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Utilization of Scots Pine (*Pinus sylvestris* L.) Timber with Defects in Production of Engineered Wood Products

Iskorištavanje borovine (*Pinus sylvestris* L.) s greškama za proizvodnju kompozitnog drva

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ABSTRACT • *This study presents opportunities for the utilization of timber by-products with defects for manufacturing engineered wood panels. Three gluing methods were proposed for this waste raw material derived from Scots pine (Pinus sylvestris L.) wood. The methods used for combining and gluing enabled a more complete and complex utilization of wood with defects. The physical properties (density and moisture content) and mechanical properties (bending strength and modulus of elasticity) of the laboratory-fabricated engineered wood panels were evaluated in accordance with the European standards. The highest density of 643 kg/m³ and bending strength values (28.6 N/mm²) were obtained from the panels manufactured using method 3 and veneered with beech veneer sheets. The modulus of elasticity of the laboratory-made engineered wood panels reached values of up to 5580 N/mm². This study demonstrated the feasibility of the utilization of defective wood pieces in the manufacturing of engineered wood panels.*

KEYWORDS: *Pinus sylvestris L.; engineered wood; knots; cross-laminated timber (CLT); solid wood panels*

SAŽETAK • *U radu je predstavljena mogućnost iskorištavanja otpadnog drva s greškama za proizvodnju kompozitnog drva u graditeljstvu. Predložene su tri metode lijepljenja otpadnog drva borovine (Pinus sylvestris L.). Metode kombiniranja i lijepljenja omogućile su potpunije iskorištavanje drva s greškama. Fizička svojstva (gustoća i sadržaj vode) i mehanička svojstva (čvrstoća na savijanje i modul elastičnosti) laboratorijski proizvedenih kompozitnih drvnih ploča za graditeljstvo ocijenjena su prema europskim standardima. Najveću gustoću (643 kg/m³) i čvrstoću na savijanje (28,6 N/mm²) imale su ploče proizvedene metodom 3 i furnirane bukovim furnirom. Modul elastičnosti laboratorijski proizvedenih kompozitnih drvnih ploča za graditeljstvo dosegnuo je vrijednost od 5580 N/mm². Ovo je istraživanje uputilo na mogućnost iskorištavanja drva s greškama za proizvodnju kompozitnih drvnih ploča namijenjenih graditeljstvu.*

KLJUČNE RIJEČI: *Pinus sylvestris L.; građevno drvo; kvrge; križno lamelirano drvo (CLT); masivne drvne ploče*

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1 INTRODUCTION
1. UVOD

The demand for various types of wood to meet consumer demands is constantly increasing. Estimates indicate that the supply of large construction timber in Bulgaria will become increasingly scarce in the coming decades (Kostov, 1993; Kostov, 2009). This trend is also observed in other countries around the world (Warde, 2006; Nazir *et al.*, 2018; Alberdi *et al.*, 2020; Odppes *et al.*, 2021). This is due to the increased logging intensity in forests, which has resulted in a significant reduction in forest areas. All of these result in a reduction in the diameter of the round wood, as well as substantial difficulties in manufacturing finished products of the desired size and quality. This, in turn, necessitates the search for methods and technologies for more rational utilization of wood resources.

Scots pine (*Pinus sylvestris* L.) is one of the most commercially important tree species used in the Bulgarian wood and wood-based industry for a wide variety of value-added applications. The exploitation characteristics of Scots pine wood have been extensively studied and are well known (Trichkov, 2016; Trichkov, 2018). This wood is widely used in construction for construction materials, fasteners, formwork panels; for the interior furnishings of residential and public buildings; for the production of furniture, flooring, paneling and joinery; in the construction of railway lines and in mining; in the chemical and pharmaceutical industry; in shipbuilding and aircraft construction. The wide application of Scots pine wood is also due to its physical, mechanical, technological, operational and aesthetic qualities. It is relatively light and has high strength indicators. It is processed without difficulty and is highly durable (Mederski *et al.*, 2015; Mclean, 2019; Burawska-Kupniewska *et al.*, 2020).

