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Decay Performance of Cross Laminated Timber Connections

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ABSTRACT: The effect of brown rot decay fungi on mechanical properties of Cross Laminated Timber (CLT) connection assemblies was investigated. CLT connections evaluated were assembled with US code approved angle bracket connectors and modelled floor-to-wall systems in mass timber buildings. Physical changes, mass loss and quasi-static cyclic tests were used to assess the performance of connection assemblies up to 40 weeks after fungal inoculation. Peak load, stiffness, energy dissipation and ductility of connections were characterized based on force-displacement data generated from the destructive test of connections. Assemblies experienced up to 57 % loss in load carrying capacity and 90 % loss in energy dissipating capacity of the connections after 40 weeks of fungal exposure. Connection stiffness was only slightly impacted over this period but wetting and redrying caused significant degradation to connection ductility.

KEYWORDS: Mass timber, biological durability, wetting,.

1 – INTRODUCTION

Mass timber (MT) has gained widespread approval among stakeholders since its introduction into the building industry in the early 1990s, with Europe currently the largest market. Most recently, private and public agencies in North America have consistently allocated resources to research these novel building materials to promote design and construction using more sustainable and environmentally friendly alternatives to conventional building materials. As a result, several large research initiatives have gained insights into seismic, fire, and connection properties. Durability studies have generally lagged other areas of MT research, but are emerging as a priority to many end users [1].

Most durability studies on MT have either only physically assessed decay fungal growth or evaluated mass loss and they typically use small specimens that may not be representative of actual materials [2]. While mass loss is a useful measure of decay, it tends to under-estimate actual effects on wood properties and is less useful when examining larger test pieces, especially if they are in test assemblies with connections [3]. As such, there is a need for holistic evaluations of the effects of biodeterioration on mechanical properties at both the material and system levels. A critical aspect of these assessments is to address potential effects of moisture intrusion and subsequent decay on building performance and safety.

The overarching goal of this study was to evaluate impacts of wetting and subsequent exposure to two brown rot decay fungi, *Gloeophyllum trabeum* and *Rhodonia placenta* on the performance of connections in CLT composed of four different timber species over a prolonged incubation period (40 weeks) under conditions suitable for aggressive fungal attack.

2 – BACKGROUND

The biological nature of MT increases potential risks of premature and accelerated deterioration by biotic agents that reduce material properties and create safety issues in structures [2,4,5]. Given suitable conditions, moulds and decay fungi, termites, and beetles can all degrade wood, either aesthetically or structurally. Moisture presence has been identified as the most critical factor under which these biotic organisms thrive [6]. Lack of protocols for on-site protection of MT against moisture ingress during construction is a general source of concern among stakeholders [7,8]. Therefore, the importance of studying the extent of damage caused by

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the resulting durability issues in buildings and their effects on the overall lifecycle performance of said buildings cannot be overemphasized.

Durability studies have generally lagged other areas of MT research but are emerging as a priority to many end users. Several authors have highlighted the need for durability studies to properly characterize the structural performance of MT elements against biological degradation [1,2,5,9]. Accelerated laboratory tests methods have been developed to characterize termite and fungal degradation in MT elements [8]. Additionally [9], recently evaluated the effects of exterior wood coatings on the resistance of cross-laminated timber (CLT) against mold and decay fungi, and concluded that a combination of surface treatments and biocides could prevent decay and improve building durability.

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3 – PROJECT DESCRIPTION

The assemblies used in this study were made from species of 3 ply ANSI/APA PRG 320 [10] compliant CLT selected across Europe and North America (Table 1). Species choices were based on the predominant species currently used in global MT markets. Douglas-fir (DF) and southern yellow pine (SYP) used in this study were manufactured in the United States, spruce-pine-fir (SPF) was manufactured in Canada and Norway spruce (NS) was sourced from Europe. The materials were exposed to two brown rot fungi, *Gloeophyllum trabeum* and *Rhodonia placenta*. These species were selected because they are used in national standards for decay tests and because brown rot fungi tend to primarily attack conifers or softwoods [4].

