Modeling of Influential Parameters on Bending Strength of Solid Wood Panels Perpendicular to the Grain

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Abstract. The paper presents the results of modeling the bending strength of wood. During the experimental examination and definition of the model, solid wood was taken, where the bending was performed perpendicular to the grain. The experiment was done with thirteen replications and the input values that varied at three levels were wood density and board thickness. The thirteen-repetition experiment also involved four repetitions in the marginal areas, so two more wood densities and two board thicknesses had to be taken. The experimental measurement was performed in the laboratory of the Technical Faculty Bihac. Based on the experimental results, a sufficiently adequate mathematical model of the breaking force of a solid wood panel perpendicular to the grain is obtained.

1. Introduction
The paper presents experimental research of the influential parameters of solid wood panel on changes in its bending strength for panels that are width - joined into a structure perpendicular to the grain. Experimental researches were performed according to the standard BAS EN 789 on samples of solid boards for different values of influential parameters of wood density \( \rho \) (g/cm\(^3\)), and thickness of solid board \( d \) (mm) which were varied at five levels, where the output parameter was the maximum bending force \( F_{\text{max}} \).

In wooden constructions, solid wood is often exposed to different types of stresses, and often to complex stresses that are necessary to know before choosing the basic material for making wood products. It is very important to know the physical and mechanical properties of wood and wood-based panel constructions for their wide application in construction and production of wooden furniture [1].

Bending strength of wood means the resistance that a highly elongated wood (wooden beam) supported at both ends or fastened only at one end provides forces that try to bend or break. Bending occurs due to the action of bending moment in the cross section of wood vertical to the plane of the cross section. Bending moments occur as a result of the action of external forces, which can be arbitrarily distributed in relation to the longitudinal axis. Bending strength is of special importance for wooden structures, most often in construction, bridge construction, mining, shipbuilding, etc., as well as in furniture and construction of carpentry structures.

2. Preparing for the experiment
Important conditions for performing the experiment are defining the conditions in which the experiment will be performed, with clearly identified parameters of the observed process, ie the choice of parameters that will be included in the modeling, realization of the experiment, optimization of the observed process...
and other activities. The choice of parameters of a process for analysis, requires prior knowledge of the processing process derived from similar processes [2].

Experimental research related to this work is based on measuring the maximum bending stress force 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 workpieces and thereafter cut into sample dimensions according to standard BAS EN 789 [3]. Production of workpieces, milling operation of wedge joints, and length and width joining in the format of the board was done in Ltd. "Rosewood" Visoko. Measurement of moisture content, determination of wood density and testing of bending strength up to the maximum fracture force was done at the Faculty of Technical Engineering Bihać.

The experiment used 20 mm thick spruce, 18 mm and 22 mm 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 (Figure 1). The final cutting of the samples was done on a two-blade format circular saw in accordance with the plan of the experiment.

![Figure 1. Panels prepared for bending](image)

The moisture content of the samples was measured with an electric moisture meter, on the surface to be 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.

The density of wood (ρ) is determined by the equation:

$$\rho = \frac{m}{V}$$

where:

- $m$ - mass of wood in [g]
- $V$ - volume of wood in [cm$^3$]

The volume of the samples was determined stereometrically, and the mass of the samples by weighing on a precise analytical balance in the laboratory at the Faculty of Technical Engineering Bihać. The mean value of the calculated wood density according to the equation (1) is: spruce 0.45 [g/cm$^3$], poplar 0.56 [g/cm$^3$], beech 0.65 [g/cm$^3$], oak 0.72 [g/cm$^3$] and ash 0.82 [g/cm$^3$].
The bending strength test was performed in the laboratory at the Faculty of Technical Engineering Bihać on a testing machine SIL-50KNAG, manufactured by Shimadzu (Figure 2), with one working cylinder, located in the upper part of the machine. The working cylinder, acting indirectly, lowers or raises the upper head, while the lower head is stationary. Then, through the computer connected to the testing machine, the bending is measured in four points, and the values of the achieved force on the bending of the test specimens can be read on the diagram.

