

Research Survey**Investigation of Joining Methods of Honeycomb Composite Panels Used in Structural Elements of Aircraft Cabin Units**

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Abstract

The design, material selection, manufacture and assembly of aircraft structural elements are critical issues in the aviation industry. This study aims to optimize the selection of joining methods of aircraft honeycomb panels by considering strength, cost, and weight parameters. Accordingly, panel type, panel thickness and joining methods were determined as input parameters, and fracture force, displacement, cost, and weight as output parameters. Tenon-mortise, double-sided bracket, single-sided bracket, and extrusion methods were investigated for L and T-type panels. Panel thicknesses were determined as 10 mm and 22 mm according to standards. Tensile test and finite element analysis were applied to the samples to examine their mechanical behavior. The weight and cost of the panels were determined by the process analysis. The obtained findings were optimized according to multi-criteria decision making and response surface analysis methods. In the optimization model, maximization of tensile strength and minimization of displacement, cost and weight was determined as the target function. At the end of the study, the optimum thickness value for both types of panels was determined as 22 mm, and the optimum joining method was tenon-mortise.

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Uçak Kabin Ünitelerinin Yapısal Elemanlarında Kullanılan Bal Peteği Kompozit Panellerinin Birleştirme Yöntemlerinin İncelenmesi**Makale Bilgisi**

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Öz

Hava taşıtlarında kullanılan yapısal elemanların tasarımı, malzeme seçimi, üretimi ve montajı havacılık endüstrisinin kritik problemleridir. Bu çalışma, mukavemet, maliyet ve ağırlık parametreleri dikkate alınarak uçak bal peteği panellerinin birleştirme yöntemlerinin seçimini optimize etmeyi amaçlamaktadır. Panel tipi, panel kalınlığı ve birleştirme yöntemleri giriş parametreleri olarak, kopma kuvveti, yer değiştirme, maliyet ve ağırlık çıktı parametreleri olarak belirlenmiştir. L ve T tipi paneller için tenon-mortise, çift taraflı braket, tek taraflı braket ve ekstrüzyon birleştirme yöntemleri araştırılmıştır. Panel kalınlıkları standartlara göre 10 mm ve 22 mm olarak belirlenmiştir. Mekanik davranışlarını incelemek amacıyla numunelere çekme testi ve sonlu eleman analizi uygulanmıştır. Panellerin ağırlığı ve maliyeti süreç analizi ile belirlenmiştir. Elde edilen bulgular, çok kriterli karar verme ve yanıt yüzey analizi yöntemlerine göre optimize edilmiştir. Analizde, çekme dayanımı maksimizasyonu, yer değiştirme, maliyet ve ağırlık minimizasyonu hedef fonksiyonlar olarak belirlenmiştir. Çalışma sonunda her iki tip panel için optimum kalınlık değeri 22 mm, optimum birleştirme yöntemi ise tenon-mortise olarak belirlenmiştir.

1. INTRODUCTION

The components of the aircraft can be classified as internal and external elements. While the external elements constitute the fuselage, wings and tail gear, the internal elements consist of equipment to meet the needs of the passenger and crew [1], [2]. These parts can be listed as overhead cabinets, armchairs, washbasin systems, galley (kitchen) equipment and bar units [3]. The structural framework of these parts usually consists of honeycomb composite panels. Honeycomb sandwich composites are preferred in the aeronautical industry due to their lightweight, high strength and low production cost compared to other materials [4]. The support of the honeycomb cells in these panels, increases the load-carrying capacity, torsion and bending resistance [5]. Also, when compared with other materials, its impact absorption properties are relatively high [6].

Composite panels go through the standard certification process to confirm their usability, like any equipment in the aerospace industry. This certification process includes every stage from design to production of panels. Even the joining methods (applied during assembly) directly affect the test results for certification. Tenon-mortise, bracket and extrusion methods are used for joining the composite panels. In the tenon-mortise joining method, one of the panels has a mortise (female) part with a certain depth, and the other has a tenon (male) part that will enter the mortise. The dimensions (thickness, depth, width, and length) of the tenon and mortise parts vary according to the standards. Bracket joining method can be used as an alternative to the tenon-mortise method. In this method, two composite panels are joined with a joining element called a bracket. Aluminium is preferred as a bracket material due to its advantage in terms of weight and cost. Extrusion method is another joining method, used especially in corner joints. In this method, an extrusion element made of aluminium with a particular geometry is used to join two composite panels. After the joining element is attached to the panels, it is fixed with an epoxy adhesive that can be cured at room temperature, does not burn, and release toxic gas.

There are many studies in the literature examining the effect of different joining methods on panel strength. Diler E.A., investigated the mechanical properties of six different T-type joint methods experimentally and

numerically. As a result of the study, he stated that “joining with 70 mm radius element” has the highest mechanical properties. He reported that “flat sandwich T-type joint” has less strength but would be preferred in positions not exposed to load [7]. Bianchi et al. joined sandwich composite panels with T-type bracket, corner, and end-to-end methods. They applied tensile, compression, shear, and torsion tests to the samples. They also modelled the structures with computer-aided analysis software and, compared the data of the analysis and the experimental results. As a result, it was stated that the strength of the bracket method is higher than other joint methods [8]. Heimbs and Pein joined glass fiber reinforced sandwich composite panels with three different joining types. They performed shear and bending tests to determine the mechanical properties of the joining types. As a result of the tests, they examined the failure behaviour of the samples. In all experiments, it was observed that the most effective factor that causes breakage was the loading speed. The samples were modelled in the LS-DYNA (computer-aided analysis software), and similar results were obtained with the tests [9].

It was determined that the studies in the literature focused on modelling composite panels and investigating their mechanical properties experimentally and numerically. However, the aircraft panels should be selected and assembled by the optimization of parameters such as cost, weight, mechanical properties, and geometric design. The novelty of this study is to determine the joining methods that provide maximum strength, minimum cost, and minimum weight. Accordingly, strength, cost and weight parameters were determined according to the location and functional properties of aircraft composite panels. L-type panels were joined with tenon-mortise, bracket and extrusion joining methods, while T-type panels were joined by tenon-mortise, double-sided bracket, and one-sided joining methods. The tensile stress of the panels was determined by tensile tests. The displacement of the joints was determined by using the computer-aided analysis software. Also, as a result of the process analysis, the cost and weight values of the panels were obtained. The results were optimized by the multi-criteria decision making and response surface analysis method.

2. MATERIAL AND RESEARCH METHODS

2.1. Joining Methods for Honeycomb Panels

L and T-type honeycomb composite panels with 10 mm and 22 mm thickness were used in this study (Table 1).

L-type panels are joined with tenon-mortise (TM), bracket (B) and extrusion (E) methods.

T-type panels were joined with TM, double-sided bracket (DSB) and one-sided bracket (OSB) methods (Figure 1). The dimensions determined in the TM application were the same as the L-type

panel. Schematic representation of the joining types is given in Figure 2. Panel and joining element sizes used in the experimental study are given in Table 1. 3M™ Scotch-Weld™ EC-9300 B / A FST epoxy adhesive was used between the panel and the joining element in all processes. This adhesive has low viscosity and resistant to chemical reactions and can be cured at room temperature. 36 test coupons were prepared with 3 replicates for each experiment. Test coupons prepared for experimental study are given in Figure 3.

