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Using the Ultrasonic Stress Wave Technique to Evaluate Structural Timber Members of an Old Masonry Building

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Abstract

Aim of study: The main objective of this study is to evaluate the current state of the structural timber members of an old masonry building by using destructive and non-destructive test methods and to determine the efficiency of non-destructive test methods by obtaining correlations between destructive and non-destructive test parameters.

Area of study: Specimens were extracted from different parts of an old semi-detached masonry building in Istanbul, Turkey. The building was built at the beginning of the 20th century in Kadıköy, a residential district in the Asia side of Istanbul.

Material and Methods: Ultrasonic stress wave test was carried out on specimens prepared from the structural members. Following the ultrasonic based non-destructive tests, the bending strength and modulus of elasticity in the bending tests were determined for the specimens.

Main results: According to the results of the experiments, it was observed that the regression correlations were high for the softwoods (fir and spruce), but relatively lower correlations were obtained for the chestnut specimens.

Highlights: Because of the good R^2 values obtained between the MOE_D and mechanical properties of the softwoods, the non-destructive stress wave technique can be recommended for the evaluation of softwoods in structures. Although chestnut showed very good mechanical properties, a satisfactory evaluation of the chestnut members could not be obtained because of the small number of specimens. Further investigation is needed with large sample groups.

Keywords: Structural Timber, Destructive Test, Non-destructive Method, Chestnut Wood, Fir Wood, Spruce Wood

Tarihi Bir Yığma Yapının Yapısal Ahşap Elemanlarının Ultrasonik Stres Dalga Yöntemi İle Değerlendirilmesi

Öz

Çalışmanın amacı: Çalışmanın amacı, eski bir yığma yapının ahşap yapı elemanlarının mevcut durumlarının tahribatlı ve tahribatsız test yöntemleri ile değerlendirilmesidir. Tahribatlı ve tahribatsız test parametleri arasındaki korelasyonlar elde edilerek tahribatsız test yöntemlerinin verimliliğinin belirlenmesi amaçlanmıştır.

Çalışma alanı: Numuneler İstanbul'da bitişik nizamda inşa edimiş eski bir yığma yapının farklı kısımlarından çıkarılmıştır. Yapı 20. yüzyılın ilk yarısında, İstanbul'un ağırlıklı olarak konut yerleşiminin bulunduğu Anadolu yakasındaki Kadıköy ilçesinde inşa edilmiştir.

Materyal ve Yöntem: Yapısal elemanlardan elde edilmiş numunelere ultrasonik stres dalga testi uygulanmıştır. Bu testin ardından numunelerin, eğilme dayanımı ve eğilmede elastiklik modülü değerleri belirlenmiştir.

Sonuçlar: Yapılan deneylerin sonuçlarına göre, yapraklı ağaçlardan elde edilen numunelerin (köknar, ladin) korelasyonları yüksektir, ancak kestane numuneleri için daha düşük korelasyonlar elde edilmiştir.

Önemli Vurgular: Yapraklı ağaçlardan elde edilen numunelerin MOE_D ve mekanik özellikleri arasındaki korelasyon değerlerinin yüksek olması sebebiyle ultrasonik stres dalga testinin bu türlerin değerlendirilmesinde kullanılması tavsiye edilebilir. Bununla birlikte, kestane ahşabı yüksek mekanik özelliklere sahip olmasına rağmen, numune sayısının az olması sebebiyle bu ağaç türü ile ilgili tatmin edici sonuçlar elde edilememiştir. Bu konuda tatmin edici sonuçlar elde edilebilmesi için daha fazla sayıda numune ile araştırma yapılması tavsiye edilmektedir.

