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Determination of the relationship between static and dynamic modulus of elasticity in beech wood

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Abstract

In this study, the relationship between the dynamic modulus of elasticity determined using the stress wave method, which is one of the non-destructive test methods, and the static modulus of elasticity determined according to the TS ISO 13061-2 (2021) standard was investigated. In this context, randomly selected beech (*Fagus orientalis* Lipsky) timbers of 12x13x110 cm3 in dimensions were used. The time of flight of the timber in the radial and longitudinal directions was determined by using a FAKOPP microsecond timer with an accuracy of 1 µs. Oven-dry densities of the beech timbers were determined according to the TS ISO 13061-2 (2021) standard. Firstly, stress wave velocity and then dynamic modulus of elasticity values were calculated with the obtained data. The beech timbers were then cut into 20x20x320 mm dimensions for the static modulus of elasticity tests. Static modulus of elasticity resistance tests of the specimens were carried out in a Shimadzu AGIC/20/50KN universal test machine according to the TS ISO 13061-4 (2021) standard. Linear regression analyses of static and dynamic modulus of elasticity results were performed. According to the results of the analyses, it was determined that there is a strong relationship between the static and dynamic modulus of elasticity.

Keywords: Non-destructive tests, Stress-wave, Beech, Modulus of elasticity, Microsecond timer

Kayın odununda statik ile dinamik elastikiyet modülü arasındaki ilişkinin belirlenmesi

Öz

Bu çalışmada, tahribatsız test yöntemlerinden birisi olan stres dalga yöntemi kullanılarak belirlenen dinamik elastikiyet modülü ile TS ISO 13061-2 (2021) standardına göre belirlenen statik elastikiyet modülü arasındaki ilişki incelenmiştir. Bu kapsamda rastgele seçilmiş 12x13x110 cm^3 boyutlarındaki kayın (*Fagus orientalis* Lipsky) keresteler kullanılmıştır. Kerestelerin radyal ve boyuna yöndeki uçuş süreleri, 1 µs hassasiyetteki FAKOPP marka mikro saniye zamanlayıcı kullanılarak belirlenmiştir. Kayın kerestelerin tam kuru yoğunlukları TS ISO 13061-2 (2021) standardına göre belirlenmiştir. Elde edilen veriler ile öncelikle stres dalga hızı ve daha sonra dinamik elastikiyet modülü değerleri hesaplanmıştır. Kayın keresteler daha sonra statik elastikiyet modülü testlerinin yürütülebilmesi için 20x20x320 mm boyutlarına getirilmiştir. Numunelerin statik elastikiyet modülü direnci testleri Shimadzu AGIC/20/50KN üniversal test cihazında TS ISO 13061-4 (2021) standardına göre gerçekleştirilmiştir. Statik ve dinamik elastikiyet modülü sonuçlarının lineer regresyon analizleri yapılmıştır. Analiz sonuçlarına göre statik ve dinamik elastikiyet modülü arasında güçlü bir ilişki olduğu tespit edilmiştir.

Anahtar kelimeler: Tahribatsız test teknikleri, Stres dalgası, Kayın, Elastikiyet modülü, Mikrosaniye zamanlayıcı

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1 Introduction

Wood is one of the traditional building materials used for various purposes since the earliest ages of human history. The mechanical properties of the heterogeneous and anisotropic wood material in different cutting directions vary depending on many factors such as wood species, wood density, anatomical structure, growing conditions, moisture content of the wood, growth defects, presence of rot, etc. Due to the large number of factors affecting the mechanical properties of wood material, the determination of the mechanical properties of wood material is not as practical as the determination of the mechanical properties of other homogeneous building materials. Especially in wood materials, due to the prevalence of growth defects, knots, fungal rot, and insect damage, small size perfect specimens conforming to the standards are traditionally used in laboratory conditions for the determination of mechanical properties. In addition to obtaining more reliable results with a low standard deviation, mechanical tests performed in laboratory conditions with small sized perfect specimens have disadvantages such as time loss and material loss. On the other hand, it is not possible to understand the resistance losses that will be caused by the defects of the large-sized wood material at the place of use (Bozkurt, 1986; Bozkurt and Göker, 1987; Dündar and Divos, 2014; İçel and Beram, 2016).

Destructive test methods are generally used to determine the mechanical properties of wood materials. With the use of destructive test methods, fracture and/or deformation occur in the wood material. In this case, the wood material cannot be reused and is lost. Due to these disadvantages, non-destructive test methods have been developed as an alternative to destructive test methods (Görgün and Dündar, 2016, 2018).