In terms of industrial wood use, the distribution of round wood according to diameter should be emphasized. Recent data from the Bulgarian Executive Forest Agency (2020), given in Table 1, show that the areas afforested with Scots pine in the country have decreased over time.

During the period 2015-2020, the total stock increased by 2.6 million m^3, primarily in plantations that have reached logging maturity, which is over 100 years. It should be noted that the majority of these forests are located in protected areas with very limited wood harvesting.

With the intensive reduction of forest stand diameter, more and more rational wood utilization is required. There are low quantitative and qualitative yields in the processing of thin logs in terms of size and quality characteristics (Heräjärvi, 2004; Campbell, 2013). The use of thin logs in the production of engineered wood products results in a significant loss of wood in the form of large and small waste, especially when multiple knots are present. The method of gluing quality wood after removing its flaws provides excellent opportunities for utilizing low-quality and thin round wood (Barbour *et al.,* 2003; Hernandez *et al.*, 2005; Lyhykainen *et al.,* 2009).

The size and number of knots in the wood have a significant impact on its physical and mechanical properties (As *et al.,* 2006; Koman *et al.*, 2013; Montero *et al.,* 2015; Burdarov, 2019; Kaiser, 2019; Wright *et al.,* 2019). The presence of many defects in the wood, particularly wood knots, significantly reduces the final quantitative yields in the production of engineered wood products. The percentage of defects in the wood is most noticeable in small-diameter logs (Koynov, 2016; Trichkov *et al.*, 2018).

To address the global shortage of wood raw materials, efforts are being made in several areas, including the search for new, alternative raw material sources, optimized use of wood and other lignocellulosic raw materials, reduction of wood waste generated during processing, recycling and upcycling of wood and wood-based materials, and efficient utilization of wood waste and by-products in various value-added industrial applications (Antov *et al.,* 2018; Antov and Savov, 2019; Neykov *et al.,* 2020; Lee *et al.,* 2022; Pędzik *et al.,* 2022).

Table 1 Distribution of afforested area (ha) and stock (m^3) of Scots pine in Bulgaria by age classes for 2015/2020 (Executive Forest Agency 2015/2020)
Tablica 1. Raspodjela pošumljene površine (ha) i zalihe bijelog bora (m^3) prema dobnim razredima za 2015. i 2020. godinu (Executive Forest Agency 2015./2020.)

Pinus sylvestris L.	**Distribution by age classes (by years), thousand ha** / *Raspodjela po dobnim razredima (po godinama), tisuće* ha								
	Total *Ukupno*	1-20	21-40	41-60	61-80	81-100	101-120	121-140	Over / *Više od* 140
2015	553.6	50.1	215.5	132.5	51.9	61.4	33.9	7.2	1.1
2020	534.2	29.6	148.9	191.6	49.4	57.1	44.9	11.0	1.7
Pinus sylvestris L.	**Distribution by age classes (by years), million m^3** / *Raspodjela po dobnim razredima (po godinama), milijuni* m^3								
2015	143.9	4.1	50.7	39.3	15.3	20.7	11.4	2.1	0.3
2020	146.5	1.9	34.4	58.1	14.8	19.0	15.0	2.9	0.4

According to industrial data, the final quantitative yields in the production of engineered wood range between 25 % and 30 % of the volume of logs. In the processing of solid wood materials for the production of engineered wood, quantitative yields reach 30-35 %. If the solid wood materials are obtained from thin logs, this percentage is significantly decreased. The remaining wood (65-70 %) in the form of large and small waste and by-products with knots, shavings, sawdust, etc., is used as raw material for manufacturing pellets, technological chips or burned for energy. Thus, the valorization of timber waste and by-products in the production of value-added products, including engineered wood, represents an efficient way to achieve sustainable resource management.

