Darius Albrektas*[1], Ernestas Ivanauskas[2], Ugnė Misiūnaitė[2]

Forecasting and Comparison of Mechanical Properties of Wooden Structure Models

Predviđanje i usporedba mehaničkih svojstava modela drvnih konstrukcija

ORIGINAL SCIENTIFIC PAPER
Izvorni znanstveni rad
Received – prispjelo: 12. 8. 2024.
Accepted – prihvaćeno: 23. 12. 2024.
UDK: 630*83; 674.038.5
https://doi.org/10.5552/drvind.2025.0227

ABSTRACT • *In this study, different methods were used to compare the mechanical properties of spruce wood. The aim was to evaluate the potential of predicting the properties and behavior of wooden structural elements containing holes and voids. The modulus of elasticity (MOE) was determined using three methods: the static 4-point bending method according to the standard EN 408:2010+A1:2012, the original dynamic transverse resonance vibration method, and the ANSYS design program. The research was carried out in two phases. In the first phase, the dynamic modulus of elasticity (MOEd) of the samples was determined without causing them any damage. In the second phase, the bending resistance and static modulus of elasticity (MOE) of the same samples were determined. Using the ANSYS program and considering the dynamic modulus of elasticity, density, and other parameters, the bending resistance and static modulus of elasticity (MOEa) were predicted. During the first stage of the study, the modulus of elasticity (MOE) was measured for different groups of samples using different methods. The results showed that the average values of MOE differed by up to 4.6 % between the different groups. In the second stage, additional samples were divided into 5 groups, and holes or voids were formed in them according to 5 different schemes. The MOE, bending resistance, MOEa, and bending resistance were determined for each group, and it was found that the average MOE values differed by up to 17 % between the different groups. The presence of holes and voids in the wood increased the anisotropy of the material, which had the most significant impact on the results. Regardless of the number of holes and voids, the damping factor increased by up to 2.1 times.*

KEYWORDS: *modulus of elasticity; coefficient of damping; predicting of mechanical properties; hole; void*

SAŽETAK • *U ovom su istraživanju primijenjene različite metode za usporedbu mehaničkih svojstava smrekovine. Cilj je bio procijeniti mogućnost predviđanja svojstava i ponašanja drvenih konstrukcijskih elemenata koji imaju rupe i šupljine. Modul elastičnosti (MOE) određen je trima metodama: statičkom metodom savijanja u četiri točke prema normi EN 408:2010+A1:2012, metodom izvorne dinamičke transverzalne rezonantne vibracije te programom za projektiranje ANSYS. Istraživanje je provedeno u dvije faze. U prvoj je fazi određen dinamički modul elastičnosti (MOEd) uzoraka bez nanošenja ikakvih oštećenja. U drugoj je fazi određen otpor na savijanje i statički modul elastičnosti (MOE) istih uzoraka. Otpor na savijanje i statički modul elastičnosti (MOEa) predviđen je uz pomoć programa ANSYS, pri čemu su uzeti u obzir dinamički modul elastičnosti, gustoća drva i drugi parametri. Tijekom prve faze istraživanja izmjeren je modul elastičnosti (MOE) za različite skupine uzoraka različitim metodama. Rezultati su pokazali da su se prosječne vrijednosti modula elastičnosti različitih skupina*

* Corresponding author
[1] Author is researcher at Kauno kolegija Higher Education Institution, Kaunas, Lithuania. https://orcid.org/0009-0000-0641-347X
[2] Authors are researchers at Kaunas University of Technology, Kaunas, Lithuania. https://orcid.org/0000-0002-2014-8390, https://orcid.org/0009-0001-9699-4366

uzoraka međusobno razlikovale do 4,6 %. U drugoj fazi dodatni su uzorci podijeljeni u pet skupina, na kojima su napravljene rupe ili šupljine prema pet različitih shema. Za svaku skupinu određeni su MOE, MOEa i otpornost na savijanje, a utvrđeno je da se prosječne vrijednosti modula elastičnosti među različitim skupinama razlikuju do 17 %. Postojanje rupa i šupljina u drvu povećalo je anizotropiju materijala, što je najviše utjecalo na rezultate istraživanja. Bez obzira na broj rupa i šupljina, faktor prigušenja povećao se do 2,1 put.

