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Strength characteristics of furniture elements with particleboard cutting waste core

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Abstract

The circular economy principles for environmentally friendly and waste-free production can be effectively applied to furniture production by utilizing cutting particleboard waste. The aim of the presented study is to establish the influence of the laminating sheet characteristics on the bending strength and modulus of elasticity of three-layer elements with a core formed from laminated particleboard cutting waste. For lamination, medium density fibreboard (MDF) with a thickness of 2.7 and 4 mm, one-sided veneered MDF with a total thickness of 3.2 mm, and three-layer poplar plywood with a thickness of 3 and 4 mm were used. The lamination was carried out with polyvinyl acetate adhesive at a temperature of 50°C and a specific pressure of 0.075 MPa. The obtained dependencies are presented in tabular and graphical form.

Keywords: particleboard cutting waste, furniture elements, lamination, MDF, plywood

Introduction

The growing shortage of raw materials and resources for furniture production (https://ec.europa.eu/eurostat/) necessitates the effective application of circular economy principles for environmentally friendly and zero-waste manufacturing. Nevertheless, successfully implemented circular business models, together with product circular design strategies, remain rare (Pei et al., 2024). A potential gap exists between the positive attitude toward the circular economy and the practical implementation of its principles, as recycling, incineration, and landfilling still take precedence over practices related to reuse (Barbaritano et al., 2019).

The production process in small-scale furniture enterprises specializing in case furniture is characterized by the generation of large amounts of waste from the cutting of laminated particleboards. These waste pieces cannot be incorporated into products due to their unsuitable colours, textures, and sizes. Their storage occupies valuable production space and complicates the workflow (Angelski et al., 2024). Moreover, the waste represents an unrealized financial resource, as the invested materials and costs are practically unrecoverable (Takacs et al., 2020).

Currently, the main approach to solving these issues involves returning the waste to laminated particleboards manufacturing plants, where it is milled for reuse (Luo et al., 2024). This process requires additional time and energy for transport and reprocessing. The re-milling particles are significantly smaller, resulting in unprofitable production of fine fractions (Wronka and Kowaluk, 2022). The particleboards produced in this way exhibit reduced mechanical properties (Luo et al., 2024). The increased laminate content in the recycled particleboard contributes to faster tool wear and lower machining precision (Król et al., 2022). When particleboards are produced from re-milled particles that have undergone two recovery cycles (i.e. triple milling), the resulting product exhibits unacceptable mechanical properties (Wronka and Kowaluk, 2022).

One of the most negative aspects of the production and use of engineered wood panels, including particleboards, is the emission of formaldehyde. Formaldehyde emission from conventional thermosetting resins is one of the most concerning issues associated with engineered wood panels (Antov et al., 2020). Currently, about 95% of adhesives used in the production of wood-based panels are formaldehyde-based resins (Kumar and Pizzi, 2019).

It is evident that re-milling should be the last resort for utilizing laminated particleboards cutting waste.

As early as 2009, Daian and Ozarska proposed a potentially effective business model based on converting wood waste into profit through on-site processing into high-value products. Therefore, it is necessary to develop and implement technologies for utilizing wood-based panel waste within furniture factories.

In 2024 Angelski et al. developed a technology for producing three-layer elements with a core made from waste parts generated from the cutting of laminated particleboards and cladding layers made of high-pressure laminate (HPL). Several problems related to the different thicknesses and decors of the waste pieces have been effectively resolved. Low-energy lamination regimes have been proposed. It has been demonstrated that the use of polyvinyl acetate adhesives ensures sufficiently high values for bending strength and modulus of elasticity of the laminated elements. A specific feature of the proposed technology is its focus on elements with a predetermined application. This allows for the development of rational schemes for arranging the core details. However, questions remain regarding the production of elements with surface layers exhibiting other decors and textures that are in demand in interior applications.

Aim and scope of work

The aim of the present study is to determine the influence of the laminating sheet characteristics on the bending strength and modulus of elasticity of three-layer elements with cores made from laminated particleboard cutting waste, and to propose effective core arrangement schemes based on the dimensional stability of the elements and the manufacturability of their production.