Anahtar kelimeler: Yapısal Ahşap, Tahribatlı Test, Tahribatsız Yöntem, Kestane Ahşabı, Köknar Ahşabı, Ladin Ahşabı

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Introduction

It is important to assess the residual structural capacity and preserve the original configuration of old timber structures to not only to evaluate the safety of a building, but also to preserve the historical heritage and sustainability of the structure. In many Mediterranean countries and Turkey, numerous historic buildings have been preserved and the procedures to preserve the architectural heritage have recently gained importance (Calderoni, De Matteis, Giubileo & Mazzolani, 2010). Because wood is mainly made of organic substances, the deterioration of wood is usually caused by biological processes. Natural defects, such as knots, checks, and cracks, also influence the strength properties of wood. There is some controversy about the influence of load history and duration on the strength properties of structural timber members, but generally, if no damage occurs during loading, it can be assumed that there is no loss in the mechanical properties (Lourenço, Feio & Machado, 2007). Several experimental studies evaluating the strength properties of old timber building members have found that the hardness and modulus of elasticity (MoE) of the specimens are particularly relevant to the results of newly cut wood and the material can be used for other purposes after dismantling (Falk, Green & Lantz, 1999; Falk, Green, Rammer & Lantz, 2000; Bektaş, Mehmet, Göker, As & Erdaş, 2004).

The strength properties of timber can be determined by destructive tests according to standardized procedures. Although this is a common practice, destructive tests are usually not acceptable in existing old buildings because of the permanent loss of the timber members. In recent years, non-destructive test (NDT) methods have also been used for the assessment of mechanical properties of timber to maintain the sustainability and integrity of old buildings (Machado and Palma 2011; Morales Conde, Liñan & Rubio de Hita, 2014). Destructive tests are also performed to increase the efficiency of NDTs and obtain additional correlations between the strength properties of wood. Correlations between the NDTs and destructive tests of different wood species have been examined in previous studies. Strong correlations have been obtained for most structural wood species.

A preliminary visual inspection must be done and is used as the principal tool during the assessment of old buildings. Nevertheless, a visual inspection can sometimes be unreliable because of the experience of the specialist or properties of the *in situ* conditions of the timber member (covered up surfaces, limited access to a number of faces, *etc*.). For this reason, during the survey of a site, other NDT methods are also applied to support the visual inspection (Calderoni et al., 2010; Faggiano, Grippa, Marzo & Mazzolani, 2011; Feio and Machado, 2015). The application of NDTs must be done by experts to prevent failures, which could lead to large-scale replacements and the consumption of natural resources during restoration (Calderoni et al., 2006; Palaia et al., 2008; Morales Conde et al., 2014).

Some of the most common NDTs are density determination and stress wave tests (sonic and ultrasonic). Because NDTs usually give limited information about the mechanical properties of the timber, different NDTs must be performed to improve the assessment accuracy (Hanhijärvi and Ranta-Maunus, 2008; Piazza and Riggio, 2008). It is important to use NDTs during the renovation and restoration of historical timber structures. These techniques protect the integrity of the building and can be more efficient and reliable if the results are supported with extensive laboratory tests that provide correlations between the different timber parameters.

In this study, the current state of the structural timber members of a one-hundred-year-old masonry building was evaluated using the ultrasonic stress wave technique and destructive tests. In particular, the relationships between the ultrasonic stress wave test results and the strength and stiffness properties of the specimens were investigated. Thus, the reliability of the ultrasonic stress wave technique was determined.

Material and Methods

Specimens were extracted from different parts of an old semi-detached masonry building in Istanbul, Turkey, which was built at the beginning of the 20th century. The building was in a residential district and it was used for residential purposes until the 1980s.

After that period, it was used as a commercial building. This type of building construction was very common at the beginning of the 20th century, and is characterized by a rectangular plan that is built semi-detached. The masonry walls were constructed with load-bearing solid brick for the lower floors. The floors were constructed with timber rafters and joists supported by masonry walls. The walls of the top floor were constructed with a timber frame covered by lath. The roof was constructed with timber framed double pitched roofing and ceramic tile covering (Fig. 1).

Figure 1. Building from the 80's

Structural wood members were extracted from the floor, wall, and roof of the building (Fig. 2). Roof and wall members were taken from the top floor and floor members were taken from the first floor of the building. Most of the wood members had a length of 1.80 m to 2.00 m with various cross sections. Some of the interior studs and diagonals were obtained directly from tree trunks, and thus their dimensions were irregular. Table 1 details the tree species, locations, dimensions, and number of structural wood members extracted from the building.