KLJUČNE RIJEČI: *modul elastičnosti; koeficijent prigušenja; predviđanje mehaničkih svojstava; rupa; šupljina*

1 INTRODUCTION
1. UVOD

Wood has been widely used as a building material since ancient times. In addition to natural wood, other wood materials are also extensively used in construction. By gluing wood (Abed *et al*., 2022; Hildebrandt *et al.,* 2017; Ramage *et al.,* 2017; Risse *et al.*, 2019; Sanscartier Pilon *et al.,* 2019), it is possible to manufacture elements of various dimensions and alter some of their properties. This includes reducing the variability of mechanical properties, minimizing the environmental impact on dimensional and shape stability, eliminating defects or anatomical elements negatively affecting mechanical properties, and expanding the range of applications.

In the near future, wood will play an even more significant role in construction. This is due to the European Climate Law signed on June 24, 2021, obliging participants in the construction market to reduce greenhouse gas (GHG) emissions by at least 55 % by 2030 and achieve climate neutrality by 2050. The European Commission introduced the Green Deal to transform the EU into a modern, resource-efficient, and competitive economy, aiming for the EU to become the world's first climate-neutral continent by 2050, with no emissions of greenhouse gases and economic growth decoupled from resource use (The European Green Deal).

To predict the behavior of an element in a construction, precise knowledge of its mechanical properties is essential. Wood exhibits a wide range of properties, including mechanical variability. For example, the modulus of elasticity along the grain of elements cut from the same wood species can vary up to 2 times (Wood Handbook, 2010; Wagenführ, 2000). The properties of elements cut from the same tree trunk can also differ (Vobolis and Albrektas, 2007). Various defects, sometimes invisible to the naked eye (e. g. internal cracks, splits, resin cavities, fiber wrap, biological damage), and anatomical elements, which are often unavoidable, further influence mechanical properties. Thus, the mechanical properties of individual specimens, even those from the same sample, can vary by 30 % or more. The dispersion of values can be further increased by defects (Albrektas and Styraite, 2022).

It is advised to employ non-destructive methods for determining mechanical properties. By doing so, the test object remains unscathed and can be utilized subsequently. As a result, when constructing crucial structures, all the elements used can be examined, rather than just a small subset.

It is a well-established fact that values obtained for a particular property of a sample may differ based on the method employed to determine it. For instance, the dynamic modulus of elasticity, ascertained by non-destructive methods, can be higher than the static modulus of elasticity of the same element (Shan-qing and Feng, 2007; Divos and Tanaka, 2005; Nzokou *et al.,* 2006). This difference must be considered while designing structures or predicting the behavior of individual elements within them.

Holes or voids are often needed for various communication purposes in static structures. By cutting or drilling voids, there is a potential crack formation and propagation risk. The spread of these cracks changes the way structures collapse, and fractures may occur even under significantly lower loads (Ardalany *et al.,* 2013). Various methods are applied to prevent the formation and spread of such cracks, including the use of screws, steel plates, plywood, fiber-reinforced polymers (FRP), etc. An effective means of reinforcing elements made from fine wood panels is through reinforcement (Yerlikaya and Karaman, 2020). Karaman (2021) determined that the effects of joints reinforced BFRP and GFRP.

Depending on the size and location of voids, they can affect the elements strength, elasticity, and plasticity in various ways (Ardalany *et al.,* 2013; Zhang *et al.,* 2018; Gauronskaitė *et al.,* 2022). It is important to understand the impact of voids and holes on the behavior of structural elements. Static destructive methods are not suitable for evaluating the individual mechanical properties of each element, as the tested object will not be suitable for use after the study. Dynamic non-destructive methods, while not damaging the test object, often indicate average material properties. A typical example is measuring the dynamic modulus of elasticity by evaluating the sound propagation speed (Baltrušaitis and Mišeikytė, 2011). In this case, the average density of the sample, the average sound propagation speed, and the average dynamic modulus of elasticity are determined without isolating the "weakest" point (which could be a hole, in the case of a wooden element, a large branch, etc.). Yet, this "weakest" point can significantly influence the behavior of the element in a structure or the behavior of the entire structure.

Computer-aided design programs can be used in scenarios where it is imperative to assess the conduct of a structure or an element following the creation of a cavity or void. By acquiring knowledge of the pertinent physical and mechanical properties of an element, it is possible to model the alterations that may occur based on the location, size, and quantity of voids.

