Barriers to the design and use of cross-laminated timber structures in high-rise multi-family housing in the United States

J. Schmidt, C.T. Griffin
Department of Architecture, Portland State University, Portland, Oregon, United States

ABSTRACT: Wood structures not only have a significantly lower embodied energy and associated carbon emissions than equivalent steel and concrete structural systems, wood is a carbon sink, removing carbon dioxide from the atmosphere and storing it in building components. The reduction of carbon dioxide is critical to addressing related energy and climate issues. Unfortunately, the structural properties and life-safety concerns have limited the use of wood to the structural systems to low-rise buildings in the United States. This paper uses the hypothetical design of a high-rise multi-family housing building using Cross-Laminated Timber (CLT) to address these barriers and highlight the potential of CLT for use in the United States. CLT adapts itself more naturally to multi-family housing than other building typologies due to the solid panel nature and limitation in spans. It has been chosen to use a high-rise design since there are stricter building codes and to understand if professionals feel CLT is capable to reach high-rise limits safely. Since post-tensioned concrete is the typical structural system currently for high-rise multi-family housing, CLT will be compared to this system. CLT is an engineered wood product consisting of glue laminated wood boards, approximately 20-60mm in thickness, with each layer set at right angles to the next layer. This cross lamination creates panels, ranging from a 3-layer 57 mm (2.24 in) panel to as thick as an 11-layer 300 mm (11.8 in) panel, capable of spanning in two directions and being used for load-bearing walls and spans. CLT was first developed in the early 1990s in Austria and Germany and has been gaining popularity in residential and non-residential applications, mainly in Europe. Currently, panels are being manufactured in a limited number of places in North America, which allows CLT to be used in a few projects while trade organizations and governmental agencies adopt specifications and codes for its use. While CLT is being used in Europe as the structural system for eight-story buildings and proposals up to seventeen stories, the barriers to the adoption of CLT for high-rise construction in the United States needs to be exposed and understood. Through the use of semi-structured interviews and surveys of design, engineering and construction professionals, this paper analyzes these barriers that include systems integration (fire-safety, acoustics, plumbing, electrical), aesthetics and information gaps.

1 INTRODUCTION

1.1 *Use of wood in building structures*

Wood is a renewable resource as long as the forests being harvested are sustainably managed or areas are set aside to treat trees as a crop, as seen in the Southeast United States forestry practices. By sustainably managing a forest, trees are harvested and the area is replanted to replenish the source. This makes sure not too many trees are harvested at once causing resource depletion. There are two certification standards that recognize sustainably managed forests for meeting their specified criteria. The two certification groups are the Forest Stewardship Council (FSC) and Sustainable Forestry Initiative (SFI). FSC has five different areas for their standards that include a general area, forest management, chain of custody, controlled wood, and pesticides.

SFI like FSC has different standards and certifications depending on the stage of the manufacturing process. There are three different types of certifications under SFI which include the forest, chain-of-custody, and sourcing while each area requires a third-party audit to achieve certification. The three different types of certification have their own criteria needed to be met in order to use the SFI stamp on their products. Though both programs are aiming for the end result of responsible forest management, FSC is the only type of wood to be recognized in LEED ratings. The programs are trying to ensure forests continue to contribute to their additional environmental benefits.

Trees do not require the use of a fossil fuel for their creation because they use the sun's energy to convert carbon dioxide to oxygen while storing the carbon. The fossil fuel use takes affect when the trees are harvested to be used as wood products. Companies have been using the bio-waste from the harvesting process as the primary energy source for their operation. After a tree has been harvested, 50% of the weight of the wood is carbon (Woodworks 2012). Wood is a "carbon sink" because it stores carbon until the point it begins to decompose meaning the more structures built out of wood, the more carbon is stored which in turn reduces the greenhouse gases in the atmosphere. With the depletion of non-renewable sources of energy, and global warming, the investigation of conserving these resources has become more pertinent. Engineered wood products are being looked at more seriously as a sustainable alternative to common structural systems. Engineered wood products are able to be built taller and denser than previously thought. The restrictions of the building code and the perceived fire potential have been restricting the use of wood as a primary structural material.

