Eco-Friendly Laminated Strand Lumber from Date Palm Rachis: Analysis of Mechanical Properties by Taguchi Design of Experiment

Ekološki prihvatljiva uslojena drvonitna građa od lisnih osi palme datulje: analiza mehaničkih svojstava *Taguchi* metodom pripreme istraživanja

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ABSTRACT • *This study was performed to use date palm rachis, as a low value bio-waste, in the manufacture of a high value added eco-friendly structural composite lumber. Taguchi design of experiments was applied to analyze the effect of raw material and product parameters on the mechanical properties of laminated strand lumber from date palm rachis. The results indicate that the composite exhibits similar or superior strength properties compared to solid lumber and engineered products from wood or other lignocellulosic material for building sector. Taguchi design of experiments was assessed as a powerful and cost effective technique to obtain optimal levels for maximizing the mechanical properties of the environmentally-friendly composite. Maximum values for the mechanical properties of date palm rachis-based LSL were obtained from a combination of 20 mm product thickness, 10 % resin content, 4mm strand thickness, and 850 kg/m^3 product density. Product thickness with an 81.3 % contribution and strand thickness with an 80 % contribution have the highest effects on the flatwise stiffness and compression strength perpendicular to grain, respectively.*

Keywords: *date palm rachis, structural composite lumber, laminated strand lumber, Taguchi design of experiments, mechanical properties*

SAŽETAK • *Ovo je istraživanje provedeno na konstrukcijskoj kompozitnoj građi proizvedenoj od lisnih osi palme datulje. Te su lisne osi odabrane kao biootpad male vrijednosti da bi se dobila građa visoke dodane vrijednosti. Taguchi metoda pripreme istraživanja primijenjena je kako bi se analizirao utjecaj sirovine i svojstava proizvoda na mehanička svojstva uslojene drvonitne građe (LSL) od lisnih osi palme datulje. Rezultati pokazuju da kompoziti*

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imaju sličnu ili bolju čvrstoću nego masivno drvo i građevinski proizvodi od drva ili od ostalih lignoceluloznih materijala. Taguchi metoda pripreme istraživanja ocijenjena je kao pouzdana i isplativa tehnika za dobivanje optimalnih mehaničkih svojstava ekološki prihvatljivih kompozita. Najveće vrijednosti mehaničkih svojstava LSL-a od lisnih osi palme datulje dobivene su za proizvod debljine 20 mm, sa sadržajem smole od 10 %, debljine vlakana 4 mm i gustoće 850 kg/m^3. Najveći utjecaj na krtost plohe i čvrstoću na tlak imaju debljina proizvoda, s 81,3 %, i debljina vlakana, s 80 % utjecaja.

Ključne riječi: *lisne osi palme datulje, konstrukcijska kompozitna građa, uslojena drvonitna građa, Taguchi metoda pripreme istraživanja, mehanička svojstva*

