EFFECTS OF ENVIRONMENTAL FACTORS ON DECAY RATES OF SELECTED WHITE- AND BROWN-ROT FUNGI

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Abstract. Assessing the impact of fungal decay in wood structures poses a major challenge for building inspectors. Although models have been developed to predict degradation rate of building components in varying climatic conditions, most are hampered by the lack of fundamental data on effects of fungal attack on engineering properties. Developing data on degradation rates in differing conditions would help enhance these models. The ability of two brown-rot and one white-rot fungus to degrade wood of three species was assessed in varying temperature and moisture conditions. Modulus of elasticity (MOE) was the most sensitive measure of fungal attack, whereas modulus of rupture (MOR) was affected more slowly. Wood species had no effect on MOR losses, but wood durability did influence fungal effects on MOR. The white-rot fungus caused comparable MOE losses to the brown-rot fungi but had a much decreased effect on MOR. Moisture content, within the range tested, had little influence on decay rates. Fungal effects tended to be slower at the lowest temperature tested (15°C) but differed little between 25 and 35°C. Results suggested that removal of wood that has been wet for some time is advisable if dynamic properties are critical. Results also supported incorporating temperature and time of wetting factors into building models.

Keywords: Decay, *Postia placenta*, *Gloeophyllum trabeum*, *Trametes versicolor*, Douglas-fir, western hemlock, southern pine, modulus of elasticity, modulus of rupture.

INTRODUCTION

Wood has been used to provide shelter for humans for thousands of years. Wood is exceptionally durable when used in properly designed, constructed, and maintained structures. However, it is prone to degradation by a variety of organisms when these practices are not followed. Typically, fungi are the most important agents of structural deterioration (Mankowski and Morrell 2000). These organisms have basic requirements for growth that include adequate temperature, oxygen, nutrients, and free water (Zabel and Morrell 1992). Generally, oxygen is not limited and, unless the wood is protected with chemicals, the food source is not limiting. In most cases, decay rates are most affected by either moisture content or temperature. Rate of decay and extent of damage can be especially important when moisture intrusion occurs in a structure and engineers must decide how much wet wood to remove.

There is compelling evidence that the early stages of fungal attack, especially by brown-rot fungi, have dramatic negative effects on wood properties, especially flexural properties such as bending perpendicular to the grain and tension. Bending strength losses as great as 60% have been observed in small specimens at mass losses as low as 2% (Wilcox 1978). Although there are a number of studies showing the effects of fungal attack on wood properties (Viitanen and

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Paajanen 1988; Kent et al 2004; Clark et al 2006; Wang and Morris 2011), few studies have examined decay rates within the broad range of temperature and moisture conditions possible in a structure. These data could be especially useful for engineers attempting to develop building performance models. For example, models developed in Australia attempted to predict building performance and decay rates using aboveground performance data generated from a limited number of field sites (Foliente et al 2002; MacKenzie et al 2007; Leicester et al 2008; Wang et al 2008). These data were based on visual assessments of wood condition. Although useful, visual assessment is prone to inaccuracy. Others have also attempted to predict decay rates with varying degrees of success (Viitanen 1997; Suzuki et al 2005; Nofal and Kumaran 2011). Developing more complete data on effects of various fungi on wood condition under varying temperature and moisture regimes could improve the predictive accuracy of these models, making them more broadly useful. In this study, we describe effects of selected decay fungi on the properties of three softwood species.

MATERIALS AND METHODS

A vermiculite decay chamber procedure was used to expose wood to fungal attack under a range of temperature and moisture regimes. The procedures were based on those described by Winandy and Morrell (1993) and further refined by Curling et al (2000).

Wood Species

Douglas-fir heartwood (*Pseudotsuga menziesii* [Mirb] Franco), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), and southern pine (*Pinus* spp.) sapwood lumber was cut into 10 × 10 × 160-mm-long beams that were free of knots and other defects. A total of 1458 beams was cut from each species. Because of the large number of samples per species, no attempt was made to end-match beams between treatments. Forty-eight beams of each species were randomly allocated to each of 30 treatment groups. Extra specimens were retained as replacements if needed.

Beams were oven-dried (105°C) for 24 h and weighed (nearest 0.001 g). A 2-mm-diameter hole was drilled 5 mm into one tangential face of each beam 80 mm from the end. The hole was drilled in such a way that it lay in the neutral axis of the beam when subjected to third-point loading (ie perpendicular to the loading direction).

Test Fungi

Two brown-rot fungi (*Postia placenta* [Fr] M Larsen et Lombard [Isolate Madison 698] and *Gloeophyllum trabeum* [Pers. Ex Fr.] Murr. [Isolate Madison 617]) and one white-rot fungus (*Trametes versicolor* [L:Fr.] Pilát [Isolate Madison R-105]) were maintained on 1.5% malt extract agar at 28°C until needed. These species are among the fungi most commonly isolated from wood in service and are among those recommended for evaluating decay resistance of wood in the American Wood Protection Association Standards (Duncan and Lombard 1965; AWPA 2010). Four-millimeter-diameter agar plugs were cut from the actively growing edge of a fungal culture and placed into a 250-mL flask containing sterile 1.0% malt extract. The flasks were incubated in stationary culture at 28°C for 10 da. The resulting fungal mycelium was collected by filtration and then rinsed with 300 mL of sterile distilled water to remove as much residual malt extract as possible. The mycelium was then washed into a container, and 250 mL of sterile distilled water was added. The mixture was briefly blended to fragment the hyphae. This material was used as the fungal inoculum for the wood samples. Although it is likely that colonization in most structures by decay fungi begins with basidiospores, consistently producing these structures in culture can be difficult. Hyphal fragments and chlamydospores were used instead because they could be easily produced in quantity. As a result, initial rates of fungal colonization may have differed between basidiospores and these propagules, but the rates of decay should have been similar once colonization began.

Decay Chambers

A modification of methods described by Curling et al (2000) was used to expose the wood to decay fungi. Autoclavable plastic bags (120 × 230 × 535 mm) fitted with a microporous filter that allowed for air exchange were used as decay chambers. Preliminary tests were performed to determine the vermiculite moisture levels necessary to bring the wood moisture content to 30-40, 60-80, or 100-130%. Six beams from a given species group were placed in each bag along with 100 g of vermiculite and the distilled water required to bring the vermiculite to the target moisture content. The bags were loosely sealed with rubber bands and autoclaved for 45 min at 121°C. The bags were then stored at room temperature to allow the wood to equilibrate to desired moisture content.