Table 1. Properties of panels and joining elements used in the experiments

Panel Type	Joining Method	Panel Size (mm)
L	TM	470 * 300 * 10
L	TM	470 * 300 * 22
L	B	470 * 300 * 10
L	B	470 * 300 * 22
L	E	470 * 300 * 10
L	E	470 * 300 * 22
T	TM	470 * 300 * 10
T	TM	470 * 300 * 22
T	OSB	470 * 300 * 10
T	OSB	470 * 300 * 22
T	DSB	470 * 300 * 10
T	DSB	470 * 300 * 22

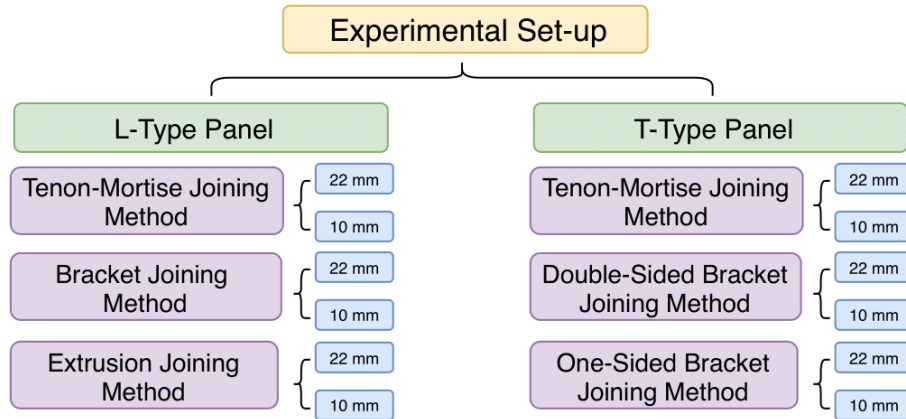


Figure 1. Experimental set-up

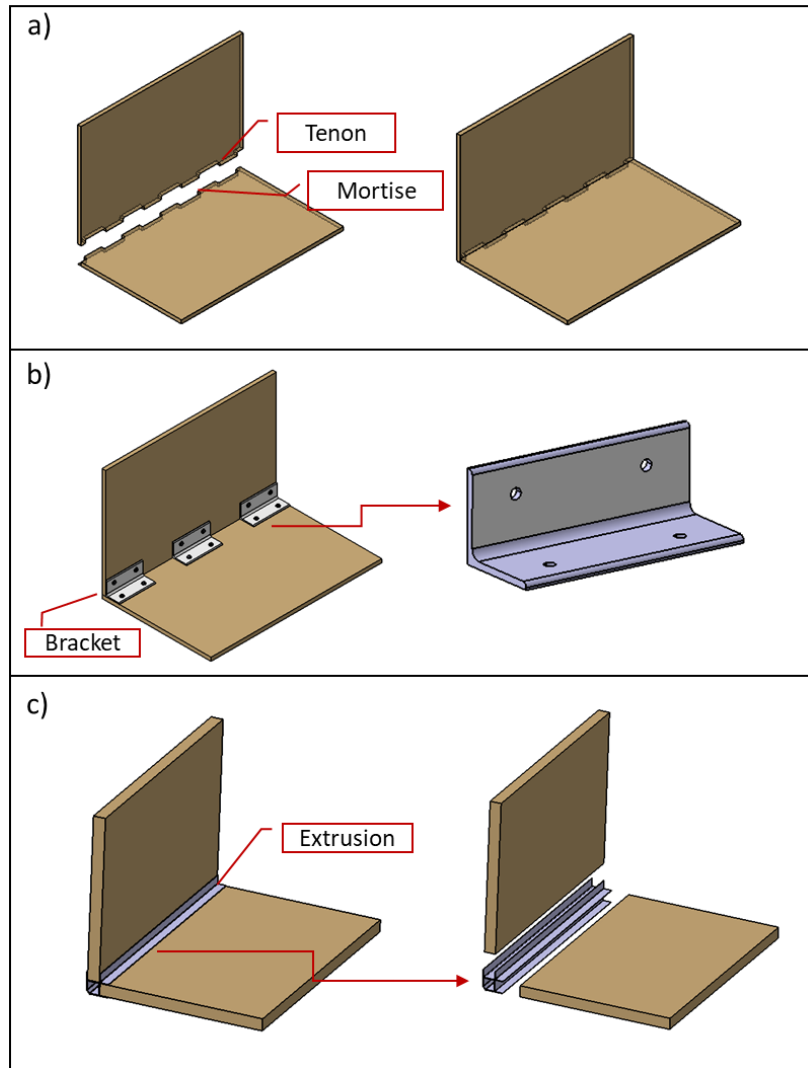


Figure 2. Schematic representation of joining types



Figure 3. Test coupons prepared for experiments

2.2. Experimental Methodology

The prepared test coupons were subjected to a tensile test at a speed of 0.01 mm/s. The test unit used included an electric winch, hoist rope, load cell, connection hook, panel connection apparatus and z-axis restrictor (Figure 4). In the first stage of the tensile test, the horizontal panel was fixed to the floor, and the vertical panel was clamped to the pulling apparatus with connection pins on both sides. A remote-controlled crane was used for loading. A load cell measuring 0-5000 N was attached to the end of the crane. The experiments were carried out by applying force to the samples in the vertical direction.

2.3. Finite Element Model for Honeycomb Panels

After applying the tensile test, finite element analysis was performed with FEMAP (computer-aided analysis software) to determine the amount of displacement in the failure zone. All test coupons were modelled in 3D with CATIA (computer-aided design software) and transferred to FEMAP. Shell element type was preferred due to high planar area/thickness ratio of geometry. Honeycomb panels were modelled using shell elements as a multi-layered composite with a first-order quadrilateral (CQUAD4) and triangular (CTRIA3) to include shear, bending and membrane deflections. Quadrilateral elements were preferred to idealize the panels. Triangular elements are acceptable for load modelling; however, triangular elements should be minimized as they are not acceptable for stress models, especially at critical locations. The elements represented multi-layered composite build-up which includes core and face sheets. Aluminium doublers were added to both sides. Material properties and ply orientation were defined according to the material specification per the commodity

design/drawing. It is important to pay attention to the core-ribbon direction as the ribbon direction generally provides a higher shear capability than the transverse (non-ribbon) direction. The core-ribbon direction may not be specified for ease of manufacturing, and the analysis must account for the most conservative lay-up orientation. Additionally, since the panel thicknesses are 10 mm and 22 mm, FEM results created using first order shear deformation theory (FSDT) were valid.

The number of elements of each geometry is given in Table 2, and an example of meshed geometry is shown in Figure 5. In similar studies in the literature, mesh sizes between 5 mm and 20 mm were used [10, 11, 12]. It has been stated that this range is sufficient for the aviation industry. For this reason, a mesh convergence graph is not needed. The value of 5 mm was used in the article, and analyses were performed on the fine mesh model. Elements were classified as plate (MAT1), laminate plate (MAT8) and rigid elements. Laminate plate for composite panels, plate element for brackets and extrusions were selected. RBE2 was chosen as a rigid element for mechanical connections. For isotropic materials, elasticity modulus, Poisson's ratio, thermal expansion coefficient, conductive coefficient, and density values of AA6061 material were defined. Orthotropic materials were classified into two different materials as ply and core. The hardness value of the ply material is 18000E, the Poisson's ratio is 0.22 and the hardness value of the core material is 0.2E, the Poisson's ratio is 0.5. The 10 mm thick panel was designed to be 0.33 mm ply on the bottom and top surfaces and 9.34 mm core in between. The 22 mm thick panel was designed to be 0.33 mm ply on the bottom and top surface and 21.34 mm core in between. The tensile strength values used in the analysis were determined based on the fracture force of each test sample.

Table 2. Number of meshes of analyzed geometries

Panel Type	L-type						T-Type					
	10			22			10			22		
Thickness (mm)												
Joining Method	TM	B	E	TM	B	E	TM	DSB	OSB	TM	DSB	OSB
Number of Elements	11092	12300	12314	11092	12300	12314	11186	18478	14975	11186	18478	14975

