Biological Durability of Cross-Laminated Timber—The State of Things

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Abstract

Cross laminated timber (CLT) is a mass timber product that is gaining popularity in construction within North America. CLT is made up of wood, a building material of biological origin. Therefore, these materials are at a risk of decay upon intrusion of moisture, a situation that could lead to loss of confidence in the material. Ensuring durability and optimum performance of building elements throughout their expected service life will require an understanding of the potential for decay and the possible consequences. This paper reviews the various possibilities of moisture intrusion in CLT, their potential effects on the physical and mechanical properties of CLT, and ultimately the associated biological decay risks. The paper concludes by enumerating variables that are critical and should be evaluated to completely understand decay in CLT panels, stemming from a thorough review of previous studies and methods used to evaluate decay in mass timber.

Timber construction is one of humankind's earliest methods of building. Woods (2016) suggested that many homes built over 10,000 years ago were constructed with timber as the primary construction material. A good example of ancient timber use is the Neolithic long house in Europe—a long narrow timber dwelling built in 6,000 BC. STREIF-Germany (2013) also claimed that timber framing techniques were historically used in countries like England, Germany, Denmark, France, Japan, and even parts of the Roman empire, although there was a proclivity to stone construction. The abundance of wood and lack of stone and necessary stonework skills in England, Germany, Denmark, and areas of France and Switzerland in the medieval and early modern times, meant that many of the buildings were framed with timbers split in half (STREIF-Germany 2013, Swenson and Chang 2020). The great cities of antiquity were, in fact, mostly composed of homes built out of untreated wood (Borràs 2010, Swenson and Chang 2020). As with any construction material, there have always been challenges with use of wood. In the Roman Empire, overcrowded cities, habitual use of firewood for cooking and heating, and the untreated nature of the timber used in buildings resulted in frequent fires (Borràs 2010). The combustibility of timber gradually led to decreased wood use in favor of the general use of fired-clay bricks as well as stone (including marble) in larger construction projects and created a negative perception about timber that remains until this day, especially in Mediterranean Europe. Conversely, timber remained important in Scandinavian countries and became the primary building material in the developing United States. A vast majority of all single-family residential dwellings in the United States are built with timber. However, the inability of timber to support heavy loads limited its use as building heights increased. Several major fires further enhanced the negative perception of timber in these applications. These issues led to limits on the height of timber-framed buildings, resulting in the dominance of steel and concrete in the mid-rise to high-rise sector (Borràs 2010, Brandner et al. 2016, Swenson and Chang 2020).

Mass Timber

Things changed in the early 1980s with the emergence of mass timber construction, whose roots can be traced back to

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Germany as a product known as Brettsperrholz (BSP). According to Brandner et al. (2016), these products were first described by Droge and Stoy (1981) for use in the web for solid web girders and then by Steurer (1989), who mentioned it in relation to timber bridge decks. The product name was translated to English verbatim to ''Cross Laminated Timber'' by Schickhofer and Hasewend (2000) and referred to as CLT. The emergence of this material created an avenue for timber to be used in taller structures (Harte 2017, Zhang et al. 2018) and intensive research on CLT began in Graz University, Austria, in 1990 (Brandner et al. 2016). A brief timeline for the product is presented in Table 1. In North America, the product was introduced in the early 2000s, mainly in Canada. A bilateral effort to standardize the product followed in 2010, led by APA-The Engineered Wood Association (United States) and FPInnovations (Canada), culminated with the publication of the ANSI/PRG 320 American National Standard in 2012. In 2015, a section with guidelines on the design of CLT was included in the National Design Specification (AWC, 2015) and subsequently in the 2018 International Building Code (ICC, 2017). This coincided with the award of Framework Project in the western United States by the US Department of Agriculture. The project is now shelved but it fueled essential research and testing activities around CLT. Sparked by the success of CLT and Mass Timber in general, the State of Oregon funded Tallwood Design Institute at Oregon State University to become the epicenter for mass timber–related research in the United States. Around the same time, the Wood Innovation and Design Centre at the University of Northern British Columbia, Prince George, Canada, became the first tall building to use mass timber products in North America while the T3 building in Minneapolis, Minnesota, was the first such structure in the United States and was completed in 2016. T3 building, however, used a nail-laminated timber, which is another class of mass timber product. Buildings such as the 8-story Carbon-12 in Portland, Oregon, the Brock Commons Residence Hall at the University of British Columbia, the 10-story Forte apartments in Melbourne, Australia, and the Mjstårnet Tower in Brumunddal, Norway, have since been built using CLT as their primary building material (Table 1).