One hundred microliters of blended inoculum of the appropriate fungus was added to the inoculation hole of each beam, and then a ridge of moist vermiculite was placed around the center of each beam to help retain the inoculum and create a stable wood moisture content. The goal was to use propagules to initiate colonization instead of large quantities of mycelium. Also, these systems used pure cultures, whereas wet wood in natural environments is often colonized by a range of fungi including molds, stain fungi, and decay fungi. The shear number of samples required to test all possible permutations of these fungi while exploring other test parameters precluded assessing the interactive effects of these fungi on wood condition. One set of beams for a given species inoculated with a given fungus was immediately removed, then the remaining bags were resealed and incubated at 15, 25, or 35°C for periods ranging from 6-36 wk. Bags were periodically opened under a laminar flow hood to allow for air exchange. One set of six beams from a given wood species/moisture content/fungus/temperature combination was removed after 6, 12, 18, 24, 30, or 36 wk of incubation. The beams were immediately tested to failure in third-point bending across a 130-mm span at a loading rate of 2 mm/min on a single point at the center on a Karl Frank Universal Testing Machine according to procedures described in ASTM (2011a) with the exception of the smaller specimen dimensions. The tests were performed while the beams were above FSP and remained in the bags. Load deflection data were continuously collected and used to calculate modulus of elasticity (MOE) and modulus of rupture (MOR). Results from the destructive tests were used to determine loading for the remaining beams at each time point. All beams remaining in the test were loaded to 30% of the proportional limit for that group of beams, and those data were used to calculate MOE of the remaining beams. MOE and MOR were expressed as a percentage of the original values determined for each wood species.

The beams that were tested to failure were then removed from the plastic bag, oven-dried (105°C), and weighed. The differences between the initial and final weights were used to calculate fungal-associated wood weight loss. The remaining beams in each bag continued to be incubated until the next sampling point.

Statistical Analysis

The experiment was a full factorial design with temperature at three levels, moisture content at three levels, and incubation time at seven levels as main effects. Data were analyzed using PROC MIXED (SAS 2008). Data were partitioned by wood species and then incubation temperature. MOE values were log transformed and a TYPE=UN(2) was used to specify for an unstructured covariance of the R matrix in which time intervals correlated with different variances at each time period. MOE and MOR values for fungal-exposed beams are presented as a percentage of the values of similarly prepared but nonfungal-exposed beams.

RESULTS AND DISCUSSION

All inoculated beams exhibited evidence of fungal colonization around the center holes within 1 wk of inoculation. Mycelium uniformly covered the beams within 6 wk of incubation at 25 or

35°C and within 12 wk at 15°C. Results indicated that conditions were ideal for fungal colonization.

Modulus of Elasticity

All three wood species experienced losses in MOE ranging from 40-60% after only 6 wk of incubation at 25 or 35°C, and most reached 100% MOE losses by 30-36 wk regardless of the fungus tested (Figures 1-3). MOE losses differed significantly among incubation periods except between 30 and 36 wk, when the losses were virtually complete and there was little opportunity for further change.

Wood species appeared to have relatively little effect on MOE losses except at the lower moisture content for the lowest temperature, at which southern pine appeared to be slightly more susceptible. The lack of a wood species effect was surprising because of the known variations in durability of the species tested. Western hemlock and southern pine sapwood are both classified as nondurable, whereas Douglas-fir heartwood is moderately durable (Scheffer and Morrell 1996). One possible explanation for this anomaly was that the location of the inoculation hole at the maximum loading point magnified any fungal effects. Douglas-fir should decay more slowly than western hemlock or southern pine in the aboveground conditions typically found within a structure (Scheffer and Morrell 1996); however, effects on MOE tend to occur much earlier in the decay process, and any differences might have been masked by the rapid colonization on all three wood species.

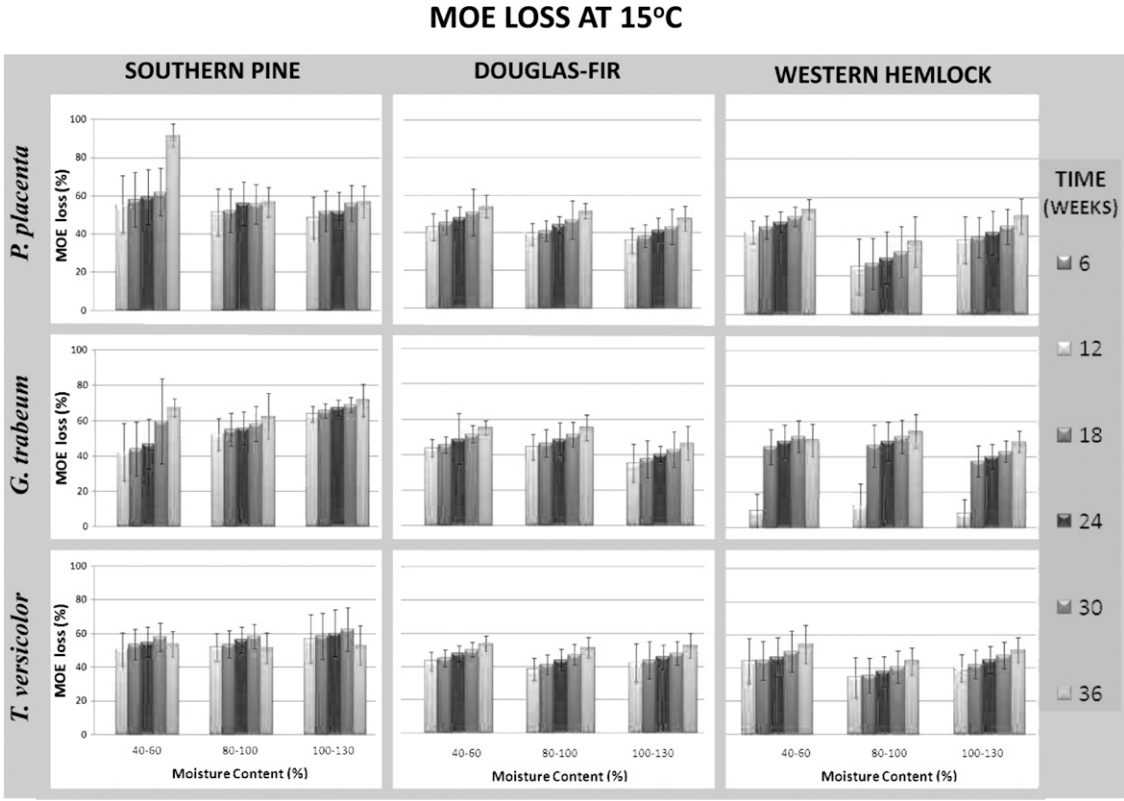

Figure 1. Effect of fungal exposure on modulus of elasticity (MOE) of southern pine, Douglas-fir, or western hemlock beams maintained at three moisture contents for 6-36 wk after inoculation with *Gloeophyllum trabeum*, *Postia placenta*, or *Trametes versicolor* and incubation at 15°C. Bars represent 1 standard deviation from the mean.

