

PLANIRANJE EKSPERIMENTA I MATEMATIČKI MODEL ČVRSTOĆE NA SAVIJANJE PLOČE OD MASIVNOG DRVETA

DESIGN OF EXPERIMENT AND MATHEMATICAL MODEL OF BENDING STRENGTH OF SOLID WOOD PANEL

Nedim Hurem
Damir Hodžić

University of Bihać

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REZIME

Cilj rada je prikazati dovoljno adekvatan i tačan matematički model sile loma ploče od masivnog drveta. U tu svrhu planiran je i urađen eksperiment sa trinaest ponavljanja. Ulazne veličine koje su se varirale na tri nivoa su gustoća drveta i debljina ploče. Pošto centralni kompozitni plan sa trinaest ponavljanja eksperimenta podrazumijeva i četiri ponavljanja na rubnim područjima, uzete su još dvije gustoće drveta i dvije debljine ploče. Sila je mjerena na način da su vlakna ploče paralelna sa smjerom savijanja ploče. Mjerenja su urađena u laboratoriju Tehničkog fakulteta u Bihaću. Signifikantnost koeficijenata modela određena je pomoću softvera R, a rezultati su prikazani pomoću softvera Design Expert.

Original scientific paper

SUMMARY

The aim of this paper is to present a sufficiently adequate and accurate mathematical model of the breaking force of a solid wood panel. For that purpose, an experiment with thirteen repetitions was designed and done. The input sizes that varied on three levels are the density of the wood and the thickness of the solid wood panel. Since the central composite plan with thirteen repetitions of the experiment also includes four repetitions in the marginal areas, two more wood densities and two solid wood panel thicknesses were taken. The force was measured in such a way that the plate fibers were parallel to the bending direction of the plate. The measurements were made in the laboratory of the Technical Faculty in Bihać. The significance of the model coefficients was determined using the R software and the results were presented using the Design Expert software.

1. UVOD

Prednosti masivnih drvnih ploča su: mala težina, velika čvrstoća, laka obrada, atraktivne boje i različite teksture. Ugodne su na dodir, djeluju toplo, dobar su izolator toplote i elektriciteta, imaju dobra akustična svojstva, te velike mogućnosti oblikovanja i dužine elemenata. Veoma značajne prednosti drveta kao materijala zasnivaju se na činjenici da je lako dostupan, ekološki prihvatljiv i obnovljiv materijal. Osim ovih prednosti, drvo ima i svoje nedostatke koje je potrebno upoznati, da bi se uspješno otklonili. To su: greške u drvetu, truhljenje, utjecaj insekata i gljiva, anizotropnost, higroskopnost, zavisnost mehaničkih osobina od sadržaja vode u drvetu, utezanje i bubrenje, te zapaljivost.

1. INTRODUCTION

The advantages of solid wood panels are: low weight, high strength, easy processing, attractive colours and different textures. It is pleasant to the touch, warmly acting, a good insulator of heat and electricity, has good acoustic properties, and great design possibilities and lengths of elements. Significant advantages of wood are based on the fact that it is an easily accessible, environmentally friendly and renewable material. In addition to these advantages, wood also has its disadvantages that need to be addressed in order to successfully eliminate them. These are: wood defects, rot, the influence of insects and fungi, anisotropy, hygroscopy, the dependence of mechanical properties on the water content in wood, shrinkage, swelling and flammability.

Cilj eksperimentalnog istraživanja je ispitati signifikantnost uticajnih parametara masivne drvene ploče, konkretno njene gustoće (ρ) i debljine (d) na njenu čvrstoću na savijanje paralelno s protezanjem drvnih vlaknaca, te analizirati eksperimentalne podatke s aspekta mogućeg postizanja veće čvrstoće na savijanje, a da se pri tom ne ugrozi kvalitet pločastog materijala i da se smanje ukupni troškovi proizvodnje.

Na osnovu eksperimentalnih rezultata, odnosno maksimalne sile savijanja u četiri tačke, shodno standardu BAS EN 789 potrebno je izvršiti modeliranje uticajnih parametara na maksimalnu silu loma (F_{max}), [2,3].

