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EXPERIMENTAL AND ANALYTICAL INVESTIGATION OF THE EFFECT OF LAYER NUMBER AND THICKNESS ON THE BENDING PROPERTIES OF GLULAM BEAMS

TABAKA SAYISI VE KALINLIĞININ GLULAM KİRİŞLERİN EĞİLME ÖZELLİKLERİ ÜZERİNE ETKİSİNİN DENEYSEL VE NÜMERİK OLARAK İNCELENMESİ

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ABSTRACT

Wooden material is used in structural elements due to its many positive properties. Recent years have witnessed a surge in research directed toward enhancing the mechanical properties of wooden beams through the utilization of materials like steel plates and fiber reinforced polymers (FRP). Layered laminated timber, a composite material crafted from wood, serves as a testament to this endeavor. These laminated timbers constitute intricate engineering elements, fashioned from layers of wood characterized by distinct levels of strength and hardness, systematically arranged as per established guidelines. The present study is geared toward a comprehensive examination of the bending characteristics exhibited by glued beams, fashioned from spruce trees, encompassing six distinct sizes and varying layer counts. The manufacturing process yields beams with diverse cross-sectional profiles, including 3-layer and 7-layer variants. By performing 4-point bending tests of the beams, maximum load carrying capacity, bending strength, and elasticity modulus values were obtained experimentally. In addition to the experimental analyses, numerical models of the produced beams were created using the finite element analysis program, and static analyses were performed. In the experimental results, it was observed that the bending properties of the beams increased as the number and size of layers increased. It was determined that the maximum load carrying capacity, bending strength, and elasticity modulus values obtained as a result of experimental and numerical analysis were very close to each other. Numerical analysis results showed that beams produced with various number of layers and thicknesses can be simulated. It has been determined that the results obtained by creating numerical models instead of experimental analyses for this type of wooden beam may be sufficient.

Keywords: Wood structure, FRP, reinforcement, glulam, finite element analysis

ÖZET

Ahşap malzeme, birçok olumlu özelliği sebebiyle yapısal elemanlarda kullanılmaktadır. Son yıllarda ahşap kirişlerin mekanik özelliklerinin iyileştirilmesi için çelik levha ve fiber takviyeli polimerler (FRP) gibi malzemelerin kullanımı üzerine araştırmalar yapılmaktadır. Tabakalı lamine keresteler ahşap malzeden üretilmiş bir kompozit malzemedir. Tabakalı lamine keresteler, tabakaları belirli kurala göre konumlandırılmış, değişen mukavemet ve sertlikteki ahşap katmanlarından yapılmış karmaşık mühendislik bileşenleridir. Bu çalışmanın amacı, altı farklı boyuttaki ve çeşitli katman sayılarındaki ladin ağaçlarından yapılan tutkallı kirişlerin bükülme özelliklerinin araştırılmasıdır. Farklı kesitli kirişler 3 katlı ve 7 katlı olarak üretilmektedir. Kirişlerin 4 nokta eğilme testleri yapılarak maksimum yük taşıma kapasitesi, eğilme mukavemeti ve elastisite modülü değerleri deneysel olarak elde edilmiştir. Yapılan deneysel analizlerin yanısıra üretilen kirişlerin sonlu elemanlar analiz programı kullanılanarak sayısal modelleri oluşturulmuş ve statik analizleri yapılmıştır. Deneysel sonuçlarda, tabaka sayısı ve boyutu arttıkça kirişlerin eğilme özelliklerinin

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arttığı gözlemlenmiştir. Deneysel analiz ve nümerik analiz sonucunda elde edilen maksimum yük taşıma kapasitesi, eğilme dayanımı ve elastisite modülü değerlerinin birbirine çok yakın değerler verdiği belirlenmiştir. Sayısal analiz sonuçları, çeşitli katman sayısı ve kalınlıklarda üretilen kirişlerin simülasyonunun yapılabileceğini göstermiştir. Bu tip ahşap kirişler için deneysel analizler yerine nümerik modeller oluşturularak elde edilecek sonuçların yeterli olabileceği belirlenmiştir.

