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Assessing the impact of wood decay fungi on the modulus of elasticity of slash pine (*Pinus elliottii*) by stress wave non-destructive testing

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ABSTRACT

Small wood specimens selected from six slash pine (*Pinus elliottii*) trees were inoculated with brown-rot and white-rot fungi and then evaluated for static modulus of elasticity (MOE) and dynamic MOE (MOE_{sw}). The experimental variables studied included a brown-rot fungus (*Gloeophyllum trabeum*) and a white-rot fungus (*Trametes versicolor*) for six exposure periods (2, 4, 6, 8, 10, and 12 weeks). The MOE_{sw} was tested by a stress wave timer prior to static bending and the results were compared via regression analyses. Regression analyses indicated good correlations between static MOE and MOE_{sw}. The R^2 ranged from 0.66 to 0.80 for non-decayed, brown-rot, white-rot, and all the specimens.

1. Introduction

Wood is a kind of biologic materials which tends to be attacked by the microorganisms, and its structure may be destroyed by fungal decay (El-Gammal et al., 1998; Taniguchi et al., 2005; Wan and Li, 2011; Bari et al., 2015). The fungal decay is one kind of the most serious microbiological deterioration because the strength of wood decreases rapidly (Howell et al., 2011; Ayrilmisa et al., 2015; Karim et al., 2016). According to the degradation mode in wood cell wall, the fungal decay can be classified into three categories: brown-rot, white-rot, and soft-rot (Ejechi et al., 1996; Irbe et al., 2011). Brown-rot and white-rot are severer compared with soft-rot considering the decay time, extent, and resulting damages to wood. In brown-rot, the celluloses and hemicelluloses of wood are broken down, while the lignin remained (Kin et al., 1996). Therefore, the decayed wood cracks into cubes and finally crumbles into powder (Babaee et al., 2015). As for white-rot, the fungus can degrade lignin as well as cellulose and hemicelluloses. However, lignin is degraded earlier in the decay process than cellulose and hemicelluloses (Schwarze and Engels, 1998).

Previous studies have shown that even during early incipient decay of wood, small changes in the chemical composition of wood can result in measurable reduction in strength before measurable weight loss has occurred (Wilcox, 1978; Winandy and Morrell, 1993; Curling et al., 2002). Therefore, it is important to early detect or identify biological decay in wood. Many techniques have applied to assess wood decay, such as weight loss (Carneiro et al., 2009), strength and modulus loss (Yu et al., 2011), microscope techniques (Schwarze, 2007), X-ray diffraction analysis (Li et al., 2011), molecular weight changes (Wang et al., 2013), thermogravimetric analysis (Popescu et al., 2010), Fourier transform infrared spectrum (Popescu et al., 2011), ^{13}C solid-state nuclear magnetic resonance (Tomak et al., 2013) and so on. Although relatively simple to perform, these techniques are often destructive and slow and usually too laborious costly to use in field diagnosis in the majority of situations (Wilcox, 1988; Machek et al., 2001). Consequently, development of rapid and non-destructive methods for timber mechanical measurement is desirable. Up to present, the non-destructive evaluation (NDE) techniques can be classified in two distinct groups: the global test methods and the local test methods (Bucur, 1996). Some researchers used local methods to investigate the mechanical properties of timber, such as such as resistograph testing (Ceraldi et al., 2001) and sclerometer tests (Branco et al., 2010). These methods are easy to handle but limited

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in a small part of the material. Some global methods are also carried out. For example, the ultrasonic testing method is based on measurements of the transit time of an ultrasonic wave in wood (Romano et al., 2016).

Stress wave NDE technique is an important global test method to fast analyze the structure of materials (Bruck, 2000; Wong et al., 2006; Karlinasari et al., 2008). The determination of the material structure is based on the speed of the wave. Ross et al. (1994) used longitudinal stress wave NDE to detect the presence of wetwood. Oliveira et al. (2002) used stress wave NDE to predict the bending property of wood. Afterwards, lots of researches have been carried out to investigate the relationship between stress wave NDE and the physical and mechanical properties of wood among different wood species (Oliveira et al., 2005; Ross et al., 2005; Menezzi et al., 2010).

