns are replaced by high strength reinforced concrete. RCS frame can be designed with seismic deformation capacity and toughness comparable to traditional steel or reinforced concrete construction. The composite RCS frames can provide cost-effective alternatives to traditional steel or reinforced concrete framing systems. Compared to traditional steel frame having reinforced concrete as the column provide material cost saving; and compared to traditional concrete frame, steel beams permit long span floor framing and minimize field labor. Much of the research emphasis has been on the design and behavior of the composite RCS beam–column connections, which pose unique challenges that are not addressed by traditional design standards. Two types of RCS connection joint details namely, "through beam" and "through column" types have been investigated. Figure 15 shows these types of joints.

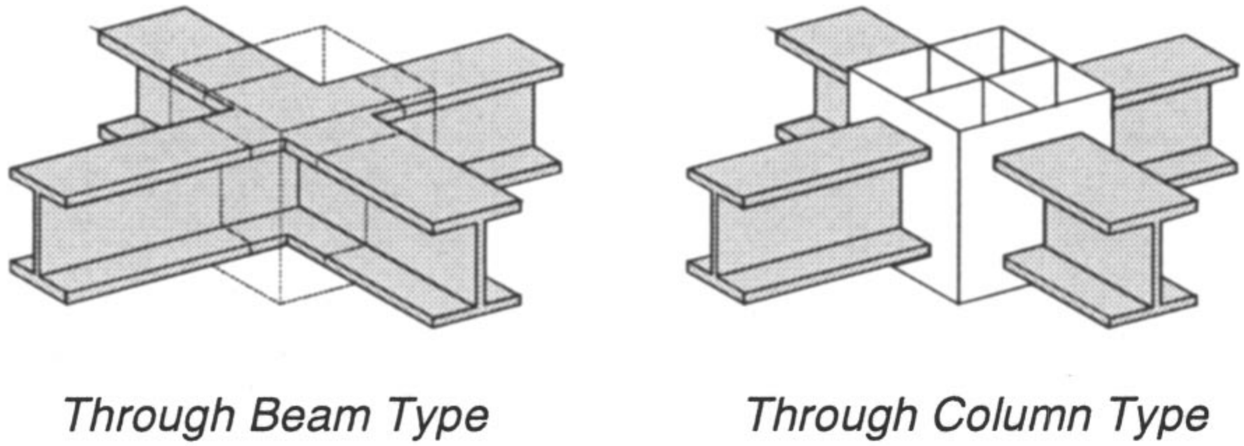


Figure 15 – Hybrid concrete steel frame connection

In a through beam type the beam runs continuous through the joint. In this way the beam is not interrupted at the point of maximum moment at the column face and therefore, avoids the fracture-critical joints that are of concern in conventional steel construction.

In a through column type the beam flanges are interrupted at the joint. This system is advantages as it minimizes the impact on the column reinforcing bar arrangement and helps with placement of concrete in the joint.

Through-beam type connections have been the preferred detail in the United States, whereas both types have been used in Japan. Overall, the tests show that, when properly detailed to mobilize internal force transfer mechanisms, RCS connections provide reliable strength and ductility for seismic design.

4.1.2 Post-tensioned concrete walls and frames for seismic-resistance – a case Study of the David Brower Center

This section summarizes the paper "Post-Tensioned Concrete Walls and Frames for Seismic-Resistance – A Case Study of the David Brower Center" by Mark Stevenson.
The use of post-tensioning in concrete structures to resist gravity loads is a well established technology with wide application. Recent advances in design practice and analysis techniques are demonstrating that post-tensioning also offers significant cost and performance benefits when incorporated into seismic resisting concrete walls and frames. Following case-study describes an innovative application of post-tensioned concrete construction in the new David Brower Center. The building is located in Berkeley, CA within 1km of the Hayward Fault. The

complex represents a model of integrated sustainable design and is rated LEED Platinum by the U.S. Green Building Council.

The building is located in a high risk seismic zone, and to protect the building against the high likelihood of a major earthquake, the structure integrates a unique combination of post-tensioned concrete walls and frames that improve performance, limit damage, and make more efficient use of construction materials. The defining feature of this system is its unique self-centering behavior, which virtually eliminates permanent post-earthquake deformations. The hybrid system combines the elasticity of the high-strength un-bonded tendons with the energy dissipation capacity of the mild-steel reinforcement to control the inelastic response of the structure.

Several benefits can be realized by the introduction of post-tensioned reinforcement to concrete seismic lateral resisting systems. Such hybrid system provides improved ductility and self-centering behavior; hence, is less prone to physical damage during earthquake shaking. The ability to eliminate residual drift represents a major innovation in seismic design. Moreover, post-tensioning allows more slender, dramatic elements wich will result in lower building weight versus a conventional concrete building. This reduces the foundation load and can be a major advantage in seismic areas. The post-tensioning provides a significant strength enhancement, substantially reducing quantities of conventional reinforcement in flexural members, resulting in more compact dimensions and improved constructability. Additionally, savings in carbon footprint and greenhouse gas emission were realized through integrating high-slag concrete in the structural system. These characteristics played an important role in meeting the sustainability goals of the David Brower Center.

4.2 Hybrid Concrete –Timber Structure Case study

Following case study summarizes the paper “Research on Seismic Behaviour of Wood-Concrete Hybrid Structure” by Haibei Xiong and Guocheng Jia. As discussed previously vertical mixed system of timber and a non-combustible material is one way of satisfying code requirement for fire safety in many countries including Canada. Shake table tests on 3 storey hybrid concrete wood specimens. The shake table tests are performed to investigate the effect of stiffness ratio between the flexible wood frame upper storeys and rigid ground-storey concrete structure. The test results suggest that seismic responses are greater for specimens with smaller stiffness ratio than that with larger stiffness ratio.

Wood frame construction and wood-concrete hybrid structure are major structural types for residential and commercial buildings in North America. Currently the seismic resistance of such system is under consideration. Some research achievements are included in building codes, such as the US International Building Code and the National Building Code of Canada. In these codes, seismic design of wood frame construction is discussed. But, the assessment of seismic resistance of wood-concrete hybrid structure is not mentioned.

In NBC and IBC, a two-stage equivalent lateral force procedure is permitted to be used for structures having a flexible upper portion above a rigid lower portion, with the stiffness of the lower portion must being at least 10 times the stiffness of the upper portion, and the period of the entire structure shall not be greater than 1.1 times the period of the upper portion considered as a separate structure fixed at the base. However, design methods are not specified for a wood-concrete building if the stiffness of concrete frame is less than 10 times the stiffness of wood frame construction. FPInnovations and Tongi University jointly conducted shake table tests of three-storey wood-concrete specimens with a range of different stiffness ratios between concrete frame and wood frame construction in order to investigate the dynamic characteristics and the seismic performances of this type of building.

The specimens consisted of a symmetric two storey wood-frame construction on top of a one storey concrete frame. Five full-scale specimens with different stiffness ratios from 2:1 to 12:1 are tested. Configurations of the specimens are provided in Table 1. The dimensions of all specimens are 6.1 m x 3.7m in plan, with 2.8 m storey height for wood frame construction and 3.0 m for reinforced concrete frame in the first storey. The cross section of the concrete column is 270mm x 270mm, and the thickness of concrete slab is 80mm. A schematic and photo of the specimen are shown in Figure 16. The test specimen was built in accordance with the prescriptive requirements of the National Building Code of Canada and Chinese Code for Design of Timber Structures.

Table 3 – Specimen configuration and ratio of stiffness between concrete frame and 2nd storey

Source: Xiong H. and Jia G. (2008), Research on Seismic Behaviour of Wood-Concrete Hybrid Structure, Proceeding of the 10th World Conference on Timber Engineering

Specimen No.	Opening size at the 2nd storey (mm)	Reinforced concrete frame ad brace type	Stiffness (kN mm)		Stiffness ratio RC/WFC frame
			RC Frame	WFC	
M1	1220	Only RC Frame, no bace	10.0	4.8	2 : 1
M2	3660		10.0	2.4	4 : 1
M3	1220	RC Frame with brace, type 1	20.0	4.8	4 : 1
M4	3660		20.0	2.4	8 : 1
M6	3660	RC Frame with brace, type 2	30.0	2.4	12 : 1

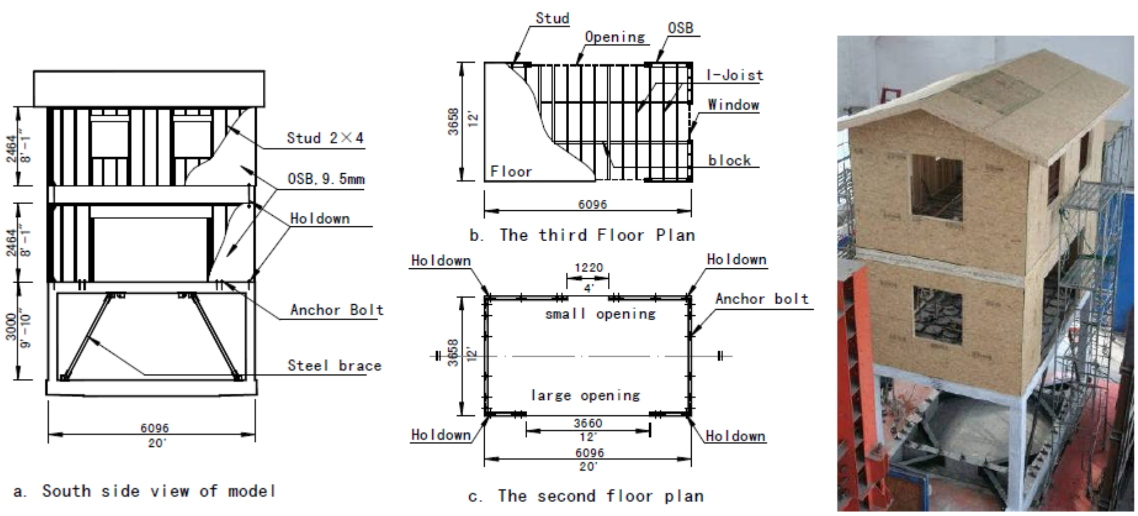


Figure 16 – Schematic and photo of wood concrete specimen

Dynamic properties of the specimens, such as the natural frequencies, damping ratios and the mode shapes are obtained by analyzing the transmission functions of acceleration response at each floor of the specimen. Figure 16 shows the first and second mode shapes of the specimens. It indicates that the greater the stiffness ratio, the more flexural the mode curves.

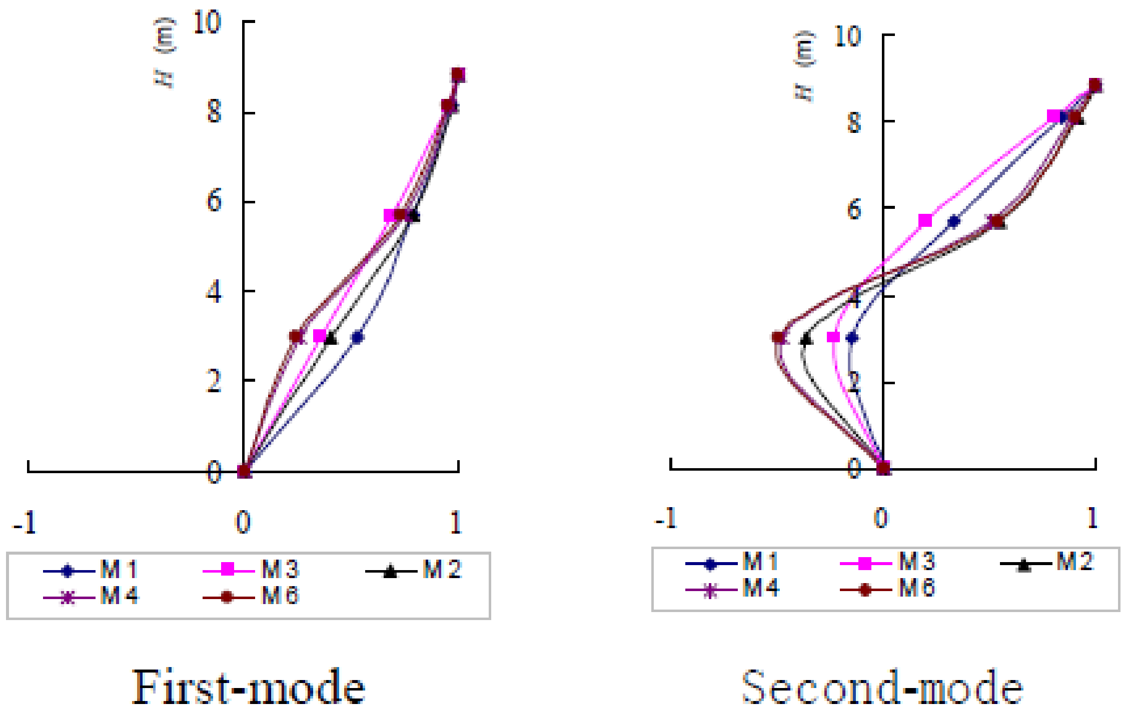


Figure 17 – Comparison of the Vibration Mode Shape

For the wood-concrete specimens, the upper wood frame construction has good seismic performance. The structures does not collapse with the maximum inter storey drift of 1/49 under the peak ground acceleration of 0.5g. The main damages is at the corners of wall panels, especially near the openings, due to nail shear failure, nail withdrawal and panel chip out.

For the wood-concrete specimens tested, the acceleration response, displacement response, acceleration amplification factor of upper wood frame structure decreases with the increase of stiffness ratio of concrete frame to wood frame. Based on the test results and numerical analysis, it can be concluded that in general, seismic response is greater for specimens with smaller stiffness ratio.

4.3 Hybrid Wood Steel Structures Case Studies

This section gives a detailed description of two studies of hybrid steel-timber structures each pertaining to structurl level hybridization and component level hybriduzation.