2. PLANIRANJE EKSPERIMENTA

Eksperimentalna istraživanja vezana za ovaj rad bazirana su na mjerenju maksimalne sile naprezanja na savijanje do momenta loma masivne ploče, izrađene u pet različitih debljina i od pet vrsta drveta: smrče, topole, bukve, jasena i hrasta, koji su prethodno obrađeni u čiste obratke i nakon toga izrezane u dimenzije proba shodno standardu BAS EN 789, [4]. Masivne ploče su proizvedene na osnovu dužinskog spajanja čistih obradaka pomoću klinastog spoja u potrebnu dimenziju dužine ploče, a nakon toga su širinski spajane u potrebnu širinu formata masivne ploče. Izrada čistih obradaka, operacija glodanja klinastog spoja, te dužinsko i širinsko spajanje u format ploče je rađeno u „Rosewood“ d.o.o Visoko, kao i izrezivanje potrebnih proba u smjeru protezanja drvnih vlaknaca, odnosno okomito na protezanje drvnih vlaknaca iz formata ploče 1800 (mm) x 1200 (mm) x d (mm). Mjerenje sadržaja vlage, određivanje gustoće drveta i testiranje proba na čvrstoću savijanja do maksimalne sile loma urađeno je na Tehničkom fakultetu Univerziteta u Bihaću.

U eksperimentu su korišteni čisti obratci smrče debljine 20 mm, topole debljine 18 mm i 22 mm, bukve debljine 16 mm, 20 mm i 24 mm, hrasta debljine 18 mm i 22 mm i jasena debljine debljine 20 mm, različitih dimenzija po dužini i širini.

Vlažnost uzoraka je mjerena električnim vlagomjerom na površini koja se obrađivala. Određivanje gustoće drveta (zapreminske mase) rađeno je po standardu BAS EN 13061-2:2016, gdje su uzete male probe dimenzija 30 x 30 x d mm.

The aim of the experimental research is to examine the significance of the influenced parameters of solid wood board, specifically its density (ρ) and thickness (d) on its bending strength in parallel with the stretching of wood fibers and the analysis of experimental data from the aspect of possible higher bending strength, while not compromising the quality of the plate material and reducing the total cost of production. Based on the experimental results, i.e. the maximum bending force at four points, in accordance with the standard BAS EN 789, modelling of the influencing parameters to the maximum fracture force (F_{max}) has to be done, [2,3].

2. DESIGN OF EXPERIMENT

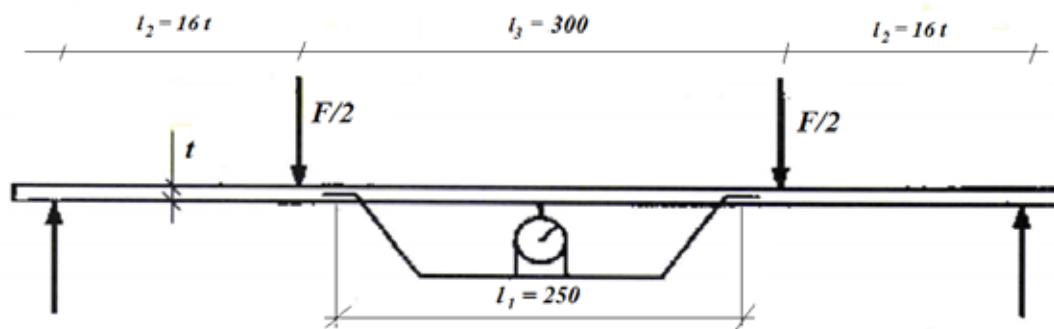
Experimental research related to this work is based on measuring the maximum bending stress forced up to the moment of fracture of a solid board, made in five different thicknesses and five types of wood: spruce, poplar, beech, ash and oak, previously processed into clean workpieces and thereafter cut into sample dimensions according to BAS EN 789, [4]. Solid boards are produced on the basis of longitudinal joining of clean workpieces by means of a wedge joint in the required dimension of the board length, and then they are widthwise joined to a flat joint in the required width of solid board format. Production of clean workpieces, wedge milling operation, and length and width joining in the format of the board was done in "Rosewood" d.o.o. Visoko, as well as cutting the necessary tests in the direction of stretching wood fibers, or perpendicular to the stretching of wood fibers from the plate format 1800 (mm) x 1200 (mm) x d (mm). Measurement of moisture content, determination of wood density and testing of tests for bending strength up to the maximum fracture force was done at the Technical Faculty of the University of Bihać.

