Outlook for Cross-Laminated Timber in the United States

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Cross-laminated timber (CLT) is a building system based on the use of massive, multi-layered solid wood panels. Although CLT as a construction system has been successful in Europe, only a handful of CLT projects have been built in the U.S. This manuscript presents the results from qualitative research, carried out with the objective of assessing the market potential and barriers to the adoption of CLT in the U.S. Insights from national and international experts were collected using semi-structured interviews. Topics included perceived benefits and disadvantages of CLT as a construction system, major barriers to its adoption in the U.S., and level of awareness about CLT among the architecture community.

Keywords: Cross-laminated timber (CLT); Massive timber; Market potential; Sustainable buildings; Awareness; Building code

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INTRODUCTION

Since the start of civilization, wood has been a material of choice due to its high strength performance relative to its weight, its cost effectiveness, and its renewable nature. However, the use of wood as a building material is not free from challenges. Being a natural material, its properties are not homogeneous, challenging its users to adopt strategies to cope with this variability (Forest Products Laboratory 2010). To counter the effects of the inherent variability of wood and to enhance its overall performance, engineered wood products (EWPs) were developed. Over the past 60 years, the development and improvement of adhesive technologies, mechanical connections, and grading and manufacturing technology has resulted in EWPs that greatly extend the possibilities for wood-based construction (Canadian Wood Council 2006).

A recent innovation in the area of EWPs, the development of cross-laminated timber (CLT), also known as “Massive Timber” (Podesto 2011), has the potential to revolutionize building construction and increase the amount of wood used for building construction in a considerable way. CLT was developed in Europe in the early 1990s, and is a building system consisting of large, solid timber panels that can be used as walls, roof and floor slabs (Lehmann and Hamilton 2011). CLT is made of 1- to 1.6-inch-thick dimensional or engineered lumber laminations that are glued or fasten together using mechanical fastenings alternating 90 degrees (Fig. 1). Research has demonstrated that this configuration helps to achieve improved rigidity, stability, and mechanical properties in two directions (Evans 2013).

During the last two decades, the use of CLT in Europe has experienced double-digit growth rates (Crespell and Gagnon 2011), and is gaining market share in Australia and

Canada. Abundant information is available and is currently being generated regarding the technical aspects of CLT (Frangi *et al.* 2009; Gagnon 2011; Mohammad *et al.* 2012). However, little to no information about the market potential of CLT in the U.S. is available, making it difficult for entrepreneurs and early adopters to propose financing for development of the market in this country.

Fig. 1. Schematic of CLT layer configuration

The goal of this qualitative study was to assess the market potential of cross-laminated timber and to identify potential barriers to its adoption in the United States. For this purpose, this study collected the perspectives of experts about the awareness, perceptions, and willingness to adopt CLT by the U.S. architecture community.

METHODOLOGY

The research approach followed for this study comprised an extensive literature review followed by a set of semi-structured interviews with CLT experts. A list of 10 experts was compiled, based on their experience and knowledge of the topic. The majority of these contacts were found in the relevant literature, while the rest were derived from recommendations by academic experts. A semi-structured questionnaire was used to obtain information and insight on topics relevant to existing and potential markets for CLT in the U.S. The experts were contacted by phone, the interviews were audio-recorded, and transcripts were created from each conversation. The list of experts included professionals from the academic, manufacturing, architecture, and industry promotion communities. Participants were located in the U.S., Canada, and Austria. The questionnaire asked for information and perspectives on the following topics: (a) knowledge and experience of respondent with CLT; (b) environmental, structural, and economic performance of CLT; (c) barriers to adoption of CLT in the U.S.; (d) awareness of CLT in the U.S. among the architecture, engineering, and construction (AEC) community; (e) cost-competitiveness of CLT compared to other construction systems; (f) types of buildings where CLT has the highest potential for adoption; and (g) other comments regarding the potential for adoption of CLT in the U.S.

Participants were contacted *via* email and phone to arrange a convenient date and time for the interviews, with the interviews conducted *via* phone in the summer of 2013. The duration of the interviews was between 10 to 35 min. Each interview recording was later transcribed and coded. Established qualitative research methods for thematic content analysis using the constant comparative method (Berg 2001) were used to analyze and to identify major themes from the transcripts. Organization and analysis of the responses were carried out using Microsoft Excel spreadsheet software (Microsoft 2010).