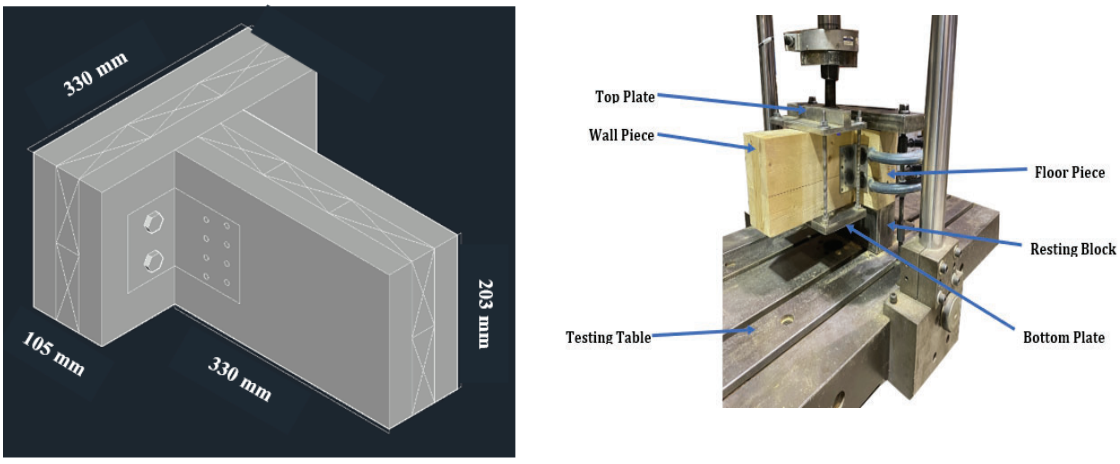

Figure 1. Schematic of connection specimen (a); Test set up (b).

4 – EXPERIMENTAL SETUP

Fungal growth and decay were evaluated in the connection assemblies using a substantially modified

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version of American Wood Protection Association Standard (AWPA) E10-16 [10]. The AWPA uses 19 mm cubes in 454 ml glass or plastic bottles with soil as the media. This scale is far too small to provide a realistic assessment of CLT connections. A modified version of the method was proposed by Sinha et al., (2020) that employed polypropylene gasket boxes (610 mm X 432 mm X 381 mm) as decay chambers to accommodate the large sizes of connection assemblies (Fig. 4.2). A 50 mm deep 4:1 mixture of potting soil and vermiculite was added to the bottom of each decay chamber to help maintain wood moisture content at the desired levels all through the experiment. Two southern pine sapwood sections (350 mm X 140 mm X 25 mm) were placed on the soil-vermiculite mixture to separate the connection assemblies from direct contact with the mixture and minimize the risk of excessive wetting at the bottom of the connection assemblies. These strips also provided additional media on which the test fungi could grow.

The size of the decay chambers and the number of samples being tested precluded the use of conventional autoclaving for sterilization. Instead, the samples were heated in a Wellons dry kiln with the wet and dry bulb temperatures set at a constant 75ºC for 14 hours. Previous studies have shown that heating about 67 ºC for a minimum of 75 minutes is sufficient to kill most fungi in timber. The assemblies were heated for 14 hours to ensure that the core of each assembly attained the desired sterilization temperature and remained at that temperature for at least 2 hours. A thermocouple inserted at the core of a connection assembly was used to determine the heating duration.

The connection assemblies were inoculated by growing the test fungi on sterile wheat grains in 0.5L cylindrical glass jars for about two weeks. 0.25L of the fully colonized grains were subsequently evenly distributed into each decay chamber in a laminar flow hood. The boxes were covered and incubated at 27ºC. Periodic burping in a laminar flow hood was used to introduce fresh oxygen into the decay chambers.

At the end of the assigned incubation period, fungal growth was removed from the assemblies and each sample was weighed. The final and beginning masses were used to calculate final moisture content. The samples were then reconditioned in a kiln at 30 C for~300- hours followed by an additional 200 hours at ~35 C until the samples reached their original moisture content.

A universal testing machine (UTM) with a 178kN hydraulic actuator head was used for cyclic quasi-static tests on the reconditioned assemblies (Fig. 1). The assemblies were oriented so that the load head applied lateral force to the connections. The floor piece rested against a back stiffener connected to the UTM table with 25 mm diameter rods. A steel plate (533 mm X 100 mm X 40 mm) attached to the UTM table with 25 mm diameter rods was used to resist rotation in the floor piece while four 200 mm diameter C-clamps prevented uplift. A steel plate (300 mm X 130 mm X 30 mm) attached to the actuator head transferred load to the connection assembly by attaching to a bottom plate of the same dimensions which supported the connections with four 13 mm diameter rods. A steel bar (305 mm X 125mm) separated the connections from the base of the UTM table to achieve maximum displacement.

