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DYNAMIC MOE TESTING OF WOOD: THE INFLUENCE OF WOOD PROTECTING AGENTS AND MOISTURE CONTENT ON ULTRASONIC PULSE AND RESONANT VIBRATION

Gry Alfredsen, Erik Larnøy
Norwegian Forest Research Institute, Høgskoleveien, Ås, Norway

Holger Militz
Institute of Wood Biology and Wood Technology, Büsgenweg, Göttingen, Germany

ABSTRACT

The aim of this study was to compare two methods for non-destructive strength testing of wood by the use of dynamic modulus of elasticity (MOE_{dyn}). The two methods are based on resonant vibration excitation and ultrasonic pulse excitation. Sound *Pinus sylvestris* L. sapwood samples treated with two copper-containing wood preservatives and two chitosan solutions were evaluated at two moisture levels. There was a significant correlation between the measurements given by the two MOE_{dyn} test devices. An analysis of variance showed significant differences between the different treatments and between different moisture levels. Potential use of the non-destructive MOE_{dyn} methods in durability testing is discussed.

KEY WORDS: durability, dynamic MOE, moisture content, resonant vibration excitation, ultrasonic pulse excitation, wood preservatives

INTRODUCTION

Mechanical properties are usually the most important characteristics of wood to be used in structural applications. Some mechanical tests are destructive like modulus of rupture (MOR) and compression strength. MOR is calculated from the maximum load (load of failure) in a bending test, using the same testing procedure as for determining the static modulus of elasticity (MOE) (Kucera 1992). There is a high correlation between MOR and MOE test results (Kollmann and Coté 1968). Strength testing of wood is relatively laborious and often requires stand-testing facilities. However, it provides quantitative and objective results.

The determination of MOE is non-destructive. The available methods for MOE can be divided into static and dynamic test methods (Hearmon 1966). Static techniques (MOE_{stat}) are the traditional methods described in most standards for MOE determination (e.g. ISO 3133 1975, DIN 52186 1978, Kucera 1992, EN 408 1995). The disadvantage in durability testing using MOE_{stat} is that the bars of the testing equipment will irreversibly damage the samples if testing is performed on already decayed wood. Dynamic methods (MOE_{dyn}) may therefore be seen as an alternative. MOE_{dyn} are based either on resonant vibration excitation or ultrasonic pulse excitation of the test sample (Hearmon 1966, Görlacher 1984, Gray 1986). A high correlation between MOE_{dyn} and MOE_{stat} has been reported (Pellerin 1965, Gerhards 1975, Görlacher 1984, Perstorper 1994, Machek et al. 1998, 2001, Grinda and Göller 2005). Although they are less frequently used, dynamic methods have some advantages compared to static methods. Assessment with MOE_{dyn} provides the opportunity for on-site measurements as well as reductions in testing time and labour costs (Machek et al. 2001). They are also of particular interest for evaluation of wood decay due to the non-destructive nature of these methods.

Strength testing, including MOE_{stat}, is considered a reliable test to evaluate fungal attack in wood (Wazny 1959, Wilcox 1978, Hardie 1980, Smith and Graham 1983, Gray 1986, Beall and Wilcox 1987, Sexton 1994, Stephan et al. 1996, 1998). A few studies have been published about the applicability of the resonant vibration method in the assessment of wood decay (Machek et al. 1997, 1998, 2001, 2004, Machek and Militz 2004, Grinda and Göller 2005), showing that vibration MOE_{dyn} is a possible alternative to MOE_{stat} in durability testing. Furthermore, the non-destructive MOE assessment proved to be a suitable tool for early detection of wood decay.

The use of ultrasound pulse excitation for determining the elastic constants of materials is well-established for homogenous materials such as metals (Green 1973). It is also an established technique for the non-destructive evaluation on both sawn timber and standing trees (Arnott et al. 2002). It is less frequently used on smaller test samples. Bauer and Kilbertus (1991) published a study on determination of fungal attack on wood using ultrasound. Jacques et al. (2004) compared the efficiency of three indirect techniques that evaluated Young's modulus (12% moisture). They claim ultrasonic testing is an interesting method for clone classification regarding Young's modulus in a clonal selection programme, whatever the sawing stage. Haines et al. (1996) determined Young's modulus for spruce, fir and isotropic materials, Haines and Leban (1997) MOE of Norway spruce, by the resonance flexure method and made comparison to other dynamic methods (including ultrasound) at 12% moisture content.