Wood has been used by humas for many millennia whether it has been used for a building material or to create a useful item. Among the oldest structures are the ancient Chinese timber frames dating back to approximately 7000 years ago (Liu 2002). Newer building materials emerged becoming stronger and more durable. The perceived fire danger of wood structures increased after a series of large fires that wiped out large portions of cities. The most well-known being the great Chicago fire of 1871 and the fire resulting from the 1906 San Francisco earthquake. These events have led to stricter building codes limiting the use of wood as a structural material. With new innovations in wood technology and safety testing, wood could be the primary structural material in larger and taller buildings than permitted by code today.

1.2 *Cross-laminated timber*

Cross-Laminated Timber (CLT) is an engineered wood product composed through laminating smaller pieces, approximately 20-60 mm (.75-2.5 in) in thickness, of wood together alternating the direction of the grain between layers in order for the panel to resist loading in both directions. CLT was first developed in the early 1990s in Austria and Germany. Recently it has been gaining popularity in residential and non-residential applications, mainly in Europe (Gagnon & Pirvu 2011). The panels currently on the market are being manufactured in a limited number of places in North America and Europe that allows CLT to be used in a few projects while experts are examining its performance.

The project type which CLT has been used in is mainly multi-family housing including towers up to nine stories tall (Gagnon & Pirvu 2011). Using CLT as the floor system being supported by glue laminated columns has also been used to construct parking garages (Crespell & Gagnon 2010). Since CLT is an engineered wood product it is restricted by building codes such as the International Building Code (IBC) that limits the height and square footage it can be used in, however there are proposals for using CLT to create high rise buildings up to seventeen stories. These will be held back until the building codes are adapted to allow for the use of CLT in larger structures. In order to change the building codes, CLT will need pass safety tests including fire resistant assemblies and seismic performance. These tests will need to show the material is capable and performing to a high standard of ratings.

1.3 *Strengths and limitation of cross-laminated timber*

CLT has multiple strengths including the ability to become its own seismic support/bracing, its ability to self-protect against fire, its lessened environmental impact, its renewable material source, but there are certain limitations to it as well. One of the primary misconceptions is since wood burns, unlike steel and concrete, it may not hold up as well in the event of a fire even though it is known steel bend in a fire and thus required additional fireproofing. Heavy timber assemblies or solid wood designs are able to reach the necessary fire resistance ratings for buildings types made out of non-combustible materials. The char rate of CLT has been tested at .67 mm per min (.02 in per min) (Gagnon & Pirvu 2011). Over the course of being exposed to fire for two hours the CLT panels will have experienced a loss of 80 mm (2.4 in) in panel thickness. If CLT is to be left exposed, adding an extra layer or two to the panel could result in having the equivalent to a two-hour fire rating. CLT is capable of having fire protection built into the aesthetic qualities of the panel.

Seismic performance is extremely important in regions of high seismic activity. Traditional structural systems need additional members and connections to integrate seismic design. Seismic design with CLT is completely controlled by the connections of the panels. Large scale tests have been performed by IVALSA (Trees and Timber Research Institute of Italy) on a seven story CLT structure in Japan (Crespell & Gagnon 2010). The structure was exposed to record earthquake simulations including the devastating Kobe earthquake (magnitude of 7.2 and accelerations of 0.8 to 1.2 g) with the result of moderate damage. The extent of the damage was found to be located around the connections. A few connections had failed, but overall the structure withstood the simulations and needed minor repairs for re-occupancy. The CLT structure showed ductile behavior and good energy dissipation mainly influenced by the mechanical connections used. CLT requires fewer materials for seismic design compared to traditional structural systems and performed well during seismic testing.

