Sustainable Timber Construction: Challenges and Opportunities

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ABSTRACT

Timber is one of the oldest construction material used by human since the dawn of civilization. The use of timber in construction has slowly diminished since the inventions of concrete and steel materials in the last few centuries. Since then, timber has been connoted with construction material that has issues with weak strength performance, fire endurance, and long-term durability. After more than a century of unpleasant perceptions, renaissance of timber in construction has started near the end of 20th century after the re-inventions of massive timber elements that have similar performance as concrete when it is used in building constructions. Particular products that have gained attention recently from architects and structural engineers are glue-laminated timber (glulam) beams and cross-laminated timber (CLT) plates due to its high strength-to-weight ratio and flexibility for use in various structural elements of multi-story buildings. With the introduction of performance-based building codes in Europe and North America, the use of massive timber elements in tall buildings has received wide acceptance and has been in competition mode with traditional reinforced concrete material. The main objective of this study is to review performances of massive timber elements in various building applications in terms of strength, cost-competitiveness, and last but not least sustainability impacts including its contribution to carbon neutrality effort. Historical and literature reviews will be given to demonstrate feasibility of timber and its massive elements for building applications with considering reinforced concrete as the benchmark. Challenges and opportunities of timber use in construction will be discussed including potential use in hybrid system in which engineers can combine material constituents used in forming structural components or systems to reach optimum performance without ignoring sustainability constraints. It is expected that the outcomes of this study will encourage architects and engineers to use more timber globally as alternative sustainable construction material beyond the regions commonly utilizing timber as construction materials for generations.

Keywords: massive timber; CLT; sustainable materials; carbon neutral; hybrid construction; tall buildings; sustainable city; LINE; NEOM

1. INTRODUCTION

Timber has enjoyed a good reputation as one of the primary construction materials used by human since the dawn of civilization. Ranging from residential dwellings to multi-story pagodas or tall churches, timber competed well with stone or masonry-based materials, particularly in the regions with abundant forest resources. After the invention of reinforced concrete and steel materials, the use of timber in construction has diminished and been limited to residential buildings and small to medium structures. The renaissance of timber started when people introduced engineering wood product (EWP) around the last mid-century as substitute for solid sawn wood. EWP is created to minimize the inherent defects carried by solid wood such as knots, checks, and cracks by combining lamination technology with optimizing wood grain orientation to achieve consistent strength and properties. The first generation of EWP manufactured and used in the building construction included glue-laminated timber (glulam), Plywood, laminated veneer lumber (LVL), parallel strand lumber (PSL), oriented strand board (OSB), oriented strand lumber (OSL), Wood I-Joist, etc. [1]. Majority of these products were used in light-frame constructions such as residential and low-story commercial buildings, in addition to versatile glulam beams that were used in heavy structures including short span bridges. In North America alone, EWP has dominated residential construction material use constituting nearly 90% of its framing. Since early 90s, however, the use of EWP has saturated and timber has faced very competitive challenges from other construction materials in order to penetrate non-residential sectors such as tall buildings and long-span structures.

Near the end of 90's, a second generation of EWP was introduced into the European construction utilizing combination of wood fiber orientation with dimensional massiveness applied through multilayer adhesive-based lamination. It is similar concept applied to that glulam timber beam, but this time it is in the form of plate with cross lamination layer to create uniform characteristics in both directions. This product is specifically called cross-laminated timber (CLT) plate (Figure 1). CLT is versatile components in building design and construction; it can be used horizontally as slab element or vertically as structural wall elements and non-load bearing wall partitions. With appropriate connectors, CLT can be used in combination with steel frame or reinforced concrete elements as hybrid or composite construction system. The multi-story building construction utilizing CLT and other EWP has been booming since CLT gained reliability recognition from structural engineers in low-rise construction. One of the first multi-story buildings constructed using massive timber elements is nine-story Stadthouse Murray Grove Apartment Complex in London, UK, designed by Waugh Thistleton Architects [2]. The building, which was completed and occupied in 2009, uses CLT as the vertical wall bearing and horizontal slab elements without any beams and columns. The building has its first story reinforced concrete frame with the main intention to prevent timber elements in direct contact with water or moisture. Major features and advantages of this building relative to reinforced concrete includes shorter construction time, higher thermal performance, and better environmental impact.