Table 1.—Major milestones in the emergence of Cross Laminated Timber (CLT) as a mass timber building material.

Serial number	Major CLT milestones	Year
1.	First mention of Laminated Timber ('Brettsperrholz')—in Germany	1981
2.	Start of Intensive Research on CLT—in Graz University of Technology, Austria	1990
3.	First residential buildings with CLT—in Germany	1995
4.	First National Technical Approvals—in Austria	2002
5.	Introduction of CLT into North America	Early 2000s
6.	Development of Product Standard in North America (PRG 320)	2012
7.	Incorporation into the Canadian National Standard for Engineering Design in Wood	2014
8.	First CLT building in North America—Wood Innovation and Design Centre, Prince George, BC, Canada	2014
9.	Incorporation into the National Design Specification for Wood Construction in the United States	2015
10.	European Technical Approvals	2015
11.	Start of intensive research on CLT in North America	2015
12.	US Dept. of Agriculture announced winners of US Tall Wood Building Prize Competition—Start of Framework Project	2015
13.	International Building Code building category types modified to include mass timber and buildings up to 18 stories allowed (in print in IBC 2021)	2019

ANSI/APA PRG 320-2019 defines cross laminated timber (CLT) as a prefabricated engineered wood product made of at least three orthogonal layers of graded sawn lumber or structural composite lumber that are laminated by gluing with structural adhesives. CLT panels may be used alongside other mass timber products and find applications in floors and walls in buildings. The word ''mass timber'' refers to a group of framing styles that use large solid wood panels for construction purposes (Kremer and Symmons 2015, Robbins 2019). Some common mass timber products that complement the use of CLT include laminated veneer lumber (LVL), glue laminated lumber (Glulam), mass plywood panel (MPP), nail laminated timber (NLT), dowel laminated timber (DLT), parallel strand lumber (PSL), and other structural composite lumber (SCL; Parajuli and Laleicke 2018, CCA 2019).

Several factors explain the increased demand for mass timber buildings. The pre-engineered and prefabricated nature of these materials reduce construction time, ultimately saving labor and material costs (Parajuli and Laleicke 2018, Hanes 2019). The reduced foundation requirements for mass timber further decrease costs or allow taller buildings on a given site. Additionally, architects can create exceptional designs with these materials and the enhanced aesthetics contribute to the increased demand for these materials (Mayo 2015). Wood encouragement policies in the United States such as the 2018 Farm bill, the Timber Innovation Act of 2017, and other state policies have also promoted the use of more environmentally friendly construction materials (AWC 2018). Mass timber products are reported to have reduced environmental impacts compared with steel or concrete (Kremer and Symmons 2015, Evison et al. 2018, Scouse et al. 2020).

Mass timber products have good strength properties, acoustic and fire performance, and perform well under high wind or seismic loads (Amini et al. 2014, Kramer et al. 2015, Popovski and Gavric 2015, Barbosa et al. 2018, Muszyński et al. 2018, Van de Lindt et al. 2018, Blomgren et al. 2019, Pei et al. 2019, Fitzgerald et al. 2020). These studies have largely addressed concerns about the use of timber in taller structures.

One area of mass timber application and research has received less attention. All building materials degrade over time, but timber is a biological material that is sensitive to biological attack under certain moisture conditions. Designs that allow water intrusion or construction practices that lead to excess wetting can create conditions suitable for fungal and insect attack. Complicated architectural designs that result in cumbersome connection details can lead to extensive moisture entry and subsequent retention.