Materials and Methods (Experimental)

Waste pieces from laminated particleboards with various decorative finishes, a thickness of 18 mm, and a density of 675 $kg \cdot m^{-3}$, were used for the core details. Some of the pieces had scratched or partially damaged surfaces. They were cut into strips with a uniform width of 23 mm and lengths determined by the arrangement scheme and the requirements of CEN EN 310:1993. The following arrangement schemes were adopted: In Scheme A, the core details were oriented along the length (L) of the element. In Scheme P, the core details were oriented perpendicular to the length (L) of the element. The combined arrangement scheme (Scheme C) is shown in Fig. 1.

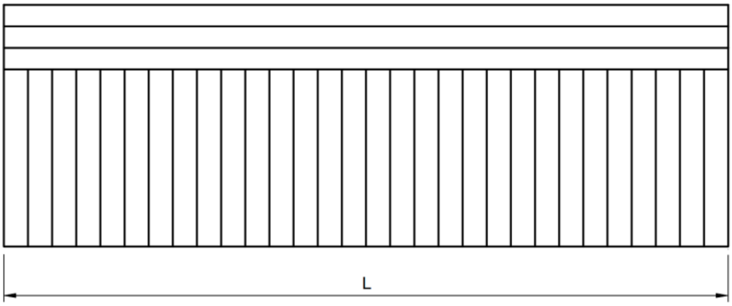


Fig. 1. Combined arrangement scheme (Scheme C) for the core details

The details were arranged side by side with their laminated sides facing each other, without being glued together and then laminated (Angelski et al., 2024).

Laminating sheets were selected from commercially available materials. According to supplier specifications, these materials comply with the requirements of European standards governing their performance characteristics. The type, thickness, and density of the materials chosen for the laminating sheets, as well as the dimensions of the tested specimens for Schemes A and P are summarized in Table 1.

Table 1. Type, thickness, and density of the laminate sheets. Dimensions of the specimens (length × width × thickness) for Schemes A and P

Material type and thickness	Series designation	Density, $kg \cdot m^{-3}$	Dimensions, mm
Medium density fibreboard, 2.7 mm, uncoated	MDF 2.7	840	600 × 50 × 28.4
Medium density fibreboard, 4 mm, uncoated	MDF 4	840	650 × 50 × 31
Medium density fibreboard, 2.7 mm, one-sided oak veneer 0.6 mm (total thickness 3.2 mm)	MDF_V 3.2	890	650 × 50 × 29.4
Poplar plywood, 3-layer, 3 mm, grade AB/BB	PL 3	430	600 × 50 × 29
Poplar plywood, 3-layer, 4 mm, grade B/BB	PL 4	410	650 × 50 × 31

All materials were conditioned for one month at 20±2°C and 60 ±5 % R.H.

A polyvinyl acetate (PVA) dispersion adhesive was used, with the following parameters: density of 1.08 $g \cdot cm^{-3}$; solid content of 50%; pressing time of 4 minutes at a bonding temperature of 50°C; open assembly time between 5 and 8 minutes; application amount of 150-200 $g \cdot m^{-2}$ (https://www.hranipex.lt/en/).

The elements were laminated using a manually loaded hydraulic press. The adhesive was applied to the laminating sheets. The lamination process conditions for each material type are presented in Table 2.

Table 2. Laminating process conditions

Series designation	Process conditions					
	Adhesive application amount, $g \cdot m^{-2}$	Temperature, °C	Specific pressure, MPa	Loading on the press, %	Hydraulic pressure, bar	Pressing time, min.
MDF 2.7	150	50	0.075	49	72	7
MDF 4	150	50	0.075	53	80	8
MDF_V 3.2	150	50	0.075	52	78	7
PL 3	175	50	0.075	48	70	7
PL 4	175	50	0.075	52	78	8

A single element was produced for each type of laminate sheet, and each arrangement scheme of the core details.

After conditioning (24 hours at 22°C and 60 ± 2% R.H.), the resulting plate elements were cut into five specimens with the same structure, in accordance with the requirements of CEN EN 310:1993, following Schemes A and P. The elements prepared using the combined arrangement scheme (Scheme C) were cut to the same lengths but with a width of 99 mm.

