Bending and energy absorption performance of novel openwork wooden panels

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Abstract

In many scientific studies, beams reinforced with synthetic fiber ribbons are modeled, wood composites and materials are designed, and structures made with hollow core boards are developed. However, no research was conducted on increasing the width of the flat wooden panels by modeling an openwork structure and obtaining them from solid panels of smaller width. The research aimed to determine the impact of wood species and inclination angle of the side walls on the stiffness, strength, and ability to absorb the energy of the new openwork panel made of curvilinear wooden slats. Three-point bending tests were performed numerically and verified experimentally. It has been shown that the stiffness of the openwork panels was lower compared to solid panels. No cracks in the glue line were observed. Walnut openwork panels demonstrated the best energy absorption capacity. Therefore, it is recommended that the openwork panels be made out of walnut and beech wood, rather than ash and oak. It is also more advantageous for the panel's construction to use the 11° inclination angle of the side walls.

1 Introduction

For centuries, wood has been the primary material for the production of furniture. It is a renewable material, but its rational use is still a challenge for designers and constructors. In the interest of the best use of wood, its protection, modification, multilayer gluing, and optimization of cross-sections ensuring sufficient stiffness and strength of the structure are carried out. In the literature, we can find many original methods to improve the mechanical quality of wood. Today many ways to attain a lighter wooden structure are on offer, some of them following partially the industrial application and only very few of them following the natural solution. The first one uses light-weight wood species limited by the availability, strengths, processability, etc. The second one is the sandwich structure made from rigid facings and cores made from soft structures. The third way to produce a

light structure is to reduce the core weight drastically, using predesigned cavities or skeletons with unique shapes and connections to the faces (Berger et al. 2016).

Gaff et al. (2015a, b, 2016, 2017) and Gaff and Babiak (2018) examined several factors for wood bendability and demonstrated that wood species, densification, and material thickness are significant factors for bendability. With increasing thickness of the beams, the bendability coefficients decrease, and the proportionality limit increases. Yaddanapudi et al. (2017) replaced lignin with the polymer in wood cells, resulting in transparent wood material. It has higher tensile strength and hardness when compared to the delignified wood. Borri et al. (2005) showed that fiber-reinforced plastic materials' external bonding increases flexural stiffness and capacity of wood. The results showed increased flexural capacity up to 60.3% compared to un-reinforced beams when three carbon fiber reinforced plastic layers (CFRP) were used. The method of applying the composite reinforcement also produced a maximum stiffness increase of 27.7%. The application by De Jesus et al. (2012) of CFRP laminates resulted in higher stiffness values compared to the ones obtained with non-reinforced beams. The interfacial shear and peeling stresses play a central role in assessing reinforced beams, and higher stiffness values were achieved by reducing interfacial stress peaks with the increase in reinforcement length.

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CFRP materials effectively reduce wood weakening and increase the bending stiffness of glued beams by 36% and about 20% for solid wood beams (Wdowiak-Postulak and Brol 2020). A comparison study between glass fiber reinforced polymer-wood sandwich beams (GFRP-W) with flatwise and sidewise directions showed that composite sandwich beams in flatwise bending tests failed under a lower load but yielded a more significant deflection than those in sidewise bending tests (Qi et al. 2017). According to Yang et al. (2013), a new fiber reinforced plastic and hybrid fiber-reinforced polymer (HFRP) can be effectively used to enhance the strengthened wood beams' ductility under the increased bending moment capacity. HFRP is also a cheaper material than carbon fiber or glass fiber. Borri et al. (2013) also tested reinforcing the solid wood with composite materials based on natural fibers in the form of fabrics (made from hemp, flax, basalt, and bamboo fibers). The use of natural fibers increases the load-carrying capacity, increasing the material's stiffness and ductility. The advantages of this solution are low production costs, low pollution emissions, and energy consumption for production.

Other methods of improving the mechanical quality of wood are producing sandwich composites using wood and wood materials or plastics. According to Anshari et al. (2012), reinforcing beams with densified wood (DW) is economical and environmentally friendly. Only a tiny amount of densified wood is required, and no bonding between the DW and the beam is necessary. In this case, observed enhancements in the bending stiffness were up to 46%, and load-carrying capacity increased by 11%. Gaff et al. (2015a) consider that sandwich materials made of wood have better bendability when a soft material is placed in its bottom layer. The bendability coefficient depends on the layer's position and its thickness in the composite.