Study Limitations

A number of limitations may have affected the results obtained from this qualitative study. Limitations include:

- Due to the small sample size, generalization of the conclusions to the population of interest is not feasible. The purpose of this qualitative study was to explore and identify major topics for CLT adoption, and this objective was achieved by interviewing a number of experts in the field. Recognized methods of qualitative analysis were used (see Methodology section). Results were used as major input for an industry-wide randomized survey (to be published). Participants working in the manufacturing sector as well as in the promotion of wood products may tend to have a positive bias for wood-based construction materials.
- Some professionals, such as engineers, contractors, and developers, who may have relevant knowledge and insights, are not represented in the sample.
- Telephone interviews typically need to be short, thus reducing in-depth discussion (Chapple 1999).

RESULTS AND DISCUSSION

Respondents' Background and Experience with CLT

The background of the respondents was diverse. Two participants were co-authors of the first U.S. edition of the CLT Handbook (FPInnovations 2013). One expert indicated having experience in manufacturing, construction, and cost estimation of CLT structures, as well as having conducted competitive analysis and cost comparisons between CLT and concrete, steel, and traditional light-frame construction. Another respondent has been conducting research on the North American production potential for CLT. The representative of an organization that promotes the use of wood in commercial buildings reported having years of experience conducting workshops, seminars, webinars, and various technical assistance efforts supporting CLT aimed at the AEC community. Two of the interviewees were involved in the experimental modeling of CLT for seismic performance. One manufacturer representative indicated that prior to establishing a CLT plant in North America, he worked as cost controller and project manager in the United Kingdom. Two other participants from industry have been pursuing research on wood and related subjects for years, which led them to work for CLT manufacturing companies as technical assistants.

Environmental Benefits of CLT

The environmental benefits of cross-laminated timber have been widely documented (Schlamadinger and Marland 1996; Winjum *et al.* 1998; Salazar and Meil 2009). Eight respondents agreed that carbon sequestration of CLT is one of its most important environmental benefits, and that this provides a unique opportunity to market the product (selling point) to environmental-conscious consumers in the U.S. (Qi *et al.* 2010; Wang *et al.* 2013). In fact, the carbon-storage capacity of wood products is gaining recognition in domestic climate mitigation programs such as the ones promoted by the Environmental Protection Agency (Malmsheimer *et al.* 2008) and the U.S. Forest Service (USDA 2011). Wood products store carbon at an approximate rate of 1.10 tonnes of CO_2 per cubic meter and do so over the time (usually decades) (Malmsheimer *et al.* 2008) that these products are in use.

Interviewees also emphasized the lower greenhouse gas emissions and lower energy input required for the manufacture of CLT panels, especially compared to the process required to produce equivalent elements from concrete or steel. Research on comparative life cycle analysis (LCA) of building materials, *i.e.*, the evaluation of environmental impacts during raw material extraction, transportation, and processing, seems to be in agreement with the participants' assertions (Wilson 2006; Bergman and Bowe 2010; Oneil and Lippke 2010; Puettmann *et al.* 2010; Silvestre *et al.* 2013; Wang *et al.* 2013). According to Malmsheiner *et al.* (2008), substitution of building elements that require intensive use of fossil fuels for their production (*e.g.*, steel- or concrete-based elements) with wood-based products helps achieve considerable reductions in carbon emissions to the atmosphere, making CLT construction systems an environmentally-friendly alternative to more energy-intensive materials. One interview respondent mentioned that LCA of existing CLT buildings showed that these buildings have a negative carbon footprint. Research conducted by Hammond and Jones (2011) in the United Kingdom showed that concrete and steel solutions contain around the same amounts of embodied CO_2 (1,984 tonnes/m^3), while an equivalent CLT system has less than a half that amount (727 tonnes/m^3). However if carbon sequestration is taken into account, CLT turns out to be carbon-negative, with a value of approximately -2,314 tons/m^3 of embodied CO_2, giving CLT an advantage in terms of environmental impact compared to other materials (Hammond and Jones 2011).

