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THE EXPERIMENTAL AND FINITE ELEMENT ANALYSIS OF DIAGONAL TENSILE TESTS CONDUCTED ON FRAME-TYPE CONSTRUCTED CORNER JOINTS

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Abstract

This study investigates the diagonal tensile strength of frame-type constructed furniture corner joints using four different joint elements; a plastic "L" corner joint, a minifix, a metal "T" joint, and a bent metal "T" pulling joint. The wooden material used in experiments was Eastern beech. Frame-type constructed furniture corner joints were supported with non-adhesive dowels. Diagonal tensile tests were conducted on test specimens in accordance with TS 5913 and ASTM 1037 standards, which represent opening and closing; they were tried under static loads taking into consideration the loads they might face during usage. The ANSYS 12.1 Release Workbench module was used for analyses. Analyses were conducted by inputting the average tensile strengths obtained from tests; the obtained ANSYS data was then compared to the real test data. The consistency level between the deformation obtained from tests and the deformation obtained from using ANSYS was 88.6%.

Keywords: Mechanical fastening; Materials Joining, Strength; Furniture joints.

1. Introduction

Furniture has become a part of daily life and is used actively in homes, schools, and offices. As with all sectors, the system used in the furniture sector also goes through numerous design phases before manufacturing. Deformation may arise in certain parts due to various loads. The designer looks for answers as to whether or not the system works securely under the said loads. Recognising the possible tensions that may arise in furniture due to working conditions under various loads beforehand, and identifying flaws is extremely important in terms of safety. The finite element method (FEM), used in numerous areas of engineering, is used in the furniture designing process, as well.

In general, furniture is assessed under three construction groups depending on their construction design; frame (skeleton) type, can (panel) type, and combined (compound winding) type. Furniture manufactured using panels is called can-type constructed furniture, those manufactured using solid frames is called frame-type constructed furniture, and those manufactured using both panels and solid frames is called combined-type constructed furniture. In general, the mechanical behaviour properties of furniture systems depend on what the elements are made from and the joining techniques used to join these elements [1, 2].

In frame-type constructed furniture, the skeleton part of furniture such as upholstered armchairs, chairs, and couches, and elements of frame systems in various chairs are joined using different joining techniques. Among these techniques, adhesive dowel joints and adhesive end to side grain joints are both techniques that have been used for years; however, the adhesive and non-adhesive use of joints that enable mechanical joints, such as screwed joints, minifixed joints, and stapled joints, are becoming more and more common [3].

Furniture corner joints are exposed to strains such as tension, compression, bending, and shearing. These strains cause joints to bend, crack, break, stretch, and come apart. The magnitude of deformation depends on the type of wooden material and the type of joint [4].

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Smardzweski and Prekrad investigated the strength features of demounted jointing in metal constructed acme joints. In their study, they talk about the advantages of mechanical joint elements [5].

FEM’s can be used in most of the phases incorporated in the designing process of modern furniture thanks to the common use of computers and developing technology. By modelling all elements of the system parametrically, all amendments can easily be made thanks to the advantage of solid modelling. Strength analyses for the system can be conducted using computer-aided analysis programmes. Computer-assisted Designing (CAD) and Computer-assisted Manufacturing (CAM) are both used in manufacturing and designing furniture, and contribute significantly to the quality of the product [6].

Cai et al analysed and compared the strength and stiffness of can constructed “moltinject” joints and dowel joints. They also managed to estimate reasonably the deformation of “moltinject” type corner joints using the finite element method [7].

Gustafsson emphasised that as technology developed finite element programmes could be used in most of the phases incorporated in the design process. In an effort to prove his argument, he used the finite element method to conduct the structural analysis of a simple chair, and indicated that the chair would have the same strength even in the event that the measurements of the elements used were reduced [8].

Gustafsson illustrated how a chair could be analysed and designed using the FEM, and provided stress diagrams and test results for an actual size chair that he built from common ash [9].

Smardzewski conducted a study to develop software that would analyse the side frame strength of skeleton furniture, in order to obtain a construction type where material use is minimal and the strength of system elements and joints are maximum. To prove his argument, he analysed the side frame of a chair. As a result, he proved that the programme he had developed was able to analyse the stiffness and strength of wooden furniture constructions correctly and rapidly [10].

