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Experimental and Numerical Analysis of Sandwich Panels Made of Different Core Materials with Plywood Facing

Eksperimentalna i numerička analiza sendvič-ploča s jezgrom od različitih materijala obloženih furnirskom pločom

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ABSTRACT • *Sandwich panels composed of different core materials with plywood facings were analyzed using experimental and numerical methods. Particleboard (PB), fiberboard (MDF), and foam materials were used as the core of the sandwich, while beech plywood was laid as the only face material. The layers of the sandwich were adhered with polyurethane adhesive. Elasticities (E) of PB, MDF, and plywood were determined in the laboratory. The E value specified by the manufacturer for the foam was used to determine the flexural behavior of sandwich panels. Results of the study indicated that the type of core material significantly affects the bending behavior of sandwich panels with plywood facings. Sandwich panels with MDF-core were observed to be more resistant in bending compared to PB and foam-core sandwich panels. Core shear failure was the dominant failure type when wood-based materials were used as core material. Buckling or tension in facing was observed when foam was used as core material. The results of the study demonstrate that numerical models can be used to accurately predict the bending behavior of the sandwich panels until failure based on yield stress and tangent modulus of the materials.*

KEYWORDS: *sandwich panels; wood-based panels; finite element analysis; bending*

SAŽETAK • *Eksperimentalnim i numeričkim metodama analizirane su sendvič-ploče s jezgrom od različitih materijala obloženih furnirskom pločom. Kao jezgra sendviča upotrijebljeni su iverica (PB), srednje gusta ploča vlaknatica (MDF) i pjenasti materijali, dok je kao obloga poslužila bukova furnirska ploča. Slojevi sendviča međusobno su zalijepljeni poliuretanskim ljepilom. Elastičnost (E) PB-a, MDF-a i furnirske ploče određena je u laboratoriju. Za određivanje savijanja sendvič-ploča poslužila je elastičnost pjene koju je deklarirao proizvođač. Rezultati istraživanja pokazali su da vrsta materijala jezgre znatno utječe na savijanje sendvič-ploča obloženih furnirskom pločom. Uočeno je da su sendvič-ploče s jezgrom od MDF-a otpornije na savijanje nego ploče s jezgrom od PB-a i pjene. Posmični lom jezgre bio je dominantan tip loma za jezgre na bazi drva. Za sendvič-ploče čija je jezgra bila pjena u oblogama od furnirske ploče uočeno je izvijanje ili vlačno naprezanje. Rezultati studije pokazuju da se, uzimajući u obzir granicu elastičnosti i tangentni modul elastičnosti materijala, numerički modeli mogu primjenjivati za točno predviđanje savijanja sendvič-ploča do loma.*

KLJUČNE RIJEČI: *sendvič-ploče; drvne ploče; analiza konačnih elemenata; savijanje*

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1 INTRODUCTION
1. UVOD

Generally, sandwich panels are structural materials consisting of outer layers with high modulus of elasticity and bending strength, and a low-density middle layer (core) (Birman and Kardomateas, 2018). In wood-based sandwich panels, the outer layers are generally veneer or plywood (PW) made of high-strength wood, and the inner layers can consist of wood-based composites such as particleboard (PB), medium density fiberboard (MDF), oriented strand board (OSB), plastic, foam, paper, or shaped core made of non-wood materials (Klímek *et al.*, 2016). The middle or core layer of sandwich panels is mainly used to transmit the load. Its function is to provide the distance between the two layers and increase the moment of inertia and bending stiffness of the panels (Noor *et al.*, 1996). Due to the low density of the core material, the sandwich panel can greatly reduce its weight under the same bearing capacity (Sandeep and Srinivasa, 2020). Furthermore, the continuous reduction of forest resources, saving materials, and reducing weight have become important in the wood-based industries (Labans and Kalniņs, 2014). Using sandwich panels in wood-based products not only saves resources but also prevents the large deformations that often occur with commercial wood composites.

The use of sandwich structures is increasing day by day. Wood-based sandwich panels are an excellent alternative to similar sandwich panels made of metal or plastics, as they are lighter and have better-bending stiffness compared to their density (Wei *et al.,* 2021). Many wood-based or vegetable materials can be used in the production of these sandwiches (Smardzewski, 2019a). Foam, cork (Kawasaki and Kawai, 2006; Lakreb *et al.*, 2015), and plastics (Kljak and Brezović, 2007) cores are commonly used as core materials in wooden sandwich panels for insulation purposes. It is also possible to manufacture prismatic core sandwich panels using eco-friendly recycled materials (Schneider *et al.,* 2016). Sandwich panels can also be reinforced with carbon fiber nowadays (Susainathan *et al.,* 2018). Besides, it should be noted that sandwich systems include typical wood-based panels covered with laminate or protective and decorative papers (Nemli and Çolakoğlu, 2005). Adhesives such as PVA, polyurethane, and urea-formaldehyde, which are widely used in the woodworking industry, are generally used to bond the layers together. Köhler *et al.* (2022) studied the Loofah sandwich panels and examined fiber-to-adhesive ratios of 1:0.5, 1:0.8, and 1:1.05. An increase in adhesive strength increases material strength and density. Compared with other commercial wood-based panels, wood-based sandwich panels have an advantage in thermal insulation (Wei *et al.,* 2021).