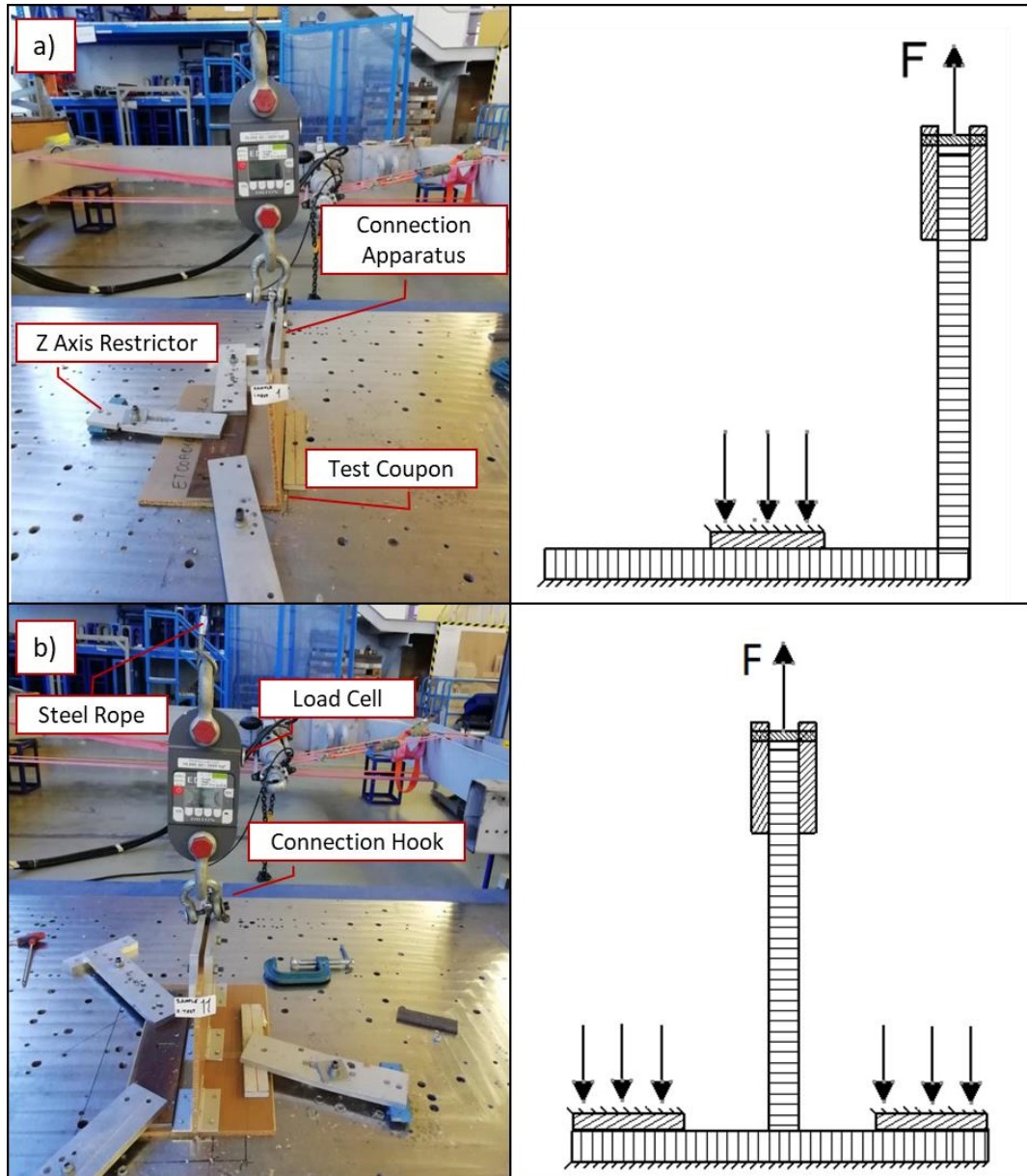


Figure 4. Tensile test principle and setup: a) L type panel, b) T type panel

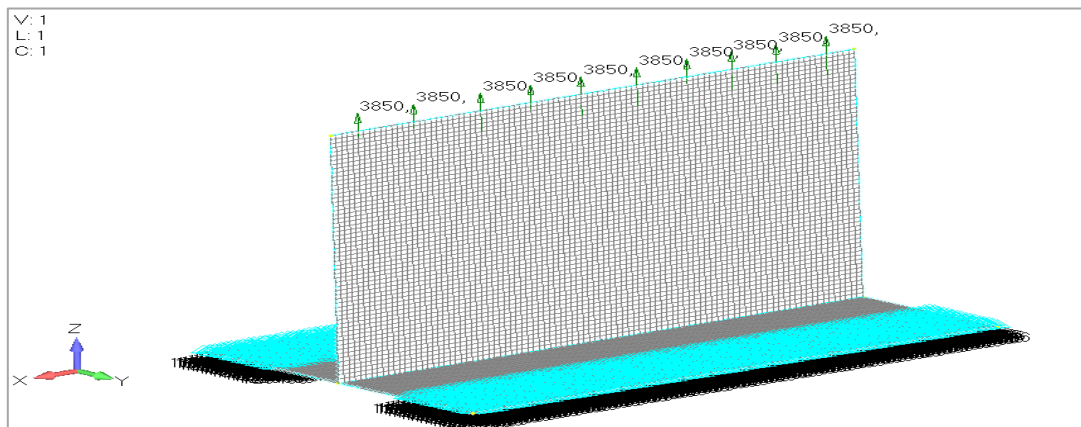


Figure 5. Meshed geometry

2.4. Optimization with TOPSIS and Response Surface Method

The variables determined within the scope of this study were analyzed by multi-criteria decision making and response surface methods. The input parameters were determined as panel type, panel thickness, joining methods (Table 3) and the output parameters were determined as fracture force, displacement, cost, and weight. These parameters were obtained by taking the average of the test results performed in 3 repetitions. The input, output and optimization parameters are given schematically in Figure 6. In the analysis, tensile strength maximization, displacement, cost, and weight minimization were determined as target functions.

Table 3. Input parameters determined in the experimental study

Panel Type	Panel Thickness (mm)	Joining Method
L	10	TM
L	10	B
L	10	E
L	22	TM
L	22	B
L	22	E
T	10	TM
T	10	DSB
T	10	OSB
T	22	TM
T	22	DSB
T	22	OSB

In the present study, TOPSIS method was preferred among multi-criteria decision-making methods. The TOPSIS method is an algorithm created on the principle of determining the closest point to the positive ideal solution and the furthest point to the negative ideal solution [13]. Alternative variables to be analyzed are compared between their maximum and minimum values in line with specific criteria [14]. Five basic mathematical expressions are needed to apply the TOPSIS method [13, 15]. These expressions are as follows.

1. Matrix normalization (Equation 1):

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad j = 1,2,3 \dots, n; i = 1,2,3, \dots, m \quad (1)$$

2. Obtaining the weighted normalized decision matrix (Equation 2):

$$V_{ij} = n_{ij}w_j \quad j = 1,2,3 \dots, n; i = 1,2,3, \dots, m \quad (2)$$

3. Calculation of ideal solutions (Equations 3 and 4):

$$\{V_1^+, V_2^+ \dots, V_n^+\} \left\{ \begin{array}{l} (Max V_{ij} | j \in K), \\ ((Min V_{ij} | j \in K') | i = 1,2,3 \dots, m) \end{array} \right\} \quad (3)$$

$$\{V_1^-, V_2^- \dots, V_n^-\} \left\{ \begin{array}{l} (Max V_{ij} | j \in K), \\ ((Min V_{ij} | j \in K') | i = 1,2,3 \dots, m) \end{array} \right\} \quad (4)$$

K : index set of utility criteria

K' : index set for negative criteria

4. Calculation of optimum ideal (Equation 5) and negative ideal (Equation 6) sets:

$$S_i^+ = \left\{ \sum_{j=1}^n (V_{ij} - V_j^+)^2 \right\}^{0.5} \quad j = 1,2,3 \dots, n; i = 1,2,3, \dots, m \quad (5)$$

$$S_i^- = \left\{ \sum_{j=1}^n (V_{ij} - V_j^-)^2 \right\}^{0.5} \quad j = 1,2,3 \dots, n; i = 1,2,3, \dots, m \quad (6)$$

5. Obtaining the proximity value for the ideal solution (Equation 7):

$$S_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad j = 1,2,3, \dots, n; i = 1,2,3, \dots, m; 0 \ll C_i \ll 1 \quad (7)$$

The highest C_i value gives the ideal result in TOPSIS method.

It is necessary to determine the weight coefficient for decision parameters in TOPSIS analysis. Tensile strength, displacement amount, cost and weight are equally important in the design and assembly applications of aircraft structural members. Therefore, the weight ratio for each output parameter was determined as 0.25 (25%). The other optimization method determined in this study was the response surface method (RSM). This method can be expressed with a quadratic polynomial regression equation (Equation 8).

$$Y = b_0 + \sum b_i x_i + \sum b_{ii} x_i^2 + \sum b_{ij} x_i x_j + e_r \quad (8)$$

In the equation, b is constant, x is the level of input parameters, and e is the total error [16].

