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EARTHQUAKE RESISTANT DESIGN AND SUSTAINABILITY THROUGH WOODEN COMPOSITES IN MULTI-STOREY STRUCTURES

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ABSTRACT

In the past, while wood as a natural building material was preferred for only housing construction, today, engineered wood products are used as structural elements even in many different projects such as, schools, airport terminals, stadiums or indoor sport centres and finally in multi-storey houses nowadays. On the other hand, the sustainability is becoming a key focus. Engineered wood products are increasingly used for earthquake resistance as well as natural insulation and sustainable design. Recent studies indicate that the earthquake resistant design through engineered wood products is achievable and affordable. The seismic design of structures typically depends on the ductility of members and connections. The innovative design techniques with wooden composites ensure that the building is functional after a major earthquake event. Within the scope of this study, the earthquake resistant design approaches and experimental results of New Zealand, Canada and Italy are addressed for multi-storey wooden/wooden-hybrid structural systems. Member and connection types, post-tensioning effectiveness, floor systems, sustainability and constructability will be focused.

INTRODUCTION

Wood is a well known building material for the centuries and some mid-rise buildings were built in the past as well (Table 1). In the 20th century, the developments in wood technology enabled the engineered wood products, i.e. glue laminated timber, to be an important alternative of steel especially in wide span buildings (e.g. grid shell domes, sport arenas etc.) with equivalent strength/weight ratio. Low-rise wood structures are also very common in Australia, Canada, Norway, Sweden and U.S. In recent years, engineered wood products have remarkable importance for the mid-rise and even tall buildings in earthquake prone regions as well. There are some innovative lateral force resisting systems for multi-storey wooden/wooden-hybrid structures nowadays. These systems arise from the proper design of the wooden elements and steel connections through their inelastic response.

Progressive research studies are under consideration on multi-storey wooden buildings. In early 1990s, the development of Cross Laminated Timber (CLT) panels by Austria, Germany and Switzerland lead to progress the multi-storey Massive Timber structures composed of CLT panels or alternatively LVL, LSL panels with proper connections. Cross lamination provides relatively high in-plane and out-of-plane rigidity. In addition, good thermal and sound insulation, fire resistance, fast and economical construction potential made CLT panels popular for sustainable multi-storey residential, commercial, and institutional buildings.

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Table 1 Traditional examples to multi-storey buildings from the past.

Pagoda at Horyuji Temple, Nara, Japan	Prinkipo Greek Orphanage, Aerial Islands, Istanbul, Turkiye	Esrefoglu Mosque, Beysehir, Turkiye
		 
5-storey, 32.4 m, built 1300 years ago. Central wooden pillar; timber, Japanese joinery	5,6-storey traditional (bagdadi) wood structure, built 115 year ago.	Masonry outer walls and prayer hall built from 42 high cedar pillars 715 years ago.

New Zealand extended the experimental investigations on post-tensioned connections (PRESSS project) for earthquake resistant multi-storey precast structures (Priestley, 1999) to the connections of Laminated Veneer Lumber (LVL) beams and columns in multi-storey wooden structures later. A new hybrid connection (Palermo et al.,2006) was developed for wooden frame systems. Cross Laminated Timber (CLT) panels were used as wall components and in slabs together with concrete topping.

Especially in Italia, large theoretical and experimental efforts (SOFIE project) (Ceccotti et.al., 2000) are dedicated to the development of energy dissipating connections through nonlinear dynamic analyses (Ceccotti et al.,2006) for the walls composed of CLT panels based on a typical 3-story structure. Japan was also the partner of this project and a 7-storey building made of CLT panels was tested in Japan (2007) successfully. The use of CLT panels in North America started in 2010. In Canada, the significant progress has been achieved with CLT Handbook (FPInnovations, 2011). Typical structural systems are designed for high-rise buildings by incorporating wood core walls, wooden perimeter framed system and steel dissipating beams according to strong column-weak beam concept. FPInnovations (2013) has been published as U.S Edition.

In this paper, the energy dissipating connections and other aspects of multi-storey wooden composite structures are focused.

