DURABILITY OF MASS TIMBER STRUCTURES: A REVIEW OF THE BIOLOGICAL RISKS

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Abstract. Mass timber structures have the potential to change wooden construction on a global scale. Numerous mass timber high-rise buildings are in planning, under development or already built and their performance will alter how architects and engineers view wood as a material. To date, the discussion of material durability and biodegradation in these structures has been limited. While all materials can be degraded by wetting, the potential for biodegradation of wood in a mass timber building requires special consideration. Identifying and eliminating the conditions that might lead to this degradation will be critical for ensuring proper performance of wood in these structures. This article reviews and contrasts potential sources of biodegradation that exist for traditional wood construction with those in mass timber construction and identifies methods for limiting the degradation risk. Finally, future research needs are outlined.

Keywords: Mass timber, cross-laminated timber, durability, wood protection.

INTRODUCTION

Wood has numerous attributes that make it an attractive building material; however, building codes have often restricted the height of timber frame buildings because of concerns about fire and life safety. Evolving mass timber technologies have opened new opportunities to use wood in taller buildings. These efforts originally centered in Scandinavia and Central Europe but have more recently expanded into Australasia and North America (Karacabeyli and Lum 2014). Mass timber's attractions include excellent seismic performance, opportunities for prefabrication, cleaner and faster on-site construction timelines, substantial carbon sequestration, avoidance of fossil-fuel intensive materials, and the potential for improved building envelope thermal performance.

Virtually, all structures, regardless of the materials employed, eventually develop some type of moisture issue, resulting from vapor condensation, roof leaks, failures at building envelope penetrations such as doors or windows, and wicking from wet foundations. Wet materials of all types will harbor mold fungi on their surfaces, leading to air quality and aesthetic concerns. Water leads to corrosion of steel, a loss of connection between the steel and the concrete in reinforced concrete and wood-fastener connections, and to the biodegradation of wood (Eaton and Hale 1992; Zabel and Morrell 1992). Moisture is an essential element for all biological agents of wood.

The ability to manage moisture is an important aspect of maintenance of all buildings. Timber structures are no different in this regard, but the hygroscopicity of wood, coupled with the tendency for wood to wet far more quickly than it dries, makes moisture management in wood buildings especially critical.

To date, most of the mass timber buildings have been constructed in locations with low decay and few insect hazards, but this is rapidly changing as the market for these structures expands. We now see mass timber buildings being erected in places with higher risks of fungal and termite attack (Scheffer 1971; Carll 2009). Mass timber structures should be capable of providing excellent performance in these locations, but special considerations need to be made to ensure that the systems are properly designed, constructed, and maintained to avoid creating conditions that foster degradation. The purpose of this treatise is to summarize the potential biological risks associated with use of mass timber, identify presently available solutions, and then outline the research needed to improve the durability of these structures.

MASS TIMBER MATERIALS

Cross-laminated timber (CLT) has received the most attention because it is a relatively new development, but mass timber buildings can be built using a variety of materials. Solid sawn mass timber remains an option, but it is increasingly difficult to source large-dimension materials, and there are limitations on the heights to which such structures can be built. Instead, engineered wood products have become the backbone of the mass timber movement. The three most common structural elements in the buildings are glue-laminated beams (glulams), laminated veneer lumber (LVL), and CLT. Parallel strand lumber (PSL) and laminated strand lumber (LSL) are also employed in some areas.

For practical purposes, glulams and CLT have similar compositions, use cold-setting resins between lamina of softwood, structural-grade dimension lumber (ie 2 × 4's, 2 × 6's etc.). Glulams are large beams or columns, with all the lamina oriented in the same direction. CLT are fabricated as large panels and comprise layers of lumber that are oriented in alternating directions. LVL contains thin layers of veneers oriented in the same direction. PSL and LSL also contain multiple layers of thin veneers, but their geometry is more convoluted.

With the exception of exterior glulams, very little glulam or CLT is protected with conventional preservatives delivered using pressure treatment, as is commonly done, for example, with decking or fencing lumber. Similarly, most LVL receive no treatment except for glue line additives used for termite protection. Thus, all of these materials present unaltered wood with some resin. From a broad perspective, mass timber structures really harken back to the time of the log cabin with a multitude of potential water trapping features. Like log structures, glulams, LVL, and CLT materials generally wet and dry far more slowly than "stick-built" structures (traditional framing using dimensional lumber). This creates special challenges for architects, engineers, contractors, and those who are charged with maintaining these structures.

MOISTURE INTRUSION

Wood is hygroscopic and its MC varies with the temperature and RH of its surroundings (USDA 2010). In theory, wood moisture contents in protected interior exposures are of little consequence for biodegradation because, in the absence of liquid water, the moisture levels that develop are below those capable of supporting most microbial attack. However, manufacturing methods for structural lumber products can create pathways for moisture intrusion in service. For example, resin is only applied to the wide faces of most CLT manufacturing in North America, leaving pathways on the narrow faces of each element in the beam or panel for moisture ingress. The differing degrees of connectivity in LVL result in the ability of moisture to move between glue lines. The veneers also contain lathe checks that create pathways through each layer, but the thin nature of the veneers and the coating of all wide surfaces with resin should create fewer open pathways. There are several published sources for recommendations for moisture mitigation for CLT (Gagnon and Pirvu 2011; Finch et al 2013; Karacabeyli and Lum 2014; Wang 2016) in practice and as design criteria; however, poor moisture management during construction and building design features such as exposed, untreated wood, and water trapping connections may introduce liquid water. Moisture accumulation can also develop from vapor condensation and plumbing leaks inside the building.

All of the composites used in mass timber structures are manufactured at moisture levels at or below their in-service MC and are normally protected during storage and shipping. Once on a construction site, however, barriers can be removed or damaged, consequently exposing members to wetting.