The experiment used pure specimens of 20 mm thick spruce, 18 mm and 22 mm thick poplar, 16 mm, 20 mm and 24 mm thick beech, 18 mm and 22 mm thick oak and 20 mm thick ash, of different dimensions in length and width.

The humidity of the samples was measured with an electric hygrometer, on the surface which was treated. Determination of wood density (bulk density) was done according to the standard BAS EN 13061-2: 2016, where small samples of dimensions 30 x 30 x d mm were taken.

Ispitne metode za određivanje mehaničkih osobina kao i dimenzija, sadržaja vlage i gustoće drveta ispitivanih uzoraka određene su prema BAS EN 789:2004 (slika 1). Metode pomoću ovog standarda se primjenjuju na pločaste konstrukcije na bazi drveta, te lijepljenog laminiranog drveta sa stalnim presjecima. Ispitivanja se moraju provoditi u uvjetima gdje je $T=20^{\circ}\text{C}$ pri relativnoj vlažnosti 65%.

Test methods for determining the mechanical properties as well as the dimensions, moisture content and wood density of the tested samples are determined according to BAS EN 789: 2004 (Figure 1). Methods using this standard are applied to wood-based panel constructions and glued laminated wood with permanent cross-sections. The tests must be carried out under conditions where $T = 20^{\circ}\text{C}$ at a relative humidity of 65%.



Slika 1. Skica eksperimenta na savijanje prema standardu BAS EN 789, [4]
Figure 1. Arrangement for bending test according to BAS EN 789 standard, [4]

U toku testiranja proba na čvrstoću savijanja konstantne su bile slijedeće veličine:

- širina proba $b = 300\text{ mm}$,
- dužina proba $l = 32 d + 300\text{ mm}$,
- brzina savijanja $v = 7\text{ mm/min}$,
- vlažnost drveta $u = 8\%$.

During the bending strength tests, the following values were constant:

- sample width $b = 300\text{ mm}$,
- sample length $l = 32 d + 300\text{ mm}$,
- bending speed $v = 7\text{ mm/min}$,
- wood humidity $u = 8\%$.

Probe su izrezivane iz masivnih drvnih ploča formata 1800 x 1200 mm u debljinama:

- ploča od bukve debljine 16 mm,
- ploča od topole debljine 18 mm,
- ploča od bukve debljine 20 mm,
- ploče od smrče debljine 20 mm,
- ploča od jasena debljine 20 mm,
- ploče od hrastovine debljine 22 mm,
- ploča od bukve debljine 24 mm.

The samples were cut from solid wood panels of 1800 x 1200 mm in thicknesses:

- 16 mm thick beech board,
- 18 mm thick poplar board,
- 20 mm thick beech board,
- 20 mm thick spruce boards,
- 20 mm thick ash board,
- 22 mm thick oak boards,
- 24 mm thick beech board.

Iz ovih ploča su sa različitih mjesta izrezivane standardne probe podužno na protezanje vlakana (13 kom.). Kad je u pitanju bukva, iz dvije masivne ploče debljine 20 mm izrezano je 5 proba dimenzija 980 x 300 x 20 mm, iz jedne masivne ploče debljine 16 mm izrezana je 1 proba, te iz jedne masivne ploče debljine 24 mm izrezana je 1 proba. Rezanje je izvršeno također prema standardu BAS EN 789 (slika 2).