1 INTRODUCTION
1. UVOD

Laminated strand lumber (LSL) is a structural composite lumber (SCL) consisting of wood strands that are glued, oriented and compressed to form one of the engineered wood products (EWPs). Almost all strands in LSL are typically oriented in on direction (Moses *et al*., 2003). By changing strand orientation, axial and flexural stiffness, and strength properties can be modified for specific applications (Moses *et al*., 2003). This material is used primarily as an alternative to traditional solid sawn lumber and other engineered wood products like laminated veneer lumber and glued laminated timber. Similar to other structural composite lumber, LSL as a relatively new wood-based product is an ideal structural solution for broad range of construction applications including rim board, millwork and window, door and garage door headers, as well as for many industrial uses. New uses for this product are still evolving including the use of LSL for vertical elements of structural frames, where the framing member heights are long and the wind loads are substantial (Wang *et al*., 2015). The quality of raw material extremely affects the properties of LSL. It can be made from less expensive and readily available underutilized timber. Nowadays, traditional strong, dense species like oak, southern pine and Douglas fir are being replaced by low quality, low diameter and less dense species like spruce, European white woods, and aspen. Although these species do not have the strength and stiffness of the above timber, they are light in color, lightweight and stable. In addition, this is an excellent way to maximize the wood fiber resources that are readily available, allowing for a cost-effective product. Faced with the risk of forest extinction and wood shortages, especially in dry and semi-dry regions such as I. R. Iran, and environmental considerations, the use of natural hardwoods, such as beech, alder, hornbeam, has been decreased. On the other hand, agricultural and horticultural residues have an excellent potential for the production of structural and non-structural wood-based composites. These materials are abundant and can be obtained at a very low cost. Date palm (*Phoenix dactylifera* L.) has long been one of the most important fruit crops in the arid regions of the Arabian Peninsula, North Africa, and the Middle East. During the past three centuries, dates were also introduced to new production areas in Australia, India/Pakistan, Mexico, Southern Africa, South America, and the United States. Dates are a main income source and staple food for local populations in many countries, in which they are cultivated, and they have played significant roles in the economy, society, and environment of those countries (Chao and Krueger, 2007). Almost every part of the date palm can be used for different purposes including fiber from the trunk and leaves, dried bundles of leaves, ribs of the leaves, and the base of the leaves and fruit stalks (Nixon, 1951; Dowson and Aten, 1962; Barreveld, 1993; Chao and Krueger, 2007). The date palm residues are usually used to produce traditional and low value products or high value added non-structural products such as hardboard (EI-Morsy 1980) and paper (Khaiari *et al*., 2010). Some of the few studies around the SCLs from solid wood are as follow: Hoover *et al*. (1992) studied the effect of strand orientation on the properties of strand panels. A novel concept of using strands from small-diameter timber to produce engineered composite Laminated Strand Ply (LSP) was presented and demonstrated by Weight (2007). Wang *et al*. (2015) and Ozcifci *et al*. (2010) determined the mechanical properties of laminated strand lumber (LSL), parallel strand lumber (PSL) and laminated veneer lumber (LVL) from aspen poplar, and Wang *et al*. (2016) evaluated the modulus of elasticity of LSL by non-destructive testing. Based on the literature review, there is a lack of information around SCL from horticultural residues. Therefore, the objective of the current study was to develop a type of laminated strand lumber from date palm rachises as an eco-friendly replacement for solid wood lumbers and engineered wood products. Taguchi design of experiments was used to analyze the effects of raw material parameters on the mechanical properties of the product.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Raw material preparation
2.1. Priprema sirovine

The date palm leaves (Figure 1) were collected from date palm plantation around Khalili village, Lamerd County, Fars province, I. R. Iran. The leaves were cleaned of midribs, spines and impurities, and then rachises were trimmed into suitable size in the Laboratory of Wood-Based Products, Department of Wood and Paper Sciences and Technology, Natural Resources Faculty, University of Tehran. The average moisture content and density of the rachises were measured as 9 % and 330 kg/m^3, respectively. Polymeric methylene diphenyl diisocyanate (PMDI) adhesive (Molecular formula C15H10N2O2, Molar Mass 250.25 g/mol, Density 1.230 g/cm^3, Melting point 40 °C, Boiling point 314 °C and Flash Point 212–214 °C)

Figure 1 Different parts of a date palm leaf (Zaid and De Wet, 2002)
Slika 1. Dijelovi lista palme datulje (Zaid and De Wet, 2002.)

was prepared from one of the importing company, Tehran, I. R. Iran.

After cleaning, the rachises were simply trimmed into suitable long strands (450 mm length, 10-30 mm width, and 2 mm and 4 mm nominal thickness) parallel to grain (Figures 2a, b). After preparation, the strands were dried to around 3 % dry based moisture content using a laboratory tray dryer at 103 °C and were kept in sealed plastic bags until billet making.

Figure 2 Strands from date palm rachises: a) single, b) bundle
Slika 2. Vlakna od lisnih osi palme datulje: a) samostalna vlakna, b) snop vlakana

2.2 Design of experiments
2.2. Planiranje pokusa

Based on the number of variables (such as product thickness, resin content, strand thickness and product density) and their levels, a suitable Taguchi orthogonal array (L8 4**1 2**3 design sheet) was chosen for design of experiments (Table 1). Taguchi method is a helpful technique for reducing the number of experiments, which requires understanding the effects of process parameters on product response, besides separating the significant factors affecting the response from less significant factors (Reddy *et al*., 2012). MINITAB 16 statistical software (State College, PA, USA) was used to analyze the experiments.