The bending ability of glued beams was also examined in the study by Ruman et al. (2017). The study examined the influence of wood species, lamella combination, type of adhesive, number of loading cycles on the deflection at the proportionality limit, deflection at the point rupture, and the ratio between the deflection at the proportionality limit and the deflection at the point of rupture in laminated wood. The results showed the most significant effects on the deflection at the proportionality limit. Thicker material can achieve a higher proportion of plastic deformation and is more suitable for molding by bending. Research was also conducted on strengthening of structures made of bamboo using thin layers of strips of young bamboo stalks (Penellum et al. 2018).

Moreover, bamboo products can be reinforced with a bamboo net, which significantly increases the stiffness and strength of structures compared to traditional wood materials (Sharma et al. 2015; Zhong et al. 2017). The research carried out by Fang et al. (2015) shows that the increase in the thickness of bamboo and glass-fiber-reinforced

polymer layers significantly affects the bending stiffness and the maximum load on the laminated beams. The study by Manalo et al. (2010) illustrates the strength and stiffness of composites made with the beams' flatwise and edgewise positions. Using the same amount of material, beams in the edgewise position could offer a 25% increase in strength compared to beams in the flatwise position. An attractive solution is strengthening multilayer beams by connecting individual layers with dowels (Loinsigh et al. 2012; Reynolds et al. 2016). New wood-based sandwich structures (plywood core and skins made either of aluminum or fiber-reinforced polymer: carbon, glass, or flax composite skins) showed that the plywood-carbon composite skins solution is the best in terms of stiffness (almost three times better than the reference aramid honeycomb-carbon and glass material) (Susainathan et al. 2017, 2018).

A separate and significant research area is searching for lightweight laminated cellular boards made of wood and plywood. New composites have strength similar to traditional plywood, but even 45% less weight (Labans and Kalnins 2014). So panels with plywood facings and different types of the core, for example: corrugated (Kavermann and Bhattacharyya 2019), with auxetic oval cells (Smardzewski 2019a) or auxetic cells in the form of arrows (Smardzewski 2019b) were designed. Testing of the sandwich panel made of okoumé plywood skins bonded to an innovative honeycomb core constituted by lozenge-shaped okoumé plywood cells showed that the composite turned out extremely light (with a density of 205 kg/m³). The composite's physical-mechanical properties meet requirements in terms of bending strength, modulus of elasticity, shear strength, traction perpendicular to faces, and dimensional stability (Negro et al. 2011). Labans et al. (2017) showed that sandwich panels with wood, plywood, foams, and thermoplastic composite core showed sufficient mechanical characteristics to be suitable for floor and wall unit implementation. Compared to a solid plywood board, sandwich-developed panels can reach up to 42% higher specific stiffness while maintaining sufficient strength characteristics. Sandwich panels of pine-wood veneer and a core of cork also show similar mechanical properties. In this way, Lakreb et al. (2015) developed natural-based products with a low ecological footprint and favorable production costs. Increasing the number of layers in the sandwich panel improved the strength of the material. According to Smardzewski and Jasińska (2016), wood-based sandwich panels with a wavy core can sustain higher loads than similar honeycomb structures because they have the shape of core cells that guarantees minimal displacements and high strength. Hayashi et al. (2003) designed MDF panels reinforced corrugated particleboards. The composite is a lightweight material with a density of 480 kg/m³ and a strength equivalent to particleboard.

Further decreasing wood composites' density has led to manufacturing the honeycomb cores from paper. The testing of sandwich panels containing kraft paper honeycomb core and wood composite facings showed that the sandwich panel's flexural creep behavior is affected by the honeycomb core shape, core and facings thickness, and facings material type (Chen et al. 2011). Hao et al. (2018) explained that the Taiji honeycomb structure has 3.5 times the compression and shear strength of commercial hexagonal ones. Using this type of core in wooden sandwich composite resulted in an increase in compression and shear strength by 1.75 times. The reinforcement of the core also results in an almost linear increase in the sandwich composite's strength. Smardzewski (2013) showed that honeycomb wood panels with paper auxetic core exhibited higher rigidity than panels with hexagonal cell core. Manufactured panels are also characterized by high orthotropic properties.

More and less simplified analytical or numerical models have also been developed to assess the bending behavior of wooden structural panels (Banerjee and Bhattacharyya 2011; Zhang et al. 2015; Li et al. 2016). They give the possibility of a balanced approach to the design of light wooden structural panels.