Anahtar Kelimeler: Ahşap yapı, FRP, güçlendirme, glulam, sonlu eleman analizi

INTRODUCTION

Timber is a material with a variety of colors and fiber structures that has excellent thermal and acoustic insulation qualities (Sahin et al., 2011; Kilincarslan and Simsek Turker, 2020a; Sahin and Onay, 2020; Sahin et al., 2020). It has been used for centuries because of its superior durability compared to other building materials, high strength/weight ratio, aesthetic qualities, ease of processing, fiber structure, and excellent thermal and sound insulation (Kermani, 1999; Kilincarslan and Simsek Turker, 2020b). Additionally, it has a lot of advantageous environmental characteristics, such as low buried energy (Falk, 2010). Timber is a material used to make beams, columns, roof trusses, poles, and construction systems like piles, slab elements, and railroad bases, as well as to shape concrete because of these qualities (Kilincarslan and Simsek Turker, 2021). Modern timber structural materials are used to construct homes, light commercial buildings, and industrial structures today (Di et al., 2022; Li et al., 2022; Moody and TenWolde, 1999). The use of wood in residential, commercial, and industrial structures as well as scaffolding, bridges, retaining walls, and transmission towers is still prevalent today (Nunnally, 2007). Nowadays, wood-based composite materials are preferred to using wood directly. To meet the growing demand for high quality timber and to reduce the consumption of forest resources, structural composite timber has been developed. To obtain higher engineering design values than those provided by raw timber, structural composite timber is used in place of raw timber in the production of engineering wood products like prefabricated wooden I-beams and other various applications (Stark et al., 2010). For roofs with spans up to 100.0 m, structural systems based on flat and sloping glue laminates have been developed. For large-scale timber constructions, many other wood-based products are used, including laminated veneer lumber (LVL) and parallel strip lumber (PSL). Similar to how these products, like flat glued laminate timber elements, are appropriate for longer spans (Thelandersson et al., 2003). The use of glue laminated timber began in the late 1800s. It saw extensive use both during and following World War II. The use of glue laminated beams has increased for both new construction and bridges. The fact that structures cannot be built entirely out of sawn wood demonstrated the usefulness and effectiveness of glued laminated beams (Stalnaker et al., 1999). The use of wooden building components has increased in a variety of application fields, such as bridges, sports facilities, and industrial facilities, in addition to the size growth of wooden structures. The adhesion of the laminated elements to one another is the most significant factor affecting the load bearing capacity and general behavior of the timber laminated beams. Numerous studies have been conducted on this topic (Tran et al., 2015; Dietsch and Tannert, 2015; Sena-Cruz et al., 2013). Kılınçarslan and Şimşek Türker (2019) tested laminated wooden beams with the same height and width of h by dividing them into 3 different groups. The stiffness and flexural strengths were not significantly affected by variations in the laminate layer thicknesses (h/4, h/6, or h/8), but there were differences in the modulus of elasticity. Even though the beams with the thickest laminate layers had the lowest elastic modulus values, the samples with the thickest layer had roughly the same outcome. The beam with the medium laminate layer thickness had the highest elasticity modulus. In this situation, choosing samples with thicker laminate layers may be more advantageous. Because there are fewer layers, less glue needs to be used, which saves labor, time, and money. Beceren Öztürk and Arıoğlu (2006) used various types of glue to create laminated timber from scotch pine wood and conducted static bending tests. According to the findings of the study, laminated timbers can produce the best results if the wood material is brought to the desired equilibrium humidity and the right glue material is used. In general, they claimed that laminated timbers made with polyvinyl acetate glue and having a bending strength of 75.24 MPa produced the best results, while layered laminated timbers made with urea formaldehyde glue and having a bending strength of 55.80 MPa produced the worst results. Using a 2.5 mm thick peeling veneer, Güray et al. (2003) investigated the effects of glue type and force direction on bending resistance in laminated wood material made from stemmed oak (*Quercus Robur* L.) wood. To create laminates for this purpose, polyvinylacetate (PVAc) and polyurethane (PU) glues were preferred. Two force directions-parallel and perpendicular to the glue line were used in the experiment. Eighty test specimens in total were bent in directions perpendicular and parallel to the glue line. These specimens were bent in accordance with the TS 2474 standard. They discovered that samples adhered with polyurethane (PU) glue had the highest bending strength (121 MPa), while samples adhered with polyvinylacetate (PVAc) glue had the lowest bending strength (90.6 MPa). Kılınçarslan and Şimşek Türker (2022) strengthened 20x20x360 mm ash beams with basalt-based fiber-reinforced polymers. Bending test of the reference and reinforced beams was carried out. It was determined that the beams reinforced with basalt-based fiber reinforced polymer fabric have flexural strength (117.11 MPa) and modulus of elasticity (12845 MPa). It was determined that the reference beams had flexural strength (99.34 MPa) and modulus of elasticity (10320 MPa). It was determined that the flexural strength value of the reinforced beam increased by 18% and the elasticity modulus value increased by 25% compared to the reference beam.