The MDF_v specimens were divided into subgroups and labelled as follows:

- AA - veneer orientation and the orientation of the core details are parallel to the specimen length (L),
- AP - veneer orientation is parallel, while the core details are oriented perpendicular to the specimen length (L),
- PA - veneer orientation is perpendicular, while the core details are oriented parallel to the specimen length (L),
- PP - both the veneer and core details are oriented perpendicular to the specimen length (L),

where the orientation of the veneer aligns with the direction of the wood grain within the veneer sheet.

The bending strength, modulus of elasticity, and dimensional stability of the obtained elements were evaluated.

The surface appearance was assessed organoleptically.

The bending strength *fm*, $N \cdot mm^{-2}$ and modulus of elasticity, $N \cdot mm^{-2}$ were determined in accordance with CEN EN 310:1993.

The degree of warping of the obtained elements was determined using a template.

For the research, a Universal testing machine with computer control WDW - 50E, manufactured by the company HST, China, 2022, was used. The measurements were carried out at a load application speed of 10 $mm \cdot min^{-1}$.

The experimental data were statistically processed using the accompanying software (MaxTest, USA).

Results and Discussion

The obtained elements from all series exhibited good surface appearance and uniformly arranged core details. An increase in the assembly time was observed for Schemes A and P due to the need for alignment of the core details.

No displacement between the core details was observed during the placement of the units in the press.

No peeling of the laminate sheets was observed during testing.

Table 3 presents the values of the coefficient of variation *V*,% and the accuracy indicator *p*,% for each series of specimens.

The values obtained for bending strength and modulus of elasticity for all series exceeded the requirements specified in EN 312:2010. Compared to the results recorded for factory-laminated particleboard with a thickness of 25 mm (Angelski et al., 2024), the bending strength was comparable or higher, while the modulus of elasticity was lower.

Table 3. The coefficient of variation V [%] and the accuracy index p [%] for each series of test specimens

Series	Number of specimens	Variation coefficient, *V* [%]		Accuracy index, *p* [%]	
		Bending strength	Modulus of elasticity	Bending strength	Modulus of elasticity
MDF 2.7A	5	4.61	1.20	2.66	0.69
MDF 2.7P	5	4.29	0.81	2.47	0.47
MDF 2.7C	5	2.18	5.20	1.26	3.00
MDF 4A	5	0.85	1.43	0.49	0.82
MDF 4P	5	5.88	1.00	2.94	0.50
MDF 4C	5	0.67	1.39	0.39	0.80
MDF_V 3.2 AA	5	4.21	1.36	2.43	0.78
MDF_V 3.2 AP	5	16.46	0.62	5.88	0.36
MDF_V 3.2 PA	5	3.75	2.17	5.20	3.06
MDF_V 3.2 PP	5	2.31	0.76	1.33	0.44
PL 3A	5	8.93	4.14	5.06	2.39
PL 3P	5	8.48	4.71	4.70	2.72
PL 4A	5	10.41	6.01	3.14	1.81
PL 4P	5	15.70	9.64	4.90	2.89

The results of the bending strength and modulus of elasticity tests for specimens laminated with HPL (Angelski et al., 2024) and MDF with a thickness of 2.7 mm are presented in Table 4.

Table 4. Bending strength and modulus of elasticity for specimens laminated with HPL, (Angelski et al., 2024) and MDF with a thickness of 2.7 mm (average values), under different core details arrangement schemes

Type of laminate sheets, arrangement scheme of the core details	HPL			MDF 2.7			Change,%		
	Scheme A	Scheme P	Scheme C	Scheme A	Scheme P	Scheme C	Scheme A	Scheme P	Scheme C
Specimen Wight, mm	50	50	99	50	50	99	50	50	99
Bending strength *fm*, $N \cdot mm^{-2}$	19.58	8.28	14.06	19.43	14.00	16.13	-0.75	69.08	14.75
Modulus of elasticity, $N \cdot mm^{-2}$	3031.6	1454.4	2093.67	2525.67	1607.00	1986.33	-16.69	10.49	-5.13

According to the results presented in Table 3, it can be observed that replacing the HPL with MDF sheets of 2.7 mm thickness leads to a 69% increase in the bending strength of elements with perpendicularly oriented core details, eliminating the need for crosswise arrangement. After assessing the shape of the specimens, a warping deflection of 0.6 $mm \cdot m^{-1}$ was recorded for elements with a core arrangement according to Scheme P (Fig. 2). This value is lower than that for elements laminated with HPL, as well as below the allowable limit (Kavalov and Angelski, 2014). No warping was detected in the specimens from the other series.