In wood construction, wood tends to wet via exposure to liquid water but dries via evaporation. As a result, drying rates are often many times slower than wetting. Drying is often further delayed in modern construction by low vapor permeance membranes, thermal insulation, glue lines in composites, and sheathing panels (Singh and Page 2016; McClung et al 2014). One attractive aspect of mass timber is the potential to reduce construction time through prefabrication, which may reduce exposure to wetting. On the other hand, pressure to accelerate construction or failure to determine how much moisture has moved into the wood during construction may result in inadequate time to dry materials that are wetted on-site before enclosure.

Moisture exposure is common during construction in North America, and there is a perception that moisture entering a structure during construction can be easily removed naturally or through application of heat before finishing the interior. This may be true with dimensional lumber; however, CLT and plywood have markedly different wetting and drying rates. Wang (2014) exposed edge-sealed 3 ply spruce-pine-fir (SPF) CLT (boards 33 $\times$ 140-mm-wide with polyurethane adhesive), 13-ply LVL, and 19-mm-thick SPF softwood plywood to an hourly 5-s water spray for 18 d (delivering $\sim$35 L of water per specimen) in the laboratory or to natural weather during a 2-mo period in Vancouver, British Columbia, Canada. The MC of the plywood increased from $<$10% to more than 70% under both exposure conditions, whereas the LVL MC increased from 6% to 30% (Fig 1). The average MC of CLT samples also increased over the wetting period, but the increases were much smaller, moving from 12% before wetting to 24% after wetting. The results highlight that LVL and plywood have characteristics such as lathe checks that can channel humid air and water into the inner plies, leading to rapid wetting (Van den Bulcke et al 2011).

Another factor to consider with water intrusion is moisture distribution: MC in wood is rarely uniform. There will be pockets of wetness that might be capable of supporting microbial growth along with other regions where the wood is too dry for biological activity, and these may be located quite close to one another. This would be particularly important with CLT where the average MC was only 24%, but areas around nonedge glued joints might be expected to reach much higher moisture levels that could support fungal attack (Morrell unpublished data).

Redrying of wetted materials can also vary widely. For example, plywood samples with an impermeable membrane on one side went from nearly 80% MC to less than 10% in approximately 60 d (with no supplemental heating source that would encourage drying) (Fig 2). CLT samples did not start out as wet as the plywood, but their moisture loss rates were far slower. The moisture contents of CLT samples covered with the same membrane on the top were still greater than 15% at the end of the 180-d drying period and greater than 20% when the underneath surfaces were also covered with 3 in. of closed cell foam. These areas could be susceptible to mold or insect attack.

Longer exposures of CLT to natural rainfall resulted in increases in MC similar to the simulated exposures. Moisture sensors embedded deep within the panels showed that MC was elevated near the surface, but water did also penetrate deep within the panel where it would be more difficult to remove (Wang unpublished data).

Exposure of small panels can be useful for assessing moisture uptake, but there is no substitute for field performance data. To generate such data, moisture levels in an 18-story building in Vancouver, British Columbia, were assessed during construction (Fast et al 2016; FII 2016;

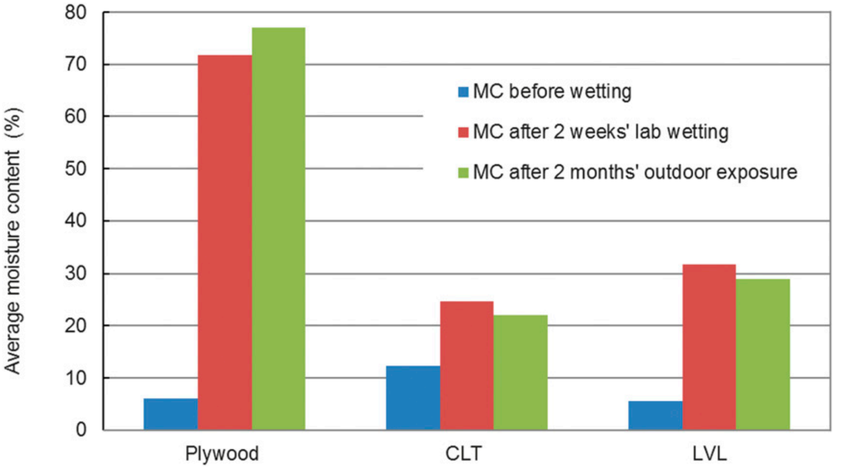

Figure 1. MC of spruce-pine-fir plywood, cross-laminated timber (CLT) and laminated veneer lumber (LVL) following an 18-d simulated rainfall exposure and 2-mo natural exposure in Vancouver (Wang 2014).

Wang and Thomas 2016). The building has 17 stories of mass timber construction sitting on a one-story concrete podium with five ply (169-mm thick) CLT floors point supported by multiple columns, mostly composted of glue-laminated timber, but with PSL columns on the lower floors.

Erection of mass timbers (glulam/PSL columns, CLT floors) started in early June and was completed in mid-August 2016. An average of two floors were erected every week by nine workers. The MC of the mass timbers was measured and information about on-site moisture protection was collected through periodic site visits (~2 wk) during both the dry weather typical of the summer and after rain events. There were a total of 31 rainy days and 124 mm of precipitation over the 71-d construction period. The weather during the construction was generally warm, dry, and windy, creating favorable drying conditions. These