The two manufacturing representatives in our sample stated that the biggest environmental benefit of CLT stems from the potential for using underutilized forest resources to manufacture CLT panels. Similar to other engineered wood products, the structural performance of CLT panels do not depend on the mechanical performance of each individual component (a lamination layer or a wood flake) but on the overall system; hence CLT presents the opportunity for using lower quality and smaller dimension material for its production. Similarly, raw materials from forests damaged by insect or disease could possibly find a high value-added use, as long as the mechanical properties of these materials are not compromised (Wilson 2012). This way, multiple benefits can be derived from using lower-value raw material for a higher-value use, with wood products that continue to benefit the environment long after timber is harvested through carbon sequestration (Salazar and Meil 2009; Wang *et al.* 2013). This will also help forest managers to manage these compromised forests more proactively and profitably while reducing existing fire hazards (Salazar and Meil 2009). According to one of the Canadian industry representatives, his company uses considerable amounts of raw material from beetle-infested pine trees in a Pacific Northwest forest, thereby allowing a more effective and efficient use of natural resources that may otherwise be wasted.

The CLT experts interviewed also noted the favorable properties of wood in respect to heat transfer and storage, especially compared other materials (*e.g.*, steel and concrete).

Experts mentioned that not only does wood have favorable heat insulation properties, but CLT makes massive use of wood for the building enclosure and the interior floors and walls, which acts as a thermal mass that stores heat during the day and releases it at night. This thermal mass can greatly reduce heating and cooling loads, shift the time of peak loads, lower overall building energy use, and improve the overall comfort of occupants (Burnett and Straube 2005). According to one of the interviewees, the insulating capacity of CLT also helps in reducing the amount of insulation material needed to achieve low operational energy consumption of the structure (Reijnders and van Roekel 1999). Mardookhy *et al.* (2013) indicate that more than 48% of the total building energy consumption corresponds to the use of room heating and cooling equipment. Consequently, improvements in the building envelope can help reduce environmental polluting emissions such as carbon dioxide originating from energy generation (Reijnders and van Roekel 1999; Mardookhy *et al.* 2013).

Structural Benefits of CLT

Some of the structural advantages mentioned by interviewees in this study are derived from the physical and mechanical properties of wood, which have made this material so popular for building construction throughout history. Six interviewees agreed that one of the most important characteristics of CLT is its strength-to-weight ratio. One participant mentioned that *"…[*CLT is*] as strong and [*performs*] as well as concrete but it weighs one-sixth of concrete,"* When loaded, wood can have a strength-to-weight ratio advantage relative to steel of 2:1, and an even more favorable ratio if compared to concrete (Architectural Record 2011). An important benefit of using a material with low weight-to-strength ratio like CLT is that lighter structures with comparable structural capabilities can be achieved. Furthermore, a lighter structure translates into smaller building foundations, which in turn translates into lower building costs. One manufacturing representative interviewed for this study explained that having less gravity loads makes CLT a far superior material over all other competing materials.

The majority of the individuals interviewed indicated that the structural characteristics of CLT make it a preferred alternative to concrete structures, especially in construction over 6 stories. There are several successful examples worldwide of CLT used in tall buildings; prominent examples include the Stadthaus, an 8-storey residential building in London, UK (KLH 2013), and the Forté Building, a 9-storey residential building in Melbourne, Australia (Lend Lease 2013). A recent report by the architecture and engineering firm Skidmore, Owings and Merrill (SOM) studied the concept of a 42-storey CLT-concrete hybrid building in Chicago, called Timber Tower Research Project (SOM 2013). One of the people interviewed mentioned that his expectation is to see CLT enabling wood buildings to reach "*new heights*," Another respondent (an engineer) voiced some skepticism on this matter, saying that he is unconvinced about the ultimate number of stories that can be built with a wood (CLT) structure. When asked to elaborate on this skepticism, the interviewee indicated that there is a lack of models to predict the performance of high-rise wooden structures and mentioned that the highest building they have modeled in the laboratory is 15 stories high. However, the most vulnerable part of a CLT structure is not the wooden panels but the connections between elements. The same expert stated that further research needs to be carried out, and improved solutions need to be created before wood-based buildings can go beyond 20 stories.

Two participants involved in research and one participant representing the architecture sector mentioned that another important structural benefit of CLT was its design flexibility. Cross-laminated timber allows designers have a plate element that can resist forces in all directions, thus allowing curved, inclined, or folded geometries without compromising the structural integrity of the structure.

According to one of the respondents, the ability of CLT to span in two directions (longitudinal and transversal) allows achieving architectural features that otherwise would be too complex or impossible to attain using wood in traditional ways. Furthermore, since the size of the structural elements is limited only by transportation and manufacturing constraints, designers are able to use fewer larger plates to create a stable construction, which translates into a more simple, less error-prone construction, with less need of specialized labor and faster completion times (FPInnovations 2013).