In recent years, considering many factors such as cost and time loss, it has been observed that experimental studies have gradually been replaced by numerical analyses. Literature studies, especially modeling studies of wooden beams are carried out with finite element software program. This study aims to experimentally and numerically investigate the bending properties of glued beams produced from spruce tree species in three different sizes and various numbers of layers. As a result of the study, the maximum load carrying capacity, bending strength, and elasticity modulus values obtained through experimental and numerical analysis were compared.

MATERIAL AND METHODS

Material

Glulam beams were provided by Nasreddin Forest Products (Naswood) in Antalya. By laminating spruce timbers with melamine formaldehyde glue and a balanced humidity of 11–12%, glulam beams are created. The GL 24h resistance class applies to the factory-made spruce glulam beams. The codes and properties of the beams tested in the study are given in Table 1.

Table 1. Codes and Properties of the Beams

Beam Code	Beams Width (mm)	Beams Height (mm)	Beams Length (mm)	Number of layers	Moisture Content (%)
S1212	120	120	3000	3	11.26
S1224	120	240	4500	7	11.10
S1414	140	140	3000	3	11.62
S1428	140	280	5300	7	11.21
S1616	160	160	3000	3	11.66
S1632	160	320	6000	7	11.45

Six different wooden beams were produced in 3 and 7 layers. S1212, S1414 and S1616 were produced as 3 layers, S1224, S1428 and S1632 as 7 layers. In Figure 1, the properties and layer thicknesses of the layers are given.