Mass timber elements have been used in Europe for over two decades, but the built environment there differs markedly from that in North America. Most of Europe has a cooler climate that is more forgiving in terms of building performance and much of the region has a low risk of seismic events. Despite the cooler conditions, there is emerging evidence that decay will occur in mass timber buildings in Northern Europe (Austigard and Mattsson 2020). Furthermore, termites are absent in most of Europe, whereas they are present in a large part of the United States as well as many other locations contemplating the use of mass timber in high rise construction. Transferring mass timber design and construction to North America required considerable effort to develop more appropriate connectors, alleviate fire concerns, and develop codes; however, durability remains to be conquered.

Common CLT Research Focus Areas

CLT received code acceptance in Europe in early 2000s and CLT use in low- to mid-rise structures grew steadily. Europe (except Italy) is not a region with high seismic activity, and therefore the performance of CLT walls and diaphragms was not well-studied when CLT entered the North American market. A growing body of research has led to increased levels of CLT adoption into US building codes and standards. Most recently, in 2018, the International Code Council approved 14 mass timber code changes, resulting in three new mass timber construction types with height limits varying from 9 to 18 stories (ICC, 2017). These changes are included in the 2021 International Building Code IBC. The height limit for a mass timber building and the extent of exposed timber will depend on the increasing level of fire protection used. Buildings between six and nine stories for example, will be required to have all exposed CLT elements designed for a 2-hour fire rating. Similarly, buildings between 9 and 12 stories will only be allowed to have limited amounts of exposed mass timber walls and ceilings (Havel 2018, Breneman et al. 2019).

These code changes were brought about by extensive research and stakeholder buy-in along the supply chain concerning the risk of fire (Kippel et al. 2014; Hasburgh et al. 2016, 2018; Muszyński et al. 2018; Shephard et al., 2020) and structural and connection performance (Pei et al. 2013, Amini et al. 2014, Popovski et al. 2014; Kramer et al. 2015, Popovski and Gavric 2015, Mahdavifar et al. 2017; Barbosa et al. 2018, Van de Lindt et al. 2018; Blomgren et al. 2019, Pei et al. 2019, Fitzgerald et al. 2020, Morrell et al. 2020). Fire-related studies have addressed issues regarding charring rate and the effect of wood species, ply configuration, and adhesives used to bond the panels. Connection and structural performance studies have focused on ensuring that building elements remain reliable and safe throughout their expected service life, damage is minimized during occurrence of a seismic activity, and damaged structures can be easily repaired. Durability and service life issues have been glossed over.

Durability research

While fire and structural performance have been extensively studied, durability has received far less attention. Although these panels are manufactured to resist large forces experienced in tall structures, their biological properties are no better than the parent material. There is an increasing recognition that moisture intrusion and its subsequent effects on durability must be considered in the use of CLT in high-rise structures (Gereke et al. 2011, Kordziel 2018, Wang et al. 2018, Zelinka et al. 2018, Kordziel et al. 2019, Riggio et al. 2019, Schmidt and Riggio 2019, Bora 2020). These studies established that moisture intrusion could cause dimensional changes in the panels and that certain moisture thresholds could result in biological degradation, but only a handful of studies (Franca et al. 2018, Mankowski et al. 2018) have examined the effects of biological agents on CLT properties.

Durability issues in timber—A brief review.—Construction materials are considered durable if they remain reliable, and resist external attack throughout their predicted service life (Van Acker et al. 2003). However, human activities coupled with natural processes can reduce the service life of structural materials (Achal et al. 2011). The cellulosic components of wood render it inherently hygroscopic, resulting in sorption and desorption of moisture depending on the surrounding climatic conditions (Militz 1993, Reinprecht 2016, Dungani et al. 2019).

Humans have long explored methods for improving timber durability. The earliest efforts involved the use of naturally durable species. The heartwood of these species contain chemicals or extractives that are toxic to or inhibit the growth of wood degrading organisms (Kirker et al. 2013, Kutnik et al. 2017, Verbist et al. 2019). Preservatives are used to enhance the durability of less durable wood species. These preservatives are generally toxic to the biological organisms and are introduced into the wood by spraying, brushing, or pressure to deliver the chemicals into the wood. The amount of chemical delivered and the depth to which it penetrates the wood determine the efficacy of the treatment process. Preservative treatments tend to work well with the sapwood of most species.