One of the most effective methods of controlling the mechanical properties of panel-type structures is the use of sandwich structures (Gozdecki and Kociszewski, 2021). By varying the material, thickness, and type of core and outer layers, sandwich panels with various properties and performances can be obtained. (Lakreb *et al.*, 2015; Smardzewski, 2019b). The bending properties of sandwich panels largely depend on the configuration of the layers, that is, the stacking order and the layer thickness relative to the midplane. This configuration dependence of flexural properties in sandwich structures can be used in lamination design to optimize the structural properties of sandwiches (Kazemi *et al.,* 2013).

Research in recent years has focused on the development of new sandwich products. However, there was a lack of fundamental research on design theory and modeling of fracture mechanisms. Although there are many types of wood-based sandwich panels, most research has focused on physical and mechanical properties (Kljak and Brezovic, 2007; Güler and Ulay, 2010; Edgars *et al.,* 2017; Gozdecki and Kociszewski, 2021; Köhler *et al.,* 2022). Several studies (Labans and Kalnins, 2014; Schneider *et al.,* 2016; Smardzewski, 2019a) show that the bending stiffness of sandwich panels can be determined by the finite element method. At the same time, bending stiffness could be estimated by ultrasonic method with a different approach (Haseli *et al.,* 2020). The finite element method and non-destructive testing can save a lot of time and economy in estimating the bending stiffness of such materials.

The aim of this study was to investigate the flexural properties of sandwich panels made of PB, MDF, and foam-core and plywood-outer layers. In doing so, (i) a three-point bending test was applied to determine the bending strength of the sandwich panels experimentally, and (ii) the experimental results were compared to numerical results.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

Commercial panels were purchased from a local supplier in the dimensions of 210 x 280 cm. PB panels were P2 grade (TS EN 312) with a density of 635 kg/m^3 and thickness of 14 mm, medium-density-fiberboard (MDF) panels were HD grade (TS EN 622-5) with a density of 789 kg/m^3 and 12 mm in thickness, polystyrene (PS) sheets were 10 mm in thickness with a 30 kg/m^3 density. Plywood panels were marine grade (high-moisture resistant) with a thickness of 4 mm and a density of 759 kg/m^3 and consisted of three plies of oriental beech (*Fagus orientalis* L.). All boards were cut into 600 mm × 600 mm dimensions and kept in controlled conditions (temperature 21 °C, relative humidity 65 %). The bending specimens were taken along the length directions of wood-based panels due to fiber direction of faces for PWs and fiber and chips mat directions for MDF and PB. Polyurethane (PUR) glue was used as an adherent between layers. Sandwich panels with outer layers consisting of PW and core layers made of PB, MDF, and PS were prepared using PUR adhesive. The amount of adhesive used for bonding the layers was 200 g/m^2 (Uysal *et al*., 2022). The produced sandwich panels were kept in cold press under 0.15 - 0.45 MPa pressure for 24 hours at room temperature and left for conditioning. 50 mm-wide bending samples were cut from the produced sandwich panels.

2.2 Methods
2.2. Metode

In the first stage of the study, the bending modulus and bending strength of the materials used in sandwich production were determined. The density and moisture content (MC, %) of the materials were also calculated. The bending strength and modulus of elasticity of MDF, PB, and PW panels were calculated according to TS-EN 310 (1999), the densities of the panels were evaluated according to TS-EN 323 (1999), and their moisture contents were calculated according to TS EN 322 (1999).

In the second part of the study, the bending curves of sandwich panels produced using wood-based composites and PS were obtained. The stiffness curves (P/δ) were obtained by subjecting the sandwich panels to the bending test using the SHIMADZU® UTM in the laboratory (Figure 1). Five replications were tested for each sample group. All tests were performed at room temperature of 21 °C and constant relative humidity of 65 %. The span of the bending samples (sandwich) was 20 times the thickness of the samples.

2.3 Numerical analysis of sandwich panels
2.3. Numerička analiza sendvič-ploča

Different modeling techniques are applied to simulate the mechanical behavior of sandwich panels. The complexity and accuracy of the models depend on what behavior the model was designed to assess. In general, it is advisable to use the simplest possible model to predict the desired phenomena (Di Sciuva *et al.,* 2015). In general, shell elements are used to model face material, while the core is modeled using solid elements.

