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EFFECT OF OPEN-HOLES ON MECHANICAL PROPERTIES OF WOOD COMPOSITE MATERIALS

SIMONA GAURONSKAITĖ, VAIDA DOBILAITĖ, MILDA JUCIENĖ
KAUNAS UNIVERSITY OF TECHNOLOGY
LITHUANIA

DARIUS ALBREKTAS
KAUNAS UNIVERSITY OF APPLIED SCIENCES
LITHUANIA

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ABSTRACT

A few variations of open-holes in wood-based pieces, particle board and plywood were modeled in this article. The modulus of elasticity and the coefficient of damping for these pieces were determined using static and dynamic methods and the effect of holes of different quantity and size on mechanical properties were evaluated. As regards to wood particle boards, it was found that the modulus of elasticity decreased to10% after drilling holes, and the coefficient of damping increased to 13%. With regard to plywood pieces these changes were up to 14.5% and up to 21.5%, respectively.

KEYWORDS: Wood particle board, plywood, open-hole, modulus of elasticity, coefficient of damping, mechanical properties.

INTRODUCTION

Pieces of furniture, construction and other structures made of wood and wood-based materials are joined together using a variety of universal or special fittings and for this purpose, in many cases, various holes, open-holes, and notches are drilled in the pieces. Most of pieces are various bending, tensile, compressive and other mechanical load-carrying structures. Wooden buildings have heavy-duty beams that require holes to be drilled to allow plumbing, electrical wiring and other technical units to pass through. Making any open-holes in a wood element causes change in concentration of tensile and compressive stresses around the open-hole, which can lead to deterioration in the mechanical properties of the pieces and various defects that impair their properties.

Research of laminated veneer lumber beams have shown that cutting a sufficiently large open-hole (the ratio of the hole diameter to the beam width is 0.4, 0.5 and 0.6) in the beam reduces its strength by 30-52% (Ardalany et al. 2013), and even by 50-69% (Zhang et al. 2018).

In order to reduce such a significant loss of strength properties, as well as to stop or prevent the formation or spread of cracks at the open-hole, various methods of beam reinforcement around the open-hole are used, such as the use of nailed or glued plywood sheets, steel panels, threaded rods and glue-in bolts. The scientific works analyze the efficiency of these methods depending on the shape of the open-hole dimensions, parameters of reinforcement method and other structural features (Aldalany et al. 2013, Zhang et al. 2018, Aldalany et al. 2012, Aicher 2011, Tu et al. 2016, Danzer et al. 2016, Aicher and Höfflin 2008).

Research showed that deterioration of mechanical properties of the specimens is relevant not only in the case of a large diameter open-hole. It was found that open-holes Ø13, Ø16 and Ø20 mm lead to reduction of bending strength by 5 -17% fir specimens, and by 13 - 23% (Chen et al. 2019) for Douglas fir wood specimens. The research of wood particle board, particle board, oriented strandboard and plywood boards has shown, that the values of bending test properties decrease due to occurrence of open-holes (Yerlikaya and Karaman 2020). However, there are few works concerning research of the effect of smaller diameter open-holes on the change in mechanical properties of wood pieces.

It is important to note that the universal mechanical testing machine and standard test methodologies were used (Chen et al. 2019, Yerlikaya and Karaman 2020) to investigate the effect of open-holes on the mechanical properties of wood pieces. Specimens of Japanese cedar and Japanese cypress wood were examined using ultrasonic waves (Mori et al. 2016). After drilling open-holes in the specimens, MOE and MOR of the specimens were found to decrease. The obtained results revealed that such a non-contact and non-destructive method is suitable for evaluation of mechanical properties of wood elements with open-holes.

An analysis of literature review showed that there is a lack of studies regarding changes in mechanical properties of wood used in the furniture industry after drilling holes, because in this area, e.g. the structural solutions used in furniture frames manufacturing (shape and dimensions of the open-hole, location in the element, ratio of dimensions of the open-hole/piece, etc.) are very different from those relevant in construction or other areas. In addition, it is important to analyze suitability of non-destructive methods for determination of mechanical properties of wood pieces with open-holes.

The objective of the thesis is to determine the effect of size and location of open-holes on the mechanical properties of wood composite materials.