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 – Timber Structures – Test methods – Determination of mechanical properties of wood based panels. The tests must be carried out under conditions where temperature \( T = 20 \, ^\circ\text{C} \) at a relative air humidity of 65 [%].

The application of the load shall be as shown in Figure 3 with the load and reaction forces applied by rollers of \( 30 \pm 1 \, \text{mm} \) diameter [3]. The distance between the load points and the supports shall be 16 times the nominal thickness, but not more than 400 [mm] and not less than 240 [mm] with an accuracy of \( \pm 1 \, \text{mm} \).

**3. Design of experiment**

In this research, we selected an experimental design with 13 replicates of which 5 were at the central point. In the case when we have 13 repetitions of the experiment, the number of repetitions is obtained using the equation [2,4]:

\[
\text{Number of repetitions} = \frac{13}{5} \times 5 - 1 = 13 - 1 = 12
\]
\[ N = 2^k + 2k + n_c = 2^2 + 2 \cdot 2 + 5 = 13 \] (2)

where:
\( n_c \) – central point experiment repetitions,
\( k \) – number of factors,
\( 2 \) – number of factor levels.

Input factors and their values for experiment are shown in table 1.

\textbf{Table 1. Input factors and their values}

| Effect | -1,414 | -1 | 0 | 1 | 1,414 |
|--------|--------|----|---|---|-------|
| Factor A – Wood density \( \rho \) [kg/m\(^3\)] | 450 (spruce) | 560 (poplar) | 650 (beech) | 720 (oak) | 820 (ash) |
| Factor B – Thickness [mm] | 16 | 18 | 20 | 22 | 24 |

Design of experiment with 13 repetitions of experiment can be graphically presented, Figure 4. According to that experimental schedule was done and exactly for each replicate of experiment type of wood and thickness was dedicated. For all 13 experiment repetitions maximum force was measured and shown in table 2 [5].
Table 2. Results of experiment

| Sample | Density $\rho$ [kg/m$^3$] | Thickness $b$ [mm] | Force $F_{max}$ [kN] |
|--------|---------------------------|-------------------|---------------------|
| P 1    | 560                       | 18                | 0,226               |
| P 2    | 720                       | 18                | 0,734               |
| P 3    | 560                       | 22                | 0,63                |
| P 4    | 720                       | 22                | 0,984               |
| P 5    | 450                       | 20                | 0,24                |
| P 6    | 820                       | 20                | 0,912               |
| P 7    | 650                       | 16                | 0,461               |
| P 8    | 650                       | 24                | 1,327               |
| P 9    | 650                       | 20                | 1,021               |
| P 10   | 650                       | 20                | 1,1                 |
| P 11   | 650                       | 20                | 1,164               |
| P 12   | 650                       | 20                | 1,077               |
| P 13   | 650                       | 20                | 1,093               |

To determine the significance of the regression coefficients for the linear model, an analysis of variance for a given experiment will be performed. Analysis of variance involves calculating the sum of squares (SS), degrees of freedom (dF) and mean squares (MS) for given input factors, interactions between them, lack of fit and error of the model, Table 3.

Table 3. Analysis of Variance (ANOVA) results

| Source of variation | Sum of squares | Degrees of freedom | Mean of squares | Fisher's coefficient | p-value | Significance |
|---------------------|----------------|--------------------|-----------------|----------------------|---------|--------------|
| A                   | 0.38           | 1                  | 0.381           | 3.54                 | 0.089   | significant  |
| B                   | 0.43           | 1                  | 0.433           | 3.38                 | 0.095   | significant  |
| Model               | 0.81           | 2                  | 0.407           | 4.704                | 0.036   | significant  |
| Error               | 1.60           | 10                 | 0.160           |                      |         |              |
| Lack of fit         | 1.56           | 6                  | 0.260           | 2.825                | 0.167   | Not significant |
| Pure error          | 0.036          | 4                  | 0.009           |                      |         |              |
| Total               | 2.42           | 12                 | 0.201           |                      |         |              |

Significance of the factors and model can be determined by calculating Fisher coefficient ($F$) and comparing it with tabular $F$ for significance of 10 % ($\alpha = 0.1$), or calculating p-value which can be determined by software R. If p-value is less than 0.1 that means source of variation is significant. In our research both factors are significant.