Several techniques for bonding small pieces of solid wood and fabricating products with enhanced mechanical properties have been developed (Nairn, 2017; Nazerian *at al.,* 2018). The lack of information on other commercial applications of large waste obtained in the production of engineered wood, aside from those mentioned above, makes it impossible to make an objective assessment of their complex recovery. This justifies the need of conducting extensive studies aimed at establishing more efficient ways of waste wood utilization in the production of finished products to replace conventional materials in the furniture industry. Therefore, the aim of this research work was to investigate the feasibility of using Scots pine timber with defects in manufacturing engineered wood panels. Different gluing methods and their effects on the physical and mechanical properties of the panels were also investigated.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Large-sized timber with various defects (knots, resin pocked, bark pocked, slop of grain, etc.) was used in this study (EN 844, 2019). These wood by-products were referred to as “waste pieces.” They were obtained from Scots pine (*Pinus sylvestris* L.) wood during the industrial production of engineered wood products at the “SREDNA GORA AD” company (Stara Zagora, Bulgaria). The by-products were sorted after determining their dimensional characteristics. Three different methods for bonding these waste raw materials and producing solid wood panels were proposed in this study. The obtained physical and mechanical properties of the products were determined.

A graphical representation of the different methods used for gluing waste pieces generated during the manufacturing of engineered wood and their assembly into the final product, i.e. glued solid wood panels, is presented in Figure 1. The length of the waste pieces was primarily determined by the size and number of knots in the wood. Waste pieces had cross-sectional dimensions of 40 mm × 140 mm. Their length ranged from 114 to 125 mm. The moisture content found in the experimental wood after conditioning was 7-8 %. This value also corresponds to the moisture content of the materials for the production of engineered wood after drying and subsequent conditioning.

In the process of sawing, respectively removing the high-quality from the low-quality wood, an insignificant amount of wood dust was found on the waste pieces with defects. However, the test wood was cleaned of wood dust before being glued. In this way, quality bonding between the individual elements was ensured.

Timber by-products with defects were obtained by cutting lamellas of the same dimensions. This ensures that the waste pieces have the same cross-sectional dimensions but different lengths. To manufacture the final product, they were first glued together by smoothing (Figure 1-1), to get a lamella of the desired length. Following the formation of lamellas of the required length, they were glued on the edges to form a

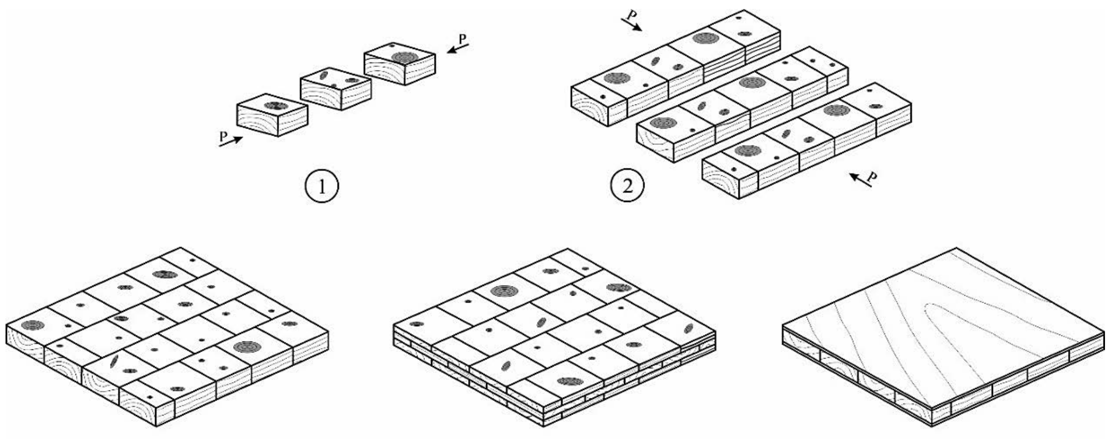

Figure 1 Bonding of Scots pine timber by-products obtained in production of engineered wood
Slika 1. Lijepljenje nusproizvoda od borovine dobivenih u proizvodnji kompozitnog drva za graditeljstvo

Figure 2 Laboratory panels made from Scots pine timber by-products
Slika 2. Laboratorijske ploče proizvedene od nusproizvoda borovine

solid wood panel, according to the presented methodology (Figure 1-2). Test specimens were cold-pressed at a pressure of 0.9 MPa in laboratory conditions. Fast drying PVAc glue was used in this study. Splicing of the waste pieces lengthwise to form lamellas, as well as the widthwise gluing of the resulting lamellas, was carried out using a laboratory hydraulic press.