Jensen et al used two theoretical solutions, with the same computer base, to analyse the axial tensile strengths of dowel joints; linear elastic fracture mechanics (ideal plasticity) analysis, and linear elastic stress analysis. After comparing the theoretical and experimental results, they stated that the sliding resistance and the fracture energy along the adhesive line were indicators of joint strength [11].

Nicholls and Crisan analysed the tension in corner joints of dowel joined and minifixed can-type constructions using the finite element method. They concluded that stress concentration points formed in solid models developed in the same way as they do in real joining, as well as determining stress distributions at corner joints [12].

Kasal et al conducted experimental and finite element analysis by establishing three different side frame types for non-adhesive – screwed wooden and composite materials. According to experiment results, the chair skeletons, made using three different types of side frames, portrayed different mechanical properties, and significant values were obtained from finite element analysis. In conclusion, they stated that joints were crucial points, and indicated that stronger joints could be achieved by using materials with higher bending strengths [13].

The aim of this study is to examine the applicability of computer aided analyses program in frame type furniture design. Finite element analyses of various frame type furniture joints were used and the strength analyses of the joined parts were carried out. Experiments were also carried out and the both results were compared.

2. Materials and Method

2.1. Wooden Material

The wooden material used to prepare test samples was Eastern beech, commonly used in our country.

2.2. Dowel

In accordance with TS 4539 standards, the dowels used in experiments were smooth grooved beech dowels with a diameter of 10 mm, and a length of 46 mm (Figure 1).

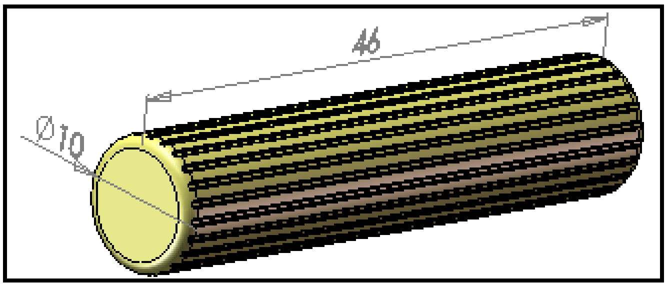

Figure 1. Dowel used in experiments.

2.3. Screw

Screws are joining elements made for various metals such as steel, brass, copper, bronze, cadmium, and aluminium that have a spiral jointer effect. Importance must be paid when drilling tap holes for screwed joints. The external diameter of the screw used must be 3.5 mm, and its thread length must be 25 mm (Figure 2).

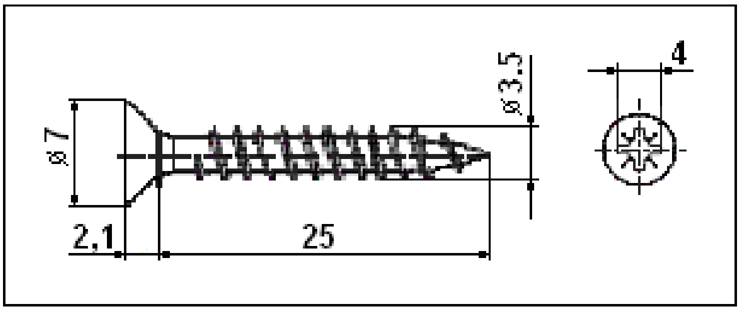

Figure 2. Screws used in experiments [14].

2.4. Minifix Joint Element

It is a joint element made from oxidation-proof metal, formed from a curved lined caused by distal points that works based on a cylindrical element (one end is screw shaped and the other end has a special form) tightening another shaped element (Figure 3). The tenacity of this joint element is increased by its internal and externals tabs. The tab in the body of the shaft enables the dowel to fit completely into its slot, and achieves a strong interlock. Minifix joint systems protect the furniture from wear due to incorrect assembly, as well as enabling easy assembly. It is not visible from the outside [15].