MATERIAL AND METHODS

Pieces made of glued plywood and wood particle board were used for the research. The research involved a multipurpose plywood intended for application in closed, dry rooms, flat sheets, without finishing coat. Particle boards are a multipurpose, three-layer board with a density of 640 - 655 kg·m^{-3} and a humidity of 9.8 – 10.7%. Plywood 690 - 710 kg·m^{-3} and 9.8 - 10.4%, resp. The research involved 50 particle boards and 50 plywood specimens with dimensions of 500 x 100 x 15 mm. The moisture content of the specimens was determined according to the EN 13183-2 standard using a Gann Hydromette moisture meter. The density was determined according to the EN 323 standard, the specimens were weighed using an electronic scale to the nearest 0.01 g and measured with a caliper (length – to the nearest 0.05 mm, thickness and width – to the nearest 0.02 mm). The dynamic modulus of elasticity, the coefficient of damping of the specimens were determined using the original methodology and equipment (Fig. 1) (Albrektas and Vobolis 2003, Timoshenko et al. 1985). The studies were performed at a frequency of 20-2000 Hz.

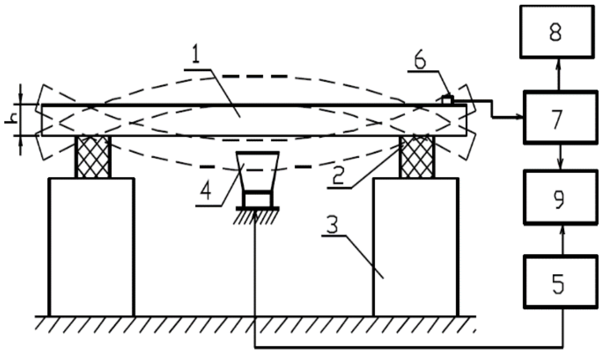

Fig. 1. The scheme of the test stand: 1 – specimen; 2 – vibration damping material (foam rubber); 3 – massive supports; 4 – loudspeaker; 5 – vibration generator; 6 – sensor; 7 – measuring instrument; 8 – oscilloscope; 9 – phase meter.

A beam-shaped body, which vibrates at a resonance (natural) frequency, depending on its anchorage, curves to a corresponding shape (mode), which in many cases is close to the mode of a theoretical isotropic beam. The *MOE* was calculated based on Eq. 1, the viscous properties (coefficient of damping) of studied specimens were evaluated based on Eq. 2:

$$E = \frac{f_{rez}^2 4\pi^2 \rho s l^4}{I A^2} \tag{1}$$

where: E – modulus of elasticity, f_{rez} – frequency of transverse vibrations, ρ – density of wood, s – cross-sectional area, l – specimens length, I – cross-sectional moment of inertia, A – method of fastening represented by a coefficient.

$$tg\delta \approx \frac{\Delta f}{f_{rez}} \tag{2}$$

where: f_{rez} – frequency of transverse vibrations, Δf – frequency bandwidth when amplitude of vibrations decreases by 0.7 times.

The static modulus of elasticity was determined in accordance to the EN 310 standard. Bending test was performed using a universal testing machine BTI-FB 050 TN (Zwick). Prior to testing, specimens were conditioned for 14 days at (20 ± 2)°C and (55 ± 5)% relative humidity. The conditioned plywood and wood particle board specimens were randomly segregated into five subgroups, BI, BII, BIII, BIV, BV, and PI, PII, PIII, PIV, PV, resp. Subsequently, the dynamic modulus of elasticity and coefficient of damping of all specimens were determined using the original methodology. Open-holes were then drilled in the specimens of subgroups II to V. Schemes of these specimens are shown in Fig. 2.

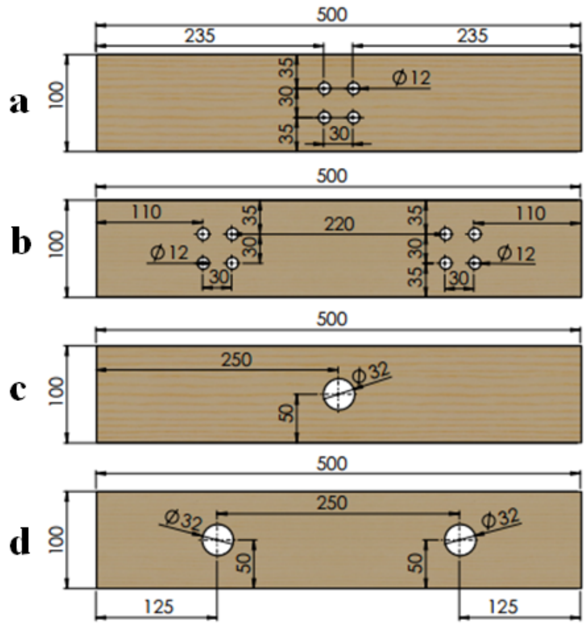

Fig. 2: Specimen drilling schemes: specimen group a – II, b – III, c – IV, d – V.