Three methods of gluing the waste pieces were proposed in this paper. In method 1, solid wood panels were formed, with the resulting lamellas glued only along the edge to form panels with the desired width. Method 2 produced three-layer solid wood panels with mutually perpendicular wood fiber arrangements. They are similar to CLT (cross laminated timber- EN 16351, 2021). Method 3 yields a bonded panel of waste pieces, which is used as a middle layer in the manufacture of veneered panels. This avoids the negative impact of defects on the aesthetic and mechanical properties of the final product.

Polyvinyl acetate (PVAc) adhesive Jowacoll 103.06 produced by Jowat was applied, while the amount of applied glue was 200-220 g/m^2. The time required to cure the test specimens was 3 hours. PVA is a fast-setting wood adhesive, suitable for cold and hot bonding of wood products with high adhesive ability of 450 N/mm^2. The combination and gluing of the manufactured elements were achieved with laboratory clamps and presses.

Depending on the performance, quick-setting and other two-component adhesives can be used (Lubis *et al.,* 2022; Savov *et al.,* 2022). The pressing pressure applied was 0.1 - 0.2 MPa. The finished panel dimensions were 650 mm × 650 mm × 38 mm. In method 3, European beech (*Fagus sylvatica* L.) wood veneers with a thickness of 1.1 mm were used. In Method 4, the specimens were tested only in the direction along the grain of the outer veneer sheets. The aim was to find out what effect the application of a beech wood veneer with the thickness of only 1.1 mm would have on the strength of the final product. In the intermediate/inner layer, the direction of the wood grains is as in Method 1 (┴). When testing several specimens in a direction perpendicular to the wood grain of the beech face veneer, the values did not differ significantly from those of Method 1 (II). Splitting occurs in the face veneer sheet under perpendicular loading. Figure 2 depicts the panels made from waste pieces in this study.

The produced engineered wood panels were conditioned until a constant mass was reached prior to physical and mechanical properties evaluation. For physical properties, density and water content of the panels were determined in accordance with BDS EN 323: 2001 and BDS EN 326-1: 2001.

The purpose of the density test was to investigate the effect of the knots and amount of glue on the density of the final product.

The mechanical properties were evaluated at the facilities of the University of Forestry, Sofia. A universal testing machine HECKERT FP 10/1 (Germany) with the test range (maximum strength) = 10000 N was used. The modulus of elasticity in static bending, as well as the bending strength parallel and perpendicular to the grain, was evaluated based on BDS EN 408 + A1: 2012. The deflection to complete destruction of the experimental wood was also observed.

The obtained data were processed using a T-test. The results were compared with values from tests of solid natural Scots pine wood, with the presence of knots (Mirski *et al.,* 2020a; Mirski *et al.,* 2020b; Wieruszewski *et al.,* 2022).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Physical properties of engineered wood panels
3.1. Fizička svojstva kompozitnih drvnih ploča za graditeljstvo

The moisture content of the engineered wood panels, fabricated from Scots pine timber pieces with defects varied from 8 % to 10 %. The values obtained for the density of the panels produced using the different methods are given in Table 2.

The average density of the panels obtained by method 1 was 581 kg/m^3. According to published data, the density of Scots pine wood is approximately 520

Table 2 Density of panel made using different methods
Tablica 2. Gustoća ploča proizvedenih različitim metodama

Type of panel *Vrsta ploče*	Method 1 *Metoda 1*	Method 2 *Metoda 2*	Method 3 *Metoda 3*
Density *Gustoća*	581 kg/m^3	607 kg/m^3	643 kg/m^3

kg/m³ (Aleinikovas and Grigaliūnas, 2006; Bluskova, 2009; Montero *et al.,* 2011; Konofalska *et al.,* 2021; Roszyk *et al.,* 2020). The 11.7 % increase in density was attributed to the presence of a large number of knots with large diameters and higher density in the experimental wood. In method 2, the average density of the panels was 607 kg/m³. The increment in density was due to the fact that the three-layer glued solid wood panel contained a high concentration of knots. The panels obtained by method 3 exhibited the highest density value of 643 kg/m³, mainly due to the presence of a large number of knots and adhesive used to bond beech veneers on the face and back of the panels.