CONNECTIONS AND ENERGY DISSIPATION

In New Zealand, the hybrid LVL beam-column and CLT wall connections include energy absorbing details. For controlled rocking as well as essentially elastic and low-damage design, self centering long unbonded post-tensioned high-strength tendons are implemented (Figure 1). The replaceable mild steel bars are accommodated into the connection region to decrease unductile behaviour of tendons and to enhance the energy absorption (Buchanan et al., 2008). CLT coupled walls are linked with U-shaped steel plates to provide coupling and energy absorption. The compressive strength parallel to grain of LVL elements is 40 MPa identical to upper limit of normal strength concrete. However, the post-tensioned wood under high compressive stresses may experience some axial shortening by creep and relaxation, especially in the perpendicular direction to grain due to poor mechanical stiffness. The losses in post-tensioning are allowed and axial shortening may require special reinforcement. Slab system composed of timber panel units includes 65 mm concrete topping on nailed plywood sheets for excellent diaphragm behaviour.

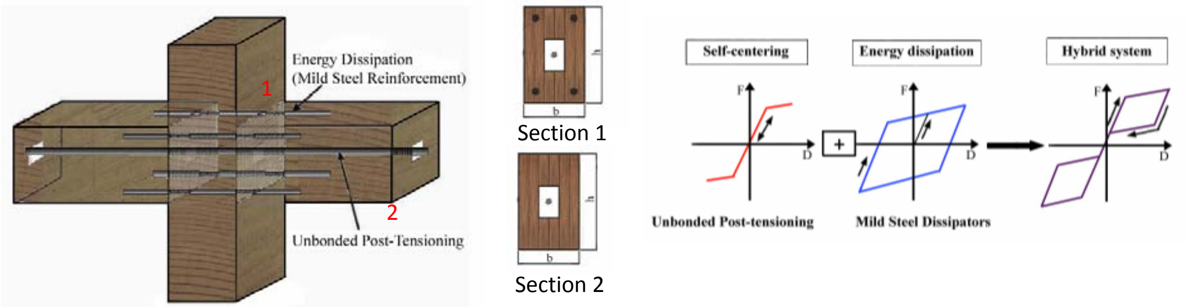

Figure 1. Typical beam-column connection and hysteretic behaviour

In Europe, typical panel connections such as hold-downs, brackets are used, but there is high energy absorption capacity is a requirement for the seismically active countries like Italy. High level pinching, low energy dissipation due to tensile and shear forces, and rapid strength/stiffness degradation are main problems in these connections (Figure 2). Several experimental studies to obtain ductile connection (i.e type, number, position, orientation of nail, screw and rivet fasteners) have been executed (Gavric et. al., 2011), e.g. recently a new type (XL stub) of stub connections (Latour et. al., 2013) used in steel structures has been presented for tensile forces and uplift to absorb high seismic energy.

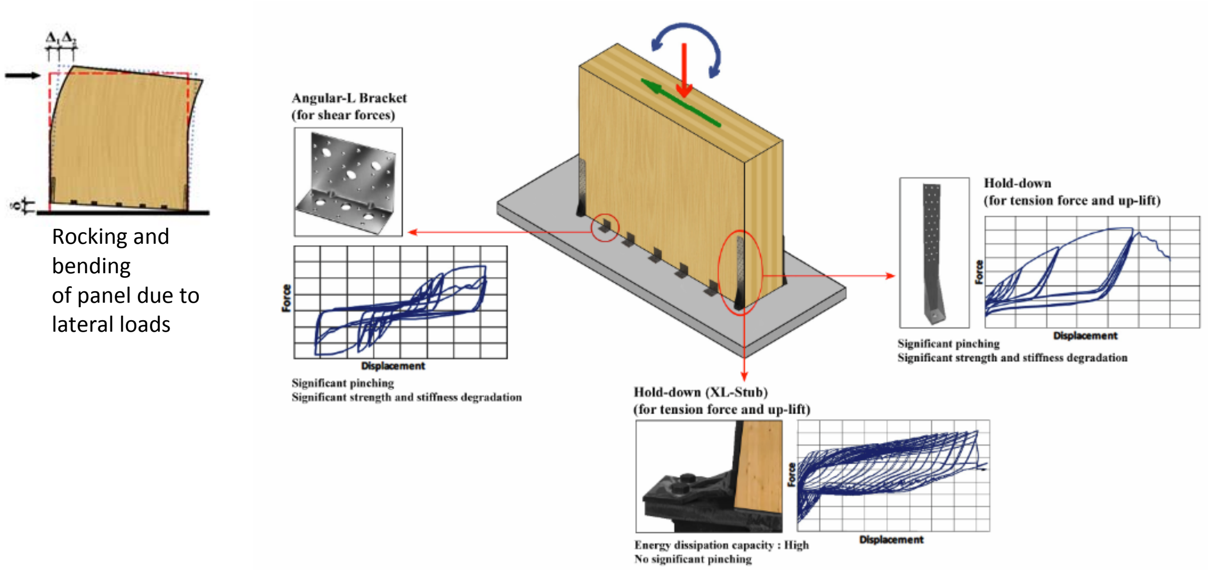

Figure 2. CLT wall panel and hysteretic behaviour of shear and tensile connections