An alternative to traditional preservative treatment is to modify wood properties to reduce susceptibility to degradation. This process involves covalently bonding a chemical group to some reactive part of the cell wall polymers (Rowell 2006, Mantanis 2017). The resulting bond can create improved physical, chemical, mechanical, and biological properties. Chemical modification is particularly attractive because it offers better aesthetics, a uniform finish, potential property enhancement, and reduced maintenance without the use of pesticides (Kumar 1994). A number of wood modification processes have been studied but furfurylation and acetylation have shown the most promise (Mantanis 2017).

Although all these methods markedly improve timber durability, their use in the construction of mass timber buildings has been limited. Availability, consistent performance, and cost are key issues with naturally durable species. Natural durability varies with species, geographic regions, and growing conditions (Taylor et al. 2002, Viitaniemi et al. 2001, Kutnik et al. 2011), and there is increasing evidence that plantation resources of some traditionally durable species are less durable than those from native forests (Scheffer and Cowling 1966, Scheffer and Morrell 1998, Kirker et al. 2013). Limited availability of durable species, as well as potential effects on resin performance have also limited the use of these materials in mass timber. Preservatives have raised issues with architects because of concerns about their potential effects on nontarget organisms (Edlich et al. 2005). Chemically modified wood eliminates the concerns with other methods; however, it remains more expensive. As a result, most timber structures are built with kiln dried wood that is otherwise unprotected against biological agents of degradation.

Physical, biological, and chemical processes can all affect the service life of a timber structure (Previati et al. 2012, Verbist et al. 2019). Mechanical abrasion and general handling are common physical activities that can affect wood properties but are generally not a major cause of degradation. The exception would be applications where timber is subjected to repeated heavy loads such as use in railways. Timber can also degrade when exposed to excessive heat and, ultimately fire. Exposure to acidic and alkaline chemicals in industrial environments can also degrade wood. UV radiation from sunlight slowly degrades the timber surface in exterior exposures and, while the depth of damage is slight, it is a major cause of wood replacement (Singh and White 1997). However, biological degradation is the most common type of damage experienced in wood (Reinprecht 2016). Fungi, bacteria, insects, and marine borers can all degrade wood, but fungi are the most important agents of biodegradation (Blanchette et al. 1989, Highley 1999).

Fungi are heterotrophic and require organic material to survive. Although wood is more resistant to degradation than other biological materials, but some fungi have evolved systems to utilize this resource. Insects can also cause damage in specific environments, with termites being the most destructive wood degrading insects (Highley 1999). Bacteria are almost always present in wood, but their effects are generally minor except when wood is immersed in water for long periods. Bacteria can then slowly decay and weaken the wood (Highley 1999, Reinprecht 2016). Marine borers degrade wood in saltwater habitats. For the purposes of mass timber, they would not be expected to have any impact on performance.

Environmental and climatic conditions such as moisture exposure, temperature, pH, and time can all contribute to the rate of biological degradation in wood. Studies (Viitaneu 1998, Carll and Highley 1999) have established a temperature range of 23°C to 30°C as optimum temperature for the growth of most fungi. However, moisture is the most critical of all the factors. Direct wetting from splashes, spills, or floods can create moisture conditions that support biodeterioration. A moisture content of 26% is suitable to initiate growth of some fungi, but most fungi require moisture levels above 30% and many have optimum levels between 40% and 60% moisture content (Singh and White 1997, Wang et al. 2018, Verbist et al. 2019). Constant humidity conditions alone will not create these moisture levels, but they can help maintain moisture levels and contribute to fungal attack.

Durability in mass timber.—Mass timber elements create the opportunity to design larger structures capable of supporting higher loads; however, their basic building block is wood that remains hygroscopic. These materials may get wet during construction and may not dry sufficiently, creating conditions for the growth of biological agents. The issue of moisture intrusion during construction is often overlooked because there is an assumption that the materials will readily dry in service. There is increasing recognition that the rapid drying processes used in conventional timber frame structures can result in excessive cracking and deformation. Cappellazzi et al. (2020) noted that prevention will be far more cost-effective than attempting to repair large elements in a complicated building assembly.

