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Research Article

Numerical Analysis of Composite Plates with Pin Connections Subjected to Axial Load

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Abstract-Nowadays, computer programs can solve many problems in a much shorter time and with less effort compared to experimental methods. The design and analysis of a problem can be examined with low error rates through these programs. The ANSYS software can provide highly accurate results in structural, thermal, and vibration analyses. In this study, the stresses in pin-plate connections of a laminated composite material were investigated using ANSYS, considering the geometric parameters such as the distance between holes, plate width, and hole diameter. Contact elements were used at the connection points where continuous contact occurs during the design. According to the results obtained, it was observed that the distance between holes/diameter and diameter/plate width ratios have a significant effect on the stresses and displacements.

Keywords: Laminated Composite, Pin-Plate Connection, Stress Analysis, Contact Element.

I. INTRODUCTION

Composite materials are created by combining two or more materials at the macro level to form new materials with enhanced properties [1]. Composite materials have found applications in many areas of our lives. They are widely used in various industries, primarily in automotive, aerospace, and marine sectors. Properties such as high strength, high stiffness, and light weight are fundamental to their application in these sectors. Various types of connections are made in the places where these materials are used. These connections can be either adhesive or mechanical in nature [2].

In engineering components, connections are made through various elements. Pins, rivets, bolts, welding, and soldering are some of these connection methods [2]. These connections can be either detachable or non-detachable. Due to their reversibility, pin connections are frequently preferred. Pin-plate connections hold a significant place among these types of connections. In these connections, the contact surface is formed between the pin hole and the lateral surfaces of the pin. From a strength perspective, stress concentration occurs at discontinuities such as holes in a region [3]. Areas with stress concentration are more susceptible to damage. Practical analyses focus on investigating critical regions in terms of damage. For this purpose, software programs such as ANSYS and ABAQUS, which provide quicker and more effective solutions, are used. ANSYS is a program that gives results close to reality in mechanical analysis. It performs analyses on solid models that are divided into a finite number of elements [4].

Various studies have been conducted on pin-plate connections in literature. El Sisi et al. [5] experimentally and numerically investigated the effect of different bolt diameters and numbers on composite-steel connections under static load. It was found that the number of bolts had a more significant impact than the bolt diameter. It was also determined that the first bolt was responsible for the damage. Jule et al. [6] analyzed damage modes between composites with four different holes, considering the distance between holes, the distance from the hole to the edge, and the ratios of width to diameter, both theoretically and numerically. They found that the strength decreased as the number of holes increased. Nimbalkar and Pawar [7] numerically examined the damage analysis of glass fiber and carbon fiber reinforced composite plates with a single hole and found that the resistance was higher in the carbon fiber reinforced composite. Çayır et al. [8] studied the effect of various notch structures and pin connections on the mechanical performance of unidirectional glass fiber reinforced composites. They found that the type of notch and the number of pins had a significant effect on the damage loads. They also determined that double-pin structures could carry higher damage loads than single-pin structures. Reza et al. [9] investigated the effect of the viscoelastic behavior of the polymer matrix of a unidirectional fiber-reinforced laminated composite on the stress distribution around a pin-loaded hole under tensile loading using a micromechanical approach and a numerical algorithm. They found that the tensile load in the fibers adjacent to the pin hole increased, while the shear stress concentration in the matrix around the pin hole decreased. Aktaş et al. [10] experimentally and numerically examined the effects of geometric parameters on the damage load and mode in glass fiber reinforced composites with single and double holes. According to the data obtained, they found that the pin hole farthest from the free edge was exposed to the highest stress. Turan et al. [11] numerically investigated the damage modes of unidirectional double-hole carbon fiber/epoxy composites for different geometric parameters and arrangements. They found that the damage modes were influenced by the geometric parameters. Kishore et al. [12] studied the effect of geometric parameters of multiple pins in unidirectional glass fiber reinforced composites using ANSYS. They demonstrated the importance of geometric parameters in structures with multiple pins. Gharge and Nanwatkar [13] focused on identifying the first damage load in composite structures with pin connections. They performed both experimental and numerical investigations for different pin diameters and arrangements and observed that changes in pin diameter and arrangement led to different types of damage.

This study focuses on investigating normal and shear stresses by varying the distance between holes, plate width, and diameter in a cross-ply carbon fiber/epoxy composite plate subjected to tensile loading. The model consists of a composite plate with two holes and steel pins, and three different F/D ratios and three different D/W ratios were used, with analyses conducted for six different scenarios.