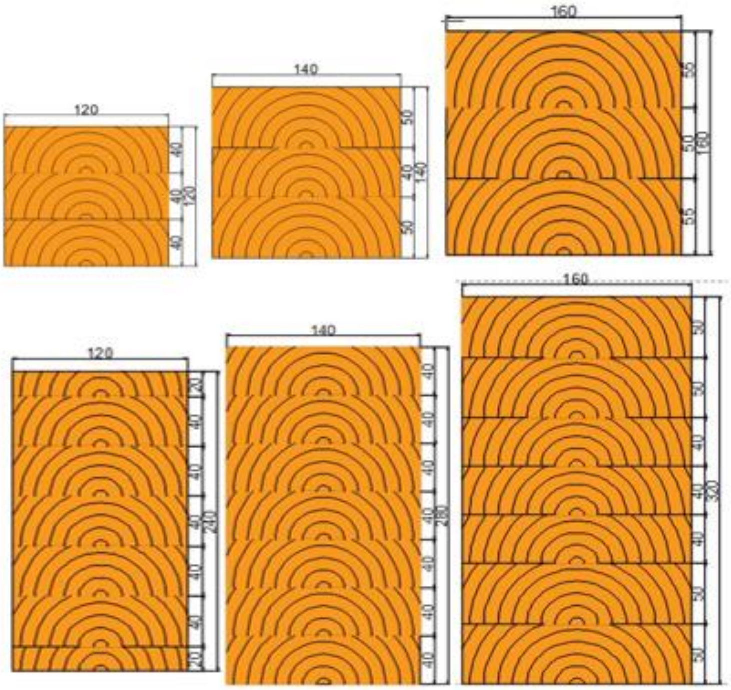


Figure 1. Properties and Layer Thicknesses of the Beam Layers

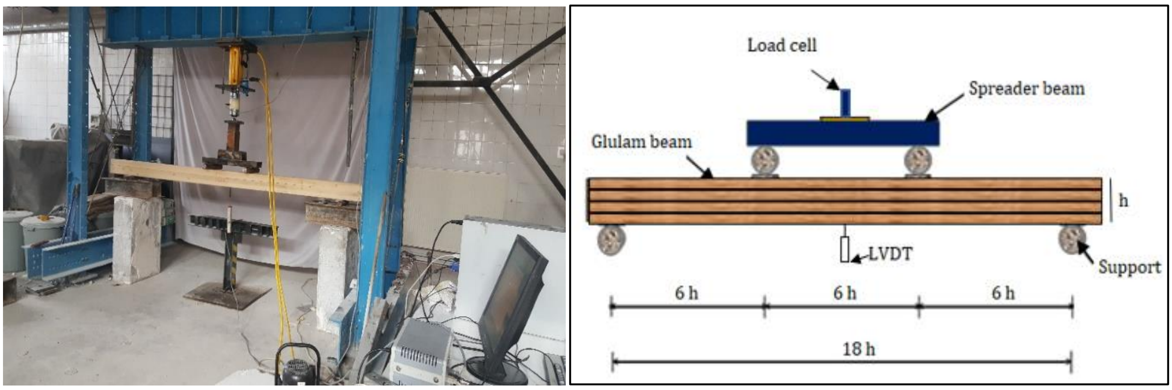
Table 2 lists the mechanical characteristics of glulam GL24 h in accordance with DIN 1052:2008 (Fosetti et al., 2015).

Table 2. According to DIN 1052:2008, Glulam GL24 h has the Following Mechanical Properties (MPa)

Properties	**Glulam GL 24h**
Bending	24
Tension parallel	16.5
Tension rectangular	0.5
Pressure parallel	24
Pressure rectangular	2.5-3
Shear and torsion	2.5
Modulus of elasticity parallel	11.600
Modulus of elasticity rectangular	390
Shear modulus	720

Experimental Test

In this study, 4 point bending tests of 6 different layered laminated timber were performed. Flexural tests were carried out at Suleyman Demirel University Civil Engineering Structure and Earthquake Laboratory. Based on GB/T 26899-2011, a static four-point load bending test (bending test Method A) was conducted with a loading speed of 8 mm/min. Each specimen had an LVDT (Linear Variable Differential Transformer) sensor installed in the middle, as shown in Figure 2.



(a) (b)

Figure 2. Experimental Setup Image (a) Experimental Setup Real Image, (b) Schematic View of the Experimental Setup

The following Equation is used to determine the modulus of elasticity (MOE) for bending and modulus of rupture (MOR) (Gao et al., 2015):

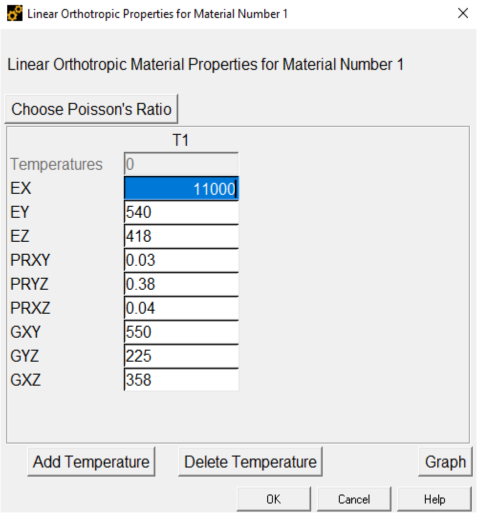
$$\mathrm{MOE}=\frac{\Delta P\,(l-s)(2l^2+2ls-s^2)}{8\Delta y b h^3} \tag{1}$$

