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Engineering Analysis Application in Furniture Making: Deformation – Equivalent Stress

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The deformation of furniture units plays a significant role in their effective and efficient way of use during the overall service life. Accurate information on the deformation of different types of furniture members can be determined and evaluated by current testing methods. However, this will not only be expensive but also destructive. Therefore, the objectives of this study were to obtain initial data to predict the types and magnitudes of deformation which take place in various furniture works due to certain stress distribution. Such predictions were carried out by employing engineering analysis within the scope of the statistical approach. AutoCAD and SolidWorks software were used to design the furniture while the ANSYS finite element program route was employed for engineering analysis in this work. The joint types and stresses were applied as follows: dowel type joints having an equivalent stress level ranging from 0.20-0.96 MPa and a deformation level ranging from 0.001-0.82 mm; mortise and tenon joints having an equivalent stress level ranging from 0.17-2.68 MPa, deformation level ranging from 0.02-0.17 mm. Minifix type joints having an equivalent stress level ranging from 0.07-17.6 MPa, and a deformation level ranging from 0.03-1.42 mm. It appears that the engineering tools used in this study can successfully be applied to determine the deformation behaviors of furniture units.

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Introduction

Wood and wood based materials are essential materials for the construction of case furniture, thus furniture construction design. To know behaviors against physical and mechanical effect types of the materials used in creating a furniture product, benefits producer and users technically, esthetically and economically. Both in design and scientific studies based on design, the data of resistance from products' and mechanical features merge is used [Efe 1994].

Today, when technology is developing rapidly, the use of computer technology has become widespread. In many steps of modern furniture design, the use of this technology is possible. Moreover, engineering design in furniture can be made by solid modeling and structural analysis programs. All the elements of the product can be modeled parametrically, and required changes can be accomplished by advantages of solid modeling and simple optimization. Likewise, product durability calculations can be performed by computer-assisted analysis programs [Efe et al. 2003].

With the rapid development of computer technology and finite element theory, the finite element

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method (FEM) has been gradually introduced into the structure analysis of wood products and wooden constructions [Mackerle 2005].

Recent studies show that of recent years examined, computer software, especially FEM are being used in the structural analysis of furniture systems. However, some methods of analysis have been developed to assess the relationship between the involved parameters on the mechanical behavior of connectors and joints in different wooden structures [Albin 1989, Eckelman 1989, Eckelmann and Rabiej 1985, Loferski and Gamalath 1989, Ozcifci 1995, Martins et al. 2013].

Cai et al. [1995] analyzed the durability and rigidity of comparison of moltinject corner joints with constructed box and dowel joints. In addition, the deflection of moltinject corner joints could logically be estimated using the finite element method.

Gustafsson [1995] emphasized that it is possible to use modern finite element programs in many steps of the design process. For this purpose, he made a structural analysis of a simple chair by the finite element method [Gustafsson 1995].

Smardzevski [1998] conducted a research project to develop a software that can analyze the durability of the structural furniture's side frames as well. For instance, he analyzed a furniture's side frame, and proved that this developed software can accurately and swiftly analyze the rigidity and durability of a wooden furniture construction[Smardzevski 1998].

Daudeville et al. [1999] theoretically and experimentally analyzed the static load carrying capacity of bolted wooden coupling, and studied the effects of different structural parameters such as the bolt diameter, and the element cross section sizes on durability. In computer-aided theoretical analyses, they have benefited from "linear elastic fracture mechanics" which is a finite element analysis method. Comparison of the experimental and theoretical results show that FEM is a suitable method for predicting the carrying capacity performance of the bolted wooden coupling [Daudeville et al. 1999].

Efe et al. [2003] constructed two school chairs with cylindrical mortise and tenon joints, and these were tested utilizing the "cyclic stepped increasing load method", and the samples were structurally analyzed by means of FEM software. As a result, they assigned that three dimensional structural analyses by means of FEM supplied reasonable estimates of the overall strength of the frame furniture.

Erdil [2002] tried design and analysis of wooden school chairs and desks having various types and dimensions by conventional structural design methods through especially selected performance test equipment and methods of durability of these products. As a result, he obtained optimum designs and dimensions, reported that the test method and equipment is relevant, also indicated that structure analysis made with finite element method provides reasonable values for furniture's overall durability [Erdil 2002].