As mentioned above, the stress wave NDE can be a good alternative for wood mechanical property examination. However, could it be used to early determine the mechanical changes of wood before fungi decay occurred? To support this hypothesis, the accelerated laboratory fungi decay test for wood was design on white-rot (*Gloeophyllum trabeum*) and brown-rot (*Trametes versicolor*) decayed of wood, and the dynamic MOE_{sw} at different stage was tested by using stress wave NDE. Prior to the stress wave test, the static MOE was tested by traditional bending test. The results of dynamic MOE_{sw} and static MOE were compared via regression analyses.

2. Materials and methods

2.1. Preparation of wood specimens

Wood logs measuring 580 mm long were collected from six slash pine trees growing in Jiangxi, China. The sapwood from the logs was cut into specimens measuring 40 (radial) × 40 (tangential) × 580 mm (longitudinal). The specimens were conditioned to 12% moisture content at room temperature in a conditioning chamber. Afterwards, randomly selected specimens were cut into stakes measuring 10 (radial) × 10 (tangential) × 160 mm (longitudinal). Wood specimens were put into a condition chamber to equilibrate at 65% relative humidity and 23 °C before the specimens were dried at 70 °C for determining the initial weight.

2.2. Fungi exposure

A 380 × 250 × 200 mm carton with a polyethylene bag lining was used as a culture vessel with sweetgum veneer feeder strips measuring 360 × 50 × 3 mm (Fig. 1). The water holding capacity of the loam culture soil was determined in accordance with ASTM C 94–2007 and found to be 23%. The polyethylene bags were sterilized at 70 °C for 72 h. The soil, water, feeder strips, and specimens were sterilized according to Schirp and Wolcott (2005) in a steam autoclave at 1.2 MPa pressure and 121 °C for 30 min. After cooling down, a measured volume of soil (about 3000 mL) was added to the culture bag, and the soil was formed into a ridge running the length of the long axis of culture vessel. The sweet gum feeder strips were first placed onto the ridge and the experimental slash pine specimens were placed on the feeder veneer perpendicular to the longitudinal direction of the feeder strips. To avoid contacting with the soil, only the middle section of the specimens was in contact with the feeder strip (Curling et al., 2000). The test fungi were inoculated onto the feeder strips (Fig. 2).

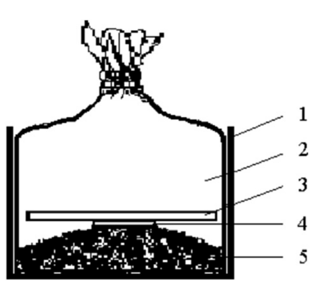

Fig. 1. Fungal exposure method. 1. Culture vessel; 2. Polyethylene bag; 3. Specimen; 4. Feeder; 5. Loam soil.

The treatments were combinations of two decay fungi and six exposure periods (2, 4, 6, 8, 10, and 12 weeks) with 30 replicates per treatment. The two fungi were 1) brown rot, *Gloeophyllum trabeum* (Pers.:Fr.) Murr. (Madison 617) and 2) white rot, *Trametes versicolor* (L: Fr.) Pilat (Madison R-105). In addition, ten specimens per treatment were run without fungi as a non-decayed. A total of 540 small, clear wood specimens were used in the study.

2.3. MOE measuring by stress wave and bending test

At the end of the 12 week study, the specimens were removed from the culture boxes and soft brushes were used to gently remove any adhering mycelium. The specimens were oven-dried prior to determining constant weight at 70 °C and were then placed in a conditioning chamber to equilibrate at 22 °C and 65% relative humidity prior to mechanical testing. After conditioning, the specimens were tested using a stress wave timer (Metrigard 239) by measuring the time transmission along the length of the wood, prior to conductive static bending tests, to determine their dynamic modulus of elasticity (MOE_{sw}). The tests were carried out according to Ross et al. (1994). In detail, the stress wave was induced in the wood by impact, and the transit time was measured with the stress wave timer. The effective zone of each stress wave measurement for all samples was 1–3/16-inch thickness and 6- to 9-inch width. The MOE_{sw} was calculated according to Eq. (1):

$$MOE_{sw} = \left(\frac{d}{t}\right)^2 \left(\frac{W}{V}\right) \frac{1}{g} \quad (1)$$

where, d, W, and V are the length, weight, and volume of measured wood sample; t is transmitted time; g is the acceleration of gravity.