$$\mathrm{MOR}=\frac{3P_{max}(l-s)}{2bh^2} \tag{2}$$

where Δy is the corresponding midspan deflection of ΔP, b is the specimen's width, h is the depth, P_{max} is the maximum load, l is the specimen's span between supports, s is the span between loading sites, and ΔP is the difference between the upper and lower loads at the proportional limit.

Finite Element Model

The software package ANSYS 2022 R1 Standard Solver is used for the numerical analysis. The model's geometry and loading configurations are chosen to match the experimentally tested beams. The end conditions, which limit the vertical movement of the beam, are modelled as pinned and roller supports. A 25mm rectangular mesh is used in the modelling process. The timber is modelled by using the SOLID45 element, which is used for the 3-D modelling of solid components (Hsissou et al., 2018). The solid element includes eight nodes with three degrees of freedom in the x, y, and z directions. SOLID45 has plasticity, stress stiffening, large deflection, large strain nodes, and various other capabilities. However, precise modelling of the complicated anisotropic behaviour of timber is impractical. To simulate the wood's behaviour, the timber's elastic characteristics are specified in an orthogonal format in the software. Figure 3 depicts the attributes of the material employed in the simulation technique (DIN 1052:2008).



Linear Orthotropic Material Properties for Material Number 1

	T1
Temperatures	0
EX	11000
EY	540
EZ	418
PRXY	0.03
PRYZ	0.38
PRXZ	0.04
GXY	550
GYZ	225
GXZ	358

Figure 3. Linear Orthotropic Material Properties of Spruce Timber, in MPa

Since glulam beams' wood laminations are modelled as separate components, all material features can be considered. Because the previous research had demonstrated a perfect connection between laminations, the melamine formaldehyde adhesive layer was not modelled due to its extremely thin thickness. Note that, as a line load is applied across the beam's width, a series of vertical displacement increments are used to perform the static small displacement analysis until the predetermined failure condition is attained.

RESULTS AND DISCUSSION

Experimental and Numerical Analysis Results

First of all, load-displacement graphs were obtained as a result of the bending test. A total of 12 experiments were carried out, 2 replications of 6 different sizes of glulam beams. Numerical analysis results are given in Figure 4. The data obtained as a result of experimental and numerical analysis are given in Figure 6 and Table 3.

The highest load carrying capacity value belongs to the S1632 coded beam (Experimental: 124.99 kN, Numerical: 125.81 kN). The lowest load carrying capacity value belongs to the S1212 coded beam (Experimental: 27.15 kN, Numerical: 27.40 kN). The maximum load carrying capacity value of the S1632 coded beam is 104% higher than the S1616 coded beam. The maximum load carrying capacity value of the S1428 coded beam is 49.21% higher than the S1414 coded beam. The maximum load carrying capacity of the S1224 coded beam is 35% higher than the S1212 coded beam. The carrying capacity of the S1616 coded beam is 11% higher than the S1414 coded beam and 34% higher than the S1212 coded beam. The load bearing capacity value of the S1632 coded beam is 40% higher than the S1428 coded beam, and 50,34% higher than the S1224 coded beam.