Lightweight in the wood-based construction and furniture industry is not a new topic. The density reduction using a sandwich structure with light cores for doors or mobile homes was confirmed by users more than five decades ago. However, the literature review shows that the cellular structure has always been associated with sandwich panels and has not been explored enough as an independent structural form. Production of openwork wooden panels is described in the paper by Skuratov (2010). The developed wooden panel features low-quality wood sufficiency for the building industry needs and low waste levels. The production of one cubic meter of panel requires a little more than 1 m³ of dry timber. Thanks to the openwork surface, panels have low density (300–350 kg/m³) and good mechanical properties, close to known solid wood panels. A similar type of openwork panel made of curvilinear wooden slats that form a hexagonal mesh was designed by Murlak (2019) and registered with the Patent Office of the Republic of Poland (Fig. 1).

Taking into account the above considerations, it was decided to verify the research hypothesis that openwork solid wood panels show high stiffness and strength, similar to solid wood panels. Therefore, the undertaken research aimed to determine the influence of the wood species and the inclination angle of the inner walls of inclusions on the stiffness, strength, and ability to absorb energy of the new type of openwork panel manufactured from curvilinear wooden slats, designed by Murlak (2019).

Fig. 1 Idea of production and use of openwork panels for furniture design

2 Materials and methods

2.1 Panels design and fabrication

Taking into account the shape and dimensional proportions of the structures designed by Murlak (2019) (Fig. 1), the tests were carried out on solid and openwork panels with a thickness and length of 18 and 1032 mm, respectively (Fig. 2). The solid panels were made of 265 mm wide solid timber (not glued) with fibers oriented along the longer side of the panel. The openwork panels were made by gluing together six curvilinear slats cut from 265 mm wide solid panels. According to Kollmann and Cote (1968), the bending strength of the curvilinear wood elements depends, among others, on the inclination of the wood fibers to the beam axis. This inclination should not exceed 10°. Therefore, in further considerations, it was assumed that the inclination of the side walls of the curvilinear slats to the longer side of the panel equals 9° and 11°. This way, the width of the openwork panels was increased to 328 and 355 mm, respectively. Thus, the width of the openwork panel compared to the width of the solid panels increased by 63 and 90 mm, respectively (Fig. 2). The authors decided to make the panels following the patent claim P.42481 (Murlak 2019). So, the side walls of the curvilinear slats to the longer side of the panel are considered for two cases only. The panels were

Fig. 2 Dimension of solid and openwork panels with inclination angle 9° and 11°, respectively

made of beech (*Fagus sylvatica* L.), oak (*Quercus robur* L.), ash (*Fraxinus excelsior* L.), and walnut (*Juglans regia* L.). The basic physical and mechanical properties of the selected wood species are presented in Table 1.

At first, the boards of 20 mm thickness were planed on both sides on a Format 4 planer (Felder Group, Żory, Poland) in order to obtain a constant thickness of 18.2 mm. Then, solid full panels and curved slats were made on the Infotec Professional milling plotter (InfoTEC CNC, Zasutowo, Poland), using a 3 mm end mill operating at a speed of 24,000 rpm (Fig. 3). All elements were sanded on a DMC MB 90 wide-belt sander (SCM Polska SP.Z.O.O., Suchy Las near Poznań, Poland) to a thickness of 18 mm. Curvilinear slats were glued with Chemolan B 4 M/D4 polyurethane adhesive (Interchemol S.A., Oborniki Śląskie, Poland). Based on previous experimental studies, an adhesive linear elasticity modulus of 820 MPa and shear strength of 16 MPa were assumed (Kamboj et al. 2020). The adhesive was applied on flat, rectangular surfaces with dimensions of 18 mm × 41 mm (Fig. 4). After applying a pressure of 0.3 MPa, the panels were left in the laboratory for 28 days for air conditioning. The relative air humidity

and temperature in the laboratory room were $65 \pm 1\%$ and 21 ± 1 °C, respectively. Under those conditions, the wood reached the hygroscopic equilibrium without changing its absolute humidity. After seasoning, an average thickness of 0.1 mm of the adhesive layer was measured using a Kern OZM 922 microscope (KERN & Sohn GmbH, Balingen, Germany).

Table 2 presents the mass and volume of the designed panels, based on the density of wood presented in Table 1. The table shows that the volume of the openwork panel with the 9° and 11° inclination angle of the side walls is smaller by 10 and 8.2%, respectively, in relation to the solid panel.