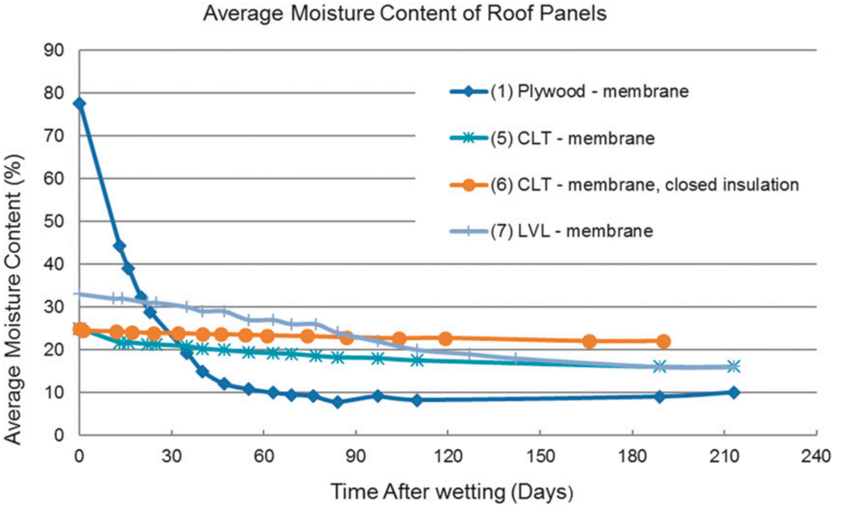

Figure 2. Moisture changes in spruce-pine-fir plywood, cross-laminated timber (CLT) and laminated veneer lumber (LVL) samples that were first wetted over an 18-d period then covered with a membrane and/or closed-cell foam before drying under cover (Wang 2014).

conditions would not be representative of the cool, wet winter conditions in this climate. MC was assessed on CLT floor panels immediately after installation, then 1, 4, and 14 d after heavy rain showers to assess the impact of a rain event on wood MC (Fig 3).

The measurements covered "normal" wood (ie no visible defect, away from end grain), end grain close to finger joints, and blue-stained sapwood of beetle-killed lodgepole pine. About 20 readings were taken 5-mm inward from the surface at random locations on CLT panels located in the southeastern part of each floor. Moisture levels varied slightly between floors, but the differences were small (2-4%) (Fig 4). Examination of moisture levels at selected times after a rainfall showed a slight increase immediately afterward but then a slow decline with time (Fig 5). It is important, however, to note that these measurements were only taken to a depth of 5 mm from the surface. Moisture levels further inward may increase more slowly, but drying rates in these zones will also be slower.

Some wood species such as spruces have inherent resistance to water uptake that should slow wetting, but even these materials will eventually sorb water to the point where biological attack can occur. Laminated beams or CLTs present a similar challenge to the uptake of liquid water, although abundant examples of decaying laminated beams clearly show that moisture will eventually reach levels suitable for microbial growth with continued wetting.

Mass timber elements will clearly absorb moisture during and after construction, although the rates will vary with composite geometry as will subsequent drying. These properties must be considered when materials become wet to avoid trapping moisture that will support microbial and insect attack.

BIODEGRADATION

As might be expected of a new product, there are few reports examining the durability of entire mass timber structures; however, the durability of mass timber elements in these buildings has been well studied. LVL, plywood, laminated beams, and PSL have all been assessed for their resistance to degradation in both laboratory and field tests (Winandy and Morrell in press). In

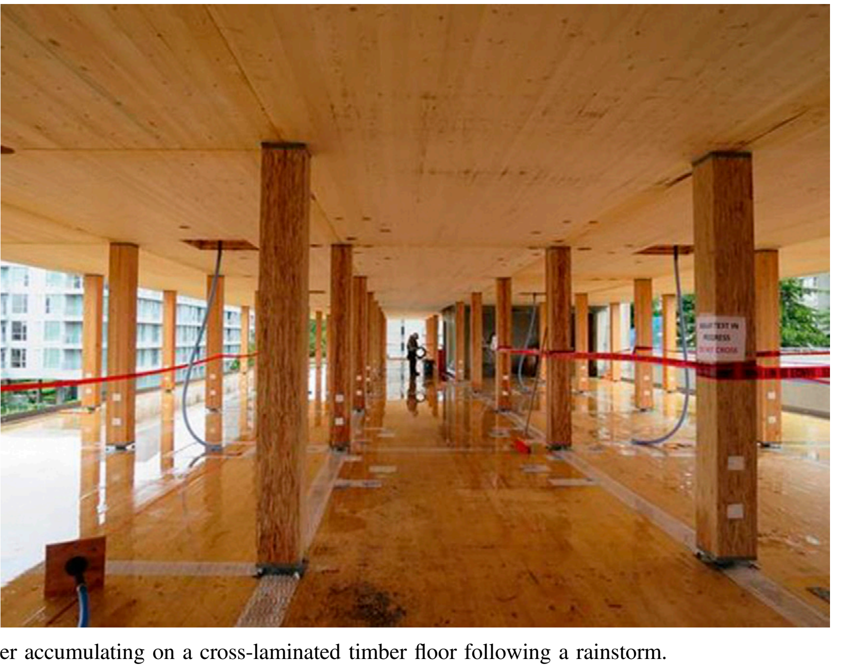

Figure 3. Water accumulating on a cross-laminated timber floor following a rainstorm.

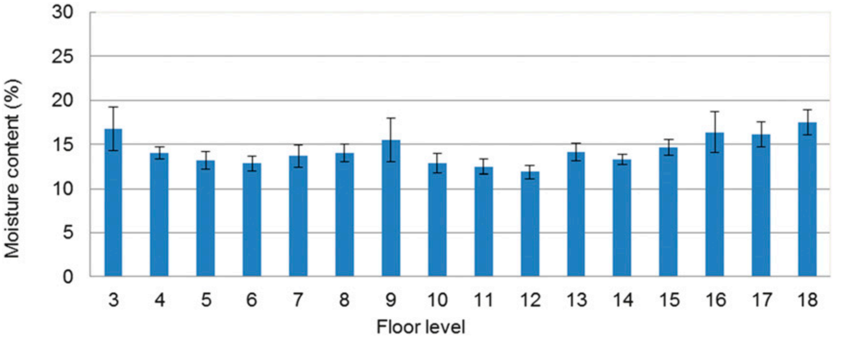

Figure 4. Moisture levels in cross-laminated timber panels on different floors during construction of an 18-story mass timber building as measured using electric resistance moisture meters (Wang and Thomas 2016). Error bars added to show that variations in MC were relatively small (Wang and Thomas 2016).

general, composite susceptibility closely parallels the degradation of solid wood substrate of the same species, although wetting also disrupts the wood/resin bond in many composites to the extent that it produces a permanent loss in properties before biological attack (Meza et al 2013; King et al 2014).