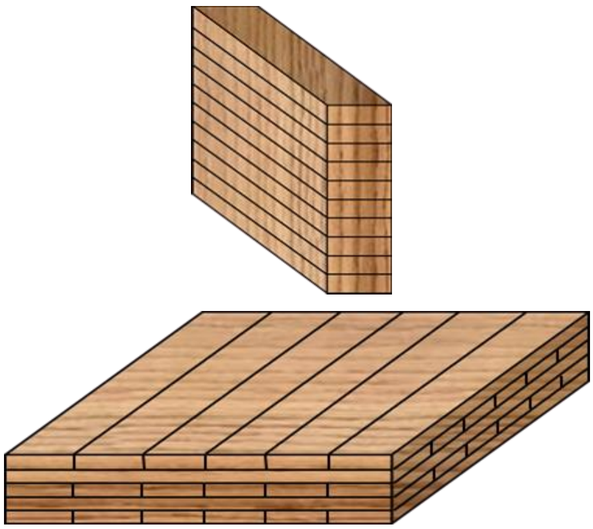

Figure 1: Massive timber products: Glulam and CLT

After successful application of mass timber elements in the Stadthouse building, there have been several multi-story building constructions utilizing CLT as the main materials along with other massive glulam beam elements, and sometimes as hybrid system with reinforced concrete or steel frame structures. The latest tall building constructed mainly with timber is Brock Commons Residential Tower in Vancouver, Canada. The building is 18-story with 53 m in total height, and as of today, it has represented world's tallest timber structure so far. The building is actually a hybrid system, where the core-shear walls uses reinforced concrete and the remaining framing are with CLT (slabs and walls) and glulam (beams and columns). As in the Stadthouse building, its first story is reinforced concrete structure. The building was designed to sustain heavy earthquake load, and timber due to its lightness fulfilled this major design requirement better relative to that had the building was designed fully with reinforced concrete elements. The trend to construct tall timber buildings has continued recently around the world, notably in North America, Europe, Australia, and Japan. Major driver for this trend is to support sustainability development goal in addition to the basic construction constraint, high performance construction with minimized cost.

The main objectives of this study is to review performances of massive timber elements in various building applications in terms of strength, cost-competitiveness, and last but not least sustainability impacts including its contribution to carbon neutrality effort. Challenges and opportunities of timber use in construction were discussed including potential use in hybrid system in which engineers can combine material constituents used in forming structural components or systems to reach optimum performance without ignoring sustainability constraints. It is expected that the outcomes of this study will encourage architects and engineers to use more timber as alternative sustainable construction material globally beyond the regions commonly utilizing timber as construction materials for generations. Potential use of timber in a futuristic city LINE of NEOM in Saudi Arabia was discussed.

2. Material And Method

In this section, major advantages of timber structure are discussed focusing on environmental impacts, structural performance under seismic load, construction time, and serviceability performances against thermal, sound, and fire.

Unlike concrete and steel, timber is renewable construction material that can be reproduced after certain period of forest cultivation. This could be good in term of supporting sustainability provided that the cultivation practice follows responsible forest management. Majority of cultivated forests in North America and Europe have been certified by independent forest management agency, such as Sustainable Forestry Initiative (SFI), Forest Stewardship Council (FSC), and Program for the Endorsement of Forest Certification (PEFC); to ensure that forest products comply with sustainable management criteria that provide environmental, social, and economic benefits. Trees grown in the forest is actually carbon sequester, converting carbon dioxide to biomass through photosynthesis process that effectively stores carbon. Therefore, timber harvested under a certified forest can be said as carbon sinker contributing to negative carbon emission. One cubic meter of timber can store roughly 1 tonnes of carbon dioxide [3]. For 900 m^3 timber used, the Stadhouse building stored around 310 tonnes of carbon instead of releasing 124 tonnes of carbon had the building constructed with reinforced concrete [2]. Table 1 shows carbon dioxide emission during production (cradle-to-gate) for materials commonly used in construction. Massive timber elements such as CLT has big potential to be carbon negative or at least carbon neutral. There have been several studies about comparative analysis between concrete and timber used in multi-story buildings, which favors timber over concrete in term of carbon emission [4-5].

Table 1: Carbon dioxide emission for common construction materials [4]

Material	Carbon dioxide emission	Unit
Steel	3,500	kg CO_2-eq/m^3
Concrete	260	kg CO_2-eq/m^3
Timber (laminated)	90	kg CO_2-eq/m^3