II. MATERIALS AND METHODS

2.1 Problem Definition

In this study, the design of a 16-layer composite plate made of carbon fiber and epoxy has been carried out. Each layer thickness is 0.5 mm, resulting in a total plate thickness of 8 mm. The orientation angle has been set to $(0°/90°)_{4S}$. Two holes have been made in the existing plate, and pins made of steel material have been prepared. Both the orthotropic composite plate and the isotropic steel pin were separately created and then assembled.

The effect of the distance between holes and hole diameter on stress has been investigated by varying the F/D and W/D ratios in the composite plate. The values of F and D were changed such that when D = 10 mm, F/D ratios of 4, 5, and 6 were considered, and when W = 20 mm, D/W ratios of 0.5, 0.4, and 0.3

were used. In the figure, F represents the distance between the centers of the pin holes, W represents the plate width, and D represents the pin diameter. The designed model is shown in Figure 1. The dimensions of the plate were taken as 120x20x8 mm.

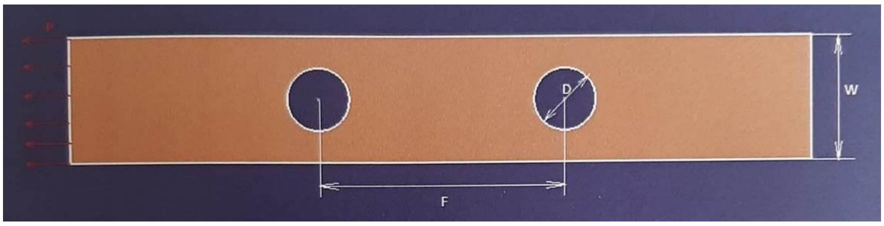


Figure 1. The designed model

2.2 Numerical method and material properties

In this study, ANSYS, a finite element analysis software, has been used. The data obtained from this program align with experimental results. The material properties for carbon fiber/epoxy are presented in Table 1. Additionally, the properties of the pin are shown in Table 2.

Table 1. Composite plate material properties [14]

Carbon/Epoxy	
E_{11}	142 000 MPa
E_{22}	10 300 MPa
E_{33}	10 300 MPa
ν_{12}	0.27
ν_{23}	0.46
ν_{13}	0.27
G_{12}	7200 MPa
G_{23}	3520 MPa
G_{13}	7200 MPa

Table 2. Pin material properties [15]

Pim	
E	200 000 MPa
ν	0.3

In the ANSYS program, a solid model was first created. The composite plate, pins, and contact elements were created separately and then assembled. The element type selected for the model was Solid-Layered 46. The created solid model is shown in Figure 2. A finite element mesh was then generated for this solid model, and a more refined mesh was applied around the hole regions. The generated mesh structure is shown in Figure 3.

In the analysis, the pin was assumed to be completely rigid, and the contact surface through which the pin passes was constrained to prevent movement in the radial direction. The lateral surfaces of the composite plate were subjected to boundary conditions in the Z direction. The pins were fixed at their lateral surfaces with all degrees of freedom (DOF) constraints. A tensile load of 7000 N was applied to the model from the left side.