After drilling, the static, dynamic modulus of elasticity and the coefficient of damping of the specimens of subgroups II - V were determined repeatedly. Fig. 3 shows the position of the specimens of subgroups II - V during bending when the center of the specimen placed on two supports is under load.

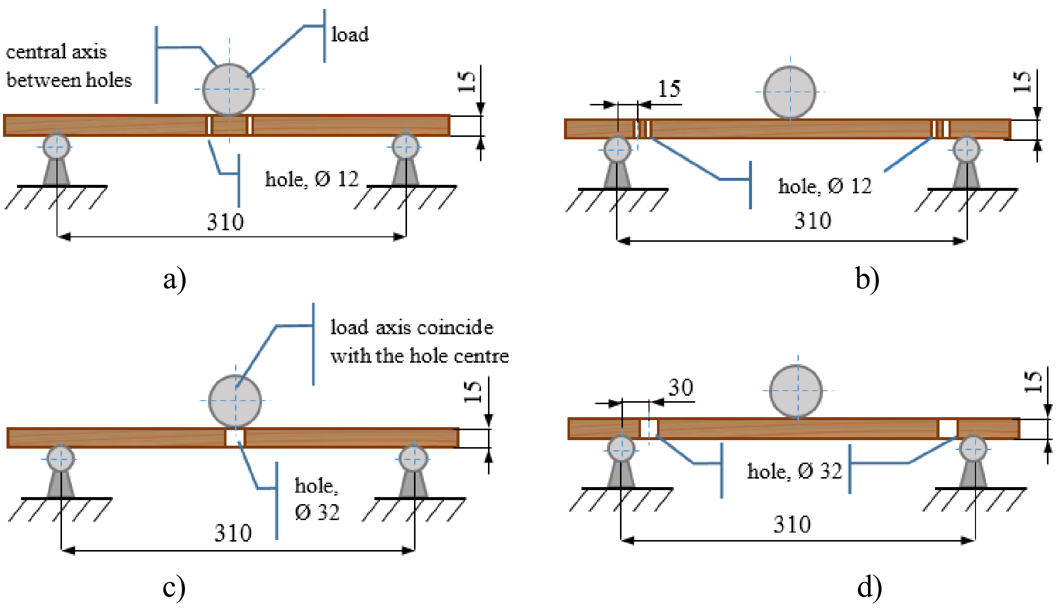

Fig. 3: Location of open-hole-support/load: group of specimens a) II, b) III, c) IV, and d) V.

All obtained values of static and dynamic modulus of elasticity and the coefficient of damping were statistically processed. The highest variance of values of the static modulus of elasticity was found in the group of wood particle board specimens B1 and is equal to 11%, and the lowest was found in the group of plywood PI specimens and is up to 6%.

RESULTS AND DISCUSSION

Open-holes of various sizes and shapes are drilled in wood and wood-based products and structures, and are usually intended for passage or fastening various communications. These holes are made in other ways as well, but they are usually drilled (Jaiprakash et al. 2020). For pieces used in the production of cabinet furniture, open-holes are made for fixing other pieces or fittings. An open-hole or notch can also serve as a design feature that gives furniture exclusivity. These areas are often damaged during use.

Average values of the dynamic and static modulus of elasticity and the coefficient of damping for groups of particle board specimens are given in Tabs. 1 and 2, resp. It is evident that the average dynamic modulus of elasticity of subgroups of wood particle board specimens varied between 3030 and 3230 MPa. This corresponds to the known values of the modulus of elasticity of wood particle board. In all cases, the modulus of elasticity decreased after drilling open-holes in the specimens. Regarding average values of the subgroups, this change ranged from 6.5 to 9.5%, and for the individual specimens the modulus of elasticity decreased to 14%. It has been found that the static modulus of elasticity of wood particle board was about 2840 MPa. The values obtained correspond to the values found by other authors (Wood Handbook 2010, Kord et al. 2016, Astari et al. 2018). The average static modulus of elasticity of groups of the board specimens with drilled open-holes was in the range of 2150 - 2640 MPa. That holes degrade the mechanical properties of wooden structures has been found and in other works (Chen et al. 2021). In addition, wood and wood-based products have a high dispersion of mechanical properties (Nowak et al. 2021).