2.2 Experiments

Five identical solid and openwork panels with an inclination angle of the side wall of 11° were made from each wood species for the experimental tests. The panels were subjected to three-point bending on a Zwick 1445 universal testing machine (Zwick Roell GmbH & Co. KG, Ulm, Germany) (Fig. 5). For the bending tests, a support spacing of 800 mm was used. It is a representative dimension for shelves and top and bottom panels used in furniture design. The panel length of 1032 mm was due to technological limitations arising during formatting on a sawing machine. During the tests, the force was recorded with an accuracy of 0.01 N and the displacement in the direction of the force with an accuracy of 0.01 mm. The speed of increasing the displacement was set at 10 mm/min, according to EN 310 standard (EN 310:1993 1993). It was assumed that the structure produced is a type of wood composite. The tests were stopped when the panel deflection of 40 mm was obtained. The limitation resulted from preliminary tests, which revealed high susceptibility of the panels to bending without damage (even up to 60 mm). Moreover, for aesthetic reasons, deflections of furniture elements exceeding 4 mm/m are considered unacceptable (Smardzewski 2015).

Based on the direct results of experimental tests, the interdependencies between the load and deflection of the panels were determined. These dependencies were used to calibrate analogical numerical models. As a consequence of the satisfactory accordance between the results of experimental tests and numerical calculations for solid and openwork panels with an inclination angle of the side

Table 1 Elastic and physical properties of selected wood species (Kollmann and Cote 1968; Cai and Ross 2010; Smardzewski 2015)

Type of wood	E_L MPa	E_R	E_T	G_{LR}	G_{LT}	G_{RT}	ϑ_{LR}	ϑ_{LT}	ϑ_{RT}	MOR MPa	Density (kg/m ³)
Beech	13,969	2284	1160	1645	1082	471	0.450	0.510	0.750	102	721
Walnut	13,760	1372	714	1084	791	267	0.495	0.632	0.718	100	609
Ash	13,200	1650	1056	1438	1016	1016	0.371	0.440	0.684	103	673
Oak	12,530	2205	2205	1163	1163	470	0.369	0.428	0.618	104	769

Fig. 3 Production of openwork panels

Fig. 4 Openwork panels with a glue line

walls of 11° , an additional numerical model of the openwork panel with an inclination angle of the side walls of 9° was developed, which was smaller by 1° from the 10°

Table 2 Volume and mass of selected types of panels

Type of wood	Mass (kg)	Inclination angle ($^\circ$)	Volume (m^3)
Beech	3.0854	9	427.93×10^{-5}
Oak	3.2908		
Ash	2.8800		
Walnut	2.6061		
Beech	3.1475	11	436.54×10^{-5}
Oak	3.3570		
Ash	2.9379		
Walnut	2.6585		
Beech	3.4287	Solid	492.26×10^{-5}
Oak	3.6569		
Ash	3.2004		
Walnut	2.8961		

Fig. 5 Bending test of solid (a) and openwork panels (b) with inclination angle 11°

value suggested in the literature, and smaller by 2° from the experimental model. Table 3 shows the markings of all test samples. Additionally, Table 4 presents the characteristics of the cross-sections of the bent panels.

The next stage of the research was to determine the energy absorbed during the bending of the panels. Energy absorption is key to testing the structural integrity in the event of failure. As shown in some articles (Jin et al. 2015; Yan et al. 2014; Schneider et al. 2016; Sun et al. 2017; Yazdani Sarvestani et al. 2018; Smardzewski 2019b; Ha and Lu 2020; Farrokhbabadi et al. 2020), the honeycomb panels exhibit excellent energy absorption properties. The energy absorption E_a (J) of the selected panels was calculated as follows:

Table 3 Symbols of selected samples and tests

Type of wood	Inclination angle (°)	Symbol	
		Experiment	Numerical calculation
Beech	9		B9-N
Oak			O9-N
Ash			A9-N
Walnut			W9-N
Beech	11	B11	B11-N
Oak		O11	O11-N
Ash		A11	A11-N
Walnut		W11	W11-N
Beech	Solid wood	BS	BS-N
Oak		OS	OS-N
Ash		AS	AS-N
Walnut		WS	WS-N

$$E_a = \int_0^{d_{max}} F_x dx, \quad (1)$$

where F_x (N) is the crushing force as a function of displacement x (m) during the crushing process, d_{max} (m) is the effective deformation distance (deflection). The next parameter for analysis was specific energy absorption by panels per unit mass given by:

$$SE_a = \frac{\int_0^{d_{max}} F_x dx}{m}, \quad (2)$$

where SE_a (J) is specific energy absorption, m is the mass of the energy absorber. SE_a is often used to compare the energy-absorbing ability of different materials and structures. The average crushing force F_c (N) was defined as follows:

$$F_c = \frac{\int_0^{d_{max}} F_x dx}{l}, \quad (3)$$

where l (m) is the displacement corresponding to the maximum load, F_x (N) is the instantaneous compression force.