From these plates, standard probes were cut longitudinally to stretch the fibers (13 pcs). In the case of beech, 5 samples measuring 980 x 300 x 20 mm were cut from two 20 mm thick solid boards, 1 sample was cut from one 16 mm thick solid board, and 1 sample was cut from one 24 mm thick solid board. The cutting was also done according to the standard BAS EN 789 (Figure 2).



Slika 2. Shema rezanja proba, [4]
Figure 2. Example of cutting schedule, [4]

Ispitivanje čvrstoće na savijanje izvršeno je u laboratoriju Tehničkog fakulteta Univerziteta u Bihaću na mašini SIL-50KNAG, proizvođača Shimadzu (slika 3.).

The bending strength test was performed in the laboratory of the Technical Faculty of Bihać on the machine SIL-50KNAG, manufactured by Shimadzu (Figure 3).



Slika 3. Savijanje ploče prema standardu BAS EN 789
Figure 3. Bending of wood according to BAS EN 789

Kod centralnog plana eksperimenta sa 2 faktora može se koristiti eksperiment sa 8 ili 13 ponavljanja. U ovom slučaju odabran je plan eksperimenta sa 13 ponavljanja od kojih su 5 u centralnoj tački. Ulazni parametri su zadani prema tabeli 1, [5].

With a central 2-factor experiment plan, an experiment with 8 or 13 replicates can be used. In this case, an experimental design with 13 replicates, of which 5 are in the central point, has been chosen. The input parameters are set according to Table 1, [5].

Tabela 1 Vrijednosti ulaznih faktora eksperimenta
Table 1 Values of experimental input factors

	-1,414	-1	0	1	1,414
Faktor A – Gustoća drveta - Density ρ [kg/m³]	450	560	650	720	820
Faktor B – Debljina ploče –Thickness of panel [mm]	16	18	20	22	24

Nakon što je urađen eksperiment na svih 13 proba dobiveni su rezultati sile loma ploča prema tabeli 2.

After the experiment was performed on all 13 tests, the results of plate fracture force were obtained according to the Table 2.

Tabela 2. Eksperimentalne vrijednosti sile loma ploče
Table 2. Experimental values of fracture force

Ponavljanje eksperimenta	Faktor A Gustoća drveta ρ [kg/m ³]	Faktor B Debljina ploče b [mm]	Sila F [kN]
Number of experiment	Density of wood ρ [kg/m ³]	Thickness of panel b [mm]	Force F [kN]
1	560	18	4,68
2	720	18	11,8
3	560	22	4,98
4	720	22	11,03
5	450	20	7,09
6	820	20	11,5
7	650	16	5,76
8	650	24	12,12
9	650	20	6,71
10	650	20	7,73
11	650	20	6,51
12	650	20	7,29
13	650	20	6,68

Nakon što su eksperimentalni rezultati dobiveni, može se pristupiti obradi matematičkog modela. Dobit će se metodom analize varijanse i utvrđivanjem signifikantnosti uticajnih parametara. Uticajni parametri su ulazni faktori, gustoća drveta i debljina ploče, te interakcija između ta dva faktora. Tabela analize varijanse (ANOVA) prikazana je u tabeli 3, [6].

Once experimental results have been obtained, the processing of the mathematical model could be proceeded. It could be obtained by the method of analysis of variance and by determining the significance of the influential parameters. Influential parameters are input factors, wood density and board thickness, and the interaction between these two factors. The variance analysis table (ANOVA) is shown in Table 3, [6].