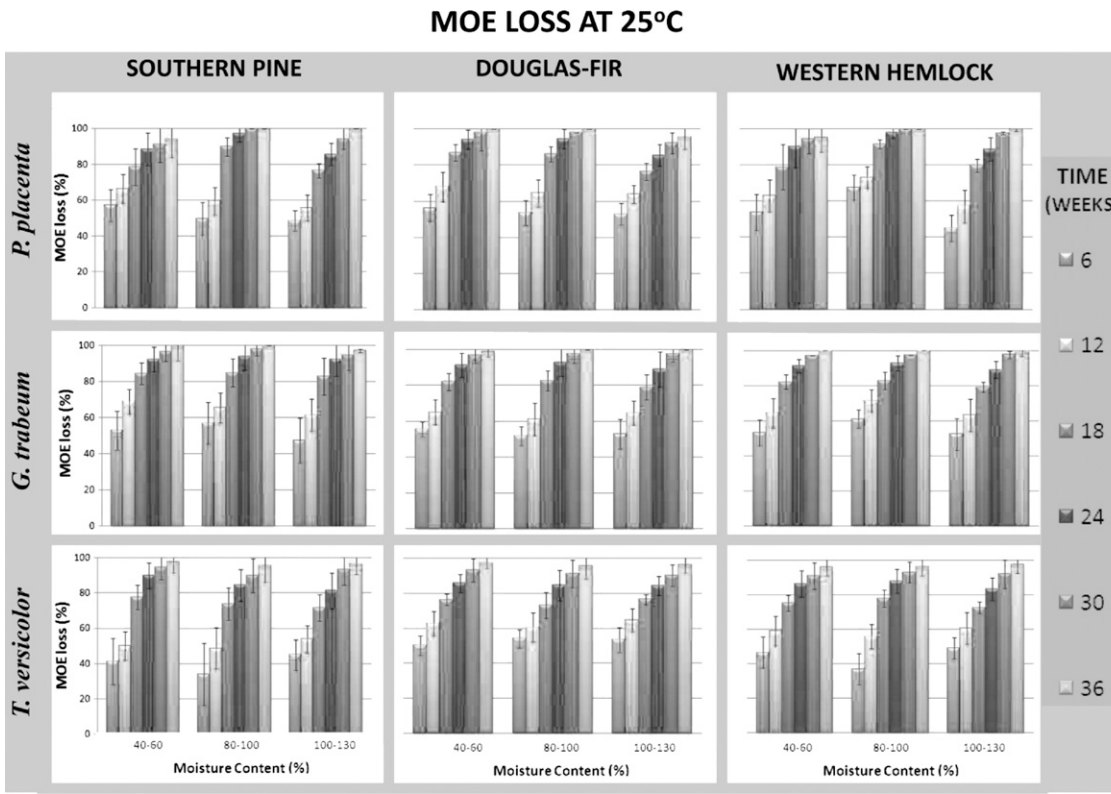

Figure 2. Effect of fungal exposure on modulus of elasticity (MOE) of southern pine, Douglas-fir, or western hemlock beams maintained at three moisture contents for 6-36 wk after inoculation with *Gloeophyllum trabeum*, *Postia placenta*, or *Trametes versicolor* and incubation at 25°C. Bars represent 1 standard deviation from the mean.

Temperature had a marked effect on MOE (Figures 1-3). There was little change in MOE during the first 6 wk of incubation for any fungus/wood species/moisture content combination when beams were incubated at 15°C, whereas beams incubated at 25 or 35°C experienced MOE losses ranging from 40-55% during that same period. MOE losses in beams incubated at 15°C increased markedly after an additional 6 wk of incubation, suggesting that the lower incubation temperature slowed but did not inhibit fungal attack. MOE losses steadily increased with time in beams incubated at 15°C but were still below those observed in beams incubated at the higher temperatures during the same time period. There appeared to be little difference in MOE loss in beams incubated at 25 or 35°C. Many decay fungi have temperature optima between 24 and 30°C, and the rates of decay decline on either side of that range (Zabel and Morrell 1992). Clearly, lower temperatures had a more pronounced effect on fungal activity. Temperature in many buildings is maintained between 15 and 20°C for most of the year. However, it is unlikely that conditions would be uniform throughout a structure. For example, temperatures in wood in an exterior wall are likely to be closer to the ambient external temperature. The lower temperature results would probably be more applicable to wood in exterior walls during the cooler times of year. Results indicate that there would be little appreciable difference in decay rates within the higher temperature ranges more typical of the building interior.

Moisture content is typically viewed as a key requirement for fungal decay, and most building design strategies are centered around either

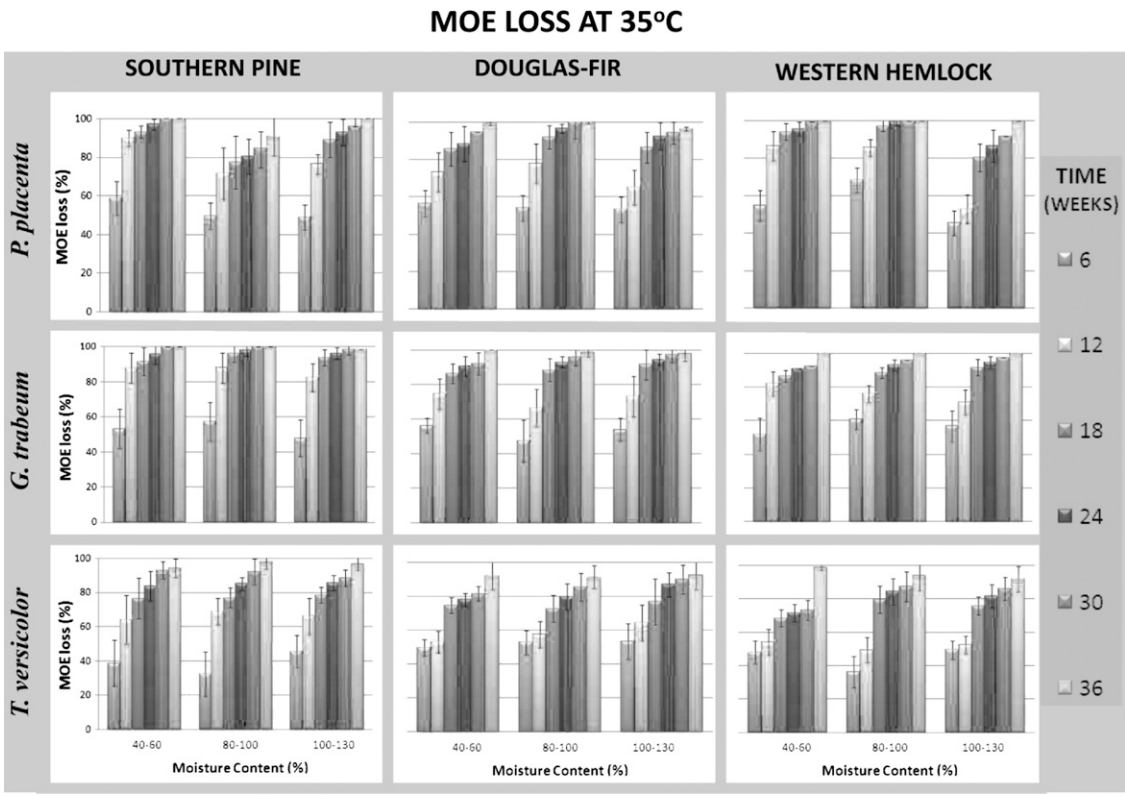

Figure 3. Effect of fungal exposure on modulus of elasticity (MOE) of southern pine, Douglas-fir, or western hemlock beams maintained at three moisture contents for 6-36 wk after inoculation with *Gloeophyllum trabeum*, *Postia placenta*, or *Trametes versicolor* and incubation at 35°C. Bars represent 1 standard deviation from the mean.