To follow the design of experiments, a total of 8 laboratory LSL blocks for the eight different combinations were prepared (Table 1).

2.3 Billet preparation
2.3. Priprema blokova

The block characteristics and constant parameters for making date palm rachis-based laminated strand lumber (LSL) are presented in Table 1 and 2.

For making the blocks, sufficient amounts of PMDI resin were sprayed onto the prepared strands us-

Table 1 Taguchi design of experiments (L8 4**1 2**4)
Tablica 1. *Taguchi* metoda planiranja pokusa (L8 4**1 2**4)

Run No. *Broj niza*	**Product thickness, mm** *Debljina proizvoda,* mm	**Resin content, %** *Sadržaj smole,* %	**Strand thickness, mm** *Debljina iverja,* mm	**Product target density, kg/m³** *Ciljana gustoća proizvoda,* kg/m³
1	12	8	4	850
2	12	10	2	750
3	16	8	2	750
4	16	10	4	850
5	18	8	2	850
6	18	10	4	750
7	20	8	4	750
8	20	10	2	850

Table 2 Constant parameters for block preparation
Tablica 2. Konstantni parametri za pripremu blokova

Parameter / *Parametar*	**Type and value** / *Vrsta i vrijednost*
Resin / *smola*	Polymeric methylene diphenyl diisocyanate (PMDI)
Billet / *blok*	Homogenous laminated strand lumber *homogena uslojena drvonitna građa*
Additive / *dodatak*	-
Dimension / *dimenzija,* mm	450 × 450
Pressing pressure / *tlak prešanja,* kg/cm²	40
Pressing temperature / *temperatura prešanja,* °C	170
Pressing time / *vrijeme prešanja,* s	540

ing a laboratory rotary drum blender consisting of an internal spray nozzle. Then, the glued strands were manually formed into mats (all strands oriented in one direction) using a man-made frame. All the mats were pressed by a hydraulic hot press, BÜRKLE, Germany, under constant pressing parameters (Table 2).

2.4 Block characterization
2.4. Karakterizacija blokova

For characterization, all the blocks were kept in a conditioning chamber at 20 °C and 65 % RH for two weeks, according to ASTM D1037 (2003). After conditioning, the blocks were cut into standard test specimens (Figure 3) and returned into the chamber to retain standard equilibrium moisture content until physical and mechanical experiments.

Characteristics of moisture content and density were measured based on ASTM D1037 (2003). Three-point static bending strength (F_b) and stiffness (E) were measured in accordance with ASTM D 5456 (2003). Compression strength (F_c) parallel and perpendicular to grain were measured according to ASTM D 198 (2003) and ASTM D 143 (2003), respectively. Shear strength (F_v) parallel to grain was measured in accordance with ASTM D 143 (2003).

2.5 Analysis of variance
2.5. Analiza varijance

Taguchi design of experiments was used for the analysis of variance. This method uses signal to noise ratio (S/N ratio) instead of the average value to interpret the trial results data into a value for the evaluation characteristic in the optimum setting analysis (Phadke 1989; Ross 1996). In Taguchi design of experiments, quality characteristics are classified into three categories: the smaller the better, the nominal the better and the bigger the better. Since, for the mechanical strength, higher values are expected, the bigger the better S/N ratio was applied in the analysis, which can be calculated using Eq. 1:

$$S/N = -10\log_{10}\left[(1/n)\cdot\sum(1/y_i^2)\right] \qquad (1)$$

Where y is the measured data and n is the number of trial (Mizamzul Mehat *et al*., 2011). The analysis of variance (ANOVA) establishes the relative significance of factors in terms of their percentage contribution to the response (Phadke, 1989; Ross, 1996). ANOVA analysis is also needed for estimating the variance of error for the effects and confidence interval of the prediction error. This analysis is performed on S/N ratio to obtain the percentage contribution of each factor (Gaitonde *et al*., 2007).

Figure 3 Examples of test specimens from date palm rachis-based LSL blocks
Slika 3. Primjeri ispitnih uzoraka LSL blokova od lisnih osi palme datulje

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Predicted versus experimental results for mechanical properties is shown in Table 3. Note that adjusted values were used to remove the variation in the properties caused by sample density tolerance (Xing *et al*., 2007). Average relative error between the measured and predicted values for the mechanical properties was 2.33 %. From the results, it can be concluded that Taguchi method can satisfactorily predict the mechanical properties of rachis-based LSL (Table 3).