Figure 2. Top floor timber framed wall.

Table 1. Structural Wood Members Extracted from the Building

Building Member		Species	Location in the Building	Number of Samples	Average Full-size Dimensions (mm)
Roof	Ridgepole	Fir	Roof	1	240×60
	Roof board	Fir	Roof	7	180×20
	Rafter	Fir	Roof	4	140×40
Wall	Stud	Fir, chestnut	Top floor	8	110×100
	Nogging	Chestnut	Top floor	2	100×100
	Diagonal brace	Chestnut	Top floor	1	90×80
Floor	Floor covering	Spruce	1st floor	8	130×20
	Floor joist	Fir	1st floor	4	130×40

The full-size wood members were inspected visually to detect visible defects and signs of deterioration, and were then sawn into relatively small laboratory specimens. Table 2 gives the dimensions of the specimens.

Table 2. Process of the Experimental Stage, NDT, and Destructive Test

Specimen		n	Dimensions (mm) (ρ, MC, US, f_b, MoE$_S$)	Dimensions (mm) (f_c)
Roof	Ridgepole	8	40×40×640	40×40×60
	Roof board	70	15×15×250	15×15×30
	Rafter	24	40×40×640	40×40×60
Wall	Stud	19	30×30×495	30×30×45
	Nogging	8	40×40×640	40×40×60
	Diagonal brace	4	40×40×640	40×40×60
Floor	Floor covering	80	20×20×330	20×20×30
	Floor joist	24	40×40×640	40×40×60

ρ – Density; MC – Moisture content; US – Ultrasonic stress wave test; f_b – Bending strength; MoE$_S$ – Modulus of elasticity; and f_c – Compression strength

Before the laboratory tests were performed, the specimens were kept in a climatic room at a relative humidity of 65% ± 5% and 20 °C ± 2 °C until the mass variation was smaller than 0.2% (Fig. 3).

Fig. 3. Full-scale test specimens

Ultrasonic-based NDTs and conventional destructive laboratory tests were performed on the test specimens prepared from the structural members. First, the moisture contents (MC) and air-dried density (ρ) of all of the laboratory specimens were determined.

Ultrasonic stress wave tests were then performed as NDTs. Following the ultrasonic tests, the bending strength (f_b) and modulus of elasticity in the bending tests (MoE$_S$) were determined for the specimens.

After the bending tests, the compression strength (f_c) test specimens were prepared from the end portion of the bending specimens. Table 2 shows the dimensions and number of specimens for both the NDTs and destructive tests.

Determination of the density

The density was determined based on the weight and volume of the specimens at an air-dried MC (12%) according to ISO 13061-2 (2014). The specimens were conditioned in a climatic room at a constant temperature (20 °C ± 2 °C) and humidity (65% ± 5%) until the mass variation was smaller than 0.2%. The mass of the specimens was measured using an electronic weighing machine with a precision of 0.01 g.

The dimensions were measured with a caliper with a precision of 0.01 mm. The average density ($\rho_{12\%}$; kg/m^3) was determined at a MC of 12% with Eq. 1,

Equation 1. Density Measurement Equation

$$\rho_{12\%} = m_{12\%} / V_{12\%}$$

where m is the mass (kg) and V is the volume (m^3) of the specimens.

Determination of the moisture content

An increase in the MC affects the MoE and f_c of timber, and consequently, it was important to determine the MC of the specimens. The MC of the specimens was determined in accordance with ISO 13061-1 (2014). First, the weight of the specimens was measured, and then they were dried in an oven until a constant weight was reached. Finally, the oven-dried mass was measured and the MC of the specimens were evaluated according to Eq. 2,

Equation 2. Moisture Content Measurement Equation

$$MC\ (\%) = (m_H - m_O)/m_O \times 100\%$$

where m_H is the initial mass of the specimen (gr) and m_O is the mass of the specimen after being oven-dried at a temperature of 103 °C ± 2 °C until a constant mass was reached (gr).