Mass timber elements can be degraded by many of the same organisms as solid wood, and it will be helpful to highlight the most important agents. The most common wood-degrading organisms are fungi, termites, postharvest beetles, and powder post beetles. As noted earlier, some moisture intrusion will be necessary for attack by most of these organisms. Postharvest beetles will not be considered herein because they are eliminated by the kiln-drying processes involved in production of these materials.

Fungi

Fungi are, by far, the most common agents of deterioration in structures and this is likely to be the case in mass timber (Mankowski and Morrell 2000). The risk of fungal attack can be considered in three sections: short-term wetting that encourages mold growth, prolonged wetting during construction that allows colonization by decay fungi that can survive for many years in the dry wood, and longer term moisture intrusion that allows decay fungi to degrade the wood.

Short-term wetting can lead to colonization by mold fungi, which grow primarily on free sugars in the sapwood and can produce copious quantities of pigmented spores in as few as 24-48 h (Robbins and Morrell 2017). There are thousands of potential mold species, and spores of these

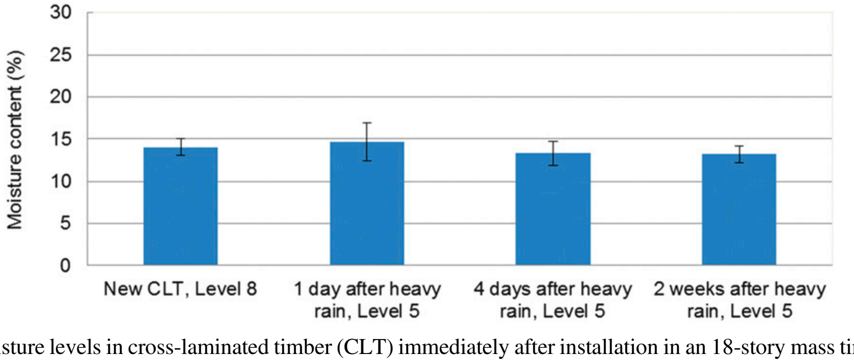

Figure 5. Moisture levels in cross-laminated timber (CLT) immediately after installation in an 18-story mass timber building compared with moisture levels 1, 4, and 14 d after heavy rain on level 5 as measured using a resistance-type moisture meter (Wang and Thomas 2016).

fungi are almost always present in the air, meaning that wood that remains wet (>20% MC on the surface) for any extended period is likely to be colonized by one or more species.

Empirical models to predict the risks of colonization by mold fungi have been developed for wooden structures and indicate that mold occurs when ambient RH ranges between 80% and 95% (Viitanen et al 2010). Molds do not appreciably affect wood properties, but their presence can cause public concern as many indoor molds have been found to be potential allergens. Molds are a constant concern for all buildings regardless of the materials employed (Ellringer et al 2000), and mold and related discoloration are an increasingly common cause for remedial treatment both during construction and in service. There have been a number of high-profile lawsuits about mold in buildings and the public generally has a low tolerance of its presence. Short-term wetting of mass timber elements or poorly controlled high-humidity conditions will ultimately lead to mold development. Mold damage can be removed and cleaned, but failure to eliminate moisture sources and to prevent continued mold growth can lead to user concerns about the relative serviceability of mass timber. Mold is also an excellent indicator of a moisture problem that may ultimately lead to decay.

Whereas mold fungi impact the cosmetic aesthetics and indoor air quality of a structure, decay fungi affect structural properties of the wood. Decay fungi require temperatures above freezing, the presence of oxygen, an accessible nutrient source (wood), and wood MC above the FSP (Zabel and Morrell 1992). An MC above around 26% and the presence of otherwise favorable conditions are generally required for decay initiation (Wang and Morris 2010), although most fungi grow more aggressively as the wood reaches 40-60% MC. The decay process is typically slow, with a long lag time where the fungus grows through the wood consuming readily accessible, nonstructural elements without causing appreciable or visible damage. This phase is followed by near linear losses in material properties as the fungus begins to degrade the structural polymers. Decay rates are typically a function of MC, temperature, and the wood species.

Many decay fungi are capable of invading mass timber (Duncan and Deverall 1964), but colonization will be most affected by wood characteristics and moisture. For example, some brown rot fungi tend to dominate in wood subjected to repeated wetting and drying, whereas others require more stable moisture levels. Under ideal conditions, brown rot fungi cause drastic reductions in strength in a relatively short time (upward of 40% strength loss with only 2% weight loss) (Wilcox 1978). White rot fungi such as *Trametes versicolor* are likely to attack much wetter wood, but tend to attack hardwoods and are likely to be less important in mass timber structures that primarily use softwood species.

One group of decay fungi that could be problematic in buildings are the true dry rot fungi: *Meruliporia incrassata* and *Merulius lacrymans*. Both produce root-like structures from soil to a timber above and can conduct water for long distances to attack wood that would otherwise be too dry to decay. Fortunately, mass timber buildings generally do not leave an exposed soil surface from which these fungi could grow. These fungi are also rare in most North American and Australasian light-frame buildings (Dietz and Wilcox 1997), but dry rot fungi should still be given consideration in CLT construction as under certain circumstances, they can cause extensive wood decay.

Oxygen, adequate temperature, and the wood food source are usually present in the built environment. As such, moisture control is generally the basis for controlling decay. However, it is highly likely that some areas within a mass timber structure will eventually experience some degree of wetting from plumbing leaks, failures of window seals, or moisture condensation. Many of these areas are concealed behind drywall or other facades that slow drying and make it difficult to detect excess moisture as well as fungal or insect attack. The inability to detect damage may allow moisture or biological properties to become much worse before they are detectable.