3.2 Mechanical properties of engineered wood panels
3.2. Mehanička svojstva kompozitnih drvnih ploča za graditeljstvo

The results obtained for the bending strength of the panels fabricated by the different methods are presented in Figure 3. The panels obtained by method 1 were tested in two directions: perpendicular to the grain (┴) and parallel to the grain (II).

Bending strength of the panels made by method 1, in direction perpendicular to the grain, ranged from 4.1 N/mm² to 5.6 N/mm², with an average value of 4.9 N/mm². It was observed that none of the tested specimens were destroyed in the adhesive joint area, but rather in the wood or at places with numerous defects. On the other hand, bending strength, in direction parallel to the grain of the panels, produced by method 1, ranged between 7.5 N/mm² and 10.6 N/mm², with an average value of 8.8 N/mm². The majority of test specimens were destroyed in the defective areas rather than at the adhesive joint site. The test specimens were destroyed in areas with numerous defects such as rotten knots, fibre twisting, oblique layering, etc.

Table 3 Statistical data of bending strength values of engineered wood panels produced in this research
Tablica 3. Statistički podatci o vrijednostima čvrstoće na savijanje proizvedenih kompozitnih drvnih ploča za graditeljstvo

	Bending strength / *Čvrstoća na savijanje,* N/mm²				
Type of panel *Vrsta ploče*	$\bar{x}$	S_x^2	S_x	m_x	p_x
Method 1 (┴) *metoda 1* (┴)	4.9	0.233	0.483	0.171	3.5
Method 1 (II) *metoda 1* (II)	8.8	1.161	1.077	0.381	4.3
Method 2 *metoda 2*	15.2	30.671	5.538	1.958	12.9
Method 3 *metoda 3*	28.6	1.738	1.318	0.466	1.6

Bending strength of the panels, produced by method 2, varied in the range from 9.1 N/mm² to 22.2 N/mm², with an average value of 15.2 N/mm². The obtained values for bending strength and modulus of elasticity for this type of panels are significantly lower (≈ 30-40 %) compared to the literature data as well as to standard EN 16351:2021 (Buck *et al.,* 2016; Sikora *et al.,* 2016; Mohd Yusof *et al.,* 2019). This lowering of the mechanical indicators is due to the fact that in the examined panels there is a large number of cut pieces, due to their size, the absence of finger joints, and also the presence of numerous defects. The density of the boards obtained by method 2 is very close to that of CLT, despite the presence of a large number of knots in the wood. Panels fabricated by method 3 exhibited the highest bending strength values, ranging from 27.0 N/mm² to 30.1 N/mm², with an average bending strength of 28.6 N/mm².

Bending strength values were calculated with an accuracy index of p_x (Table 3). For panels made by using method 1 (┴, II) and method 3, p_x was less than 5

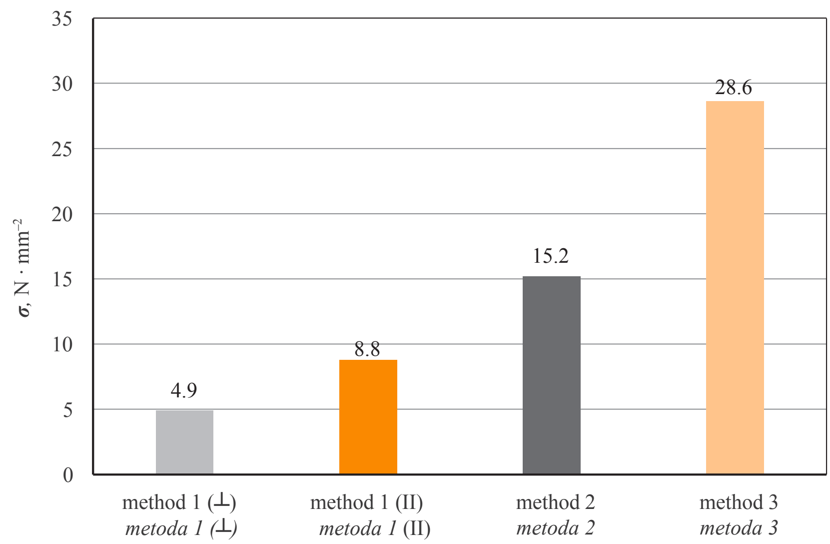

Figure 3 Bending strength of laboratory panels fabricated from Scots pine timber by-products
Slika 3. Čvrstoća na savijanje laboratorijskih ploča proizvedenih od nusproizvoda borovine

