

# Effect of Stacking Sequences on Failure Behavior of Pinned E-Glass/Epoxy Composite Plates

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## ABSTRACT

In this study, the effect of stacking sequences on failure behavior of pinned composite plates was investigated. The laminated composite plates were made from epoxy matrix and glass fibers as reinforcement material. To observe the influences of joint geometry and stacking sequence on the failure mechanism, failure analysis were carried out experimentally. The nine different laminated composite plates were tested. The edge distance-to-hole diameter ratio ( $E/D$ ) of specimens was designed from 1 to 6. Besides, the specimen width-to-hole diameter ratio ( $W/D$ ) was only considered as 6. Experimental results point out that failure behavior is strictly influenced from both stacking sequences and geometrical parameters of composite specimens.

**Key Words:** Failure analysis, Laminated composite, Pin joints, Failure mode

## Pim Bağlantılı E-Glass/Epoksi Kompozit Plakalarda Tabaka Dizilişlerinin Hasar Davranışına Etkisi

### ÖZET

Bu çalışmada, pim bağlantısı yapılmış kompozitlerin tabaka dizilişlerinin hasar davranışına etkisi incelenmiştir. Tabakalı kompozit plakalar epoksi matris ve takviye elemanı olarak cam liflerinden üretilmiştir. Bağlantı geometrisinin ve tabaka dizilişinin hasar oluşumu üzerine etkilerini gözlemek için hasar analizi deneysel olarak yapılmıştır. Dokuz farklı tabakalı kompozit plaka test edilmiştir. Deneysel numunelerinin serbest ucunun delik çapına oranı ( $E/D$ ), 1'den 6'ya kadar farklı boyutlarda tasarlanmıştır. Bunun yanı sıra, numune genişliğinin delik çapına oranı ( $W/D$ ), tüm numunelerde 6 olarak hazırlanmıştır. Deneysel sonuçları, kompozit numunelerin hazırlanmasındaki boyut değişkenleri ve tabaka dizilişlerinin hasar davranışını önemli bir biçimde etkilediğini göstermiştir.

**Anahtar kelimeler:** Hasar analizi, Tabakalı kompozit, Pim bağlantıları, Hasar tipi

### 1. INTRODUCTION

Mechanical properties of glass-fiber composite materials make them attractive for structural applications where high strength-to-weight and stiffness-to-weight ratios are required. Bolts, pins or rivets have been used extensively in these applications for transferring load between the structural components (1). Among the different techniques for joining structural members, mechanical fastening through a pin is a common choice owing to low cost, simplicity, and facilitation of disassembly for repair (2). Contrary to many metallic structural members, for which the strength of the joints is mainly governed by the shear and tensile strengths of the pins, composite joints present specific failure modes because of their heterogeneity and anisotropy (3).

Icten and Sayman (4) investigated failure load and mode in an aluminum-glass-epoxy sandwich composite plate, with a circular hole, which was

performed a traction force by a pin, experimentally. Okutan (5) carried out both numerical and experimental investigation to determine the failure behavior of mechanically fastened fiber-reinforced laminated composite joints. Mechanical properties and strengths of the composite were also obtained experimentally. Tests were applied on single pinned joints in two different stacking sequences of laminated composites. An experimental investigation was performed on a fiber glass/aluminum (FGA) laminate in order to characterize its behavior under pin and bolt-bearing conditions by the Caprino et al. (6). They reported that in pin bearing, the limit width-to-diameter and edge distance-to-diameter ratios necessary to avoid unsafe failure modes were lower than those usually quoted for classical laminates. A simple model to design safe pin-bearing joints, previously proposed for fiber-reinforced plastics, was effective also for the FGA. The study of the failure modes suggested that the aluminum layers play a major role in determining failure. The latter was due to the shear buckling of the individual laminate, which was decoupled from each other by extensive delamination/ debonding phenomena.