The potential for mold development during mass timber construction is mitigated by the fact that the wood is dry when fabricated (<15% MC), is usually covered in plastic during shipping, and on-site construction is rapid. Internal moisture after construction is much more difficult to predict or manage. Proper mechanical ventilation systems can reduce the risk of elevated humidity developing in a structure, but systems in hot/humid climates often operate below the dew point, encouraging moisture condensation on cooler surfaces. Leaks through improperly installed or deteriorated sealing around fenestration and from faulty plumbing represent examples of water sources that, in theory, never exist but that, in reality, frequently occur. These incidents can cause major damage, damage that may be particularly challenging in mass timber.

Factors that may affect decay rates of mass timber elements include dimensions of the element as well as the type of resin employed (Brischke and Meyer-Veltrup 2015). Larger elements will wet more slowly, but their drying rates will be correspondingly slower, creating more stable conditions for fungal attack. A final consideration will be how the various elements in a mass timber building are connected. Failure to create pathways for moisture egress will lead to moisture accumulation that may eventually reach levels capable of supporting microbial attack.

Insects

Insects commonly occurring in large pieces of untreated wood in structures can be divided into two general groups, the wood-digesting insects and the wood-using insects (Amburgey 2008).

Wood-digesting insects such as termites and the larvae of wood-boring beetles use wood as a food source for all or a part of their life cycle. The first mass timber buildings were built in northern Europe where there is little or no risk of termite attack. More recently, buildings have been constructed in North America, Australia, and southern China where termites are present (Jones and Eggleton 2010). Subterranean termites can be extremely aggressive, exploiting cracks in the foundation to migrate upward to attack untreated wood. Termite attack in mass timber buildings may be particularly problematic because it will be difficult to detect without some form of intrusive inspection. Protection using either chemical or physical barriers will be essential for performance of structures build in areas with high termite pressure (Morris 2000).

The two most important termite groups likely to attack mass timber are subterranean and dry-wood termites, but it is important to remember that there are other regionally specific termite species that must be considered in design and maintenance. Subterranean and dry-wood termites are both present in North America (Fig 6) and pose a significant control challenge. Of these two groups, the subterranean termites are the most destructive, and their wide distribution in the United States makes them an insect of critical concern for the use of mass timber.

Subterranean termites (Rhinotermitidae) generally cause more severe damage to wood in service than dry-wood termites. Su (2002) estimated that annual economic damage by subterranean termites worldwide was 22 billion dollars. Subterranean termite workers randomly forage through the soil and generally establish colonies in buildings by entering from ground nests after the building has been constructed. *Coptotermes formosanus* (Shiraki), the Formosan subterranean termite, is an introduced species in the United States and also moves from the ground upward, but this species has also been shown to initiate aboveground infestations in structures where wood remains wet for prolonged periods, such as from roof leaks. Thus, mass timber could be prone to aboveground attack by *Coptotermes* if moisture levels are sufficient for flying reproductives ("alates") to initiate a colony. Telltale signs of subterranean termite presence aside from damaged wood include earthen tubes or runways built by these insects over the surfaces of the foundation or other exposed areas to reach the wood above. Detecting active infestations in mass timber structures may be challenging, both because of the complexity of the structures as well as the need for drywall sheathing (to meet certain

Figure 6. (a) The northern limit of recorded damage done by subterranean termites in the United States; (b) the northern limit of damage done by dry-wood termites (Moore 1979). Note: Termite damage has also been noted in southern British Columbia and Ontario, Canada (PI Morris, FPInnovations, Vancouver, British Columbia, Canada).

fire code requirements) that would block visual access to evidence of termites. As with fungal attack, moisture exclusion can play an important role in limiting potential subterranean termite attack. As with other timber structures, termites can best be controlled using multiple lines of defense (Morris 2000). The use of chemical (soil termiticide) and physical barriers (steel mesh/granular soils) beneath the structure or treated wood are required in the building codes where termites are present (IRC 2015).

Dry-wood termites (Kalotermitidae) nest in wood with low MC and thus could potentially be a problem for untreated CLT in service. Dry-wood termites can live in wood without exogenous moisture. Colonies of these termites are generally smaller than subterranean termites, but dry-wood termites can cause considerable localized damage because they are difficult to detect and reinfestation often occurs. In the United States, dry-wood termites only occur in a narrow strip of territory extending from central California around the southern edge of the continental United States to Virginia (Fig 6) and in the West Indies and Hawaii. They can be excluded by screening of vents and other openings, but are difficult to detect once they invade a structure. If a dry-wood colony is found, spot treatment with a chemical insecticide can be effective if the reproductives are killed; however, because of their cryptic habits, treatment for dry-wood infestation often involves tenting and fumigation of the entire structure.

The second important group of wood-digesting insects is the larvae of wood-boring beetles. There are species in several beetle families that undergo larval development in dried wood, but we will focus on the beetle groups that attack softwoods: The ptinids or furniture beetles (Bouchard et al 2011) (formerly Anobiids) and the cerambicids (or longhorn beetles). Their life cycle takes 2-3 yr to complete, and they require wood moisture contents between 13% and 20% for viable infestation (Moore 1979). Moisture contents in most modern buildings are generally too low for ptinid beetle development, but wood components can reach moisture conditions favorable for attack if ventilation is inadequate or in more humid regions of the United States. This is especially a problem in air-conditioned buildings where water condenses on cooled exterior surfaces. Susceptibility to beetle infestation can be alleviated by lowering the MC of wood through improved ventilation, dehumidification, and the judicious use of insulation and vapor barriers. Insecticides such as boron, pyrethroids, or imidcloprid are used to remediate infestations along with fumigation.