Due to inherent lightness with high strength-to-weight ratio, massive timber structures perform well under seismic load. There have been many studies demonstrating effectiveness of massive timber structures loaded under dynamics earthquake. A group of European and North American timber engineers demonstrated via a full-scale shake table test that multi-story CLT building can sustain a strong earthquake without significant and permanent damages [6]. They observed that the earthquake energy was efficiently dissipated through many ductile connections distributed throughout CLT's plate-to-plate joints. It is a common practice in timber joints to apply fastening system using combination between long-screws and concealed-slender metal connectors such that structural ductile failure can be forced to occur in the connections rather than in the brittle timber elements. As a hybrid system involving steel frame skeleton, mid-rise building with massive timber plate element as horizontal diaphragms responses well under seismic load. Asiz and Smith conducted comparative studies between reinforced concrete and CLT slabs used in hybrid multi-story buildings loaded under extreme seismic loads [7]. They found that CLT slab performed better responding to these seismic loads relative to the reinforced concrete slab. Other studies confirmed this finding [8-9]. They also observed that the in-plane rigidity of CLT diaphragms, which is important aspect to distribute lateral load to shear wall system, was comparable to that of reinforced concrete slab. For comparison purpose, Table 2 shows basic mechanical properties including modulus of elasticity and strengths of CLT relative to concrete and steel.

Table 2: Mechanical properties comparison [7]

Property	Steel	Concrete	CLT
Directional property	isotropic	nearly isotropic	orthotropic
Density (kg/m3)	7200	2400	400
Elastic modulus (GPa)	200	25	E1=9, E2=4.5, G12=0.5
Poisson's ratio	0.30	0.25	ν12=0.3
Strength (MPa)	250	fc=27.5, ft=3	ft-1=20, ft-2=15, fc-1=30, fc-2=25, fshear=5
Notation: E = modulus of elasticity; G = modulus of rigidity; 1 = CLT major direction; 2 = CLT minor direction; t = tension; c = compression			

Construction time required to install massive timber particularly CLT elements in building is normally quicker relative to reinforced concrete elements. This is again due to inherent lightness of timber leading to easy handling and quick assembly of its structural elements. Furthermore, CLT shifts traditional timber construction from framing to plate system saving time significantly in connection assemblies. As was demonstrated in the Stadhouse building, the construction time with CLT panels is estimated 30% quicker compared when it is constructed with concrete [10]. Traditional in-situ concrete slab construction needs at least 21 days to set compared to CLT construction assembly that needs around 4 days. The shorter construction time, i.e. less construction cost, is in fact leads to major decision to select CLT as the primary structural element for the Stadhouse building. One might consider that prefabricated concrete panel could potentially compete with CLT panel in term of construction time. Heavier handling machinery is needed for concrete panel, at least three to six times the capacity of that of CLT panel, leading to higher cost associated with labor and equipment rents. Self-drilling threaded screws driven into timber components requires relatively more straightforward labor training compared to welding or fastening high strength bolts in concrete panel construction.

Timber has lower thermal conductivity than concrete due to its large porosity needed to distribute water during tree lifetime. This makes timber is a good thermal insulator for building envelopes. Seven-inch thick (178mm) CLT has thermal resistance value around 10 times lower than that of concrete with similar thickness, 400 times lower than that of steel [1]. The Stadhouse building demonstrated that CLT-building envelope achieved intended higher thermal resistance value with minimum thickness of CLT (128mm) and 100mm insulation layer [2]. With respect to sound transmissibility, there was original concern that timber has poor performance resisting acoustic transmission. This is one of the notorious issues commonly observed in light-frame timber buildings. However, CLT buildings have significantly higher density relative to the light frame one and this can reduce sound transmission with proper junction detailing between panels. Another serviceability issue raised for massive timber building is fire performance. Massive timber has naturally charred during the burning process preventing fire to penetrate further into the timber cross sectional area [1]. With additional protective layer such as gypsum wall-board or mortar for floor finishing, minimum fire rating (e.g. 90 minutes) can be achieved for CLT panel.

3. DISCUSSION

This section is devoted to discuss future challenges of timber construction covering availability issue, building code and regulation, and education. Few opportunities are also discussed exploring potential use of timber in ‘non-timber countries’.

One of the major hurdles utilizing massive timber element such as CLT in construction is availability. Unlike any other EWP products heavily consumed in light-frame construction, CLT production is still in its infancy at the world stage. The European market leads the production and consumption of CLT and its utilization in building construction, followed by the Canadian market. While potential huge market like in the US, only fraction of construction community has started utilizing CLT in low-rise to medium-rise buildings application. This is despite the fact that the US is a country with strong culture of building with wood, 90% of its residential construction is with wood. Survey distributed to American architects about awareness, perception, and willingness to adopt CLT in building construction showed that 4.3% of them were aware about CLT [11]. The number is expected to increase due to new CLT manufacturing facilities being open in the US. Australia and East Asian countries like Japan, South Korea and China are also starting introducing CLT to the market using their local wood species. Other countries are in the stage of research to develop CLT material from local hardwood species and need to investigate further building connection systems that can handle the propensity of hardwood to splitting failure [e.g. 12].

