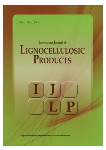

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Assessing the flexural strength changes in decayed wood of Iranian beech (*Fagus orientalis*) by using of nondestructive stress wave method

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Abstract

The aim of this study was to evaluate sound and decayed wood of Iranian beech *(Fagus orientalis)* with a nondestructive stress wave method. Wood samples, with dimensions of 9 by 19 by 200 mm were decayed in laboratory soil-bed tests, based on European pre-standard ENV-807. The decay was evaluated by measuring bending dynamic modulus of elasticity (MOE_d) and longitudinal dynamic modulus of elasticity ($MOE_{d,l}$), using a NDT stress wave method after 6, 12, 18 and 24 weeks of exposure. The static modulus of elasticity (MOE_s) and percentage of mass loss were also measured at the different stages of exposure. The results show that both static and dynamic MOE measurements provide a more sensitive insight into property changes from fungal degradation compared with mass loss percentages. In this regard MOE_d is more reliable compared with $MOE_{d,l}$. There was also a good correlation (r=0.97) between the MOE_s and MOE_d for both sound and decayed Iranian beech.

Keywords: Beech, Decayed wood, Mechanical properties, Nondestructive stress wave.

1. Introduction

Nondestructive testing (NDT), allows properties of materials to be investigated without damage or destruction and the method saves experimental time. NDT methods are also used extensively for wood property evaluations, either in laboratory experiments or in real field inspections (Brazee et al., 2011; Ishiguri et al., 2013). Dynamic NDT techniques including stress wave, ultrasonic, acoustic emission and vibration techniques have long been used, in which measuring the dynamic modulus of elasticity, via dynamic parameters such as frequency and speed of wave propagation, is the main target.

These dynamic NDT methods can reliably assess the decay of wood, especially in primary stages (Brazee et al., 2011, Emerson et al., 2002; Machek et al., 2001; Ross et al., 1996; Wang, 2013; Zhiyong et al., 2000). Decay changes the natural structure of wood so the mechanical strength of wood and modulus of elasticity (MOE) are affected by it. Hence, by measuring the MOE in different periodic stages of decay, the influence of decay on wood can be evaluated. Measuring the dynamic MOE can also be achieved by NDT as an *in situ* evaluation (Emerson et al., 2002; Mora et al., 2009; Pellerin, 1965; Zhiyong et al., 2000) and the stress wave technique is one of the methods which is now used widely for inspections of wood load-bearing members. Previous studies (Chudnoff et al., 1984; Gerhards, 1981; Guntekin at al., 2013; Haines et al., 1996; Machek et al., 2004; Wessels et al., 2011; Zhiyong et al., 2000) show that there are good relationships between static MOE and dynamic MOE. These relationships depend on species, grain direction and existence of other defects (such as knots).

The fundamentals of the stress wave method and its applications have been explained by Ross and Pellerin (1988). This method can be applied in evaluation of members in wood structures (Ross and Pellerin, 1994), decayed wood (Ross et al., 1996), and also standing trees (Wang et al., 2000). Previous studies are mostly focused on the longitudinal stress wave method for measuring the compression strength of samples by using transmission time.

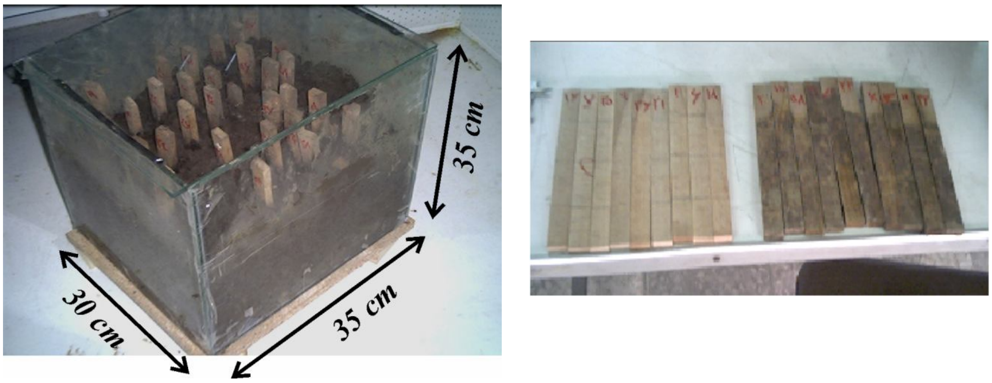
Iranian beech *(Fagus orientalis)* is one of the most important commercial species used in Iran's wood industries. The primary objective of this study was to investigate the application NDT stress wave technique for evaluating the strength of sound and decayed wood of Iranian beech and also to validate this method for evaluation of the properties of other Iranian species. Small samples were decayed in the laboratory and the results are shown based on mass loss percentage and relationships between static MOE and dynamic MOE. In order to generate comprehensive data, wave propagation was evaluated in both parallel and perpendicular directions.