In Canada, according to FFTT system developed in 2008, the cost analyses based on 12 and 20-storeys wooden buildings indicated the cost competitiveness compared with RC structure [1]. This system allows plan flexibility up to 20 storeys. Floors may be CLT or LSL panels with or without concrete topping. By applying the strong column-weak beam concept in earthquake prone region (B.C, PGA=0.46g), an 12-storey typical structural system is composed of perimeter moment frame with glulam columns, wood core walls and the wide-flange beams between perimeter frame system and core wall. Ductile steel beams with reduced section enable plastic hinges during the earthquake. University of British Columbia's (UBC) 4-storey Bioenergy Research and Demonstration Facility (2012) and 5-storey Earth Sciences Building (2012) are the recent applications of innovative wooden structures. Steel box connectors integrated into glulam beam and column members, use of glulam Chevron braces, knife-plate connectors to attach glulam beams to glulam columns, glulam braces to glulam beams and glulam beams to CLT walls have innovative ductile details (Figure 3).

Figure 3. Ductile details from new buildings of UBC

CONSTRUCTABILITY AND SUSTAINABILITY

The countries such as Austria, Finland, Canada that have developed forest industry and certified forest areas, e.g Canadian forests account for 10 % of world’s forests and 42 % of the world's certified forest area. Less than 1% of Canada’s forests are annually harvested [2]. Meanwhile, in recent years, B.C forest industry has been significantly affected by pine beetle epidemic and mill curtailments. Multi-story wooden buildings are encouraged and to alternatively use LVL and LSL elements in FFTT system are studied to make use of lower grade lumbers. The share of wooden structures within building stock is over 90% in North America and Scandinavian countries, and 45% in Japan [3].

LVL members are composed of 3 mm veneers glued into billets 1.2 m wide. The length is only limited with transportation possibility and the production with affordable prices is possible. In New Zealand, LVL beams and columns are from radiata pine through renewable plantation forests. In the production of CLT panel, the standard width is 3 m, lamella thickness is 15-45 mm, thicknesses up to 50 cm and spans longer than 10 m are possible. Austria and Germany generally use spruce, larch and pine. Spruce-pine-fir species are often used in Canada, and radiate pine in New Zealand and Australia. Good thermal and sound insulation, fire resistance, fast and economical construction potential made CLT panels popular for sustainable multi-storey residential, commercial, and institutional buildings. However, it should be noted that CLT panels are more prone to creep behaviour under constant load compared with glulam elements. CLT wall and slab panels of massive structures are growing rapidly especially in Europe countries. In Europe, the modular design (balloon-frames) made of CLT panels are popular and preferred for construction rate and economy. In New Zealand, prefabricated structural elements assembled on-site are connected with post-tensioned tendons and/or bar.

In recent innovative multi-storey engineered wood structures, 60 year lifetime is proposed. Cost analyses compared with equivalent RC structures in earthquake prone regions revealed innovative wooden structures to be competitive and affordable. The typical characteristics of recent innovative multi-story wooden structures are given in Appendix Table by summarizing from [1-12].

Wood as a natural material has perfect thermal insulation characteristics (0.11, 012 W/m.K), its thermal conductivity is given in Figure 4 compared with other natural and unnatural building materials. According to FPInnovations (2013), total energy use in a wooden structure is ~50% lower than equivalent steel structure and ~35% lower than equivalent RC structure. In New Zealand, the semi-prefabricated floor system composed of timber panels and concrete topping increases the acoustic separation, thermal mass, fire resistance and reduces heating/cooling energy demand.

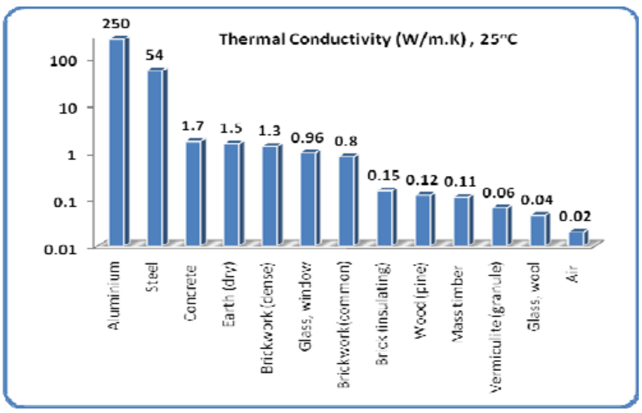

Figure 4. Thermal conductivities of some materials in log. scale compared with wood