Because of relatively new material with limited availability, building code and regulation could be another obstacle to promote utilization of massive timber in structural and building applications. Fortunately, building code around the world has been geared toward performance or objective based code recently rather than prescriptive based. This means engineers could design structures using innovative materials that meet stated objectives. In the past, for example, code stated that concrete shall be used for fire resistant wall or floor. In the objective building code, two hour fire rating shall be met, regardless of the materials used. This type of building code will help new material including massive timber elements for non-traditional application. Education and training is another challenge. Design and analysis of structures with reinforced concrete and steel materials are normally required and are common course for majority of civil engineering and architectural students. This is not the case for timber design, which is normally offered either as technical elective or early graduate school course in civil engineering. There needs to be major overhaul in the civil engineering curriculum both at the undergraduate and graduate level to incorporate timber as equally important material for construction. Strong inter-collaboration is required between civil engineering and wood science programs in teaching and research.

Utilization of timber in countries with big tropical forest resources such as Indonesia and Brazil has faced stiff resistance from environmentalist due to deforestation issue. Most of their forest products are used for non-structural applications such as furniture and building finishes due to texture beauty of hardwood species. Application in construction is limited to temporary supported structure and roof framing of small buildings. To promote more use of timber in the regions, forest management and product companies in the tropics need to catch up in complying with international standards for sustainability forest management [13]. Also, research and development to investigate feasibility of massive timber in construction is needed.

Expanding furthermore utilization of timber construction in ‘non-timber countries’ like in the Middle East region will be a big challenge. However, due to several advantages timber has over concrete particularly with respect to the environmental impacts plus its inherent beauty, timber material is always very attractive to non-traditional architects. Building construction is booming in the Middle East, particularly in Saudi Arabia due to high demand from fast growing population propelled by strong high oil price. Mega and landmark infrastructure projects accompanied with green initiatives have been introduced in Saudi Arabia to promote tourist industry and to attract more investors. It has been set that Saudi Arabia will be a carbon neutral country by 2050. Current landmark project the LINE introduces Saudi and world communities a futuristic smart and sustainable city designed in a 170 km long-line (with 500 m high by 200 m wide) across the northern desert area of Saudi Arabia. The city is intended to be populated with 9 million residents and will be equipped with various modern infrastructures with no carbon emission, i.e. zero-net carbon city [14]. It is an eye-catching project since it will utilize renewable and abundant solar generated power to run the city, and this is combined with utilization of various green materials (Figure 2). The initial estimated cost to build this city is 500 billion dollars. This will be a huge opportunity for timber and timber-based materials to enter green construction market in Saudi Arabia with major sellable attribute as the only carbon neutral or even carbon storage material. Since it is not a local material, timber producers needs to demonstrate that shipping globally, handling during construction, and recycling at the end of its lifecycle will not add significantly to the carbon emission. As discussed previously, the cradle-to-gate cycle (production and manufacturing) of timber will contribute to negative carbon emission. Therefore, it is anticipated that the whole cradle-to-grave of timber will contribute to carbon neutral or even carbon negative considering the massiveness of timber used.

Figure 2: Future sustainable buildings under the LINE of NEOM [13]

By combining with concrete or steel as hybrid (mix) construction, timber has more opportunities to be used for tall building applications. Designing vertical column components of tall building with timber could pose a long-time performance issue due to creep-induced shortening. Reinforced concrete or steel is relatively stable material against creep and it is good for designing column and shear wall components of tall buildings. While horizontal slab components can be designed with CLT plate to improve lateral load response due to earthquake or wind and at the same time to reduce demand in the foundation system. To avoid significant differential shortening, attention to connection detailing is important when reinforced concrete shear wall and timber columns are used for tall building. As building gets taller, sensitivity to excessive wind induced vibration is critical for ultra-lightweight floor system. Active or passive damping system need to be applied in this situation as applied for regular building with concrete floor slab.

4. Conclusions

Timber could become a global commodity for building construction since it can be designed to meet local needs and fulfill sustainability requirements. Structural engineers have demonstrated that buildings constructed with massive timber elements have similar performances relative to that of concrete buildings and in some cases perform better. However, more manufacturing facilities of massive timber elements need to be built particularly in Europe and North America to cope with continuous growth in demand. In addition, research and development in the areas of material and fastening technology is urgently needed to promote timber as alternative sustainable green material for construction. Hybrid construction between timber and concrete or steel is a preferable approach for tall buildings to get optimized performance of each materials in a loaded structural system. Finally yet importantly, building code and regulation needs to be upgraded to incorporate performance-based rather than prescriptive-based to increase a change for timber competing equally with other materials.

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