Table 3. Experimental and Numerical Analysis Results

	Experimental				**Numerical Analysis**			
Beams Code	**Max Load (kN)**	**Max Deflection (mm)**	**MOE (MPa)**	**MOR (MPa)**	**Max Load (kN)**	**Max Deflection (mm)**	**MOE (MPa)**	**MOR (MPa)**
S1212	27.15	31.15	9806	36.15	27.40	31.35	9833	36.49
S1414	50.21	34.02	10826	41.17	51.20	34.62	10849	41.98
S1616	61.10	40.35	10944	46.14	61.46	40.52	10962	42.68
S1224	62.06	69.85	15987	46.46	62.73	70.15	16090	46.97
S1428	74.92	70.00	17639	49.15	76.22	70.25	16496	50.00
S1632	124.99	70.15	17763	58.36	125.81	70.28	17846	58.74

The highest amount of displacement was seen in the S1632 coded beam (70.15 mm). The lowest displacement amount was observed in the S1212 coded beam (31,15 mm). As a result of modeling with the ANSYS software program, it was determined that it gave results in parallel with the experimental results. With the increase in section size, the load carrying capacity and displacement amounts also increased. Flexural strength and modulus of elasticity values are given in Figure 5.

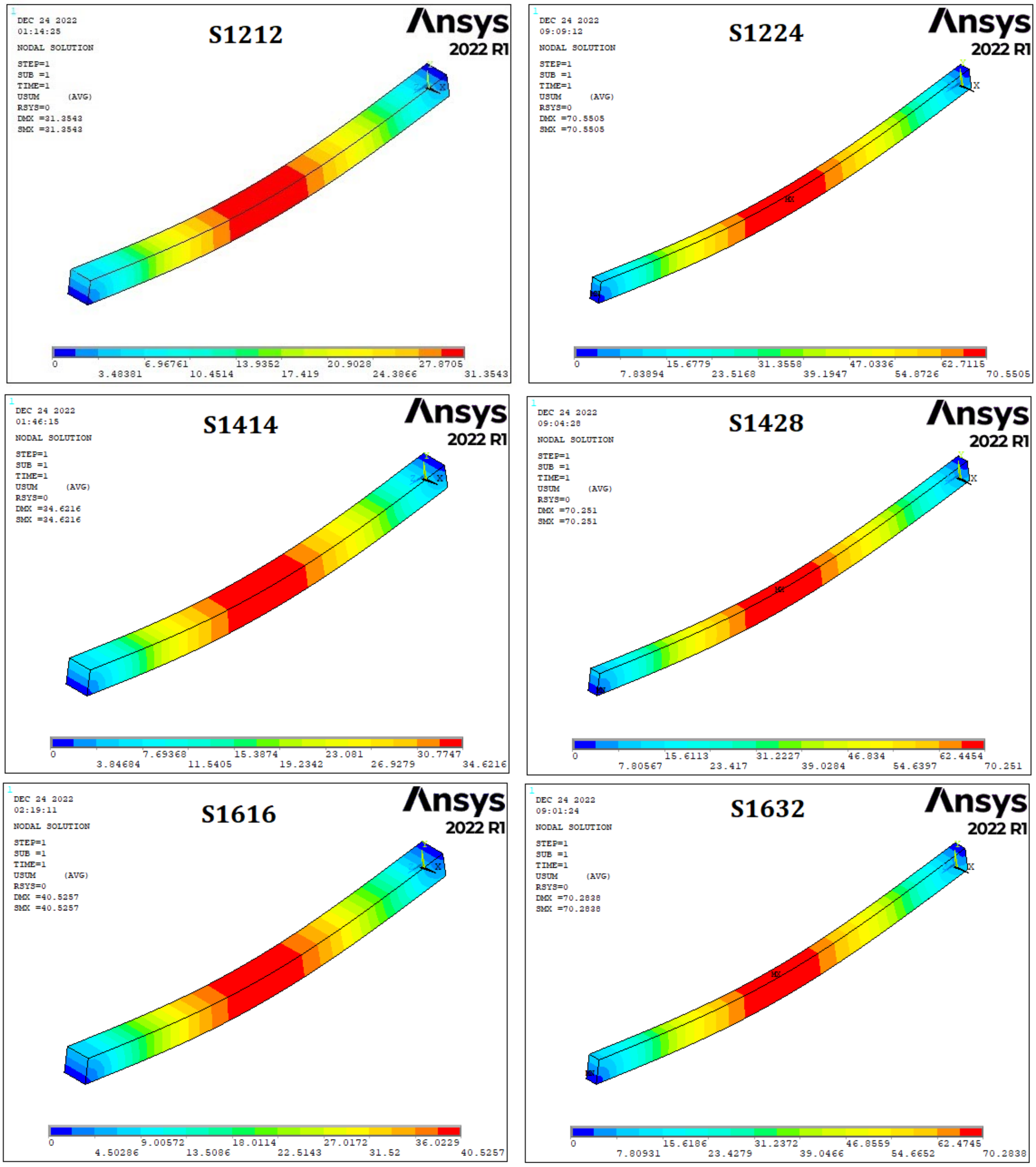


Figure 4. ANSYS Software Program Analysis Images