CLT acts similar to older load-bearing masonry structures that start wider at the base and when loads lessen begins to taper to a thinner wall at the top. Each panel thickness is capable of supporting up to five stories of structure. Keeping load bearing masonry design in mind, the thickest panel will be at the bottom of the overall assembly and every five stories gained in height, the panel thickness will reduce by one size. For a twenty-story tower, the panel size at the bottom will be a 9-layer panel, at floor six it would change to a 7-layer panel, at floor 11 it would change to a 5-layer panel and finally at floor 16 it would change to a 3-layer panel for the remainder of the floors. Even though columns tend to mimic this idea, they do not take up nearly as much floor space, nor do they begin to divide a building by having repeated structural walls. CLT's repetitive nature and modular pieces do make for a shorten construction time and require less labor. Since there are two trades required to assemble a CLT system versus approximately 12 for a post-tensioned concrete system, it leads to less confusion on site and a speedier assembly, which in some cases shorten the construction schedule by 50% (Crespell & Gagnon 2010). The installation of a single panel, measuring up to an approximate size of ten feet wide by sixty feet long, can be as little as 15-20 minutes. Murray Grove, a CLT housing development in London, was constructed by four carpenters in 27 days averaging 3 days per floor.

The distance CLT is able to span is one of its primary limitations. Using a five layer floor panel approximately 150 mm (6 in) thick has the capability of spanning 5.5 m (18 ft), while jumping up to the seven layer floor panel which is approximately 235 mm (9.25 in) thick has the capability of spanning 8.5 m (28 ft). CLT being a solid panel system and the limited spans lends this structural system towards multi-family housing rather than office or warehouse space. Wood transfers sound easily which leads to poor acoustical performance and another limitation of CLT. The acoustical performance needs to be increased through the addition of acoustical insulation, sleeper studs, and a wall covering. This increases the overall system thickness which leads to an assembly which is approximately 150 mm (6 in) thicker than concrete for an 8.5 m (28 ft) span.

2 METHODOLOGY

2.1 *Overview*

Through a two-phase process, opinions about the barriers to using CLT were collected from stakeholders involved with the design and construction of multi-family housing. Phase I consisted of a semi-structured group interview with Portland, Oregon based stakeholders sponsored by a local architecture firm that focuses on multifamily housing. Portland, the largest city in Oregon with the metro area containing of over 60% of the state's population, has a strong green building industry complete with local demand, a critical mass of firms specializing in green building, qualified employees, and a robust supply chain (Allen & Potiowsky 2008). Consequently, this study had a deep pool of experienced and knowledgeable green building professionals from which to draw. A questionnaire consisting of questions focusing on the barriers to using CLT included topics such as establishing performance criteria for structural systems in multifamily housing, barriers to the use of wood materials and CLT, information gaps, and the reliability of information sources. The primary goal of Phase I was to collect feedback on the questionnaire itself and identify participants for Phase II.

Phase II of the data collection consisted of an online survey to reach a wider range of stakeholders. A list of building and design professionals was generated based on feedback from Phase I, and a link to the survey was e-mailed to these individuals. The survey asked a series of questions to extract the exact reasons why CLT was not currently being specified for multifamily projects in the United States. The survey not only exposed the barriers inhibiting the products use but also educated the professionals making the decision on structural choice by providing information they may not have known. The questions have been aimed at specific items suspected of being the barriers. A question asked respondents to rank categories in order of importance with regards to choosing a structural system leaving the option open for the respondent to add additional categories they felt were not covered by the survey. Outlined in Section 3, the results of the survey have confirmed the need for existing research areas and established new topics for potential research.

2.2 *Participants and data collection*

All of the interviewees and survey participants for this study have experience with multifamily housing projects of different scales and are responsible for different aspects of specifying structural materials. Architects and engineers made up roughly two-thirds of all participants (Table 1).

Table 1. Fields of interview and survey participants for Phase I and Phase II of data collection.

	Architecture	Engineering	Construction	Developer	Other	Total
Phase I	7	1	1	0	1	10
Phase II	23	10	5	3	12	53
Total	30	11	6	3	13	63
Percent (%)	48	17	9	5	21	100

The responses to the online survey in Phase II were recorded over a period of three months to ensure an adequate number of responses. The results were downloaded to an excel spreadsheet and analyzed by discipline of the respondents to see if there were any trends associated with one over another. The survey and the spreadsheet of results are too large to be reproduced in this paper, but relevant findings are discussed in the following section.