Hu [2018] established tenon fit in its width direction had important effects on the ultimate tensile load resistance and stiffness of round-end mortise-and-tenon joints. In this study, mean ultimate tensile loads and stiffness of evaluated mortise-and-tenon increased significantly as tenon fit increased from 0 to 0.2 mm with an increment of 0.1 mm. The increase in ultimate tensile loads of mortise-and-tenon joints was because the oversize of joint tenon in its width caused the size expansion in its thickness direction which resulted in pressure increase between mortise and- tenon flat contact surfaces and led to a good interfacial bonding and uniformly distributed shear stress between the flat contact surfaces of mortise-and-tenon joints.

As engineering techniques have entered into furniture design, the need for quantitative values has begun to change this situation somewhat, and information is now available that can be used to design certain types of furniture joints. There is still a great amount of research that remains to be done in this area, however [Eckelman 2003].

Nicholls and Crisan [2002] analyzed stresses and strains in box constructed with dowel and minifix type connection elemented corner coupling with finite element method. Consequently, the stress concentration area formed in a solid model is formed as actual combining and distribution of stresses in corner coupling can be accurately predicted [Nicholls and Crisan 2002].

Smardzevski and Ozarska [2005] constructed a mathematical model of a semi-rigid screw joint of the confirmat type and a numerical model of cabinet furniture construction made of PB loaded with a bending moment. They have established that one of the most dangerous situations was when stresses become concentrated on edges of chipboards and lead to permanent shape deformations and reduction of the joint load carrying capacity.

Sjödin et al. [2008] established the results of the effect of friction between dowels and the surrounding timber showed that the load-bearing capacity of a single dowel-type joint was increased with developing the surface roughness of the dowels.

Imirzi and Efe [2013] have studied the bending strength and stiffness properties of L-type corner joints with dowels, dowels-screws and PVAc glue in cabinet type furniture made of PB with 14, 16 and 18 mm thickness laboratory and by FEM (ANSYS®). The comparisons have divulged that computer model have showed more rigid behavior than the experimental element and have reached the fracture as the maximum difference of 12.61% have been established for dowel-screw joints and 14 mm PB.

Chen and Lyu [2018], there is no relevant standard and regulation for dowel joint of furniture structure, it is very important to study the structural properties of furniture assembled by dowel joints by experimental and simulation measures to define optimal geometrical parameters [Chen and Lyu 2018]. With the rapid development of computer and related analysis techniques, FEA has been applied to aeronautical, automotive, biomechanical and many other industries to determine the stresses and strains in complicated mechanical systems Dar et al. [2002].

According to the results of the literature studies, Lotake et al. [2019] used ANSYS in a research they made connection road with different materials, Sudarshan and Roy [2019] made thermal analysis by using cylinder head block with ANSYS program, Bhowmilk et al. [2019] made dynamic analysis of composite electric power transmission tower by ANSYS.

The aim of this study; bringing products made by same type of wood and three types of constructions by installation together (1), examining behaviors of products that are installed together with two different loads by ANSYS engineering analysis (2), provide comparison of construction analyses results (3), and supporting data by variance analyze results (4).

Material and methods

While wooden table was used as product in the research, AutoCAD and SolidWorks software were used for design and ANSYS finite element software program was preferred for engineering analysis application.

In the study, table was used as a product, and oak type was used as wood material. The type of tree used (oak) was determined as the oak tree type because it is one of the most preferred tree species in restaurants and cafes. The benches, constructions and foot tables are all made of solid oak. In addition, since the aim of the study was not to reveal the differences between tree species, it was studied with a single tree species. Some physical and mechanical properties of oak wood are given in Table 1 [Wood Handbook, 1999].

Table 1. Mechanical properties of oak wood

Properties	Oak
Young's Modulus (MPa)	11500
Density (D_{12}) (g/cm^3)	0.69
Poisson's Ratio (MPa)	0.33
Tensile Yield Strength (MPa)	88
Compressive Yield Strength (MPa)	60

Design of Table and Assemblies

The selected tables are squares and rectangulars in two different sizes, 80 × 80 cm and 80 × 120 cm. Table legs are in the form of a single leg of 4. The drawings of these tables in AutoCAD design program are as shown in Figure 1. Tabletop thickness and leg thickness can be accepted as 20 mm, and 4 × 4 cm, respectively.