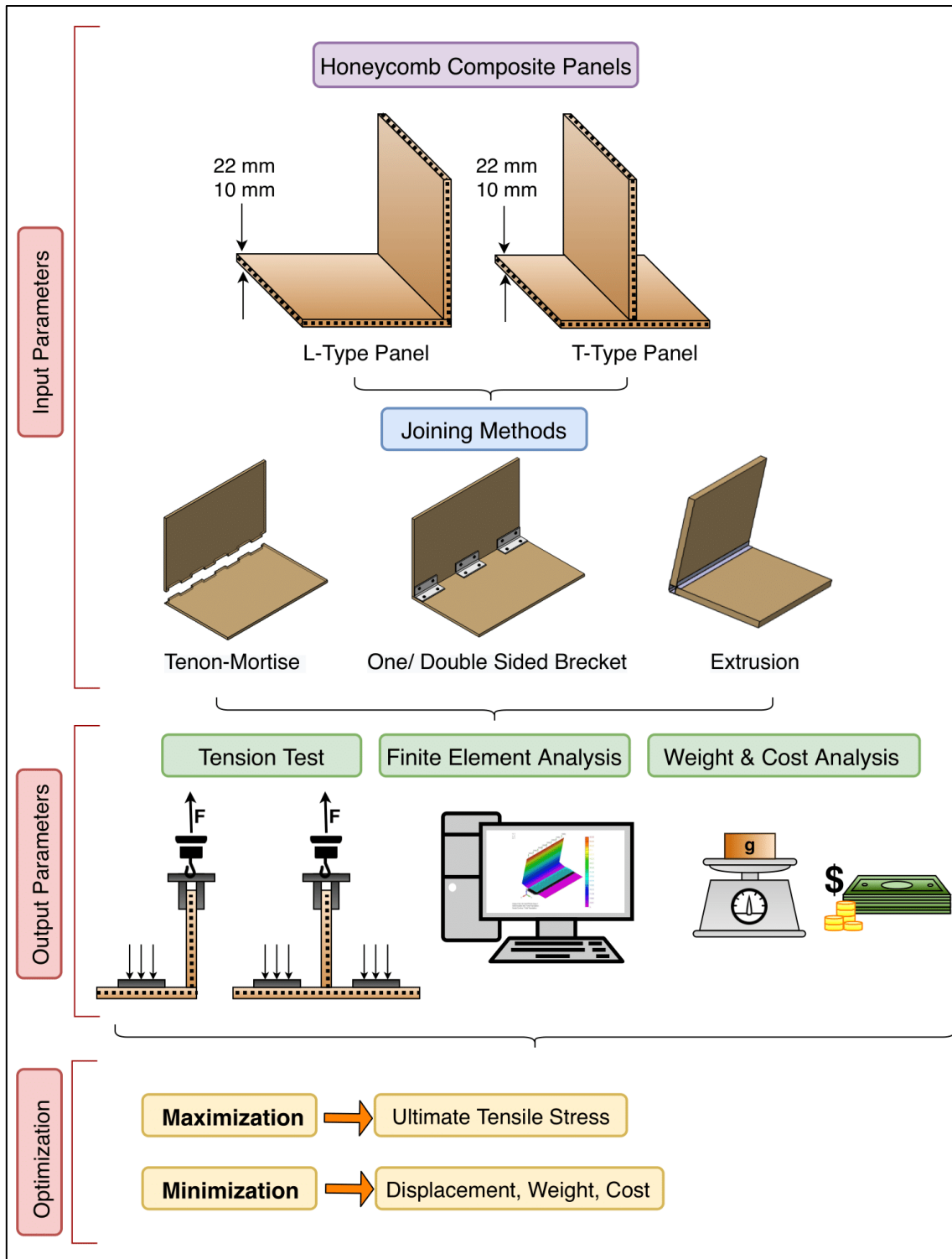


Figure 6. Schematic representation of input, output, and optimization parameters.

3. RESULTS AND DISCUSSION

3.1. Tensile Test Results

The fracture forces obtained as a result of the 3-repetitive tensile test for L type panels are given in

Table 4. When the average force is examined, the joining methods that gave high fracture force for 10 mm

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panels were as B, E, TM, for 22 mm panels were as E, B, TM respectively. In the TM joining method, the separation of the panels was caused by the breakage of the adhesive applied to the tenon-mortise structure. Outer layers of the panels and tenon-mortise parts were not damaged during pulling (Figure 7a), but in 22 mm panel deformation occurred in the inner areas where the adhesive was applied (Figure 7b).

breaking off. This 10 mm panels were not deformed as a result of this separation (Figure 7e). However, in 22 mm panels deformation occurred in the lower part of the panel where the extrusion is fixed (Figure 7f). When the experimental results are examined, it was determined that the tensile strength of the panels is related to the panel thickness and the rigidity of the joining process [17].

When the applied force exceeds 3.00 kN in 10 mm L type panels joined with the B method, the panel fixed to the floor started to bend. The separation of the two panels was the result of separating the inserts from the panel with cured adhesive. During this separation, ruptures occurred in the outer layer of the panel. Inserts in the panel fixed to the floor were not damaged, but deformation occurred in the inner part of the panel due to bending (Figure 7c). The separation of the 22 mm panels was the result of the separation of the inserts from the panel with cured adhesive. During this separation, the adhesive around the insert caused ruptures in the outer layer of the panel, but the inserts in the panel exposed to tension were not damaged (Figure 7d). 10 mm L-type panels joined by the E method were separated as a result of the extrusion part

The rigidity of the joining process can be related to the geometry of the joining element, the amount of adhesive and the adhesive applied surface area. In the B method, (which gave the highest fracture force in 10 mm panels), the inserts were fixed to the panel with adhesive, and then a mechanical connection was provided with bolts. In the E method, (which gave the highest fracture force in 22 mm panels), the adhesive was applied to the panels along the extrusion-panel joint edge. In these two methods, the joining of the panels was provided by both the joining element and the adhesive. In the TM method, without an external joining element, the adhesion of tenon-mortise was achieved. This caused the fracture force to be lower. Additionally, in terms of panel thickness, 22 mm panels were broken at a higher strength than 10 mm panels.

Table 4. Tensile test results of 3 repetitions for L-type panels

Panel Thickness (mm)	10			22		
Joining Methods	TM	B	E	TM	B	E
1. Test Results (kN)	2.60	3.85	3.20	4.80	5.00	6.00
2. Test Results (kN)	2.85	4.20	2.15	5.85	6.00	6.55
3. Test Results (kN)	3.40	3.85	3.95	5.55	5.25	5.75
Average Fracture Force (kN)	2.95	3.96	3.1	5.4	5.41	6.1

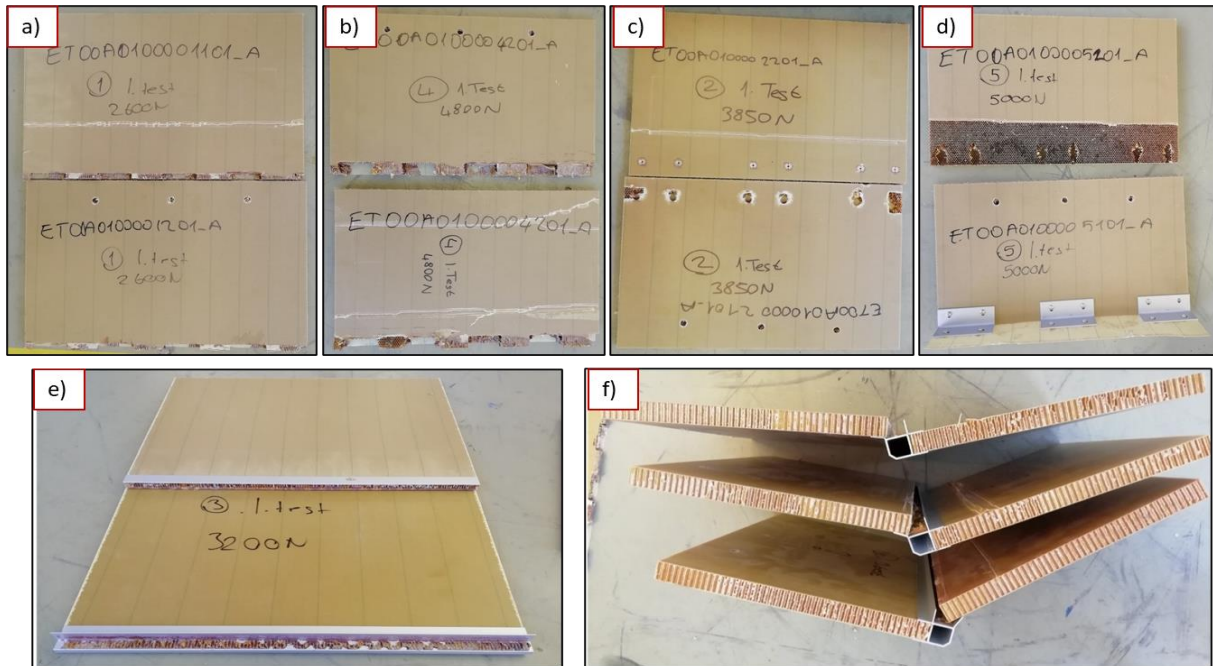


Figure 7. Samples broken as a result of the tensile test: a) 10 mm TM, b) 22 mm TM, c) 10 mm B, d) 22 mm B, e) 10 mm E, f) 22 mm E

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The fracture forces obtained as a result of the 3-repetitive tensile test for T-type panels are given in Table 5. The joining methods that gave high fracture force for 10 mm panels were as DSB, OSB, TM, for 22 mm panels were as DSB, TM, OSB, respectively. In the TM method, the two panels were separated as a result of breaking of the adhesive. The tenon-mortise structure of both samples was not deformed, but it was observed that the 10 mm panel fixed to the floor deformed (Figure 8a and b).