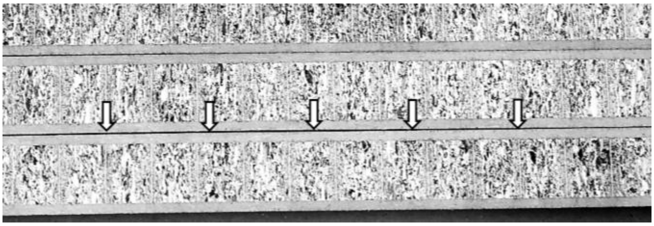


Fig. 2. The element warping

To stabilize the shape and improve the manufacturability of the core arrangement, it is recommended to place two perpendicularly oriented core details at the ends of the element (Fig. 3).

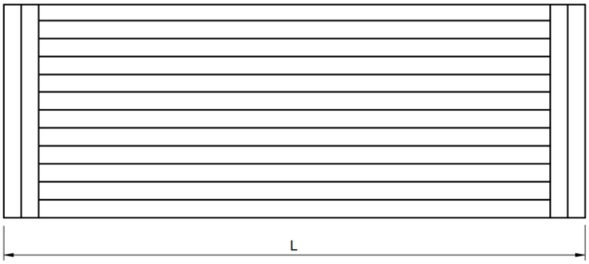


Fig. 3. Recommended arrangement scheme of the core details

An analysis of the failure patterns in the specimens with core details arrangement according to Scheme P revealed a higher percentage of fractures occurring within the individual details rather than between them (Fig. 4A). In all experiments, the accuracy indicator p was below 3%, indicating that the fracture location had no significant effect on the bending strength values. The structural delamination of MDF used as cladding sheets under compressive load indicates that the internal structure of the MDF is the weakest part of the elements. For the core details oriented along the length and those in the combined arrangement (Fig. 4B), the observations were identical.

A B

Fig. 4. Destruction of elements laminated with MDF under bending stress: A - Elements from Series P; B - Elements from Series C

The results of the bending strength and modulus of elasticity tests for specimens from series MDF 2.7 and MDF 4 are presented in Table 5.

Table 5. Bending strength and modulus of elasticity for specimens laminated with 2.7 mm and 4 mm MDF (average values), under different core detail arrangement schemes

Type of laminate sheets, arrangement scheme of the core details	MDF 2.7			MDF 4			Change,%		
	Scheme A	Scheme P	Scheme C	Scheme A	Scheme P	Scheme C	Scheme A	Scheme P	Scheme C
Specimen Wight, mm	50	50	99	50	50	99	50	50	99
Bending strength *fm*, $N{\cdot}mm^{-2}$	19.43	14.00	16.13	24.53	18.075	22.67	26.24	29.11	40.50
Modulus of elasticity, $N{\cdot}mm^{-2}$	2525.67	1607.00	1986.33	2875.00	2054.75	2524.67	13.83	27.86	27.10

The results presented in Table 4 show that increasing the thickness of the MDF cladding sheet from 2.7 mm to 4 mm results in an increase in bending strength and modulus of elasticity in the range of 14% to 41%. After assessing the shape of the specimens, a warping deflection of 0.8 $mm{\cdot}m^{-1}$ was recorded for all elements. The highest deflection value was observed in elements with a core arrangement according to Scheme P. The failure mode and mechanism of the specimens from the MDF 2.7 and MDF 4 series were found to be identical.

The results of the bending strength and modulus of elasticity tests for specimens from series MDF_v 3.2 depending on the orientation of the veneer and the core details relative to the length of the element, are presented in Table 5.