The old house borer (*Hylotrupes bajulus* [L.]) belongs to the Cerambicidae and is the only member of this large beetle family that infests seasoned wood. The preferred wood MC for *Hylotrupes* larvae is 15-25% (Amburgey 2008). The degree of risk in a structure will likely depend on the wood species involved. For example, southern pine, with its high proportion of sapwood, may be much more susceptible to this type of damage than Douglas-fir or SPF, which have proportionally higher levels of heartwood. Glue lines in some composites are also likely to limit attack, rendering materials such as LVL less susceptible to attack than CLT or laminated timbers.

Powderpost beetles and old house borers may not become an immediate problem in mass timber because they tend to attack wood that has been in service for longer periods of time, but they may become more important as the building ages.

Wood-using insects do not use cellulose as a food source, but instead excavate wood as a substrate to live in. Examples include carpenter ants and carpenter bees. Carpenter ants (Formicidae; *Camponotus* spp.) commonly occur in colonies in stumps, trees, or logs. Their presence in mass timber structures will likely depend on building location with structures in more forested areas more likely to see infestations. In general, carpenter ants prefer higher MC wood, but as a colony grows in size, they may eventually mine the surrounding sound wood. Carpenter ants readily initiate viable colonies in lower density nonwood substrates such as Styrofoam insulation that is commonly used in many building applications (Mankowski and Morrell 2011). In some cases, the presence of nests can be indicators of associated moisture and fungal attack. Although carpenter ants are not likely to cause massive damage to structures, their presence can be an annoyance and will likely require some thought in design to mitigate against possible attack.

Carpenter bees (Formicidae; *Xylocopa* spp.) chew 12- to 17-mm-diameter tunnels into uncoated softwood for nests (Amburgey 2008). Carpenter bees reuse the same tunnels each year, and eventually, tunnels can become several centimeters long. Holes may extend the full thickness of the wood in thin wood, such as siding. Exposed uncoated wood in mass timber structures would be especially attractive to carpenter bee attack. Old bee galleries could also potentially be attractive to other wood-destroying insects, particularly flying termite reproductives.

The potential for insect attack has long been a part of specifying engineered wood products such as glulam, LVL, and PSL and led to incorporation of treatments where necessary. These same pre- and postfabrication processes could be potentially applied to mass timber (Smith and Wu 2005).

PREVENTION

The current building code is particularly good at reducing conducive conditions. The height above grade, slope of grade away from structure, and insulation requirements all help to mitigate wet conditions that support the development of wood-destroying pests. The risk of subterranean termite attack and the susceptibility of the sill plate to decay fungi are also addressed by building code. However, the remediation of homes in North America for all wood-destroying pests is a multibillion dollar industry. Repair of mass timber buildings will be especially challenging because of the difficulty in accessing elements and the large size of the individual members. Thus, preventing deterioration will be especially important in these structures. There are a variety of existing approaches to prevention that may be suitable for specific elements in a mass timber building.

Natural Durability

Mass timber products are usually produced from the same softwood species used for structural applications. In North America, this includes Douglas-fir, hemlocks, spruces, pines, and true firs (*Pseudotsuga menziesii*, *Tsuga* spp., *Picea* spp., *Pinus* spp., and *Abies* spp., respectively). These species have heartwood with low to moderate natural resistance to fungal and termite attack (Scheffer and Morrell 1998). Although some other "naturally durable" softwood species contain heartwood that is highly resistant to fungal and termite attack (Arango et al 2006), these species typically are more costly and most have lower mechanical properties (Line et al 2005). Extractives in some naturally durable heartwoods may also interfere with adhesive performance (Hse and Kuo 1988) or accelerate fastener corrosion (Zelinka and Stone 2011).

The moisture absorbing and desorbing properties of wood species and types (eg sapwood vs heartwood) can markedly impact the amount of time wood MC exceeds fiber saturation under fluctuating environmental conditions. Some woods naturally take up liquid water more slowly and desorb more rapidly (Morrell and Francis 2008; Van Acker et al 2014). The use of moisture-resistant woods such as western red or Alaskan yellow cedar may be one strategy for limiting moisture ingress, but would not be completely effective in protecting wood exposed to long-term wetting (Morris et al 2011).

Barriers

There is considerable interest in the use of physical barriers to protect untreated wood from fungal or insect attack and a variety of membranes are presently used to protect exposed elements from moisture intrusion. Barriers can entail a wide range of materials including simple paint films, water repellents, urethane coatings, and a host of other water-shedding materials. Barrier technologies continue to improve, but ultimately, these approaches must be used cautiously because these materials rely on proper application, have limited service lives, and must be maintained to remain effective. There is considerable need for further research on the ability of barriers to limit moisture ingress into mass timber structures, as well as the ultimate service life these barriers may provide. Barriers can also, in some circumstances, exacerbate moisture problems by retarding drying of wet wood.

Preservatives

Adding chemical preservatives is the most common method for improving the durability of wood structural materials that are suitable for exterior exposures, including fencing, decking, and utility applications such as poles and railway crossties. Oil-borne products such as creosote, pentachlorophenol, or copper naphthenate are often used for industrial applications; however, these would be unsuitable for mass timber buildings. Water-based preservative formulations are available for residential applications where surface cleanliness is important. Waterborne systems generally use copper as the primary protectant, with secondary organic biocides to protect against copper tolerance. Colorless, completely organic biocides are also available for nonsoil contact exposures. Boron is also colorless and would be suitable for this application, if used where it would be protected from leaching.

Wood structural elements for interior applications generally do not receive preservative treatment (with the exception of sill plates), on the assumption that wood will remain dry and thus resistant to attack by insects and fungi. Damaged wood in conventional light-frame homes is also relatively easy to access for repair. The assumptions associated with conventional wood buildings have, thus far, also been applied to mass timber. However, there are precedents for the preservative treatment, including by pressure processes, of interior wood structural members, for example, in Hawaii, which has severe termite risk, and in New Zealand, where the fungal decay risk is high and the decay resistance of the timber is low. There is also an increasing market for either pretreated framing or posttreatment spray on applications of framing to protect against decay and insect attack, although these treatments are not required in the building codes.