Tabela 3. Analiza varijanse za model sile loma ploče od drveta
Table 3. Analysis of variance for the fracture force model of wood panels

Izvor varijacije Source of variation	SS	dF	MS	F	P	Značaj Significance
A	47,07	1	47,07	16,29	0,0023	Značajan significant
B	9,08	1	9,08	3,44	0,093	Značajan significant
Model	56,15	2	28,07	9,72	0,004	Značajan significant
Greška Error	28,88	10	2,88			
Odstupanje od modela Lack of fit	27,84	6	4,64	1,80	0,296	nije značajan not significant
Čista greška Pure error	1,042	4	0,26			
Ukupno Total	85,04	12	7,08			

Signifikantnost parametara može se odrediti pomoću Fisherovog koeficijenta F ili parametra p . Fisherov izračunati broj se upoređuje sa tabličnim i , ako je veći, parametar je signifikantan za unaprijed definirani nivo signifikantnosti. Pomoću parametra p može se odrediti signifikantnost parametara koristeći softver R. Naredbom `1-pf` (koeficijent F , stepen slobode parametra, stepen slobode greške) dobiveni su brojevi kako je prikazano u slijedećem kodu, [2,7].

```
> 1-pf(16.29,1,10)
[1] 0.0023761
> 1-pf(3.44,1,10)
[1] 0.0933194
> 1-pf(9.72,2,10)
[1] 0.0045217
> 1-pf(1.8,6,4)
[1] 0.29634
> 1-pf(1.8,6,4)
[1] 0.29634
```

Prva tri reda koda predstavljaju ulazne faktore A i B, te ukupan model. Dobiveni brojevi su manji od 0,1 što znači da su ulazni parametri i ukupan model signifikantni za nivo signifikantnosti $\alpha = 0,1$. Zadnji red predstavlja odstupanje od modela koje je veće od 0,1 što znači da odstupanje nije signifikantno, pa je prema tome model adekvatan za primjenu. Na kraju, konačan izraz modela za određivanje sile loma ploče kod koje je paralelno protezanje drvnih vlakana je u obliku:

$$F_{max} = -21,97 + 0,029\rho + 0,53b \quad (1)$$

Nakon dobivanja jednačine modela korisno je provjeriti homogenost disperzija eksperimenta u tački ponavljanja pomoću Cochranovog kriterija, te adekvatnost modela određivanjem koeficijenta višestruke regresije. Provjera homegonosti disperzija po kriteriju Cochran pokazala je da je Cochranov koeficijent modela $K_h = 0,533$, što je manje od tablične vrijednosti za prikazani centralni plan eksperimenta, koja iznosi $K_t = 0,544$, pa se može zaključiti da je disperzija rezultata eksperimenta u tački ponavljanja eksperimenta homogena. Vrijednost koeficijenta regresije modela izračunata je I iznosi $R = 0,9288$, znači da linearni model sile loma ploče opisuje tačnost rezultata eksperimenta sa 92,88%, što je vrlo dobra tačnost modela.

The significance of the parameters can be determined using the Fisher coefficient F or the parameter p . The Fisher calculated number is compared with the tabular one and if it is higher, the parameter is significant for a predefined level of significance. Using the parameter p , the significance of the parameters using the software R can be determined. With the command `1-pf` (coefficient F , degree of freedom of the parameter, degree of freedom of error) numbers as shown in the following code are obtained, [2,7].

```
> 1-pf(16.29,1,10)
[1] 0.0023761
> 1-pf(3.44,1,10)
[1] 0.0933194
> 1-pf(9.72,2,10)
[1] 0.0045217
> 1-pf(1.8,6,4)
[1] 0.29634
> 1-pf(1.8,6,4)
[1] 0.29634
```

First three lines of code represent the input factors A and B and the overall model. The numbers we obtained are less than 0,1 what means that the input parameters and the overall model are significant for the significance level $\alpha = 0,1$. The last row represents a deviation from the model that is greater than 0,1 what means that the deviation is not significant and therefore the model is adequate for application. Final expression of the model for determining the fracture force of a board, in which the stretching of wood fibers are parallel, is as follows:

After obtaining the model equation, it is useful to check the homogeneity of the dispersions of the experiment at the point of replication using the Cochran criterion and the adequacy of the model by determining the multiple regression coefficient. Checking the homogeneity of dispersions according to the Cochran criterion showed that the Cochran coefficient of the model $K_h = 0.533$, which is less than the tabular value for the presented central plan of the experiment which is $K_t = 0.544$, so it can be concluded that the dispersion of experimental results is homogeneous. The value of the regression coefficient of the model was calculated and is $R = 0.9288$, which means that the linear model of the plate fracture force describes the accuracy of the experimental results with 92.88%, which is a very good accuracy of the model.