Some of the respondents also stressed the fire performance of CLT elements. While people often mistakenly assume that wooden buildings behave poorly in fires, research has shown that CLT elements perform exceptionally well (Schmid *et al.* 2010; Fragiacomo *et al.* 2013). In fact, large-sized wood members have shown an inherent ability to provide fire resistance because of their unique charring properties (Crespell 2011). Respondents mentioned that CLT panels burn slowly and predictably and form a char-layer, and the non-charred internal wood layers retain their strength and dimensional stability to thereby delay the collapse of structural members. Respondents indicated that in some respects, CLT has an inherent fire resistance better than an unprotected steel structure. One interviewee mentioned that his research showed that CLT panels, due to their "*massiveness*" and "*tightness*," provide an extremely favorable barrier for gases and high temperatures during a fire situation improving compartmentalization.

Finally, researchers with a background in engineering interviewed for this study viewed the seismic performance of CLT as another major structural advantage of the material. Recent research (Popovski *et al.* 2010; Pei *et al.* 2012) found that the massive properties of CLT are advantageous when subjected to lateral forces. Results from these tests on single CLT wall panels showed that the connection layout and design has a strong influence on the overall behavior of the wall. CLT panels are not ductile by themselves but panel to panel connection provide the ductility required in seismic conditions. (Pei *et al.* 2012).

Economic Benefits of CLT

Nine out of ten respondents recognized the speed of construction as one of the main cost advantages of building with CLT. In fact, the prefabricated nature of CLT allows building elements to be delivered to the construction site ready to install, shortening building completion time and requiring less qualified personnel (-FPInnovations 2013). One respondent stated that CLT elements *"…can be installed in one-third of the time compared to other products*," Respondents also mentioned that faster construction means fewer chances for on-site accidents and less disruption to the surrounding community, with positive consequences for the total costs associated with the construction (*e.g.*, insurance, safety, and goodwill). Two respondents mentioned that the speed of construction was particularly attractive to developers, who can realize the return on their investments more quickly: *"…[*CLT*] can go up so quickly that the people who are paying the bills for the projects can start making money from their investment much sooner"* and *"…so you save* *time, and get to move into that building sooner and the savings from that alone are quite substantial,"* WoodWorks (2013) highlights the rapid on-site construction that may take as little as three to four months for buildings of up to nine stories (Lehmann and Hamilton 2011), less than half the time compared to traditional construction methods. The controlled manufacturing environment in which CLT panels are made also helps reduce waste, cut total production time, and facilitates the final installation thanks to high precision work (since CLT panels are cut using computer numerical control machines at the factory), which potentially reduces the occurrence and costs derived from problems during construction and post-construction.

Three of the respondents working in manufacturing pointed out that CLT presents an opportunity to use local resources. Research regarding the use of underutilized hardwood species for CLT manufacturing in Italy (CLT is typically made with softwood species) concluded that the manufacture of these panels contributes to the valorization of locally available wood resources and to the development of the local wood-based industry (Callegari *et al.* 2010).

Disadvantages of CLT

Six of our respondents agreed that the main disadvantage of cross-laminated timber is the large volume of wood required for its manufacture. One respondent with experience in design and calculation of CLT structures estimated that CLT panels use three times more wood than a wood-frame system solution. While this might be seen as an advantage with regard to to carbon storage, participants indicated that this need for larger volumes of raw material also implies a higher cost, which can cause CLT-based solutions to be non cost-competitive for some applications. The large volume of wood used in the manufacture of CLT also may affect public perception about the system; as one respondent pointed out: "*people will say that perhaps it is a lot of fiber engaged in CLT,"* while another respondent added that the depletion of our forests "… *is a misconception because countries such as ours [Canada], with good forest management practices, do not have deforestation concerns,"* The same can be said for the U.S., where the forest area has not changed during the last 100 years and where about a quarter of the private forestland is managed using forest certification standards (Alvarez 2007; Espinoza *et al.* 2012). This perception needs be overcome to really open the market for massive wood products.

Another disadvantage mentioned by some of the respondents was related to the acoustic performance of CLT systems. One researcher mentioned that usually acoustic problems occur due to shortcomings in the installation and the lack of proper linings. Recent research found that thanks to its massive nature, CLT-based systems achieve good acoustic performance and provide adequate noise control for both airborne and impact sound transmissions, especially if sealant and other types of acoustic membranes are used to provide air tightness and improve sound insulation at the interfaces between the floor and wall plates (Gagnon 2011). Figure 3 shows a schematic of the floor assembly tested at the Technical Center of Forest, Wood Products and Furniture in 2006 in France (FPInnovations 2013); these tests showed that CLT floors built with proper insulation can achieve and exceed preferred (50 dB) and targeted (55 dB) sound insulation thresholds.