The highest flexural strength (Experimental: 58.36 MPa, Numerical: 58.74 MPa) and modulus of elasticity (Experimental: 17763 MPa, Numerical: 17846 MPa) belong to the S1632 coded beam. The lowest flexural strength (Experimental: 36.15 MPa, Numerical: 36.49 MPa) and elasticity modulus (Experimental: 9806, Numerical: 9833) values belong to the S1212 coded beam. The flexural strength value of the S1632 coded beam is approximately 20-27% higher than the S1616 coded beam. The flexural strength value of the S1428 coded beam is approximately 16% higher than the S1414 coded beam. The flexural strength value of the S1224 coded beam is approximately 22% higher than the S1212 coded beam. The modulus of elasticity value of the S1632 coded beam is approximately 23-38% higher than the S1616 coded beam. The modulus of elasticity value of the S1428 coded beam is approximately

34-38% higher than the S1414 coded beam. The modulus of elasticity of the S1224 coded beam is approximately 34% higher than the S1212 coded beam.

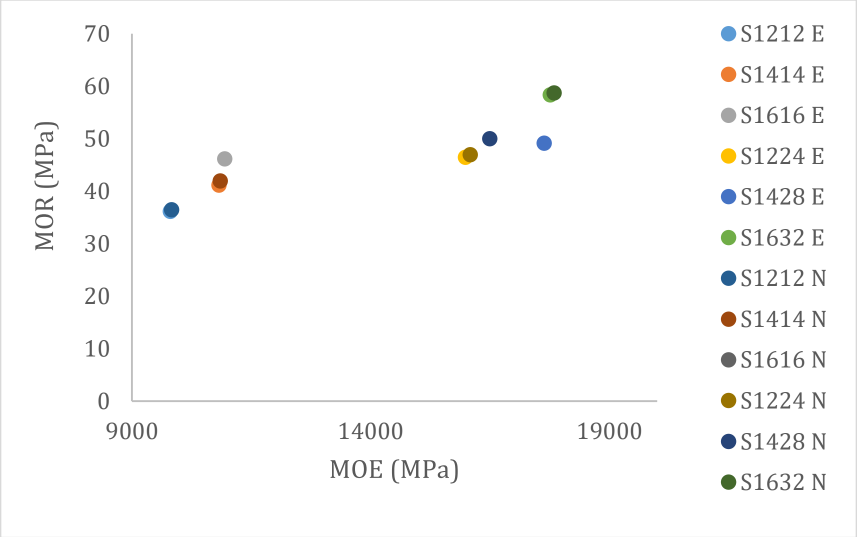


Figure 5. MOE and MOR Experimental (E) and Numerical (N) Results

The modulus of elasticity (Experimental: R^2=0,89, Numerical: R^2=0,90) and modulus of rupture (Experimental: R^2=0,92, Numerical: R^2=0,96) values obtained as a result of numerical and experimental analysis gave close results, as shown in Figure 6.