Objective of the study: To evaluate the possibility of predicting the behavior and properties of an element using computer-aided design software.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The research employed spruce wood specimens that were free from visible defects, large branches, or other anatomical features that could have influenced the mechanical properties of the wood. The wood was purchased from a company selling wood products in Lithuania. Before testing, the cut samples were kept for two weeks in laboratory conditions with the temperature of 20-22 °C and the relative humidity of 55 – 60 %. A total of 70 specimens were examined, with dimensions measuring approximately 600 mm × 40 mm × 30 mm, and a moisture content ranging between 10.4 % and 11.6 %. The density of the specimens ranged from 403 to 451 kg/m^3. The length of the specimens was measured with a ruler with a precision of 1 mm, while the width and thickness were measured with a caliper having a precision of 0.05 mm. The mass of the specimens was measured with scales having a precision of 0.01 g, and the moisture content was measured using an electronic moisture meter in line with standard EN 13183-2:2003, EN 13183-2:2003/AC:2004, with a precision of 0.1 %.

The dynamic modulus of elasticity (*MOEd*) and coefficient of damping of the specimens were determined using an original methodology based on the transverse resonance vibration method (Vobolis and Albrektas, 2007; Gauronskaitė *et al.,* 2022). The bending resistance and static modulus of elasticity of the specimens were also determined using the methodology of standard LST EN 408:2010+A1:2012. Additionally, the behavior of the specimens was simulated using the ANSYS design program.

The four-point bending scheme and the specimen in the testing machine are presented in Figure 1.

ANSYS is one of the most popular engineering analysis programs due to its versatility, used for modeling, analysis and optimization in various engineering fields. This program allows you to perform element analysis (mechanical load, deformations, stresses). It is used in the development, optimization of product design, analysis of structural strength, stability, etc.

The study was conducted in two stages. In the first stage, 20 specimens were randomly selected, and their dynamic modulus of elasticity and coefficient of damping were determined. Subsequently, bending resistance and static modulus of elasticity were measured. The ANSYS design program used the available data (specimen density, dynamic modulus of elasticity) to determine the bending resistance and static modulus of elasticity. Finally, all the obtained values were statistically analyzed, and the results are presented in Table 1.

In the second stage, the remaining specimens were randomly divided into 5 groups of 10 specimens each (Groups II-VI), and holes and voids were drilled in accordance with the provided diagrams (see Figure 2).

The holes and voids are shaped in such a way as to have the greatest influence on the mechanical properties of the specimens during bending according to a scheme developed by the authors of this work. Subsequently, the dynamic modulus of elasticity and coefficient of damping of these specimens were determined. Bending resistance and static modulus of elasticity were also measured using the "four-point" bending method. Using the available data (specimen density, dynamic modulus of elasticity), the ANSYS design program determined the bending resistance and static modulus of elasticity. All values obtained were statistically processed (standard deviation (SD) was calculated).

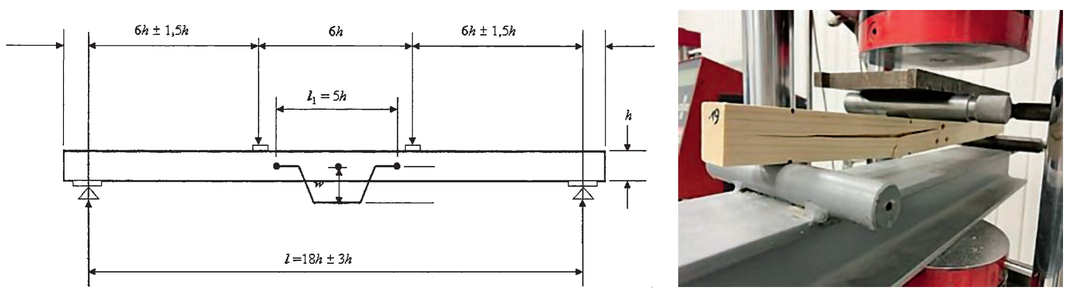

Figure 1 Four-point bending scheme (a) and specimen in testing machine (b); here *h* – specimen thickness; *l* – distance between supports
Slika 1. Shema savijanja u četiri točke (a) i uzorak u ispitnom uređaju (b); *h* – debljina uzorka, *l* – udaljenost između nosača