Non-destructive testing methods emerged with the development of instrumentation techniques in the 20th century. In some studies conducted in the 1960s, dynamic test results were determined by using the vibration method for non-destructive testing of structural timbers. By using non-destructive testing methods, information can be obtained about the physical and mechanical properties of the wood material, the growth defects it contains, the physical and biological damages it suffers, etc. without damaging the material. Non-destructive testing methods used in wood are generally classified as mechanical, acoustic, electromagnetic, and nuclear techniques (Bucur, 2003; Hoyle, 1961; İçel and Beram, 2016; Niemz, 2008; Pellerin, 1965; Ross and Pellerin, 1994; Senft et al., 1962; Tanasoiu et al., 2002).

The most widely used non-destructive test method is the acoustic evaluation method. With the stress wave method, which is one of the acoustic evaluation methods, the evaluation of the mechanical properties of industrial products and building timber can be carried out very quickly and easily (Dackermann et al., 2014; Divos, 2000; Divos et al., 2011; Dündar and Divos, 2014; Dündar et al.,2012; Dündar et al., 2013).

The aim of this study is to examine the relationship between the dynamic modulus of elasticity (MOEdyn) determined by the stress wave method, which is one of the non-destructive test methods, and the static modulus of elasticity (MOEstc) determined according to the TS ISO 13061-2 (2021) standard.

2 Material and Methods

2.1 Material

Beech (*Fagus orientalis* Lipsky) timbers obtained from Kastamonu/Turkey were used in this study. Five timbers were randomly selected from the 12x13x110 cm^3 timbers produced from beech sapwood. The timbers were carefully inspected to make sure they had no growing problems, knots, etc. The obtained timber was conditioned at 65±5% relative humidity and 20±2°C temperature. After conditioning, the moisture content of the timbers was measured with a moisture meter with a precision of 0.1 g and found to be 13.4%, 12.7%, 12.6%, 13.2%, and 12.9%, respectively.

2.2 Methods

Within the scope of the study, firstly, the MOE_{dyn} values of beech timbers were determined by the stress-wave method. FAKOPP microsecond timer device with a sensitivity of 1 µs was used in the measurements. The microsecond timer basically measures the velocity of the sound wave (time of flight) sent into the material between the sensors. Defects such as rot, knots, etc. that may be present in the material reduce this speed.

Time of flight measurements were performed in longitudinal and radial directions for all timber groups. Figure 1 shows representative images of the tests performed on beech timber. The sensors were carefully positioned to face each other throughout the tests. Measurements were made at 10 different points randomly selected from each cutting direction. The average flight time values were recorded by hitting three times to the red-coloured sensor with a 100 g hammer at each point. After the measurements, the stress wave velocities of beech timbers were calculated according to Equation 1.

$$\vartheta = \frac{l}{t} \, x \, 10000 \qquad (1)$$

Where; ϑ is stress wave velocity (m/s); l is distance between sensors (cm); t is time of flight (µs).

Figure 1. Determination of time of flight on beech timber

After the time of flight measurements were performed on the timbers, separate density and MOE_{stc} test specimens were prepared from each of the timbers numbered 1, 2, 3, 4, and 5. Density samples were prepared according to the TS ISO 13061-2 (2021) standard with dimensions of 20x20x30 mm^3. The prepared test specimens were dried in a laboratory type oven at 103±2 ºC until they reached constant weight. After drying, they were allowed to cool for 30 minutes in a desiccator containing phosphorus pentoxide. The dimensions of the density samples were measured using a Mitutoyo digital micrometer with an accuracy of 0.001 mm and the weights were measured using a balance with an accuracy of 0.001 g. The oven-dry densities of beech samples were calculated according to Equation 2. MOE_{dyn} values of beech timbers were calculated according to Equation 3 using the oven-dry densities and stress wave velocities of beech timbers.

$$\rho_0 = \frac{\omega}{v} \tag{2}$$

Where; ρ_0 is oven-dry density (g/cm^3); ω is oven-dry weight (g); v is volume (cm^3).

$$MOE_{dyn} = \frac{\vartheta^2 \times \rho_0}{1000} \tag{3}$$

Where; MOE_{dyn} is dynamic modulus of elasticity (N/mm^2); ϑ is stress wave velocity (m/s); ρ is oven-dry density (g/cm^3).