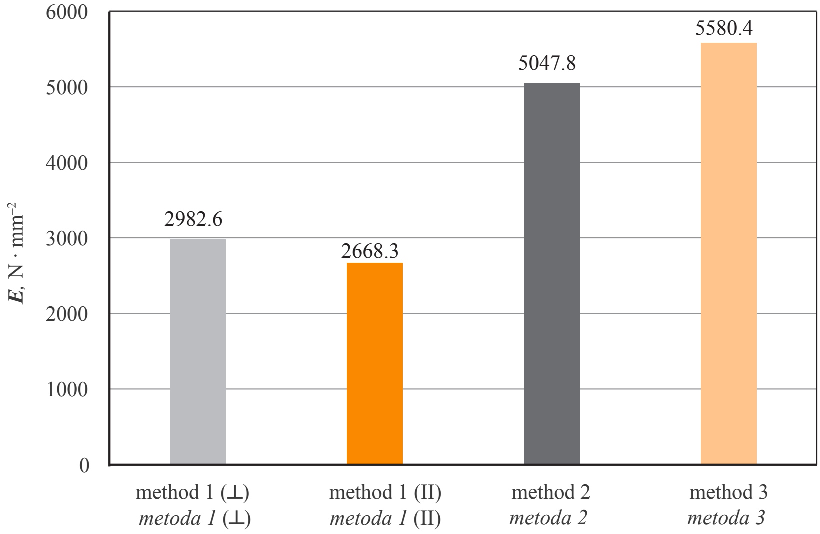

Figure 4 Modulus of elasticity (E, N/mm^2) of laboratory panels fabricated from Scots pine timber by-products
Slika 4. Modul elastičnosti (E, N/mm^2) laboratorijskih ploča proizvedenih od nusproizvoda borovine

%, i.e. the results obtained were statistically significant. With regards to the panels fabricated by method 2, a large scatter relative to the mean was observed (p_x = 12.9 %). This could be attributed to the three layers of thickness, as well as splicing in the width of the waste pieces. This was done with spliced lengths that were randomly overlapped.

A graphical representation of the results obtained for the modulus of elasticity and deflection of the engineered wood panels, fabricated in this research, is presented in Figure 4 and Figure 5.

According to the data presented in Figures 4 and 5, the modulus of elasticity and flexural strength are directly related. According to method 1 (⊥), the experimental wood was destroyed when the deflection reached 4.3 mm at a limit value of 354 N. Method 1 (II) test specimens were destroyed at a limit value of 758 N and deflected of 7.1 mm. The results of methods 2 and 3 for the destruction of test specimens were 1233 and 2659 N, respectively. Methods 2 and 3 calculated deflection values of 7.2 and 8.4 mm, respectively.

After conducting a *T*-test, it was found that for the modulus of elasticity (E) and bending strength (σ), method 1 (⊥) and method 1 (II), there is a statistically significant difference between the values. Accordingly, p-value = 0.026. Therefore, the direction of testing has an influence on the modulus of elasticity. This is also true for bending strength, p-value = 0.000006. In meth-