The comparison of specific mechanical properties of LSL from date palm rachis, lumber from solid wood and some structural composite lumber is shown in Table 4.

For rachis-based LSL, average specific bending strength (164.75 MPa) is approximately the same as the average value for clear wood (168.74 MPa) and is higher than that of structural composite lumber (around

Table 3 Comparison of measured and predicted values for mechanical properties of rachis-based LSL
Tablica 3. Usporedba izmjerenih i predviđenih vrijednosti mehaničkih svojstava LSL-a na osnovi lisnih osi palme datulje

Run No. *Broj niza*	F_b (MPa)				E (GPa)				F_c (MPa)				F_v ∥ (MPa)	
	Flat / *Ploha*		**Edge** / *Rub*		**Flat** / *Ploha*		**Edge** / *Rub*		∥		⊥			
	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.
1	117	142	51	59	32.1	25.7	7.63	6.7	28	27	1.5	1.49	3.7	4.25
2	137	112	52	43	24.6	19.6	7.44	8.4	20	21	0.64	0.70	3.82	3.26
3	111	136	58	67	20	16	7	6	27	26	0.53	0.46	3.79	4.34
4	171	146	105	96	25.7	21.8	9.3	10.2	45	46	1.2	1.24	6.1	5.54
5	94	68	61	53	14.1	12.9	5.8	6.73	35	37	0.86	0.92	4.96	4.40
6	113	138	76	82	15.1	15.4	7.5	6.6	49	48	2	1.94	4.84	5.4
7	221	196	104	95	19.8	16.9	9.2	10.1	36	37	1.55	1.61	6.23	5.67
8	80	105	71	80	16.8	14	17.1	16.2	41	40	0.64	0.58	4.37	4.92

F_b – bending strength / *čvrstoća na savijanje*; E – modulus of elasticity / *modul elastičnosti*; F_c – compression strength / *čvrstoća na tlak;* F_v – shear strength / *smična čvrstoća*

Table 4 Bending strength, bending stiffness and compression strength for different wood-based structural materials
Tablica 4. Čvrstoća na savijanje, krutost na savijanje i čvrstoća na tlak za različite konstrukcijske materijale na bazi drva

Material / *Materijal*	**Reference** *Referenca*	**Mechanical properties (specific value*)** *Mehanička svojstva (specifične vrijednosti*)*		
		F_b, MPa	E, GPa	F_c ∥, MPa
Clear wood / *drvo*				
White oak / *bijeli hrast*	(Cai and Ross, 2010)	154.12	18.05	-
Red maple / *crveni javor*	(Cai and Ross, 2010)	171.09	20.95	-
Douglas-fir (Coastal) / *američka duglazija (Coastal)*	(Cai and Ross, 2010)	178.1	28	-
Western white pine / *zapadnoamerički bijeli bor*	(Cai and Ross, 2010)	176	26.5	-
Longleaf pine / *dugoiglični bor*	(Cai and Ross, 2010)	169.5	23.14	-
Spruce (*Picea abies*) / *smreka (Picea abies)*	(Malanit *et al.*, 2011)	163.64	19.32	-
Structural composite lumber *Konstrukcijska kompozitna građa*				
Glulam / *lijepljeno lamelirano drvo*	(Cai and Ross, 2010)	71.52-104.37	22.5-24.17	-
LVL	(Cai and Ross, 2010)	84.45-123.11	27.4-27.49	-
LVL	(Ozcifci *et al.*, 2010)	161.27	19.768	124.67
PSL	(Ozcifci *et al.*, 2010)	136.87	17.874	99.66
LSL	(Ozcifci *et al.*, 2010)	123.66	16.045	83.82
Bamboo-based OSL**	(Malanit *et al.*,. 2011)	82.24	13.81	-
Date palm rachis-based LSL (number of treatment) / *LSL na bazi lisnih osi palme datulje (broj tretmana)*				
1		135.83	37.794	29.80
2		182.59	32.794	30.86
3		147.46	26.645	32.46
4		201.08	30.199	56.65
5		110.08	16.588	44.49
6		150.96	20.157	61.80
7		295.90	26.094	51.55
8		94.09	19.824	44.71