excluding moisture or, if that cannot be achieved, ensuring that air circulation is sufficient to prevent its buildup. Moisture plays critical roles in the decay process, serving as a reactant in enzymatic hydrolysis, a diffusion agent for enzymes and wood breakdown products, and as a wood swelling agent. It is generally accepted that fungi, with the exception of true dry-rot fungi, do not cause appreciable decay unless free water is present. For most woods, the FSP occurs between 27 and 30% (FPL 1999). Fungal decay is presumed to increase as moisture content increases to the point at which it is no longer limiting. It will decrease as moisture content increases to the point at which the excess moisture begins to constrain cell lumen space, thereby limiting oxygen. Actual moisture contents sometimes differed from the targets and would be expected to increase as decay progressed as a result of fungal respiration coupled with decreased wood mass. The moisture regimes examined in these trials were within the range at which moisture was neither limiting nor so high as to exclude oxygen. Moisture content did not appear to have any effect on decay rate within the range tested, which is consistent with the need for free water but suggests a limited ability to increase the rate of decay with further increases beyond the FSP. Results suggest that, once moisture contents increase within this range, decay proceeded at a steady rate that was unaffected by further increases in moisture level. Although moisture contents can sometimes become extreme near moisture sources, they often fall off with increasing distance from the source. Building inspectors are challenged to distinguish between wood that has merely been wetted and that in which prolonged wetting has allowed fungal

attack to begin to degrade the lignocellulosic matrix. Although evidence of fungal growth on the wood surface is a helpful indicator of colonization, it is not necessarily a predictor of wood condition. This problem is compounded by the fact that some wood properties, such as MOE, are severely affected at very early stages of fungal attack when there is little evidence of damage. The very rapid MOE losses, coupled with the lack of an appreciable difference in decay rates with moisture level, suggest that once the wood has become wetted for any appreciable period under suitable temperature regimes, the inspector must consider the damage to be sufficient to contemplate replacement if dynamic properties are critical to performance, even when there is no obvious sign of deterioration. The difficulty is determining when wetting occurred and then determining the probability that a decay fungus has successfully colonized the material.

Fungi that degrade wood have a wide range of physiologic capabilities that allow them to thrive in varying conditions. Standard decay testing procedures account for this variation by using a number of fungi to assess both natural durability and durability of materials that are supplementally protected (AWPA 2010; ASTM 2011b). The three fungi evaluated in this study have markedly different ecological niches. *Gloeophyllum trabeum* and *Postia placenta* both produce brown-rot decay. The former fungus is more commonly found on wood exposed out of direct soil contact and is presumed to be more adapted for decaying under changing moisture regimes. *Postia placenta* is found throughout North America but tends to be found in wetter, more stable environments. For example, it is among the most important internal decay fungi in the heartwood of Douglas-fir utility poles (Morrell et al 1987, 1988). *Trametes versicolor* produces white-rot attack. Although it is found on softwoods, it is more prevalent on hardwoods (Duncan and Lombard 1965). Most laboratory studies indicate that this fungus is less capable of causing substantial degradation on softwoods. In this study, there was sometimes slight evidence of differences in MOE losses with the white-rot fungus at the early stages of attack, but there was no overall difference in MOE loss with fungal species. The lack of a fungal effect on decay rate was perplexing, but it may reflect the test conditions and the polymers affected at the early stages of fungal attack. Although the greatest impact of fungal attack on wood properties occurs through cellulose depolymerization, the early stages of attack by most fungi are concentrated on compounds stored in the ray cells as well as the hemicelluloses. Hemicellulose degradation is believed to play a role in losses in dynamic properties such as MOE (Winandy et al 2000). All three fungi tested would be expected to follow this pathway; however, decay rates for the white-rot fungus was expected to slow as it confronted the more complex softwood lignocellulose matrix.

In general, test conditions were established so that neither moisture nor temperature was limiting. Also, all fungi were introduced as hyphae with some chlamydospores (for *P. placenta*) and no exogenous nutrients. This would presumably reflect how fungal hyphae might be introduced into a building. Although spores might produce slower colonization rates, it is unclear if this would translate into a differential decay rate once colonization was initiated. This would merit further study. The system provided a reasonable representation of a building wall cavity with the exception that the wood moisture levels were uniform rather than following gradients with distance away from a moisture source.

The lack of differences in MOE losses with fungal species in the range of conditions tested indicates that once a decay fungus became established, the MOE effects were relatively rapid and substantial. This assumption merits further testing on other fungi typically associated with decay of wood products. It does, however, suggest that developing data on the rates at which fungal propagules enter building cavities after wetting might help to better refine building decay prediction models. These data could then be used in conjunction with the time of wetting and temperature to predict risk of decay (Momohara et al 2012).

Location of the inoculation point also probably affected the results. Because all inoculum was delivered at the same point at which the beams were loaded, any fungal effect on the beams was probably magnified. Smith et al (1992) noted that a decay fungus (*P. placenta*) rapidly colonized Douglas-fir beams but had a less pronounced effect on flexural properties at these early stages. The concentration of inoculum at the beam center would maximize any fungal effect on flexural properties measured at the same point.

Modulus of Rupture

Unlike MOE, MOR decreased relatively slowly with incubation time but was more affected by test conditions (Figures 4-6). Most beams retained some strength, but several of those incubated for 36 wk in the warmer test conditions broke while being removed from the bags. The MOR declines indicated that conditions were suitable for aggressive fungal attack even in the absence of soil or exogenous nutrients. These conditions closely replicate those found within portions of a wall cavity. The exception was *T. versicolor*, which produced small and inconsistent changes in MOR during the exposure period. For this reason, the MOR discussion will be confined to the two brown-rot fungi.