Moisture intrusion.—Moisture intrusion is possible throughout the service life of any mass timber structure, making it essential that moisture does not reach levels that are detrimental to the structural health of the elements. Moisture intrusion is common during building construction depending on climatic conditions and the time it takes to completely enclose a structure (Lepage 2012, Kordziel et al. 2019, Schmidt and Riggio 2019). Locations such as uncoated edges and connections are particularly at risk of moisture accumulation (Schmidt et al. 2019), potentially leading to losses in physical and mechanical properties of the panels and connections (Sinha et al. 2020). Nairn (2017) noted that differential moisture expansion between individual lamina in non-edge-glued panels can propagate existing precracks, while natural cracks caused by residual stresses due to changes in moisture and temperature will form in edge-glue panels. These changes have the potential to affect mechanical properties such as shear modulus and Poisson's ratio as well as thermal and moisture coefficients (Nairn 2016). Apart from the formation of cracks, interlaminar stresses caused by differential swelling and shrinkage often result in physical deterioration such as cupping, checking, interfacial shearing, and possibly delamination (Schmidt et al. 2019). The mechanical properties of connections used in such panels might also be adversely affected. Silva et al. (2016) showed that every 1% increase in moisture content in the range of 12% to 18% led to a 1.8% decrease in withdrawal resistance of self-tapping screws in CLT. Prolonged exposure of panels to moisture during construction resulting in moisture contents above 30% could also create conditions conducive to fungal decay (Zabel and Morrell 1992). Thus, the benefits of moisture exclusion are clear, but numerous studies show that it is almost impossible to avoid some elements becoming wet enough during construction for fungal attack (Lepage 2012, McClung et al. 2013, Schmidt and Riggio 2019). Construction of mass timber structures during periods with low chance of rainfall, the use of protective canopies during construction, and delivering panels just in time could all help reduce the risk of wetting during construction (Schmidt and Riggio 2019, Cappellazzi et al. 2020).

Moisture intrusion in service presents a much great challenge because of the difficulty in locating leaks in a timely manner and effectively removing the moisture without adversely affecting panel or even structural integrity. Plumbing leaks, membrane failures, construction defects, and even moisture trapped during the construction phase can all lead to postconstruction issues. Austigard and Mattsson (2020) studied five in-service mass timber buildings and observed that construction error was responsible for moisture intrusion in four of the structures while leakage was the cause in the last one, with fungal decay present in three and mold growth in the remaining two. They also observed that drying took between one week and several months depending on the extent of wetness in the structural elements, the season of the year, and the presence of insulation and other drying barriers. McClung et al. (2013) discovered that the type of water resistive barrier used to enclose panels can be responsible for the rate of removal of moisture in wet elements. High-permeance materials tended to facilitate removal of trapped moisture; however, the drying rate was slow in low-permeance materials leading to prolonged conditions that favored fungal attack. Detecting moisture intrusion in service can be very difficult and cumbersome as a result of design barriers or sheathing that obscures surfaces where moisture might accumulate.

Prior research.—Biological durability studies of mass timber structures (Table 2) are limited, but a number highlight the potential for moisture intrusion, decay and loss in properties (Wang et al. 2018, Cappellazzi et al. 2020). Wang et al. (2018) documented the risks of biodeterioration in mass timber buildings and concluded that mass timber elements will most likely be degraded by either fungi or insects. The authors suggested that insects such as dry-wood termites, powder post-beetles, or old house borers that could tolerate low moisture levels or subterranean termites that could move up from the soil posed the greatest risk of aging mass timber. The authors concluded that the unique characteristics of wood in relation to durability must be considered to avoid issues in mass timber structures. Likewise, Cappellazzi et al. (2020) noted that moisture intrusion during construction of mass timber exposed it to the risk of fungal attack. Sinha et al. (2020) formulated a method to characterize the effects of biological decay on CLT connections, concluding that both the physical and mechanical properties of the connections could be affected but extensive research would be needed to ascertain the effects of time, wood species and fungi species on these properties.