Table 6. Bending strength and modulus of elasticity for specimens faced with MDF_v 3.2 mm (mean values), depending on the orientation of the veneer and the core details relative to the element length. Change in values relative to the MDF 2.7 series. Differences based on the orientation of the veneer and core details. Specimen width: 50 mm

Assessment indicator	MDFv 3.2				Change relative to MDF 2.7, %				Difference due to veneer orientation, %		Difference due to core detail orientation, %	
	AA	AP	PA	PP	AA	AP	PA	PP	AA-PA	AP-PP	AA-AP	PA-PP
Bending strength *fm*, $N{\cdot}mm^{-2}$	28.37	18.27	20.80	13.00	46.0	30.5	7.0	-7.1	-26.7	-28.8	-35.6	-37.5
Modulus of elasticity, $N{\cdot}mm^{-2}$	3683.33	2786.00	2882.33	1912.33	45.8	73.4	14.1	19.0	-21.8	-31.4	-24.4	-33.7

The results presented in Table 5 show a significant influence of the presence of veneer in the cladding sheet on the bending strength and modulus of elasticity of the produced elements. The orientation of the veneer relative to both the core detail orientation and the element length (L) is of importance. Due to the sufficiently high values of the studied parameters, crosswise arrangement of the core details is not required. To achieve minimal anisotropy of the elements, it is recommended that the veneer be oriented perpendicular to the length of the core details.

After assessing the shape of the specimens, a warping deflection of 0.8 $mm \cdot m^{-1}$ was recorded for the elements from group PP, which decreased in groups AP and PA. No warping was detected in group AA. To stabilize the shape and improve the manufacturability of the core arrangement, it is recommended to place two perpendicularly oriented core details at the ends of the element. With the proposed core arrangement scheme, the modulus of elasticity of the three-layer element will be comparable to that of a factory-produced laminated particleboard with a thickness of 25 mm.

The failure mechanism of the specimens from series MDF_v 3.2 (Fig. 5) corresponds to the failure mechanism of the elements from series MDF 2.7 (Fig. 4).

A B

Fig. 5. Damaging of MDF_v specimens under bending stress: A - Elements from Series AA; B - Elements from Series PP

The results of the bending strength and modulus of elasticity tests for specimens laminated with three-layer poplar plywood with thicknesses of 3 mm and 4 mm are presented in Table 7.

The values of the evalueted parameters obtained for all series exceed the requirements of the standard. The bending strength values obtained for the PL 3 series are comparable to those recorded for the MDF 2.7 series.

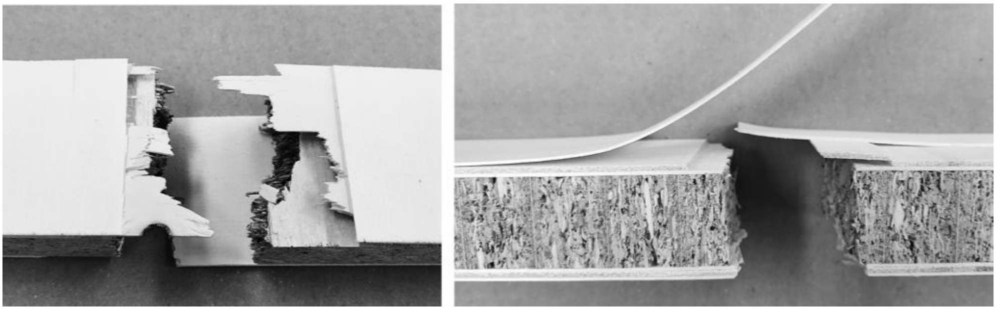
Due to the higher accuracy indicators for the PL 4 series ($p < 10\%$), it can be concluded that the change in the values of the evaluated parameters, resulting from the increase in plywood thickness for core details oriented along the length, is insignificant.

Warping was observed in the specimens from all series. The warping deflection for PL 3 is comparable to that observed in Scheme P for MDF 2.7, as well as for groups AP and PA. With the increase in the thickness of the cladding layer, warping in the longitudinally oriented core details increases, indicating improper orientation of the plywood laminating sheets relative to the core details.

Table 7. Bending strength and modulus of elasticity for specimens from series PL 3 and PL 4 (average values), under different core detail arrangement schemes. The wood grain in the face veneer of the plywood is oriented along the length of the element

Type of laminate sheets, arrangement scheme of the core details	PL 3		PL 4		Change,%	
	Scheme A	Scheme P	Scheme A	Scheme P	Scheme A	Scheme P
Specimen Wight, mm	50	50	50	50	50	50
Bending strength *fm*, N·mm^{-2}	22.43	13.67	22.00	17.77	-1.93	30.00
Modulus of elasticity, N·mm^{-2}	2966.00	1719.33	2876.67	2033.33	-3.01	18.26

The failure of the elements from both PL 3 series is characterized by delamination of the plywood layers (Fig. 6).