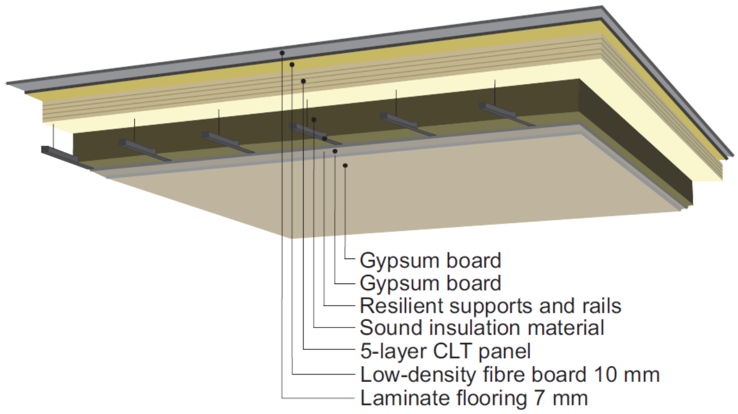

Fig. 2. Cross-section of a tested CLT floor assembly. Source based on information from CLT Handbook (FPInnovations 2013)

An architect interviewed for this study mentioned that some technological barriers exist due to the solid nature of the CLT system, requiring professionals to change the way they design buildings for services like mechanical, electrical and plumbing. This respondent's assertion is supported by findings by Griffin *et al.* (2013), who states that systems that usually are hidden inside a wall frame (*e.g.*, plumbing and electrical) now need extra attention regarding their integration with the structure, which can imply more planning and manufacturing costs.

Another disadvantage of CLT that was mentioned during the interviews is the fact that a sizeable percentage of people still do not completely trust the durability qualities of wood as a building material. Generally, wood is seen as more of a liability compared to concrete, steel, or masonry. Individuals may believe that wood is not able to withstand time, and that its biological nature implies higher maintenance costs (Lehmann and Hamilton 2011). One of the researchers interviewed indicated that his main concern about the structural performance of CLT is the durability of the material, especially since wood is susceptible to moisture-related problems. This issue could also be mitigated through appropriate design practices.

Awareness of CLT in the Architecture Community

When respondents were asked about the level of awareness of CLT in the architecture community, about half indicated that awareness is currently low or very low. When asked to elaborate, several of the respondents mentioned that this low level of awareness is due to the short time this material has been available in the U.S. market. In particular, two researchers agreed that professionals not familiar with the wood industry are less likely to know about the existence of CLT. One researcher stated that *"... because the marketing for this product is coming from the wood industry, people not connected with the wood industry are not aware of the product*." A second group of respondents indicated that the level of awareness of CLT in the architecture community has been steadily growing over the past five years as a consequence of the increased publicity of CLT systems by organizations that promote the use of wood in the U.S.

One participant of the study with a background in engineering stated that the level of awareness is *"higher in the architectural area* [as] *they tend to know about it, whereas from the engineering standpoint, it is lower,* [since] *they are less knowledgeable about* *wood materials."* The same participant mentioned that the national engineering curriculum does not include in-depth information of wood as a material. Over the past few decades, educational programs on wood science and technology have been declining (Testa and Gupta 2004). In part for this reason, engineers tend to be less aware of wood materials, and thus more inclined to choose other materials which are widely and intensively covered in their educational programs. It is not unexpected that most construction professionals are more at ease with the design of steel and concrete structures and are more likely to shy away from considering wood structures as an alternate system, even when it is feasible, sustainable and cost-effective (Gupta and Gopu 2005). One manufacturing representative also pointed out that the level of awareness about CLT is location-dependent. According to this respondent, in regions with more tradition in wood-based construction (*e.g.,* the Pacific Northwest) a higher level of awareness exists, while in regions with less wood construction tradition (*e.g.,* the Southeast) awareness is notably lower.

Barriers to the Adoption of CLT in the U.S.