Figure 1 Bending test of sandwich panels constructed in the study
Slika 1. Ispitivanje sendvič-ploča na savijanje

Numerical calculations were performed using the *ANSYS Mechanical APDL* (Structural, static) *v.2023* (ANSYS, Inc. Canonsburg, Pa, USA). In the numerical models of sandwich panels, all layers of the sandwich are assumed to be isotropic. Material properties presented in Table 1 were used for modeling sandwich panels. The discretization of the numerical model was achieved using *SOLID186* elements with approximately 30,000 elements and 50,000 nodes. *SOLID186* is a high-order 3-dimensional 20-node solid element that exhibits quadratic displacement behavior. It is the most frequently preferred element for modeling structural problems. The element is defined by 20 nodes with three degrees of freedom per node: translations in the nodal *x*, *y*, and z directions. The tetrahedral element option was used. Nodal loads as a force of *P/2* were applied to upper mid-span nodes. Models were simply supported on both ends. A perfect bonding was assumed between the faces and the core at the contact zone so that the glue command available through the

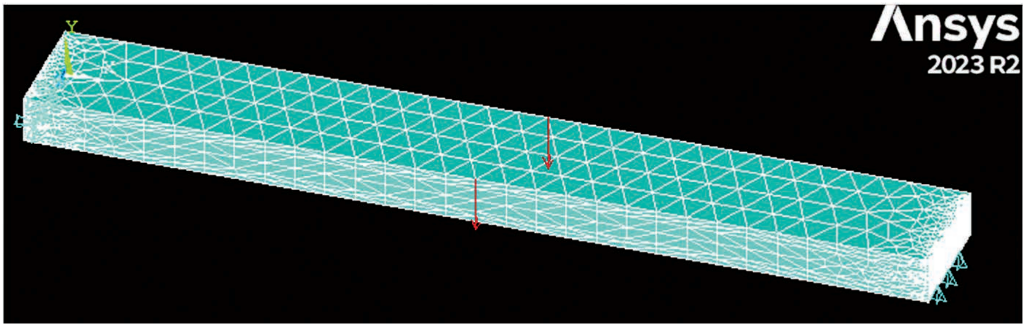


Figure 2 Numerical models created using ANSYS mechanical APDL
Slika 2. Numerički modeli izrađeni uz pomoć ANSYS mehaničkog APDL-a

operate option of the software was applied. The "*Glue Volumes*" module is used in the ANSYS package program to stick the mechanical properties of the model together. The *VGLUE* command (*ANSYS*^{TM}) is used to generate a new volume of the sandwich material by "*gluing*" all three solid parts. This operation is only valid in the case when the interfaces are coplanar. The mid-span panel deflection and maximum stress and strains at various locations on facings were extracted as an output result of numerical analysis. Load/deformation (stiffness) curves were created using the ANSYS and compared with the stiffness curves of real sandwich panels tested in the laboratory. Figure 2 illustrates one of the models created using ANSYS mechanical APDL. Plasticity was introduced using strain hardening (bilinear material) option available through ANSYS, which requires yield and tangent modulus.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The density, *MC* (%), and bending properties of materials tested in the study are presented in Table 1. Average stress-deformation curves representing the materials tested in the laboratory are shown in Figure 3. Although specimens belong to wood-based composite materials, their stress-deformation behavior differs due to their raw materials and manufacturing processes. Bending curves illustrated that plywood had superior bending capacity compared to other wood-based materials. The experimental results of wood-based panels indicated that stress-deformation curves can be considered as bilinear, having linear region, yield, and following plastic region (Figure 2). This information is crucial to construct numerical models by using ANSYS. Tested plywood, MDF, and PB panels seemed to have a yield point of approximately 90, 20, and 7 MPa, respectively. Those of the tangent modulus were calculated as 2000, 1700, and 300 MPa, respectively. The bending properties of sandwich panels tested in this study are similar to those reported by Gozdecki and Kociszewski (2021).

Figures 4-6 show the bending test results and numerical modeling obtained from sandwich composite panels with different core materials. The stress–deflection curves of the sandwich panels presented bilinear curves, which include initial linear elastic region fol-

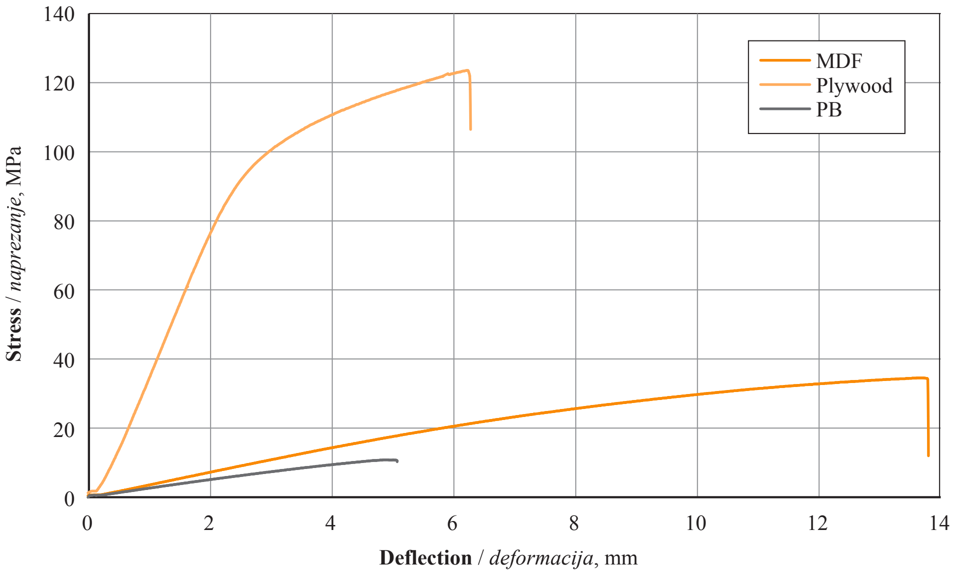


Figure 3 Average stress – deformation curves for materials tested in bending
Slika 3. Prosječne krivulje *naprezanje – deformacija* za materijale ispitane na savijanje