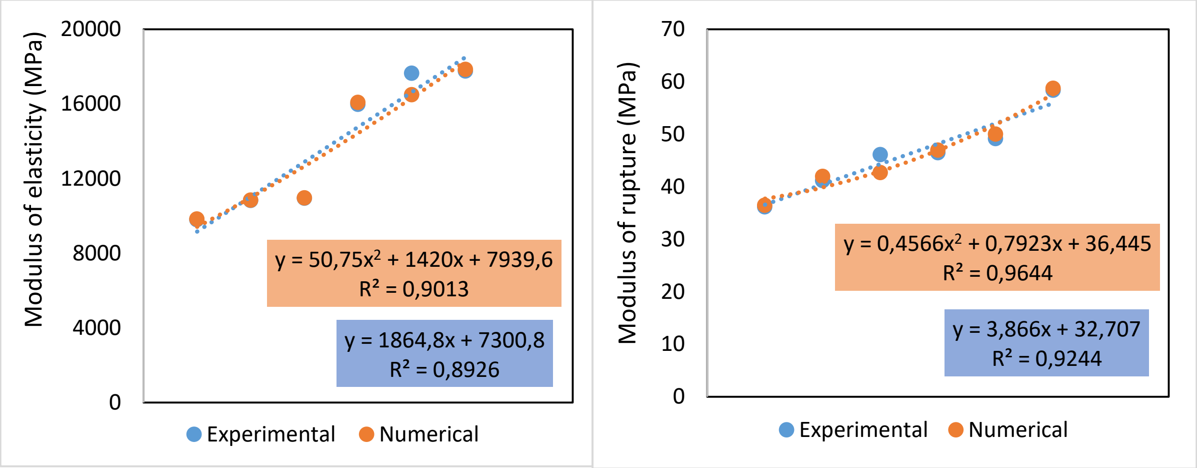


Figure 6. Numerical Analysis and Experimental Analysis Results

Failure Modes

During the initial phase of loading, the specimens underwent elastic deformation. As the load increased, plastic deformation occurred in the specimens. At this point, the specimens started to exhibit numerous minor compression wrinkles. The bending rigidity of the specimen decreased marginally, and the deformations increased significantly. The bottom laminates eventually experienced their maximum tensile stresses. Figure 7 shows three typical failure modes noticed in final displacement.

Ohuchi et al., (2009) and Ouchi et al., (2013) reached a conclusion in terms of experimental research based on bending tests of hinoki (*Chamaecyparis obtusa*) and sugi finger-jointed laminae. In these studies, block specimens that assumed the finger-joint part and were glued under various adhesive conditions were used in block shear tests to examine the ideal adhesive condition in the finger-joint part that influences the strength properties of the large-scale finger-jointed laminae. In conclusion, evaluating finger-joint properties is crucial for glulam with good strength properties.

Figure 7. Typical Failure Modes of Specimens (A) Shear Failure of Splitting of Timber (B) Splitting of Timber (C) Shear Failure of Splitting of Timber

CONCLUSIONS

Bending properties of beams produced in 6 different cross-sections, different layer numbers, and thicknesses, were investigated experimentally and analytically. The specimens experienced elastic deformation during the initial loading stage. The specimens underwent plastic deformation as the load increased. The specimens now began to show numerous small compression wrinkles. The specimen's slight reduction in bending rigidity was accompanied by a marked increase in deformations. Maximum tensile stresses eventually reached the bottom laminates.

The load bearing capacity of 7-layer beams is approximately 35-104%, flexural strength is 20-27%, and the modulus of elasticity is 23-38% higher than 3-layer beams. Therefore, the load carrying capacity values of 7-layer beams increased compared to 3-layer beams. The lowest flexural strength and elasticity modulus values belong to the S1212 coded beam, and the highest flexural strength and elasticity modulus values belong to the S1632 coded beam. The bending properties increased with the increase in size. It was determined that the maximum load carrying capacity, bending strength, and elasticity modulus values obtained as a result of experimental and numerical analysis were very close to each other. Numerical analysis results showed that beams produced with various number of layers and thicknesses can be simulated. It has been determined that the results obtained by creating numerical models instead of experimental analyses for this type of wooden beams may be sufficient.

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