Ultrasonic test

The transmission time of the ultrasonic wave was measured by a Sylvatest Duo (CBS-CBT, Les Ecorces, France) with conical probes at a frequency of 22 kHz. The equipment emitted a wave that was transmitted through the length of the specimen (L; m) from the transmitter probe to the receiver probe. The "time of flight" (ToF; s) between the probes was measured, and thus the velocity of transmission was calculated with Eq. 3,

Equation 3. Measurement of Velocity Equation

$$V = L / ToF$$

where V is the velocity (m/s).

By using the V and ρ of the specimen, the dynamic modulus of elasticity (MoE_D; N/mm^2) was determined with Eq. 4,

Equation 4. Measurement of Dynamic Modulus of Elasticity

$$MoE_D = V^2 \times \rho$$

The wave transmission time was recorded for each specimen with a direct method in the parallel to the grain direction, as is shown in Fig. 4.

Fig. 4. Ultrasound measurement on a small specimen

Determination of the ultimate strength during static bending

Three-point bending tests were done on the specimens with a Lloyd LS100 universal test machine (Lloyd Instruments, Ametek Company, West Sussex, UK), as is shown in Fig. 5. The specimens were prepared in the form of rectangular prisms, each having a square cross-section of no less than 20 mm × 20 mm and length of 12 to 16 times the height of the test piece, depending on the full length of the structural member taken from the building.

Fig. 5. Bending test set-up

The applied force was transferred to the specimen in the tangential direction. The loading speed was set so that the failure would occur within 60 s to 120 s. The f_b (N/mm^2) of the specimens was calculated with Eq. 5,

Equation 5. Measurement of Ultimate Strength during Static Bending

$$f_B = \frac{3}{2}\frac{PL}{bh^2}\ (N/mm^2)$$

where P is the maximum bending load (N), l is the specimen span (mm), b is the specimen width (mm), and h is the specimen depth (mm).

Determination of the modulus of elasticity during static bending

The MoE_S was determined during the static bending test on the same specimen. The force-controlled procedure consisted of several loadings of the elastic deformation limit. The minimum load, maximum load, and corresponding deformation of the specimens were measured by loading the specimen at a constant rate. The MoE_S was determined with Eq. 6,

$$MoE_S\ (N/mm^2) = \frac{\Delta P}{\Delta F}\frac{l^3}{4bh^3}$$

where ΔP is the load increment below the elastic limit (N), ΔF is the increment in the corresponding deformation, l is the specimen span (mm), b is the specimen width (mm), and h is the specimen depth (mm).

Determination of the ultimate stress during compression parallel to the grain

Compression stress parallel to the grain tests (Fig. 6) were done on specimens with a square cross-section of at least 20 mm and length along the grain that was 1.5 to 4 times greater than the cross-sectional dimensions (Table 2). The loading speed was set so that the failure would occur within 60 s to 120 s.

The f_c (N/mm^2) was obtained by dividing the load cell value by the cross-sectional area of the specimen (Fig. 6).

Fig. 6. Compression test parallel to the grain

After the nondestructive and destructive tests, based on the laboratory test results, linear regression models were obtained by using the SPSS program (IBM, New York, USA) in order to present the relationship between mechanical properties and nondestructive methods.

Results and Discussion

According to the initial visual inspection of the full-size wood members and considering that the building was approximately one-hundred years old, the building members were well preserved because of the constant MC and continuous residential and commercial use. The specimens had some defects, such as cracks and checks, and evidence of insect attacks. Most of them had dead or sound knots, while several others had knot holes. Some of the specimens had cracks, shakes, deteriorated parts, and holes because of insect attacks and nails. In particular, the rafters and flooring had some damage caused by insect attacks. Mechanical deformation (such as twisting, cupping, and bowing) was not observed in any of the specimens.

Table 3 presents the mean ρ, MC, V, and MoED results of the NDTs for the fir (*Abies cilicica*), chestnut (*Castanea sativa*), and spruce (*Picea abies*) specimens.

