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Stress – deformation relations of Scotch Pine (*Pinus sylvestris* L.) wood under different conditions

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ABSTRACT: Aim of this study is to determine the effect of moisture content on the stress and deformation values of scotch pine (*Pinus sylvestris* L.) wood on bending strength, modulus of elasticity in bending and compression strength parallel to the fibers values. These were tested using TS ISO standards under air dry, over fiber saturation point (FSP) moisture content, steamed over FSP and cooled conditions and stress – deformation values were obtained. In addition, the stress and deformation values at the elastic limit and the deformation values of the material after the elastic limit were examined. As a result, it was determined that moisture content and steaming treatment caused decrease in all resistance types but increased the amount of deformation. While the averages of the over FSP and steamed samples were different in bending resistance and modulus of elasticity in bending, it was determined that there was no difference between the pretreatment groups in compression strength. It can be said that the strength and deformation values of the materials to be used especially in high moisture content areas should be selected in accordance with the place of use according to the results of the study.

Keywords: Scotch Pine, Steaming, Bending, Compression, Moisture, Deformation

Sarıçam (*Pinus sylvestris* L.) ahşabının farklı koşullarda gerilme deformasyon ilişkileri

ÖZ: Bu çalışmanın amacı, sarıçam (Pinus sylvestris L.) ahşabının gerilme ve deformasyon değerlerine rutubet miktarının, lif yönüne paralel olarak eğilme direnci, eğilmede elastikiyet modülü ve basınç direncine etkisini belirlemektir. Bunlar TS ISO standartları kullanılarak hava kurusu, lif doygunluk noktası (LDN) üzerinde ve LDN üzerinde buharlama ve soğutma koşullarında test edilmiş ve gerilme - deformasyon değerleri elde edilmiştir. Ayrıca elastik sınırda oluşan gerilme ve deformasyon değerleri ile malzemenin elastik sınır sonrası göstermiş olduğu deformasyon değerleri incelenmiştir. Sonuç olarak LDN üzeri rutubet ve buharlama işleminin tüm direnç türlerinde azalmaya neden olduğu fakat deformasyon miktarlarını arttırdığı tespit edilmiştir. Eğilme direnci ve eğilmede elastikiyet modülünde LDN üzeri ve buharlanmış örneklerin ortalamaları farklı iken basınç direncinde ön işlem gruplarının kendi arasında farklı bulunmadığı tespit edilmiştir. Çalışma sonucunda elde edilen bulgulara göre özellikle yüksek rutubetli alanlarda kullanılacak olan malzemelerin direnç ve deformasyon değerlerinin kullanım yerine uygun olarak seçilmesi gerektiği söylenebilmektedir.

Anahtar kelimeler: Sarıçam, Buharlama, Eğilme, Basınç, Rutubet, Deformasyon

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1 Introduction

Wood is an important engineering material and has been used since ancient times. It is important to know the properties of wood correctly to choose suitable materials for the place of use. Scots pine (*Pinus sylvestris* L.), which is the most widely distributed pine species throughout the world, can be found across Eurasia. Scots pine is also one of the most important wood species grown in Turkey by covering approximately 6.8% of total forestland (Büyüksarı, et al. 2017; Güntekin and Akar, 2019). Since scotch pine has a large heartwood and has high resistance and sounding properties, it can be used as wire poles, mine poles and pile poles in round form, and it can also be used as scaffolding poles in in-water construction if impregnated. Scotch pine is widely preferred for structural purposes due to its high resistance and easy processing properties despite its low density. It is used in the production of columns and beams as carriers in buildings and tensioners, struts, supports, bracing, sidings, purlins and rafters in roof trusses. It can also be utilized in bridge construction, shipbuilding and construction of vehicles (Kurul, 2023).