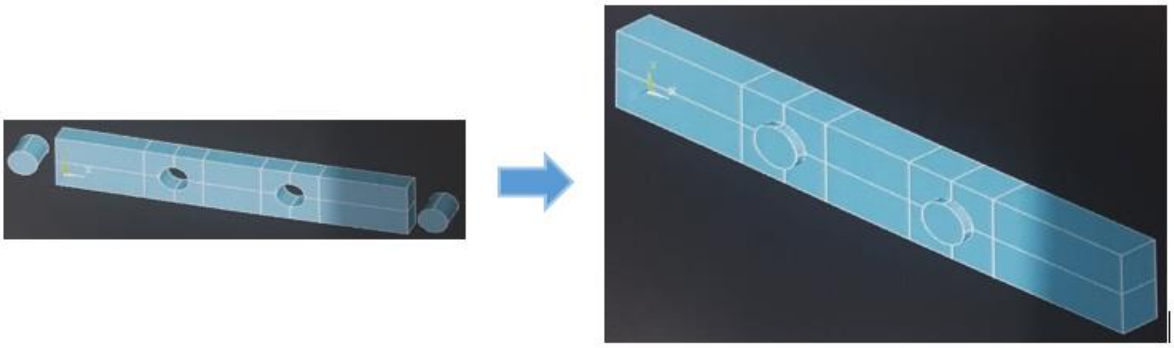


Figure 2. Solid model

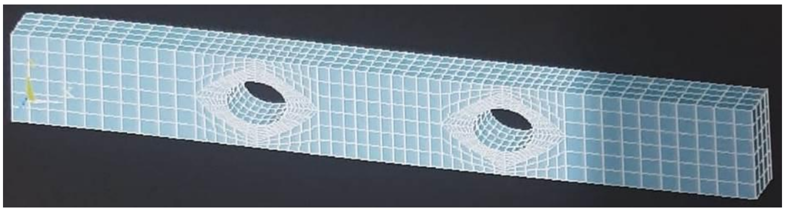
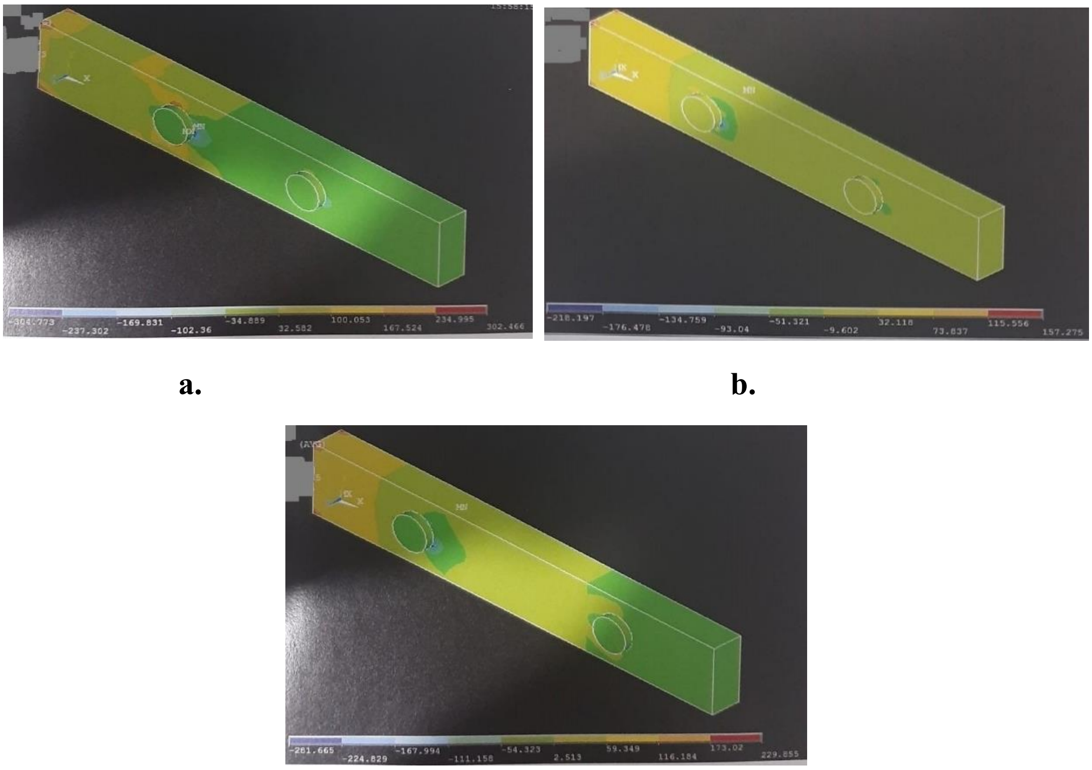