Table 3. Experimental Results of the NDTs

Member	Species	ρ (kg/m^3)	MC (%)	Ultrasonic Test (Direct Method, Parallel to the Grain)	
				V (m/s)	MoE$_D$ (N/mm^2)
Roof	Fir	426.40 (57.50)	11.56 (0.45)	6050.75 (621.05)	15682.54 (4481.55)
Wall	Fir	402.32 (16.89)	12.49 (0.43)	5083.23 (529.50)	11492.16 (3241.02)
	Chestnut	569.79 (40.13)	12.03 (0.30)	4879.53 (300.60)	12321.89 (1613.21)
Floor	Fir	411.93 (34.70)	12.37 (0.31)	5680.15 (199.24)	14798.77 (1283.47)
	Spruce	482.90 (66.60)	12.46 (0.46)	5596.17 (438.17)	16168.66 (4417.88)

The values in parentheses are the standard deviations.

The literature densities of recently sawn fir, chestnut, and spruce wood are 430 kg/m^3, 570 kg/m^3, and 470 kg/m^3, respectively (Bozkurt and Göker 1996). When the values were compared, it was found that the densities of the chestnut and spruce specimens were consistent with the literature values. However, the fir specimens from the wall and floor had slightly lower densities.

The MC of all of the specimens had been measured between 10% to 12%, which corresponded to the MC of a sound wood specimen measured under normal ambient conditions.

The ultrasonic test results that are shown in Table 3 represent the average V measurements of the readings. The average V values differed between the fir specimen groups. The results were consistent with the literature values for coniferous tree species. However, the wall fir specimens again had slightly lower values than the other specimens (Ross 2015). The V results of the chestnut and spruce specimens were in accordance with other research results (Lourenço *et al.* 2007).

The mean values of the f_b, MoE$_S$, and f_c of the destructive tests are given in Table 4.

Table 4. Experimental Results of the Destructive Tests

Member	Species	f_c (N/mm^2)	Bending	
			f_b (N/mm^2)	MoE$_S$ (N/mm^2)
Roof	Fir	40.86 (8.28)	66.84 (21.39)	10009.86 (3050.91)
Wall	Fir	33.85 (4.76)	46.20 (11.15)	6294.41 (906.25)
	Chestnut	46.32 (4.67)	65.84 (13.12)	8643.58 (1314.05)
Floor	Fir	36.08 (4.23)	54.17 (12.17)	8277.08 (1298.81)
	Spruce	42.75 (7.23)	67.25 (17.67)	9973.12 (2180.84)

The values in parentheses are the standard deviations.

When the strength values of the specimens were compared with the literature values for new wood without defects, the results were similar for the chestnut and spruce specimens (Berkel 1970; Bozkurt and Göker 1996; Sousa 2013).

The strength values for the wall fir specimens were lower than those found in the literature, which indicated the presence of decay (Berkel 1970; Bozkurt and Göker 1996; Korkut 2008). The ρ and V of the wall fir specimens were also found to be lower than those of the other fir specimens from the roof and floor, which confirmed the possibility of deterioration.

Correlations between the Destructive and Non-destructive Tests

Based on the laboratory test results, the NDTs and destructive tests were statistically analyzed by means of linear regression using the SPSS program. The fit regression was evaluated with the coefficient of determination (R^2), which ranges from 0 to 1. High values of the coefficient indicate a strong linear relationship between the parameters.

Correlations with the modulus of elasticity

Table 5 shows the correlations between the V and MoE$_S$ for the fir, spruce, and chestnut specimens. Concerning the simple regression model, the V had a good correlation for the fir and spruce specimens. Also, a useful correlation was obtained for the chestnut specimens.

Table 5. V and MoE$_s$ Correlations between the NDT and Destructive Test Results

Species	R^2	Equation
Fir	0.73	$MoE_S = 4.2946V - 15374$
Spruce	0.63	$MoE_S = 4.0683V - 12906$
Chestnut	0.53	$MoE_S = 3.194V - 6941.6$

Table 6 shows the correlations between the MoE$_D$ and MoE$_S$ for the fir, spruce, and chestnut specimens. Good correlations were found between the two parameters for the fir and spruce specimens. When the results were analyzed for the chestnut specimens, a relatively weak correlation was found between the parameters.