Table 1 Some physical and bending properties of materials tested in the study
Tablica 1. Neka fizička svojstva i svojstva na savijanja materijala ispitanih u studiji

Material *Materijal*	**Density, kg/m^3** *Gustoća,* kg/m^3	***MC*, %**	***E*, N/mm^2**	**σ, N/mm^2**	**Max. deflection at failure, mm** *Najveći progib pri lomu,* mm
PB	635	8.1	1540 (76)	11.18 (0.81)	5.07
MDF	780	8.0	3084 (80)	31.96 (1.07)	13.79
Plywood	750	11.5	10066 (919)	118 (5.65)	6.25
Foam	30		10		
P-PB-P	720		7205 (430)	53.39 (0.85)	14.5
P-MDF-P	809		7311 (247)	65.59 (8.4)	18.5
P-foam-P	432		2213 (114)	20.28 (0.81)	35

*Values in parenthesis are standard deviations / *vrijednosti u zagradama standardne su devijacije* lowed by plastic deformation. The curves of the two specimens with PB and MDF core materials were steep and had good linearity in the elastic stage. In contrast to that, the foam-core material yielded mostly parabolic curves, which is a sign of more plastic deformation. It can be concluded that layer properties are reflected in the behavior of sandwiches.

Sandwich panels with PB- and MDF-cores behaved significantly stiffer than sandwich panels with foam-cores. It is well-known that the stress-strain be-

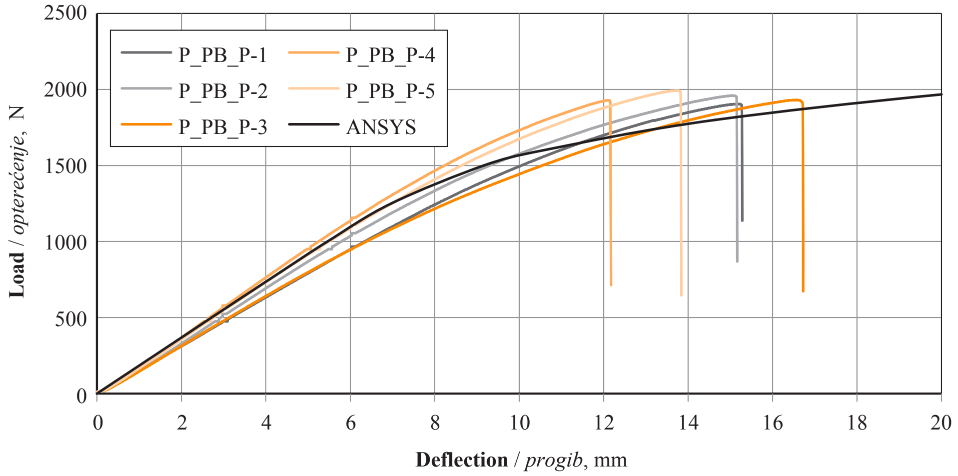


Figure 4 Load – deflection curves of PB core sandwich materials
Slika 4. Krivulje *opterećenje – progib* sendvič-materijala s PB jezgrom

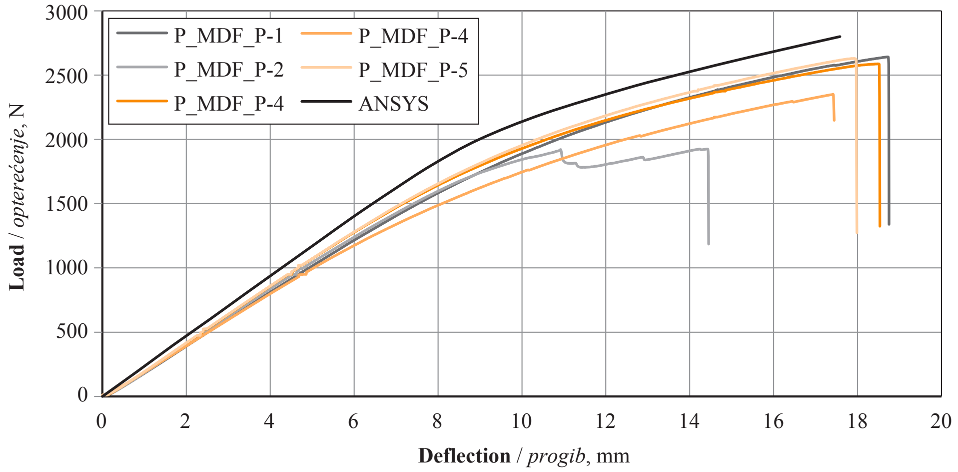


Figure 5 Load – deflection curves of MDF core sandwich materials
Slika 5. Krivulje *opterećenje – progib* sendvič-materijala s MDF jezgrom