Load was applied according to an abbreviated Basic Loading History CUREE protocol [11] with connections loaded to a target displacement of three times the CUREE reference displacement (Fig. 2). A reference displacement of 12.7mm was selected based on results from monotonic tests of samples of all four CLT species. The protocol contained 41 cycles loaded at a rate of 12.3 secs per cycle, resulting in a total test duration of 8 mins and 25 secs for each connection test. The actuator load and displacement were continuously recorded as a force-displacement hysteresis curve that was then used to develop a backbone curve, an envelope of the hysteresis curve.

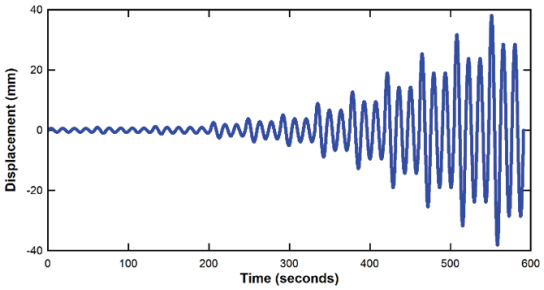

Figure 2. Loading Protocol based on [11]

5 – RESULTS

Mass losses 10 weeks after inoculation varied widely, ranging from 3.2 to 12.2 % with slightly higher losses with R. placenta (Table 1). Mass losses steadily

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increased over the next 30 weeks but only reached averages ranging from 8.6 to 15.6 % with losses again higher with R. placenta.

The mass losses were far lower than those typically found in laboratory decay tests such as the AWPA E10 soil block; however, the exposure conditions and sample dimensions were markedly different. The soil block test exposes 19 mm cubes on fungal colonized wood feeder strips placed directly on the soil. As a result, moisture levels can steadily increase and the high surface to volume ratio of the test specimens increases the ability of the fungus to degrade the wood. Our test array exposed much larger materials using wheat grains as the fungal inoculum source. The assemblies also exposed both radial/tangential and cross sections to fungal attack and contained glue lines that might have affected fungal ingress. The lower mass losses are still useful for assessing changes and would be more consistent with the earlier stages of decay. Previous studies suggest that substantial changes in flexural properties are associated with mass losses below 10 % [4] especially with brown rot fungi.

Table 1. Mass Loss

Exposure **Time (Weeks)**	Assembly Mass Losses (%)							
	Douglas-fir		Norway spruce		spruce pine fir		southern pine	
	G. trabeum	*R. placenta*	*G. trabeum*	*R. placenta*	*G. trabeum*	*R. placenta*	*G. trabeum*	*R. placenta*
10 wks.	**3.2**	**7.5**	**8.5**	**12.2**	**6.5**	**10.9**	**7.0**	**8.7**
(COV)	(27.9)	(28.8)	(27.9)	(30.6)	(6.4)	(23.3)	(20.2)	(49.1)
20 wks.	**6.2**	**8.3**	**9.7**	**13.8**	**9.2**	**10.8**	**11.7**	**12.1**
(COV)	(24.6)	(32.7)	(27.8)	(22.6)	(25.4)	(35)	(37)	(33.8)
30 wks.	**8.6**	**15.1**	**12.2**	**17.2**	**11.8**	**13.8**	**11.4**	**14.7**
(COV)	(17.3)	(38.8)	(26.3)	(36.3)	(28.2)	(28.2)	(36.5)	(29.9)
40 wks.	**8.6**	**13.9**	**13.4**	**12.3**	**10.8**	**12.7**	**13.2**	**15.6**
(COV)	(35.9)	(43.1)	(48.5)	(16.1)	(19.7)	(23.1)	(27.7)	(21.9)

Values represent means of 10 replicates per material per fungus per incubation time

Mass losses increased steadily with incubation time for DF and SYP exposed to R. placenta but increased more sporadically with NS and SPF. DF is classified as moderately durable compared to the other species, but the mass loss differences were minor. It is unclear whether the adhesive bonds affected decay rates, but this appeared unlikely given the proximity of advanced decay adjacent to glue lines.

The connections were designed to fail by yielding and nail pull out or fracture [12], but fungal degradation modified the failure modes. In many instances, failure was observed in the wood instead of the fasteners with failure along the glue-line the most common mode. DF assemblies were most susceptible to this failure mode, with bond line failure observed after as little as 10 weeks of incubation while SPF only experienced bond line failure after 30 weeks. Splitting failure along the grain of the middle lamella was observed in many southern pine samples, suggesting that total adhesive failure had occurred before the connections were tested and shifting the load to this lamella. The data tended to be highly variable even in the dry controls, reflecting the inherent variability of the timber which was further complicated by the variable effects of fungal decay across the assembly.