Figure 3. Finite element mesh

III. RESULTS AND DISCUSSION

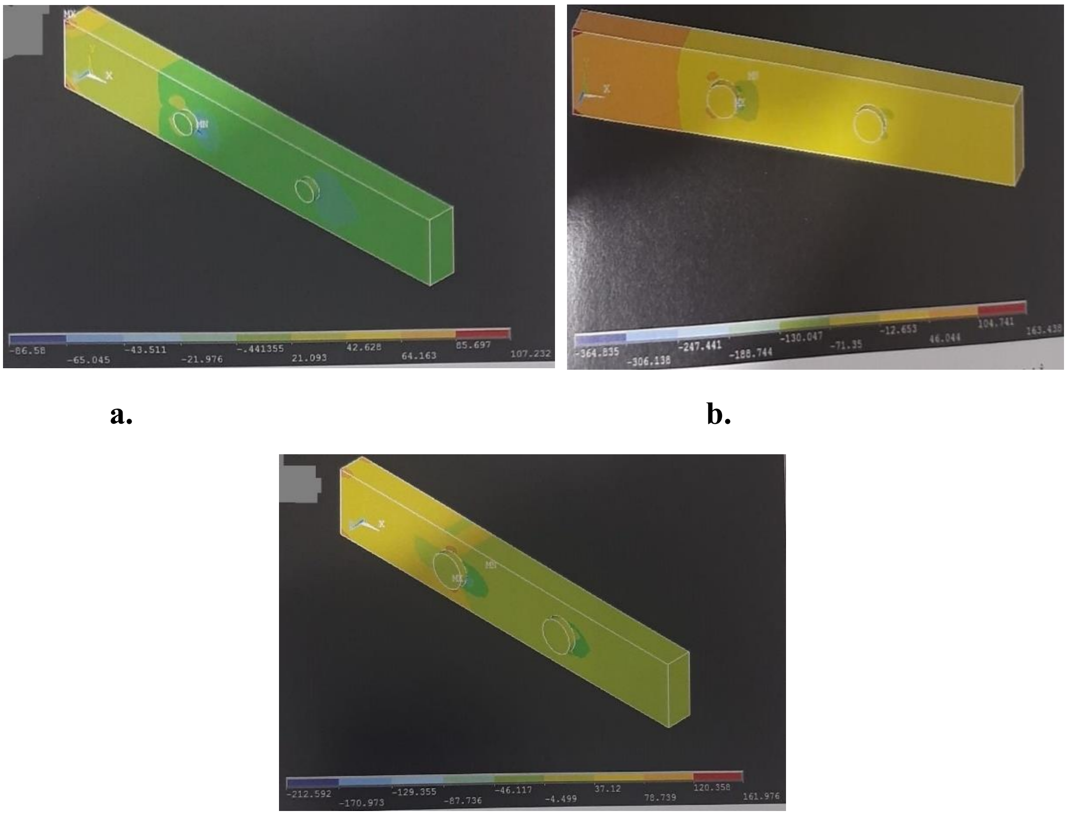
For the connection element consisting of a carbon fiber/epoxy composite plate and a steel pin, the displacement, normal stress, and shear stresses were examined by changing the F/D and D/W ratios. Since the tensile load is applied in the x-direction on the plate, the stress in this direction is presented. In Figure 4, the normal stresses in the x-direction are shown for F/D values of 4, 5, and 6, while in Figure 5, the normal stresses in the x-direction are shown for D/W values of 0.3, 0.4, and 0.5.



a. **b.**

c.

Figure 4. Normal stresses in X direction for a. F/D=4, b. F/D=5, c. F/D=6



a. **b.**

c.

Figure 5. Normal stresses in X direction for a. D/W=0.3, b. D/W=0.4, c. D/W=0.5

In Figures 4 and 5, the lowest and highest stress values for the composite plate and pin are shown in color. The color scale ranges from blue (representing the lowest stress) to red (representing the highest stress). The critical areas for damage are the red-colored regions, where the highest stresses occur. The normal and shear stress values for the F/D ratio are provided in Table 3. Additionally, Table 4 presents the displacement values for the F/D ratio. In Figure 6, the stress values for these ratios are compared side by side.

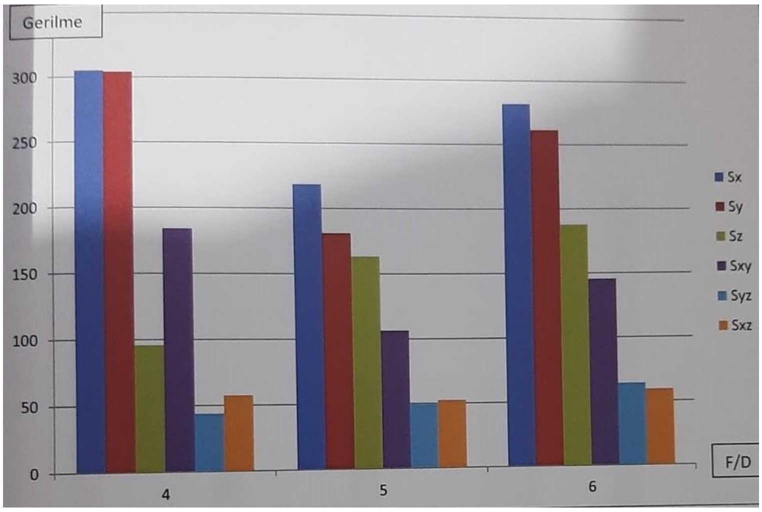


Figure 6. Graph of tensile and shear stresses at different F/D ratios

According to Figure 6, as the F/D ratio increases from 4 to 5, the stress values for Sx, Sy, Sxy, and Sxz decrease, while the stresses for Sz and Syz increase. When the F/D ratio reaches 6, all stress values increase compared to the ratio of 5. Overall, the highest stress values occur when the F/D ratio is 4.