4.3.1 Feasibility and detailing of post-tensioned timber buildings for seismic areas

Following section summarizes the recent research conducted in the University of Canterbury in Christchurch, New Zealand and described in the paper "Feasibility and Detailing of Post-tensioned Timber Buildings for Seismic Areas" by T. Smith, S. Pampanin, A. Buchanan and M. Fragiacomo.

Researchers from the University of Canterbury in Christchurch, New Zealand, recently conducted an extensive research to develop new hybrid structural systems and connections for multi-storey laminated vaneer timber buildings in earthquake-prone areas. These connections will allow timber buildings to survive and remain serviceable after earthquakes.

The innovative hybrid jointed ductile timber connections are conceptually similar to post-tensioned precast concrete building systems. The connections join prefabricated structural timber elements using unbonded post-tensioning so that the opening and closing of an existing gap accommodates seismic demand during an earthquake. This design keeps the structural elements in the elastic range and limits residual damage following a seismic event.

The performance of the system is further improved by combining the self-centering properties of the unbonded tendons with energy dissipation devices that are replaced after seismic events. While the post-tensioning provides a desirable recentering characteristic, the dissipation devices allow adequate energy absorption by the system.

Figure 18 shows a conceptual hybrid solution for LVL beam-column connections based on the combination of post-tensioning and internal dissipaters (e.g. epoxied mild steel bars).

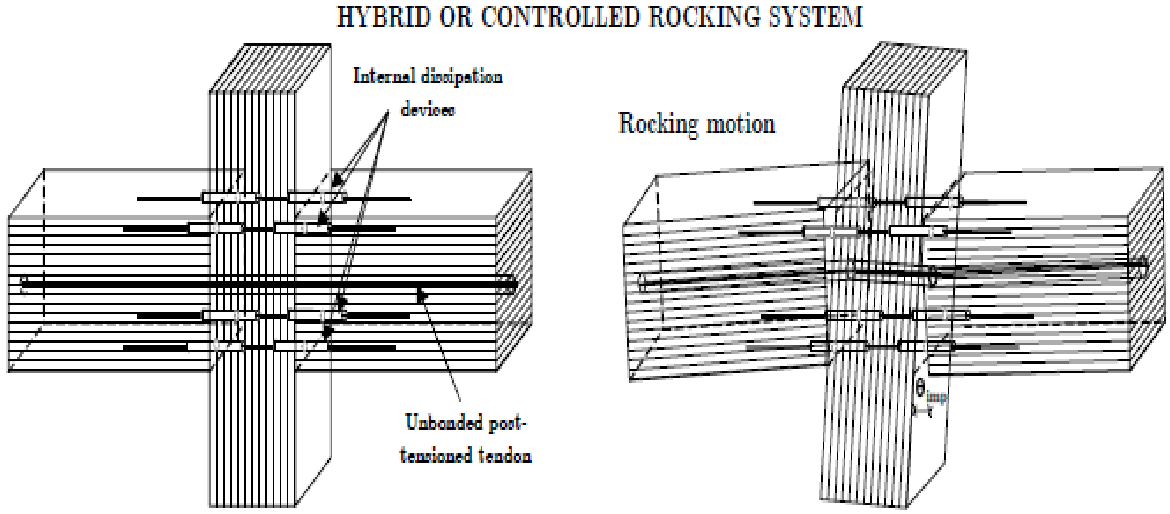


Figure 18 – Basic concept of hybrid jointed ductile connections for LVL frame systems

As shown in Figure 19, in a post-tensioned jointed ductile connection a "controlled rocking" motion occurs with the opening and closing of an existing gap at the critical interface. When compared to pure rocking motion, the prestressing force (initial prestress plus additional contribution due to elongation of the tendons) provides a restoring force counteracting excessive opening (rotation demand), reversing the rocking motion, and closing the gap completely after an earthquake. The additional non-prestressed reinforcement can provide further limitations to the gap rotation demand, by increasing the strength of the connection as well as reducing the seismic demand (energy dissipation contribution).

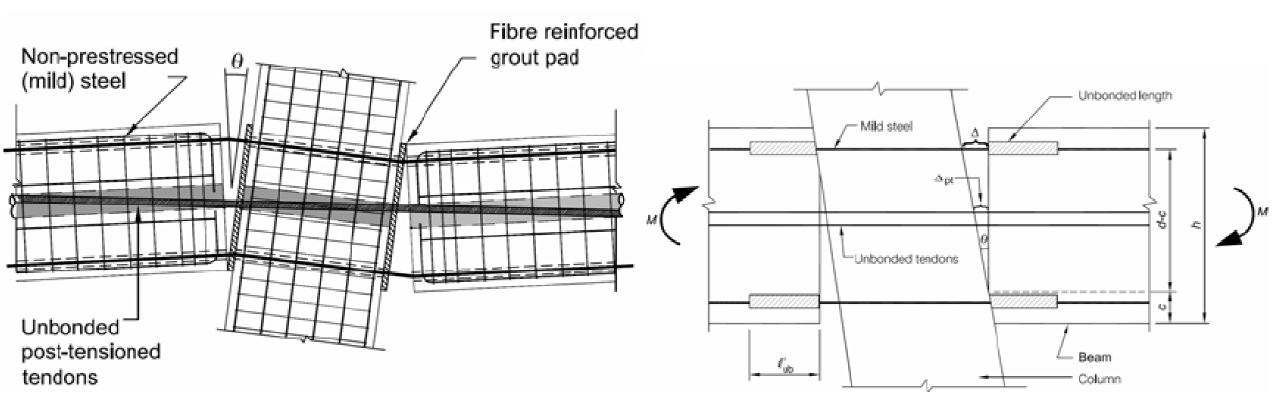


Figure 19 – Controlled rocking mechanism at the critical connection in a hybrid beam-column connection

An extensive research is carried out on beam-to-column, column-to-foundation and wall-to-foundation subassemblies for the implementation of laminated veneer lumber (LVL) hybrid solutions. Figure 20 shows the test assembly. The tested connections show excellent results some of which are presented in Figures 21, Figure 22 and Figure 23 below.

Figure 20 – Test assembly of the connections

A stable "flag shaped" hysteretic loop is observed in all the cases with negligible residual displacement, confirming the self-centering characteristics of the hybrid systems. The equivalent yielding point corresponds to the actual yielding of the dissipation devices, while the total moment capacity of the system increases with the increasing drift levels due to the elongation of the tendons. No degradation of stiffness and no structural damage are observed and a maximum drift level of 4.5% is achieved during all tests apart from that of the wall which was stopped due to the tendon approaching yield. This rapid increase in tendon tension will not occur in the actual assembly due to the increased length of the tendon in a real building, reducing the variation in strain.

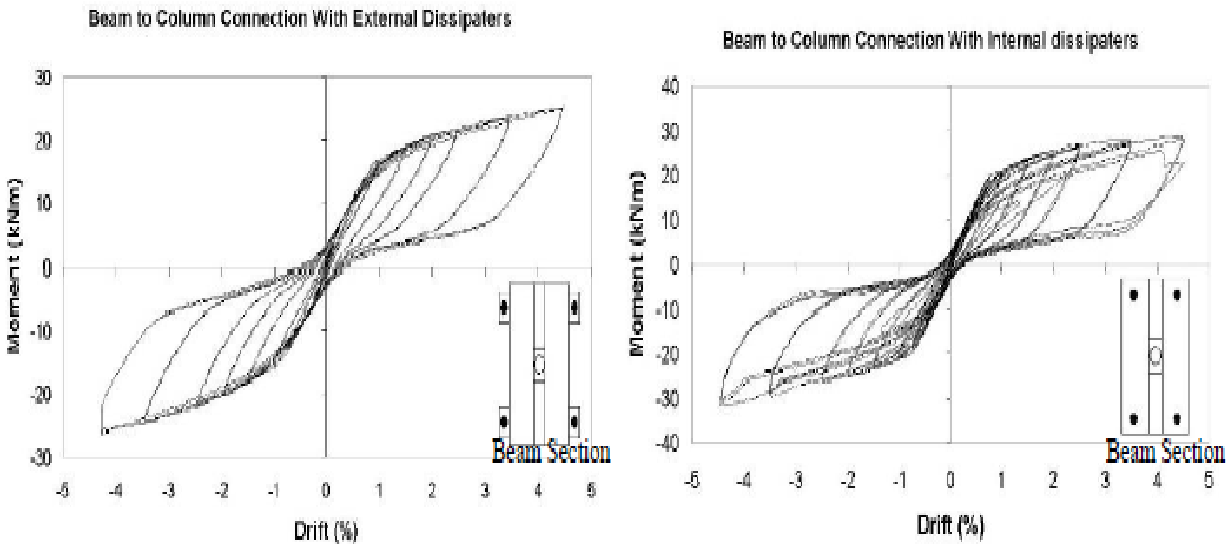


Figure 21 – Hysteric loops from test on beam-to-column connection a) with external dissipaters. b) with internal dissipaters

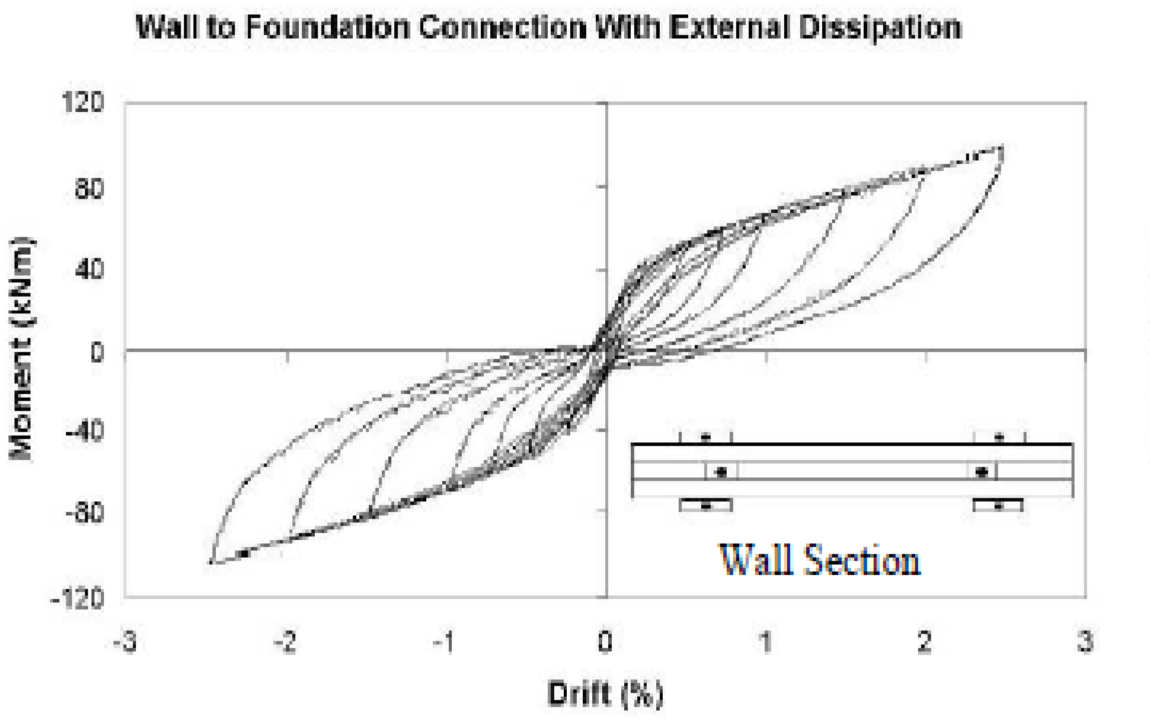


Figure 22 – Hysteric loops from testing on wall-to-foundation connection

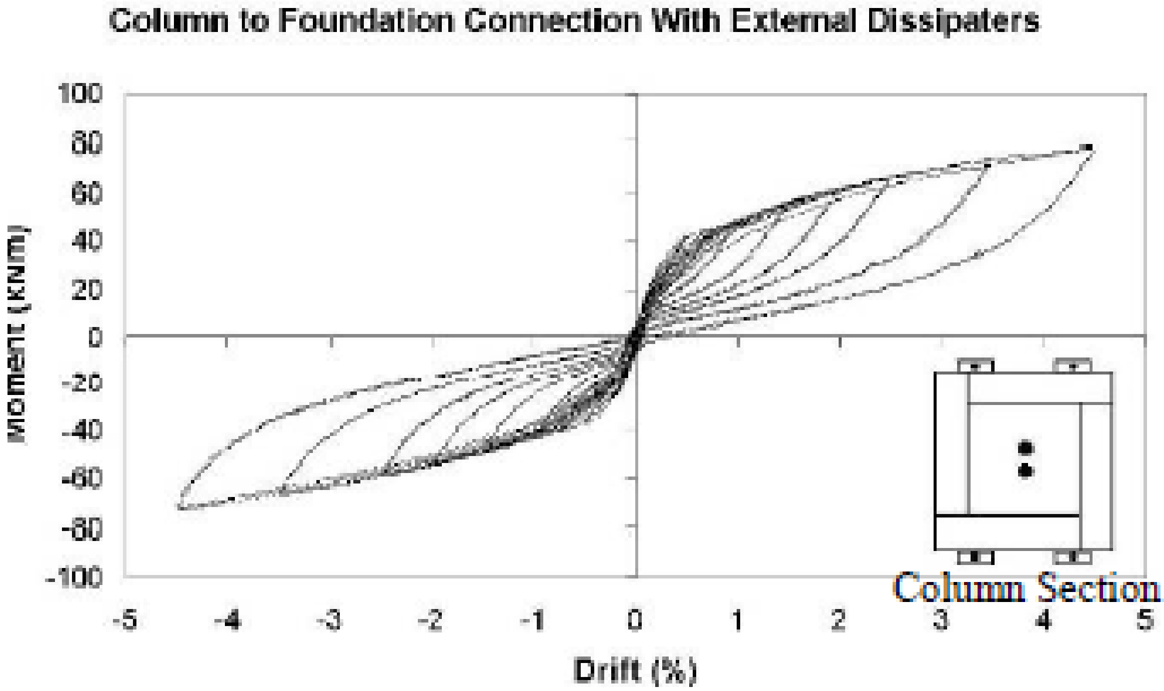


Figure 23 – Hysteric loops from testing on column-to-foundation connection

Further to this testing, coupled and parallel wall systems have been investigated. For multiple wall systems, dissipative devices can be based on the relative motion between two adjacent walls, not the gap formed between the wall and the foundation. Different methods of dissipation have been investigated. The most effective of these was the use of U Shaped Flexural Plates (UFP), as seen in Figure 24.