Pairwise comparisons indicated that there were no significant differences in stiffness and cumulative energy between dry and wetted controls except for the southern pine. However, ductility was significantly lower in assemblies subjected to wetting and drying. The wet control group was used for all comparisons with fungal exposed samples of the same wood species.

Slight downward progressions in the peak load were observed for connections inoculated with G. trabeum across all species for up to 20 weeks of exposure with

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average decreases of 14%, 19%, 1%, and 14.7% in DF, NS, SPF, and SYP CLT, respectively (Table 2). However, maximum average decreases in peak loads of between 16% and 43% were observed across all specimens between 30 and 40 weeks of incubation with the smallest decreases in SPF and the largest in SYP. Connection assemblies exposed to R. placenta experienced slightly higher levels of decay with average reductions of around 21 % to 33 % in the first 20 weeks of exposure across all CLT species and a further decrease of around 40% and 57% of connection capacity on further exposure between 30 and 40 weeks. The higher capacity losses observed with R. placenta exposed connections may be due to increased incidence of glue line failure which was observed in the connection assemblies for all four species.

Slight reductions in ductility were observed in connections inoculated with either fungus with increased exposure time, but the reductions were not statistically significant.

Table 2. Strength Loss

Treatment	Douglas-fir		Norway spruce		spruce pine fir		southern pine	
Dry Controls	**32276**		**28259**		**27320**		**30548**	
(COV)	(2.4)		(4.0)		(4.6)		(5.1)	
Water Controls	**33856**		**31167**		**29303**		**31790**	
(COV)	(4.1)		(5.3)		(6.0)		(12.0)	
Exposure Time (wks.)	*G. trabeum*	*R. placenta*	*G. trabeum*	*R. placenta*	*G. trabeum*	*R. placenta*	*G. trabeum*	*R. placenta*
10	**30597**	**30428**	**28443**	**27262**	**26812**	**27043**	**29608**	**27650**
(COV)	(9.0)	(16.1)	(8.8)	(24.7)	(18.7)	(13.6)	(18.2)	(33.0)
20	**28983**	**26547**	**25881**	**22622**	**29102**	**22339**	**27100**	**21087**
(COV)	(15.3)	(33.6)	(16.7)	(26.7)	(20.0)	(35.9)	(23.7)	(31.2)
30	**28220**	**20381**	**23583**	**13323**	**27106**	**21455**	**18123**	**19580**
(COV)	(15.4)	(35.8)	(30.1)	(46.2)	(22.4)	(32.5)	(42.6)	(43.8)
40	**24009**	**18822**	**22699**	**16264**	**24673**	**25814**	**20299**	**16637**
(COV)	(17.5)	(45.2)	(34.6)	(36.0)	(25.4)	(16.0)	(50.0)	(30.7)

For average cumulative energy dissipation in tested connections, a 30 % to 50 % loss in cumulative energy dissipation was observed across all species inoculated with G. trabeum after 10 weeks of exposure. Further degradation in energy dissipating capacity was observed with increased exposure time and by 40 weeks of exposure, averages of 70 % to 84 % losses were observed across all four CLT species exposed to this fungus. Connection assemblies exposed to R. placenta lost more than 50% of their energy dissipating capacity after 10 weeks of exposure and only SPF retained more than 10 % of its original capacity after 40 weeks of exposure. The results suggest that decay around the connections diminished the ability of the connection to dissipate energy. Kent et al. [13] observed a 60% drop in energy dissipation for changes as small as a 0.1 decrease in specific gravity of the wooden material in a simulated shear wall assembly.

A slight statistical significance was only observed in DF and SYP inoculated with R. placenta over the 40-week period. However, pairwise comparisons between dry and wet controls showed that moisture was more detrimental to connection ductility and resulted in almost 50% decrease in ductile capacity. These declines may reflect increased brittleness observed in the dowel fasteners after wetting and redrying.

6 – CONCLUSION

Brown rot fungi had a detrimental impact on the connection assemblies with the areas around the bond line observed as critical locations for failure propagation in decayed CLT assemblies. The large surface area of MT elements contributed to the

observed slow biodeterioration. The two fungi studied in this experiment showed similar trends but different degrees of severity on the connection assemblies. G. trabeum significantly impacted the properties of connections especially load carrying and energy dissipating capacities over the 40-week exposure period. The degree of damage was slightly greater in connections inoculated with R. placenta.

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