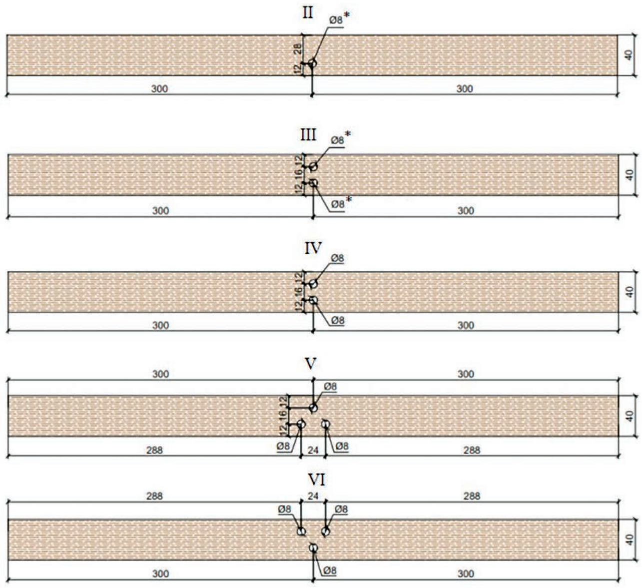

Figure 2 Schematics of drilling holes and voids in specimens: here II–VI are numbers of groups; * denotes a non-through hole in specimen, and holes have a depth of 15 mm (we called it „the void“)
Slika 2. Sheme bušenja rupa i šupljina u uzorcima: II. – VI. su brojevi skupina; * označava neprolaznu rupu na uzorku, a rupe su dubine 15 mm (nazvali smo ih *šupljinama*)

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

In the first stage of the study, the average values and standard deviations of the mechanical properties were determined for the tested specimens within each group, as presented in Table 1.

As expected, it was discovered that the (*MOEd*) is higher than the (*MOE*). The difference between the two is around 360 MPa, which is equivalent to 4.6 %. Other studies conducted by different researchers also showed similar differences between the static and dynamic modulus of elasticity (Divos and Tanaka, 2005; Nzokou *et al.,* 2006; Shan-qing and Feng, 2007). The ANSYS design program yielded an average static modulus of elasticity of 285 MPa, which is 3.7 % higher than the actual bending case. The differences are most likely due to the fact that the design program does not consider material heterogeneity. Additionally, fractures tend to occur at the weakest point of the specimen, which could be a result of a minor crack, a defect in the fiber structure, or other factors. The design program may not take into account these "weakest points," which could also explain the lower average bending resistance obtained in real-life situations compared to the design program. The standard deviation could also be related to these differences. Typical examples of specimen failure are presented in Figure 3, illustrating the behavior of wood during bending.

It was noticed that the failure of one specimen (Figure 3a) happened at the location where it was under load, whereas another specimen (Figure 3b) did not fail in the location where the highest stresses were expected, but rather in its close vicinity. The location of the sample breakdown can be determined by any internal structural feature, including the aforementioned invisible one. The reasons for this variation in failure locations were the structural characteristics of each specimen. The compared design program ANSYS does not "see" these material structure features. For this reason, there may be a discrepancy between the mechanical properties determined in the laboratory and those

Table 1 Average mechanical properties values of specimen groups without voids and holes
Tablica 1. Srednje vrijednosti mehaničkih svojstava skupina uzoraka bez *šupljina* i rupa

Group *Skupina*	***MOEd***		**tgδ**		σ_w		***MOE***		σ_{wa}		MOE_a	
	Average value, MPa	*SD*, MPa	Average value, r. u.	*SD*, r. u.	Average value, MPa	*SD*, MPa	Average value, MPa	*SD*, MPa	Average value, MPa	*SD*, MPa	Average value, MPa	*SD*, MPa
I	7859	544	0.029	0.0023	62.2	4.7	7499	464	71.4	2.9	7784	360

Note: here *MOEd* – dynamic modulus of elasticity, *tgδ* – coefficient of damping, σ_w – bending resistance; *MOE* – static modulus of elasticity, σ_{wa} – bending resistance, calculated with ANSYS; MOE_a – modulus of elasticity, calculated with ANSYS
Napomena: MOEd – dinamički modul elastičnosti, tgδ – koeficijent prigušenja, σ_w *– otpor na savijanje; MOE – statički modul elastičnosti,* σ_{wa} *– otpor na savijanje izračunan uz pomoć programa ANSYS;* MOE_a *– modul elastičnosti izračunan primjenom programa ANSYS*

a

b

Figure 3 Typical examples of samples fracture
Slika 3. Tipični primjeri loma uzoraka

Table 2 The average mechanical property values and their standard deviations for specimen groups with voids and holes
Tablica 2. Srednje vrijednosti mehaničkih svojstava i njihove standardne devijacije za skupine uzoraka sa *šupljinama* i rupama