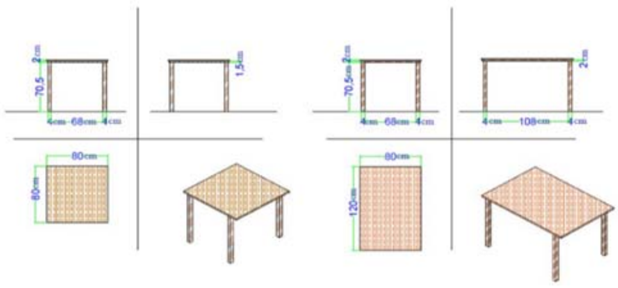

Fig. 1. AutoCAD program designs for tables

Leg-corner joints are generally vertical joggled joints at the junctions of furniture and construction elements, and serve for the joining of vertical furniture construction elements (legs) and horizontal furniture construction elements with narrow surfaces. All these horizontal and vertical individual elements are arranged in the construction group approximately or vertically. This type of joining is preferably applied in solid wood [Kurtoğlu and Dilik 2016]. In this context, minifix joint, dowel joint and mortise-and-tenon joint through many forms of joining were used to be used in this study.

Minifix with size of 4.5 mm (diameter for shaft hole), 34 mm (depth), 15 mm (dwell diameter), hole depth is selected and applied to drill 4 mm below the shaft depth axis. Two minifixes having same sizes were used for each leg. Dowels with size 12 × 80 mm (width × length) were prepared from the above mentioned oak wood, respectively. Mortise and tenon with size 20 × 70 mm (width × length) were prepared from the above mentioned oak wood, respectively. The paragraphs of the minifix, dowel and mortise-tenon are designed with SolidWorks design program and these constructions are presented in Figure 2.

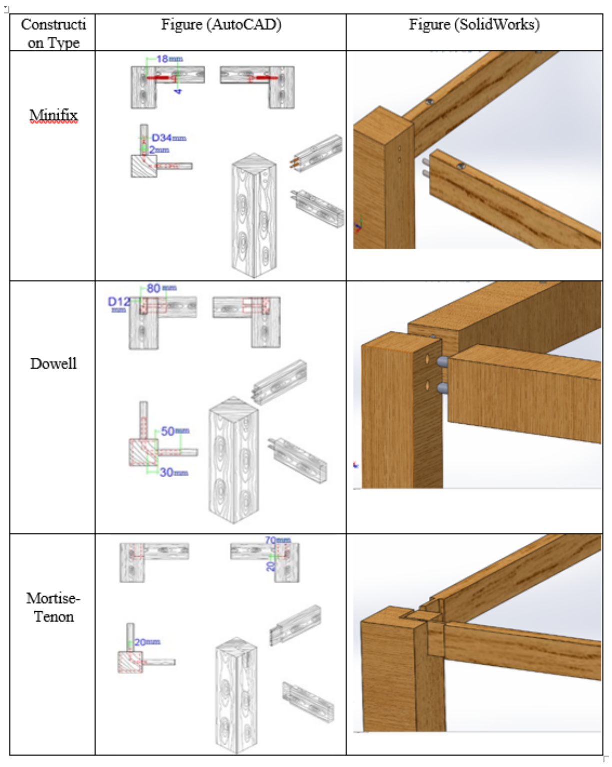

Fig. 2. AutoCAD and SolidWorks drawings of constructions

Static Analysis by Finite Element Method

The 3D geometric test model is designed using SolidWorks software. Then the assembled products were subjected to static tests with the ANSYS finite element software. The model has then imported into ANSYS software to calculate and analyze. Deformation and stress analyzes under 200 and 400 N loads were carried out in accordance with TS EN 15372 standard. The selected 3 construction types were applied as point load to table. The physical and mechanical properties of the oak tree used in the analysis were used into the program from Table 1 for material description. In addition, the application was performed to short sides and long sides of the rectangular tables separately. The default amount of space between fasteners and sockets in connections has been neglected. In order to simplify the analysis time, the joint is simplified to be interference fit joint without glue.