Wood species had a major effect on MOR losses although the effect was sometimes tempered by the test fungus. In general, southern pine appeared to experience greater MOR losses than

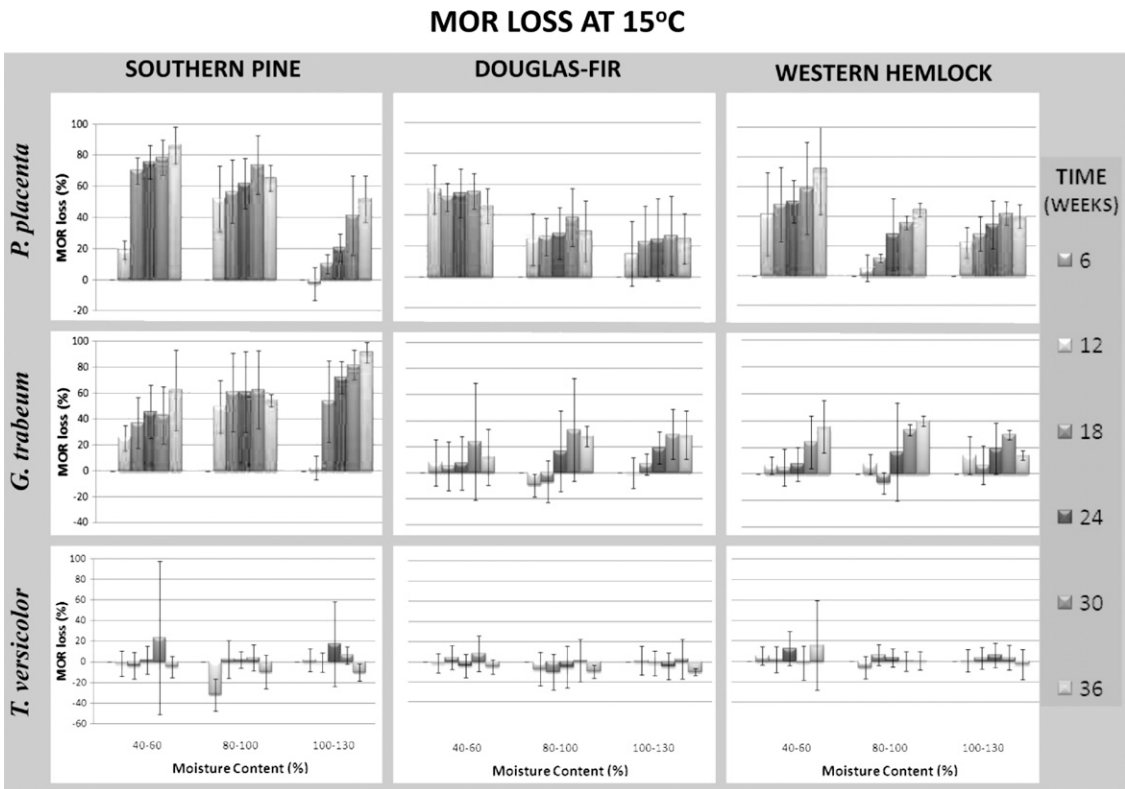

Figure 4. Effect of fungal exposure on modulus of rupture (MOR) of southern pine, Douglas-fir, or western hemlock beams maintained at three moisture contents for 6-36 wk after inoculation with *Gloeophyllum trabeum*, *Postia placenta*, or *Trametes versicolor* and incubation at 15°C. Values represent means of six beams, whereas bars represent 1 standard deviation from the mean.

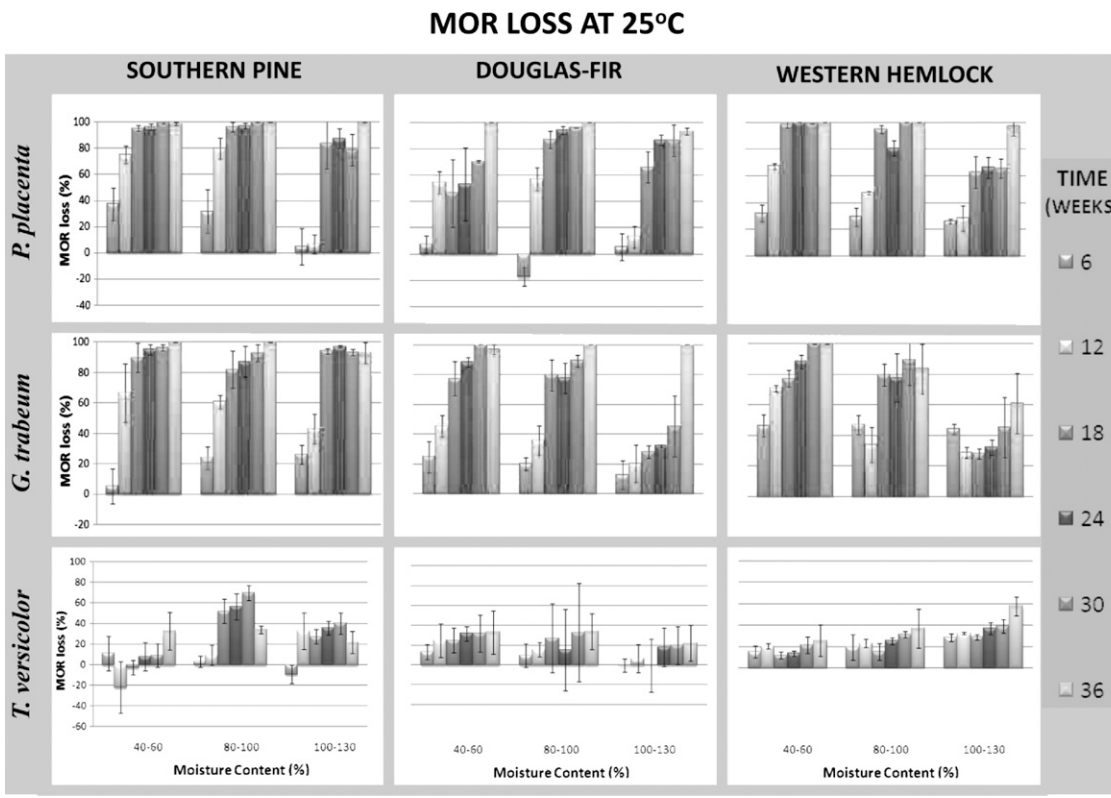

Figure 5. Effect of fungal exposure on modulus of rupture (MOR) of southern pine, Douglas-fir, or western hemlock beams maintained at three moisture contents for 6-36 wk after inoculation with *Gloeophyllum trabeum*, *Postia placenta*, or *Trametes versicolor* and incubation at 25°C. Values represent means of six beams, whereas bars represent 1 standard deviation from the mean.

either western hemlock or Douglas-fir; however, this effect was negated in some conditions when *Postia placenta* was used as the test fungus. *Postia placenta* is a common inhabitant of Douglas-fir heartwood, and the ability of this fungus to degrade the moderately durable heartwood was clearly evident in our results. Similarly, *G. trabeum* appeared to be more aggressive on southern pine than western hemlock, although both species are classified as nondurable. This fungus and a closely related species, *Gloeophyllum saepiarium*, are common decayers of pine window frames (Duncan and Lombard 1965).