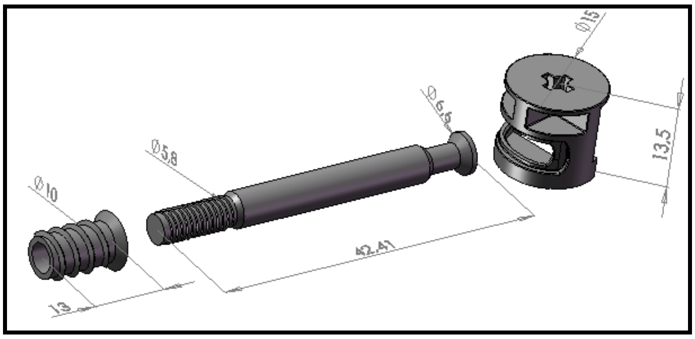

Figure 3. Minifix Joint Element

2.5. Plastic "L" Corner Joint Element

The plastic "L" corner joint element makes securing joints in furniture, and disassembling and reassembling furniture, when necessary, easy (Figure 4) [15]. The contact surface area of the joint element was 1537.14 mm^2.

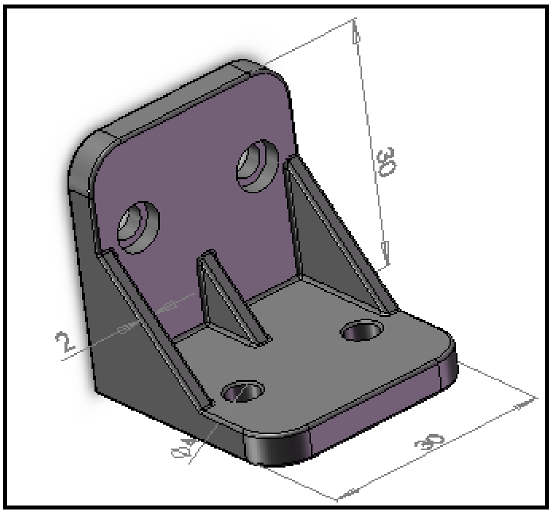

Figure 4. Plastic “L” Corner Joint Element

2.6. “T” Pulling Corner Joint Element

The “T” pulling corner joint element has the ability to be arranged according to the thickness of the material to be joined. It is used to secure corner joints (Figure 5). The contact surface area of the joint element was 684.19 mm^2.

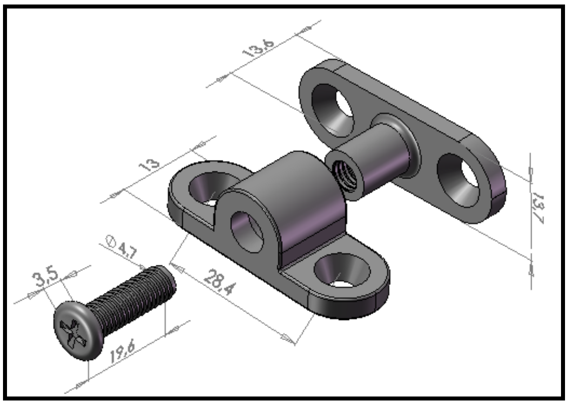

Figure 5. “T” Pulling Corner Joint Element

2.7. Bent Metal “T” Pulling Joint Element

The bent metal “T” pulling joint element is a practical joint element used as a corner joint in furniture and kitchen cabinets. In general, it comprised of two elements; one is joined to the horizontal panel, and the other is joined to the vertical panel (Figure 6). The contact surface area of the joint element was 731.02 mm^2.

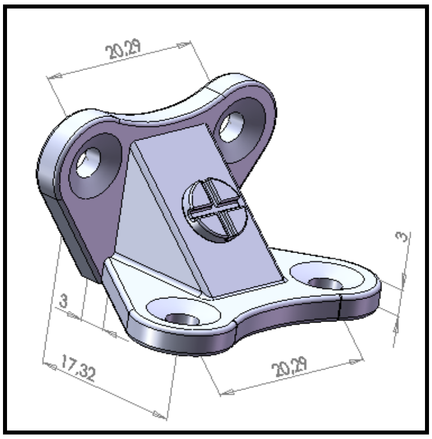

Figure 6. Bent Metal “T” Pulling Joint Element

2.8. The Preparation of Test Samples

The wooden material was randomly chosen from the market. After being brought to it rough measurements, it was kept at 20 ±2 C° in an environment that could be ventilated but received no sunlight, with a humidity of 65±5 %, for approximately six months, until it reached a humidity level of 12%. Attention was paid to make sure that the wooden material obtained from the market was not cracked, knotted, dry, or affected by insects.

While the widths of the samples were determined in accordance with TS 5913, their lengths were determined by taking into consideration the minimum and maximum measurements of the test equipment [16]. Every test sample comprised of an A and B element (Figure 7). Element A was 259 x 41 x 41 mm, and element B was 300 x 41 x 41.