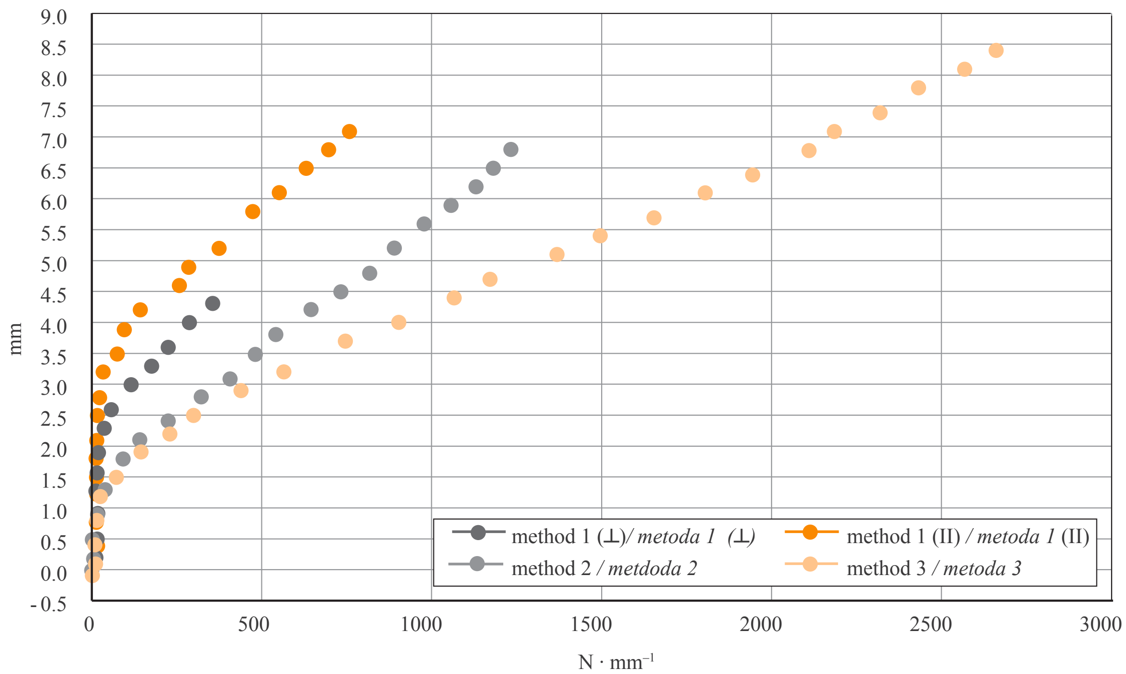

Figure 5 Deflection of test specimen until complete destruction (N/mm)
Slika 5. Otklon ispitnog uzorka do potpunog pucanja (N/mm)

od 2 and method 3, there is no difference in modulus of elasticity (E, p-value = 0.035), but there is a difference in bending strength (σ, p-value = 0.000172).

4 CONCLUSIONS
4. ZAKLJUČAK

The present study has a significant potential for future research, as industrial practice produces a huge amount of waste wood in the form of large pieces.

The possibilities of using three gluing methods in the production of engineered wood panels from Scots pine timber by-products with defects were demonstrated in this research. The method involving veneering of the panel surfaces demonstrated the best mechanical properties. A promising alternative use for this wood waste is also to assemble the defective wood pieces into a CLT-like structure. There is a significant amount of wood loss, varying from 65 % to 70 % in the production of engineered wood, in the form of sawdust, shavings, small and large residues. The rationale for using the described methods of manufacturing engineered wood panels is due to the following: the solid wood materials intended for the production of engineered wood were dried to a final humidity of 8-9 %, which is also the humidity of the waste pieces used; the lamellas were treated with a four-sided planer prior to format cutting, which is a requirement for the same cross-sections of the waste pieces; a technological opportunity is created by the correct geometric shape of the obtained waste pieces, which makes gluing easier by smoothing the end-to-end butt joint. Another technological operation is saved when splicing waste pieces lengthwise. Moreover, the absence of finger joints reduces processing time, wood and adhesive consumption. The factors described above, as they save many technological operations, are a significant prerequisite for the use of this raw material in the production of glued wood products. The determined physical and mechanical properties allow the use of the laboratory-produced panels in the furniture industry and even as a construction material. The bending strength results, ranging from 4.9 to 28.6 N/mm^2, were comparable to some of the most commonly used wood-based panels. In this case, products that can largely replace conventional materials in industry are obtained. These products can be widely used when high mechanical properties are not required, including table tops, partition walls, cladding, door frames, etc. The industrial reuse of timber by-products for manufacturing engineered wood panels with acceptable exploitation properties could greatly contribute to maximize the resource efficiency and enhance the competitiveness of wood industry companies.

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