Tab. 1: Values of dynamic (dMOE) and static (MOE) modulus of elasticity for wood particle board specimens.

Subgroup	**BI**	**BII**		**BIII**		**BIV**		**BV**	
Open-hole	-	-	+	-	+	-	+	-	+
dMOE (MPa)	3105	3231	3026	3144	2953	3092	2822	3021	2745
MOE (MPa)	2837	-	2540	-	2638	-	2154	-	2379

The obtained static modulus of elasticity of the specimens was about 8.5% lower than the dynamic one. Analogous results were obtained in other works (Albrektas and Navickas 2017, Divos and Tanaka 2005, Chauhan and Sethy 2016, Nowak et al. 2021). The average static modulus of elasticity of groups of the board specimens with drilled open-holes was in the range of 2150 - 2640 MPa. Regarding open-holes drilled at the ends of the specimens their static modulus of elasticity was 11 – 13% lower than the dynamic one and close to the difference between the static and dynamic modulus of elasticity of the co-examined specimens. This can be explained by the fact that by defining the dynamic modulus of elasticity, the average mechanical property of the whole specimen material is determined. Determination of the static modulus of elasticity by loading the specimen at three points results in creation of a concentrated load. When the specimen is subjected to a concentrated load at the point of defect (open-hole), its resistance obtained, as well as its modulus of elasticity, is much lower.

Tab. 2: Values of coefficients of damping for particle board specimens.

Subgroup	**BI**	**BII**		**BIII**		**BIV**		**BV**	
Open-hole	-	-	+	-	+	-	+	-	+
Coefficient of damping (r.u.)	0,022	0.024	0.026	0.023	0.026	0.020	0.023	0.022	0.025

Drilled open-holes also caused a change in the coefficient of damping of the specimens. It is apparent that the average coefficient of damping of subgroups of wood particle board specimens varied from 0.022 to 0.024 r.u. In all cases, the coefficient of damping increased after drilling open-holes in the specimens. Taking into account the average values of subgroups, this change ranged from 7.7 to 13.0%, and the coefficient of damping for individual specimens increased up to 20%. The average value of the coefficient of damping increased the most in group IV specimens. In other works has also found that coefficient of damping increases with decreasing MOE (Brémaud et al. 2009, Albrektas and Vobolis 2004).

The average values of the dynamic and static modulus of elasticity and the coefficient of damping for groups of plywood specimens are given in Tabs. 3 and 4, resp.

Tab. 3: Values of dynamic (dMOE) and static (MOE) modulus of elasticity for plywood specimens.

Subgroup	**PI**	**PII**		**PIII**		**PIV**		**PV**	
Open-hole	-	-	+	-	+	-	+	-	+
dMOE (MPa)	10470	10970	10056	9710	9055	10048	8790	10916	9695
MOE (MPa)	9695	-	8367	-	8245	-	6973	-	8636

As is obvious, the average dynamic modulus of elasticity of the subgroups of plywood specimens varied in the range of 9700 - 11000 MPa. This corresponds to known values of the modulus of elasticity of plywood (Forest Products Laboratory 2010). In all cases, the dynamic modulus of elasticity decreased after drilling open-holes in the specimens. Taking into account the average values of subgroups this change ranged from 7 to 14%, and for individual specimens the modulus of elasticity decreased up to 17%. The static modulus of elasticity was found to be about 7.5% lower than the dynamic one (Albrektas and Navickas 2017, Shan-ging and Feng 2007, Divos and Tanaka 2005, Nzokou et al. 2006, Zalcmanis et al. 2018). When the open-holes in the specimens are drilled at the ends, the average static modulus of elasticity of their groups is 9 - 11% lower than that of the dynamic modulus of elasticity. For groups where open-holes were drilled in the center of the specimens, the average static modulus of elasticity was 17–21% lower than the dynamic one. This can be explained analogously, as in the case of wood particle board - the dynamic modulus of elasticity shows the average mechanical properties of the specimen material. Under static concentrated load, the loaded point of the specimen is characterized.