A majority of respondents indicated that the main barrier for the adoption of CLT in the U.S. was the fact that CLT-based systems are not included in the International Building Code (IBC 2012). According to Blomgren (2012), designers who want to use CLT for a project must request permission from local authorities, but the multiple jurisdictions that come into play (local, regional, and national) with such requests complicate the process. One of the respondents, working at a national wood-based products research facility, mentioned that in the U.S. the American Wood Council created task committees to begin the process of adding CLT to its National Design Specifications (NDS 2012). However, the extensive research and testing required for inclusion in the NDS typically takes several years, thus completion is not expected until late 2014 or 2015. The same respondent, who is also part of the National Design Specification for Wood Construction committee, stated that CLT is expected to be available nation-wide by 2015. Recently, two Canadian provinces (Quebec and British Columbia) amended their building codes to allow buildings made of wood up to six stories. In comparison, the UK, Norway, and New Zealand place no height restrictions on "*safely-made*" wooden high-rise (Lehmann and Hamilton 2011). In the U.S., efforts by the Canadian research institute FPInnovations and the APA (The Engineered Wood Association) have been undertaken towards removing code barriers and to regulate CLT construction. For this purpose, a U.S.-Canadian CLT Standard Committee was instituted and, in parallel, the American National Standards Institute (ANSI) approved the ANSI/APA PRG 320-2011 Standard (APA 2013) (*i.e.,* Standard for Performance-Rated Cross Laminated Timber) in December 2012. The ANSI/APA PRG 320 standard provides requirements and test methods for quality (wood, adhesives, and dimension tolerances), resistance (bending, modulus of elasticity, shear, and bonding) and appearance (architectural and industrial) of CLT and was developed as a standart for Canada and the U.S. (APA 2013).

Another barrier to the adoption of CLT mentioned during the interviews was the availability of information and education about CLT. The participants representing the architecture sector indicated that, as one respondent put it, "*architects and engineers are aware [of CLT] but [between] being aware [and] being proficient, there is lack of education."* Another respondent added that "*it is going to take a little time to understand the product and probably [there is a] need of training, seminars, or similar activities, to* *get people more comfortable [with CLT]."* Such comments are most likely related to the previously discussed lack of education in wood materials in many educational curricula, especially in engineering. In that sense, according to two respondents, architects tend to be more receptive to wood-based construction systems, while engineers seem to prefer concrete and steel due to their educational background.

The limited availability of CLT in the national market is also seen as an important barrier to the successful adoption of the material in the U.S. market. At the moment, CLT for structural purposes is not currently produced commercially in the U.S., making it difficult for users to choose CLT over other materials which are more readily available. Currently, opting for a CLT solution implies extra transportation costs, since the panel will have to be imported from Europe or Canada. One respondent stated that "*if you don't have any capacity or any production in the United States then […] no one knows* about this *product."*

Another potential barrier to the successful adoption of CLT systems in construction is the widely perceived disadvantage of wood as a building material. Typical concerns center around fire requirements and insect-attack problems. More generally, wood is seen as a risky option in comparison to concrete, steel, or masonry. Furthermore, social acceptance also plays a vital role in the implementation of any innovation (Yuan *et al.* 2011) and changes in behavior have frequently been listed as the number one barrier to the adoption of new products (Lehmann 2012).

Technical issues of CLT panels as a threat to successful adoption were mentioned by one respondent from the research community. This individual pointed out that lateral and shear design of CLT still needs considerable research. One U.S. manufacturing representative mentioned issues in the manufacturing sector as a potential barrier to successful adoption. This person explained that their company's main struggle is to get the necessary equipment for the production of CLT from Europe, as such equipment cannot be currently procured by U.S. manufacturers.

Cost-Competitiveness of CLT

When asked about the competitive position of CLT compared to traditional building systems, a majority of experts interviewed concluded that CLT is cost-competitive compared to concrete structures for certain applications. This is consistent with preliminary research conducted by FPInnovations and published in the U.S. version of the CLT Handbook (FPInnovations 2013). Cost competitiveness of CLT is mainly driven by the short construction times compared to more traditional building materials such as concrete or steel. Lend Lease, the developers of the first 10-story wooden apartment building in Melbourne Australia, compared the time (38 days *vs* 20 weeks) and manpower (6 technicians *vs* 30 technicians) it took to build the Forté building with CLT to the time required to build an equivalent concrete structure (Lend Lease 2013).