Franca et al. (2018) studied the resistance of CLT, parallel strand lumber (PSL), and laminated veneer lumber (LVL) using mass loss over a 4-week exposure to termites and showed that untreated CLT was susceptible. A parallel study conducted by Stokes et al. (2017) showed that mold and decay fungi were visible in addition to termite attack, indicating that the parent materials in these products remained susceptible to degradation. These studies were of limited duration and need to be evaluated in longer term tests under more realistic conditions.

Mankowski et al. (2018) reported the initial results evaluating the effects of different treatment regimens on termite resistance of Douglas-fir (*Pseudotsuga menziesii*) CLT in proximity with the ground. The samples were protected from direct moisture using ventilated waterproof covers. Although the conditions created in this study were somewhat harsh because it is unlikely that CLT will be used in such proximity to the ground, the exposure represented more severe conditions intended to accelerate attack. No termite attack was observed after 6 months, but average moisture content had increased from 11.4% to 23.7%, approaching moisture contents suitable for fungal growth. The results illustrate the risk of moisture uptake, even if direct wetting is inhibited.

Singh et al. (2019) evaluated the resistance of radiata pine (*Pinus radiata*) CLT, LVL, and oriented strand board (OSB) exposed to *Oligoporus placenta,* or *Antrodia xantha*. Some samples were wetted using overhead sprinklers to simulate 3 months of rainfall exposure in Rotorua, New Zealand (NZ) while others were soaked in water. The soaking regime was designed to raise the moisture content of the samples above 25%. The samples included NZ-made OSB, US manufactured OSB, LVL, and boron-treated CLT subjected to leaching and soaking regimes as well as untreated CLT samples that were only subjected to the soaking regime. They found no significant differences in fungal growth as a result of the leaching or soaking regime; however, fungal growth in LVL was lower compared with the other materials

Table 2.—Findings from previous biological durability studies on mass timber.

Reference	Methods	Focus of research
Cappellazzi et al. (2020)	Literature review	• Reviewed the effects of moisture intrusion on the elements of mass timber. • Outlined methods to reduce moisture intrusion both during construction and throughout service life of the structure. • Proposed a collaborative research to study biological durability of mas timber.
Wang et al. (2018)	Literature review	• Outlined the risks of moisture intrusion in mass timber structures. • Identified all possible agents of decay in mass timber. • Identified possible methods to prevent decay in mass timber.
Franca et al. (2018)	Experimental	• Termites • Studied the weight loss of CLT, LVL, and PSL samples after a 4-week exposure.[a]
Mankowski et al. (2018)	Experimental	• Termites • Douglas-fir (*Pseudotsuga menziesii*) • Studied the effects of different termiticide treatment regimens on resistance of CLT samples in proximity to the ground.
Singh et al. (2019)	Experimental	• Fungi • Radiata pine (*Pinus radiata*) • Physically evaluated the resistance of different structural building materials including mass timber products to two different fungi species.
Sinha et al. (2020)	Experimental	• Fungi • Douglas-fir (*Pseudotsuga menziesii*) • Proposed a method to evaluate fungi decay in mass timber elements using physical and mechanical parameters.
Austigard and Mattsson (2020)	Field survey	• Fungi • 12 mass timber structures in Norway • Evaluated the cause of moisture intrusion in structures. • Evaluated the types and causes of damage present, if any. • Norway spruce (*Picea abies*)

[a] CLT is cross laminated timber; LVL is laminated veneer lumber; and PSL is parallel strand lumber.

possibly as a result of the elevated pressing temperatures and the pH of adhesive. OSB and untreated CLT showed little resistance to *O. placenta* while treated CLT samples were resistant regardless of leaching, but the authors did express concerns about the aggressiveness of the fungi employed. In a more recent study, Austigard and Mattsson (2020) identified *Gloeophyllum sepiarium,* a fungus well-adapted to large variations in temperature and heavy wetting as one of the fungi responsible for decay in outdoor elements of Norwegian mass timber structures and *Antrodia* sp. associated with decay in elements not exposed to outdoor conditions. This report highlighted the importance of protecting CLT elements used in balconies and galleries by water-tight layer and fittings, quick drying response to wetted elements, and the need for more research to understand the consequences of moisture intrusion in CLT.