There are various ways that preservative chemicals could be added to mass timber elements, including dip-diffusion, as a glue line additive and pressure treatment.

Treatment Methods before Layup

Dip/spray. One potential method for limiting biodegradation of mass timber elements would be pre-layup immersion of individual members in a water-diffusible biocide. The most likely treatment for most composites would be boron, which has a long history of successful use for limiting both fungal and insect attack (McQuire and Goudie 1972). Boron can diffuse with small amounts of free moisture and is active at low concentrations in the wood. In principal, a boron solution could be sprayed on lumber, allowed to diffuse inward, and then the surface would be lightly sanded before resin application. The resulting panels would contain small amounts of boron that would be available to inhibit fungal attack in the event the panel was wetted in service. However, the levels required for long-term protection in wood subjected to repeated wetting would be difficult to achieve with a spray-on treatment. The approach would also require evaluation to ensure that the treatment did not adversely affect resin curing or the resulting bond properties.

Pressure treatment. These systems use vacuum alone or vacuum/pressure cycles to deliver chemical more deeply into the wood. Such systems would likely be used to impregnate individual pieces before layup because of the large size of the finished product and the potential for waterborne preservative treatments to swell the wood. Pre-layup treatment also carries with it issues including the need to plane or sand samples before gluing to ensure proper bonding and the need to dispose of treated wood shavings.

The American Wood Protection Association (2016) has developed standards for wood preservatives and treatment for glulams and other composites and is presently working to develop standards for other mass timber materials such as CLT. In many cases, pressure treatment may be more than is needed to protect the timber if the wetting is limited and is likely to be detected within a few months.

Dip- or spray coatings applied after manufacture. Mass timber elements could potentially be treated with low moisture uptake, dip-diffusion or spray-on treatments. Such treatments could provide effective surface protection against mold, but would require significant penetration to be effective against decay and termites (Stirling and Morris in press). The degree of penetration achievable would depend on the wood species, the preservative formulation, and also upon the nature of the product (ie dimensions, number of lamina, and number of glued faces).

Glue line additives. Glue line additives have long been used to protect composites from insect attack. These treatments are added to the resin shortly before application and provide barriers against termite and beetle attack. However, glue line treatments have primarily been used for products composed of veneers or strands with a high surface area to volume ratio. They are unlikely to be effective for CLT because the treatments lack the ability to move out of the resin and into the surrounding wood for substantial distances. The potential for introducing fungicides into the resin that can be mobilized in the event of wetting merits further study.

Modified wood. There are a number of strategies to alter the chemistry of the wood to change its moisture behavior or reduce its suitability for fungi or insects.

Thermal modification has been reported to improve the dimensional stability, reduce hygroscopicity, and increase decay resistance (Esteves and Pereira 2008). However, it can also reduce mechanical properties (Boonstra et al 2007; Aro et al 2016) and does not improve resistance to termites (Shi et al 2007). Because larger pieces require longer heating times because of the gradient in heat transfer, mass timber would likely be fabricated from wood that was thermally modified before layup. It would be important to confirm that the process did not negatively affect bonding.

Chemical modification involves the reaction of a reagent with the wood polymeric constituents, resulting in the formation of a covalent bond between the chemical and the substrate (Hill 2006). The two most common forms are acetylation, where acetic anhydride is reacted with wood, and furfurylation, where furfural alcohol is polymerized in the wood (Lande et al 2004; Hill 2006). Both products are produced in Europe and have limited availability elsewhere. Chemically modified wood may be suitable for mass timber applications, but a thorough understanding of the material properties as a result of the modification is critical to ensure maximum longevity and utility of the material. Chemically modified wood may have reduced swelling, improved biological resistance, and improved weathering performance, but this can come at the expense of bond strength and other mechanical properties (Rowell 1996; Rowell et al 2009; Ringman et al 2014; Zelinka et al 2016). Modified wood is also substantially more expensive than unmodified wood or wood treated with traditional preservative systems. Guidance documents have been created to describe the data necessary for standardization of thermally and chemically modified wood (AWPA 2016). However, these documents do not consider their application in mass timber products.

DETECTION OF MOISTURE AND BIODEGRADATION

Detecting moisture and biological attack in mass timber structures before damage occurs will be a major challenge because of limited exposed wood surface area and the potential for most of the wood to be hidden from view behind facades or drywall. There are a variety of strategies for detection including moisture-sensing systems, regular visual inspection, and nondestructive evaluation (NDT).

MC Monitoring

Elevated humidity and wood MC levels can be detected using a variety of electronic equipment. Humidity controls are a standard component of air-handling systems and wood moisture meters are available as portable or stationary units. Such sensors have been incorporated in some mass timber structures already; however, as noted earlier, MC can vary widely within and between wooden elements in the same structure, so there will always be a risk that moisture problems exist that are not being detected. Mass timber buildings in areas with a high risk of decay or insect attack could be constructed with built-in sensor systems so that conditions conducive to biodeterioration are detected long before they become a problem.

Visual

Visual detection of moisture and biodegradation problems in wood structures is problematic. Mold problems may be visible, but the elevated moisture conditions that facilitate mold growth may not be. Also, visible wood surfaces are more likely to dry rapidly. Enclosed, invisible spaces are more likely to harbor elevated moisture levels and thus experience fungal growth. As mentioned earlier, fungal decay can be well advanced before visual change is evident. Finally, termites, the most serious insect pest problem, normally avoid exposure to dry or drying conditions and thus are usually not seen (except during alate production).

NDT

A variety of NDT techniques have been developed to help detect wood deterioration problems and to estimate residual structural integrity. Technologies employed include sound wave transmission, resistance to drilling and puncturing, and ground-penetrating radar (Ross and Pellerin 1994). Some of these technologies are likely applicable to mass timber structures, but their focus is on assessing problems after they have occurred (ie for remediation). Another NDT method may be thermal imaging using IR spectroscopy which detects changes in temperature that may reflect moisture intrusion. Although none of these techniques detects actual infestations, they identify areas of concern. This would allow an inspector to target the areas most likely to have conditions conducive to biological attack for further investigation.