Variance analysis

Analysis of variance based *F*-test was applied to evaluate the importance factor on the deformation and stress. This analysis investigates the following for each parameter given in Eqs. (1) and (2):

$$\left.\begin{aligned} &H_0 : \mu_1 = \mu_2 = \ldots = \mu_\alpha \\ &H_1 : \mu_i \neq \mu_j \text{ for at least one pair } (i, j) \end{aligned}\right\} \quad (1)$$

The F value is calculated by:

$$F_0 = \frac{SS_A / \alpha - 1}{SS_E / N - \alpha} = \frac{MS_A}{MS_E} \quad (2)$$

The terms of (α-1) and (N-α) are the degrees of freedom and the error degrees of freedom for the parameter A, respectively. MS_A and MS_E are indicated the sum squares of means and errors for the variable A, respectively. The null hypothesis is rejected when the F_0 is higher than critical value of $F_{\alpha,\alpha-1,N-\alpha}$, where α is the level of the significance [Saleem et al. 2015]. Table 5 presented the P -value is less than 0.05 showing the model is significant at 95% confidence level. In this instance the values of n, r^2, f^t, fd, nd were resulted in importance factors.

Table 5. Deformation and Stress Parameters and Level

Symbol	Parameters	Unit	Level (-1)	Level (0)	Level (+1)
A	Construction type	-	Dowel	Mortise-Tenon	Minifix
B	Dimensions of Material	cm	80 × 80	80 × 120	-
C	Load	N	200	400	-

Main effects plot

Main effect plot is applied to find the differences between level means for one or more factors. It shows the response mean for each parameter level connected by a line. If this plot line is horizontal (parallel to the x-axis), it has no effect on the output. If the main plot line isn't horizontal, it has an effect on the output. In this work, the effects of construction type, dimensions of product, and load were experimentally investigated

Results and discussion

Static Analysis by Finite Element Method

Static structural analyze was started with:

1. Material properties (Poisson's constant, compression strength, tensile strength, etc. from Table 1).
2. Structural description of tables (SolidWorks drawings of constructions).
3. Mesh settings (Standard mesh).
4. The position of force and boundary conditions (Forces 200N-400N, force direction, fix supports in tables legs).
5. Analysis solutions.

The results of dowel, mortise-tenon and minifix for short edge (se) and long edge (le) loadings are shown in the Tables 2, 3, 4 and Figure 3a, 3b and 3c respectively.

Table 2. Analysis results of dowel type coupling

Construction Type	Edge type	Dimensions Of Material	Load	Total Deformation		Stress	
				Max	Min	Max	Min
Dowel		80 × 80 cm	200 N	0.010 mm	0.001 mm	0.20 MPa	0.02 MPa
Dowel	(se)	80 × 120 cm	200 N	0.001 mm	0.001 mm	0.20 MPa	0.10 MPa
Dowel	(le)	80 × 120 cm	200 N	0.020 mm	0.010 mm	0.60 MPa	0.06 MPa
Dowel		80 × 80 cm	400 N	0.820 mm	0.002 mm	0.40 MPa	0.04 MPa
Dowel	(se)	80 × 120 cm	400 N	0.027 mm	0.005 mm	0.40 MPa	0.20 MPa
Dowel	(le)	80 × 120 cm	400 N	0.060 mm	0.010 mm	0.96 MPa	0.10 MPa

Table 3. Analysis results of mortise-tenon type coupling

Construction Type	Edge type	Dimensions Of Material	Load	Total Deformation		Stress	
				Max	Min	Max	Min
Mortise-Tenon		80 × 80 cm	200 N	0.09 mm	0.02 mm	0.80 MPa	0.60 MPa
Mortise-Tenon	(se)	80 ×120 cm	200 N	0.12 mm	0.02 mm	0.82 MPa	0.29 MPa
Mortise-Tenon	(le)	80 ×120 cm	200 N	0.07 mm	0.06 mm	1.45 MPa	0.16 MPa
Mortise-Tenon		80 × 80 cm	400 N	0.05 mm	0.04 mm	1.16 MPa	0.17 MPa
Mortise-Tenon	(se)	80 × 120 cm	400 N	0.17mm	0.05 mm	1.60 MPa	0.17 MPa
Mortise-Tenon	(le)	80 × 120 cm	400 N	0.11mm	0.10 mm	2.68 MPa	0.29 MPa