There are two possible cases for fire resistance: Encapsulation and charring calculation method. In heavy timber structures, element thickness must be over 8 cm for fire resistance. Especially for high-rise wooden structures, 2-hour fire resistance is a code requirement. This necessity can be provided via the encapsulation method of 2-layers of 16 mm type X gypsum board. However, encapsulation may not be the exclusive remedy on the contrary to light-framed wood structures. Instead, to predict the charred thickness and to take additional thickness into consideration to carry loads during/after fire is an alternative in heavy timber structures. Charring rates is 0.65mm/min for CLT/LSL panels and 0.635mm/min for glulam elements (EN 1995,1-2). The charcoal protects the remaining uncharred layers against heat. For 2-hour fire resistance in the worst scenario case without sprinklers, additional charring thicknesses of 8.8 cm, 9.4 cm and 8.3 cm [1] are provided for CLT floor, CLT wall and glulam elements, respectively.

CONCLUSIONS

Heavy timber multi-storey structures composed of wooden composite elements have been gaining popularity in residential and non-residential buildings nowadays. Rigid CLT panels provide practical solutions especially for the countries having no seismic activity, however the countries in earthquake prone regions such as Canada, New Zealand, Italy study on the analysis and experiments of new ductile connections and construction techniques. Classical connections (bracket, hold-down etc.) having low energy absorption capacity are evaluated with experiments and innovative connections are developed. In view of sustainability, the positive properties such as low-energy usage, rapid construction ability, carbon store and decrease in carbon emissions make popular these wooden green multi-storey buildings.

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Appendix Table Recent innovative buildings and some characteristic properties

Characteristics of Projects	SEISMIC ACTIVITY				
	NO OR VERY LOW		ACTIVE		NO RISK BUT WIND and EARTHQUAKE DESIGN
Name of project	Stadthaus (2009)	Confederation College-REACH Building- (2011)	NMIT Arts and Media Building (2010)	UBC, Earth Sciences Building (2012)	LifeCycle Tower (Under construction)
Location	Hackney, London	Thunder Bay,Ontario,Canada	Nelson, New Zealand	Vancouver, Canada	Dornbirn, Austria
Design and Analysis	o Waugh Thistleton Architects o Techniker	o FORM Architecture and Engineering	o Irving Smith Jack Architects o Aurecon	o Perkins+Will Architects o Equilibrium Consulting Inc.	CREE (Creative Renewable Energy and Efficiency)
Building features	9-Storey, Residential o Timber system:9 weeks (4 men) o Fully completed in 49 weeks	3-Storey Area: 3,716 m^2 Cost :$22,260,000 PGA : < 0.04g	3-Storey Area**:** 2,900 m^2 Const. period: 123 days The cost: $ 8,850,000 PGA : 0.22g	5-Storey (North wing) Area: 15,794 m^2 Cost : $58,700,000 PGA : 0.46g	30-Storey, Multi-functional
Components of structure	o Massive timber system fully composed of spruce CLT panels o Steel bracket connections o Encapsulation with gypsum boards	o Glulam columns (90% spruce and 10% lodge pole pine) and beams o CLT panel walls o Tree columns in atrium	o Post-tensioning+mild steel for energy dissipation o LVL columns, beams and shear walls o Composite slab: LVL panels with concrete topping	o Glulam frame system o CLT canopy and roof o Composite slab (LSL+foam+RC) o Glulam Chevron braces with knife-plate connectors o Transfer trusses o Charring method for fire	o Glulam double columns and hybrid beams o Composite slab (timber+RC) o CLT panel walls o Integrated mechanical services through double ribbed beams
Photograph					
"Green building" features	o 186 tonnes of carbon stored o 125 tonnes of carbon saved (equivalent to 21 years of carbon emissions) o Wood Awards 2008, Timber in Construction Awards 2008, Timber Journal Awards 2008	o LEED Silver certification o Environmental Stewardship Award 2008 o Zero Waste Action Team certification	Awards: World Architecture Festival 2011-Shortlisted**,** New Zealand Timber Design Awards, Institution of Structural Engineers UK's Structural Awards, Property Council of New Zealand	o LEED Gold standards o 6169 tonnes embodied energy o 2600 tonnes of CO_2 stored o Annual purchased energy use 1,120 MJ/m^2 -54% reduction-	