Respondents were skeptical, however, when comparing cost effectiveness of CLT with other wood-frame systems. Four participants mentioned that they think it unlikely that CLT systems will ever be cost-competitive with traditional light wood-frame construction, as the volume of wood required for the panels is three times the volume used in a wood-frame structure and weights around six times more. One respondent who has been performing cost and materials requirement comparisons for CLT and wood-frame systems stated that the volume of wood required greatly depends on the type of building. The taller the building, the more load the panels will have to support, thus the thicker the elements will need to be. Thus, an industrial one-storey building will demand fewer resources than a 10-storey apartment building.

A manufacturing representative from Europe mentioned that the cost-competitiveness of CLT should not only be evaluated on the initial investment, but that a long-term calculation reveals even more favorable economics: "*[CLT is] cost-competitive because it already has thermal insulation, […] and for sure it might be a little bit more expensive in the beginning, but when you also include the maintenance costs it turns out to be absolutely cost-competitive."* Hameury (2004) showed that massive timber enclosures require less insulation materials to achieve comfortable inner temperatures, and if designed and installed correctly, CLT panels require little to no maintenance (Sutton 2011). One of the main reasons for the need of maintenance are moisture-related problems. Successful moisture management starts with minimizing the amount of water brought in by the material during construction. Thus, the manufacture of CLT, as regulated by the ANSI/APA PRG 320-2012 standard (APA 2013), follows established protocols for measuring the moisture content of CLT panels to minimize the occurrence of moisture problems in the enclosure once the panels are installed.

Suitable Uses for CLT

Cost-competitiveness is, to a large extent, related to the building type. When experts were asked about the types of buildings for which CLT will be most suitable, all respondents agreed that CLT-based construction systems should be more suitable for high-rise buildings over six stories, where the panels can replace less environmentally-friendly materials such as concrete or steel. As mentioned before, CLT systems offer structural performance comparable to concrete for high-rise buildings, while reducing construction time considerably, since CLT shortens the waiting times until another floor can be built. While concrete needs to be cured for at least 28 days before 90% of the material's final strength is reached and the formwork for the next floor can be placed (Kosmatka 2011), CLT does not require any curing time on the construction site. Also, as a prefabricated system, CLT enables the reduction of noise, the use of heavy lifting equipment and construction site congestion, in particular in downtown areas.

Four of our ten respondents mentioned that another suitable use for CLT as an alternative to concrete is for large box-like industrial or commercial buildings (*e.g.*, supermarkets, industrial buildings, convention pavilions, or sport venues). Those uses require long spans and tall walls that can be cost-competitive with CLT-based systems.

Respondents working in research-related fields saw a large potential for CLT due to its alleged superior structural performance. These respondents mentioned that CLT-based systems can find a niche market as a construction material for buildings subjected to seismic forces. Also, two experts stated that massive timber CLT is well-suited for earthquake prone areas, while another expert mentioned that CLT can also be used in regions where hurricane, tornado and earthquakes shelters are required. For extreme conditions like hurricanes and tornados, the lightness of a structure reduces the lateral loads, and wood buildings consequently have more flexibility than concrete or masonry structures which are more prone to collapse (Tonks and Chapman 2009; Schmitt 2012). Numerous joints and connections in CLT, as well as the attachment of sheathing, provides countless load paths in the event of lateral forces. If one connection is overloaded, its share of the load can be picked up by adjacent connections (Canadian Wood Council 2010), creating a surprisingly strong structure.

None of the respondents considered the single-family residential building sector as a major market for CLT systems. Some elaborated that this sector is dominated by wood-frame construction systems, which are highly efficient and cost-effective for this application.

Potential for Adoption of CLT

The group of CLT experts interviewed for this study were asked about the potential of nationwide adoption of CLT in the U.S. Even though eight of the respondents agreed that the system had a great potential to become the next environmentally-friendly alternative to traditional materials like concrete, masonry, or steel, there were a few exceptions. Two researchers and one architect agreed in that the adoption will most likely to depend on the region, in a similar manner as awareness of CLT. According to our respondents, adoption is more likely to occur in areas where the tradition of constructing with wood is stronger. In those regions, the public and construction professionals have less prejudice towards wood-based construction systems and are more open to accept new products. However, respondents believed that the adoption of CLT will be more of a challenge in regions where concrete, steel, or masonry have a long tradition. As one researcher stated, the adoption of CLT *"[…] would face challenges in the South because of [the concern for] termites, this might require [chemically] treating CLT. But in the Northern, Eastern, and Western regions of the United States, I think there is a big potential for buildings constructed with CLT*."