There are many factors that limit the use of wooden material in the structural field such as moisture content, physical mechanical properties, knots, spiral grain, exposure to fungal and insect attacks. One of the major problems of using wood materials is the effect of moisture content on their physical and mechanical properties (Güntekin and Akar, 2019). The mechanical properties of wooden materials changes depending on the moisture content (Güntekin and Akar, 2019; Ross, 2021). Many elastic and strength properties of wood decrease below the fiber saturation point (FSP) as the moisture content increases(Panshin and Zeeuw, 1970). The allowable stresses remain within the elastic limit in calculating the allowable stresses. In addition to the stress and maximum load at the elastic limit, deformation values at the elastic limit are also important depending on material size, moisture and material properties. Wood materials can be steamed for different purposes. These are ensuring color uniformity in the material, improving hygroscopic properties, reducing internal stresses in the wood material and sterilization against insects and fungi (Kantay, 2014; Şendağ, 2018).

Elastic properties have an important role in wooden materials as well as resistance values. However, studies on wood in the literature are generally limited to strength properties, and even if studies have been carried out on elastic capabilities, not enough studies have been carried out(Güntekin and Akar, 2019; Güntekin, et al., 2015; Lawrance et al., 2007, Şendağ, 2018). No change can be mentioned in its shape and dimensions unless an external force is applied to the wooden material. When a sufficient amount of force is applied to the material, changes in its shape and dimensions, i.e. deformations, are expected(Bozkurt, 1966; Renaud, Rueff and Rocaboy, 1996). Elasticity is defined as the complete recovery of deformations occurring in a solid material at low stresses by taking its previous state after the load is removed. Elastic properties are valid in solids below a certain limit called the elastic limit, plastic deformations or fractures occur above the elastic limit (Bozkurt 1966; Bozkurt and Göker, 1987; Kollmann and Cote, 1968). The zone between the elastic limit and the fracture point in the load deformation curve is called the semi-plastic (2^{nd}) zone (Berkel, 1970).

The mechanical properties of a wood material are a measure of its resistance to external forces and its suitability. External forces are the forces that try to change the size or shape of a certain wood material by external influence. The mechanical properties of wood materials are important for many uses such as furniture, vehicles, tools and tool handles and their suitability for use in building and construction purposes (Bozkurt, 1966; Bozkurt and Erdin, 2011; Ross, 2021). Bending strength is the resistance of the wood material fixed at one or both ends against the forces applied perpendicular to the fibers and trying to bend. It is used in strength calculations especially in materials used as beams. Compressive strength is the resistance to forces that work against compressing and pressing the wood material and plays an important role in the use of wood as a building material (Bozkurt and Erdin, 2011; Bozkurt and Göker, 1987; Ross, 2021).

The aim of this study was to determine the stress and deformation relationships, elastic limit stress and deformation values, and the total deformation of scotch pine wood under different conditions for compression and bending properties. Since the moisture content of wood has a very important role in strength and deformation, the effect of high moisture content on wood material has been investigated. The properties of the steamed samples were tested considering the effects they may be exposed to in their places of use.

2 Material and Method

2.1 Material

In this study, scotch pine timber was supplied from the "Kuruoğlu Kerestecilik ve Dış Tic. A.Ş" as material. In material selection, it was paid attention that the annual rings of the materials should be regular and there should be no knots, rot, etc. The timbers were brought to the dimensions of 20 x 20 x 360 mm in Istanbul University - Cerrahpaşa, Faculty of Forestry Laboratory and kept in the acclimatization room at 65 ± 5% relative humidity at a temperature of 20±2 °C until they reached constant weight (Figure 1-A).

The air-dried timbers were divided into 3 groups and one of the groups was tested in this way and the other two groups were kept in water to be raised over FSP. Finally, one of the groups kept in water was steamed. The steaming process was carried out with saturated water vapor in a steaming boiler under 1.2 bar pressure for 40 minutes (Figure 1-B). Samples were cooled before performed tests to eliminate other heat factors affecting on wood after the steaming process.