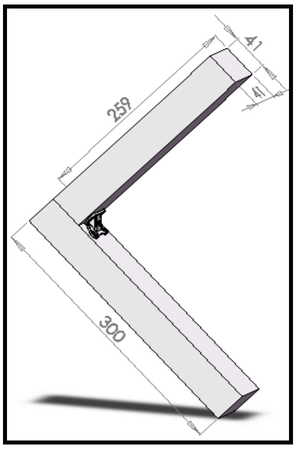

Figure 7. Dimensions of Test Samples

Dowels were used in order to increase the strength of the system and support joining elements. A ø10 28-mm deep hole was drilled for element A, and a 22-mm deep hole was drilled for element B. The distance between the dowels was 21 mm (Figure 8). The contact surface area of wooden materials (A and B) was 2885.84 mm^2.

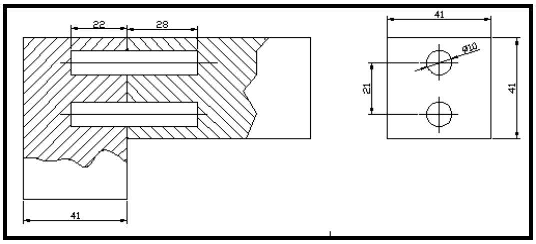

Figure 8. Measures of Drills in Dowel

2.9. The Experiments

A 5000-kg capacity Universal Zwick Roell Z50 test device was used in experiments. The highest diagonal tensile strengths were transferred to the computer. Figure 9 illustrates the diagonal tensile test layout.

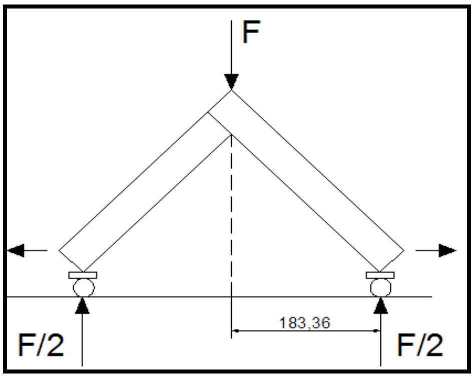

Figure 9. Diagonal Tensile Test Setup

Stated below is the equality used to calculate the moment force for the diagonal tensile tests.
Mç=F maxç x Lb /2.
Where;
Mb= Moment (Nm)
F maxb= Maximum force at fraction (N)
Lb= Moment arm (m).

2.10. Computer-Based Analysis

Nowadays, the FEM is a numerical method effectively used to resolve complex engineering problems. The fundamental purpose of the FEM is that it breaks down a complex problem and finds a solution. The solution domain of the FEM comprises of sub-regions called finite elements, which there are a lot of, which are simple, small, and connected. These elements are connected to one another with nodal points [17].

The parametric solid models in this study were prepared using the SolidWorks programme. The Workbench module of ANSYS was used to conduct the finite element analysis of joints. Force was applied to the test apparatus in the direction of A. Freedom was given in the direction of y from sides B and C (Figure 10).

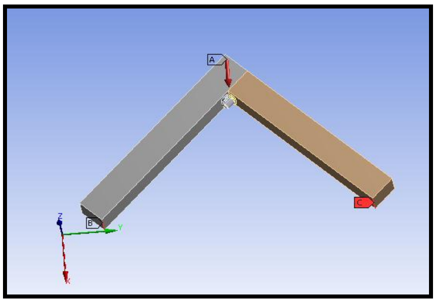

Figure 10. ANSYS 12.1 Realise Workbench Diagonal tensile practice.

The sections of the joints were meshed tighter to increase analyses reliability. For the sample to be analysed, the phases of ANSYS Workbench are that it establishes its CAD model, defines its material, meshes it, and applies loads to it.

Table 1 illustrates the mechanical properties inputted to the ANSYS 12.1 Workbench module for the eastern beech. Table 2 illustrates the mechanical properties of the metal joint element. Table 3 illustrates the mechanical properties of the plastic “L” joint element.

Table 1. Properties of Metal Joint Elements.