Meola et al. (7) studied an experimental investigation on an innovative Glare Fiber Reinforced Metal Laminate (FRML) with the goal to define its

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strength and behavior in the case of mechanical joints. Several specimens were prepared by varying width and hole-to-edge distance and tested in pin-bearing way without lateral restraints, which was the most critical testing procedure in the simulation of mechanical joints. Specimens, after bearing stress, were analyzed in both non-destructive and destructive ways. Yılmaz and Sinmazcelik (8) aimed to investigate the bearing performance of random oriented short fiber reinforced polyphenylenesulphide (PPS) composites which are widely used in various engineering applications. Both geometric parameters and chemical corrosion effects on the bearing performance of the material were examined. Liu et al. (9) studied mechanical joints with combinations of various composite thicknesses and pin diameters. Composite material produced woven glass fabric and phenolic matrix was examined. Sixteen joint configurations based on four composite thicknesses and four pin diameters were investigated. Both experiments and finite element analysis were conducted in that study.

In this study, the effect of stacking sequences on failure behavior of pinned composite plates was investigated. To determine the effects of joint geometry and stacking sequence on the failure mechanism, failure analysis were carried out experimentally. The nine different laminated composite plates were tested.

**2. MATERIALS AND METHODS**

Laminated composite plates used in experiments, were manufactured in Izorel Firm in Izmir. The dimensions of a pinned-joint are shown in Figure 1. Laminated composite rectangular specimen of length  $L+E$ , the thickness  $t$  and width  $W$  with a circular hole of diameter  $D$  is considered. The values of  $W$  and  $D$  are fixed as constant values of 30 and 5 mm, respectively. The thickness of each specimen is 3 mm. The hole is at a distance  $E$ , from the free edge of the specimen. A pin is placed at the center of the hole and a uniform tensile load  $P$  is performed to the specimen. The tensile load is also parallel to the specimen and it is symmetric with respect to the centerline.

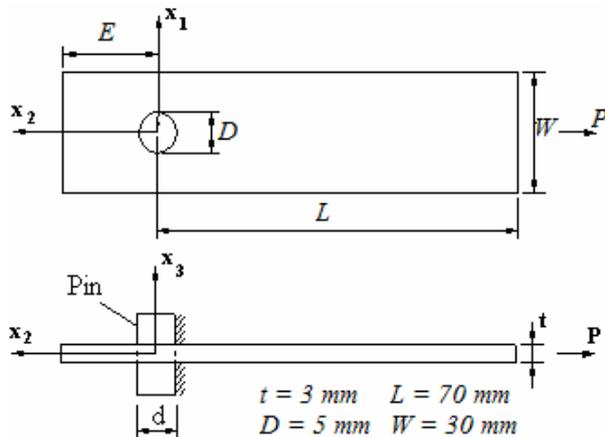


Figure 1 The dimensions of a pinned-joint

To determine the effects of joint geometry and stacking sequence on the failure behavior parametric studies were performed experimentally. The edge distance-to-hole diameter ratio ( $E/D$ ) was designed as from 1 to 6. The other important parameter was material parameter related to laminate composite material arrangement. For this intention, laminated plates were arranged as nine different stacking sequences differ from each other as illustrated in Table 1. Each laminated plate was produced to stick eight laminas onto together under press and heat, symmetrically. After the production process, the laminated plate had a nominal thickness of 3 mm at a volume fraction of 60%. Mechanical properties of laminated composite plate are presented in Table 2 (10). Standard mechanical tests were carried out to determine these mechanical properties of glass-epoxy laminated composite material (11-13). The schematic illustration of a unidirectional fiber reinforced lamina with global and material coordinate systems is presented in Figure 2 (14).

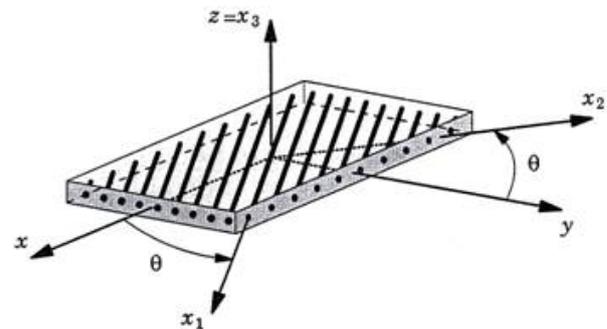


Figure 2 The global and material coordinate systems

The experiments were carried out in tension mode by the Instron-1114 Tensile Test Machine at a crosshead speed of 0.5 mm/min at Mechanics Laboratory in Dokuz Eylül University. Experimental setup for pinned-joint testing configuration is shown in Figure 3 (4), schematically.