Temperature also affected MOR losses in a manner that was similar to that observed with MOE with smaller MOR losses at 15°C. MOR losses also tended to be lower on Douglas-fir and western hemlock. Unlike the MOE results, however, MOR losses did differ between 25 and 35°C. Although there were variations in results, MOR losses tended to reach higher levels faster at 25°C compared with 35°C. Reasons for the lack of effect on MOE compared with MOR are unclear. Clearly, MOE is more affected by the rapid depolymerization associated with early stages of decay. These losses reflect degradation of both hemicelluloses and cellulose and subtle changes in the cell wall matrices can have profound effects on elasticity. It is possible that the more substantial depolymerization of cellulose necessary for MOR losses is more affected by temperature. Interestingly, this effect was also noted with the white-rot fungus, which produced the most substantial effects on MOR at 25°C. Elevated activity at this temperature is especially

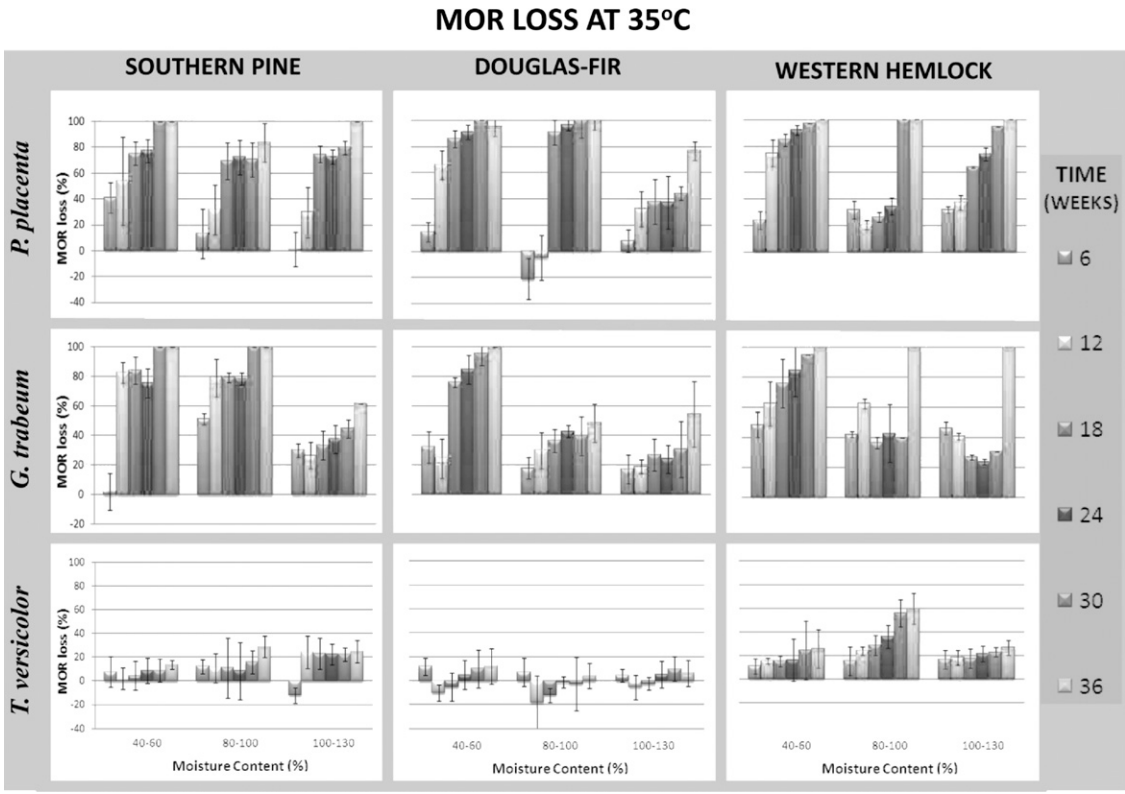

Figure 6. Effect of fungal exposure on modulus of rupture (MOR) of southern pine, Douglas-fir, or western hemlock beams maintained at three moisture contents for 6-36 wk after inoculation with *Gloeophyllum trabeum*, *Postia placenta*, or *Trametes versicolor* and incubation at 35°C. Values represent means of six beams, whereas bars represent 1 standard deviation from the mean.

important because it brings the optimum for fungal growth much closer to the temperatures typical of many buildings in warmer climates. It also implies that building decay models must consider temperature.

Moisture content appeared to have a much greater effect on MOR than MOE, but the effects were inconsistent. For example, mean MOR in southern pine beams exposed to *G. trabeum* at 15°C appeared to decline slightly more slowly with increasing moisture content, whereas it decreased more quickly with increased moisture content for both Douglas-fir and southern pine at 35°C. Higher moisture contents should decrease the void volume of the wood and therefore available oxygen. Although not completely limiting, lower oxygen availability would be less important at 15°C because the fungus is likely to be less physiologically active than it would be at 35°C. The results suggest that incorporating wood moisture content into building models will require consideration of upper and lower limits for predicting decay rates.

There were obvious differences in MOR losses between the white-rot fungus and the two brown-rot species tested. White-rot fungi are typically less active on softwood species, and results were consistent with that premise. There did appear to be marked differences in MOR losses between the two brown-rot fungi when they were incubated at 15°C. *Gloeophyllum trabeum* produced much smaller MOR losses on both Douglas-fir and western hemlock. This effect disappeared at 25 and 35°C, suggesting that the response was

related to the ability of the test fungi to function at somewhat lower temperatures. The overall trends suggest that the decay fungus had less effect on predictive modeling as temperatures to which the wood was exposed rose.

Wood Weight Loss

Mass loss has traditionally been used as a measure of fungal effects on wood properties, but it clearly is a poor predictor because of the enzymatic damage occurring in the early stages of decay, which is not associated with mass loss. Mass losses were generally associated with MOE losses, but mass losses were often within the error range for the tests at early decay stages, whereas MOE losses often approached 40-60% (Table 1). Also, there was little external evidence of substantial fungal attack in terms of softening, checking, or other defects that would suggest loss of integrity at these early stages.

The inability to detect the degree of decay in wetted wood using mass loss or visual assessments highlights two important aspects of predicting and managing decay in structures. First, the absence of obvious wood damage is not necessarily a predictor of integrity. Thus, the current practice of removing obviously wetted wood when it is apparent that the wetting has occurred for some period of time (months) appears to be a valid approach because of the inability to determine when the wood became wetted and, furthermore, when or if a fungus entered the wood. The inability to determine the timing of these events limits the flexibility of the inspector. This would obviously be a function of the durability of the wood species and a function of the wood member. For example, a single decaying stud observed after removal of the sheathing might be left in place if the moisture source could be eliminated, but a decaying shear wall or floor joist might require more aggressive action. The second aspect of the inability to accurately predict the extent of decay relates to how data are used to construct building performance models. The most robust model produced to date is the Australian model, which uses climatic data (primarily rainfall and temperature) coupled with prior field performance data from a range of species in both soil and aboveground exposures to provide performance predictions. Climatic data have long been used to predict decay risk (Scheffer 1971), but the Australian models based on performance data create special issues because the field data were developed using a visual assessment scale. Although the scale emphasized the importance of early decay on condition by dropping the rating sharply with seemingly minor decay, even this approach has drawbacks. Most notable is the inability to distinguish minor surface decay on exceptionally durable timbers that still retain high percentages of their original properties from more uniform decay in less durable species that extends more deeply into the wood. Developing effective predictive models for wood performance will require more realistic data that examine engineering properties. At present, those data are lacking, making it difficult to accurately predict wood performance compared with other materials. Nondestructive methods for predicting wood condition have been explored in a variety of conditions, but none has achieved the degree of precision necessary to act as decision-making tools. There is a continuing need for improved methods for assessing wood condition in situ.