The elastic properties of wood are characteristic for solid bodies below a certain limit of stress; above this limit, however, plastic deformations or failure will occur (Kollmann and Coté 1968). From MOE_{stat} measurements it is known that mechanical properties of wood decrease with increasing moisture content (Kollmann and Coté 1968, Skaar 1988).

When using ultrasound below the fibre saturation point, the water molecules move in phase with the vibrating wood cell wall (Wang and Chuang 2000, Wang et al. 2002). However, above the fibre saturation point free water accumulates in the cell lumen and has a relatively low binding strength with the cell wall (Wang and Chuang 2000, Wang et al. 2002). Consequently, free water molecules can not oscillate simultaneously with the cell wall material at a high frequency vibration. Because of the reversed phase motion of free water and cell wall material, vibration loss increases rapidly when wood moisture content is above the fibre saturation point (Wang and Chuang 2000). Thus, the velocity of ultrasonic waves decreases with the increase of moisture content (Wang 1984, Nakamura and Nanami 1993, Bucur 1995, Wang and Chuang 2000, Wang et al. 2002). Sobue (1993) suggested a simulation equation in which a "k" value was defined as the ratio of the weight of free water vibrating simultaneously with wood cell wall material to the weight of total free water.

Alternative wood protecting systems, such as metal-free preservatives and modified wood, can also influence the cell wall and consequently also the mechanical properties (Militz et al. 1997). Different strength test methods might therefore be influenced differently by different wood protecting systems.

The aim of this experiment was to study whether wood preservatives or other wood protecting agents might influence ultrasonic MOE_{dyn} test methods on sound wood samples at two moisture levels. The goal was also to learn more about the use of ultrasonic MOE_{dyn} on sound samples. This necessary basic information is prerequisite for the successful further testing of the method as a potential alternative method for the objective evaluation for durability testing on decayed test samples.

MATERIAL AND METHODS

Samples without faults, 20 x 20 x 300 mm, were prepared from *Pinus sylvestris* L. sapwood, n = 48 samples for each solution treatment. Two wood preservation systems were used as model compounds; conventional copper-containing wood preservatives and chitosan. Chitosan has shown promising results in screening tests as an environmentally benign enhancement of wood durability (Alfredsen et al. 2004, Eikenes et al. 2005). The samples were tested at two moisture levels: conditioned to constant weight at 20°C, 65% RH and water saturated. After MOE_{dyn} testing of the conditioned samples, they were impregnated with water using 1 hour of vacuum. The mass of all samples was measured at both moisture levels. The weight gain after the impregnation was lower for the two chitosan treatments than for the other treatments. Two MOE_{dyn} testing devices were used: Pundit Plus – ultrasound (CNS Farnell, UK) and GrindoSonic MK5 'industrial' - acoustic vibration (J. W. Lemmens N. V., Belgium). The experiment test parameters are presented in Table 1.

Tab. 1: Five wood preservative treatments were tested at two wood moisture levels using two different MOE_{dyn} test methods, Pundit Plus - ultrasonic and GrindoSonic - vibration. n = 48

Wood preservative treatment:
1. Low molecular weight chitosan – LMWC (38.9 kg/m^3)
2. High molecular weight chitosan – HMWC (19.7 kg/m^3)
3. CCA - Kemwood K33 (5 kg/m^3)
4. Cu - Wolmanit CX8 (12 kg/m^3)
5. Control – untreated Scots pine (*Pinus sylvestris* L.) sapwood
Wood moisture content:
1. Conditioned at 20°C, 65% RH
2. Water saturated after 1 hour vacuum impregnation with water

When using the GrindoSonic, the vibration energy was introduced into the specimens through a light tap on the middle of the sample. A transducer that was in contact with the specimen detected the resulting vibration. The procedure is further discussed by Machek and Militz (2004). The MOE dynamic was calculated based on Formula (1), derived by Hearmonn (1966):

$$MOE_{dyn} = \frac{4 \cdot \pi^2 \cdot L^4 \cdot f^2 \cdot p \cdot A}{m^4{}_l \cdot I} \cdot \left(L + \frac{I}{L^2 \cdot A} \cdot K_l \right) \tag{1}$$

where: I = moment of inertia (mm^4), A = area of the cross section (mm^2), f = frequency (kHz), p = mass density (g/mm^3), L = length (mm), K_l = 49.48, m_l = 4.72.