Potential methods of decay evaluation.—Decay resistance in wood and wood products can be characterized using many different methods. Accelerated laboratory tests such as those described in American Wood Protection Association Standards E10 and E 30 (AWPA, 2020) as well as the European Normal Standard EN113 (CEN,1996)use small blocks of wood or wood-based materials that are conditioned and then exposed to standard decay fungi under controlled temperature and moisture conditions that favor active fungal attack. Decay resistance of the block is determined by the mass loss experienced over the exposure period. This method is simple, rapid, and accurate for small blocks of wood, but it is difficult to replicate with larger samples reflective of mass timber elements. Additionally, unlike solid lumber, CLT panels contain resin layers that may create barriers to fungal attack.

Field tests that expose specimens to outdoor conditions expected during the service life of a building have also been employed. These methods do not expose the wood to specific biological agents, but rather create conditions that are conducive to attack by fungi and insects (notably termites). Nondestructive methods are used to inspect the specimens and check for growth of any biological agents. The stake test (AWPA E7-15), decking test (AWPA E25-15), and horizontal lap-joint test (AWPA E16-16) found in (AWPA, 2020) book of standards are examples of these kinds of tests. Like the laboratory decay tests, evaluating decay using the field tests is simple and straight forward but the conditions in these tests in terms of moisture are far more severe than those likely to be present in a mass timber structure. There are several tests, which expose wood above the ground. The ground proximity test exposes specimens on concrete blocks, avoiding direct contact with the soil, and covered with a permeable shade cloth to give direct protection from sun but allow moisture intrusion. Although this method is simple, rapid, and efficient in evaluating decay in solid timber, the larger sizes and longer test times required for mass timber make replication difficult. In addition, visual ratings and mass loss in timber are major parameters used to evaluate decay, but these are inadequate for mass timber.

Although some aspects of the risk of degradation of mass timber elements can be inferred using small-scale testing, full-scale tests are still necessary. The difficulty with such tests is the large number of parameters (physical chemical, biological, and mechanical). The large sample dimensions required also limit the number of replications and tests generally take longer because the decay rate remains the same.

Research Needs

Research in the field of bio-deterioration of mass timber remains a work in progress and will require a great deal of attention to be fully understood. The engineering nature of the materials and their applications make them unique, hence requiring specialized methods. Proper research of decay in CLT will involve the following:

1. Creating methods that test samples representative of the scale of mass timber including elements such as unglued edges and bond lines. This will require decay chambers that are larger than the usual.
2. Simulation of realistic moisture intrusion cycles to initiate and sustain decay in the samples while avoiding excessive wetting.
3. Sterilization processes that eliminate contaminating fungi, do not adversely affect the mass timber properties, and still maintain moisture levels suitable for the growth of the test fungus.
4. Creating optimum temperature conditions, usually between 23°C and 30°C in the decay chamber, which are sufficient to initiate and sustain fungal growth throughout the period of inoculation.
5. Identifying a suite of methods beyond mass loss, including chemical tests, physical tests, and nondestructive imaging, to evaluate the changes caused by decay.
6. Creating moisture trapping conditions that closely simulate those likely to occur in structures, especially around critical connections.
7. A central data repository for free exchange of data and information among all major stakeholders.

Conclusion and Next Steps

Continued acceptance of mass timber for construction will depend on its reliability and long-term performance. Efforts should ensure that these products perform as expected throughout the service life of the structure. Decay development in structures will have obvious effects on structural properties, but equally detrimental will be a loss in confidence on the material within the design community. Understanding the effects of moisture intrusion on decay development will help better highlight the importance of moisture management and help engineers assess properties when moisture intrusion and decay does develop.

Wood species, fungal species, time, and building ecology constitute just some of the variables that need to be studied to comprehensively understand the risks of decay and its effect on mass timber properties. Although some wood species are known to at least exhibit some form of resistance against biological agents, others are easily degraded.

Comprehensive methods, which account for the sizes of mass timber elements and simulate the right decay conditions, must be used to replace the old methods, which create harsh conditions and are designed for small specimens. Visual evaluation of decay is insufficient and should be relegated to reliable methods, which adequately describe the changes that take place in mass timber.

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