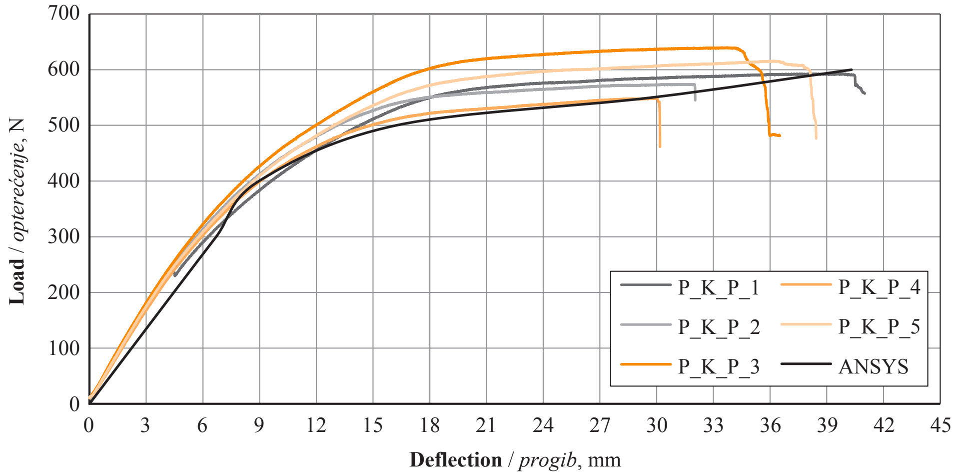


Figure 6 Load – deflection curves of foam core sandwich materials
Slika 6. Krivulje *opterećenje – progib* sendvič-materijala s jezgrom od pjene

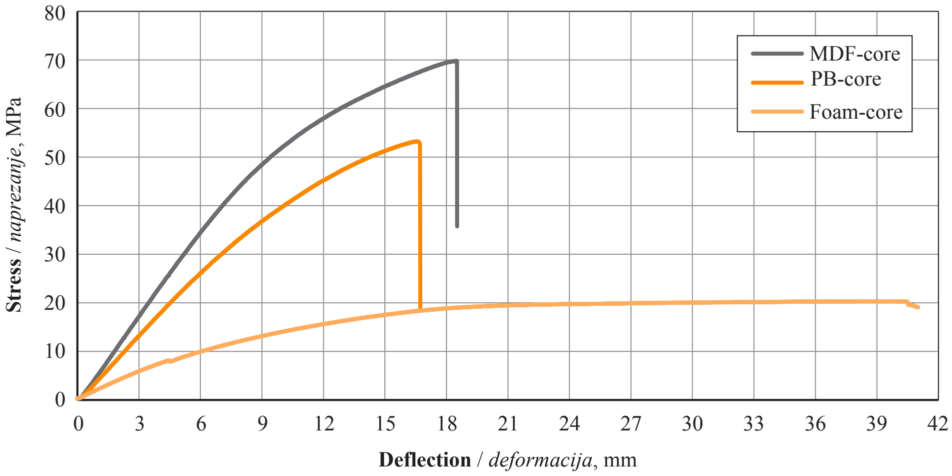


Figure 7 Comparison of bending curves of sandwich panels with different core materials
Slika 7. Usporedba krivulja savijanja sendvič-ploča s jezgrom od različitih materijala

havior of wood in compression parallel or perpendicular to grain is nonlinear (Goodman and Bodig, 1971). Consequently, bending fractures in sandwich panels made with plywood facings are expected to present non-linear load-displacement behavior. This non-linear behavior may end with a brittle fracture.

The average bending strength of sandwich panels with PB core material and plywood facings is measured as 53 MPa, while the average total deflection at the failure is determined as 13.4 mm. PB-core sandwich panels have the average bending stiffness of 7205 MPa, which is slightly lower than MDF-core sandwich panels with a bending strength of 65 MPa and a bending stiffness of 7311 MPa, The average total deflection at failure measured for MDF-core sandwich panels is 18 mm. Thickness of the core material may also contribute to the overall bending stiffness. Thus, sandwich panels made of MDF core having the same core thickness may yield much more stiffness than PB core sandwiches. This is also valid in terms of the bending strength of the MDF core sandwich panels. Foam-core sandwich panels had the greatest total deflection at the failure, while they had the lowest bending stiffness and bending strength.