One of the respondents, a U.S. researcher, mentioned that the potential for CLT adoption was highly related to the "*green building*" movement, indicating that this movement is the "*wild card*" to the successful adoption of massive timber (*e.g.*, CLT) elements. Espinoza *et al.* (2012) stated that this environmental movement is driven by market demand, thus if the "*green building*" movement keeps growing, there are great chances that CLT systems will gather momentum and be widely used in the country in the not too distant future. In this context, the implementation of green building credit programs such as LEED from the Green Building Council will greatly promote the use of wood (Qi *et al.* 2010; Atlee 2011). The LEED program establishes a system where buildings need to satisfy certain requirements to earn points to achieve different levels of certification. One of these requirements relates to the materials chosen for the building envelope, encouraging the use of sustainable materials (such as wood from certified sources) and waste reduction (Wang *et al.* 2013). The CLT-based systems are uniquely positioned to fare well on both of these requirements. However, one respondent voiced doubts about whether the conditions needed for the successful adoption of CLT-based construction systems at a national level (*i.e.*, national availability, overcome people's misconceptions about wood, and acceptance in the engineering community, among others) will ever be met. Should this respondent's worries materialize, the future of CLT in the U.S. may just be as a small niche market product.

Findings from this study stress the importance information and education will have on CLT adoption levels by architects. We conclude that the future success of a CLT-based construction system in the U.S. depends on information reaching the target audience. The current level of awareness and existing perceptions about the material may make it difficult to create a market for CLT. The diffusion of knowledge is essential in the process of public acceptance of any new product, as it takes time and effort to get people to trust a new construction system. However trust can only be earned by proven success. In that sense, it is important to make the system available so that professionals willing to try the system are not discouraged by the costs of having to import the product. The experience of these early adopters of the system will serve as the best reference for those considering CLT.

CONCLUSIONS

1. The main benefits of CLT-based systems, based on expert interviews, come from using a natural, renewable resource like wood as opposed to energy-intensive and non-renewable materials like concrete or steel. Another important benefit of CLT-based systems over traditional construction systems is the shorter construction time needed, since CLT is a prefabricated system in which panels come to the construction site ready to be installed. The CLT-based systems reduce labor time, on-site waste, the occurrence of accidents, and disturbances to the site's surroundings, all of which have a positive effect on total construction costs. Structurally, CLT offers performance comparable with concrete or steel, with a reduction of the weight. The layered configuration of CLT grants the panels good rigidity, stability, and mechanical properties, allowing CLT to be used as walls, floors, roofs, elevator shafts, and stairways, to name a few possible applications.
2. Experts interviewed mentioned that CLT has technical drawbacks such as its acoustic and vibration performance, especially when the design does not require insulation layers. According to experts, construction professionals should never use bare CLT floors without acoustic membrane on one side or without ceiling. Another concern voiced by several respondents was the volume of wood utilized in the manufacture of CLT panels. According to one expert, CLT panels use three times more wood than a wood-frame system.
3. Regarding the level of awareness about CLT-based construction systems among architecture professionals, there was almost universal consensus among respondents that the awareness is still low in the U.S. Reasons given include the novelty of the system and regional variances, and that professionals working and living in areas with a larger tradition of wood-based construction appear to more likely to be familiar with CLT-based systems.
4. Barriers to adoption of CLT-based construction systems in the U.S. mentioned by the respondents were building code compatibility, availability of CLT in the domestic market, and misconceptions about wood as a building material. In particular, the current absence of CLT manufacturing operations in the U.S. requires that CLT elements must be imported from Canada or Europe, which adds to the total costs.
5. Responses regarding cost-competitiveness indicate that cross-laminated timber can be a cost-competitive alternative to concrete structures, especially for buildings over six stories high. This is in great part due to the dramatically reduced construction time needed for CLT-based systems. Most experts agreed that CLT is cost-competitive for

high-rise commercial or multi-family residential buildings and low-rise commercial and industrial buildings, where a wood-frame system cannot be used. Respondents also agree that the system will not be cost-competitive for applications where light wood-frame construction is an option.

6. Experts indicated that the future of CLT is promising and that the adoption of the system nationwide is possible and currently happening. However some participants showed some skepticism, based on their experience with the adoption of CLT-based systems in other parts of the world. These skeptics stated that CLT-based systems can end up finding a niche market in some regions while acceptance of the system will be rather difficult in regions with a tradition of construction in concrete, masonry, or steel.

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