MOE_{stc} test specimens were prepared with dimensions of 20x20x320 mm. The tests were carried out on a Shimadzu AGIC/20/50KN universal testing machine according to the TS ISO 13061-4 (2021) standard (Figure 2). In order to carry out the tests, the distance between the abutments is set to 280 mm. MOE_{stc} was calculated according to Equation 4.

$$MOE_{stc} = \frac{P\ x\ l^3}{4\ x\ b\ x\ h^3\ x\ f} \tag{4}$$

Where; MOE_{stc} is the modulus of elasticity (N/mm^2), P is a force equal to the difference between the arithmetic mean of the lower and upper limits of loading in the zone of elastic deformation (N), l is the distance between abutments (mm), b is the width of the test sample perpendicular to the annual rings (mm), h is the width of the test specimen tangential to the annual rings (mm) and f is the deflection in the net bending area, the difference between the arithmetic means of the results for deflections measured at the upper and lower limits of loading (mm).

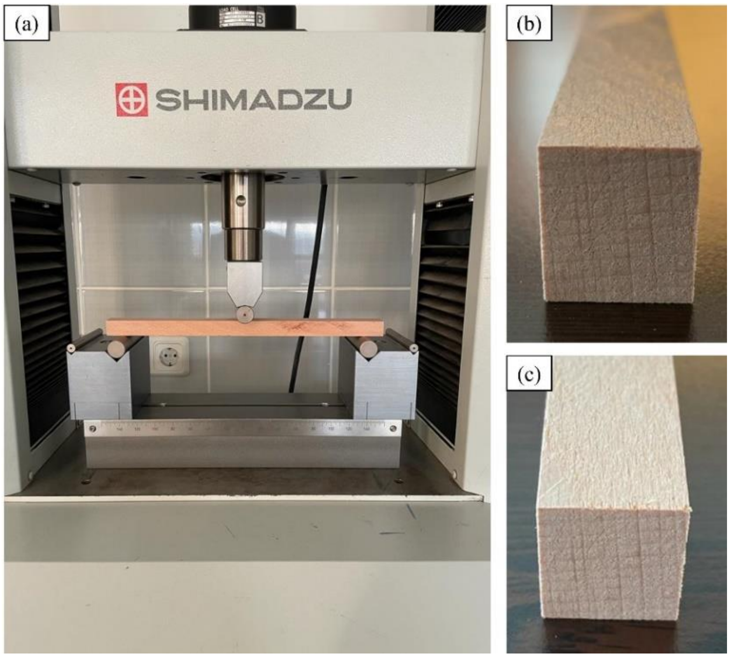

Figure 2. Static modulus of elasticity test (a); test samples (b, c)

3 Results and Discussion

The results of the oven-dry density tests performed on the test specimens taken separately from each beech timber within the scope of the study are given in Table 1. The mean oven-dry density values of each timber were calculated and it was found that there was no significant difference between the mean values. It was determined that the oven-dry density of the beech timbers used in the study was 0.615 g/cm^3.

Table 1. Oven-dry density of beech timbers

Timber Number	Density (g/cm^3)
1	0.617±0.008
2	0.613±0.003
3	0.621±0.011
4	0.611±0.005
5	0.612±0.007
General Mean	0.615±0.004

Time of flight measurements of beech timbers in radial and longitudinal directions were performed and stress wave velocity values were calculated according to Equation 1 (Table 2). When the results were analyzed, it was found that the stress wave velocities of beech timbers were between 1669-1698 m/s in the radial direction and 4807-4883 m/s in the longitudinal direction.

Table 2. Descriptive statistics

Timber Number	Stress Wave Velocity (m/s)		MOE_{dyn} (N/mm^2)	MOE_{stc} (N/mm^2)
	Radial Direction	Longitudinal Direction		
1	1680±37*	4883±78	14666±472	10724±610
2	1675±33	4823±29	14309±173	10353±616
3	1698±27	4807±20	14213±119	10741±897
4	1682±22	4817±27	14268±158	10715±716
5	1669±36	4836±52	14381±312	10495±870

*Standard deviation

According to the studies in the literature, it is stated that the stress wave velocity values of a solid wood material should be in the range of 1000-1500 m/s in the radial direction and 3500-5000 m/s in the longitudinal direction (Dackermann et al., 2014; White & Ross, 2014). On the other hand, in the manual of the FAKOPP microsecond timer device used in time of flight measurements, it is stated that the mean stress wave velocity in the radial direction for beech species (*Fagus sylvatica*) is 1650 m/s (FAKOPP, 2022). It is understood that the results obtained in this study are compatible with the literature.