A B

Fig. 6. Damaging of Plywood 3 specimens under bending stress: A - Elements from Series A; B - Elements from Series P

The failure is adhesive, occurring primarily between the middle layer and the inner layer of the element. The failure of the plywood occurs simultaneously with the failure of the element (Fig. 8). The failure mechanism differs from that observed in elements laminated with HPL (Angelski et al., 2024).

The failure mechanism observed in the specimens from the PL 4 series corresponds to that of the elements from the MDF and MDF_v series. In some specimens with perpendicularly oriented core details, residual deformation was observed in the failure zone in the direction of loading, without any delamination of the plywood (Fig. 7).

Fig. 7. Residual deformation in the failure zone of a PL 4 series element

Fig. 8 present the studied detail's stress-strain relationships.

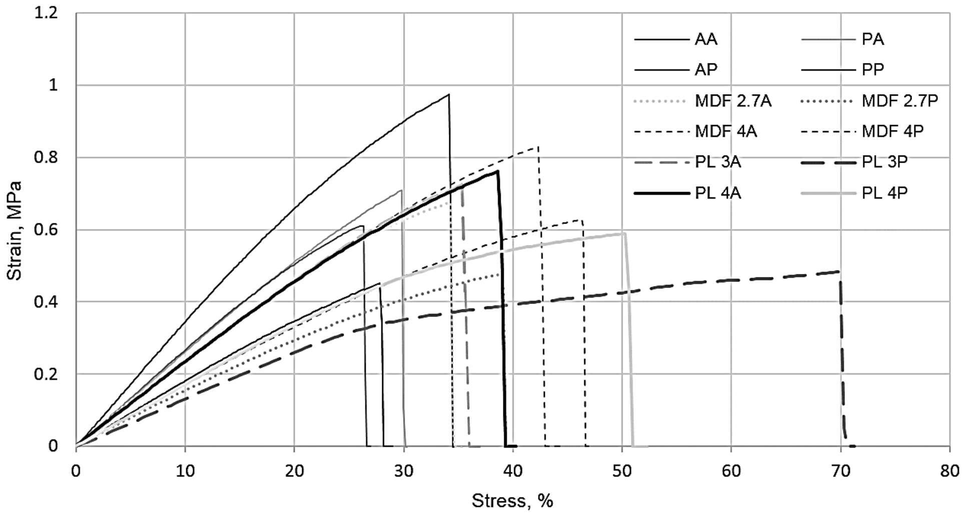


Fig. 8. Stress-strain relationships (in percent of thickness) of 50 mm wide specimens

The relationships presented in Fig. 8 indicate a similar failure mechanism of the specimens across all series and all conducted experiments.

Conclusions

The present study shows changes in shape, bending strength, and modulus of elasticity of three-layer elements with cores made from laminated particleboard cutting waste, when laminated with materials of varying types and characteristics. A polyvinyl acetate dispersion adhesive was used. The lamination was carried out on a hydraulic press at a temperature of 50°C and a specific pressure of 0.075 MPa.

It was established that the produced elements are anisotropic, and that the values of bending strength and modulus of elasticity are within the standardized limits for engineered wood panels. It was also determined that the type and mechanical properties of the laminating sheets significantly influence the dimensional stability and mechanical performance of the manufactured elements.

Compared to similar elements laminated with HPL, an increased dimensional stability was observed.

Compared to factory-produced particleboard with a thickness of 25 mm, the bending strength varied between -11% and +94%, while the modulus of elasticity ranged from -43% to +30%.

When laminated with MDF, the thickness of the cladding sheet influences the values of the evaluated parameters.

When using one-sided veneered MDF for lamination, it is recommended that the veneer be oriented perpendicular to the length of the core details.

To achieve improved performance, it is recommended that, when laminating with three-layer poplar plywood, the wood grain in the face veneer be oriented parallel to the core details.

It can be concluded that the developed schemes and technologies have potential for effective application in the production of small- to medium-sized structural elements for furniture across various price ranges.

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