When using the Pundit Plus at 200kHz, an ultra/phonic conductivity gel (Pharmaceutical Innovations Inc.) was applied on the cross sections of the wood specimens to improve the contact between the transducers and the wood sample, and the transit time was measured. The setup parameters were: 500V of the transmitter pulse, metric units, continuous pulse mode, manual log mode and a pulse repetition frequency of 10 pulses per second. To calculate MOE the following formula (2) was used:

$$MOE_{dyn} = \left(\frac{l}{t} \right)^2 \cdot \frac{m}{v} \tag{2}$$

where: l = length of sample (mm), t = transit time (μs), m = mass at measured moisture level (kg), v = volume at measured moisture level (m^3).

As known from literature (e.g. Sobue 1993, Wang et al. 2000, Wang et al. 2002) free water in the cell lumen interfere with the ultrasound measurements. By comparing the correlation between ultrasonic and vibration MOE on samples conditioned at 20°C / 65% RH and at water saturation, a "k" value of 0.72 was calculated, which means there was approximately 72% free water vibrating simultaneously with the cell wall material with the ultrasonic pulse. The result is supported by Sobue (1993), with "k" = 0.78 for *Cryptomeria japonica* (L. f.) D. Don and 0.79 for *Chamaecyparis obtuse* (Sieb. & Zucc.) Endl. using ultrasound at 200kHz. The density of water saturated samples was multiplied with the "k" value in Formula 2.

RESULTS

The calculated MOE_{dyn} results from the ultrasound were always higher, around 4000MPa (approximately 30% higher in conditioned samples and 37% above fibre saturation), than the calculated resonant vibration results. As expected, there were lower values at fibre saturation than in conditioned samples. A regression analysis was performed. There was a significant correlation, p = 0.000, between all the test series of the two MOE_{dyn} testing devices for all treatments and at both moisture levels. In Fig. 1 the fitted regression line for each treatment is shown together with the model for the regression line and R^2. The R^2, the amount of the variation explained by the model, was high.