Furthermore, there are heritage wooden buildings in the Gorgan area (North Iran) which are important from the point of view of culture and tourism. A secondary objective of this study was to introduce the stress wave method as a timely and cost-effective technique for the evaluation of load-bearing members in these buildings.

2. Material and methods

Wood samples, with dimensions of 9 mm by 19 mm by 200 mm were decayed in laboratory soil-bed tests, based on European pre-standard ENV-807 (1993). Edge cut and clear samples were prepared from the sapwood component of beech trunks without any defects and grain slope. The chamber conditions, namely a temperature between 26 and 28 °C and relative humidity between 70 and 80% RH, were controlled to promote fungal growth and attack. In total, 63 wood samples were assessed as follows: 36 samples for fungal decay, 20 samples for control of moisture content of soil and 9 samples as sound (control) samples.

Firstly, samples were oven-dried for 24 hours followed by water saturation in order to achieve 50% moisture content. Then, they were inserted vertically in prepared soil chambers (Figure 1a) to approximately one-third of their length (6.5 cm) above soil level in order to observe the changes in the samples. The chamber was covered with a glass plate containing holes to equalize conditions inside and outside of the chamber. The chamber was kept inside an incubator under the recommended standard conditions.



(a)

Figure 1. (a) Controlled soil chamber used for decaying of wood and (b) decayed samples.

The decay was evaluated by measuring bending dynamic modulus of elasticity (MOE_d) and longitudinal dynamic modulus of elasticity ($MOE_{d,l}$), using a NDT stress wave method after 6, 12, 18 and 24 weeks of exposure. The static modulus of elasticity (MOE_s) and percentage of mass loss were also measured at the different stages of exposure. At each stage 10 decayed samples were randomly selected and studied (in week 24, 4 samples were studied). Before starting the decay of samples, the properties of sound (control) samples were studied by NDT and static methods to obtain baseline values.

In order to obtain stress wave in wood samples, a hand-held electronic hammer was used. Two types of waves, namely longitudinal (Figure 2a) and bending (Figure 2b), were generated by impacting the hammer on freely supported samples. For each mode on one sample, the hammer was impacted three times and the average value was calculated. The resulting signals were received by an accelerometer and a Fast Fourier Transformation (FFT) analyser was used to analyse the data and show the waves on an oscilloscope.

Longitudinal and bending stress wave was used in order to calculate, respectively, longitudinal dynamic modulus of elasticity ($MOE_{d,l}$) and bending dynamic modulus of elasticity (MOE_d) by using Hearmon's equations (Hearmon, 1966) in which the frequency is used instead of wave speed.

The static modulus of elasticity (MOE_s), measured in a three-point bending test, and percentage mass loss were also measured at the different stages of exposure.

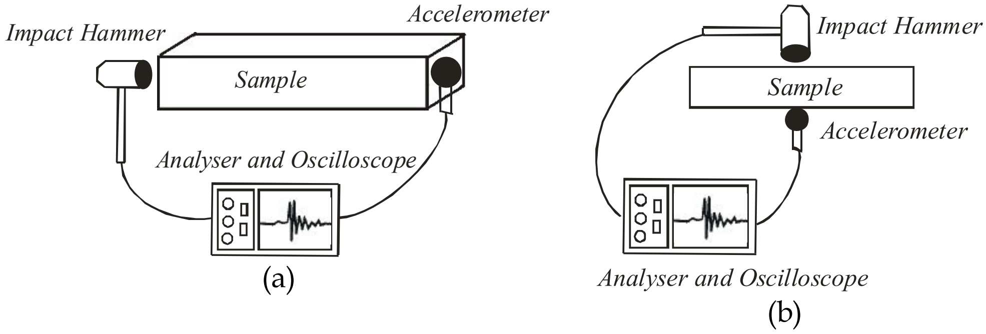


Figure 2. Set-up sample for generating wave in (a) longitudinal and (b) bending modes.

3. Results and discussion

3.1. Effect of exposure time

The results show that the percentage loss of measured parameters, namely weight, MOE_d, $MOE_{d,l}$ and MOEs is increased by exposure time (Figure 3). In other words, each parameter, by itself, can follow the progress of decay in Iranian beech wood. In general, both static and dynamic MOE measurements provide a more sensitive insight into property changes from fungal degradation compared with mass loss percentages (Figure 3). In this regard MOE_d is more sensitive compared with $MOE_{d,l}$.