2.3 Numerical models of panels

Figure 6 presents models for numerical calculations of solid and openwork panels composed of 223,507 nodes and 174,804 elements (average), including quadrilateral elements of type R3D4, linear hexahedral elements of type C3D8R, and COH3D8 cohesive elements. Type R3D4 elements were used to model supports, type C3D8R elements for modeling wood, and COH3D8 for glue line. The numerical model of wooden elements was described with the use of the orthotropy plasticity material model (Kawashita et al. 2012; Qiu et al. 2014; Tran et al. 2015; Smardzewski 2019a). In the cited articles, the non-linear elastic properties of wood have been pointed out many times. Therefore, in this study, non-linear models were also used, both due to the orthotropy of the wood as well as the geometric nonlinearity of the model. The material constants are shown in Table 1, and the directions of the orthotropy are presented in Fig. 6, where L, R,

Fig. 6 Numerical model of solid (a) and openwork panels (b). Points A, B, C, D, E, F, G, H illustrate places for normal stress control**Table 4** Characteristics of panel cross-sections

Panel type	Cross-sectional area (m ²)	Moment of inertia (m ⁴)	
		I_x	I_y
Solid	$4.770 \cdot 10^{-3}$	$128.790 \cdot 10^{-9}$	$25.165 \cdot 10^{-6}$
9°	$3.783 \cdot 10^{-3}$	$102.157 \cdot 10^{-9}$	$35.790 \cdot 10^{-6}$
11°	$3.783 \cdot 10^{-3}$	$102.157 \cdot 10^{-9}$	$42.235 \cdot 10^{-6}$

T show anatomical directions of wood: longitudinal, radial, and tangential, respectively. A glue line joined the slats. The behavior of glue lines was modeled using the Cohesive Zone Model (CZM) through standard COH3D8 cohesive elements. The cohesive stiffness was estimated from the glue line isotropic mechanical properties (Smardzewski 2019a; Kamboj et al. 2020), assuming that the interfacial stiffness represents the elastic deformation of a glue-line layer of 0.1 mm in thickness. The panels were supported and loaded similarly, as shown in Fig. 5. The fixed supports and cross-head were assumed as perfectly rigid bodies. Between them and the panels, a surface-to-surface contact with a friction coefficient of 0.2 was modeled. The crosshead movement controlled the load value, causing the sample to be deflected by 40 mm at half its length.

Prior to starting numerical calculations, the models were first calibrated by selecting the appropriate mesh density and the number of iterations to obtain a satisfactory agreement between the load–deflection relationships determined numerically and in experimental tests. The calibration was finished successfully when the results were achieved, with no more than a 5% difference. The stresses at the wooden slats' A–H points were then calculated (Fig. 6a). Stresses in the glue line were also calculated (Fig. 4), and then, using Eqs. 1–3, the absorbed energy, specific energy absorption, and crushing force were calculated. Figure 7 shows examples of deflections and stresses distribution in bending panels.

The commercial ABAQUS/Explicit v. 6.14 software (Dassault Systemes Simulia Corp., Waltham, MA, USA) was used for numerical calculations. All computations were

performed at the Poznan Supercomputing and Networking Center (PSNC) using the Eagle computing cluster.

3 Results and discussion

3.1 Effect of inclination angle on stiffness and strength of panels

Figure 8a shows the average values for the experimental dependence between the load and deflection of the bent panels. This figure shows that for the same deflection value of 40 mm, the maximum forces are greater for solid panels and smaller for openwork panels. For solid panels made of beech, walnut, ash, and oak wood, the maximum bending forces are equal to 2983 N, 2935 N, 2842 N, and 2455 N, respectively. The decreasing values of bending forces result from decreasing values of linear elasticity modulus for selected wood species, 13,969 MPa, 13,760 MPa, 13,200 MPa, and 12,530 MPa, respectively (Table 1). For openwork panels with an 11° inclination angle of side walls made of beech, walnut, ash, and oak wood, the maximum bending forces are respectively lower by 12.3%, 3.4%, 22.5% and 13.0%. The obvious reason for the lower values of bending forces of openwork panels is their 20.6% lower moment of inertia of the I_x (m⁴) cross-section compared to the moment of inertia of the solid panels' cross-section (Table 4). However, what is interesting is that in the case of walnut wood, the stiffness of the solid panels was only 3.4% higher compared to the openwork panels, and in the case of ash wood, this difference