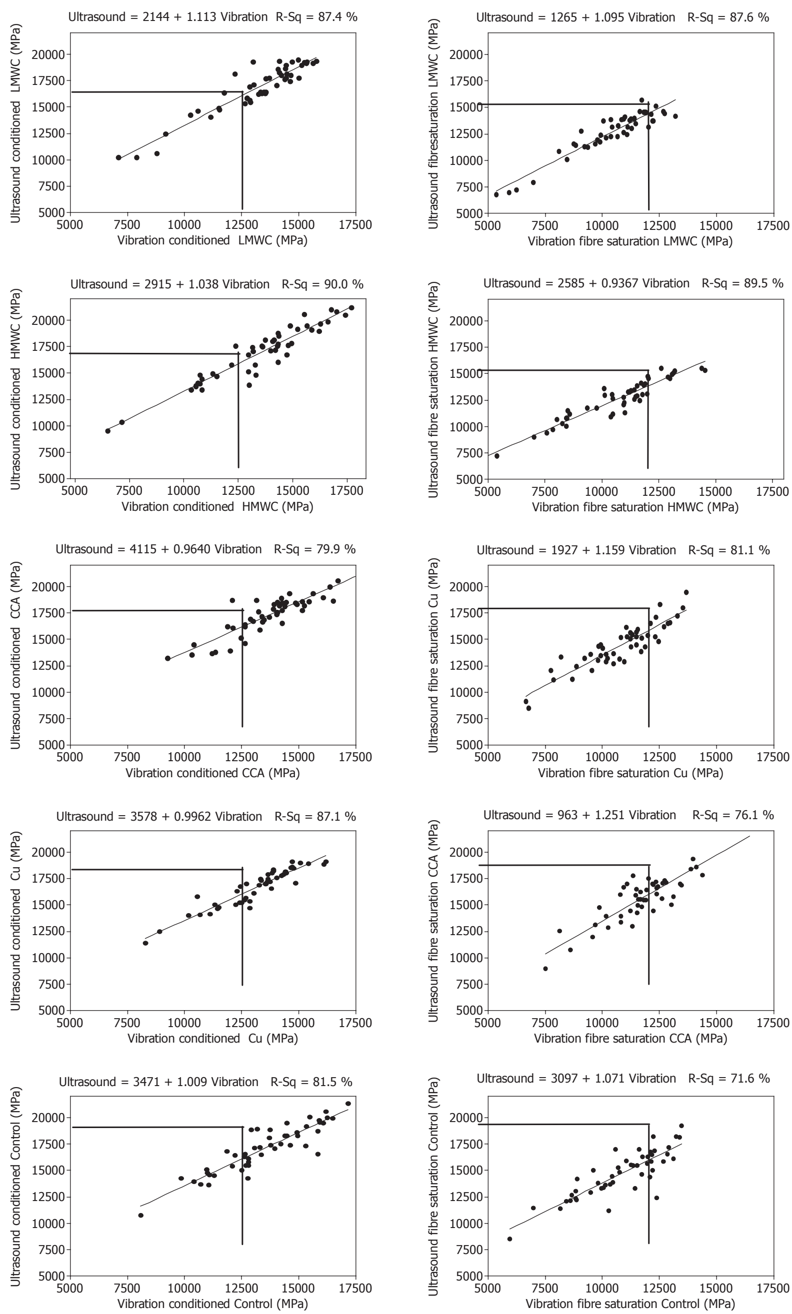

Fig. 1: Fitted regression line plot for each treatment at different moisture levels, ultrasound vs. vibration method given in MPa. The lines indicate the difference in calculated MOE between the two methods

The regression analysis revealed a significant correlation between MOE_{dyn} results from the two test devices. Therefore, to simplify the further analysis of the effect of wood protecting agents and moisture, the vibration method data were subtracted from the ultrasound data to give a new response variable for the further analysis: MOE-diff. An analysis of variance was performed on MOE-diff versus moisture, preservative treatment and the interaction of moisture and preservative treatment. The analysis of variance gave a significant difference ($p = 0.000$) between the different treatments and different moisture levels. The effects of moisture and treatment were nearly equal; $F = 28.51$ for preservative treatments and $F = 27.06$ for moisture. The interaction effect of moisture and treatment was also significant ($p = 0.000$, $F = 24.22$).

To compare pairs of means of the different preservative treatments, Tukey's Test was used. There was no significant difference ($p = 0.231$) between the two chitosan treatment solutions. The high and low molecular weight chitosan treatments were significantly different ($p = 0.000$) from the CCA, Cu and control treatments. No significant difference was found between the control and the two cupper containing treatments, CCA ($p = 0.998$) and Cu ($p = 0.820$), and neither was the CCA treatment significantly different from the Cu treatment ($p = 0.626$).

DISCUSSION

In this study the regression analysis revealed that MOE_{dyn} testing using ultrasonic pulse excitation was significantly correlated with resonant vibration excitation on small sound samples of wood using different wood protecting agents at two moisture levels. The results from the ultrasound were consistently higher than the calculated resonant vibration results. From literature it is already known that the use of different methods to determine MOE leads to different absolute values of MOE. Higher values from MOE_{dyn} compared to MOE_{stat} is found by using vibration (Kollmann and Coté 1968, Görlacher 1984, Machek et al. 2001, Grinda and Göller 2005) and even higher values using ultrasound (Haines et al. 1996, Haines and Leban 1997, Jacques et al. 2004). There are several reasons for these differences. Firstly, the MOE_{dyn} ultrasound above fibre saturation is calculated using a correction factor "k" (Sobue 1993). Further adjustments of "k" will probably give better results. Another reason is due to differences in the nature of the measurement devices. The aim of the research was to measure strength differences, and this difference is maintained in this test using ultrasound versus vibration. For the purpose of the specific research, whether the ultrasound is higher than the vibration is not of essence, as long as they showed a highly significant correlation. No problems occur if the test is consistently performed with the same test equipment, or if the conversion factor between the different test methods is known.