Prevention of Wetting during Construction

Mass timber may be vulnerable to mold during construction when the building is not complete and components are exposed to precipitation under limited drying conditions. Risk can be minimized by protecting mass timber from precipitation during transportation, on-site storage, and construction. Plastic wraps are often used to protect individual components during transport and storage, but these barriers must be at least partially removed during construction, creating the risk of moisture intrusion. Coatings may also provide some short-term protection against water ingress. In some cases, all or part of the construction site may be protected from precipitation by a temporary tent. This approach is rarely employed in North America, where the more common approach is to allow moisture to enter during construction, but then to apply heat to accelerate drying after the building is closed. This approach works well with dimension lumber that has a much higher surface to volume ratio, but may be less effective on mass timber, with its relatively slow drying rate. An alternative or complementary approach could use surface-applied moldicidal treatments to protect mass timber during the construction phase. This protection could potentially extend in-service depending on the concentration and stability of the treatment employed.

RESEARCH NEEDS

Mass timber has tremendous potential to create sustainable structures while sequestering carbon and creating rural employment opportunities; however, it is critical to recognize that these structures still consist of a biological material that can degrade. These are a number of areas where further research is needed to develop better methods for protection and identify improved monitoring techniques.

- Data on moisture loads for mass timber during wet-weather construction in a variety of climates as well as drying rates: Most of the information on moisture behavior during construction has been generated under laboratory conditions or during fair-weather construction.
- Influence of building design on moisture intrusion: Although architects learn detailing, they also create designs that tend to expose wood to wetting. Data illustrating the effects of these designs on wetting could be incorporated into undergraduate programs.
- Data on moisture loads for mass timber during wet-weather construction in a variety of climates as well as drying rates: Most of the information on moisture behavior during construction has been generated under laboratory conditions or during fair-weather construction.
- Low-cost, whole-building monitoring for moisture intrusion: Very limited work has been done on moisture intrusion in mass timber systems in service. This is nontrivial because it is virtually impossible to instrument an entire building or to predict where moisture intrusion occurs. The development of low-cost sensors as well as models that help engineers to determine where best to place sensors in a structure would allow for earlier detection of moisture issues.
- Effects of decay on properties of mass timber: Decay of a single stud in a light-frame building has minimal effect on building integrity, but similar damage to a post or cross-brace can seriously jeopardize the structural integrity of a post and beam system. The effect of lost cross-sectional area on glulam strength is reasonably easy to calculate, but the effects of decay on CLT are more difficult to predict, particularly at the early stages of development. It is likely that early decay may not appreciably alter the performance characteristics of a structure, but developing data will be critical for maintaining consumer confidence in the structure.
- Coatings to limit moisture uptake during construction: Some construction companies are using coatings, but many breathable water-repellant products have not been tested sufficiently to allow informed, objective recommendations to be made to practitioners.

- Methods for pretreating mass timber members (veneers or laminates) before layup: These products likely will not require heavy-duty wood treatment to limit the risk of fungal or insect attack, but there are no data on the performance of barrier-treated elements in these types of composites.
- Novel preservative treatments for finished CLT panels: Surface-applied treatments that penetrate into the wood may be the best approach; however, these products need to be capable of penetrating a wide range of species including refractory woods.
- The performance of hybrid systems: There is considerable interest in using chemically modified wood in CLT, but the costs for including these materials in the entire structure would be prohibitive. Using these products on only the exterior might provide some protection, but research is needed to confirm that this approach does not inadvertently lead to a difficulty detecting and remediating internal decay/insect issues.
- Gluing-treated lumber into mass timber without planing: Research to date has not provided a simple method for bonding-treated lumber without removing the well-treated surface and producing treated planer shavings.
- Methods for detection of decay and termite attack in mass timber systems: There are a variety of traditional methods for detecting decay in light-frame buildings, but most will be less effective in mass timber. Methods for detecting damage in utility poles and large timbers may be more appropriate than those developed for light-frame systems; however, interior and exterior wall layers may make it more challenging.
- The effects of moisture intrusion on mass timber integrity: Wetting above the FSP has well-known effects on glue line bonds, but these effects remain understudied in many mass timber elements. Understanding the effects of wetting on long-term performance will be critical for assuring specifiers and architects that these buildings will perform as intended.
- Remedial treatments for mass timber systems: Suitable methods of application are needed to reduce the cost of and time involved with drilling numerous holes into a structure along with techniques to ensure rapid penetration of remedial treatments to all the vulnerable parts of a mass timber structure that has been exposed to conditions conducive to fungal and/or termite attack. Mold damage will be the most common occurrence in these structures. Eliminating the conditions that allowed the fungus to grow is relatively simple, but cleaning up afterward poses a challenge. Eradication of termites will also pose a challenge because it may be difficult to deliver treatments to active colonies deep inside a building element. Baiting systems are not effective for dry-wood termites and may be less effective for Formosan subterranean termite colonies associated with plumbing leaks because workers would not need to forage outside the timber component nor would there be a connection to the soil, where traditional bait systems are employed. Fumigants such as sulfuryl fluoride, if still a valid option in the future, will be slower to penetrate mass timber than light-frame structures where they are commonly used.

CONCLUSIONS

The development of mass timber structures has the potential to revolutionize the use of timber in buildings. However, failure to take into account the unique characteristics of wood related to durability could sharply curtail interest in these structures. The successful use of mass timber in North America will require architects, engineers, manufacturers, and construction personnel to come together to craft systems that minimize the risk of moisture intrusion and accumulation. These systems will include moisture protection in transit and during erection, careful design to create water-shedding surfaces, proper installation of mechanicals to avoid moisture accumulation, proper use of membranes and other water-shedding devices, the use of more durable wood materials where appropriate, and regular maintenance to ensure that all of the elements continue to perform as expected.

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