Fig. 7 Example of numerical calculation of solid (a) and openwork panels (b)

Fig. 8 Relationship between load and deflection of solid and openwork panels for the experimental test (a), and the numerical calculation (b), where BS, OS, AS, WS are solid beech, oak, ash, walnut panels, and B11, O11, A11, W11 openwork beech, oak, ash, walnut panels with inclination angle 11° , respectively, *N* results of numerical calculation

equaled 22.5%. This may give preference to walnut wood and limit the use of ash wood as a raw material for making openwork panels. Figure 8b shows the results of numerical calculations for analogically loaded solid and openwork panels with an 11° angle of inclination of the side walls. This figure shows that for a deflection of 40 mm, the maximum forces for solid panels made of beech, walnut, ash, and oak wood equal to 2861 N, 2858 N, 2787 N, and 2508 N, respectively, whereas for openwork panels with an 11° inclination angle of the walls, the maximum bending forces are respectively lower by 7.7%, 5.6%, 17.1% and 13.9%. Thus, Fig. 8 shows that the results of numerical calculations are accordant with the results of the experimental studies. The differences between the values of experimental bending force for solid panels equal 4.1%, 2.6%, 1.9%, 2.2% for beech, walnut, ash, and oak, respectively. However, the differences for openwork panels equal 0.1%, 6.3%, 3.4%, 0.2% for beech, walnut, ash and oak wood, respectively.

To fully illustrate the satisfactory consistency of the numerical calculations with the results of laboratory tests, not only in relation to the values of maximum forces but also in terms of the load–deflection relationship, Fig. 9 compares the curves determined experimentally and numerically. This figure clearly shows that the curves determined numerically correspond satisfactorily with the experimental curves. Therefore, it was concluded that the calibration of the numerical model was carried out correctly, and the results of the numerical calculations could

be used in the further argument. On this basis, numerical calculations were carried out for openwork panels with a 9° inclination angle of the side walls. Figure 10a summarizes the load–deflection relationships for openwork panels, while Fig. 10b shows the values of the maximum forces causing a deflection of 40 mm for solid and openwork panels.

Figure 10a shows that the load–deflection curves for openwork panels with 9° and 11° inclination angles of the side walls coincide. In contrast, Fig. 10b shows that the values of maximum forces causing deflection of these panels are minor and do not exceed 37 N. Of course, there is a significant difference between the values of the maximum forces causing bending of solid and openwork panels. In the case of panels with an 11° inclination angle of the side walls, the maximum forces are lower by 8.5%, 6.9%, 18.3%, and 15%, respectively, for beech, walnut, ash, and oak, and for panels with an inclination angle of 9° equal to 7.7%, 5.6%, 17%, and 14%.

The presented results show that making openwork panels out of solid panels with an inclination angle of the side walls 9° and 11° reduces their stiffness from 7.7 to 18.3%. At the same time, a minor decrease in stiffness was recorded for openwork panels made out of walnut wood (from 5.6 to 6.9%). Therefore, it is recommended to produce openwork panels from walnut, and then beech and oak wood, preferring the 11° angle of inclination of the side walls, which ensures the greatest width of the panel.

Fig. 9 Relationship between load and deflection. Comparison results of the numerical calculation and experimental test for solid (a), and openwork panels (b), where BS, OS, AS, WS are solid beech, oak, ash, walnut panels, and B11, O11, A11, W11 openwork beech, oak, ash, walnut panels with inclination angle 11°, respectively, N results of numerical calculation

Fig. 10 Relationship between load and deflection—comparison results of the numerical calculation for openwork panels with inclination angle 9° and 11°, where B, O, A, W, respectively beech, oak, ash, walnut (a), and maximum load under panels bending, where S solid panels (b)

Table 1 shows that the difference between the greatest modulus of elasticity E_L of beech and the walnut, ash, oak is equal to 2%, 6%, and 11%, respectively. For E_R and E_T modules it is 66%, 38%, 4% and 62%, 10%, 45%, respectively. The difference of the maximal forces causing the beech sample (9° and 11°) to deflect by 40 mm compared to the other samples is equal to 2%, 15%, and 23%, respectively. This regularity illustrates that the panel stiffness increases with an increase in the modulus of linear elasticity of the wood. At the same time, the differences between linear modules of wood elasticity and the differences between the bending forces of panels are adequate to each other. The orthotropic nature of wood and differences between the modules of wood elasticity across the grain also significantly influence the measured forces.