Nakon što je dobivena jednačina modela mogu se prikazati i uporediti rezultati sile loma dobivene eksperimentom i modelom, tabela 4.

After obtaining the equation of the model, the results of the fracture force obtained by the experiment and the model can be shown and compared, Table 4.

Tabela 4. Uporedni prikaz eksperimentalnih i modelskih rezultata sile loma

Table 4. Comparative presentation of experimental and model results of fracture force

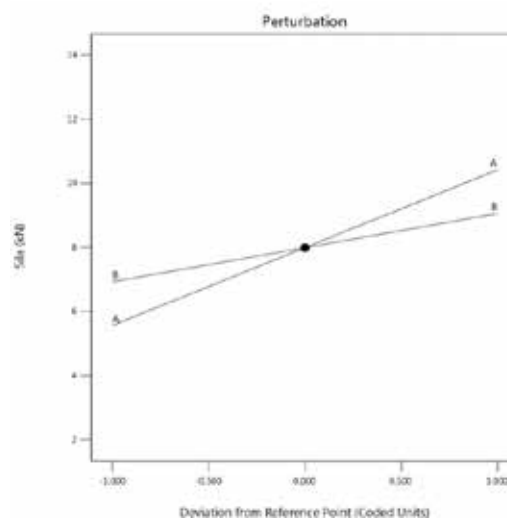
<i>Exp</i>	F_{exp}	F_{model}
1	4,68	4,93
2	11,8	11,33
3	4,98	5,93
4	11,03	10,57
5	7,09	6,18
6	11,5	12,41
7	5,76	5,36
8	12,12	9,6
9	6,71	7,48
10	7,73	7,48
11	6,51	7,48
12	7,29	7,48
13	6,68	7,48

3. REZULTATI I DISKUSIJA

Za potrebe ovog rada i potvrđivanje dobivenih statističkih rezultata korišten je softverski paket *Design Expert*. To je komercijalni softver koji služi za planiranje eksperimenta i optimizaciju rezultata, te statističku obradu i vizualni prikaz. Pomoću dijagrama poremećaja mogu se uporediti efekti svih ulaznih faktora u određenoj tački eksperimentalnog prostora. Slika 4 prikazuje dijagram poremećaja ulaznih faktora modela za centralnu tačku.

3. RESULTS AND DISCUSSION

For the purposes of this paper and to confirm the obtained statistical results, Design Expert software package is used. It is commercial software used for experiment planning and optimization of results, as well as statistical processing and visual display. Using perturbation plot, the effects of all input factors at a given point in the experimental space can be compared. Figure 4 shows a perturbation plot of the input factors of the model for centre point.