Table 3. Stresses for F/D ratios

F/D	**4**	**5**	**6**
Sx (MPa)	304.773	218.197	281.665
Sy (MPa)	303.815	180.891	261.092
Sz (MPa)	95.565	163.256	187.488
Sxy (MPa)	183.929	106.204	145.23
Syz (MPa)	43.655	49.302	63.865
Sxz (MPa)	57.28	52.33	59.017

According to Table 4, the displacement values for Ux, Uy, and Uz decrease up to the F/D ratio of 5, and at the F/D ratio of 6, they show a slight increase.

Table 4. Displacements for F/D ratios

F/D	**4**	**5**	**6**
Ux (mm)	0.0607	0.1805	0.2510
Uy (mm)	0.0705	0.0193	0.0233
Uz (mm)	0.0364	0.0051	0.0075

The normal and shear stress values for the D/W ratio are provided in Table 5. Additionally, Table 6 presents the displacement values for the D/W ratio. In Figure 7, the stress values for these ratios are compared side by side.

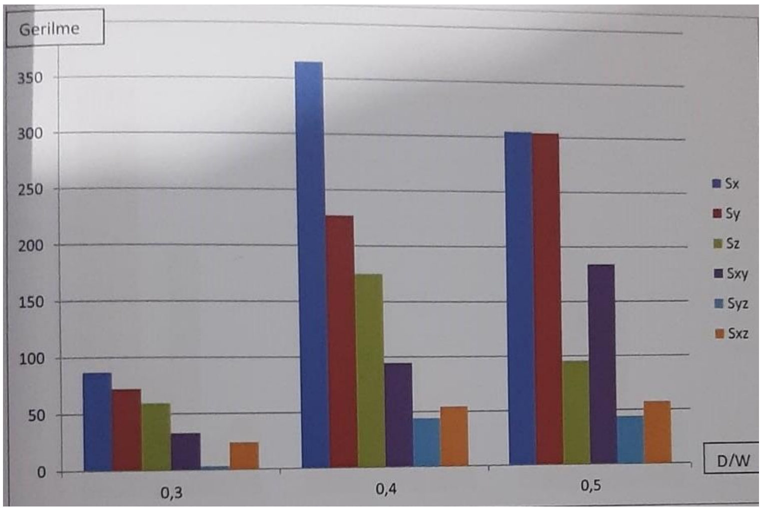


Figure 7. Graph of tensile and shear stresses at different D/W ratios

According to Figure 6, as the D/W ratio increases from 0.3 to 0.4, all stress values increase. When the D/W ratio reaches 0.5, Sx and Sz decrease, while Sy and Sxy increase. The stresses Syz and Sxz remain nearly unchanged. The highest stress values for Sx, Sz, and Syz occur when the D/W ratio is 0.4, while the highest stress values for Sy, Sxy, and Sxz occur when the D/W ratio is 0.5.

Table 5. Stresses for D/W ratios

D/W	**0.3**	**0.4**	**0.5**
Sx (MPa)	86.58	364.835	304.773
Sy (MPa)	71.821	227.012	303.815
Sz (MPa)	59.291	174.766	95.565
Sxy (MPa)	32.712	94.493	183.929
Syz (MPa)	3.019	43.76	43.655
Sxz (MPa)	23.904	54.477	57.28

According to Table 6, the displacement values for Ux and Uy increase as the D/W ratio increases. However, the Uz displacement decreases up to a D/W ratio of 0.4, and then it increases at a D/W ratio of 0.5.

Table 6. Displacements for D/W ratios

D/W	**0.3**	**0.4**	**0.5**
Ux (mm)	0.1589	0.2355	0.3100
Uy (mm)	0.0151	0.0238	0.0171
Uz (mm)	0.0371	0.0069	0.0364

IV. CONCLUSION

The results obtained from the study of pin-connected cross-ply carbon fiber/epoxy composite with different geometric parameters are summarized below.

- For the cases where F/D is 4, 5, and 6, the highest values for Sx, Sy, and Sxy occur at a ratio of 4, while Sz, Syz, and Sxz are highest at a ratio of 6.
- The displacements are as follows: for Ux, the highest displacement occurs at F/D = 6, while for Uy and Uz, the highest displacements occur at F/D = 4.
- For the cases where D/W is 0.3, 0.4, and 0.5, the highest values for Sx, Sz, and Syz occur at a ratio of 0.4, while Sy, Sxy, and Sxz are highest at a ratio of 0.5.

- The displacements are as follows: for Ux, Uy, and Uz, the highest displacements occur at D/W = 0.5, 0.4, and 0.3, respectively.

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