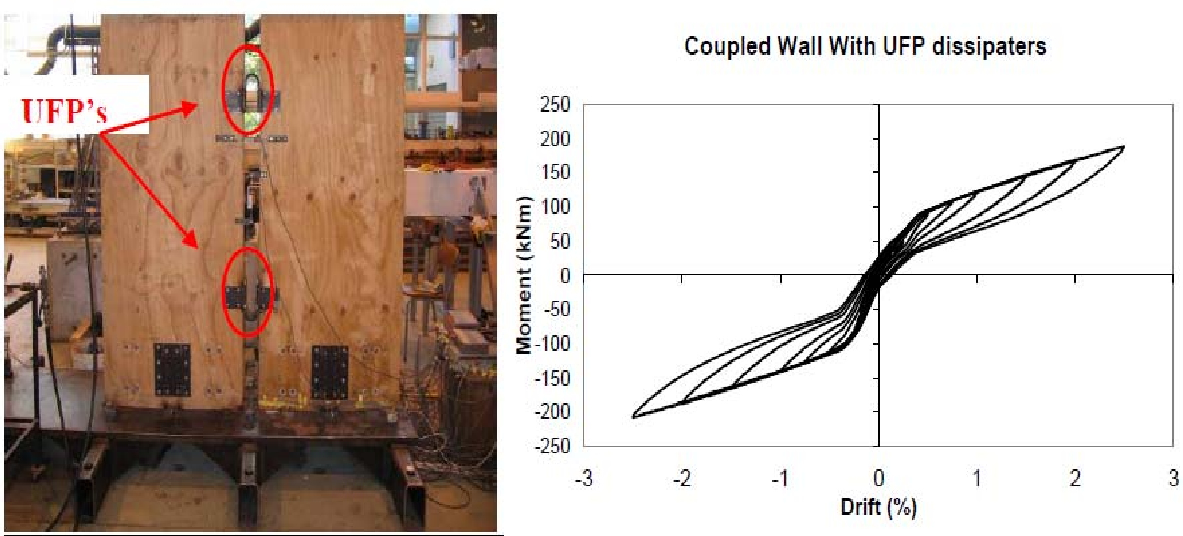


Figure 24 - Result from coupled walls with UFP dissipation

A case study of a six storey timber office building in a moderate seismic area is analysed and a virtual design is carried out allowing investigation of different methods of structural analysis, and development of many construction and connection details for rapid construction.

An initial cost analysis for the building has compared the timber building to steel and concrete structures that have been designed to the same seismic and architectural standards. The total cost of these buildings is shown below in Table 4, with cost breakdown in Figure 25.

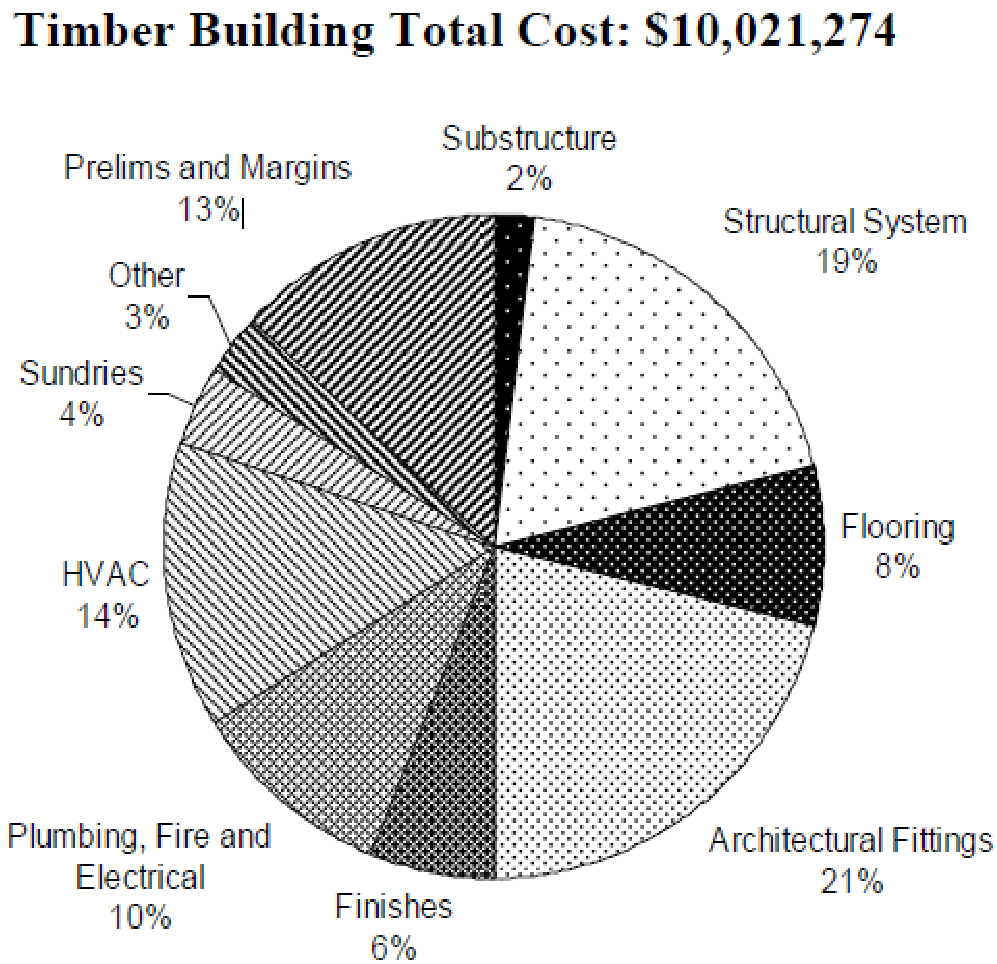


Figure 25 - Cost breakdown of the case study

Table 4 –Total cost of case study building options

Source: Smith, T., Pampanin S., Buchanan A., Fragiacomo M. (2008) Feasibility and Detailing of Post-tensioned Timber Buildings for Seismic Areas. Wairakei, New Zealand, New Zealand Society of Earthquake Engineering (NZSEE) Conference, 11-13 Apr 2008. Proceedings of the 2008 New Zealand Society of Earthquake Engineering (NZSEE) Conference, Online

	Timber	Steel	Concrete
Total Cost	$10020000	$9370000	$9430000

As shown above the steel and concrete building options cost approximately $500,000 (5%) less than that of the timber option. Although the structural timber system costs considerably more than that of the steel or concrete systems it represents a small portion of the buildings overall cost ensuring the total cost difference is modest. Further to this the cost of construction is likely to be offset by the rapid construction time using light pre-fabricated sections on site. It is also expected that the cost over time will decrease as the technology matures. Actual costs will come available as real buildings are constructed.

4.3.2 Hybrid timber/steel retail structure-Sainsbury's Dartmouth – England

The following case study is the summary of the paper, "Hybrid timber steel retail structure Dartmouth-Devon, United Kingdom" by B & K Timber Structures. Sainsbury Dartmouth warehouse in Devon, England is a hybrid structure comprised of hybrid frames of steel and timber. Following section describes structural detailing such as connections and bracings used in Sainsbury Dartmouth warehouse. Moreover, it describes the challenges faced with building the hybrid retail store, and techniques used to overcome these challenges. Further, the benefits of constructing a hybrid timber steel structure rather than an all timber structure are discussed.

The store is built in glued laminated timber as the primary structural material. Glued laminated timber is attractive to large retailers for several reasons. It is cost effective, aesthetically pleasing, environmentally friendly, and will increase fire resistance of the building. Using timber will reduce the cost of the structure. The price of structural steel components is rising, mainly due to the rising cost of energy, whilst the corresponding increases in timber have been much less. Timber provide a warmer and more relaxed environment and customers greatly appreciate it. Timber has a vastly reduced impact on the environment, due to its carbon content (the carbon storage effect) and the lower energy required producing, process and transporting the material. In fire, timber members char on faces exposed to fire but still retain strength and stiffness by virtue of the much cooler core within the charred surfaces and thus their performance is predictable and collapse is unlikely.

The store comprises 18,500 ft^2 of selling space at the front of the building, 6,500 ft^2 of storage space at the back on ground level and a similar floor area above on a mezzanine level which accommodates offices and heavy plant equipment. The front of store is structurally supported with laminated spruce columns, shaped rafters and purlins. The exception being the external columns at the very front of the store, which are in larch – chosen for its greater durability (rated moderately durable) that removes the need for preservative treatment. The back of the store is very similar but uses steel columns instead of timber. The roof is braced with tubular steel members.

Cladding to the building comprises insulated composite wall panels with either timber shiplap boards or lime render. Figure 26 below is the 3D view of the warehouse showing framing components.

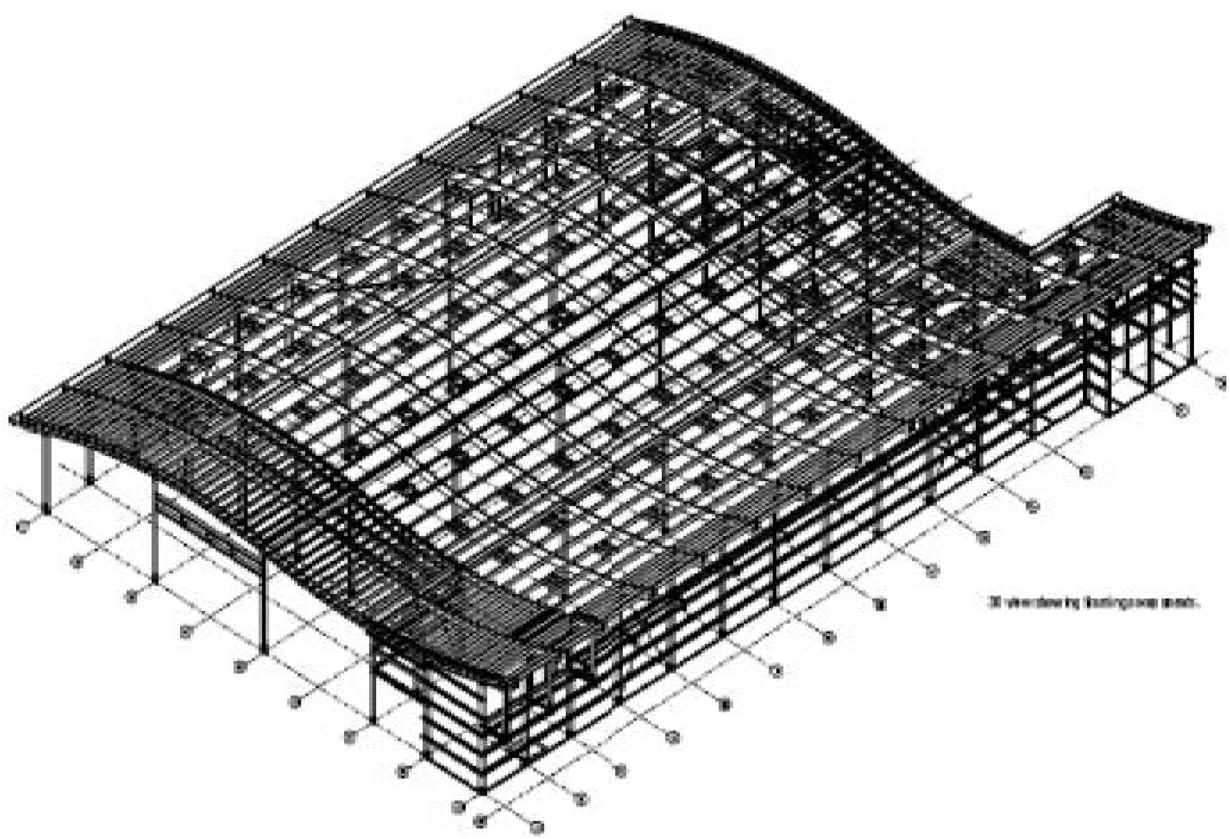


Figure 26 – 3D view of the framing

Mixing steel with the timber structures provides further advantages. Cladding to the building comprises insulated composite wall panels with either timber shiplap boards or lime render. This was the original intention, however the loadings required for the mezzanine concrete floor (where heavy plant is housed), whilst possible in timber, required very large sections and cumbersome associated beam to column connections which were more expensive than steel. The environmental carbon impact calculations showed that by using timber for the front of the store, the overall impact was still 'negative' because the gains from using timber more than compensated for the steel at the back of the store. Had timber been used in the back of store area it would have required additional protection to cope with pallet and forklift truck damage.

Bracing was required in the 'plane' of the roof across the store. Since the main glulam 'S' members were to be the dominant focus it was decided to use steel for the cross-bracing because slimmer sections were possible.

Connection details were most important challenge in designing the hybrid building. Columns to foundation beam to column and roof bracings design details are described. The method used to fix timber columns to the foundations is similar to the typical steelwork base plate. This allows each column to be erected independently without relying on neighbouring columns or raking props, which both increases efficiency and reduces the chance of damage to the timber. Key features of this design are described in the following and are illustrated in Figure 27.