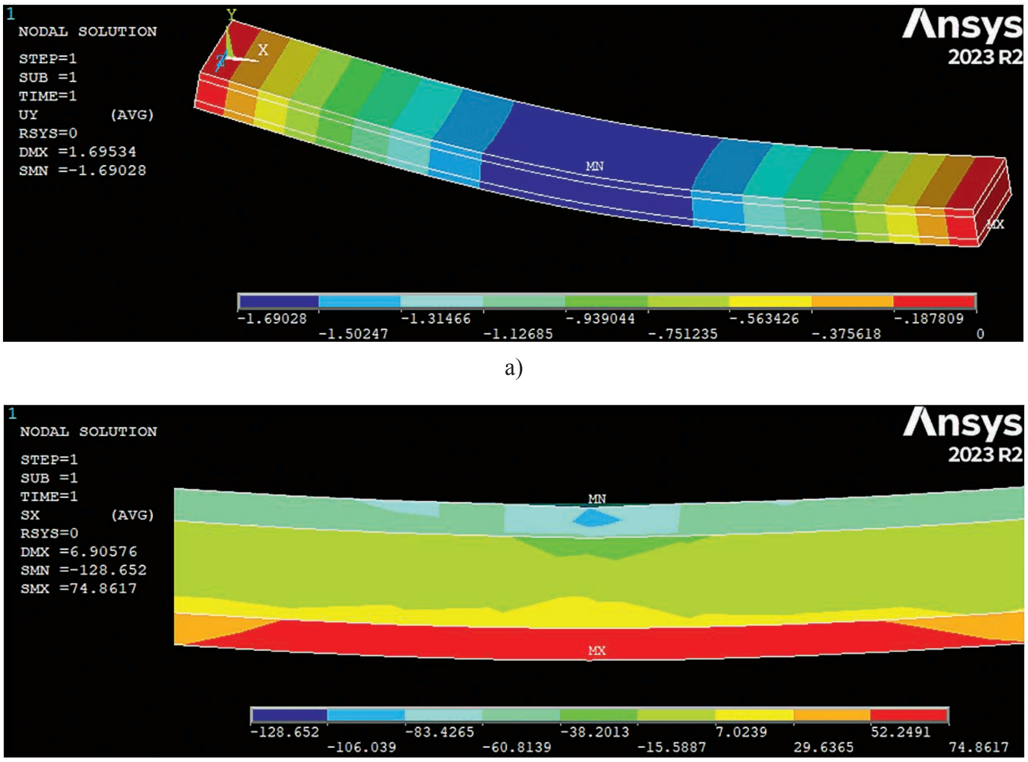
As shown in Figure 7, it is critical to note that both initial stiffness and ultimate load were obviously distinct for sandwich panels with different core materials.

A comparison of the numerical and experimental results showed that the deflection behavior of sandwich panels until failure is in good agreement with the simulation results of ANSYS (or slightly over prediction as shown for MDF core sandwiches). The numerical models assumed a perfect bond between the layers of the sandwich panels. This was confirmed by the failure types, which were never observed in the bond of the core and face layers. The numerical models are more detailed and they presented stress concentrations, which was a sign of a higher probability of failure (Figure 8).

Numerical modeling of non-linear behavior was challenging because the data that would define the elastoplastic behavior of wood-based panels are not available in the literature, which significantly complicates the modeling. Using yield stress and tangent modulus of materials in numerical modeling make it possible to obtain non-linear behavior of sandwiches and more precise results.

Several studies related to the FEM modeling of sandwich panels under bending loading can be found in the literature. Most studies established good agreement between numerical models and experimental outcomes (Alade *et al.,* 2023). Some studies reported over-prediction. Since internal defects or irregularities are inevitable while using wood, over-prediction of numerical models may be somehow expected. Kljak *et al.* (2018) revealed that the use of isotropic models in the modeling of PB panels instead of a three-layer orthotropic model yields more precise results within the linear-elastic limit.

The accuracy of numerical models may depend on the type and number of the elements, geometry and loading scheme used. Solid elements may yield better prediction than plane elements, and second order elements have a high degree of accuracy than first order elements. In numerical modeling, meshing with simple elements such as plane182 (4 node) or solid 186 (8 nodes), having moderate number of elements and isotropic element properties in modeling of simple bending, may yield accurate results. Results reported by Edgars *et al.* (2017) and Kljak *et al.* (2018) support this idea. Complicated loading schemes or geometries may require the use of high order quadratic elements such as solid 186 (20 nodes), orthotropic element properties and higher number of elements. Recent investigations engaged in non-linear behavior using orthotropic properties (Kljak and Brezović 2007; Labans and Kalnin, 2014; Fang *et al.,* 2015; Smardzewski, 2019a; Mohammadabadi *et al.*, 2019; Mohammadabadi *et al.*, 2020) presented highly



a)

b)

Figure 8 Deformation (a) and stress (b) obtained using ANSYS software (DMX – maximum deformation, SMN – minimum stress and SMX – maximum stress)
Slika 8. Deformacija (a) i naprezanje (b) dobiveni primjenom ANSYS softvera (DMX – najveća deformacija, SMN – najmanje naprezanje i SMX – najveće naprezanje)

accurate results. Nevertheless, few predictive models are established to better understand the non-linear mechanical behavior of sandwich structures with wood elements. In general, elastoplastic behavior with strain hardening has also been presented in the modeling of wood joints (Serrano, 2001; Guan *et al*., 2009).

In the case of using MDF- or PB-core panels, their dominant failure type was mainly due to the failure of MDF or PB. On the contrary, those of foam-core panels were mainly due to the failure of the adhesive between the layers of plywood (Figure 9). It is well-known that particle or fiber-based wood panels are weak in shear; it is particularly true that the presence of flaws and the discrepancies in internal bond strength may contributed to the shear failure. The identical phenomena may have also contributed to the increased bending deflection during experiments. The higher shear strength of the foam materials may cause the diversion of stress concentrations from the core to the face material. Delamination or splitting that prevailed in the plywood facings supports this idea. As mentioned in the literature, the most common failure patterns for sandwich beams were shear failure, indentation, and face yield (Hao *et al*., 2018).