Group *Skupina*	***MOEd***		**tgδ**		σ_w		***MOE***		σ_{wa}		***MOEa***	
	Average value, MPa	*SD*, MPa	Average value, r. u.	*SD*, r.u.	Average value, MPa	*SD*, MPa	Average value, MPa	*SD*, MPa	Average value, MPa	*SD*, MPa	Average value, MPa	*SD*, MPa
II	6655	631	0.047	0.0058	46.5	4.4	5462	719	61.1	5.2	7132	664
III	6943	574	0.044	0.0030	52.6	3.9	5803	421	63.7	5.0	7355	436
IV	6215	208	0.049	0.0040	41.5	2.0	5144	380	56.6	2.1	6619	75
V	7085	650	0.046	0.0040	43.9	3.0	6195	553	64.1	6.2	7171	702
VI	7218	55	0.043	0.0050	44.3	3.8	5295	492	65.4	0.5	7626	22

Note: here *MOEd* – dynamic modulus of elasticity, *tgδ* – coefficient of damping, σ_w – bending resistance; *MOE* – static modulus of elasticity, σ_{wa} – bending resistance, calculated with ANSYS; MOE_a – modulus of elasticity, calculated with ANSYS
Napomena: MOEd – dinamički modul elastičnosti, tgδ – koeficijent prigušenja, σ_w *– otpor na savijanje; MOE – statički modul elastičnosti,* σ_{wa} *– otpor na savijanje izračunan uz pomoć programa ANSYS;* MOE_a *– modul elastičnosti, izračunan primjenom programa ANSYS*

calculated. The obtained coefficient of damping corresponds to the values of wood coefficient of damping obtained in previous studies (Vobolis and Albrektas, 2007; Gauronskaitė *et al.,* 2022; Albrektas and Styraite, 2022). The average mechanical property values and their standard deviations for specimen groups with voids and holes formed according to the discussed schemes are presented in Table 2.

Apparently, the average modulus of elasticity for specimens with voids or holes is lower than for those without them. It can be concluded that both specimens with voids and those with holes have statically obtained modulus of elasticity values close in magnitude (around 1000 MPa) or about 13-17 % lower than the dynamic modulus. This difference is significantly greater than when evaluating specimens without voids. The reason for this is that, during assessment of dynamic modulus of elasticity, voids only facilitate the bending of the specimen, whereas during static bending, they significantly weaken the bending zone, leading to specimen failure. Figure 4 presents several typical specimen fracture cases.

It has been observed that specimens typically fail where the highest load is applied and where voids or holes are formed. Group VI stands out from all other groups as in this case, the difference between static and dynamic modulus of elasticity is approximately 1900 MPa or about 27 %. Upon analyzing the results and failure zones of specimens, it has been concluded that the fiber in the failure zone of several specimens in this group was weaker and further weakened by the presence of voids. After excluding these specimens, the difference is significantly smaller. Figure 4 presents variant "e" as an example of such a specimen.

The ANSYS design program determined a modulus of elasticity that was slightly higher than the *MOEd* (about 400 MPa or about 6-7 %). This can be explained by the fact that the dynamic modulus of elasticity determines the frequency of vibrations when the specimen deflects in one mode (Vobolis and Albrektas, 2007; Gauronskaitė *et al.,* 2022). Voids are where the specimen bends and they "facilitate" the bending. The design program also evaluates voids in the bending zone. However, the real result is worse than the theoretical one, likely due to the anisotropy in materials and uneven distribution of properties. This is also true for average bending resistance, which is practically 17 – 31 % lower than that determined by the design program. Figure 5 shows examples of specimen failure and stress distribution simulated by the design program.

It has been observed that the highest stresses that should make the specimens fail, are supposed to form