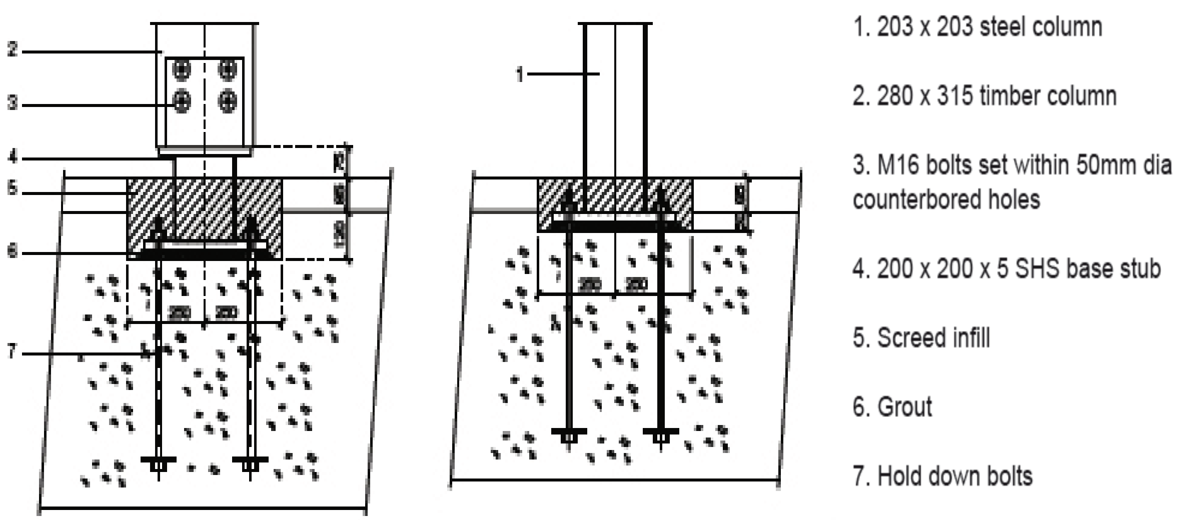


Figure 27 – Typical base detail for timber (left) and steel (right) column

A traditional base plate is extended upwards by a 200 SHS steel section so that the horizontal capping plate on which the bottom of the timber column bears is at least 75mm above finished floor level. Free standing external larch columns employ a longer SHS extension piece so that the timber is at least 200mm clear of the external paving level. A fin plate is welded to the capping plate that is then let into the bottom of the column and secured with four bolts, countersunk where necessary. The timber overhangs the cap plate so that any water will drip clear of the capping plate and minimize the risk of moisture being drawn up the end grain of the timber. The steel assembly is galvanized before assembly and the column finally erected on holding down bolts in the traditional steelwork manner thus allowing adjustment of the columns both horizontally and vertically.

The timber structure was braced with systems of diagonal tie rods in a similar manner to that employed on steel structures. Connections to timber columns were made with bolted on steel cleats.

The bracing in the roof was provided by tubular steel sections capable of working in tension or compression. Connection to the roof beams were made with bolted on steel cleats. Figure 28 is a picture of the connection between timber column to glulam roof member (left) and steel column to glulam roof member (right).

Figure 28 – Head of the timber column (left) and steel column (right) to glulam roof member

An important issue in the design was the accommodation of possible dimension variations of the glulam members due to moisture changes in the timber, particularly at the connections between steel and timber. Slotted holes in the steel were provided to allow for possible cross grain movement of the timber thus minimizing the risk of longitudinal splitting of the glulam.
This detail, which was used in conjunction with both the timber and steel columns, ensured that the load was transferred in bearing on to the head of the columns. Some expansion in length of the steel columns on heating is designed for and this is catered for by the slots mentioned above and general tolerances in the system.

4.4 Hybrid Concrete –Steel-Timber Building Case Study

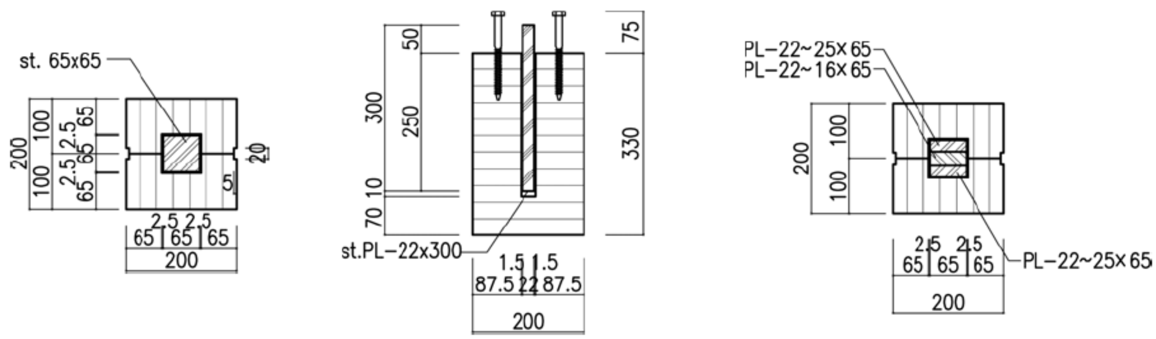
The following case study is a summary of the paper "The design and installation of a five-story new timber building in Japan" by Koshihara Mikio. The case study involves a hybrid vertical mixed system of concrete and timber-steel composite members. The advantages of such hybrid system as well as the load carrying mechanism and joint details are discussed.

4.4.1 Overview of the Kanazawa M building

Timber buildings have always been popular in Japan. However, major concerns with timber buildings are their seismic performance and fire resistance. From 1950 to 1987 wooden buildings over 13m height were prohibited by law. Revision of the Building Standards Law 2000 allowed the construction of buildings four-story or taller with fire-resistance performance. The five-story Kanazawa M building (Kanazawa M Bldg.) built in 2005 is the first timber-based hybrid building in Japan. Experimental tests verified the seismic performance, buckling capacity and fire resistance of Kanazawa M building as required by the Building Code of Japan. The possibilities of middle-rise and high-rise timber buildings are extended by completion of this building.

In this building, first-story is built in reinforced concrete construction and from second to fifth stories is built in timber-based hybrid construction. In structural framing, the performance-based design method is applied and the safety against seismic forces is verified by conducting some static structural experiments about the seismic performance of shearing wall and the buckling stress of timber-based hybrid column. In fire resistance system, fireproof construction is required for this building. Three fireproof elements, column, girder and bracing, are tested for 1 hour fire resistive period. The fire resistance of the members are verified using a beam-loaded heating test, a column-loaded heating test, and a joint heating test. All elements prove to have enough properties for 1 hour fire resistance.

The building uses laminated timber with built-in steel materials for columns, beams, and braces to satisfy the structural and fire resistance requirements of a five-story building. The cross section of each member is shown in Figure 29. In all these members, the steel frame carries the structural load and the wood side pieces prevent lateral buckling and increase the fire resistance of the member.



column beam brace

Figure 29 – Cross section of column, beam and brace

The column is square laminated timber (larch E105-F300, 200 x 200 mm) with built-in square steel bars (SS400, 65 x 65 mm). The beam is laminated timber (200 x 330 mm) with steel plates (SS400, PL-22x300). The cross section of a brace looks identical to that of a column, which is necessary for fire resistance certification.

The floors and roofs are made of reinforced concrete slabs joined together with lag screws and steel plates built into the beams.
The longitudinal walls are load-bearing and made of nailed plywood. The lateral walls are non load-bearing, because of setting braces.

4.4.2 Vertical load

The timber and steel frame function together as a structural member in the second to fifth stories of a timber-based hybrid structure.

Since the vertical deformation is equal between the timber and the steel frame, vertical load is shared depending on their ratio of flexural rigidity, EI. (E: Young's modulus, I: Geometric moment of inertia). The flexural rigidity ratios EI / ΣEI are shown in Table 5.

Table 5 – Flexural rigidity table of timber and steel frame

Source: Koshihara M., and Isoda H.(2005), The design and installation of a five-story new timber building in Japan, Summary of technical papers of annual meeting architectural institute of Japan, c-1, pp.201-206,

	E (N/mm^2)	I (mm^4)	EI (Nmm^2)	EI/ΣEI
Timber frame	1.05×10^4	5.55×10^8	0.583×10^{13}	0.366
Steel frame	2.05×10^5	4.95×10^7	1.01×10^{13}	0.634

As mentioned previously the beam is comprised of laminated timber and steel plates. The timber and steel frame of the beam are joined at a beam edge using drift pins to transmit the load from the timber to the steel frame. In this way, the steel frame bears the entire shear force.

As shown in Figure 30, the column-beam connection is made using high tension bolts to join gusset plate from the steel frame of the column and the steel frame of the beam. The holes in the side of the timber frame are filled with timber after high tension bolts are clamped.

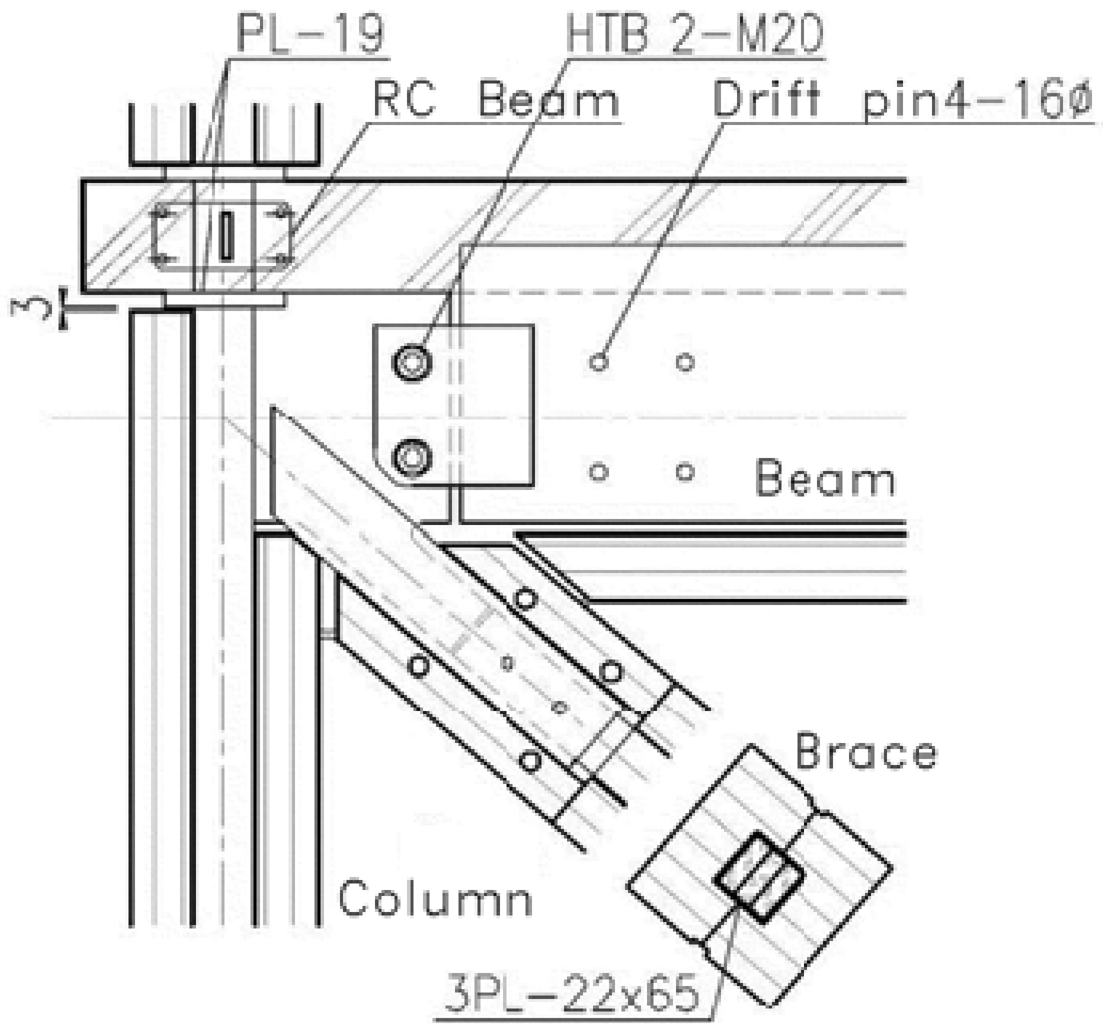


Figure 30 – Lateral joint system

The column is square laminated timber with built-in square steel bars. Vertical load is transmitted to the steel frame of a column through a gusset plate. 3 mm clearance is used when combining timber with the steel frame; as a result the vertical loading of timber is avoided. The major function of the timber of the column is to restrain the bucklng of steel. The structural experimentation shows, alone, the steel frame of the column buckles at about 20% of the yield stress. However, the timber-based hybrid column does not buckle when the steel frame yielded to axial force compression because the timber functions as a buckling restraint.

4.4.3 Horizontal load

A lateral timber-based hybrid beam bears axial force and produces a reaction force of braces during an earthquake. The steel frame bears axial force, the timber frame functions as a buckling restraint, and calculations confirms the absence of buckling within the safety limits of applied axial force

During a lateral earthquake, a timber-based hybrid column produces a reaction force of brace. And the brace bears axial force during a lateral earthquake. As mentioned previously, the column does not buckle when the steel frame yields to axial force of compression. Moreover, buckling of the brace is not also observed.

As shown in Figure 31, during a longitudinal earthquake, vertical shear force is transmitted from the plywood bearing wall to the timber of the column through the vertical frame. The timber has a bearing plate of the steel frame (PL-19) at both ends of the timber of the column, and when the timber collides against the bearing plates, axial force is transmitted to the steel frame of the column. Therefore, during an earthquake, the timber functions as a buckling restraint.