Table 4. Analysis results of minifix type coupling

Construction Type	Edge type	Dimensions Of Material	Load	Total Deformation		Stress	
				Max	Min	Max	Min
Minifix		80 × 80 cm	200 N	0.05 mm	0.03 mm	1.12 MPa	0.12 MPa
Minifix	(se)	80 × 120 cm	200 N	1.02 mm	0.18 mm	0.82 MPa	0.07 MPa
Minifix	(le)	80 × 120 cm	200 N	1.13 mm	1.02 mm	11.3 MPa	1.37 MPa
Minifix		80 × 80 cm	400 N	1.42 mm	0.05 mm	1.04 MPa	9.42 MPa
Minifix	(se)	80 × 120 cm	400 N	1.05 mm	0.06 mm	15.6 MPa	1.70 MPa
Minifix	(le)	80 × 120 cm	400 N	0.10 mm	0.14 mm	17.6 MPa	1.13 MPa

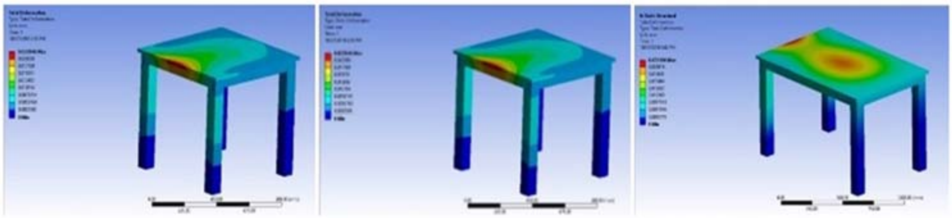

Fig. 3a. The type of construction that was least affected by the loading was the dowel

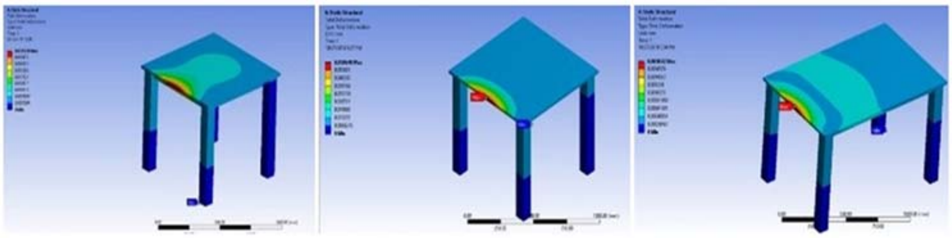

Fig. 3b. The type of construction that was most affected by the loading was minifix

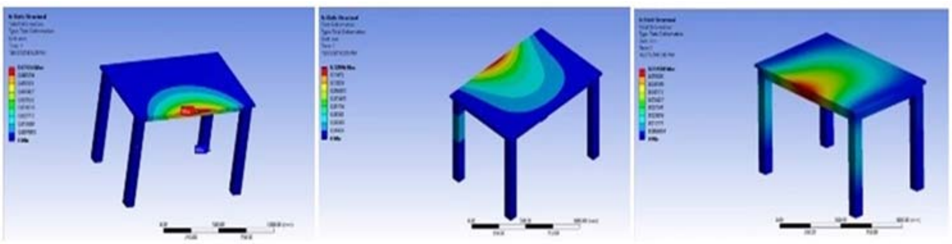

Fig. 3c. As a result of both types of loading, the long sides of the rectangular tables were the parts where deformation and stresses occurred mostly

Finite elements method static analysis were performed for each type of constructions. According to the results, the least affected construction was dowel type joint with the equivalent stress of 0.20-0.96 MPa and deformation of 0.001-0.82 mm. On the other hand the mortise and tenon type joint results followed dowel joint results with equivalent stress of 0.17-2.68 MPa, deformation of 0.02-0.17 mm. In previous studies Dowel-type joints have been found to be more durable [İmirzi and Efe 2013; Chen and Lyu 2018], which also supports the results. In the current work, the minifix construction type was more affected by the applied forces than the other two construction types. Nicholls and Crisan [2002] analyzed the stress concentration area in a solid model joined by dowel and minifix type fasteners using the finite element method and found that the stresses in the minifix corner joint were higher than in the dowel joint. The deformations and stresses on the long side were higher according to analysis data where forces were applied to the short sides and long sides of the tables.