*Properties divided by specific gravity; **oriented strand lumber / **Svojstva podijeljena prema specifičnoj težini; **građa s usmjerenim iverjem*; F_b – bending strength / *čvrstoća na savijanje*; E – modulus of elasticity / *modul elastičnosti*; F_c – compression strength / *čvrstoća na tlak*

1.42 times). Furthermore, average specific stiffness for rachis-based LSL is approximately 17 % and 33 % higher than that of clear wood and structural composite lumber, respectively. Comparing the maximum values for the materials, specific bending strength for treatment No. 7 is approximately 66 % and 140 % higher than that of Douglas-fir and medium density laminated veneer lumber, respectively. In addition, specific stiffness for treatment No.1 is approximately 35 % and 37 % higher than that of Douglas-fir and medium density laminated veneer lumber, respectively (Table 4). From the specific bending strength and stiffness values presented in Table 4, it can be deduced that the rachis-based LSL is an appropriate alternative to clear wood and structural composite lumber for structural purposes (Cai and Ross, 2010; Ozcifci *et al*., 2010; Malanit *et al*., 2011).

The highest specific compression strength parallel to grain value was obtained in treatment No. 6 as 61.80 N/mm^2, which is lower than that of LVL, PSL, and LSL from poplar wood, being 102 %, 61 %, and 36 %, respectively. It may be due to lower maximum crushing strength of date palm rachis strand than that of solid wood strand, and penetration of resin into more porous structure of date palm rachis than that of solid wood. On the other hand, the structure of samples and

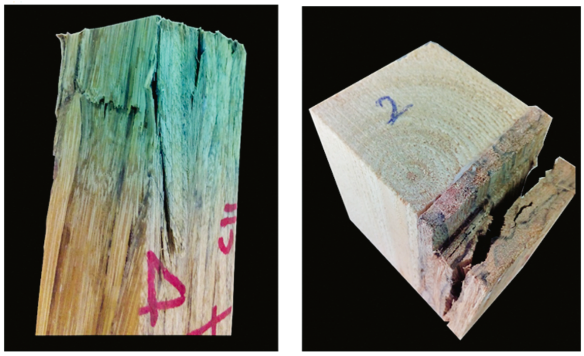

Figure 4 Fracture modes for test specimens: Compression strength parallel to grain (left), shear strength parallel to grain (right)
Slika 4. Načini loma ispitivanih uzoraka: čvrstoća na tlak paralelno s vlakancima (lijevo), smična čvrstoća paralelno s vlakancima (desno)

test conditions were different. Fracture modes of test specimens in compression and shear strengths parallel to grain are shown in Figure 4.

S/N ratio values for parameters and delta values are shown in Table 6 and 5, respectively. The highest S/N ratio indicated the optimal combination of the parameters. S/N ratio also showed the importance of the order of parameters.

Table 5 Results of delta value for all mechanical properties
Tablica 5. Rezultati delta-vrijednosti za sva mehanička svojstva

Parameter *Parametar*	F_b		E		F_c		F_v ‖
	Flat / *Ploha*	**Edge** / *Rub*	**Flat** / *Ploha*	**Edge** / *Rub*	‖	⊥	
Product thickness / *debljina proizvoda*	2.5	4.4	5.7	5.5	4.8	4.4	2.8
Resin content / *sadržaj smole*	0.5	0.8	0.2	2.5	1.3	0.2	0.3
Strand thickness / *debljina iverja*	3.2	2.4	1.6	2.2	2.2	7.4	1.7
Product density / *gustoća proizvoda*	2.0	0.02	0.6	1.4	1.4	0.08	0.2

F_b – bending strength / *čvrstoća na savijanje*; E – modulus of elasticity / *modul elastičnosti*; F_c – compression strength / *čvrstoća na tlak;* F_v – shear strength / *smična čvrstoća*

Ranking of the parameters was determined by comparison of delta values (Table 5). The delta value is equal to the difference between maximum and minimum values for each parameter level (Hamzacebi, 2016). Table 5 shows that the order of importance in maximizing the mechanical properties of the specimens is as follow: For flatwise bending strength, strand thickness, followed by product thickness, product density and resin content. For edgewise bending strength and shear strength parallel to grain, product thickness, followed by strand thickness, product density and resin content. For flatwise stiffness and compression strength parallel to grain, product thickness, followed by strand thickness, product density and resin content. For edgewise MOE, product thickness, followed by resin content, strand thickness and product density, and for compression strength perpendicular to grain, strand thickness, followed by product thickness, resin content and product density.