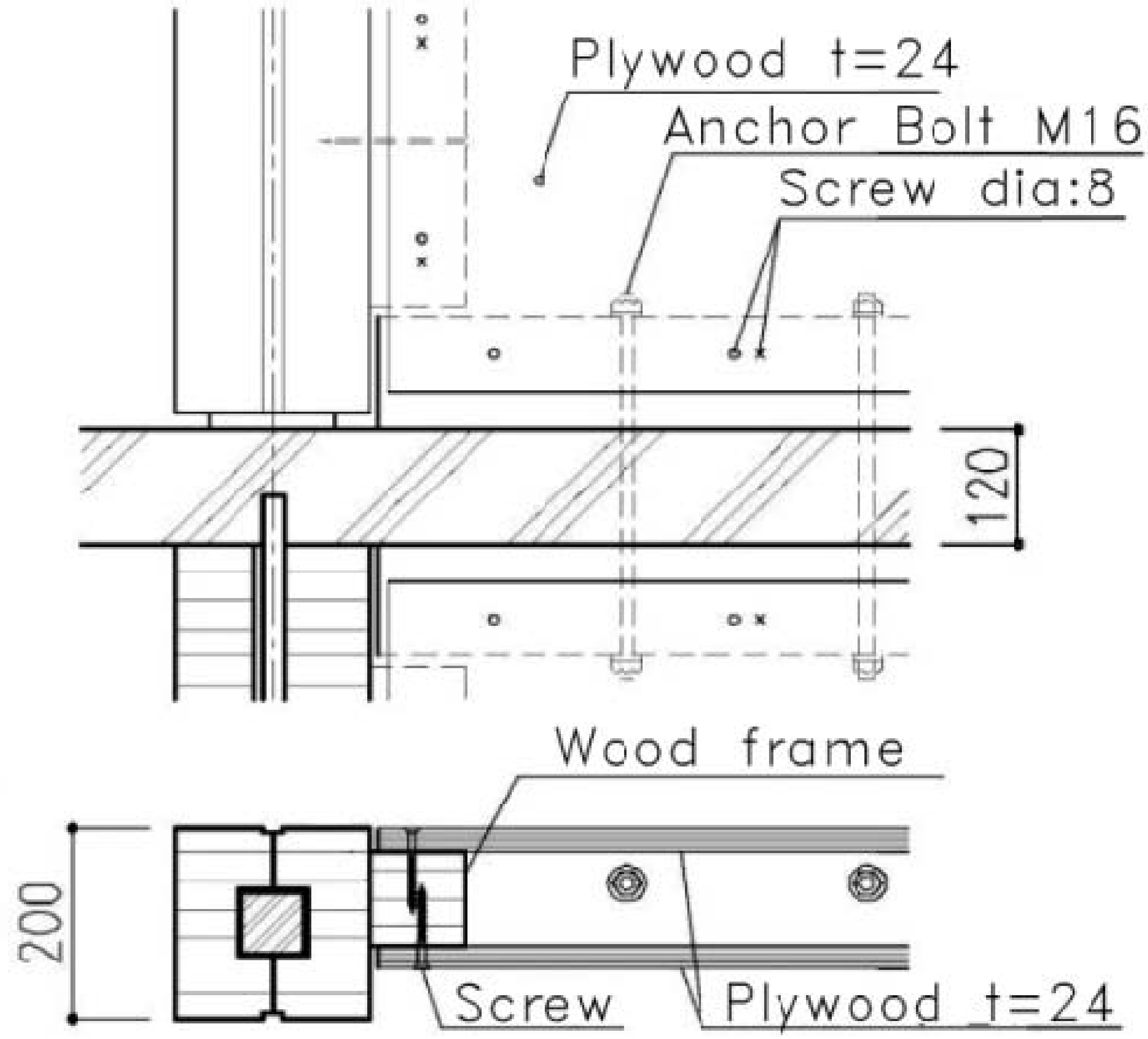


Figure 31 – Longitudinal joint system

A plywood bearing wall bears horizontal force during a longitudinal earthquake. As shown in Figure 31, the bearing wall consists of 24 mm structural plywood, 8 mm diameter screws and both vertical and horizontal frames of laminated timber arranged around the plywood.

5.0 SOFTWARE INVESTIGATION

Four different software packages used to model steel and timber structures are investigated. Software packages are: SesimoStruct, ANSYS, SapWood, and OpenSees. Special consideration is given to the types of analysis the software can perform, and the capability of the software to model linear and non-linear materials; isotropic and orthotropic materials, built-up and composite sections. Finally advantages and disadvantages of each software package are discussed.

5.1 ANSYS

ANSYS is a finite element software package. Seven types of analysis can be performed by ANSYS; namely, static, modal, harmonic, transient dynamic, spectrum, buckling and explicit dynamic analysis.

Most ANSYS element types are structural elements, ranging from simple spars and beams to more complex layered shells and large strain solids. Most types of structural analyses can use any of these elements.

With ANSYS linear and non linear structural elements can be chosen for analysis. Material properties can be linear or nonliniear, isotropic or orthotropic, and constant or temperature-dependent.

Steel is a linear isotropic material and with ANSYS, one can choose constant, isotropic, linear material properties from the material library available.

Contrary to steel, wood is a non-linear orthotropic material. For non linear material, if the stress-strain diagram of the wood member is known, the user can approximate the curve with linear interpolation between the points and enter the multilinear stress-strain relationship data in ANSYS. This will allow ANSYS to more accurately model the plastic deformation of the material.

ANSYS supports curve fitting for hyperelastic, creep and viscoelastic material behaviour. Temperature dependency is also supported for all three behaviours. Curve fitting is used to derive coefficients from experimental data that user supplies for the material. Curve fitting involves comparing the experimental data to certain nonlinear material models built into ANSYS. With this feature, user is able to compare experimental data versus ANSYS-calculated data for different nonlinear models. Based on these comparisons, user decides which material model to use during solution.

The ANSYS finite element software denotes orthotropic material properties by associating them with the corresponding material axes as shown below:

Ex, y, z – Young's modulus in the longitudinal, tangential and radial directions respectively.

Gxy, yz, zx – Shear modulus in the x-y, y -z and z-x planes respectively.

nxy, yz, zx – Major Poisson's ratio in the x-y, y-z, and z-x planes respectively.

Table 6 below lists the available materal models in ANSYS.

Table 6 –ANSYS material library

Linear Material	Non-Linear Material			Specialized Material
Elastic Isotripic	Elastic	Inelastic	Inelastic	Gasket
Elastic Anisotropic	Hyperelastic	Rate Independant	Curve Fitting	Joint Elastic
Elastic Orthotropic	Multilinear Elastic	Rate Dependant	Prony	Creep
		Non Metal Plasticity	Maxwell	Composites
		Cast iron		

Moreover, ANSYS allows the analysis of sandwich and built up cross sections. The cross section can be comprised of a number of orthotropic materials. This is very useful for various wood products such as glued laminated timber where the material is composed of multiple layers of timber with various modulus of elasticity. It is possible to specify the mesh quality for the section solution.

ANSYS can also be used to model hybrid steel timber members. The ANSYS program allows the user to model composite materials by using specialized elements called "layered elements". Once the model is built using these elements, any structural analysis (including nonlinearities such as large deflection and stress stiffening) can be performed.

To ease the modelling process, ANSYS supplies a library of eleven commonly-used beam cross section shapes, and permits user-defined cross section shapes. When a cross section is defined, ANSYS builds a numeric model using a nine node cell for determining the properties (Iyy, Izz etc.) of the section and for the solution to Poisson's equation for torsional behaviour.

5.2 SeismoStruct

SeismoStruct is a Finite Element package capable of predicting the large displacement behaviour of space frames under static or dynamic loading. SeismoStruct enables the user to perform seven different types of analysis: dynamic and static time-history, conventional and adaptive pushover, incremental dynamic analysis, eigenvalue, and non-variable static loading.

Material model available are: steel, concrete, fibre reinforced polymer (FRP) and shape memory alloy (SMA). By making use of these material types, the user is able to create an unlimited number of different materials, used to define the cross-sections of structural members. The software is limited in terms of modelling wood. Table 7 shows the material models available in SeismoStruct.

Table 7 –SeismoStruct material library

Steel	Reinforced Concrete	Composites
Bilinear steel model	Trilinear concrete model	Nonlinear FRP-confined concrete model
Menegotto-Pinto steel model	Nonlinear constant confinement concrete model	Superelastic shape-memory alloys model
Monti-Nuti steel model	Nonlinear constant confinement concrete model with tension softening	Trilinear FRP model
Bilinear steel model	Nonlinear variable confinement concrete model	Elastic material model
	Nonlinear constant confinement model for high-strength concrete	

Twelve element types are available in SeismoStruct. These elements are: Inelastic frame elements , Inelastic plastic hinge frame elements, Elastic frame element , Inelastic infill panel element , Inelastic truss element, Link elements , Mass elements and Damping element . By making use of these element types, the user is able to create an unlimited number of different elements classes that are not only able to accurately represent intact/repaired structural members (columns, beams, walls, beam-column joints, etc.) and non-structural components (infill panels, energy dissipating devices, inertia masses, etc.) but also allow the modelling of different boundary conditions, such as flexible foundations, seismic isolation, structural gapping/pounding, and so on.

SeismoStruct takes into account both geometric nonlinearities and material inelasticity. True structural behaviour is inherently nonlinear, characterised by non-proportional variation of displacements with loading, particularly in the presence of large displacements or material nonlinearities. The spread of inelasticity along the member length and across the section depth is explicitly modelled in SeismoStruct allowing for accurate estimation of damage accumulation.
Distributed inelasticity elements are becoming widely employed in earthquake engineering applications. In SeismoStruct, use is made of the so-called fibre approach to represent the cross-section behaviour, where each fibre is associated with a uniaxial stress-strain relationship; the sectional stress-strain state of beam-column elements is then obtained through the integration of the nonlinear uniaxial stress-strain response of the individual fibres (typically 300-400) in which the section has been subdivided.

Large displacements/rotations and large independent deformations relative to the frame element's chord (also known as P-Delta effects) are taken into account in SeismoStruct, through the employment of a total co-rotational formulation based on an exact description of the kinematic transformations associated with large displacements and three-dimensional rotations of the beam-column member.

Many features of SeismoStruct make it an exceptionally user-friendly and practical software package. It has a *Wizard* facility which helps in creation of frame building models. The Wizard facility enables the user to create regular/irregular 2D or 3D frame models and run all types of analyses on the fly. The whole process takes no more than a few seconds.

Moreover, the program includes predefined materials and sections which help to speed up the modelling process. Currently, nineteen section types are available in SeismoStruct. These range from simple single-material solid sections to more complex reinforced concrete and composite sections. By making use of these section types, the user is able to create up to 500 different cross-sections, used to define the different element classes of a structural model. Examples of sections used to model steel elements are: solid and hollow rectangular section, solid and hollow circular section, symmetric T section, Asymmetric general shape and I-section.

5.3 SAPWood

This analysis program, developed based on the Seismic Analysis of Woodframe Structures (SAWS) and computer program for the Cyclic Analysis of SHEar Walls (CASHEW) concepts, is aimed at providing both researchers and practitioners with a user-friendly software package which is capable of performing nonlinear seismic structural analysis and loss analysis for woodframe structures. As it is apparent from its name, SAPWood is only intended for analysing wood frame structures.

The analysis options currently in SAPWood include: Traditional nonlinear time domain earthquake excitation, Incremental Dynamic Analysis (IDA), System (hysteresis) Identification and Multi-case IDA, assembly level analysis (SAPWood-NP).

SAPWood is essentially a toolbox which allows the user to build, load, modify, and save a light frame wood structural model for various seismic-related analyses. Structural elements such as beams cannot be modelled explicitly by SAPWood. There are two types of models currently available in SAPWood: the first one is a bi-axial structural model which was introduced by Folz and Filiatrault (2002) in the SAWS program. This model has three degrees of freedom (DOF) in each storey with a rigid diaphragm assumption. The second one is a simplified lumped-mass shear building model which has only 1DOF at each story level, and can be useful for preliminary uni-directional analysis and simplified design approaches. Table 8 shows the SAPWOOD material library.

Table 8 –SAPWood material library

Wood Shear Wall Hysteretic Models
Linear
Bilinear
SAWS Ten Parameter Model
Evolutionary Parameter Hysteretic (EPHM) Model

SAPWood also provides the user the ability to build and analyze light frame wood shearwalls using nonlinear connector's elements such as nails, hold-down devices and screws. This enables the analysis of woodframe structures beginning at the fastener level when assembly (shearwall) test data is not available.

SAPWood also provides the option of obtaining the shearwall and drywall component parameters directly from a database that is provided with the program. However, the parameters from the database should only be used to conduct preliminary trial analysis since the variation of real shearwall behavior cannot be reflected by the fixed database.

There is also a fitting tool within SAPWood that provides the user with semi-automatic fitting of shearwall test hysteresis data for any one of the four possible spring models that can be used in a SAPWood structural model. Currently, there are four spring models included in the SAPWood package: linear spring model, bilinear spring model, SAWS-type ten-parameter hysteretic model ("CUREE model" from CUREE-Caltech project), and a 16-parameter evolutionary parameter hysteretic model ("EPHM model"). If the user has wall hysteresis data from a cyclic wall test, it can be loaded into the "manual fit" tool to find the parameters.

Also included in Version 1.0 of SAPWood is a preliminary loss estimation module, in which vulnerability analysis and long term loss simulation can be performed to evaluate the economic loss of a structure during earthquakes. The analysis is limited to basic structural components.

5.4 Opensees Navigator

OpenSees Navigator is a MATLAB based graphical user interface, with advanced capabilities for modeling and analyzing the nonlinear response of systems using a wide range of material models, elements, and solution algorithms.

OpenSees Navigator can perform static, transient and eigenvalue analysis. Result of the analysis include: deformed shape of the element, eigenvalue, displacement, velocity, acceleration, incremental displacements, eigenvectors, and reaction forces with and without inertia at each node.