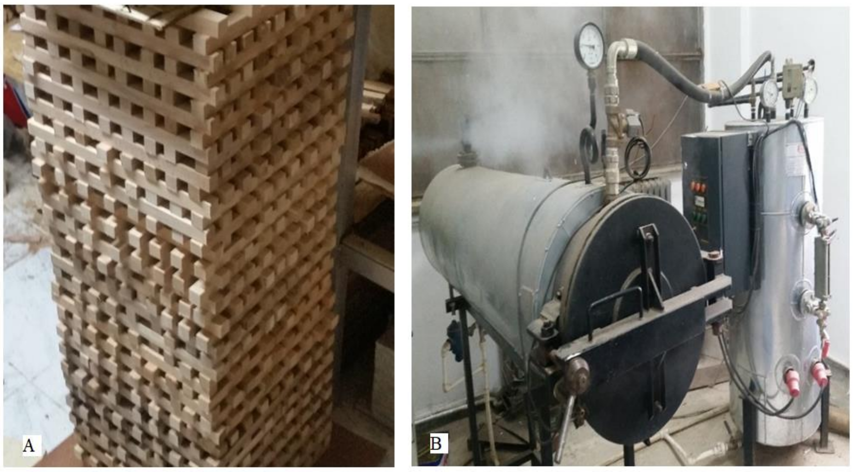

Figure 1. Acclimatized samples (A), Steaming process (B)

2.2 Method

2.2.1 Determination of density and moisture content

Density and moisture content of samples determined according to TS ISO 13061-1 (2021) standard. In order to determine the air dry density, 48 clean samples' radial and tangential dimensions were measured and recorded with a Mitutoyo digital micrometer with a precision of 0.001 mm. The dimensionally measured samples were weighed with a precision scale with a precision of 0.01 g. and their weights were determined. Density of the samples was determined using Equation 1.

$$D_{12} = \frac{m}{V} \tag{1}$$

Where ; D_{12}: air-dry density (kg/m^3), m: weight of the sample (kg), v: volume of the sample (m^3).

20 x 20 x 30 mm pieces were cut from the region that is close to the fracture zone for bending strength samples to determine the moisture contents of the samples. Test samples were used for compression strength to determine the moisture content. Moisture samples for all groups weighed a precision of 0,01 g immediately after tests and placed in the drying oven at 103±2 °C and kept in there until weight of the samples became stable. Moisture contents of the samples were calculated in Equation 2.

$$m_c = \frac{m_{1-} m_2}{m_2} \times 100 \tag{2}$$

Where; m_c: moisture content of the sample (%), m_1: first weight of the sample (g), m_2: oven-dry weight of the sample (g).

2.2.2 Determination of compression strength parallel to the grain

Compression strength parallel to the grain tests was performed by TS ISO 13061-17 (2019) standard. For this purpose, 30 clear samples of 20 x 20 x 30 mm were prepared for each sample group. Calculations were made using the equation 3.

$$\sigma_b = \frac{F}{b \times h} \text{ MPa} \tag{3}$$

Where; σ_b: Compression strength (MPa), F: load at fracture (N), b and h: cross-sectional dimensions of the sample (mm).

2.2.3 Determination of bending strength

Bending strength specimens were tested in a universal testing machine (Figure 2) with a capacity of 100 kN by TS ISO 13061-3 (ISO, 2021). The span length was set as 15h of the sample thickness during the tests. The cross-sectional dimensions of the specimens were measured with an accuracy of 0.01 mm from the midpoint of the length axis with the width in the radial direction and the thickness in the tangential direction. The test speed was set at 1.5 ± 0.5 min for the specimens to fracture and the load was applied tangentially to the radial face of the specimens at the midpoint of the annual rings. The force (Pmax) at the moment of fracture of the specimens was recorded with a sensitivity of 1 N and the bending strength was calculated with the help of the Equation 4.

$$\sigma_E = \frac{3 \times P \times L_S}{2 \times b \times h^2} \tag{4}$$

Where; σ_E: Bending resistance (MPa), Pmax: force at fracture (N), Ls: Span length (mm), b: Sample width (mm), h: Sample thickness (mm).