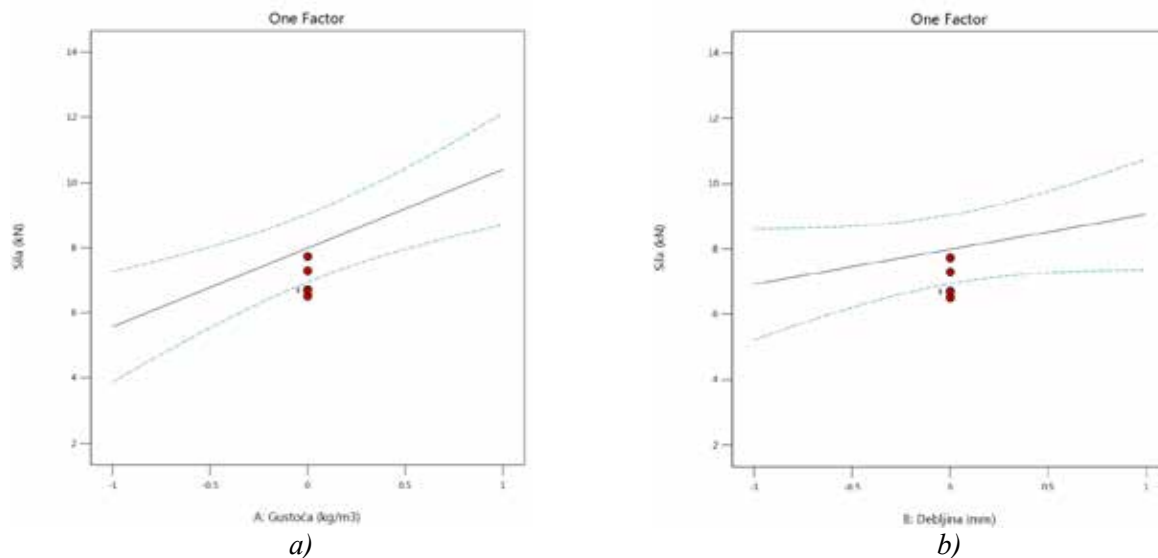


Slika 4. Dijagram poremećaja ulaznih faktora

Figure 4. Perturbation plot of input factors

Na dijagramima na slici 5. prikazana je zavisnost izlazne vrijednosti modela, sile loma od ulaznih veličina, gustoće drveta i debljine ploče. Na apscisi ulaznih veličina minimalna vrijednost prikazana je sa „-1“, a maksimalna vrijednost ulazne veličine sa „+1“. Sa dijagrama se može vidjeti da vrijednost sile loma zavisi značajnije od gustoće drveta, odnosno da vrijednosti sile loma brže rastu kako se gustoća povećava.

The diagrams in Figure 5 show the dependence of the output value of the model, the fracture force on the input quantities, wood density and plate thickness. On the abscissa of the input quantities, the minimum value is shown with "-1" and the maximum value of the input quantity with "+1". It can be seen from the diagram that the value of the fracture force depends more significantly on the density of the wood, i.e. that the values of the fracture force grow faster as the density increases.

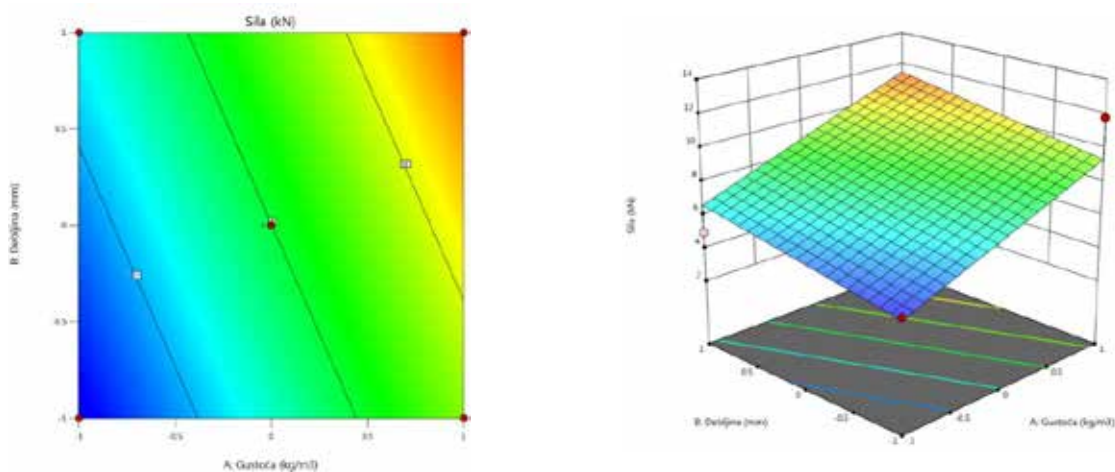


Slika 5. Zavisnost sile loma od ulaznih veličina eksperimenta, a) gustoća, b) debljina

Figure 5. Dependence of the fracture force on the input parameters, a) density, b) thickness

Zavisnost sile loma od međusobne interakcije ulaznih veličina može se grafički prikazati i pomoću konturnog dvodimenzionalnog dijagrama, slika 6a., kao i pomoću trodimenzionalnog prikaza, slika 6b.