Density	7850 kg m3
Modulus of Elasticity	2E405 Mpa
Poisson Ratio	0,3
Bulk Modulus	1,6667E+11 Pa
Modulus of Shear	7,6923E+10 Pa
Yield Stress	250 MPa
Tensile Stress	460 MPa

Table 2. Properties of Eastern beech [18].

Modulus of Elasticity (X)	14010 MPa
Modulus of Elasticity (Y)	1160 MPa
Modulus of Elasticity (Z)	2280 MPa
Poisson Ratio XY	0,448
Poisson Ratio YZ	0,073
Poisson Ratio XZ	0,708
Modulus of Shear XY	470 MPa
Modulus of Shear YZ	1640 MPa
Modulus of Shear XZ	1080 MPa
Yield Stress	50 MPa
Tensile Stress	75 MPa

Table 3. Properties of Plastic “L” Corner Joint Element.

Density	950 kg m^-3
Modulus of Elasticity	1100 MPa
Poisson Ratio	0,42
Bulk Modulus	2,2917E+09 Pa
Modulus of Shear	3,8732E+08 Pa
Yield Stress	25 MPa
Tensile Stress	33 MPa

2.11. Data Evaluation

Multiple variance analysis was used to determine the effect joint types had on the diagonal tensile performance of “T” type corner joints. In the event that differences were p< 0.05, the least significant difference (LSD) test was applied to determine the significance of the difference among groups.

3. Findings and Discussions

3.1. Diagonal Tensile Strength

Table 4 illustrates the mean, lower limit, upper limit, and standard deviation for the diagonal tensile strength of test samples.

Table 4. Statistical Results about Diagonal Tensile Testing for N type joint

Dimension (mm)	Joint Type	Average (N)	Standard Deviation (N)	Lower limit (N)	Upper limit (N)
	‘T’ Tensile	1294,3	344,85	1064,6	1524
	Bent Metal “T”	1693,4	300,11	1463,7	1923,1
	Plastic ‘L’	645,4	137,12	415,73	875,07
	Minifix	470,6	83,41	240,93	700,27

Table 5 illustrates the results of the multiple variance analysis, conducted to determine the effect joining elements have on the diagonal tensile strength of test samples.

Table 5. Results of Multiple Variance Analysis

	Sum of Squares	Degree of freedom	Mean Square	F Value	Significance level (p<0,05)
Model	4853665,74	3	1617888,58	27,57	0
Interaction	21050442,11	1	21050442,1	358,69	0
Joining	4853665,74	3	1617888,58	27,57	0
Error	938998,63	16	58687,41		
Total	26843106,48	20			

Multiple variance analysis, conducted to identify the effect joint element type has on diagonal tensile strength, was statistically significant 95% in confidence interval. Table 6 illustrates the results of the Duncan Test, conducted to determine the applications in which the difference is important.

Table 6. Results of Duncan Test

Interactions	Average	Homogeneity Group
Minifix	470,6	A
Plastic ‘L’	645,4	A
‘T’ Pulling	1294,3	B
Bent Metal ‘T’	1693,4	C

According to the results of the Duncan Test, there is a significant difference with a 5% error among joining elements and different groups are shown in different homogeneity groups. Moreover, the minifix joint and the plastic “L” joint are shown under the same homogeneity group as no significant difference was found between them according to the results of the Duncan test.

3.2. Finite Element Analysis Results

3.2.1. Minifix Joints

The dowel of minifix pulling shaft was forced to pull in the y direction as elements A and B were given freedom at the sides with the effect of the load applied from a side A. The highest tension arose where the minifix pulling shaft joined the dowel. The deformation obtained from ANSYS was 19.32 mm (Figure 11).

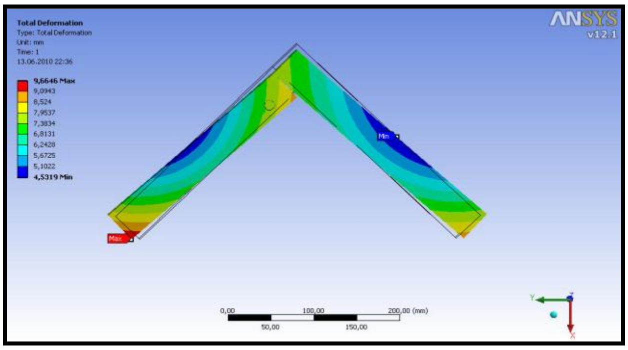

Figure 11. FEM analysis of Minifix Joint

3.2.2. Plastic “L” Joint

As a result of the tensile strength, the highest tension, 187.69 MPa, was obtained at the interior of element A, and the end of the dowel. There were breaks at both ends of the dowel. The deformation obtained from ANSYS was 10.001 mm (Figure 12).