Based on "the bigger the better" issue, Table 6 shows the optimal parameter levels for mechanical properties of rachis-based LSL. As concluded from the table, the forth level of product thickness (20 mm), and the second levels of resin content (10 %), strand thickness (4 mm) and product density (850 kg/m^3) were the optimal values for maximizing shear and compression strength parallel to grain and edgewise bending strength. The optimal values for other mechanical properties were as follow: for flatwise bending strength, the second levels of product thickness (16 mm) and strand thickness (4 mm), and the first levels of resin content (8 %) and product density (750 kg/m^3). For flatwise stiffness, the first levels of product thickness (12 mm) and resin content (8 %), and the second levels of strand thickness (4 mm) and product density (850 kg/m^3). For compression strength parallel to grain, the third level of product thickness (18 mm) and the second levels of resin content (10 %), strand thickness (4 mm) and product density (850 kg/m^3), and for compression strength perpendicular to grain, the third level of product thickness (18 mm), second level of strand thickness (4 mm) and the first levels of resin content (8 %) and product density (750 kg/m^3) (Table 6 and Figure 5).

Table 6 shows that the forth level of product thickness (20 mm), and the second levels of resin content (10 %), strand thickness (4 mm) and product density (850 kg/m^3) were the optimal values for maximizing the mechanical properties of date palm rachis-based LSL. Based on the F-value, it should be noted that, while the parameters significantly affect flatwise stiffness at 5 % confidence interval, the effects of product thickness, resin content, strand thickness and product density are not significant on the other mechanical properties (Table 7). The strands used in this study had a constant length of 450 mm and thicknesses of 2 mm and 4 mm with slenderness ratios of 225 and 112.5, respectively. A model by Simpson (1977) indicated that increasing the slenderness ratio resulted in an initial increase of tensile strength, which then began to level off at higher ratios. Barnes (2001) concluded that, by increasing the L/t ratio, the stress transfer angle be-

Table 6 Optimal parameter levels for mechanical properties
Tablica 6. Optimalne razine parametara mehaničkih svojstava

Parameter *Parametar*	**Level** *Razina*	**Signal to noise ratio** / *Omjer signala i šuma*						
		F_b		E		F_c		F_v ‖
		Flat *Ploha*	**Edge** *Rub*	**Flat** *Ploha*	**Edge** *Rub*	‖	⊥	
Product thickness, mm *debljina proizvoda,* mm	12	42	34.2	88.9	77.5	27.5	-0.03	11.5
	16	42.7	37.8	87.1	78.1	30.9	-2	13.6
	18	40.2	36.5	83.2	76.3	32.3	2.3	13.8
	20	42.4	38.6	85.1	81.9	31.6	-0.03	14.3
Resin content, % *sadržaj smole,* %	8	42.1	36.3	86.2	77.2	29.9	0.18	13.1
	10	41.6	37.2	86	79.7	31.2	-0.07	13.4
Strand thickness, mm *debljina iverja,* mm	2	40.2	35.6	85.3	78.5	29.4	-3.6	12.4
	4	43.4	38	86.9	78.4	31.7	3.7	14.1
Product density, kg/m^3 *gustoća proizvoda,* kg/m^3	750	42.9	36.80	85.8	77.7	29.8	0.09	13.2
	850	40.8	36.82	86.4	79.2	31.3	0.01	13.4

F_b – bending strength / *čvrstoća na savijanje*; E – modulus of elasticity / *modul elastičnosti*; F_c – compression strength / *čvrstoća na tlak;* F_v – shear strength / *smična čvrstoća*