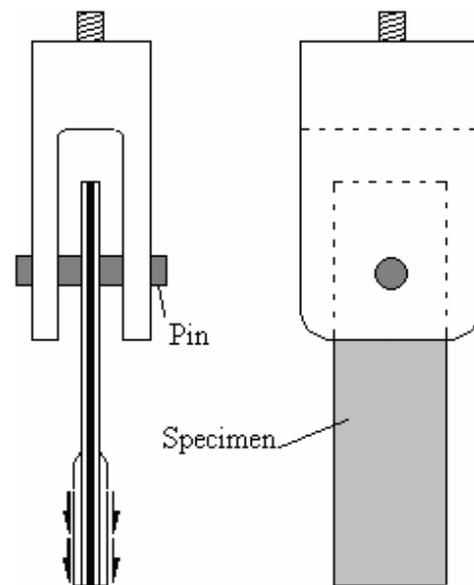


Figure 3 Experimental setup for the pinned-joint fixture

As seen from this figure, the lower edge of the specimen clamped and loaded from the steel pin by stretching the specimens. The load versus pin displacement curves for all composite specimens were plotted via a computer connected to the test machine. To calculate the strength of single bolt loaded composite specimens, the bearing strength is defined as,

$$\sigma_b = \frac{P}{Dt} \quad (1)$$

where  $P$ ,  $D$  and  $t$  are defined as tensile applied load, bolt hole diameter and thickness of the specimen, respectively. In addition, the pinned-joints under tensile loads generally damage in four basic modes that is named as cleavage mode, net-tension mode, shear out mode and bearing mode.

These failure modes are shown in Figure 4 (4, 12-13). However, combinations of these failure modes are possible in practical applications.

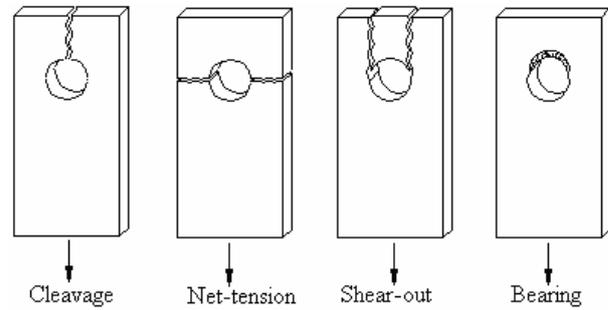


Figure 4 Common failure modes in pinned composite plates

Table 1 Stacking sequences of laminated composite plates

Group	Stacking sequence	Average thickness (mm)	W/D	E/D	Number of stacked lamina
1	$[0^{\circ}/0^{\circ}/90^{\circ}/90^{\circ}]_s$	3	6	1, 2, 3, 4, 5, 6	8
2	$[0^{\circ}/0^{\circ}/60^{\circ}/-60^{\circ}]_s$	3	6	1, 2, 3, 4, 5, 6	8
3	$[0^{\circ}/0^{\circ}/60^{\circ}/60^{\circ}]_s$	3	6	1, 2, 3, 4, 5, 6	8
4	$[60^{\circ}/60^{\circ}/-60^{\circ}/-60^{\circ}]_s$	3	6	1, 2, 3, 4, 5, 6	8
5	$[0^{\circ}/0^{\circ}/45^{\circ}/-45^{\circ}]_s$	3	6	1, 2, 3, 4, 5, 6	8
6	$[0^{\circ}/0^{\circ}/45^{\circ}/45^{\circ}]_s$	3	6	1, 2, 3, 4, 5, 6	8
7	$[45^{\circ}/45^{\circ}/-45^{\circ}/-45^{\circ}]_s$	3	6	1, 2, 3, 4, 5, 6	8
8	$[0^{\circ}/0^{\circ}/30^{\circ}/-30^{\circ}]_s$	3	6	1, 2, 3, 4, 5, 6	8
9	$[0^{\circ}/0^{\circ}/30^{\circ}/30^{\circ}]_s$	3	6	1, 2, 3, 4, 5, 6	8