3 FINDINGS

The survey results highlight a number of barriers to the use of CLT in multifamily housing including systems integration (fire-safety, acoustics, plumbing, electrical), aesthetics and information gaps. Of the professionals surveyed, 77% have heard of CLT, but only 58% of them knew the capabilities and attributes of the product. If they had not heard of the product or knew the attributes of it, they were provided a paragraph to read to help them gain an understanding to what the product was and its capabilities. With the given information and their own knowledge from working professionally, they were then prepared to answer the remaining questions. The majority of the remaining questions were asking for a yes or no answer in the comparison of cross-laminated timber and post-tensioned concrete in specific design areas. When asked if they felt CLT would be a viable alternative to post-tensioned concrete in multi-family housing, 92% answered yes, and 77% felt it would still be viable if codes were to allow its use in high-rise construction. This indicates professionals think a timber structure is capable of fulfilling the same structural need in high-rise structures.

When designing multi-family housing, many issues involving the integration of building systems and design considerations arise. Items such as acoustical values, systems integration, and architectural finishes are influenced by the building codes. The materials used for these items need to meet minimum requirements ensuring a minimum amount of satisfaction of the future inhabitants. Acoustical sound transference occurs in three different situations through multi-family housing: ceiling to floor, unit to unit through a common wall, and unit to public space along a corridor wall. Respondents answered if they felt CLT or post-tensioned concrete would perform better in each of these three situations. 49% felt CLT would perform better in ceiling to floor transmittance, while unit to unit and unit to public space transmittance had 63% and 54% respectively of the respondents answer the same way. The same comparison was asked of system integration and 58% felt CLT would perform better even though it is a solid wall system. 79% of the respondents felt CLT could be used as an architectural finish similar to how post-tensioned concrete is usually exposed on ceilings.

When exposing CLT as an architectural finish, since it is comprised of wood, fire performance is an important factor. When asked to compare the fire performance of CLT and post-tensioned concrete, 15% responded CLT would perform better in fire. The fire performance of a structure can be overshadowed by potential construction cost savings.

When evaluating a structural system, labor and materials are influential in the decision. According to the respondents, 19% felt labor savings was more important, 3% felt material savings was more important, and 58% felt they held equal value. The respondents were asked if they felt CLT would have a lower material cost and if it would require less labor to better understand how they though it would match up. 89% felt CLT would require less labor and 69% felt it would have a lower material cost. These questions had been aimed to understand the view on economic sustainability of CLT but questions were also asked about the environmental sustainability. The questions asked if they felt CLT or post-tensioned concrete would have a lower embodied energy or embodied carbon. 89% and 78% felt CLT would have a lower embodied energy and embodied carbon respectively. For a tabulated list of the responses broken down by field of employment please reference the chart in conclusions section.

The respondents were then asked to rank a number of factors, in order of their importance, when choosing a structural system for their project. The results are shown in Figure 1. This table indicates which factors have more influence when a decision is to be made on the structural system with "1" being the highest priority and "12" being the lowest. The results from this ranking question reinforce previous research about how green structural materials are selected (Griffin et al. 2010) with cost, building codes and seismic performance amongst the most highly ranked criteria.

Answer	1	2	3	4	5	6	7	8	9	10	11	12	Responses
Acoustical Performance	1	3	1	1	1	6	7	7	8	5	4	0	44
Fire Risk	4	6	6	11	5	8	2	6	0	1	0	0	49
Construction Costs	19	8	7	9	6	0	1	1	0	1	0	0	52
Building Codes	15	10	5	7	3	2	5	1	2	1	0	0	51
Appearance	3	2	4	0	6	5	6	8	3	8	1	0	46
Systems Integration with a Solid Wall System	1	4	2	3	5	3	4	2	13	5	0	1	43
Thermal Performance of the Envelope	6	2	6	4	5	11	7	5	1	0	0	0	47
Familiarity with System	2	9	5	4	2	4	3	4	4	10	0	0	47
Sustainability	3	7	3	2	10	7	7	7	1	1	0	0	48
Seismic Performance	10	9	12	6	4	1	1	1	4	1	0	0	49
Other	4	1	0	2	0	1	0	0	0	1	0	0	9
Other	0	1	0	1	0	0	0	0	0	0	0	0	2
Total	68	62	51	50	47	48	43	42	36	34	5	1	-

Figure 1. Survey results ranking structural system selection factors.