MOE_{dyn} values of beech timbers were calculated according to Equation 3. It was determined that the mean MOE_{dyn} values varied between 14213-14666 N/mm^2. On the other hand, the average MOE_{stc} values determined by using small-size perfect specimens were found to be between 10353-10741 N/mm^2. As in many studies, MOE_{dyn} values were higher than MOE_{stc} values in this study (Guntekin et al., 2014; Teles et al., 2011). There was approximately 26% difference between the MOE_{dyn} and MOE_{stc} values. This difference is thought to be due to the creep that occurs during the performance of the MOE_{stc} test (Divos and Toshinari, 2005; Perstorper, 1994; Tanaka et al., 1991).

In order to question the effectiveness of determining mechanical properties by stress wave method, the data obtained by non-destructive test methods were compared with the results obtained by destructive test methods.

Table 3. Regression analysis results.

Timber Number	*p* - value	R^2	Model
1	0.0002	0.8388	y = 7072.35 + 0.70x
2	0.0149	0.5441	y = 12163.39 + 0.20x
3	0.0003	0.8149	y = 12923.32 + 0.12x
4	0.0032	0.6834	y = 12312.46 + 0.18x
5	0.0004	0.8087	y = 10991.48 + 0.32x

The *p*, R^2 values and regression models obtained for each timber by regression analysis in the comparisons are given in Table 3. It is seen that the p value is less than 0.05 for all timbers. On the other hand, R^2 values vary between 0.54 and 0.83. This shows that there is a strong relationship between MOE_{dyn} and MOE_{stc} values for each beech timber.

The regression graph, *p*, R^2 values, and regression model obtained when MOE_{dyn} and MOE_{stc} values obtained from all timbers are evaluated together are shown in Figure 3.

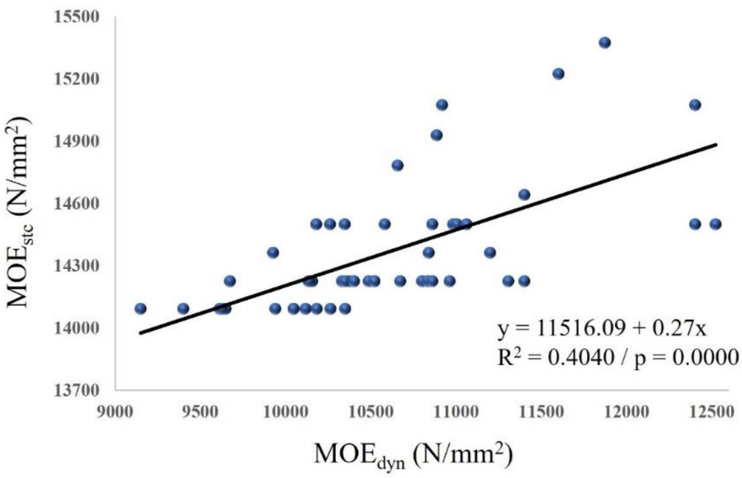

Figure 3. Relationship of static and dynamic modulus of elasticity.

Figure 3 shows that there is a relationship between MOE_{dyn} and MOE_{stc} values. The most appropriate linear regression line passing through the points was obtained as "y = 11516.09+0.27x". At the same time, the R^2 value of the model was found to be 0.4040. According to all these results, it can be said that if MOE_{dyn} increases by one unit, MOE_{stc} will increase by 0.27 units.

4 Conclusions

As a result of this study, in which the relationship between MOE_{dyn} obtained by using the stress wave method, one of the non-destructive test methods, and MOE_{stc} obtained by using destructive test methods in beech wood was examined, the following can be said:

- As a result of the destructive and non-destructive tests, it was found that there was a strong correlation between MOE_{stc} and MOE_{dyn}.
- When the data obtained from all beech timbers were evaluated together, according to the linear regression analysis, it was determined that if MOE_{dyn} increased by one unit, MOE_{stc} would increase by 0.27 units.
- By proving the existence of the relationship between MOE_{stc} and MOE_{dyn} and modelling this relationship with regression analysis, reliable predictions of the mechanical properties of structural beech timber by the stress wave method can be achieved.
- It is recommended that the relationship between MOE_{dyn} measured in planted trees and MOE_{dyn} measured after the same trees become timber should be modelled.

Author Contributions

Emre Birinci: Determination of the study topic, design of the experiment, obtaining data, analyzing and commenting on the data, writing and publishing the article.

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Conflict of interest statement
The author declare no conflict of interest.

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