Variance analysis

Table 6 showed the ANOVA for R_a given in suggested model. It is found that the P-value is less than 0.05 showing the model is important at 95% confidence level. This model shows that lack-of-fit error is insignificant indicating that the fitted model is accurate enough to predict the response. The model summary that R^2 and Adj-R^2 values were found as 87,74% and 73,94% for stress, respectively.

Table 6. Analyze of Variance for Stress: Construction Type, Dimensional of Material, Load

Source	DF	Adj SS	Adj MS	F-Value	P-Value
A	2	207.591	103.795	11.98	0.004
B	1	20.041	20.041	2.31	0.167
C	1	47.472	47.472	5.48	0.047
AB	2	28.107	14.053	1.62	0.256
AC	2	92.983	46.492	5.37	0.033
B	1	1.217	1.217	0.14	0.718
Error	8	69.311	8.664	0.05	0.949
Lack-of-Fit	2	1.202	0.601		
Pure Error	6	68.110	11.352		
Total	17	565.182			

Table 7 showed the ANOVA table for R_a given in suggested model. It is found that the *P*-value is less than 0.05 showing the model is important at 95% confidence level. This model shows that lack-of-fit error is insignificant indicating that the fitted model is accurate enough to predict the response. The model summary that R^2 and Adj-R^2 values were found as 90,26% and 51,72% for deformation, respectively.

Table 7. Analyze of Variance for Deformation: Construction Type, Dimensional of Material, Load

Source	DF	Adj SS	Adj MS	F-Value	P-Value
A	2	2.39427	1.19714	46.39	0.000
B	1	0.21437	0.21437	8.31	0.020
C	1	0.21344	0.21344	8.27	0.021
AB	2	0.28371	0.14186	5.50	0.031
AC	2	0.23170	0.11585	4.49	0.049
B	1	0.05290	0.05290	2.05	0.190
Error	8	0.20647	0.02581	5.40	0.046
Lack-of-Fit	2	0.13270	0.06635		
Pure Error	6	0.07377	0.01229		
Total	17	0.07377			

Main effects plot

The main effects obtained according to the results appearing from the stress applications carried out on the furniture are shown Figure 4a In this work, the effects of construction type, dimensions of product, and load were experimentally investigated. The value of stress increased with minifix for construction type, 80 × 120 of dimensions type and 400 N for load. However, according to Figure 4a the value of stress increased with minifix, 80 × 120 and 400 N.

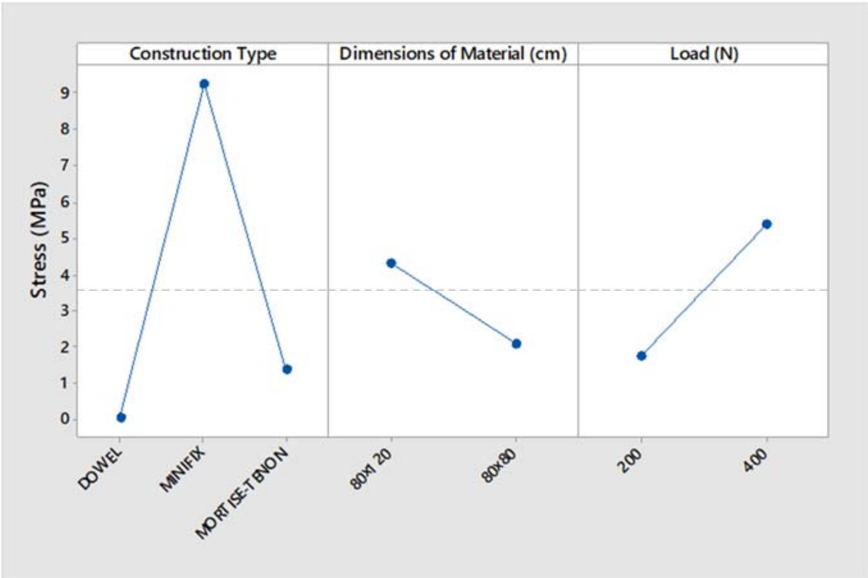

Fig. 4a. Main effects results for stress.