OpenSees Navigator is capable of modeling linear and nonlinear materials, including wood, steel and concrete. Types of materials currently available are uniaxial material including concrete, elastic, elastic perfectly plastic, hysteretic, hardening, steel and viscous and nD material including elastic-isotropic, plane stress, plate fiber. OpenSees Navigator is limited in terms of modelling composite cross-sections. Table 9 lists the available material models in OpenSees Navgator.

Table 9 –OpenSees material library

Uniaxial Material	nD Material
BoucWen	ElasticCrossAnisotropic3D
Concrete01	ElasticIsotropic
Concrete02	FluidSolidPorous
Concrete03	J2Plasticity
Elastic	MultiaxialCyclicPlasticity
ElasticNoTension	PlaneStress
ElasticPP	PlateFiber
ElasticPPGap	PressureDependMultiYield
Fatigue	PressureDependMultiYield02
Hardening	PressureDependentElastic3D
Hysteretic	PressureIndependMultiYield
MinMax	Template3DElastoPlastic
Parallel	
Series	
Steel01	
Steel02	
Viscous	

To ease the modelling process, the software includes predefined beam model, stick model, moment frame, zipper frame, inverted V frame, and single area mesh. Moreover, OpenSees Navigator includes AISC database. User can easily select desired sections and the sections properties will be loaded. It also includes AISC design checks for bending capacity, compression capacity, shear capacity and PMM (axial load P and bending moments M_x and M_y) interaction. Other design toolboxes available are NSP and Performance-Based Earthquake Engineering (PBEE).

5.5 Conclusion of Software Investigation

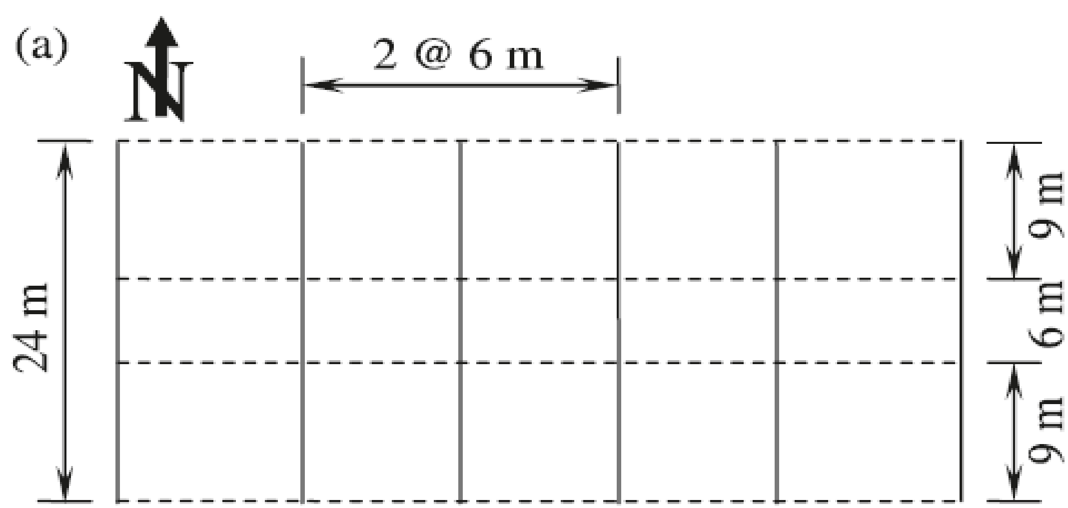
Among the four software packages investigated, ANSYS is found to be the only suitable software to model hybrid wood steel structures. ANSYS includes linear isotropic material model which can be used to model steel, and non-linear orthotropic material model which can be used to model wood. Moreover, ANSYS includes a special element called “layered” element. By using this element, one is able to model laminated wood members such as Oriented Strand Board (OSB) which are comprised of a number of different orthotropic materials.

6.0 ANSYS CASE STUDY-FIVE STOREY STEEL TIMBER HYBRID STRUCTURE

ANSYS is used to model a hybrid five storey building consisting of steel frame and OSB shear walls. The purpose of the analysis is to perform a static analysis and see the effect of wood shear walls on the lateral deformation of steel frame building.
The design of the steel frame and the loading is based on the paper "Seismic design and performance evaluation of steel-frame buildings designed using the 2005 National building code of Canada" by Md Yousuf and Ashutosh Bagchi.

6.1 Steel Frame

The paper has considered 5 storey, 10 storey and 20 storey buildings. But in this report only the 5 storey building is considered. A simplified floor plan and elevation of a 20-storey building frame are shown in Figure 32a and 32b, respectively. The plans of all other buildings are identical. For simplicity, framing and connection details have not been shown in this Figure.



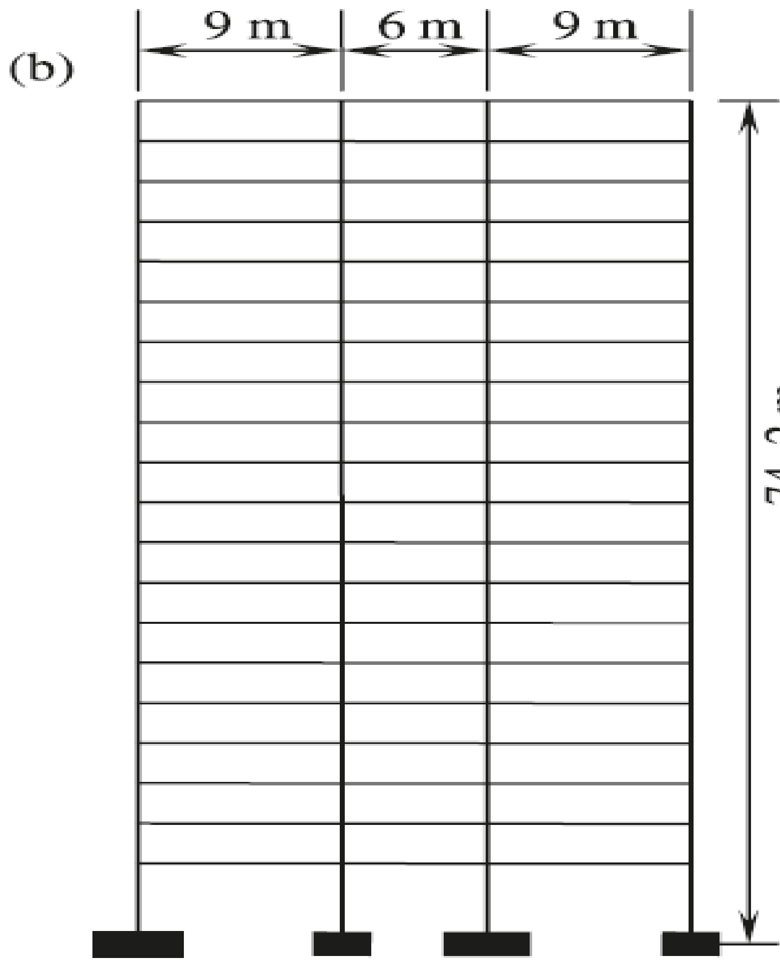


Figure 32 – a) Floor plan b) Elevation plan of a 20-storey building

The buildings are assumed to be situated in Vancouver. They consist of series of frames in the east-west (E-W) direction and three bays in the north-south (N-S) direction, and it is along this latter direction (N-S) that their performances were evaluated. The two N-S exterior bays were 9m in length, the one interior N-S bay was 6 m, and centre to centre spacing of the E-W frames was 6m. First storey height of each building was 4.85 m, and all other storeys were 3.65 m high. The frames are symmetrical along the vertical centre line, and all the transverse frames are assumed to be Type D ductile moment-resisting frames as defined in CSA S16-01(CSA 2001).

The following loadings are considered in the design: gravity loads consisting of dead load D, and live load, L and seismic load E. Dead loads are comprised of the self weight of the frame elements and the weights of non-structural component. The computed dead load is 3.4 kPa for the roof and 4.05 kPa for a typical floor. The live load on a typical floor is assumed to be 2.4 kPa as suggested in NBCC 2005. The roof snow load is calculated to be 2.32 kPa.

For the seismic load, the equivalent static load (ESL) procedure as provided in NBCC 2005 is used in the preliminary design of the buildings, and this is followed by modal and dynamic analysis.

The design base shear is distributed along the height of the frame in the form of an inverted triangle from top to bottom, as also suggested in NBCC 2005, and the force assigned to each storey level is proportional to the weight and storey height of the respective storey. The design base shear is 154.7 kN. When modelling using ANSYS, the base shear is assumed to be only proportional to the storey height. Figure 33 below shoes the distribution of the base shear.

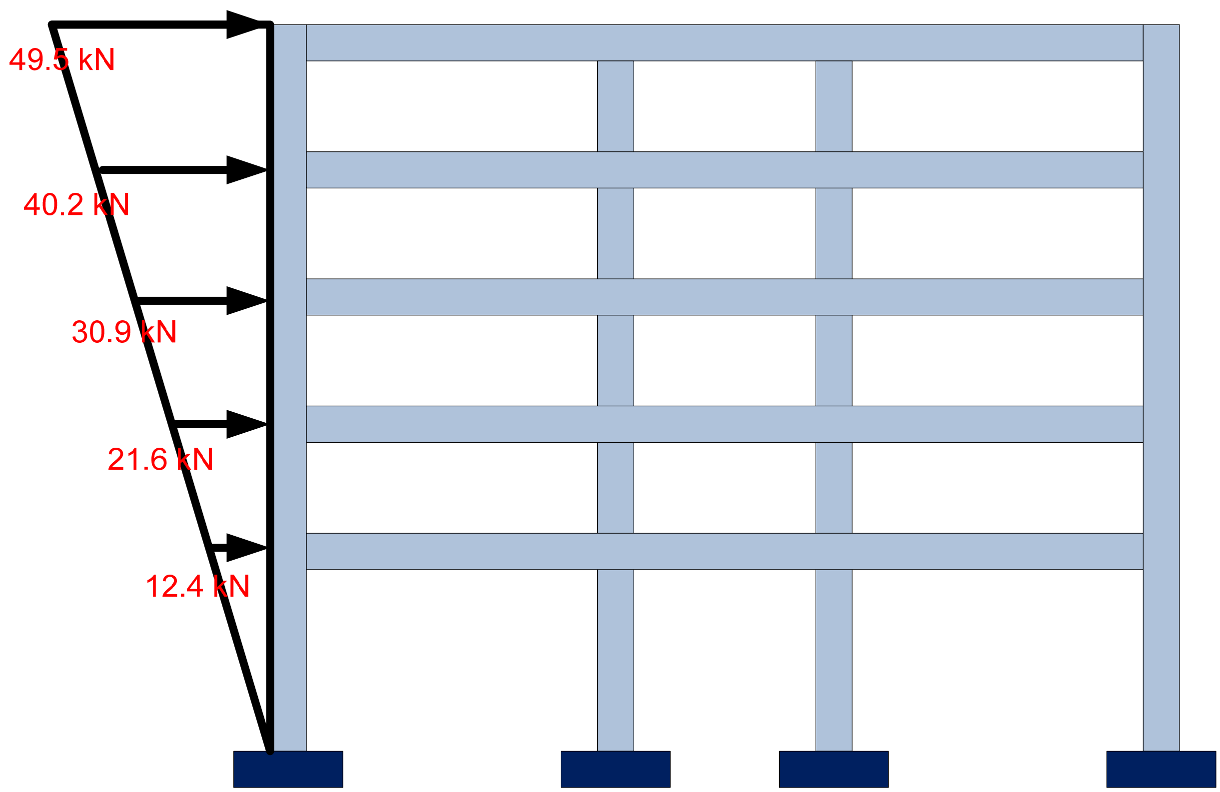


Figure 33 – Distribution of design base shear

All steel sections used in the design, whether beams or columns, are assumed to have yield strength, FY, of 345 MPa. The modulus of elasticity of steel, E, is assumed to be 200 GPa. The details of the beam and column sections for the frame are given in Table 10.

Table 10 – Details on beam and column sections used in design

Source: Yousuf, M., and Baghchi, A. 2009. "Seismic design and performance evaluation of steel-frame buildings designed using the 2005 National building code of Canada", In Proceedings of the 9th Canadian Conference on Earthquake Engineering, Paper No. 1327, Ottawa, Ont.

	Top storey	**Other storeys**
Beam dimensions	W 310 x 79	W 310 x 86
	External	**Internal**
Column dimensions	W310 x 179	W310 x 253

6.2 Shear Wall

Buildings are subjected to lateral loading due to earthquakes and wind forces, which causes the structure to sway sideways. In order for the building to remain stable, it must have a vertical bracing system that is capable of transferring the horizontal loading to the foundation. Shear walls are vertical elements of the horizontal force resisting system. More specifically, a shear wall is a wall which is designed to resist shear, the lateral force which causes the bulk of damage in earthquakes. Shear walls also provide lateral stiffness to prevent the roof or floor above from excessive side-sway. When shear walls are stiff enough, they will prevent floor and roof framing members from moving off their supports. Also, buildings that are sufficiently stiff will usually suffer less nonstructural damage. Figure 34 below shows the two functions of shear wall.