The analysis of variance using MOE-diff data showed significant differences between the different treatments, between the two different moisture levels and also for the interaction effect. From wood physics it is known that the moisture content influences most mechanical wood properties, including MOE. The effect of moisture was as expected; higher wood moisture is known to reduce wood strength (Kollmann and Coté 1968). For MOE tests there is generally no change in the effect of moisture above the fibre saturation point. Ultrasound MOE increase above fibre saturation, an effect previously found by several studies (e.g. Wang and Chuang 2000, Wang et al. 2002, Sobue 1993) and a correction value "k" for water in the cell lumen is needed (Kollmann and Coté 1968). One needs to exert great care with regard to the moisture level in the samples when using ultrasound MOE_{dyn} testing apparatus which is also the case when using other MOE test devices. Wang and Chuang (2000) found that the moisture content below the fibre saturation point had a larger effect on ultrasonic velocity than that above fibre saturation, and they recommended measuring ultrasound MOE above fibre saturation. When comparing the MOE_{dyn} measurements, the results serve as a reminder to be aware of the differences that might occur due to different wood preservative treatments. This is shown in the variance analysis and further analysed in Tukey's test. No differences were detected between the high and low molecular weight chitosan treatments. However, the chitosan treatment measurements were significantly different from those on the CCA-treated, Cu-treated and control samples. By vacuum impregnation with water, the chitosan samples showed lower water retention than the other samples. The reason why the chitosan samples were different from the other treatments is most likely a hydrophobic effect of chitosan, or clogging of tracheids. The interaction effect between moisture and wood preservative treatment in the analysis of variance was almost as strong as the separate effects of treatment and moisture. This is another indication of the hydrophobic effect of chitosan compared to the other treatments. One thus needs to be aware that wood preservative treatments or modifications with hygroscopic properties, or other properties affecting water absorbance, may influence the elastic properties and water retention capacity of wood. There is no problem with using MOE if, from the beginning of the test, the same device is used at a known moisture level. When measuring MOE_{dyn} above fibre saturation, an option is to increase the impregnation time to assure full water penetration.

A potential use of the MOE_{dyn} ultrasound method might be as an alternative objective method for evaluating the strength loss in wood durability testing. Mechanical tests have been proved to be particularly sensitive to fungal decay are MOR and MOE_{stat} (Wazny 1959, Wilcox 1978, Sexton et al. 1993). The measurement of the strength properties of decayed wood is of interest as strength loss during wood decay can be detected earlier than mass loss (Hartley 1958, Bravery and Lavers 1971, Gray 1986). The assessment of MOE is of particular interest due to the non-destructive nature of the measurement. An advantage of using MOE is that very early decay can be measured. Machek et al. (1998, 2001) found that MOE_{stat} and MOE_{dyn} losses determined for decayed wood specimens followed the same trend as the mass loss. However, MOE determination provided a much higher sensitivity compared to mass losses. In field testing MOE has the advantage of providing objective quantitative values, and not only subjective visual evaluation values. Another aspect is that by evaluating fungal attack in test stakes, mass loss determination is not adequate, because the main area attacked is relatively small compared to the whole stake (Machek et al. 1997). MOE_{stat} is a non-destructive test on sound samples but not on decayed samples. One disadvantage with MOE_{stat} as with MOR is that stand-testing facilities are needed. Inspection of field trials MOE_{dyn} also has the advantage that it can be used onsite, and that the measurement only takes a few seconds. For repeated testing of decayed wood, e.g. field test stakes, using moisture content above fibre saturation is most likely the best method. The aim is to avoid interrupting the biological colonisation pattern in the stakes excessively. Water impregnation can also influence the fungi, but this is expected to be a reversible influence. Weeks of conditioning out of soil contact would most likely do more harm than a fast water saturation of the samples.

Both the ultrasound and the vibration method have proved to be applicable on sound samples. Therefore it also has a potential for use in durability testing of decayed samples. However, a correction value ("k") has to be calculated when measuring above fibre saturation.

CONCLUSIONS

In this study two methods for dynamic modulus of elasticity testing of wood were compared; ultrasonic pulse excitation and resonant vibration excitation on samples with different wood preservatives at two moisture levels. Both methods are fast and non-destructive. There was a high statistically significant correlation between the two methods for all treatments at both moisture levels. The ultrasound gives higher values than the vibration method, a familiar finding in earlier studies. Both methods seem to be applicable for testing the resistance of wood against fungi. The study gives necessary basic information about the use of ultrasonic and vibration MOE on sound samples. This information is needed for further evaluating the methods for durability testing on decayed test samples.

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Gry Alfredsen
Norwegian Forest Research Institute
Høgskoleveien 8
1432 Ås
Norway
Phone: +47 64 94 90 00
Fax: +47 64 94 29 80
E-mail: gry.alfredsen@skogforsk.no

Erik Larnøy
Norwegian Forest Research Institute
Høgskoleveien 8
1432 Ås
Norway
Phone: +47 64 94 90 00
Fax: +47 64 94 29 80

Holger Militz
Institute of Wood Biology and Wood Technology
Büsgenweg 4
D-37077 Göttingen
Germany
Phone: +4955 13 93 558
Fax: +4955 13 99 646