The static MOE of the wood sample was tested according to Chinese standard GB/T 1936.2–2009, which was a four-point bending test. The tension side of the decayed wood specimens in the static bending test was the side that had been in contact with the feeder. All tests were performed in the radial direction.

3. Results and discussion

3.1. Effect of fungi type on decay

The data for weight loss and strength loss in slash pine wood after six periods of exposure in white-rot and brown-rot decay fungi are listed in Table 1. The results demonstrated that with increasing time, the weight and MOE losses increased (except for the white-rot exposure of 6 and 8 weeks), indicating the slash pine

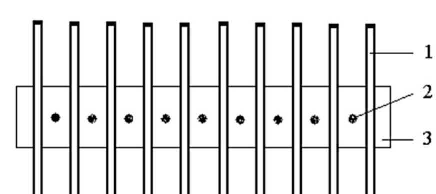

Fig. 2. Fungal inoculation on feeder. 1. Specimen; 2. Fungi; 3. Feeder.

Table 1
Comparison of mechanical property and weight loss on different fungi types.

Fungi	Dependent variable[a]	Exposure period (weeks)					
		2	4	6	8	10	12
White-rot[b]	Weight loss (%)	0.63	0.66	0.79	1.03	1.08	1.20
	MOE loss (%)	0.96	5.35	−0.63	1.20	7.53	6.04
Brown-rot	Weight loss (%)	−0.01	1.12	3.43	6.63	9.72	11.59
	MOE loss (%)	0.27	8.53	15.50	16.69	23.15	25.42

[a] All loss values were calculated based on the control test.
[b] For each period, 30 replicates of white-rot or brown-rot samples were tested.

wood underwent fungal decay. Compared with exposure period of 2 weeks, considerable MOE losses occurred before any appreciable weight loss occurred after exposure of 4 weeks. For example, from 2 weeks to 4 weeks of brown-rot exposure, the weight loss of slash pine increased from 0 to 1.12%, while the MOE loss increased from 0.27% to 8.53%. Besides, the weight and MOE losses of all specimens caused by the brown-rot fungi were greater than those exposed to the white-rot fungi, with the exception of early stages of decay (2 weeks of exposure). One explanation may be brown-rot decay fungi degrade mainly the cellulose and hemicelluloses by depolymerization without extensive loss of lignin, and the white-rot decay fungi mainly degrade the lignin component of wood. It was known that the mechanical properties of wood were mostly related to cellulose, while lignin has less of a structural role compared to cellulose (Goodell et al., 1997). In addition, the slash pine wood is a kind of softwood (coniferous wood), which is showed lower fungi resistance to brown-rot than white-rot. Therefore, the loss of mechanical properties of wood during brown-rot decay is significant. It should be mentioned that after 6 and 8 weeks of exposure, the MOE losses of the wood in white-rot decreased to −0.63% and 1.20%, respectively, which might account for the deviations.

There was a good correlation between weight loss and mechanical property reduction, especially the brown-rot decay. There was a 15% decrease in MOE even before 3% loss in weight. MOE decreased rapidly after 7% weight loss. The data (except for the initial 2 weeks exposure period) showed that the ratio in the comparative loss in mechanical properties compared to weight loss was 3.8:1 for MOE, for specimens exposed to *G. trabeum*. The result for specimens exposed to *T. versicolor* was 4.1:1 for MOE.