Figure 2. Performing bending test

2.2.4 Determination of modulus of elasticity in static bending (MOE)

Determination of the modulus of elasticity was performed according to TS ISO 13061-4 (2021) standard. Static bending samples were used for the determination of MOE. Calculations were made by using equation 5.

$$E = \frac{\Delta P \times {L_s}^3}{\Delta f \times 4 \times b \times h^3} \quad (5)$$

Where; E: Modulus of elasticity (MPa), ΔP: Force (N), L_s: Span clearance (mm), Δf: deformation (mm), b: sample width (mm), h: sample heigth (mm).

2.2.5 Identification and examination of deformations

Load-deformation data were obtained by using the automatic recording feature of the load and deformation amounts of the test device used in the experiments. Deformation amounts corresponding to 100 N load were determined by utilizing the obtained data.

The point where the linear region of the load-deformation graphs of the tested samples ends was accepted as the elastic limit and the load of this point was recorded with a precision of 1 N and the deformation of this point was recorded with a precision of 0.01 mm. The load-deformation graphs and the differences between the deformation occurring at the load levels were used in determining the elastic limit. While deviations from linearity can be seen in the graphs, the last load level with constant deformation increase is accepted as the elastic limit since the deformation increase between two load levels is constant until the elastic limit and starts to vary after the elastic limit.

Sample deformations were compared in terms of the lengths and total deformations of 2nd zone. The differences were investigated by comparing the load values of the sample groups for which a deformation increase was expected but not statistically significant.

2.2.6 Statistical analysis

Differences were determined by applying one-way analysis of variance at 95% confidence level using the SPSS 21 program to compare the data. If there was a difference in the analysis results, Duncan test was applied to determine the group differences.

3 Results and discussions

The mean density was determined as 560 kg/m^3 according to the results of density measurements. Scotch pine air-dry density given as 530 kg/m^3 (As et al., 2001) and 520 kg/m^3 (Bozkurt and Erdin, 2013).

Öktem (1994) stated that FSP of the scotch pine was 29,8% in moisture contents of the test specimens given in Table 1. It can be said that the tested samples at high moisture content are over-FSP since the over-FSP and steamed groups' moisture contents are higher than this value.

Table 1. Mean moisture contents of specimens (%)

Test		Compression	Bending
Pre- treatment	Air dry	12.56	11.64
	FSP	30.51	34.95
	Steamed	32.28	35.9

3.1 Bending strength and MOE

In the Table 2, mean values of the results of bending strength and MOE were shown and Duncan test results were given as letters A, B and C, and every letter indicates different group values.

Table 2. Results of bending strength and MOE

Process	σ_{EM}	σ_{EK}	EL		F_{2B}	F_T	MOE
			σ	F			
Air - Dry	87.39 (A)	87.39 (A)	36.82 (A)	2.81 (A)	8.78 (C)	11.59 (C)	10090.12 (A)
Over-FSP	48.41 (B)	41.40 (B)	24.89 (B)	2.19 (B)	17.46 (B)	19.65 (B)	8197.24 (B)
Steamed	38.11 (C)	32.18 (C)	14.19 (C)	1.58 (C)	22.27 (A)	23.85 (A)	6905.12 (C)

σ_{EM}: Maximum Stress in bending (MPa) σ_{EK}: Fracture stress in Bending (MPa) EL: Elastic Limit σ: Stress (MPa) F: Deformation (mm) F_{2B}. : 2nd zone length (mm) F_T: Total Deformation (mm) MOE: Modulus of Elasticty (MPa)

When the bending strength data were examined, the decrease in the fracture stress in bending of the over FSP and steamed samples compared to the air-dried samples was determined as 50.62% and 61.62%, respectively. The fracture occurred at maximum stress in air-dried samples after 14.40% stress loss in over-FSP samples and 15.56% stress loss in steamed samples. When the maximum stress comparison was made, it was determined that there was a significant difference between the averages of all pre-treatment groups for maximum stress in bending and fracture stress in bending at a 95% confidence level as a result of the Duncan test.