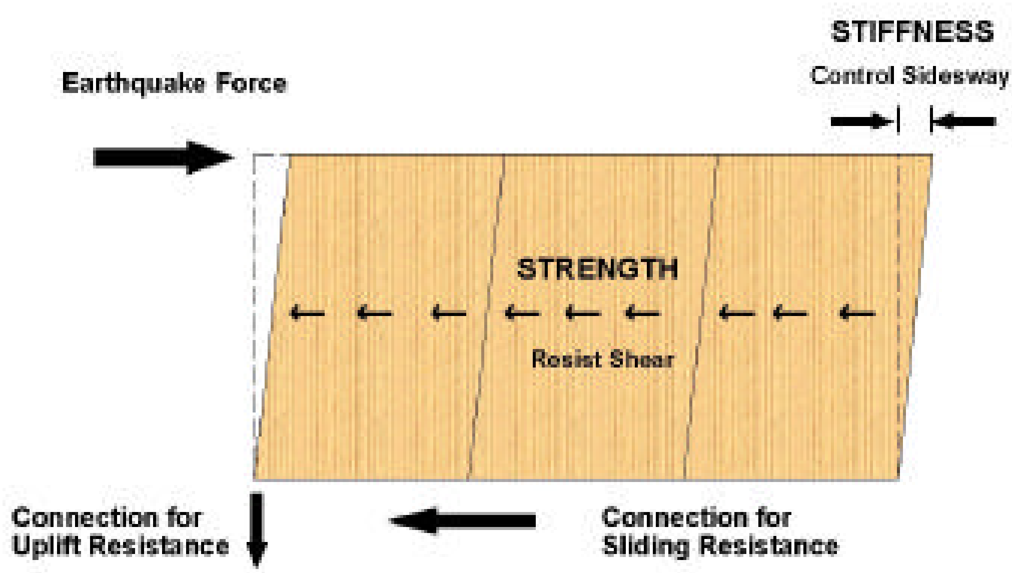


Figure 34 – Two functions of a shear wall

The strength of the shear wall depends on the combined strengths of its three components: lumber, sheathing and fasteners. When all of the components are properly in place, the shear wall can provide its intended strength. For shear wall sheathing, the 1994 Uniform Building Code (UBC) permits the use of gypsum wallboard, cements plaster, fiberboard, wood particleboard, plywood and oriented strand board (OSB). In this case study, OSB is chosen to be the structural sheathing material. Oriented Strand Board (OSB) is a mat-formed panel product made of strands bonded with exterior type resins under heat and pressure. OSB panels consist of four or five layered mats. Most mills use uniformly thick strands up to 4-1/4" long and 1" wide. Exterior or surface layers consist of strands aligned in the long panel direction. Inner-layer layers consist of cross or randomly aligned strands (Canadian Wood Council, 2005). Figure 35 shows a typical OSB.

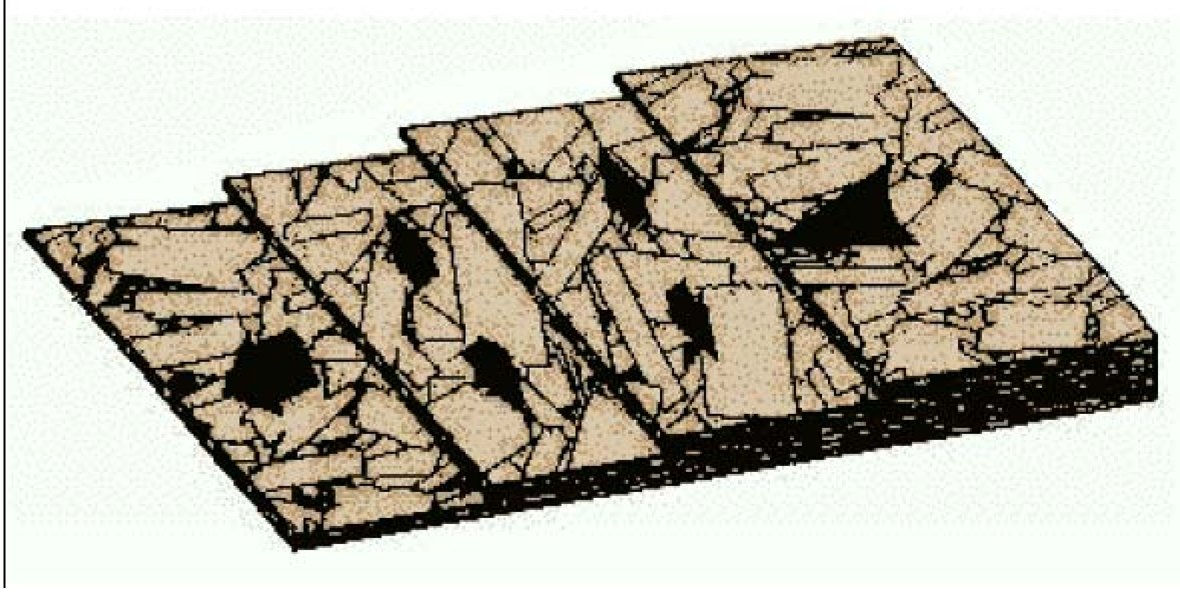


Figure 35 – Oriented Strand Board

The shear wall used in this case study consists of 3 layers each with a thickness of 2mm. The properties of each layer are summarized in table 11 below. Some of the properties are obtained from direct testing at the University of British Columbia and the rest are typical values normally used in industry.

Table 11 – Properties of the 3 layered OSB board

	Face(zero)	Core(90)
Ex	4160 MPa	740 MPa
Ey	1650 MPa	2520 MPa
Ez	400 MPa	250 MPa
Gxz	85.7 MPa	44.6 MPa
Gyz	55.7 MPa	68.6 MPa
Gxy	1250 MPa	1250 MPa
vxz	0.226	0.226
vyz	0.226	0.226
vxy	0.226	0.066

6.3 ANSYS Modeling

The five storey hybrid steel wood structure is modeled with ANSYS. Two cases are considered inorder to determine the most cost effective way of implementing shear walls in the design. Diagrams of the two hybrid models are shown in Figures 36 and 37.

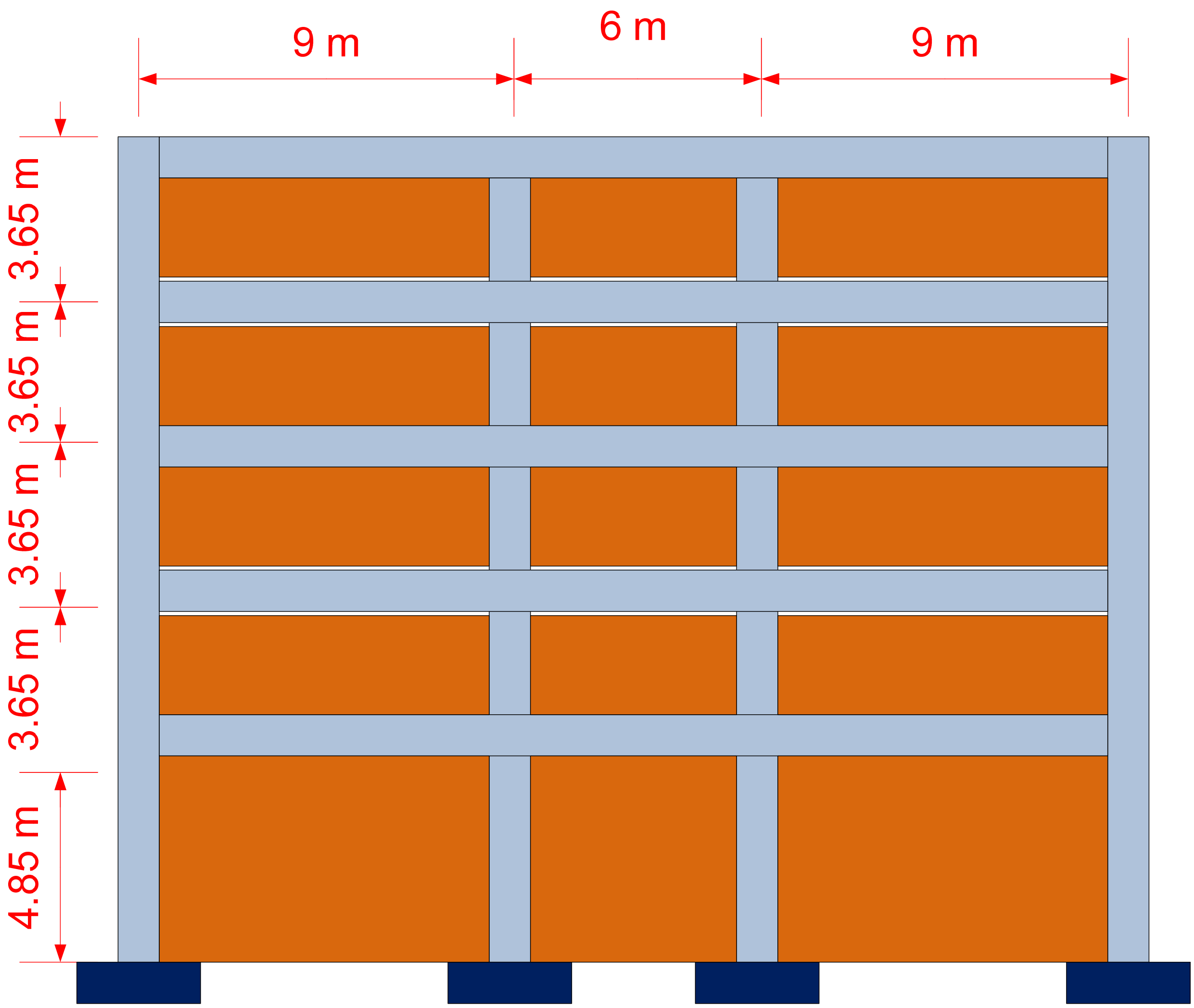


Figure 36 – Five storey hybrid wood steel model-full shear wall design

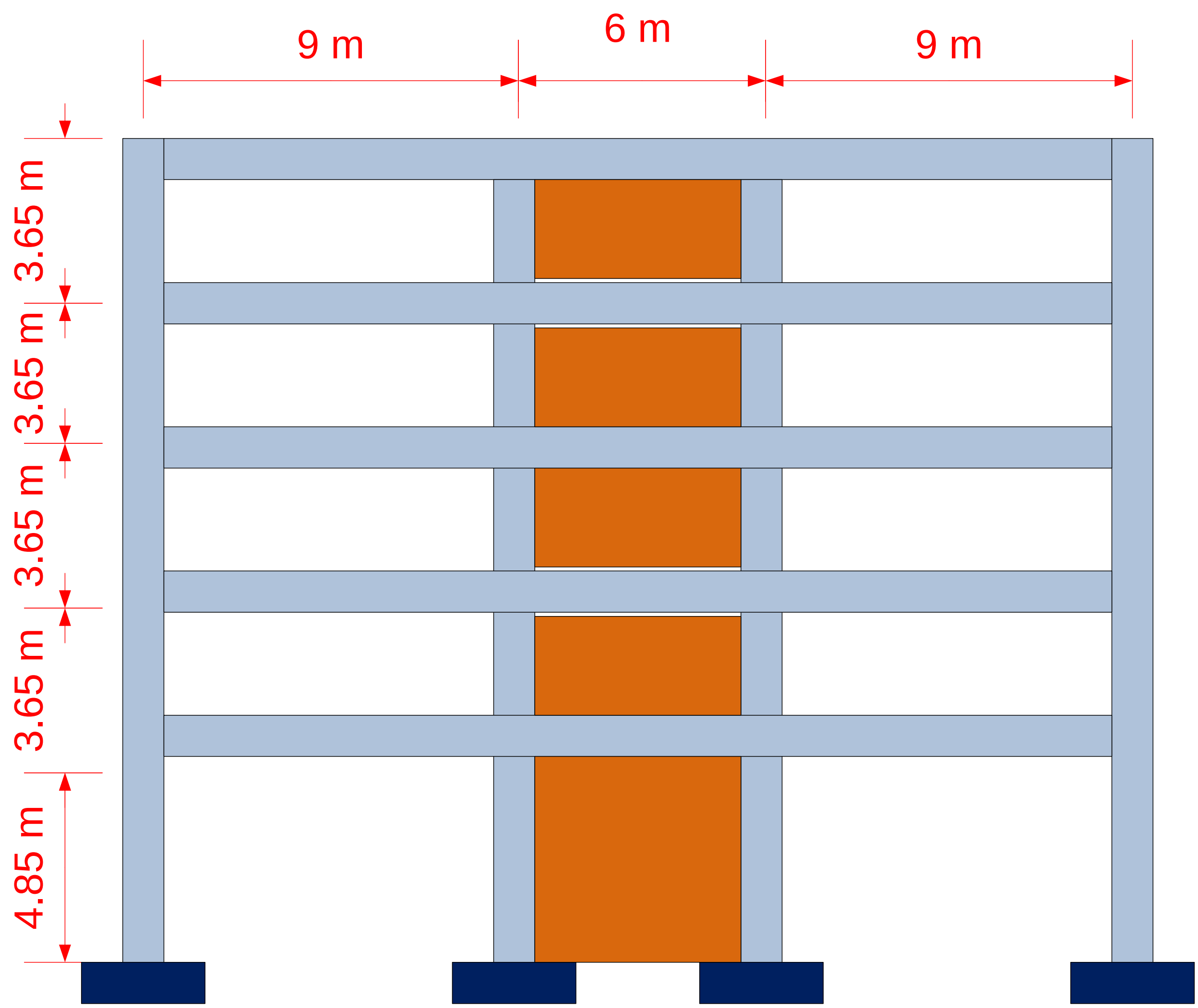


Figure 37 – Five storey hybrid wood steel model- shear wall only in centre core

Three cases are considered for static analysis and the maximum lateral deflection in each case is obtained and compared. The first case (Case 1) considers the steel frame alone. The obtained deflection is 7.056 mm. Figure 38 shows the deformed shape, shear force, normal force and bending moment diagram of the steel frame.