The differences in the strength of the designed and manufactured panels are interesting too. Figure 11a, b shows the variation of normal stresses σ_z (MPa) at points A–H on the cross-section of the bent panel. This figure shows that the stresses in openwork panels have a non-linear course. Their value increases from the outer edges (points A and H) towards the panel axis, reaching a maximum at points B and G, which is on the inside of the first outer curvilinear slats. Then the stresses σ_z (MPa) decrease and reach a minimum at points D and E, near the middle slats' outer surfaces. The difference between the highest and the lowest normal stress does not exceed 10 MPa. At the same time, the maximum stresses (Fig. 11c) are significantly lower than the bending

Fig. 11 Normal stress σ_z distribution in selected points of openwork panels with inclination angle: 11° and 9° (a), solid panels (b), and maximal normal stresses σ_z (c), where B11, O11, A11, W11 beech, oak, ash, walnut openwork panels with inclination angle 11°, B9, O9, A9, W9 beech, oak, ash, walnut openwork panels with inclination angle 9°, respectively, N results of numerical calculation, S solid panels

strength of the selected wood species (Table 1). In this case, the safety factor for wooden elements of openwork panels varies from 1.89 to 2.09. For solid panels (Fig. 11b), the σ_z stresses (MPa) run almost linearly in the direction of the panel axis. As in the case of openwork panels, the maximum value of these stresses (Fig. 11c) does not exceed the bending strength of wood, which in this case is also manifested

Fig. 12 Reduced (Von Mises) stresses in the glue line: stress distribution in glue line of openwork panel with inclination angle 9° (a), and the effect of wood species and inclination angle on the maximum reduced stresses in the glue line (b)

by a high safety factor varying from 1.72 to 1.83. This indicates that each proposed type of wood and each angle of inclination of the side walls in the openwork panels ensure good bending strength of the wooden slats.

In the performed tests, there is no detected failure in the slats. The main reason for this is the character of the test performed. In this case, bending deflection equal to 40 mm stopped the test. For this reason, the maximum stresses (Fig. 11c) are significantly lower than the bending strength of the selected wood species (Table 1).

Figure 12a shows the distribution of reduced stresses in the selected glue line, characteristic for all calculations (see Fig. 4). This illustration shows that the greatest stresses are concentrated in the corners of the glue line, and the smallest stresses close to zero value occur in the center of the surface of the glue line. This distribution is characteristic for adhesive and shape-adhesive corner joints subjected to bending (Smardzewski 1996, 2002, 2008; Imirzi et al. 2015). The scope of the cited works and the results of numerical calculations (Smardzewski 2019a, b) show that the adhesive joint's crack initiation may take place where the most significant stresses occur, i.e. in the corners of the adhesive joint. However, the average shear stress of the adhesive joint is at a much lower level. The value of the maximum reduced stresses at the corners of the glue line for analyzed openwork panels is shown in Fig. 12b. In the case of panels with a side wall inclination angle of 9°, the presented values exceed the shear strength of the adhesive used (16 MPa).

During the tests, however, no damage was observed in the glue lines of the bent panels. This is due to the fact that the average reduced stress in the adhesive joint for all analyzed openwork panel structures did not exceed 3 MPa, thus it was significantly lower than the strength of the adhesive joint. At the same time, the values of shear stresses in the adhesive joints were significantly lower, as shown in Fig. 13.

The numerical calculations confirmed by experimental tests show that apart from sufficient stiffness, the openwork panels are characterized with very high strength of both wooden slats and glue lines. This means that the tested structures can be safe and durable.

3.2 Energy absorption characteristic

Energy absorption is an important indicator for assessing the amortization effectiveness of the engineering structure under study. Comparing the energy absorption capacity of the openwork structure with the solid panels allows choosing the best solution. Figure 14a, b shows the dependence of the absorbed energy on a deflection for openwork and solid panels, while Fig. 14c compares the values of the maximum energy absorbed by individual panels. This figure shows that the energy absorption curves are progressive, and the amount of energy absorbed disproportionately rises with increasing deflection of the panels. During bending, most of the energy is absorbed by solid panels made of ash wood (69.2 J). The remaining solid panels made of beech, walnut, and oak wood absorb energy in the amount of 61.6 J, 61.4 J, and 51.1 J, respectively. In the case of openwork panels

Fig. 13 Shear stresses in the glue line: stress distribution in glue line of openwork panel with inclination angle 9° (a), the effect of wood species and inclination angle on the shear stresses in the glue line (b)