Table 2 Mechanical properties of laminate

$E_1$ (MPa)	$E_2$ (MPa)	$G_{12}$ (MPa)	$\nu_{12}$	$X_t$ (MPa)	$Y_t$ (MPa)	$X_c$ (MPa)	$Y_c$ (MPa)	S (MPa)	$V_f$ (%)
36200	15400	6340	0.28	935	87	935	151	84	60

### 3. RESULTS AND DISCUSSION

Failure modes of tested specimens are presented in Table 3. As seen in this table, 3 different failure modes are observed as shear out, bearing and mixed (bearing+cleavage) modes. When  $E/D=1$ , shear-out failure mode occurs for all stacked specimens. In addition, the shear-out failure modes are also observed for Group 1, when  $E/D=1, 2$ , and 3. If the  $E/D$  ratio is equal to 2 and 3 for all Groups except Group 1, the mixed failure modes are created, generally. The occurrence of mixed mode is a combination of bearing and cleavage mode. In other words the bearing failure mode is started firstly and then the cleavage failure occurs. In this study, net tension failure mode is not observed, since the  $W/D$  ratio is selected as only 6. Some previous studies cited in the references are pointed out this result. According to literature, the net-tension failure mode is observed for small  $W/D$  ratios with high  $E/D$  ratios, especially.

The maximum failure loads depending on  $E/D$  ratio are shown in Figure 5. This figure points out that the maximum failure loads are increasing by increasing  $E/D$  ratio. For each stacked specimen, the failure loads is very small if the  $E/D=1$ . Besides, when  $E/D=2$ , the failure loads are increased but this increasing value is not enough for a safety design. When  $E/D$  is equal and greater than 3, the rising of failure loads is not high values. Therefore, the critical  $E/D$  ratios are seen as 1 and 2. The highest values of failure loads are obtained for Group 6,  $(0^{\circ}/0^{\circ}/45^{\circ}/45^{\circ})_s$ , specimens for all  $E/D$  ratios, whereas the lowest values of it are calculated for Group 4,  $(60^{\circ}/60^{\circ}/-60^{\circ}/-60^{\circ})_s$ , specimens for  $E/D=3, 4, 5, 6$  and Group 9,  $(0^{\circ}/0^{\circ}/30^{\circ}/30^{\circ})_s$ , specimens for  $E/D=1, 2$ . The highest value of maximum failure load is calculated for Group 6 and  $E/D=5$  as 6298 N, while the lowest value of it is obtained for Group 9 and  $E/D=1$  as 618 N.

Table 3 Failure modes of tested specimens

E/D	Group1	Group2	Group3	Group4	Group5	Group6	Group7	Group8	Group9
1	S	S	S	S	S	S	S	S	S
2	S	BC							
3	S	BC	B	BC	BC	BC	BC	BC	BC
4	BC	B	B	B	B	B	B	B	B
5	B	B	B	B	B	B	B	B	B
6	B	B	B	B	B	B	B	B	B