Panels joined with the DSB method were separated as a result of the inserts and cured adhesive tearing the panel. In the 22 mm panel, the inserts were separated from the panel (Figure 8c), while the inserts in the 10 mm panel were not damaged (Figure 8d). During the separation of 22 mm panels joined by OSB method, the adhesive around the insert caused tears in the outer

layer of the panel (Figure 8e). In 10 mm panels, the adhesive around the insert was separated without tearing the panel (Figure 8f).

The most rigid method for joining T-type panels was determined as DSB. Joining the 10 mm and 22 mm panels from both sides resulted in the highest fracture force. In 10 mm panels, the OSB method gave a better result than the TM method. It was observed that the use of one-sided brackets in these panels is sufficient for a rigid connection. However, in the 22 mm panel, the TM method gave a better result than the OSB method. In this higher thickness panel, the one-sided joint was not sufficient in terms of rigidity. There is 13.26% difference between DSB and TM for 22 mm panels. It can be claimed that the load-carrying capacity of TM was as high as DSB for panels of this thickness.

Table 5. Tensile test results for 3-repetitive T-type panels

Panel Thickness (mm)	10			22		
Joining Methods	TM	DSB	OSB	TM	DSB	OSB
Test Results (kN)	3.50	6.25	4.45	7.80	10.00	5.95
Test Results (kN)	4.00	5.05	4.55	10.00	10.95	6.10
Test Results (kN)	4.05	5.50	4.40	10.65	11.85	6.30
Average Fracture Force (kN)	3.85	5.60	4.46	9.48	10.93	6.11



Figure 8. Samples broken as a result of the tensile test: a) 22 mm TM, b) 10 mm TM, c) 22 mm DSB, d) 10 mm DSB, e) 22 mm OSB, f) 10 mm OSB

3.2. Finite Element Analysis

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The amount of displacement to occur in the samples was determined by finite element analysis based on the fracture forces obtained as a result of the tensile test. The displacement results for the L-type panel are given in Table 6, and the analysis outputs are shown in Figure

9 and 10. According to the analysis results, the joining method that gave the highest displacement was the E method for 10 mm and 22 mm panels. The TM method gave both the lowest fracture force and the lowest displacement for panels of both thicknesses.

Table 6. Displacement results for L-type panel

Panel Thickness (mm)	10			22		
Joining Methods	TM	B	E	TM	B	E
Average Fracture Forces (kN)	2.95	3.96	3.10	5.40	5.41	6.10
Displacement (mm)	185.5	337.5	386.9	71.77	100.9	163.5

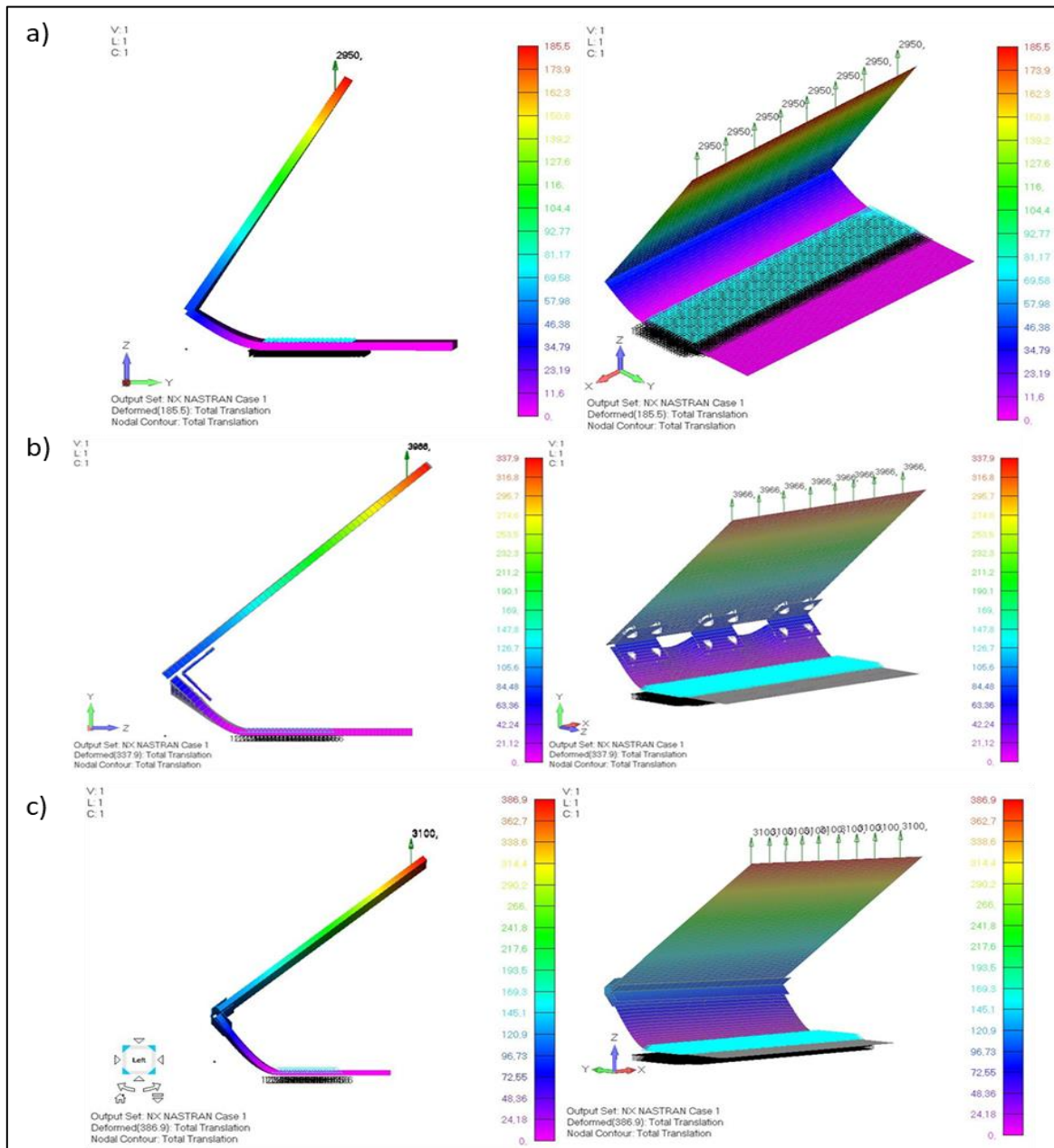


Figure 9. Displacement results for a 10 mm thick L-type panel: a) TM method, b) B method, c) E method