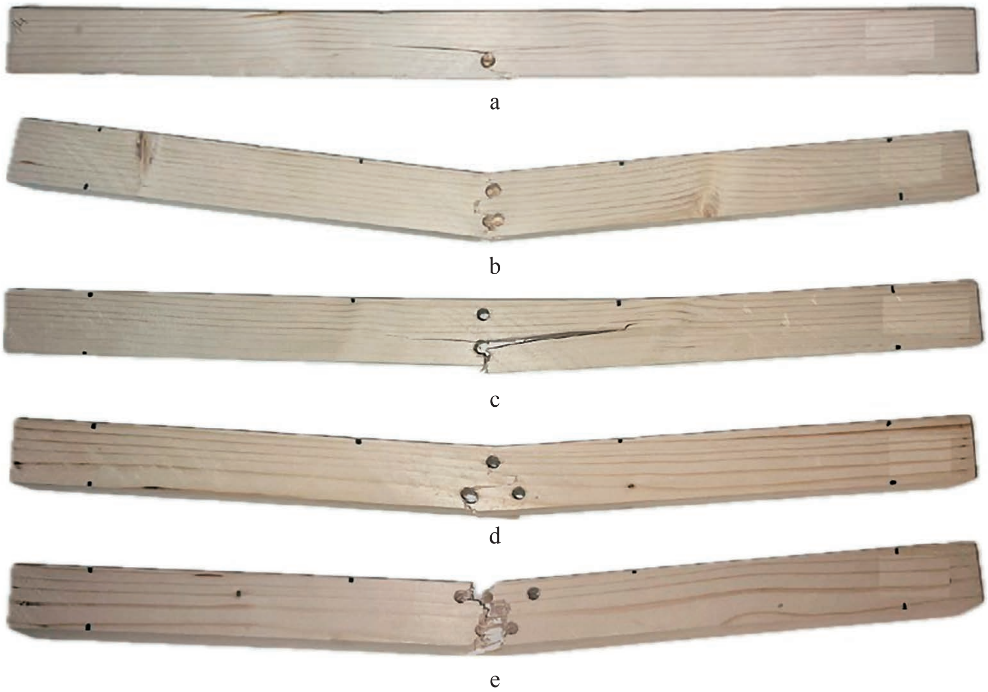

Figure 4 Typical specimen fracture cases
Slika 4. Tipični primjeri loma uzoraka

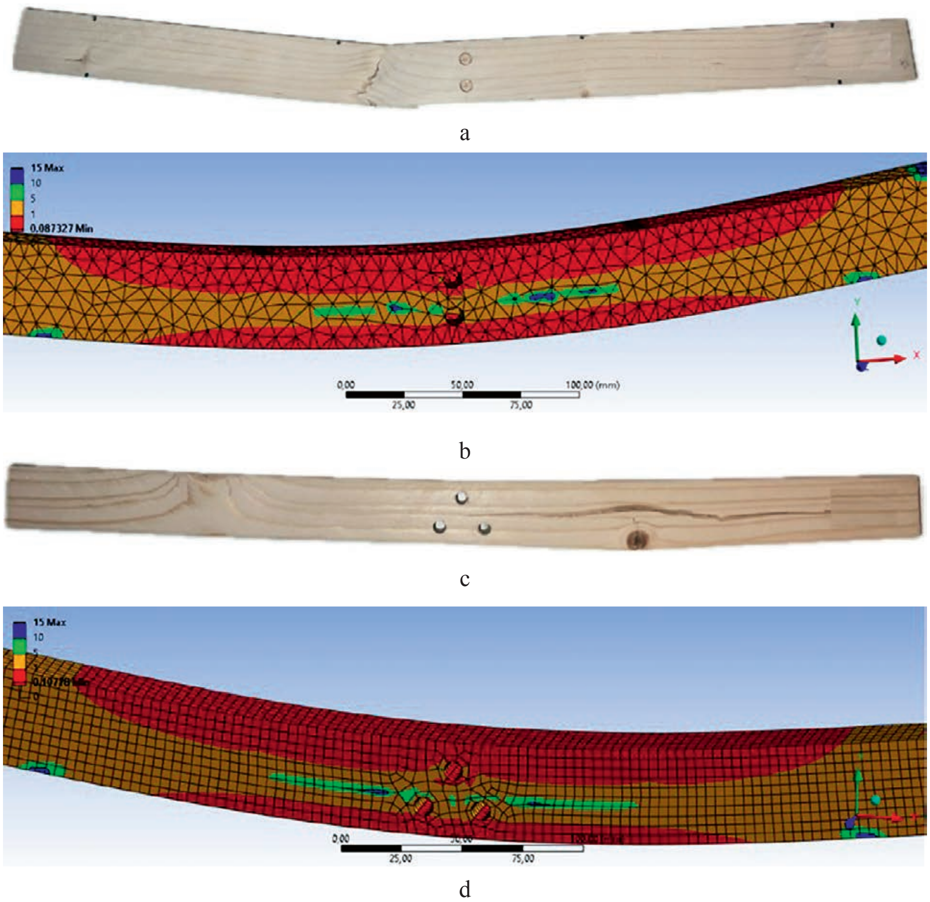

Figure 5 Examples of stress distribution simulated by design program for specimen failure (a, b – one from group III, c, d – one from group V)
Slika 5. Primjeri raspodjele naprezanja simuliranog programom za proračun loma uzorka (a, b – jedan uzorak iz skupine III., c, d – jedan uzorak iz skupine V.)

symmetrically around the voids that are created. However, in practice, due to the unique nature of wood structure, the specimens fail asymmetrically under load, most likely at the weakest points.