The current results illustrate the ability of common building fungi to cause rapid losses in dynamic properties and slower but steady losses in mass and flexural properties of wood members in conditions typically found in structures in which fungal attack is initiated from a combination of wetting and ingress of fungal spores or hyphae with no exogenous nutrients. Fungal species clearly affected rate of decay, whereas wood species, within those tested, was less important. The current inability to determine when fungal attack has been initiated makes it difficult to develop models that use environmental conditions such as moisture content or temperature as predictors of degree of decay in wetted wood. For example, the rate at which decay fungi colonize wood has been estimated to range from 0.05-0.2/yr (Winandy and Morris 2002; Clark et al 2006;

Table 1. Effect of fungal exposure on wood mass of southern pine, Douglas-fir, and western hemlock beams at three moisture contents for 6-36 wk after inoculation with *Gloeophyllum trabeum*, *Postia placenta*, or *Trametes versicolor* and incubation at 15, 25, or 35°C.

Moisture content (%)	Fungus	Exposure time (wk)	Wood weight loss[a] (%)								
			Southern pine			Douglas-fir			Western hemlock		
			15°C	25°C	35°C	15°C	25°C	35°C	15°C	25°C	35°C
40-60	*G. trabeum*	6	0	0.56	0.76	0	2.21	2.31	0	3.88	3.88
		12	0.36	13.31	20.70	1.88	7.22	11.09	1.51	13.74	7.09
		18	5.55	1.70	41.20	2.13	18.50	15.80	3.10	26.90	28.30
		24	8.52	53.66	47.32	2.64	27.41	21.05	4.18	36.19	29.62
		30	8.42	67.04	49.54	3.64	29.46	24.49	7.87	37.87	31.54
		36	13.49	69.61	53.00	4.19	33.10	25.36	10.49	41.08	31.40
	P. placenta	6	0	1.71	2.01	0	1.58	1.60	0	1.04	0.64
		12	1.89	11.34	10.81	1.53	9.80	10.63	1.02	13.34	11.64
		18	4.17	18.10	16.60	3.11	19.00	23.50	3.98	29.20	33.50
		24	16.14	30.60	17.50	8.00	18.77	24.52	11.65	31.46	24.29
		30	17.44	31.55	21.60	11.18	23.34	35.44	12.26	31.67	45.81
		36	18.77	39.75	30.50	15.13	29.45	35.19	13.01	33.32	46.20
	T. versicolor	6	0	0.96	0.85	0	0.27	0.27	0	1.03	0.27
		12	1.68	4.37	1.29	0.27	1.19	0.75	0.24	0.43	1.36
		18	2.11	10.50	2.40	0.72	1.60	3.20	0.45	3.30	1.70
		24	2.81	12.78	6.69	0.43	1.02	1.67	0.32	2.51	2.64
		30	4.67	16.12	7.11	0.94	1.82	2.58	0.24	2.01	4.06
		36	5.00	16.66	9.97	0.75	0.63	2.73	0	1.90	5.37
80-100	*G. trabeum*	6	0	6.88	7.40	0	2.91	2.78	0	2.56	2.48
		12	0.45	39.52	49.41	0.62	10.61	6.82	0.63	13.85	13.68
		18	2.42	56.10	31.31	3.42	23.90	16.70	4.31	21.50	29.80
		24	5.16	57.18	18.83	3.93	31.64	22.71	5.09	40.42	39.17
		30	16.95	62.54	52.65	4.50	35.90	39.90	7.42	49.73	41.49
		36	15.85	61.78	53.60	6.10	43.25	42.91	8.81	55.85	42.25
	P. placenta	6	0	0	1.03	0	0.20	0.47	0	2.00	0.31
		12	0.79	22.38	4.28	1.98	13.64	2.03	0	10.00	4.23
		18	4.84	51.00	7.90	4.29	30.00	24.30	6.16	31.00	30.20
		24	15.15	53.10	14.50	6.01	63.00	30.01	9.57	34.33	31.88
		30	17.26	59.07	20.02	8.03	64.34	34.52	9.71	45.43	31.19
		36	21.53	64.91	35.70	10.12	64.47	35.94	13.17	47.40	34.61
	T. versicolor	6	0	0.24	0.30	0	1.02	1.06	0	1.77	1.58
		12	0.79	5.38	3.00	1.63	3.24	2.06	0	1.49	3.38
		18	3.18	14.40	5.30	2.69	0.10	4.20	3.96	2.00	4.10
		24	3.33	18.10	6.75	2.84	1.98	4.63	6.35	2.37	5.41
		30	4.00	17.02	11.99	3.90	3.01	4.81	7.11	4.54	5.50
		36	5.90	18.86	16.10	4.12	3.49	3.40	11.12	6.33	5.87
100-130	*G. trabeum*	6	0	1.33	3.10	0	0.96	1.12	0	1.47	1.39
		12	1.19	20.24	6.68	0.76	9.95	5.78	1.56	4.07	6.56
		18	4.76	39.80	10.50	12.37	13.50	12.30	1.43	8.40	27.50
		24	5.48	46.70	32.59	19.63	23.56	13.24	0.40	30.68	29.10
		30	7.13	58.15	57.09	21.99	23.45	23.63	1.00	32.79	29.58
		36	7.67	60.44	59.40	22.03	29.61	33.78	1.15	35.45	31.90
	P. placenta	6	0	0.42	0.88	0	1.63	1.66	0	2.43	1.54
		12	3.99	32.24	3.12	1.63	11.87	2.57	2.80	3.80	2.92
		18	5.91	43.60	5.10	5.73	24.50	20.50	6.09	22.30	2.80
		24	5.49	47.39	11.10	11.71	28.79	10.08	9.74	23.93	4.38
		30	21.83	44.99	15.70	12.94	33.20	12.56	11.61	37.09	5.82
		36	22.91	52.16	19.86	16.91	32.87	13.65	13.71	39.19	18.12
	T. versicolor	6	0	1.59	1.83	0	1.67	1.37	0	0.34	0.27

(continued)

Table 1. *Continued.*

Moisture content (%)	Fungus	Exposure time (wk)	Wood weight loss[a] (%)								
			Southern pine			Douglas-fir			Western hemlock		
			15°C	25°C	35°C	15°C	25°C	35°C	15°C	25°C	35°C
		12	0.55	5.37	6.50	0.73	1.44	1.68	0.95	0.31	2.19
		18	2.17	10.40	4.90	1.26	0.40	2.30	1.95	1.90	2.00
		24	3.64	15.81	4.88	3.23	2.49	18.97	3.77	0.54	4.67
		30	3.75	18.37	4.21	2.13	4.30	41.78	4.66	1.23	1.03
		36	4.35	19.18	3.81	4.00	4.82	45.30	4.28	0.42	8.80

[a] Values represent means of six replicates per time point.