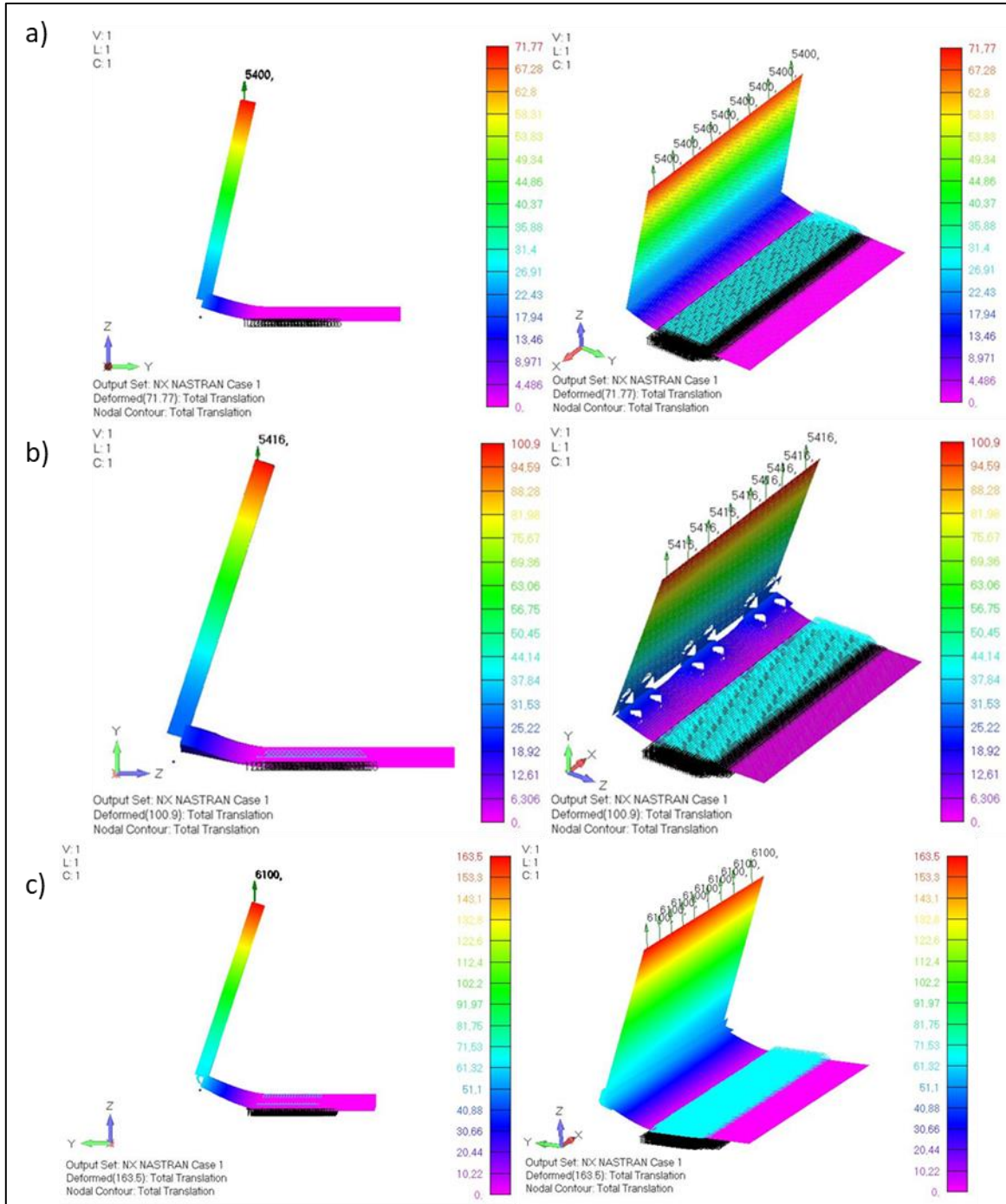


Figure 10. Displacement results for 22 mm thick L-type panel: a) TM method, b) B method, c) E method

The displacement results for the T-type panel are given in Table 7, and the analysis outputs are given in Figure 11 and 12. According to the analysis results, joining method that gave the highest displacement was the TM method for both thickness panels. Although the DSB method gave the highest fracture force, it gave the lowest amount of displacement. For this reason, it is seen that the optimum joining method for T-type panels in terms of strength and displacement was DSB method.

The fracture force data obtained from real experiments were defined in the finite element analysis program. It was aimed to analyze the displacement data and stress change from the finite element program visually. Since a uniform geometry was not used in real experiments, displacement data were obtained with finite elements. It is seen in the analysis images that the stresses were concentrated at the point of application of force. However, real deformations occurred at the junction points. For this reason, it is difficult to claim that finite element analysis gave results with sufficient accuracy.

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The reason for the inconsistency in the experimental and analysis results is that the mechanical properties of the applied adhesive cannot be adequately defined. The mechanical properties of the adhesive material should be determined to solve this problem. On the other hand,

the direction of deformation in the analysis results showed that the geometry-force definition is at an adequate level. Bending strain occurred where the connections were weak.

Table 7. Displacement results for T-type panel

Panel Thickness (mm)	10			22		
Joining Methods	TM	DSB	OSB	TM	DSB	OSB
Average Fracture Forces (kN)	3.85	5.60	4.46	9.48	10.93	6.11
Displacement (mm)	168.4	26.23	125	174.9	22.76	63.55

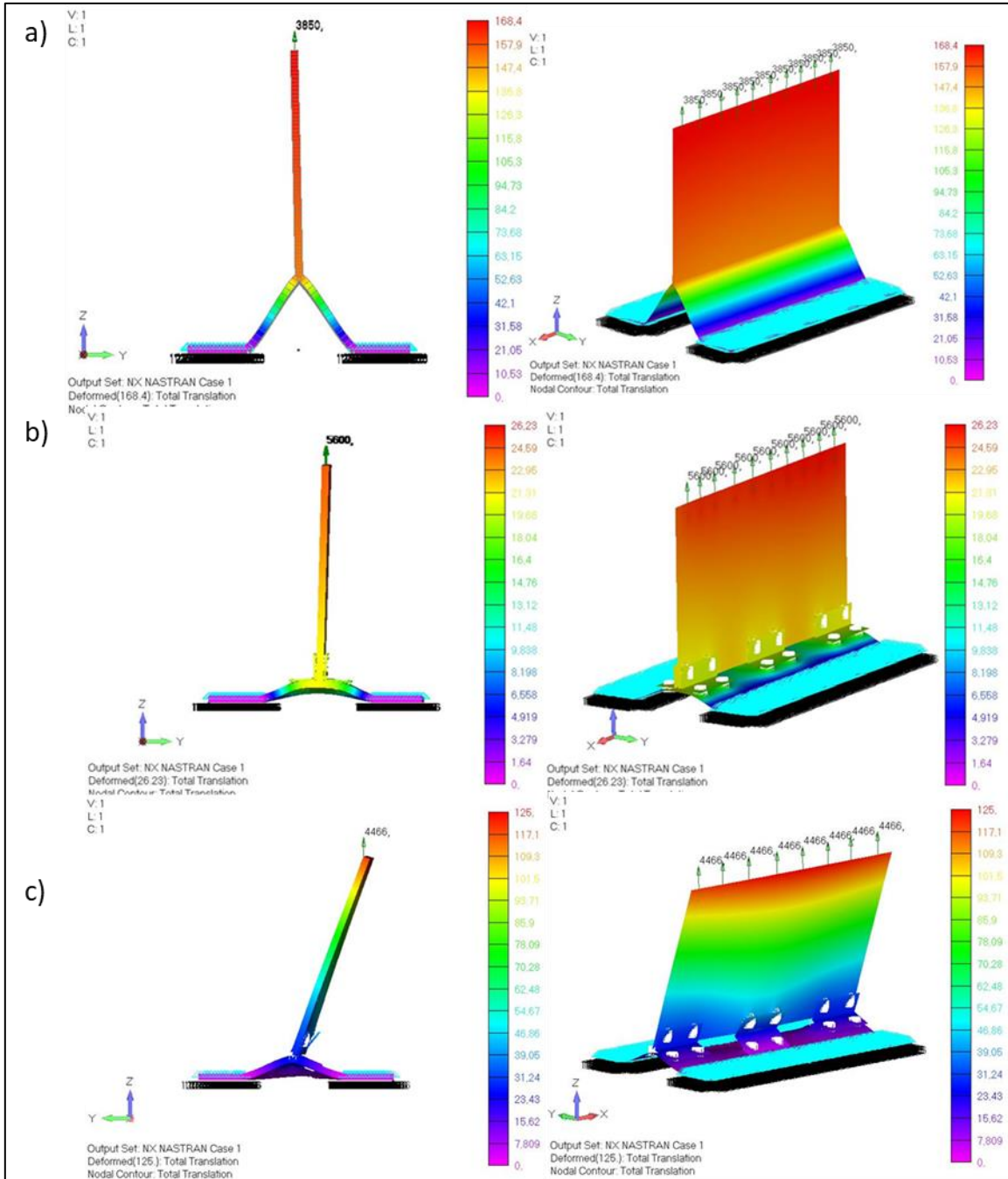


Figure 11. Displacement results for a 10 mm thick T-type panel: a) TM method, b) DSB method, c) OSB method