The dependence of the fracture force on the interaction of the input quantities can be graphically represented by a contour two-dimensional diagram, Figure 6a, as well as by a three-dimensional representation, Figure 6b.

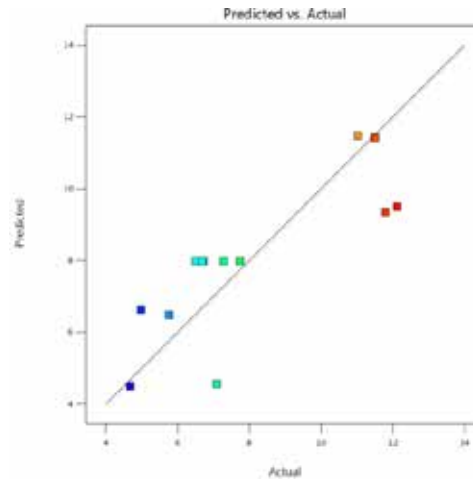


Slika 6. Grafički konturni prikaz, a) dvodimenzionalni, b) trodimenzionalni

Figure 6. Graphical contour representation, a) two-dimensional, b) three-dimensional

Grafički je moguće prikazati i raspored eksperimentalnih i modelskih vrijednosti sile loma, slika 7. Ovaj dijagram pomaže da se otkriju stanja eksperimenta u kojima izlazne vrijednosti nemaju dobra poklapanja s eksperimentalnim veličinama.

It is possible to graphically show the distribution of experimental and model values of the fracture force of Figure 7. This diagram helps detecting experimental states in which the output values do not match well with the experimental quantities.



Slika 7. Raspored eksperimentalnih i modelskih vrijednosti sile loma
Figure 7. Distribution of experimental and model values of fracture force

Prema teoriji, tačke podataka treba da su ravnomjerno raspodijeljene u odnosu na liniju koja bi trebalo da je pod uglom od 45° . U primjeru linearnog modela izlazne veličine parametra sile loma kod ploče s paralelnim protezanjem vlakana na horizontalnoj osi su eksperimentalne, a na vertikalnoj modelske vrijednosti i raspored modelskih vrijednosti u odnosu na eksperimentalne je dobar.

4. ZAKLJUČAK

Nakon dobivenih rezultata eksperimenta, te modela sile loma može se zaključiti da je dobiveni model dovoljno dobar i adekvatan za prikazane početne uslove, koji definišu gustoću drveta odnosno debljinu masivne ploče drveta. Disperzija rezultata u tački ponavljanja eksperimenta je homogena, a adekvatnost modela izračunata pomoću koeficijenta višestruke regresije je preko 90 %, te se može zaključiti da je model vrlo dobar i adekvatan.

Vrijednost sile loma ploče od masivnog drveta zavisi i od gustoće drveta i od debljine ploče. S porastom obje vrijednosti raste i veličina sile loma, s tim da je rast veći kako raste gustoća materijala, što znači da je ovaj parameter više uticajan u modelu.

According to the theory, the data points should be evenly distributed in relation to the line, which should be at an angle of 45° . In the example, the output magnitudes of the fracture force parameter in a plate with parallel fiber stretching on the horizontal axis are experimental and, on the vertical, the model values and the distribution of model values in relation to the experimental ones is good.

4. CONCLUSION

After obtaining the results of experiment and the breaking force model, it can be concluded that the obtained model is good enough and adequate for the presented initial conditions, which define the density of wood or the thickness of solid wood panel. The dispersion of the results at the point of repeating the experiment is homogeneous and the adequacy of the model calculated using the multiple regression coefficient is over 90% and it can be concluded that the model is very good. The value of the breaking force of a solid wood board depends on both the density of the wood and the thickness of the board. As both values increase, so does the magnitude of the fracture force, but the growth increases as the material density increases, which means this parameter is more influential in the model.

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Corresponding author:

Damir Hodžić

University of Bihać,

Faculty of Technical Engineering

Email: damir.hodzic@unbi.ba

Phone: + 387 61 795094