4 CONCLUSIONS

The number one barrier to any new movement is knowledge, and it appears there is an adequate awareness of Cross-Laminated Timber, but the results indicate a lack of knowledge on the attributes and capabilities of CLT. Once the respondents knew the capabilities of CLT they felt confident it could become a viable alternative to post-tensioned concrete in multi-family housing even in high-rise construction.

Fire performance was another response that illustrated CLT as the poorer performer even though respondents felt it could be used as an architectural finish. This could be interpreted as to say they are aware of the fire risk associated with CLT and realize it would perform worse than post-tensioned concrete, but knew there were fire mitigation strategies allowing it to be exposed. This is where current research would help inform them as to the newly understood fire performance of CLT. There are more current fire performance tests indicating CLT is capable of being completely exposed and having adequate fire resistance ratings to meet code requirements. Additional fire protection could be as simple as adding an additional layer to each side of the layers required for structural integrity. This would be able to give an additional hour of fire protection and could give another option for an interior finish.

The environmental and economic sustainability questions indicate CLT is believed to be better in both aspects. Not only do the majority of the respondents feel CLT will require less labor but also believe it will cost less. CLT requires only a crane operator and carpenters while on the other hand post-tensioned concrete requires pump men, workers to set up the formwork, lay the rebar and tensioning cables, and to pour the concrete. It also requires most trades on hand to set in the rough in spots for the various services needed within the building. CLT has a much simpler construction process than post-tensioned concrete, which comes through as construction savings. Similar to the construction process, CLT also had a simpler manufacturing process with the added benefit of carbon storage in timber. This leads to CLT to have a lower embodied energy and embodied carbon than post-tensioned concrete.

When ranking all factors in order of importance it becomes clear construction costs, building codes, and seismic performance rank as the number one factor for choice of a structural system. The cost is the reason why these three categories are the most important. These requirements determine how much of the budget needs to be allotted for the structural system, and any reduction of this allotment means money can be put into other areas. The fire risk and thermal performance categories round out the top five. These two categories dealing with the user comfort and their life safety have specific codes requirements, which cannot be changed. The codes and construction costs heavily influence the choice of a structural system, and any savings in costs while meeting code, will persuade professionals to choose one system over another.

Many of the potential barriers have been discussed. These have shown, in a few cases, CLT is a highly competitive material for primary structural use. In the sustainability for the environment movement, wood is being looked at more for its capabilities as a renewable alternative structural system. CLT, an engineered wood product, is being used over in Europe in buildings upwards of eight stories and proposals up to seventeen stories. The first building typology CLT would be used for in high-rise buildings would be multi-family housing. This typology presents many design issues, and understanding if CLT can hold up to the tests would be a large step in the direction of it becoming a renewable alternative structural system.

5 REFERENCES

Cole, R. J., & Kernan, P. C. (1996). Life-cycle energy use in office buildings. *Building and Environment*, 31(4), 307-317.

Crespell, P., & Gagnon, S. (2010). *Cross Laminated Timber: a Primer.* Vancouver, British Columbia: FPInnovations.

Gagnon, S., & Pirvu, C. (Eds.). (2011). *CLT Handbook: Cross-Laminated Timber.* Vancouver, British Columbia: FPInnovations.

Griffin, C.T., Knowles, C., Theodoropoulos, C., & Allen, J. 2010a. Barriers to the implementation of sustainable structural materials in green buildings. In: Cruz P, editor. *Structures and Architecture: Proceedings of the 1st International Conference on Structures & Architecture (ICSA2010)*. Guimarães, Portugal, 21-23 July 2010. 1315-1323.

Liu, X. (2002). The Qin and Han Dynasties. In N. S. Steinhardt (Ed.), *Chinese Architecture*. New Haven: Yale University Press. pp. 33-60.

Perez-Garcia, J., Lippke, B., Briggs, D., Wilson, J. B., Bowyer, J., & Meil, J. (2005). The environmental performance of renewable building materials in the context of residential construction. *Wood and Fiber Science*, 37, 3-17.

Woodworks. (2011*). Wood Design & Building Series: Wood and Carbon Footprint*. Tacoma, Washington: Woodworks. Available at: http://woodworks.org/publications/information-sheets/