It is seen that the amount of deformation increased as a result of pretreatments, but the maximum stress and load values decreased. In other words, it was observed that more deformation occurred at lower load and stress values. This can be explained by the increase in humidity and steaming. As a result of the analysis of variance for elastic limit values, it was observed that there was a difference between the averages of all pretreatment groups for both stress and deformation values. The elastic limits of the pretreatment groups were 36.82 MPa stress and 2.81 mm deformation in air-dried materials, 24.89 MPa stress and 2.19 mm deformation in materials above FSP and 14.19 MPa stress and 1.58 mm deformation in steamed samples. For pine wood, it is seen that as the total load carried by the material decreases, the elastic limit load and deformation values also decrease. Wangaard (1950) states that the elastic limit occurs with a stress of 25.51 MPa for pine wood in fresh state and 41.37 MPa for air-dried materials. In the literature, the decrease in the elastic limit stress value was 38.33%. In the study, the decrease in stress from air dry material to moisture above FSP was determined as 32.40%.

When the total deformations of the samples were compared, there was a difference between the averages of all groups. While the least deformation was measured in air-dried samples, the most deformation was measured in steamed samples. The highest deformation was obtained in steamed samples with 23.85 mm while the lowest deformation was obtained in air-dried samples with 11.59 mm. The total deformation of the samples above FSP was measured as 17.46 mm. When the deformations occurring at the fracture loads were compared with the air-dried material, it was observed that the samples over FSP fractured at 803 N and the air-dried samples had a deformation of 3.80 mm at 800 N load. The vaporized specimens fractured at 641 N and the air-dried specimens had a deformation of 2.75 mm at 600 N. A 459% increase occurred in the samples above FSP and an 867% increase occurred in the steamed samples compared to the air-dried samples. According to these values, it can be said that high humidity and steaming significantly increase the deformation ability of pine wood. The stress and deformation data for bending stress obtained from the samples are presented in relation to the load in Figure 3.

It was determined in the analysis of variance performed of the pre-treatment group averages of the modulus of elasticity of scotch pine wood that there was a difference between the group averages and it was seen that the averages of all groups were different from each other as a result of the Duncan test. The decrease in the modulus of elasticity values of the FSP and steamed samples compared to the air-dried state was determined as 18.26% and 31.57%, respectively. While the modulus of elasticity of pine wood is given as 12410.56 MPa at the air-dry state, it is stated as 9514.76 MPa in a fresh state. The amount of decrease in the literature values was determined as 23.34% (Wangaard, 1950). In other study, Korkut et al. (2008) stated that stress loss of scotch pine due to heat on modulus of elasticity was 7,39 % for 120 °C for 2 hours and 32,12 % for 180 °C for 10 hours.