3.2. Dynamic MOE

The MOE_{sw} determined from stress waves testing for the specimens after decay treatment were less than destructive MOE values from the static bending tests. The results were of MOE changes with exposure time are shown in Figs. 3 and 4. Due to the variation of wood in its anisotropy and heterogeneity, the MOE changes with exposure time are not very clear considering the error bars. However, it seemed a more clear decrease trend with static MOE and dynamic MOE_{sw} was observed during brown-rot than that during white-rot. One explanation may be the slight effect of white-rot fungi on mechanical properties during incipient decay. To show the relationship between static MOE and dynamic MOE_{sw}, the linear regression was calculated for all specimens on non-decayed, white-rot, brown-rot. The results are shown in Figs. 5–7, respectively. Table 2 illustrates the relationship between static MOE and dynamic MOE_{sw} for all specimens with non-decayed, white-rot, and brown-rot fungi decay at different stages of wood decay. These results showed the correlation between MOE_{sw} and static bending MOE was good for non-decayed, white-rot, brown-rot and all the specimens, and the R^2 (coefficient of determination) ranged from 0.66 to 0.80.

As shown in Figs. 5 and 6, the R^2 of MOE_{sw} and static bending MOE were relatively low for non-decayed specimens and white-rot inoculated specimens. But the R^2 for brown-rot specimens MOE (static bending and MOE_{sw}) was relative large which might be caused by the extension of results range (Fig. 7). Table 3 lists the static MOE and dynamic MOE_{sw} values for non-decayed, white-rot and brown-rot decayed wood. The results indicated that the variability of mechanical properties for non-decayed and white-rot fungi treated specimens is smaller than that of specimens after brown-rot decay treatment, while the data for brown-rot decayed

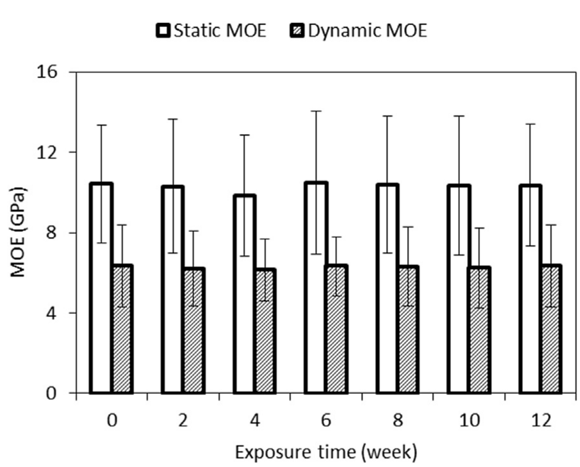

Fig. 3. MOE changes of wood with exposure time during white-rot decay.

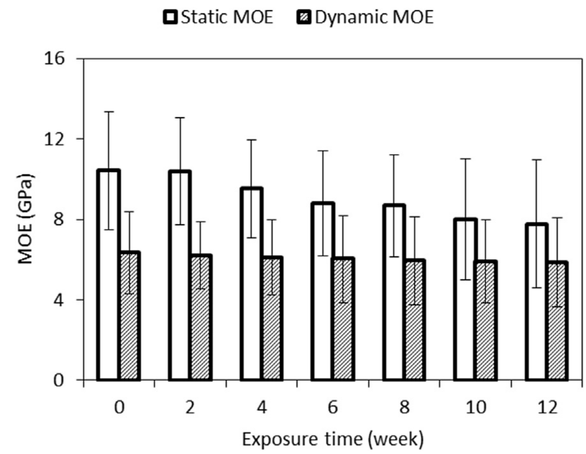

Fig. 4. MOE changes of wood with exposure time during brown-rot decay.

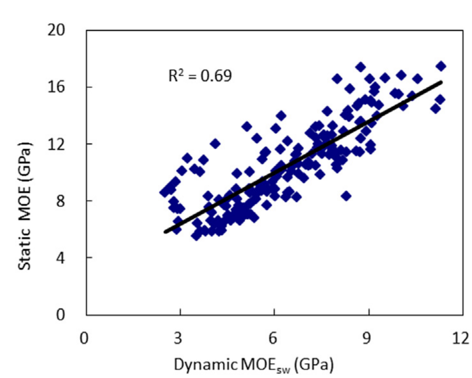

Fig. 5. Relationship of dynamic MOE (MOE_{sw}) to static MOE of slash pine wood without decay.