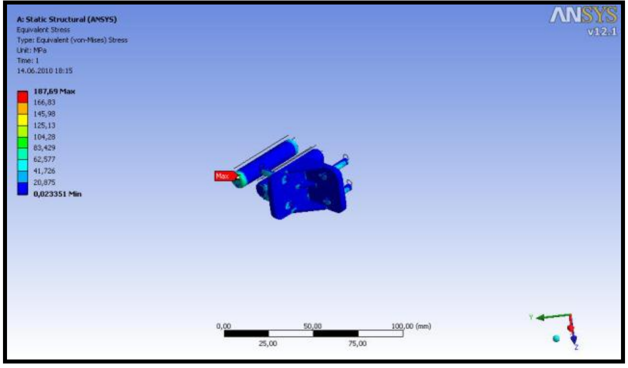

Figure 12. FEM Analysis of Plastic ‘L’ Corner Joint Element

3.2.3. “T” Pulling Joint

As a result of the tensile strength, the highest tension, 1478 MPa, was obtained in the joint where it joined the screw. The deformation obtained from ANSYS was 11.443 mm (Figure 13).

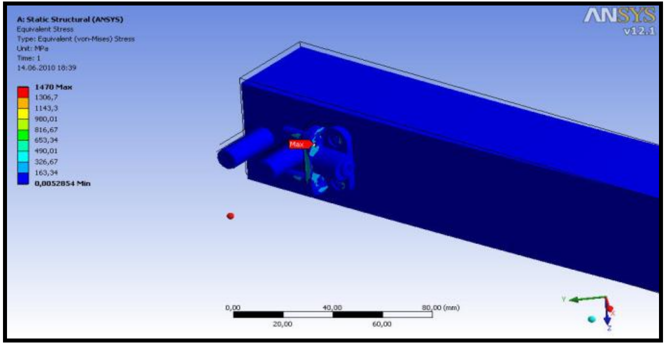

Figure 13. FEM Analysis of “T” Pulling Corner Joint Element

3.2.4. Bent Metal 'T' Pulling Joint

As a result of the tensile strengths the lower part of the joint forces the part on top. This is where the highest tensions were obtained (Figure 14).

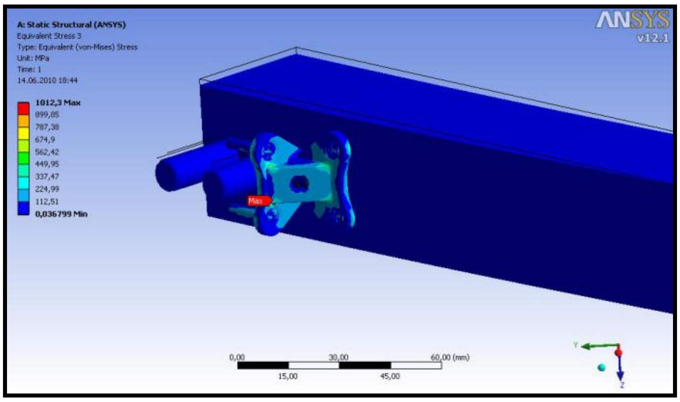

Figure 14. FEM Analysis of Bent Metal "T" Pulling Joint Element

3.2.5. Deformation Characteristics and the Comparison of Test Results

According to deformation results in Table 7, there are some harmonies between experimental and ANSYS results. The consistency level between the deformation obtained from tests and the deformation obtained from using ANSYS was 88.6%. The highest consistency can be seen in Plastic "L" joint element and Curved Metal "T". However, there is a disharmony in Bent metal "T" pulling joint element. According to test results, the bent metal "T" joint element had the highest tension strength, and the minifix joint element had the lowest tension strength. The reason why the bent metal "T" pulling joint element had the highest tension strength was because its joining surface areas to the wooden material were more than the others. According to the data obtained from ANSYS and test results, the reason why the plastic "L" joint element, the "T" pulling joint element, and the bent metal "T" pulling joint element are better than the minifix joint is because they are joined to wood with screws; in other words, it is the screw tabs holding on to the fibre. In addition, as only one dowel is used in minifixed joints because of joint features, the strength is lower.