The main effects obtained according to the results appearing from the deformation applications carried out on the furniture are shown Figure 4b. In this work, the effects of construction type, dimensions of material, and load were experimentally investigated. The value of deformation increased with minifix for construction type, 80 × 120 for dimensions type and 400 N for load. However, according to Figure 4b the value of deformation increased with minifix, 80 × 120 and 400 N.

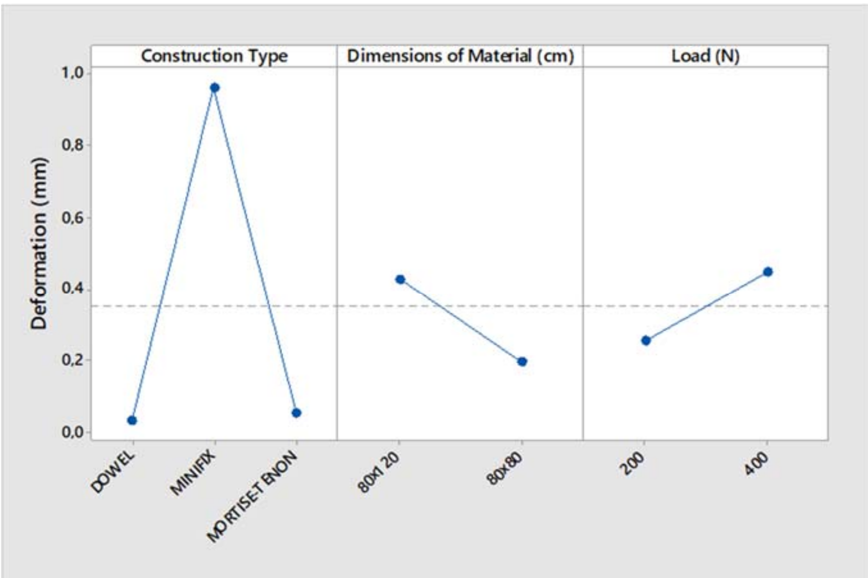

Fig. 4b. Main effects results for deformation.

Conclusions

In this study, mortise and tenon, dowel and minifix joint types were applied in table model joints produced from oak wood solid material and their strength bearing performances under static loads were determined and evaluated. The results obtained are given below.

Different results were obtained for each of the three types of constructions statically analyzed by finite element method. According to the results, the least affected construction is the dowel type joint with 0.20-0.96 MPa equivalent stress and 0.001-0.82 mm deformation. Also, mortise type joint is close to dowel type joint with 0.17-2.68 MPa equivalent stress and 0.02-0.17 mm deformation. The Minifix construction type was found to be more affected by the applied forces than the other two construction types. This study shows that researchers can also compare their results with different constructions, wood materials and furniture using the FEM analysis method.

The forces applied to the short sides and long sides of the rectangular tables showed that the deformations and stresses on the long sides were higher according to the analysis data.

The forces applied to the short sides and long sides of the rectangular tables showed that the deformations and stresses on the long sides were higher according to the analysis data. ANOVA analysis demonstrated that furniture construction type, dimensions of material and load. The effects of construction type, dimensions of material, and load were experimentally investigated. The model summary that R^2 and $Adj\text{-}R^2$ values were found as 87.74% and 73.94% for stress and 90.26% and 51.72% for deformation, respectively.

Interactions of construction type, load, construction type and load properties were significant for stress in the analyze of variance. However, interactions of construction type, dimensions of material, load, construction type and dimensions of material, construction type and load were significant for deformation in the analyze of variance.

It has been seen that the use of computer technology in design of furniture elements and analysis therefore can provide important facilities for designers and manufacturers.

Using computer technology in design of furniture elements and analysis can offer important opportunity to obtain preliminary information about the resistance of the designed furniture under the loads. Additionally, this approach can provide significant facilities to designers and manufacturers in order to be made improve before the production and use of the furniture.

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