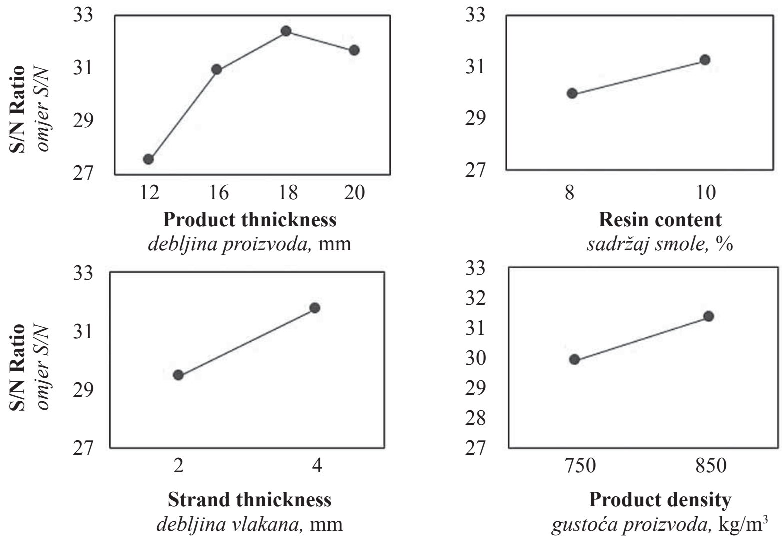

Figure 5 Main effect plot of S/N ratio for compression strength parallel to grain
Slika 5. Prikaz učinka omjera S/N na čvrstoću na tlak u smjeru vlakanaca

tween strands decreased, tending to a more efficient stress transfer between strands. A study by Stoffko (1960) for the ratios ranging from 35-300 showed a similar trend with strength values. On the other hand, another effect of raising the slenderness ratio is that the total surface area of strands is increased. As surface area increases, the amount of resin required to transfer stresses to adjacent strands also increases. Consequently, according to this study, the relationship between the surface area and mechanical properties would be more significant than the effect of stress transfer angle on the mechanical properties, especially since a good bond is required for stress transfer.

The results of ANOVA analysis and the percentage contribution of each parameter on the mechanical properties of rachis-based LSL are shown in Table 7 and 8. Product thickness most highly affected edgewise bending strength, flatwise and edgewise MOE, and compression and shear strengths parallel to grain. In addition, strand thickness had the highest effect on flatwise bending strength and compression strength perpendicular to grain. For flatwise bending strength, the contribution of strand thickness was 34.33 %. The second parameter was product thickness, with a 17.11 % contribution, followed by product density, and resin content, with a contribution of 12.4 % and 1.44 %, respectively. For edgewise bending strength, the contribution of product thickness was 47.4 %. The second parameter was strand thickness (33.38 % contribution), followed by resin content (3.5 %) and product density (0.016 %). For flatwise stiffness, the contribution of product thickness was 81.3 %. The second parameter was strand thickness (13.76 % contribution), followed by product density and resin content, with an influence of 4.3 % and 0.6 %, respectively. For edgewise stiffness, the contribution of product thickness was 58.85 %. The second parameter was resin content (19.97 % contribution), followed by product density (10.86 % contribution) and strand thickness (2.014 % contribution). For compression parallel to grain, the contribution of product density was 54.82 %. Strand thickness (22.55 % contribution) was the second parameter, followed by resin content and product density with an influence of 14.81 % and 6.26 %, respectively. For compression strength perpendicular to grain, the contribution of strand thickness was 80 %. The second pa-

Table 7 Results of ANOVA analysis of effects of parameters on mechanical properties
Tablica 7. Rezultati ANOVA analize utjecaja parametara na mehanička svojstva

S.O.V	DF.	***F*- value** / *F-vrijednost*						
		F_b		E		F_c		$F_{v\parallel}$
		Edge *Rub*	**Flat** *Ploha*	**Edge** *Rub*	**Flat** *Ploha*	∥	⊥	
Product thickness / *debljina proizvoda*	3	0.16^{ns}	0.94^{ns}	27900^{*}	2.4^{ns}	11.9^{ns}	3.8^{ns}	0.4^{ns}
Resin content / sadržaj smole	1	0.04^{ns}	0.17^{ns}	620^{*}	2.4^{ns}	9.6^{ns}	0.0^{ns}	0.01^{ns}
Strand thickness / *debljina vlakana*	1	0.99^{ns}	1.8^{ns}	14180^{*}	0.24^{ns}	14.6^{ns}	55^{ns}	0.8^{ns}
Product density / *gustoća proizvoda*	1	0.36^{ns}	0.0^{ns}	4430^{*}	1.3^{ns}	4.07^{ns}	1^{ns}	0.01^{ns}
Error / *pogreška*	1	-	-	-	-	-	-	-
Total / *ukupno*	7	-	-	-	-	-	-	-