Table 7. Comparisons of Test and ANSYS deformation in diagonal tensile tests

	Test deformation (mm)	Ansys deformation (mm)
Minifix	17,298	19,32
Plastic 'L'	9,404	10,001
'T' Pulling.	15,104	11,443
Bent Metal 'T'	17,628	16,77

During diagonal tensile tests, the lower section of the bent metal "T" pulling joint cuts through the part left on top as a result of the tensile strength. The corner sections, where tension is high (dangerous) are illustrated in red in Figure 15.

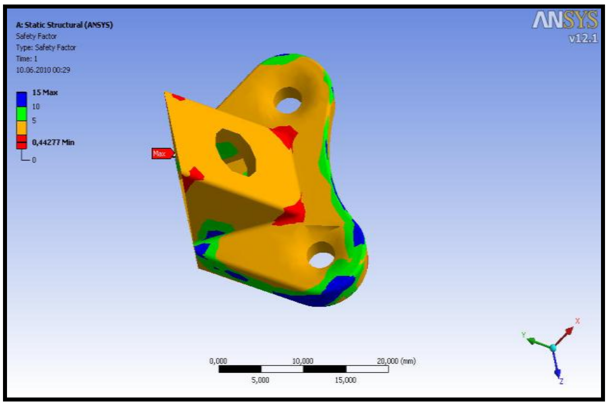

Figure 15. Secure locally of Bent Metal "T" Pulling Joint Element

The highest tension for the deformation section of the joint was 1012.3 MPa (Figure 16).

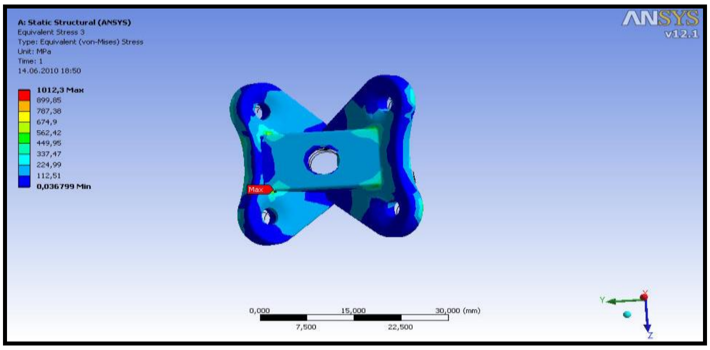

Figure 16. Tension Values of Bent Metal "T" Pulling Joint Element

Figure 17 illustrates the sections where joint elements were deformed during tests. Tears occurred in joint element as a result of strain. Results of ANSYS analysis also illustrate that tensions are dense in the same regions in Figure 15.

Figure 17. The experimental deformations of Bent Metal "T" Pulling Joint Element

4. Conclusion and Suggestions

In the study, finite element analysis was conducted for joints by defining the orthotropic material in the ANSYS® finite element programme. The results obtained from the finite element analysis were compared to the test results. Comparison conclusions illustrated that the computerised FEM was very similar to the real behaviour. The consistency between deformations obtained from test data and ANSYS was 88.6%. ANSYS data was a lot more detailed in comparison to tests. As a result of loads applied, the joint was exposed to a bending force. According to ANSYS data, the highest tension was seen in joining elements. As a result, cracks and separations occurred in the joining elements. In conclusion, it is possible to state that joints are crucial and represent the strength of the system.

The non-dense structure of the wood should be taken into consideration in order to obtain reasonable results from computer-assisted analysis; this is why material definition should be orthotropic. Extensive meshing in corner joint regions is important for the reliability of the analysis. According to the finite element analysis, the most tension occurs in the joining elements. According to tests, the most fractures occur at the joining elements. As a result, attention should be paid to the choice of the joining element when designing frame-type constructed furniture.

Using FEM in furniture design has improved quality and reduced the need for creating and testing a physical prototype in design. However, FEM is not adequate alone. It should be supported with detailed design and the results of the experimental tests.

In addition, for computer aided engineering applications, particularly most of the analysis software, the wooden material characteristics are not defined. The wood, displays a specific behavior with its heterogeneous and anisotropic structure and therefore it is needed to develop special coefficients suitable to wood or virtual resistance values with another approach [19].

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