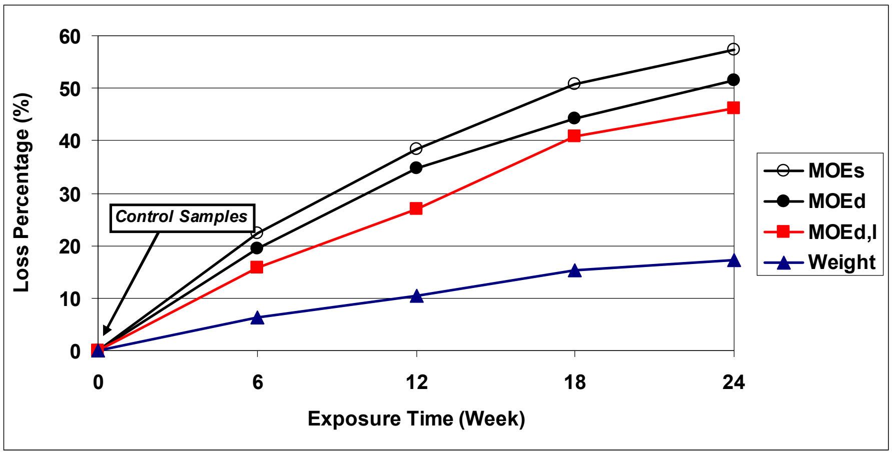


Figure 3. Loss percentage of measured parameters versus exposure time.

In addition, Figure 4 shows that both dynamic and static MOE are able to evaluate the progress of decay as their rates reduce as the exposure time increases. It should be noted that the values of MOE_d and MOE_s are very close to each other, especially during the first stages of decay, for instance at week 12. In general, the magnitude of the measured MOE is in the order of $MOE_{d,l} > MOE_d > MOE_s$.

These findings indicate that in the first stages of decay, in which the mass loss is not appreciable, measurement of either static or dynamic MOE can lead to a confident evaluation of decayed wood. However, dynamic MOE, and particularly MOE_d provides non-destructive parameters which can be useful for *in-service* inspections.

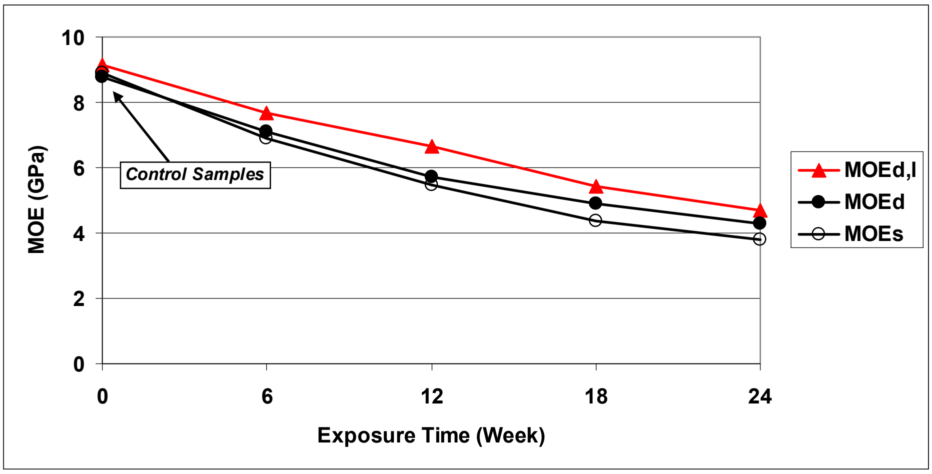


Figure 4. Dynamic and static MOE plotted versus exposure time.

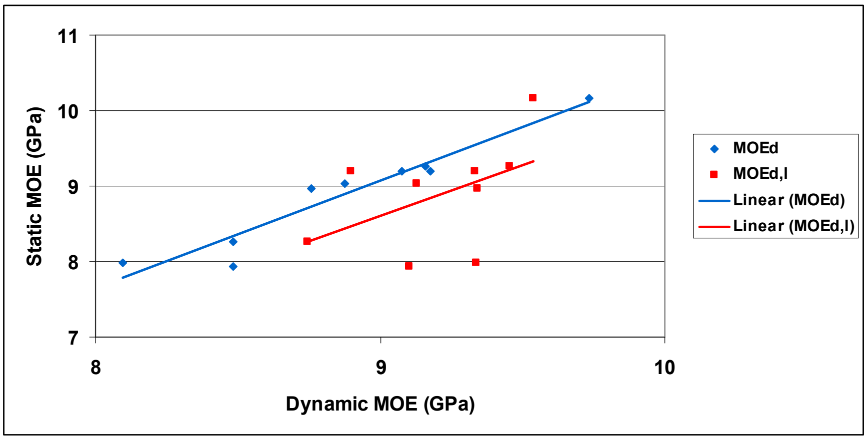
3.2. Relations between dynamic and static MOE

Statistical analysis demonstrates that there are good coefficient of determination correlations (0.93) between the MOE_d and MOE_s for decayed and sound samples (Table 1). Furthermore, a good correlation exists for all samples (0.97) indicating that NDT method used in this study can be considered for evaluation of decayed wood of Iranian beech. These results are very applicable for inspection of old heritage structures which are now important from a cultural point of view.