Fig. 14 Relationship between energy absorption E_a (J) and deflection (mm) (a, b). Maximum E_a (J) for solid and openwork panels (c), where B11, O11, A11, W11 openwork beech, oak, ash, walnut panels with inclination angle 11°, B9, O9, A9, W9 openwork beech, oak, ash, walnut panels with inclination angle 9°, respectively, S solid panels

with a 9° inclination angle of the side walls, the amount of energy absorbed depends on the type of wood. Compared to solid panels, openwork panels made of ash and beech absorb respectively 19.3 and 7.0% less energy, while openwork panels of walnut and oak consume 2.5 and 2.9% more energy, respectively. The increase in the inclination angle of the side walls of the curved slats from 9° to 11° results in a slight reduction in the amount of absorbed energy. Compared to solid panels, openwork panels of ash and beech

(11°) absorb 20.6 and 7.6% less energy, respectively, while openwork panels of walnut and oak consume respectively 3.7 and 3.9% more energy.

The change of specific energy absorption depending on the deflection of solid and openwork wooden panels is shown in Fig. 15a, b. Figure 15c shows the maximum values of the specific absorption energy. These figures show that walnut wood panels absorb the most energy per unit of mass. Openwork panels with 9° and 11° inclination angles of the side walls absorb respectively 24.4 and 23.7 J/kg,

Fig. 15 Relationship between specific energy absorption SE_a (J/kg) and deflection (mm) (a, b). Maximum SE_a (J/kg) for solid and openwork panels (c) where B11, O11, A11, W11 openwork beech, oak, ash, walnut panels with inclination angle 11°, B9, O9, A9, W9 openwork beech, oak, ash, walnut panels with inclination angle 9°, respectively, S solid panels

while solid panels absorb 21.1 J/kg. Openwork panels of ash with side walls inclination angles of 9° and 11° absorb respectively 19.4 and 18.7 J/kg, and solid panels—21.0 J/kg. Thus, an increase in the specific energy absorption was observed for solid ash wood panels. This is directly related to the large amount of energy absorbed by these panels during bending (Fig. 14). For panels of beech and oak, these trends are similar to those made of walnut. Openwork panels with side walls inclination angles of 9° and 11° absorb 18.6 J/kg, 16.1 J/kg, 18.1 J/kg, and 15.7 J/kg, respectively, while solid panels absorb 17.6 and 15.7 J/kg, respectively.

The presented analysis shows that the most favorable are openwork structures made of walnut wood, followed by beech and oak wood.

Figure 16 shows a histogram of the maximum bending force of the panels per unit of deflection. According to the histogram (Fig. 14) for a constant deflection value (40 mm), the maximum bending force of 1.68 kN is for a solid ash panel. The lowest bending forces of 1.33 and 1.31 kN fall on oak openwork panels made of curvilinear slats with the inclination angle of the side walls of 9° and 11°, respectively.

4 Conclusion

Based on the analysis of the direct results of experimental research and numerical calculations, the research hypothesis was verified, proving that openwork panels of solid wood show high stiffness and strength, similar to solid wood panels. Thus, the influence of the type of wood and the inclination angle of internal walls on the stiffness, strength, and ability to absorb energy were determined for a new type of openwork panel made of curvilinear wooden slats. It has been shown that the stiffness of openwork panels with a side wall inclination angle of 9° and 11° is lower by 8.5–18.3% compared to solid panels. In the case of openwork panels

Fig. 16 Maximum crushing force for solid and openwork panels, where B11, O11, A11, W11 expanded beech, oak, ash, walnut panels with inclination angle 11°, B9, O9, A9, W9 beech, oak, ash, walnut panels with inclination angle 9°, S solid panels

with a 9° side wall inclination angle, the stiffness was lower by 7.7–17%. Beech wood panels showed the highest stiffness, and oak wood panels the lowest. Each of the openwork panels is also characterized by high bending strength. For a deflection of 40 mm, the safety factors for curvilinear, wooden elements of openwork panels ranged from 1.89 to 2.09, and for solid panels from 1.72 to 1.83. For a given deflection, no cracks in the glue lines were observed due to the low average values of the shear and reduced stresses. Compared to solid panels, the ability of openwork panels to absorb energy is very favorable. The best properties in this respect were exhibited by walnut wood for both side wall inclination angle values (24.4 and 23.7 J/kg). Considering the above, recommendations can be given to preferably produce openwork panels out of walnut and beech wood, rather than of ash and oak. It is also more advantageous for the openwork structure to use the 11° inclination angle of the side walls, allowing for maximum expansion of the panel width relative to the solid panel. The conducted study also proved the correctness of the performed numerical calculations and the compliance of these calculations with experimental tests.

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