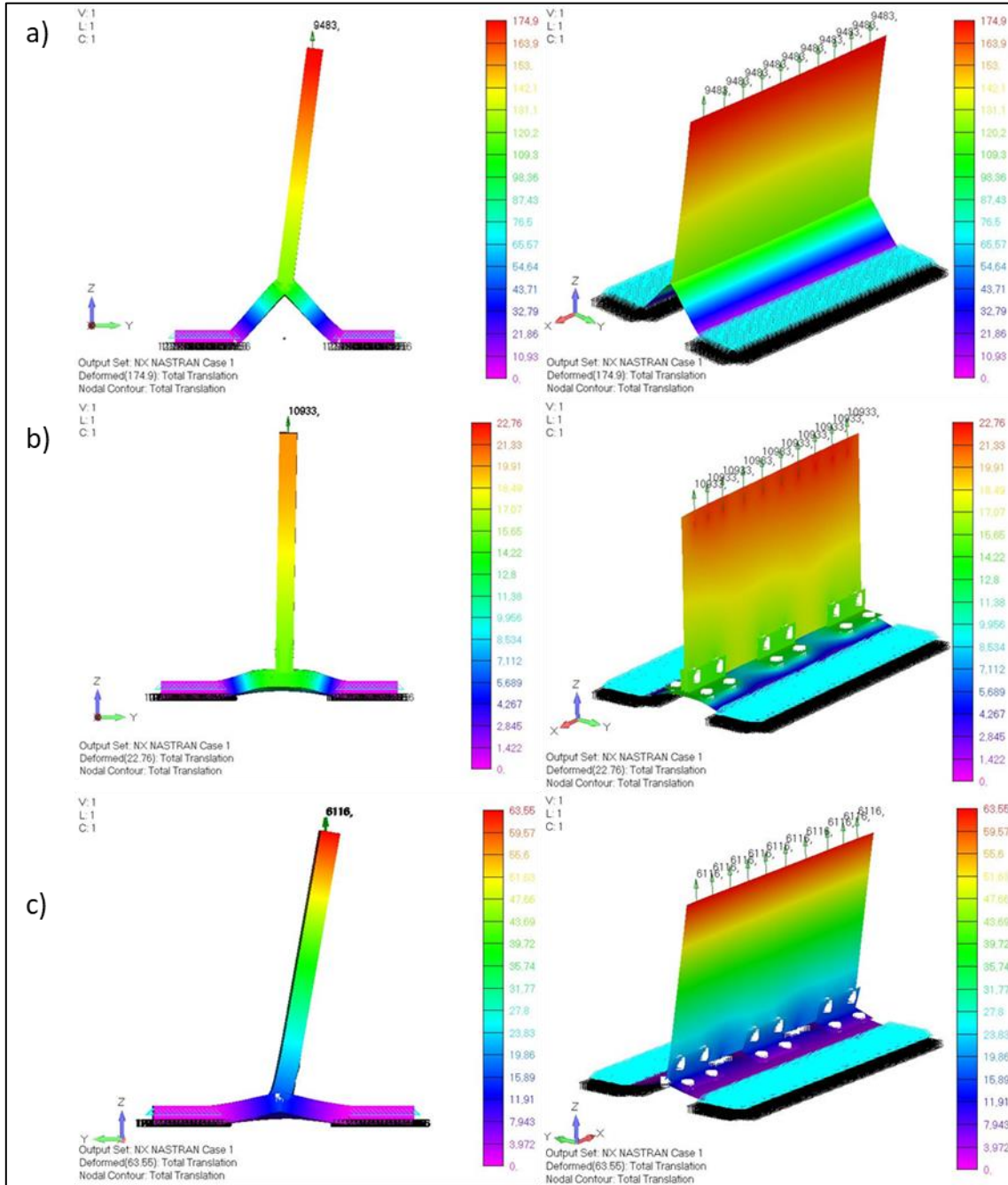


Figure 12. Displacement results for 22 mm thick T-type panel: a) TM method, b) DSB method, c) OSB method

3.3. Process Analysis

In the process analysis phase of this study, the weight and cost parameters of panels were determined. Accordingly, the weight and cost calculations of the panels were made by examining variables such as panel dimensions, adhesives, connecting elements, design, production, and assembly of panels. The cost-weight results obtained for L-type panels are given in Table 8 and for T type panels in Table 9. Cost-effective joining methods for L-type panels of both thicknesses were E, TM, and B, respectively. The material cost is low since

a joining element is not used in the TM method. However, the process cost was higher than other joining methods. In addition, TM method gave the lowest result in terms of weight. For L-type panels, TM method can be chosen as the optimum joining method because it gave low results in terms of cost and weight. The lowest cost method for 10 mm thick T-type panels was the OSB method, and for 22 mm thick panels was the TM method. For T-type panels, the TM method can be chosen as the optimum joining method because of its

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low cost and weight results. Optimum joining methods determined based on all variables will be discussed in the next section.

Table 8. Cost-weight values for L-type panels

	Tenon-mortise		Bracket		Extrusion	
	Amount	Cost (\$)	Amount	Cost (\$)	Amount	Cost (\$)
10 mm Thick Panel (m ²)	0.141	24.13	0.141	24.13	0.141	24.13
22 mm Thick Panel (m ²)	0.141	32.29	0.141	32.29	0.141	32.29
Adhesive (ℓ)	0.15	8.55	0.10	5.70	0.15	8.55
Insert	0	0	12	4.2	0	0
Extrusion	0	0	0	0	1	3.96
Bracket	0	0	3	12.91	0	0
Bolt	0	0	12	1.2	0	0
Stamp	0	0	12	0.12	0	0
	Duration (min)	Cost (\$)	Duration (min)	Cost (\$)	Duration (min)	Cost (\$)
Design	30	12.6	25	10.3	20	8.4
Panel Cutting	40	26.4	35	23.1	25	16.5
Deburring	10	4.1	15	6.2	5	2.1
Adhesive Application	10	4.1	20	8.2	15	6.2
Joining	20	8.2	0	0	20	8.2
Assembly	0	0	15	6.2	0	0
Total Cost of 10 mm (\$)		88.08		102.26		78.04
Weight of 10 mm (g)		489		735		644
Total Cost of 22 mm (\$)		96.24		110.42		86.2
Weight of 22 mm (g)		656		901		904

Table 9. Cost-weight values for T-type panels

	Tenon-Mortise		Double-Sided Bracket		One-Sided Bracket	
	Amount	Cost (\$)	Amount	Cost (\$)	Amount	Cost (\$)
10 mm Thick Panel (m ²)	0.141	32.29	0.141	32.29	0.141	32.29
22 mm Thick Panel (m ²)	0.141	40.45	0.141	40.45	0.141	40.45
Adhesive (ℓ)	0.15	8.55	0.10	5.70	0.15	8.55
Insert	0	0	18	11.82	12	4.2
Extrusion	0	0	6	12.91	3	12.91
Bracket	0	0	24	2.16	12	1.2
Bolt	0	0	24	0.24	12	0.12
Stamp						
	Duration (min)	Cost (\$)	Duration (min)	Cost (\$)	Duration (min)	Cost (\$)
	30	12.6	25	10.5	25	10.5
Design	45	29.7	40	36.4	35	23.1
Panel Cutting	10	4.1	15	6.2	10	4.1
Deburring	10	4.1	20	8.2	15	6.2
Adhesive Application	20	8.2	0	0	0	0
Joining	0	0	20	8.2	15	6.2
Assembly		58.7		69.5		50.1
Total Cost of 10 mm (\$)		99.54		134.62		109.37
Weight of 10 mm (g)		107.7		142.78		117.53
Total Cost of 22 mm (\$)		633		1171		908
Weight of 22 mm (g)		633		1171		908

3.4. Optimization

Since L and T-type panels are used in different applications, the optimization was carried out separately for both panel types. The input parameters (panel type, panel thickness, joining methods) and

output parameters (fracture force, displacement, cost, weight) considered in the analysis are given in Table 10.

Table 10. Input and Output Parameters

Panel Type	Panel Thickness (mm)	Joining Method	Fracture Force (N)	Displacement (mm)	Cost (\$)	Weight (g)
L	10	TM	2950	62.89	88.08	489
L	10	B	3966	85.1	102.26	735
L	10	E	3100	124.8	78.04	644
L	22	TM	5400	39.21	96.24	656
L	22	B	5416	18.63	110.42	901
L	22	E	6100	26.8	86.2	904
T	10	TM	3850	42.78	99.54	499
T	10	DSB	5600	4.289	134.62	971
T	10	OSB	4466	27.98	109.37	719
T	22	TM	9483	18.44	1077	633
T	22	DSB	10933	2.081	142.78	1171
T	22	OSB	6116	10.39	117.53	908

3.4.1. TOPSIS Analysis

The TOPSIS analysis result for the L-type panel is given in Table 11. According to TOPSIS method, 22 mm thickness and TM joining method were determined as the ideal solution for L-type panel. In ideal solutions, the E joining method with 22 mm thickness was 2nd, and the B joining method with 22 mm thickness was 3rd order. The TOPSIS analysis result for the T-type panel

is given in Table 12. According to TOPSIS method, 22 mm thickness and DSB joining method were determined as the ideal solution for T-type panel. In ideal solutions, the TM joining method with 22 mm thickness was 2nd and, the DSB joining method with 10 mm thickness was 3rd order.