However, the correlation between $\text{MOE}_{d,l}$ and MOE_s depends on whether the wood is sound or decayed wood (Table 1). The weak correlation in sound samples is very strange whose explanation requires more investigations. Figure 5 demonstrates the relations between these parameters.

Table 1. Correlation and regression equations between static and dynamic MOE for Iranian beech.

Samples	MOE_s and $\text{MOE}_{d,l}$		MOE_s and MOE_d	
	R^2	Equation	R^2	Equation
Sound	0.23	$MOE_s = 1.33 MOE_{d,l} - 3.36$	0.93	$MOE_s = 1.43 MOE_d - 3.77$
Decayed	0.83	$MOE_s = 0.9 MOE_{d,l} - 0.37$	0.93	$MOE_s = 1.08 MOE_d - 8.2$
All	0.89	$MOE_s = 1.05 MOE_{d,l} - 1.22$	0.97	$MOE_s = 1.11 MOE_d - 0.94$



(a)

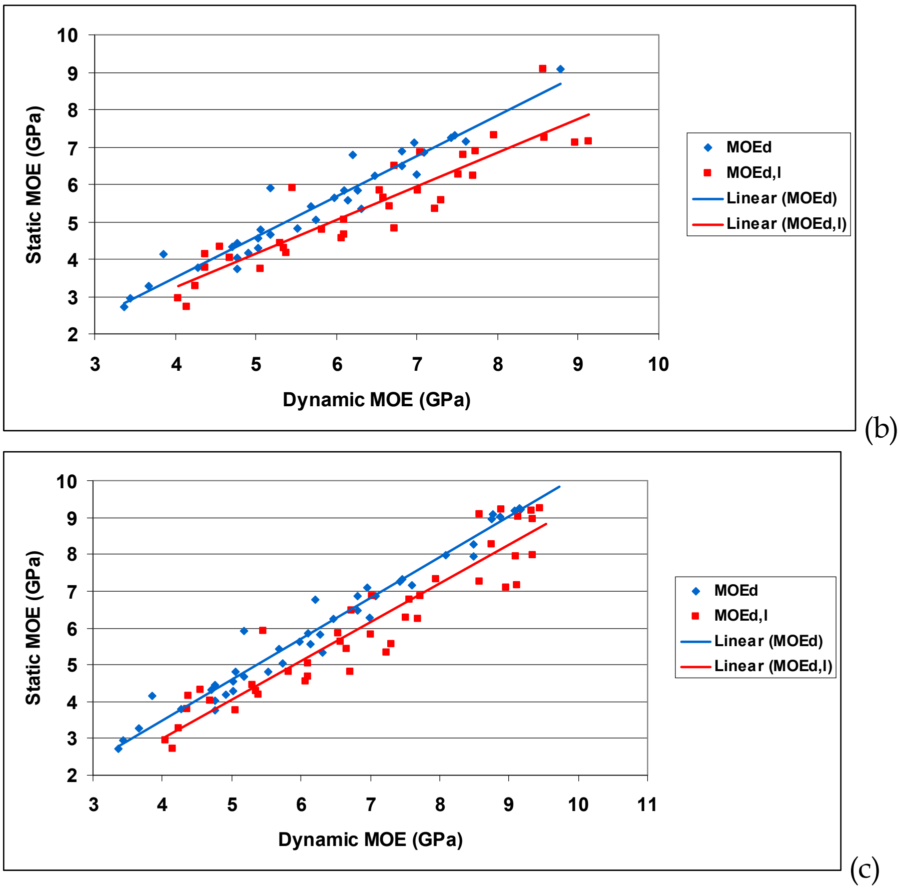


Figure 5. Relations between static and dynamic MOE for Iranian beech in (a) sound, (b) decayed and (c) all samples.

4. Conclusions

1. Dynamic MOE measurements provide a more sensitive measure of property changes from fungal degradation compared with mass loss percentages.
2. MOE_d measured in bending is more reliable compared with the longitudinally measured $MOE_{d,l}$ for decayed wood evaluation, especially in the primary stages of decay.
3. The order of magnitude of measured MOE is $MOE_{d,l} > MOE_d > MOE_s$.
4. There is good correlation (R^2) between the MOE_d and MOE_s (0.97), as well as the $MOE_{d,l}$ and MOE_s (0.83) for decayed wood of Iranian beech.

Acknowledgments

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