Wang and Morris 2011). The wide range in potential rates of colonization coupled with the fact that decay fungi also compete with other fungi further complicates the predictability of the system. Clearly, there is a need for developing a considerable body of additional data assessing other fungal species/material combinations and for developing improved nondestructive tools for those assessing both fungal- and water-associated damage.

CONCLUSIONS

Decay fungi appeared to be uniformly capable of affecting MOE at very early stages of attack regardless of fungus or wood species when introduced in pure cultures, whereas the effects of fungal attack on MOR were less uniform and more affected by wood species. Results imply that, unless there is prior knowledge of when wetting began in a structure, any wetted wood should be carefully inspected when addressing retrofitting wood subjected to moisture intrusion in a structure until more efficient methods for nondestructively assessing wood condition are developed.

REFERENCES

ASTM (2011a) D 143-09. Standard test methods for small clear specimens of timber. Pages 20-50 *in* Annual book of ASTM standards. Vol. 4.09 Wood. American Society for Testing and Materials, West Conshohocken, PA.

ASTM (2011b) D 2017-05. Standard method of accelerated laboratory test of natural decay resistance of woods. Pages 248-252 *in* Annual book of ASTM standards. Vol. 4.09 Wood. American Society for Testing and Materials, West Conshohocken, PA.

AWPA (2010) E 22-09. Standard accelerated laboratory method for testing the efficacy of preservatives against wood decay fungi. Pages 429-435 *in* AWPA annual book of standards. American Wood Protection Association, Birmingham, AL.

Clark JE, Symonds P, Morris PI (2006) Resistance of wood sheathing to decay. Pages 45-55 *in* Proc Wood Protection 2006, March 21-23, 2006, Omni Royal Orleans Hotel, New Orleans. Forest Products Society, Madison, WI.

Curling S, Winandy JE, Clausen CA (2000) An experimental method to simulate incipient decay of wood by basidiomycete fungi. Doc. no. IRG/WP 00-20200. International Research Group on Wood Protection, Stockholm, Sweden. 13 pp.

Duncan CG, Lombard FF (1965) Fungi associated with principal decays in wood products in the United States. Res Pap WO-4 USDA For Serv, Washington, DC. 31 pp.

Foliente GC, Leicester RH, Wang C-H, MacKenzie CE, Cole IS (2002) Durability design for wood construction. Forest Prod J 52(1):10-19.

FPL (1999) Wood handbook: Wood as an engineering material. Gen Tech Rep FPL-GTR-113 USDA For Serv Forest Prod Lab, Madison, WI. 463 pp.

Kent SM, Leichit RJ, Rosowsky DV, Morrell JJ (2004) Effects of wood decay by *Postia placenta* on lateral capacity of oriented strandboard sheathing and Douglas-fir framing members. Wood Fiber Sci 36:560-572.

Leicester RH, Wang C-H, Cookson LJ (2008) A reliability model for termite attack on housing. Reliab Eng Syst Saf 93(3):468-475.

MacKenzie CE, Wang C-H, Leicester RH, Foliente GC, Nguyen MN (2007) Timber service life design guide. FWPA Project No. PN07.1052. Forest & Wood Products Australia, Melbourne, Australia. 109 pp.

Mankowski M, Morrell JJ (2000) Incidence of wood-destroying organisms in Oregon residential structures. Forest Prod J 50(1):49-52.

Momohara I, Ota Y, Sotome K, Nishimura T (2012) Assessment of decay risk of airborne wood-decay fungi II: Relation between isolated fungi and decay risk. J Wood Sci 58:174-179.

Morrell JJ, Corden ME, Graham RD, Kropp BR, Prybylowicz P, Smith SM, Sexton CM (1987) Basidiomycete colonization of air-seasoned Douglas-fir poles. Proc American Wood-Preservers' Association 83:284-296.

Morrell JJ, Newbill MA, Sexton CM, Zahora AR (1988) Fungal colonization of preservative treated Douglas-fir poles during storage. Forest Prod J 38(1):21-22.

Nofal M, Kumaran K (2011) Biological damage function models for durability assessments of wood and wood-based products in building envelopes. European J Wood and Wood Products 69(4):619-631.

SAS (2008) The SAS system. SAS Institute, Inc., Cary, NC.

Scheffer TC (1971) A climate index for estimating potential decay in wood structures above ground. Forest Prod J 21 (10):25-31.

Scheffer TC, Morrell JJ (1996) Natural durability of wood: A worldwide checklist. Research Contribution 22. Forest Research Laboratory, Oregon State University, Corvallis, OR. 58 pp.

Smith S, Morrell JJ, Freitag C (1992) Residual strength of Douglas-fir sapwood and heartwood as affected by fungus colony size and number of colony forming units. Forest Prod J 42(4):19-24.

Suzuki H, Kitadani Y, Suzuki K, Iwame A, Nagai H (2005) Development on damage functions of wood decay for building envelope design. Doc. no. IRG/WP/05-10556. International Research Group on Wood Protection, Stockholm, Sweden.

Viitanen H (1997) Modeling the time factor in the development of brown-rot decay in pine and spruce sapwood: The effect of critical humidity and temperature conditions. Holzforschung 51(2):99-106.

Viitanen H, Paajanen L (1988) The critical moisture and temperature conditions for the growth of some mold fungi and the brown rot fungus *Coniophora puteana* on wood. Doc. no. IRG/WP/1369. International Research Group on Wood Protection, Stockholm, Sweden.

Wang C-H, Leicester RH, Nguyen M (2008) Probabilistic procedure for design of untreated timber poles in-ground under attack of decay fungi. Reliab Eng Syst Saf 93:476-481.

Wang J, Morris PI (2011) Decay initiation in plywood, OSB, and solid wood under marginal moisture conditions. Doc. no. IRG/WP/11-20469. International Research Group on Wood Protection, Stockholm, Sweden.

Wilcox WW (1978) Review of literature on the effects of early stages of decay on wood strength. Wood Fiber Sci 9(4):252-257.

Winandy JE, Clausen CA, Curling SF (2000) Predicting the effects of decay on wood properties and modeling residual service-life. Pages 261-263 *in* Proc 2nd Annual Conference on Durability and Disaster Mitigation in Wood-Frame Housing, November 6-8, 2000, Madison, WI.

Winandy JE, Morrell JJ (1993) Relationship between incipient decay, strength, and chemical composition of Douglas-fir heartwood. Wood Fiber Sci 25(3):278-288.

Winandy JE, Morris PI (2002) Limiting conditions for decay in wood systems. Doc. no. IRG/WP/02-10421. International Research Group on Wood Protection, Stockholm, Sweden.

Zabel RA, Morrell JJ (1992) Wood microbiology: Decay and its prevention. Academic Press, San Diego, CA. 476 pp.