F_b – bending strength / *čvrstoća na savijanje*; E – modulus of elasticity / *modul elastičnosti*; F_c – compression strength / *čvrstoća na tlak;* F_v – shear strength / *smična čvrstoća*; ^{ns} – non significant / ^{ns} – *nije značajno;* * – significant in 5 % confidence interval / * – *značajno s pouzdanošću od 5 %*

Table 8 Results of contribution (%) of parameters on mechanical properties
Tablica 8. Rezultati utjecaja parametara na mehanička svojstava (u postotcima)

Parameter *Parametar*	F_b		E		F_c		$F_{v\parallel}$
	Edge / *Rub*	**Flat** / *Ploha*	**Edge** / *Rub*	**Flat** / *Ploha*	‖	⊥	
Product thickness / *debljina proizvoda*	17.1	47.7	81.3	58.85	54.8	17	38
Resin content / *sadržaj smole*	1.44	3.5	0.6	19.97	14.8	0	0.35
Strand thickness / *debljina vlakana*	34.4	33.4	13.8	2.014	22.6	80	27
Product density / *gustoća proizvoda*	12.4	0.02	4.3	10.86	6.3	1.7	0.35
Error / *pogreška*	34	15.6	0	8.29	1.5	1.2	34
Total / *ukupno*	100	100	100	100	100	100	100

F_b – bending strength / *čvrstoća na savijanje*; E – modulus of elasticity / *modul elastičnosti*; F_c – compression strength / *čvrstoća na tlak; F_v* – shear strength / *smična čvrstoća*

rameter was product thickness (17 %) contribution, followed by product density (1.7 % contribution). The percentage contribution of resin content was zero. Then, for shear strength parallel to grain, the contribution of product thickness was 37.8 %. The second parameter was strand thickness (27.21 % contribution), followed by resin content and product density, both with the same influence of 0.35 % (Table 8).

In Table 8, the error term contains information around three sources of variability in the results such as uncontrollable factors, factors that are not considered in the experiments, and experimental error. As a general rule of thumb, if the contribution of the error term is less than 50 %, this is a good experiment (Li *et al.*, 2013). In this study, the contribution of error (0 %, 1.2 %, 1.54 %, 8.29 %, and 15.6 % for flatwise stiffness, compression strength perpendicular to grain, compression strength parallel to grain, edgewise stiffness, and edgewise bending strength, respectively) was found to be very low (Table 8).

Therefore, it can be concluded that the proposed ANOVA analysis can satisfactorily be used to determine the relative significance of the effect of each factor on the mechanical properties. For flatwise bending strength and shear strength parallel to grain, the contribution of error term is high, but lower than 50 %, showing that the analysis for these two properties is acceptable, as well.

4 CONCLUSIONS
4. ZAKLJUČAK

In this study, the possibility of making date palm rachis-based LSL as an eco-friendly structural composite lumber and the effects of strand thickness, resin content, product density, and product thickness on the mechanical properties of the specimens were investigated using Taguchi design of experiments. Based on the results, it can be concluded that:

Date palm rachis-based LSL can be an appropriate alternative to clear wood-based and structural timber-based green structures.

Taguchi design of experiments is a powerful and cost effective technique to analyze the effects of raw material and product parameters. As a result of L8 orthogonal array, 8 experiments were carried out instead of 96.

Product thickness is the most effective parameter on the mechanical properties, followed by strand thickness.

The forth level of product thickness (20 mm), and the second levels of resin content (10 %), strand thickness (4 mm) and product density (850 kg/m^3) were optimal values for maximizing the mechanical properties of date palm rachis-based LSL.

Product thickness with an 81.3 % contribution and strand thickness with an 80 % contribution have the highest effects on the flatwise stiffness and compression strength perpendicular to grain, respectively.

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