Tab. 4: Values of coefficients of damping for plywood samples.

Subgroup	PI	PII		PIII		PIV		PV	
Open-hole	-	-	+	-	+	-	+	-	+
Coefficient of damping (r.u.)	0.012	0.012	0.013	0.012	0.014	0.011	0.014	0.011	0.013

Apparently, the average values of the coefficient of damping of subgroups of plywood specimens varied from 0.011 to 0.012 r.u. In all cases, drilling open-holes in the specimens resulted in an increase in the coefficient of damping. Taking into account the average values of subgroups, this change ranged from 8 to 21%, and for individual specimens the coefficient of damping increased to 25%. The most significant increase of the coefficient of damping was observed in group IV specimens. As for the failure mode of specimens (failure mode), it can be said that due to the structure of the material it was observed only in plywood specimens; for wood particle board specimens consisting of wood particles that are glued together, separations occurred in the inner layers of the board under load, however no failure line, cracking, bursting or other structural damage became apparent. For plywood specimens during breakage cracks appeared in the inner layers of the plywood (typical case); in some cases, the separation of the glued layers became apparent (Fig. 4), failure line is visible in the outer layer, resulting in reduced bending strength of the specimen. During bending, the upper surface layer of the specimen is compressed and the lower one is subject to tension. When the force exceeds wood tensile strength limit values, the fiber ruptures. The specimen deforms due to internal cracks either in the layers of wood (plywood) (probably they are less plastic) or between the layers (probably due to poor adhesion). The location of open-hole did not affect failure mode of the specimen; failure always appeared at the point of load.

a) b)

Fig. 4: Failure mode for wood particle board specimens: a) top view, b) side view.

Apparently, the values obtained correspond to the known values of the modulus of elasticity and the coefficient of damping of these materials. It is obvious that due to the structure of the composite materials the plywood has a much higher modulus of elasticity than the wood particle board. On average, this difference is equal to 3.42 times for the static modulus of elasticity and about 3.37 times for the dynamic one. The coefficients of damping varied less (about 1.8 times). The drilled open-holes changed the mechanical properties of the specimens – the modulus of elasticity of all specimens decreased, while the coefficient of damping increased. In all cases, the mechanical properties of the specimens were mostly changed due to a large open-hole drilled in the center of the specimen (group IV). Regarding the wood particle board, a similar modulus of elasticity was caused by two open-holes of the same diameter drilled at the ends of the sample (group V).

CONCLUSIONS

(1) Open-holes (holes) change the mechanical properties of the specimens - the modulus of elasticity (static and dynamic) decreases, and the coefficient of damping increases. *(2)* The large diameter open-hole drilled in the center of the specimen mainly determines the mechanical properties of the specimen – the modulus of elasticity mostly decreases, and the coefficient of damping mostly increases (up to 15% and up to 21% for the groups of specimens tested, respectively). Open-holes located at the ends of the specimen or the one smaller in diameter have less effect on the change in mechanical properties (up to 14% and up to 15% for the groups of specimens tested, respective). *(3)* Open-holes at different locations and with different diameters have a different effect on changes in the static and dynamic modulus of elasticity – the dynamic modulus of elasticity characterizes the average properties of the specimen material, while the static modulus characterizes properties at the specific location. Depending on the location and diameter of the open-holes, the difference between static and dynamic modulus of elasticity can vary from 7 to 21%. *(4)* The location of the open-hole did not affect the failure mode of the specimen; in all cases the failure appeared at the point of load. When the load is applied perpendicular to the open-hole, no cracks appear at its edges which would spread deep into the specimen.

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SIMONA GAURONSKAITĖ
KAUNAS UNIVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING AND DESIGN
STUDENTU ST. 56
LT – 51424 KAUNAS
LITHUANIA

VAIDA DOBILAITĖ, MILDA JUCIENĖ*
KAUNAS UNIVERSITY OF TECHNOLOGY
INSTITUTE OF ARCHITECTURE AND CONSTRUCTION
TUNELIO ST. 60
LT – 44405 KAUNAS
LITHUANIA
*Corresponding author: milda.juciene@ktu.lt

DARIUS ALBREKTAS
KAUNAS UNIVERSITY OF APPLIED SCIENCES
FACULTY OF TECHNOLOGIES
PRAMONĖS PR. 20
LT – 50468 KAUNAS
LITHUANIA