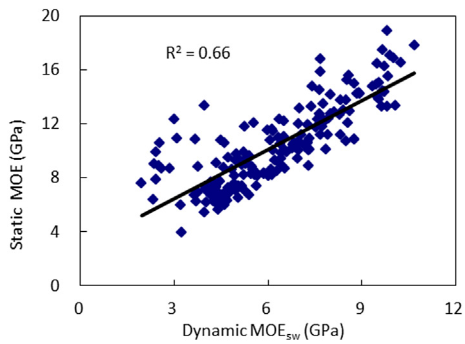

Fig. 6. Relationship of dynamic MOE (MOE_{sw}) to static MOE of slash pine wood after white-rot decay.

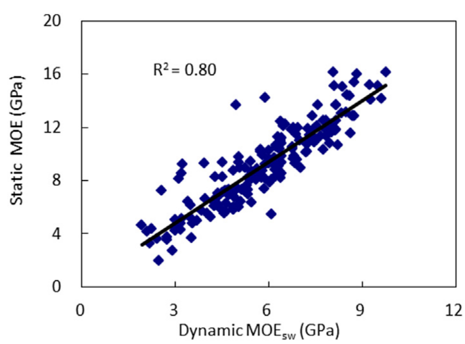

Fig. 7. Relationship of dynamic MOE (MOE_{sw}) to static bending MOE of slash pine wood after brown-rot decay.

Table 2
Correlation between the static MOE and dynamic MOE_{sw} as determined for all specimens with different fungi decayed wood.

Specimens	n[a]	Correlation coefficient R^2	Regression equation
Non-decayed	180	0.69	y = 1.20x + 2.78[b]
White-rot	180	0.66	y = 1.21x + 2.82
Brown-rot	180	0.80	y = 1.53x + 0.23
All	540	0.71	y = 1.31x + 1.92

[a] n is the replicates of tested samples.
[b] y is the static MOE and x is the dynamic MOE_{sw}.

wood contained more variability of mechanical properties. Fig. 8 shows that the relationship of dynamic MOE (MOE_{sw}) to static bending MOE of all specimens, and the R^2 of MOE_{sw} and static bending MOE were 0.71, which showed an acceptable liner relationship.

Table 3
Static MOE and dynamic MOE_{sw} as determined for all specimens with different fungi decayed wood.

Fungi		Non-decayed	White-rot	Brown-rot
n[a]		180	180	180
MOE (GPa)	Mean	10.42	10.34	9.21
	Min	5.56	3.95	1.94
	Max	17.45	18.92	16.16
	STD	2.95	3.03	3.19
MOE_{sw} (GPa)	Mean	6.35	6.22	5.87
	Min	2.52	1.96	1.92
	Max	11.30	10.68	9.76
	STD	2.03	2.03	2.21

[a] n is the replicates of tested samples.

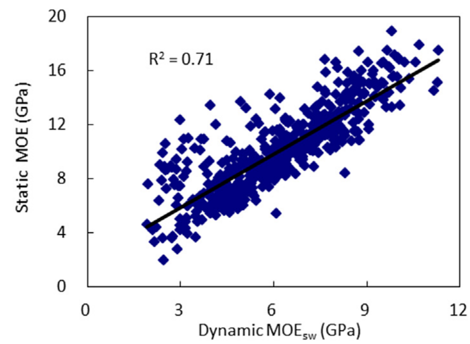

Fig. 8. Relationship of dynamic MOE (MOE_{sw}) to static bending MOE of all specimens.

4. Conclusion

The accelerated laboratory tests to assess wood decay and the use of stress wave NDE for assessing residual strength of wood with at different stages of decay were investigated in this study. The specimens inoculated with brown-rot and white-rot fungi were tested for dynamic MOE (MOE_{sw}) using a stress wave timer prior to static bending and the results were compared via regression analyses. Regression analyses indicated good correlations between static MOE and MOE_{sw}, and the R^2 ranged from 0.66 to 0.80 for non-decayed, white-rot, brown-rot and all the specimens. The R^2 for brown-rot specimens MOE was larger than that of the non-decayed and white-rot specimens, suggesting the high linear relationship between static MOE and dynamic MOE_{sw} of wood in brown-rot decay. The stress wave NDE approach investigated here provided a fairly simple, reliable and non-destructive method to assess wood decay.

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