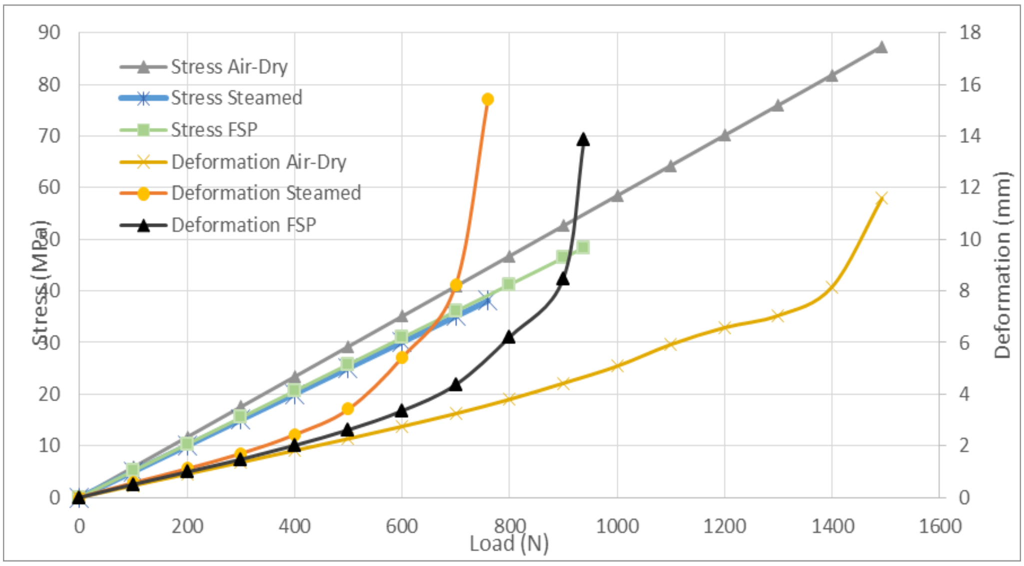

Figure 3. Stress – Deformation graph depending on load for bending

3.2 Compression strength parallel to the grain

Mean values of compression test were given in Table 3. The mean of maximum compression stress of air-dry samples was statistically different from the mean of the other groups. The amount of decrease in the maximum compression stress of the FSP and steamed samples compared to the air-dried state is 54.68% and 55.68%, respectively. Dündar (2005) reported that the compression strength of scotch pine wood was between 50,69 Mpa and 57,58 Mpa. In this respect, the strength of air dry materials is close to the literature values. Wangaard (1950) stated the compression strength of scotch pine wood is 21,23 Mpa in green condition and 50,61 Mpa in an air-dry state. In a different study, Korkut et al., (2008) state that heat treatment affects the strength of scotch pine. They stated that the strengths decreased as the amount and duration of temperature increased. The amount of decrease between these values is 58,05%. In this respect, the data are consistent with previous studies.

Table 3. Results of compression tests.

Process	σ_b	σ_{bk}	EL		F_{2B}	F_T
			σ	F		
Air - Dry	43.97 (A)	43.97 (A)	33.78 (A)	0.95 (A)	0.73 (B)	1.69 (B)
Over-FSP	19.53 (B)	17.39 (B)	14.08 (B)	0.61 (B)	1.58 (A)	2.19 (A)
Steamed	19.98 (B)	17.43 (B)	13.64 (B)	0.59 (B)	1.55 (A)	2.14 (A)

σ_b: Maximum Stress in compression (MPa) σ_{bk}: Fracture stress in compression (MPa) EL: Elastic Limit σ: Stress (MPa) F: Deformation (mm) F_{2B}. : 2nd zone length (mm) F_T: Total Deformation (mm)

In the case of fracture strength of compression, it was observed that the average of the air-dry samples was different and higher than the other two groups. The decrease in the fracture strength of compression of the FSP and steamed samples was determined 60,54 % and 60,47%, respectively.

It was determined that the average of air-dried samples was different and higher than the other two groups in the analyses on elastic limit stress and deformation values. The elastic limit of the air-dried samples was determined as 33.78 MPa stress and 0.95 mm deformation. While it was determined as 14.08 MPa stress and 0.61 mm deformation in the samples over FSP, it was determined as 13.64 MPa stress and 0.59 mm deformation in the steamed samples. The amount of decrease in elastic limit stress values compared to air-dried samples was determined as 58.32% and 59.62% for FSP and steamed samples, respectively. Wangaard (1950) gives the elastic limit stress value of pine wood as 36.74 MPa for air-dried material and 16.61 MPa for green material. The decrease in the literature values is 54.79%. It is clearly seen that the obtained values are compatible with the literature values. The growing conditions and anatomical and chemical structure of wooden material can be effective in this situation. Figure 4 shows the stress and deformation values depending on load for compression strength.