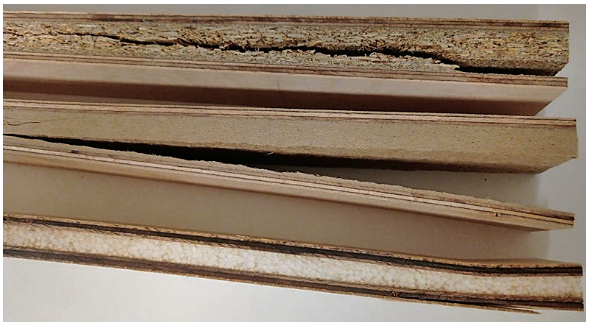


Figure 9 Failure types observed for sandwich panels constructed
Slika 9. Uočene vrste lomova na sendvič-pločama

Results indicated that stress concentration is located at the mid-part of the sandwich panels. When sandwich panels are subjected to bending, compressive stresses act on the surface while tensile stresses act on the bottom. Since the yield stresses of the materials used in the construction of the sandwiches are different, it is important to know the lower values of these stresses that will start to cause failure. Wood has lower yield stresses in compression, perpendicular directions, and shear; whichever reaches the critical level will cause the failure.

4 CONCLUSIONS
4. ZAKLJUČAK

Results of the study have shown that the type of core material has a significant effect on the bending behavior of sandwich panels with plywood facings.

Panels with the MDF core are more resistant to bending compared to panels with PB- and foam-core.

Although the foam core deflects more, it can carry the load for a long time.

Numerical models can be used successfully in the prediction of the bending behavior of the sandwich panels constructed in the study.

Numerical models can be adapted to predict the behavior of new sandwich materials with different thicknesses.

The nonlinearity of sandwich constituents was successfully defined by using yield and tangent modulus.

The suitability of the model to simulate the nonlinear behavior of sandwich panels until failure is demonstrated.

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5 REFERENCES
5. LITERATURA

1. Alade, A. A.; Ibrahim, A., 2023: Application of finite element method for mechanical characterization of wood and reconstituted lignocellulosic-based composites – A review. Recent Progress in Materials, 5 (1): 1-24. https://doi.org/10.21926/rpm.2301003
2. Birman, V.; Kardomateas, G. A., 2018: Review of current trends in research and applications of sandwich structures. Composite: Part B, 142: 221-240. https://doi.org/10.1016/j.compositesb.2018.01.027
3. Di Sciuva, M.; Mattone, M.; Tazzini, A.; D'Agostino, D., 2015: FEM modeling of a composite sandwich laminate with LS-DYNA for aerospace applications. Enginsoft Newsletter, 12 (2): 43-48.
4. Edgars, L.; Kaspars, Z.; Kaspars, K., 2017: Structural performance of wood based sandwich panels in four-point bending. Procedia Engineering, 172: 628-633. https://doi.org/10.1016/j.proeng.2017.02.073
5. Fang, H.; Sun, H.; Liu, W.; Wang, L.; Bai, Y.; Hui, D., 2015: Mechanical performance of innovative GFRP-bamboo-wood sandwich beams: Experimental and modelling investigation. Composite: Part B, 79: 182-196. https://doi.org/10.1016/j.compositesb.2015.04.035
6. Goodman, J. R.; Bodig, J., 1971: Orthotropic strength of wood in compression. Wood Science, 4: 83-94.
7. Gozdecki, C.; Kociszewski, M., 2021: The properties of sandwich panels made of standard wood-based panels. Annals of Warsaw University of Life Sciences SGGW Forestry and Wood Technology, 114: 125-130. https://doi.org/10.5604/01.3001.0015.2411
8. Guan, Z. W.; Zhu, E. C., 2009: Finite element modelling of anisotropic elasto-plastic timber composite beams with openings. Engineering Structures, 31: 394-403. https://doi.org/10.1016/j.engstruct.2008.09.007
9. Güler, C.; Ulay, G., 2010: Some technological properties of foamed composite (sandwich) panels. Süleyman Demirel Üniversitesi Orman Fakültesi Dergisi, A (2): 88-96 (in Turkish).
10. Haseli, M.; Layeghi, M.; Hosseinabadi, H. Z., 2020: Evaluation of modulus of elasticity of date palm sandwich panels using ultrasonic wave velocity and experimental models. Measurement, 149: https://doi.org/107016. 10.1016/j.measurement.2019.107016
11. Hao, J.; Wu, X.; Oporto, G.; Wang, J.; Dahle, G.; Nan, N., 2018: Deformation and failure behavior of wooden sandwich composites with Taiji honeycomb core under a three-point bending test. Materials, 11: 2325. https://doi.org/10.3390/ma11112325
12. Kawasaki, T.; Kawai, S., 2006: Thermal insulation properties of wood-based sandwich panel for use as structural insulated walls and floors. Journal of Wood Science, 52: 75-83. https://doi.org/10.1007/s10086-005-0720-0
13. Kazemi, Y.; Cloutier, A.; Rodrigue, D., 2013: Design analysis of three-layered structural composites based on post-consumer recycled plastics and wood residues. Composites: Part A, 53: 1-9. https://doi.org/10.1016/j.compositesa.2013.06.002
14. Klímek, P.; Wimmer, R.; Brabec, M.; Sebera, V., 2016: Novel sandwich panel with interlocking plywood kagome lattice core and grooved particleboard facings. BioResources, 11 (1): 195-208. https://doi.org/10.15376/biores.11.1.195-208
15. Kljak, J.; Brezović, M., 2007: Influence of plywood structure on sandwich panel properties: Variability of veneer thickness ratio. Wood Research, 52 (2): 77-88.
16. Köhler, R.; Jurisch, M.; Mayer, A. K.; Mai, C.; Viöl, W., 2022: Loofah sandwich panels: The effect of adhesive content on mechanical and physical properties. Materials, 15: 7129. https://doi.org/10.3390/ma15207129
17. Kljak, J.; Španić, N.; Jambreković, V., 2018: Comparison of finite element models for particle boards with homogenous and three-layer structure. Drvna industrija, 69 (4): 311-316. https://doi.org/10.5552/drind.2018.1764
18. Labans, E.; Kalnins, K., 2014: Experimental validation of the stiffness optimization for plywood sandwich panels with rib-stiffened core. Wood Research, 59 (5): 793-802.
19. Lakreb, N.; Bezzazi, B.; Pereira, H., 2015: Mechanical behavior of multilayered sandwich panels of wood veneer and a core of cork agglomerates. Materials & Design, 65: 627-636. https://doi.org/10.1016/j.matdes.2014.09.059
20. Mohammadabadi, M.; Yadamab, V.; Smith, L., 2019: An analytical model for wood composite sandwich beams with a biaxial corrugated core under bending. Composite Structures, 228: 111316. https://doi.org/10.1016/j.compstruct.2019.111316
21. Mohammadabadi, M.; Jarvis, J.; Yadama, V.; Cofer, W., 2020. Predictive models for elastic bending behavior of a wood composite sandwich panel. Forests, 11 (6): 624. https://doi.org/10.3390/f11060624
22. Nemli, G.; Çolakoğlu, G., 2005: The influence of lamination technique on the properties of particleboard. Building and Environment, 40 (1): 83-87. https://doi.org/10.1016/j.buildenv.2004.05.007
23. Noor, A. K.; Burton, W. S.; Bert, C. W., 1996: Computational models for sandwich panels and shells. Applied Mechanics Reviews, 49 (3): 155-199. https://doi.org/10.1115/1.3101923
24. Sandeep, S. H.; Srinivasa, C. V., 2020: Hybrid sandwich panels: A Review. International Journal of Applied Mechanics and Engineering, 25 (3): 64-85. https://doi.org/10.2478/ijame-2020-0035