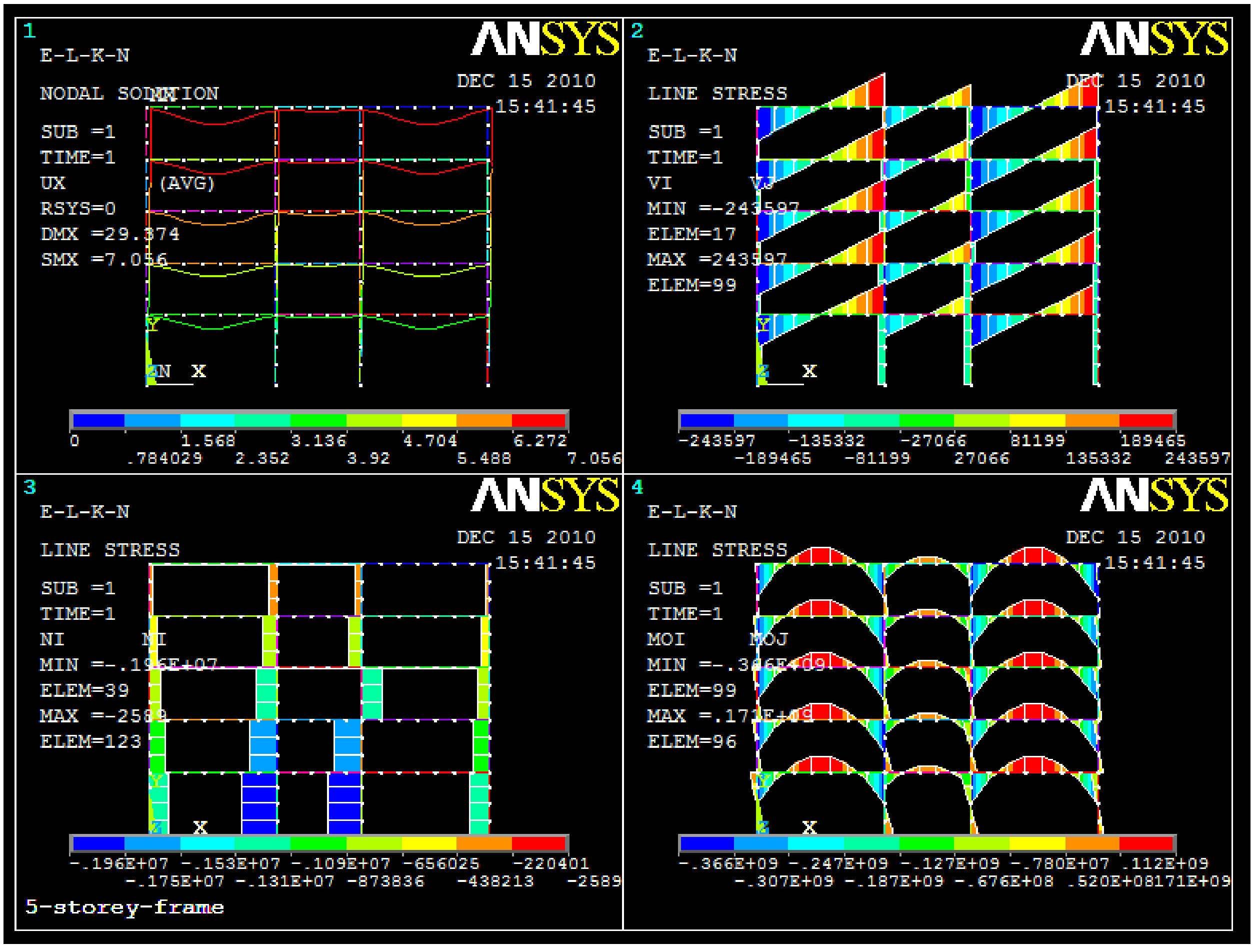


Figure 38 – Deformed shape, shear force, normal force, bending moment of the five storey steel frame

In the second case (Case 2), the wooden shear walls are implemented in every span of the frame. This is the extreme case, and is not normally used in construction since it is not cost effective and not necessary to have shear walls in all spans. However, it is decided to use this case in order to observe the maximum effect of wooden shear walls on the deflection of the frame. As shown in Figure 39 the maximum lateral deflection is 4.699 mm.

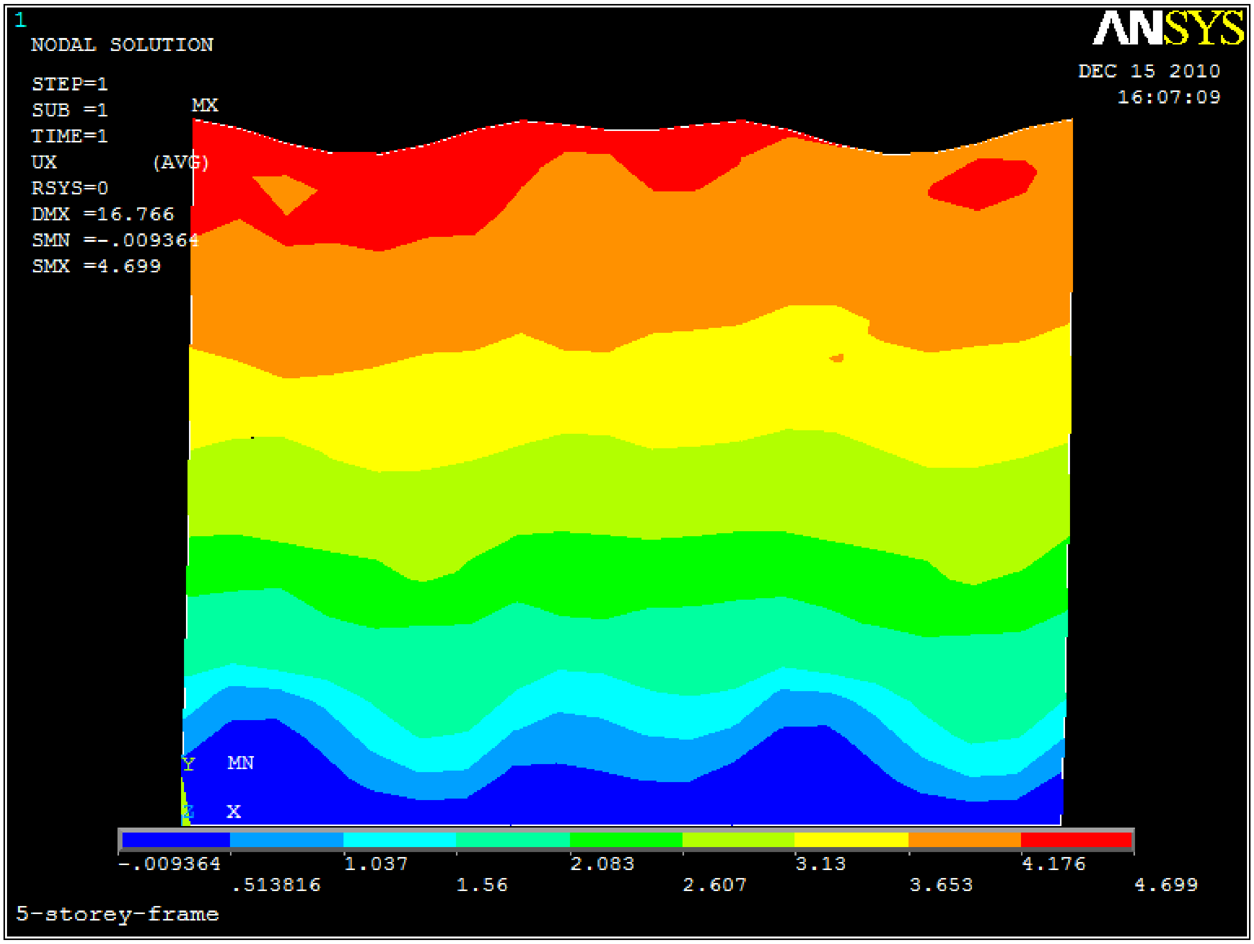


Figure 39 – Deformed shape of the five storey frame with OSB shear wall in all spans

Figure 40, shows the deformed shape of the steel frame with OSB shear wall installed only in the centre of the frame. The maximum lateral deflection is found to be 6.279 mm.

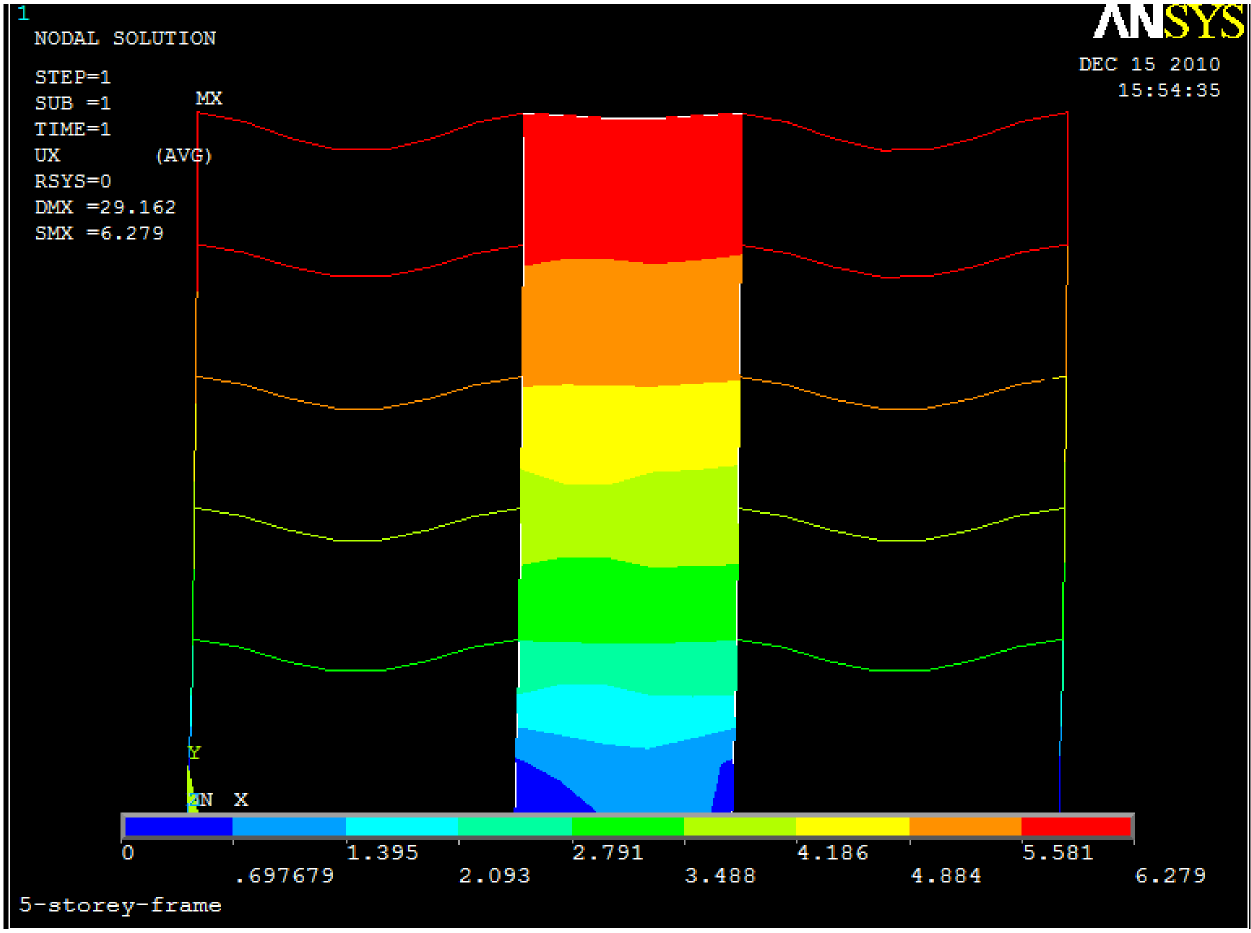


Figure 40 – Deformed shape of the five storey frame with OSB shear wall installed in the centre

The results of the analyses are summarized in Table 12. The deflection in each case is compared to the deflection of the steel frame alone and is shown in terms of percent difference.

<table>
<tr><th></th><th>Deflection (mm)</th><th>% Difference</th><th>% Difference</th></tr>
<tr><td>Case 1</td><td>7.056</td><td></td><td></td></tr>
<tr><td>Case 2</td><td>4.699</td><td>33%</td><td rowspan="2">25%</td></tr>
<tr><td>Case 3</td><td>6.279</td><td>11%</td></tr>
</table>

Table 12 – Result of static analysis on the hybrid steel timber building

As shown in Table 12 above, the shear wall reduces the deflection of the steel frame. Installing the shear walls in all spans will reduce the deflection by 33% and installing the shear walls only in the centre will reduce the deflection by 11%. As shown in Table 11, installing the shear walls in all spans will reduce the deflection by 25% more than having the shear walls only in the middle span. However, interms of the cost, the cost of installing shear walls in all spans is approximately 60% more than the cost of installing shear walls only in the centre. Therefore, it is not cost effective to have shear walls in all spans.

7.0 CONCLUSION

Case studies and examples presented in this report all indicate the benefits of hybrid timber-steel constructions. Some advantages of hybrid timber-steel construction includes: enhanced seismic performance, better fire resistance, cost savings and increase in sustainability. Timber and steel can be paired at component levels and/or at the building system levels. Component level hybridization exists when a mix of steel and timber is employed within a structural element. Building System hybridization exists when a structure is simply constructed using both timber and steel members and the structural work is being shared between the two structural members. In both types of hybridization, connection between steel and timber is the main challenge. A major problem at the interface is expansion of steel due to temperature differential, and shrinkage of wood due to change in humidity. In some cases, designers have overcome this problem by providing slotted holes in the steel which can allow for some movement and avoid lateral splitting of timber. Moreover, another way is to post-tension the timber member. Post-tensioning, ensures that the timber member always remains under compression after being subjected to a combination of tensile and compression forces arising from the applied external forces and the internal forces arising from temperature and moisture content change.

The result of investigating four software packages; namely, ANYS, SeismoStruct, SAPWood and OpenSees Navigator suggests that ANSYS is the most suitable software package for modeling hybrid structures. The reason is that ANSYS is capable to model linear and nonlinear, orthotropic and isotropic and layered and composite material.

A case study of a hybrid five storey structure consisting of steel frame and wood shear wall is modeled using ANSYS. The result of the case study indicates that wood shear wall greatly reduces the lateral deflection of the steel frame.

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