The coefficient of damping increased up to two times regardless of the formation of a void or a hole. Such defects compromise specimen integrity, and results are consistent with similar studies (Gauronskaitė *et al.,* 2022; Albrektas and Styraitė, 2022). These studies also evaluated the influence of element integrity on the coefficient of damping. In the first case, holes required for fittings to secure furniture parts were modeled, and in the second, wood drying defects (cracks formed during improper drying) were modeled.

4 CONCLUSIONS
4. ZAKLJUČAK

The values of mechanical properties for wood specimens were determined through various methods and simulated using a design program. The correlation between the different methods and the program simulation showed a relatively small margin of error. However, the modulus of elasticity for the same specimen varied up to 7.1 % when determined by different methods, with an average group difference of up to 4.6 %.

When a significant defect (especially in the bending area) is present in a specimen, its resistance to static bending or static modulus of elasticity decreases more than when evaluated by dynamic transverse resonance vibration method or simulated by the design program. This is because the dynamic method only partially eliminates the anisotropy of wood. The design program "assumes" that wood is an isotropic and homogeneous material and evaluates only the defects that are specified by the designer. As a result, the modulus of elasticity determined by different methods for the same specimen can differ by up to 24 %, with the average group difference being up to 17 %.

The standard deviation of the modulus of elasticity values in all specimen groups has been calculated to be large, up to 13 % from the average value. This suggests that there is a significant variation in the mechanical properties of the material, regardless of the nature or quantity of voids formed in the specimen.

The study found that the place of presence of voids and holes did not impact the coefficient of damping. However, when voids or holes were present in individual specimens, the coefficient of damping increased by a factor of 1.5 to 2.1.

In order to improve the precision of computer-aided design programs in predicting the characteristics and behavior of an element, extensive testing is required. This testing should involve altering the location, quantity, and size of voids, as well as analyzing different wood properties and design programs. The research conducted in this study has shown that this method is feasible and can be partially relied upon to obtain results. Although the results obtained by different methods are quite different, the general trends remain. Also, a large dispersion of results has been obtained, which is typical for most research results due to the peculiarities of wood structures.

5 REFERENCES
5. LITERATURA

1. Abed, J.; Rayburg, S.; Rodwell, J.; Neave, M, 2022: A Review of the performance and benefits of mass timber as an alternative to concrete and steel for improving the sustainability of structures. Sustainability, 14 (9): 5570. https://doi.org/10.3390/su14095570
2. Albrektas, D.; Styraite, A., 2022: Modelling and investigating real-world drying defects in wood. Drvna industrija, 73 (2): 115-123. https://doi.org/10.5552/drvind.2022.2040
3. Ardalany, M.; Fragiacomo, M.; Carradine, D.; Moss, P., 2013: Experimental behavior of Laminated Veneer Lumber (LVL) joists with holes and different methods of reinforcement. Engineering Structures, 56: 2154-2164. https://doi.org/10.1016/j.engstruct.2013.08.034
4. Baltrušaitis, A.; Mišeikytė, S., 2011: Strength and stiffness properties of the Lithuanian grown scotis pine (*Pinus sylvestris*): non destructive testing methods vs static bending. Wood Research, 56 (2): 157-168.
5. Divos, F.; Tanaka, T., 2005: Relation between static and dynamic modulus of elasticity of wood. Acta Silvatica & Lignaria Hungarica, 1: 105-110.
6. Gauronskaitė, S.; Dobilaitė, V.; Jucienė, M.; Albrektas, D., 2022: Effect of open-holes on mechanical properties of wood composite materials. Wood Research, 67 (1): 41-50. https://doi.org/10.37763/wr.1336-4561/67.1.4150
7. Hildebrandt, J.; Hagemann, N.; Thrän, D., 2017: The contribution of wood-based construction materials for leveraging a low carbon building sector in Europe. Sustainable Cities and Society, 34: 405-418. https://doi.org/10.1016/j.scs.2017.06.01
8. Karaman, A., 2021: Bending moment resistance of t-type joints reinforced with basalt and glass woven fabric materials. Maderas. Ciencia y Tecnología, 23: 1-12. https://doi.org/10.4067/s0718-221x2021000100444
9. Karaman, A.; Yildirim, M. N.; Tor, O., 2021: Bending characteristics of laminated wood composites constructed with black pine wood and aramıd fiber reinforced fabric. Wood Research, 66 (2): 309-320. https://doi.org/10.37763/wr.1336-4561/66.2.309320
10. Karaman, A.; Yildirim, M. N., 2021: Effects of wood species of the dowels and fiber woven fabric types on bending moment resistance of l-shaped joints. Wood Industry and Engineering, 3 (2): 12-22.
11. Nzokou, P.; Freed, J.; Kamden, D. P., 2006: Relationship between non destructive and static modulus of elasticity of commercial wood plastic composites. Holz als Roh und Werkstoff, 64: 90-93. https://doi.org/10.1007/s00107-005-0080-x
12. Ramage, M. H.; Burridge, H.; Busse-Wicher, M.; Fereday, G.; Reinolds, T.; Shah, D. U.; Wu, G.; Yu, L.; Fleming, P.; Densley-Tingley, D.; Allwood, J.; Dupree, P.; Linden, P. F.; Scherman, O., 2017: The wood from the trees: The use