25. Schneider, C.; Zenkert, D.; Deshpande, V. S.; Kazemahvazi, S., 2016: Bending energy absorption of self-reinforced poly(ethylene terephthalate) composite sandwich beams. Composite Structures, 140: 582-589. https://doi.org/10.1016/j.compstruct.2015.12.043
26. Serrano, E., 2001: Glued-in rods for timber structures – a 3D model and finite element parameter studies. International Journal of Adhesion and Adhesives, 21 (2): 115-127. https://doi.org/10.1016/S0143-7496(00)00043-9
27. Smardzewski, J., 2019a: Experimental and numerical analysis of wooden sandwich panels with an auxetic core and oval cells. Materials & Design, 183: 108159. https://doi.org/10.1016/j.matdes.2019.108159
28. Smardzewski, J., 2019b: Wooden sandwich panels with prismatic core – Energy absorbing capabilities. Composite Structures, 230: 111535. https://doi.org/10.1016/j.compstruct.2019.111535
29. Susainathan, J.; Eyma, F.; De Luycker, E.; Cantarel, A.; Castanie, B., 2018: Experimental investigation of impact behavior of wood-based sandwich structures. Composites. Part A: Applied Science and Manufacturing, 109: 10-19. https://doi.org/10.1016/j.compositesa.2018.02.029
30. Uysal, M.; Eren, O.; Karatay, H.; Memis, D., 2022: Investigation of bending properties of cross-laminated timber made of Uludağ fir and black pine. Turkish Journal of Forestry, 23 (4): 313-319 (in Turkish). https://doi.org/10.18182/tjf.1166361
31. Wei, P.; Chen, J.; Zhang, Y.; Pu, L., 2021: Wood-based sandwich panels: A review. Wood Research, 66 (5): 875-890. https://doi.org/10.37763/wr.1336-4561/66.5.875890
32. ***TS EN 310: 1993, Wood-based Panels – Determination of Modulus of Elasticity in Bending and of Bending Strength, 1993.
33. ***TS EN 312: 2012, Particleboards – Specification.
34. ***TS EN 322: 1999, Wood-based panels – Determination of moisture content.
35. ***TS EN 323: 1999, Wood-based panels – Determination of density.
36. ***TS EN 622-5: 2009, Fiberboards – Specifications. Part 5: Requirements for dry process boards (MDF).

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