Equation which can give us maximum force for bending strength of wood panel perpendicular to the grain is:

$$Y = F_{max} = -3.228 + 0.026\rho + 0.116b$$  \hspace{1cm} (3)

By including the values for wood density and panel thickness in equation (3), values of the maximum force can be obtained according to the presented model. Table 3 shows the values of the maximum force according to the model and according to the experimental results.
Table 4. Maximum force according to the experimental results and according to the model

| Sample | $F_{eksp}$ [kN] | $F_{model}$ [kN] |
|--------|----------------|-----------------|
| P 1    | 0.226          | 0.316           |
| P 2    | 0.734          | 0.732           |
| P 3    | 0.63           | 0.78            |
| P 4    | 0.984          | 1.196           |
| P 5    | 0.24           | 0.262           |
| P 6    | 0.912          | 1.224           |
| P 7    | 0.461          | 0.318           |
| P 8    | 1.327          | 1.246           |
| P 9    | 1.021          | 0.982           |
| P 10   | 1.1            | 0.982           |
| P 11   | 1.164          | 0.982           |
| P 12   | 1.077          | 0.982           |
| P 13   | 1.093          | 0.982           |

After obtaining the model equation, it is useful to check the homogeneity of the dispersions using the Cochran criterion and the adequacy of the model by determining the multiple regression coefficient. Calculated Cochran criterion was $K_h = 0.531$, which is less than table value for Cochran for input factors ($K_t = 0.544$). That means dispersions of the model results is homogeneous.

The calculated value of the regression coefficient is $R = 0.9786$ and that means that the linear model describes the accuracy of the experimental results with 97.86%, which is an excellent accuracy of the model.

4. Discussion of results
For the purposes of this paper and to confirm the obtained statistical results, the Design Expert software package was used. It is a commercial software used for experiment planning and optimization of results, as well as statistical processing and visual display [5, 6].

Using Perturbation Plot diagram, the effects of all input factors at a particular point in the experimental space can be compared. Figure 5 shows a perturbation plot diagram of the input factors of the model for the central point.

![Figure 5. Perturbation plot diagram of the input factors](image)
The diagrams in Figure 6 show the dependence of the output value of the model, the maximum force on the input factors, the density of the wood and the thickness of the panel. On the input size abscissa, the minimum value is displayed with "-1" and the maximum value of the input size with "+1". It can be seen from the diagram that the value of the maximum force increases relatively proportionally with the increase in the density of the plate or the thickness of the panel.

![Figure 6](image)

**Figure 6.** Dependence of the output value on the input factors a) density; b) thickness

The dependence of the output value of the model, the maximum force, on the interaction of input factors can be graphically represented by contour two-dimensional diagrams, Figure 7 as well as by three-dimensional display, Figure 8. The diagrams show the values of input factors in coded values from "-1" to "1" and the output value of the maximum force in the values obtained using the model.

![Figure 7](image)

**Figure 7.** Contour two-dimensional diagram - dependence of the output value of the model, the maximum force, on the interaction of input factors
Figure 8. Contour three-dimensional diagram - dependence of the output value of the model, the maximum force, on the interaction of input factors

It is possible to graphically show the distribution of experimental and model values of the maximum force, Figure 9.

Figure 9. Distribution of model values (predicted values) in relation to the experimental ones (actual values)

This diagram helps to detect experimental points in which the output values do not match well with the experimental values. According to the theory, the data points should be evenly distributed in relation to the line, which should be at an angle of 45°. On the horizontal axis are experimental and on the vertical axis model values and the distribution of model values in relation to the experimental ones is good.
5. Conclusion
After the obtained results of the experiment and the model of maximum force, 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
repetition of the experiment is homogeneous and the adequacy of the model calculated using the multiple
regression coefficient is over 90% and we can conclude that the model is very good and adequate. The
value of the maximum 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 maximum force, with the
growth increasing as the density of the material increases, which means that this parameter is more
influential in the model.

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