of timber in construction. Energy Reviews, 68 (1): 333-359. https://doi.org/10.1016/j.rser.2016.09.107
13. Risse, M.; Weber-Blaschke, G.; Richter, K., 2019: Eco-effi ciency analysis of recycling recovered solid wood from construction into laminated timber products. Science of The Total Environment, 661: 107-119. https://doi.org/10.1016/j.scitotenv.2019.01.117
14. Sanscartier Pilon, D.; Palermo, A.; Sarti, F.; Salenikovich, A., 2019: Benefits of multiple rocking segments for CLT and LVL Pres-Lam wall systems. Soil Dynamics and Earthquake Engineering, 117: 234-244. https://doi.org/10.1016/j.soildyn.2018.11.026
15. Shan-qing, L.; Feng, F., 2007: Comparative study on three dynamic modulus of elasticity and static modulus of elasticity for Lodgepole pine lumber. Journal of Forestry Research, 18 (4): 309-312. https://doi.org/10.1007/s11676-007-0062-4
16. Vobolis, J.; Albrektas, D., 2007: Comparison of viscous elastic properties in wood of leaf and coniferous tree. Materials Science, 13 (2): 147-151.
17. Wagenführ, R., 2000: Holzatlas: mit zahlreichen Abbildungen München: Fachbuchverlag Leipzig im Carl Hanser Verlag, Leipzig (in German).
18. Yerlikaya, N. C.; Karaman, A., 2020: Effect of the fabric reinforcement of structural holes in wood based panels. Wood Research, 65 (3): 485-496. https://doi.org/10.37763/wr.1336-4561/65.3.485496
19. Yildrim, M. N.; Karaman, A.; Zor, M., 2021: Bending characteristics of laminated wood composites made of poplar wood and GFRP. Drvna industrija, 72 (1): 3-11. https://doi.org/10.5552/drvind.2021.1913
20. Zhang, X.; Que, Y.; Wang, X.; Li, Z.; Zhang, L.; Han, C.; Que, Z.; Komatsu, K., 2018: Experimental behavior of laminated veneer lumber with round holes, with and without reinforcement. BioResources, 13 (4): 8899-8910. https://doi.org/10.15376/biores.13.4.8899-8910
21. *** EN 408, 2010+A1:2012: Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties European Committee for Standardization, Brussels.
22. ***The European Green Deal. Striving to be the first climate-neutral continent. An official website of the European Union. https://ec.europa.eu/newsroom/know4pol/items/664852
(Accessed Jan. 15, 2024).
23. ***Wood Handbook, 2010: Wood as an Engineering Material. Centennial Edition. Forest Products Laboratory. Wood handbook – Wood as an engineering material. General Technical Report FPL-GTR-190. WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison.

Corresponding address:

DARIUS ALBREKTAS
Kauno Kolegija Higher Education Institution, Pramones st. 20, LT-50468 Kaunas, LITHUANIA,
e-mail: darius.albrektas@ktu.lt