Table 11. TOPSIS analysis result for L-type panel

Panel Type	Panel Thickness (mm)	Joining Method	Si+	Si-	Top	Pi	Rank
L	10	TM	0.0952168	0.1097723	0.2049891	0.535503	4
L	10	B	0.1159573	0.0669145	0.1828718	0.3659094	5
L	10	E	0.1696471	0.0504126	0.2200597	0.2290861	6
L	22	TM	0.045411	0.1410525	0.1864634	0.7564617	1
L	22	B	0.0686892	0.164051	0.2327402	0.7048676	3
L	22	E	0.0594035	0.1609446	0.2203482	0.7304106	2

Table 12. TOPSIS analysis result for T-type panel

Panel Type	Panel Thickness (mm)	Joining Method	Si+	Si-	Top	Pi	Rank
T	10	TM	0.2087814	0.0889826	0.297764	0.2988359	6
T	10	DSB	0.099543	0.1768291	0.2763721	0.6398225	3
T	10	OSB	0.1507285	0.0910733	0.2418018	0.3766445	4
T	22	TM	0.0784411	0.1531077	0.2315488	0.661233	2
T	22	DSB	0.0889826	0.2087814	0.297764	0.7011641	1
T	22	OSB	0.0932574	0.1541333	0.2473907	0.623036	5

3.4.2. Response Surface Analysis

Optimization results obtained according to the Response Surface method are given in Figure 13. According to the results, the optimum panel thickness for both panel types was found to be 22 mm and the joining method as TM. As a result of the selection of the optimum parameter for the L-type panel, the resulting fracture force was found to be 5400 N, the

displacement was 39.210 mm, the cost was 96.240 \$ and the weight was 656 g. As a result of the selection of the optimum parameter for the T-type panel, the resulting fracture force was found to be 9483 N, the displacement was 18.44 mm, the cost was 107.70 \$, and the weight was 633 g. In both optimization methods carried out within the scope of this study, the optimum

thickness value for L and T-type panels was found to be 22 mm. As a result of both optimization methods, optimum joining method for L-type panel was found as TM. As a result of Response Surface analysis for T-

type panel, the optimum joining method was TM, while as a result of TOPSIS was found to be DSB. TM method gave the second-best result in TOPSIS analysis. This result is at an acceptable level.

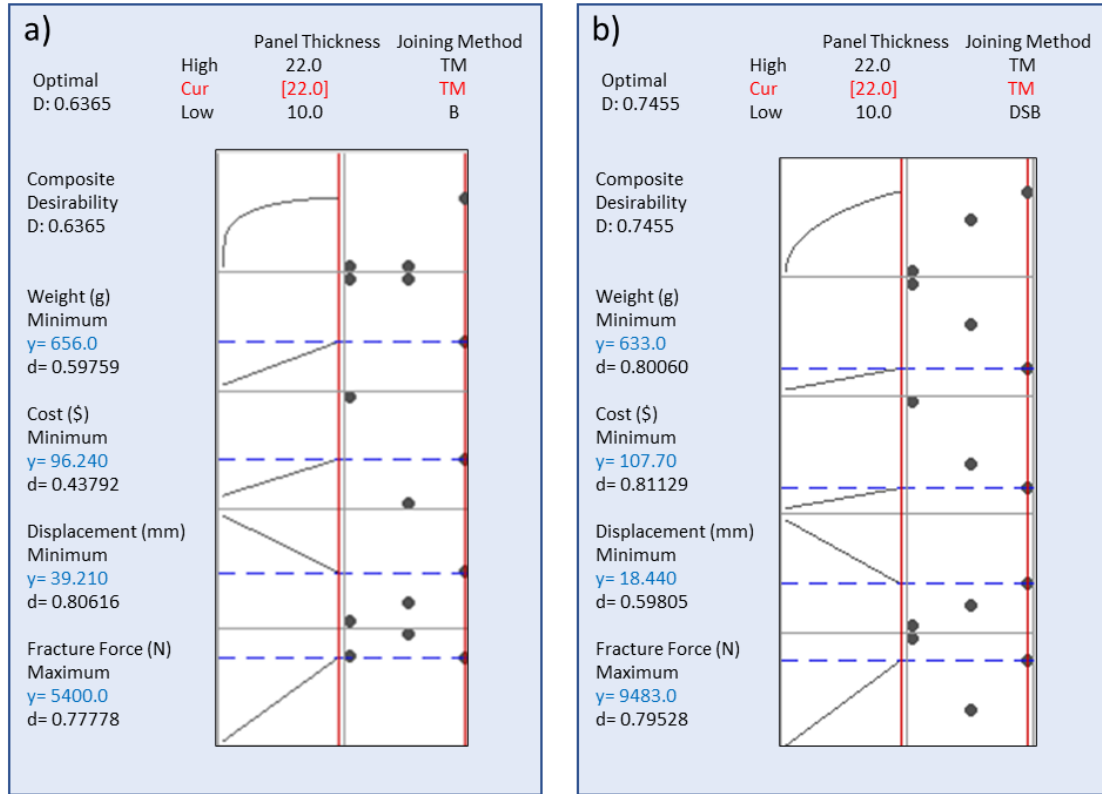


Figure 13. Optimization results according to Response Surface Method; a) L-type panel, b) T-type panel

4. CONCLUSION

Within the scope of this study, the strength, displacement, cost, and weight parameters of aircraft composite panels were defined, and the optimum panel thickness and joining methods were determined. Findings obtained according to analysis and experimental results are as follows:

- According to the tensile test results, the joining methods that gave high fracture force for 10 mm L-type panels were as B, E, TM, for 22 mm panels were as E, B, TM, respectively.
- In the B method, the inserts were fixed to the panel with adhesive, and then a mechanical connection was provided with bolts. In the E method the adhesive was applied to the panels along the extrusion-panel joint edge. In these two methods, the joining of the panels was provided by both the joining element and the adhesive. In the TM method, the joining process was achieved by adhering only the

tenon and mortise parts. This may have caused the fracture force to be lower.

- The joining methods that gave high fracture force for 10 mm T-type panels were as DSB, OSB, TM, for 22 mm panels were as DSB, TM, OSB, respectively.
- In 10 mm T-type panels, it was observed that the use of one-sided brackets was sufficient for a rigid connection. However, in the 22 mm panels, the one-sided joint was not sufficient in terms of rigidity. It can be claimed that the load-carrying capacity of TM was as high as a double-sided joint for panels of 22 mm thickness.
- According to the finite element analysis results, the joining method that gave the highest displacement was the E method for 10 mm and 22 mm L-type panels.

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- The joining method that gave the highest displacement was the TM method for both thickness T-type panels.
- As a result of the analysis, it was observed that the maximum stress concentrates at the force application points. However, real deformation occurs at the junction points. The reason for this inconsistency is that the mechanical properties of the adhesive were not sufficiently defined. On the other hand, the direction of deformation in the analysis results showed that the geometry-force definition is at an adequate level.
- More accurate analyzes can be made by defining the material used as an adhesive to the analysis program.
- Cost-effective methods for L-type panels of both thicknesses were E, TM, and B, respectively, and the low-weight method was TM.
- For T-type panels of both thicknesses, the TM method was the best joining method in terms of cost and weight.
- As a result of both optimization methods, optimum joining method for L-type panel was found as TM.
- As a result of RSM for T-type panel, the optimum joining method was TM, while as a result of TOPSIS the optimum joining method was DSB. TM method gave the second-best result in TOPSIS analysis.
- Panels used according to the standards were 10 mm and 22 mm thick. Panel production in different thickness values is required for optimum construction design. Future studies can be designed to determine the optimum thickness.

Nomenclature and Abbreviation Table

TM	Tenon-mortise
E	Extrusion
B	Bracket
OSB	One-sided bracket
DSB	Double-sided bracket
TOPSIS	Technique for order preference by similarity to ideal solution
n	Evaluation factor
m	Number of decision points
j	Criterion
i	Alternative
k	Decision maker
K'	Cost criteria
K	Benefit criteria
S_i^+	Positive ideal measure of discrimination
S_i^-	Negative ideal measure of discrimination
C_i	The relative closeness to the ideal solution
b	A constant
x	The level of input parameters
e	Total error
RSM	Response surface method
FSDT	First order shear deformation theory

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