A statistically significant difference was found between the 2nd zone lengths of scotch pine wood compression samples at a 95% confidence level. The average of air-dried samples differed from the other two groups. When the pine wood compression samples were analyzed in terms of total deformations, it can be said that the average of air-dry samples showed a significant difference compared to the other two groups and a low value was obtained. The minimum deformation was measured in air-dried samples with 1.68 mm and the maximum deformation was measured in samples over-FSP with 2.19 mm. The total deformation amount of the steamed samples is 2.14 mm. When the deformation amounts shown by the air-dried samples are compared, the samples above FSP carried a maximum load of 8317 N and 0.58 mm deformation was measured in air-dry samples at 8000 N load. The steamed samples carried a maximum load of 8512 N and 0.65 mm deformation was measured at 9000 N load in air-dry samples. Considering these values, the deformation of the samples over FSP increased by 378% and the deformation of the steamed samples increased by 329%.

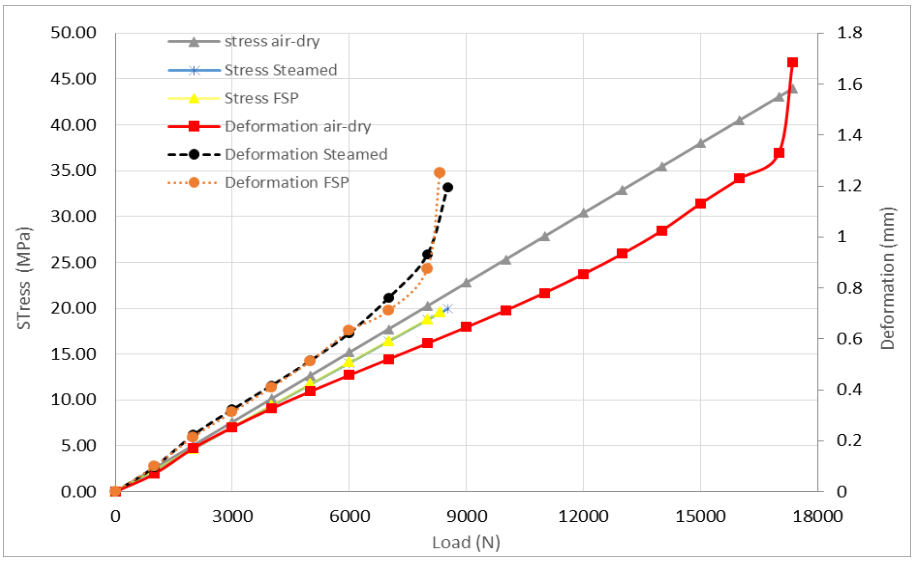

Figure 4. Stress – Deformation graph depending on load for compression

4 Conclusions

- It can be said that the increase in moisture content and steaming process significantly decreases the resistance properties of wood material according to the findings obtained from this study. Deformation values are affected by moisture increase and steaming, but the effect varies according to the type of stress.
- In bending stresses, increase of moisture content and steaming of wood caused a decrease in strength and an increase in deformation. The growing conditions and anatomical chemical structure of the wood are thought to be effective in this situation.
- Similarly, increased moisture content and steaming of material affect the strength and deformations of material in compression strength parallel to the grain.
- Steaming and moisture increase affect material differently on compression and bending strength. While the means of all 3 groups were different in bending strength, no difference was found between steaming and humidity in compressive strength.
- The allowable stresses remain within the elastic limit when calculating the safety stresses. It can be said that deformation values at the elastic limit are also important depending on material size, moisture and material properties in addition to the stress and maximum load at the elastic limit.
- In this study, elastic limit deformation values were determined for different properties. It is thought that the allowable deformation values should be determined according to the wood species, sample sizes, humidity and defect properties in addition to the stresses allowed in practice with the determination of these values. Data will be provided to the practitioners and safer use of wood in structural use will be ensured.
- In addition, reductions in strength values should be taken into account in the use of wood material as a load carrier, especially in areas with high equilibrium humidity or waterlogged areas, and design calculations should be made accordingly.

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Author Contributions
Akın Şendağ: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nusret As**: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

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Conflict of interest
We confirm that there is no conflict of interest.

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