Table 6. MoE$_D$ and MoE$_S$ Correlations between the NDT and Destructive Test Results

Species	R^2	Equation
Fir	0.71	$MoE_S = 0.6212MoE_D + 279.7$
Spruce	0.73	$MoE_S = 0.5448MoE_D + 903.56$
Chestnut	0.32	$MoE_S = 0.4639MoE_D + 2926.9$

Correlations with the bending strength

Table 7 shows the correlations between the V and f_b for the fir, spruce, and chestnut specimens. When the results were analyzed, useful correlations were found for the fir and spruce specimens and a weak correlation was found for the chestnut specimens.

Table 7. V and f_b Correlations between the NDT and Destructive Test Results

Species	R^2	Equation
Fir	0.55	$f_b = 0.0225V - 69.45$
Spruce	0.61	$f_b = 0.0333V - 119.79$
Chestnut	0.30	$f_b = 0.0233V - 48.081$

Table 8 shows the correlations between the MoE$_D$ and f_b for the fir, spruce, and chestnut specimens. Good correlations were found for the fir and spruce specimens. A weak correlation was found for the chestnut specimens between the two parameters.

Table 8. MoE$_D$ and f_b Correlations between the NDT and Destructive Test Results

Species	R^2	Equation
Fir	0.57	$f_b = 0.0037MoE_D + 6.4658$
Spruce	0.68	$f_b = 0.004MoE_D + 2.3918$
Chestnut	0.21	$f_b = 0.0036MoE_D + 21.057$

Correlations with the compression strength parallel to the grain

Table 9 shows the correlations between the V and f_c for the fir, spruce, and chestnut specimens. The linear regression results showed useful correlations for the fir and spruce specimens. A weak correlation was obtained for the chestnut specimens.

Table 9. V and f_c Correlations between the Non-destructive and Destructive Test Results

Species	R^2	Equation
Fir	0.43	$f_c = 0.0077V - 6.0173$
Spruce	0.48	$f_c = 0.0116V - 22.211$
Chestnut	0.32	$f_c = 0.0088V + 3.5611$

Table 10 shows the correlations between the MoE$_D$ and f_c for the fir, spruce, and chestnut specimens. Good correlations were found between the two parameters for the fir and spruce specimens. A weak correlation was found for the chestnut specimens.

Table 10. MoE$_D$ and f_c Correlations between the NDT and Destructive Test Results

Species	R^2	Equation
Fir	0.57	$f_c = 0.0014MoE_D + 18.199$
Spruce	0.70	$f_c = 0.0017MoE_D + 15.485$
Chestnut	0.13	$f_c = 0.001\ MoE_D + 33.673$

Conclusions

According to the results of the research; the initial visual inspection on the wood members showed no remarkable defects that could have led to instability in the specimens. Some specimens had cracks and shakes caused by nails and some members had been affected by insect attacks.

The air-dried density, stress wave velocity, and strength values are in good accordance with the literature values for new wood for the chestnut, spruce, and fir specimens. However, the values for the wall fir specimens were found to be lower than those in the literature, which indicated possible deterioration.

Linear regressions were proposed for the MoE$_S$, f_c, and f_b using ultrasonic testing. The regression correlations were high for the softwoods (fir and spruce), but relatively lower correlations were obtained for the chestnut specimens.

The regression analysis showed that both the V and MoE$_D$ are good predictors of the strength properties for the examined species. For softwoods, approximately 57% to 73% of the strength properties was explained by the MoE$_D$, while 43% to 73% was explained by the V. For chestnut, the R^2 values varied between 0.12 and 0.53. The only reasonable R^2 value was between the V and MoE$_S$ ($R^2 = 0.53$). This was probably caused by the small number of specimens and heterogeneous structure of the hardwoods.

Because of the good R^2 values obtained between the MoE$_D$ and the f_c and f_b properties of the softwoods, the non-destructive stress wave technique can be recommended for quantitative evaluation of softwoods in structures.

Although chestnut showed very good mechanical properties, a satisfactory evaluation of the chestnut members could not be obtained because of the small number of specimens. Further investigation is needed with large sample groups.

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