C: Cleavage mode, S: Shear-out mode, B: Bearing mode

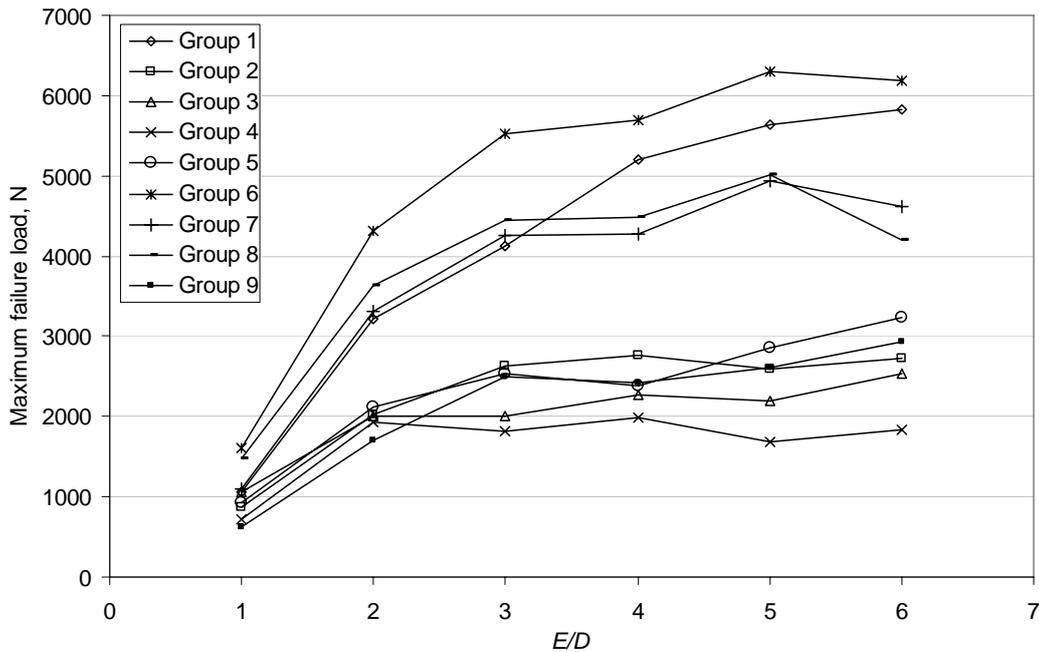


Figure 5 The maximum failure loads depending on E/D ratio

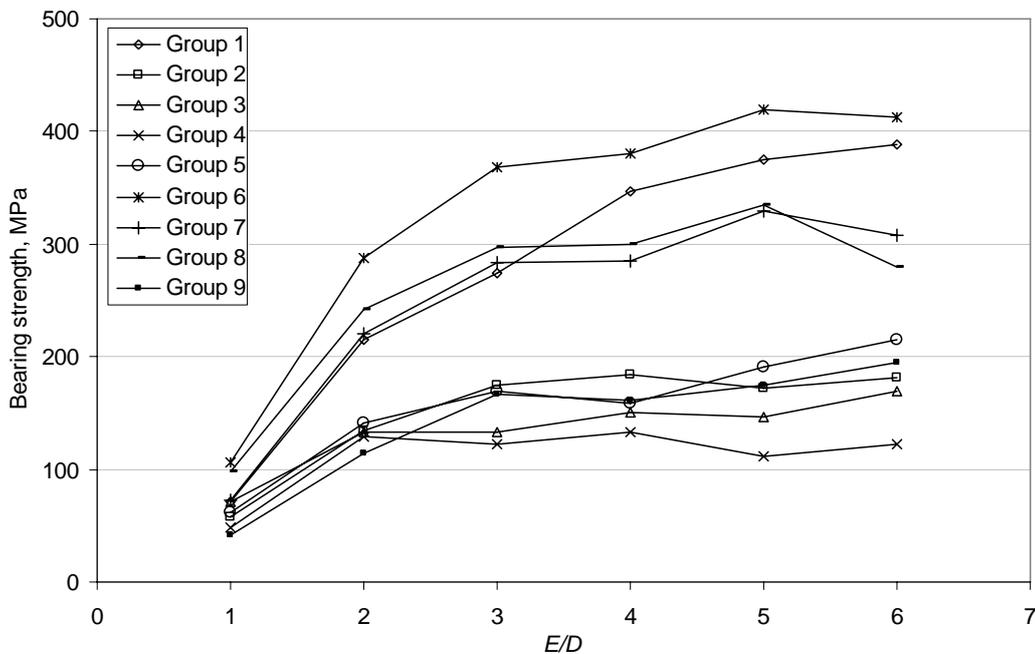


Figure 6 The bearing strengths depending on E/D ratio

The bearing strengths depending on E/D ratio are illustrated in Figure 6. The bearing strength was computed utilizing Equation 1. Therefore, the highest values of bearing strengths were calculated for Group 6,

(0°/0°/45°/45°)<sub>s</sub> specimens. Besides, other explanations mentioned for Figure 5 are also valid for Figure 6. Additionally, the highest value of bearing strengths was obtained 420 MPa for Group 6, when  $E/D=5$ , whereas the minimum value of it is 41 MPa for Group 9, when  $E/D=1$ . The providing a good structure, a designer must avoid from using of  $E/D=1$  and 2 ratios, especially. The load capacity of any composite part having these ratios is very lower than other ratios.

#### 4. CONCLUSIONS

According to the present study results, the following remarks can be concluded that;

- Both maximum failure loads and bearing strengths of the composite specimens are increases by increasing  $E/D$  ratio, generally.
- When  $E/D = 1$ , the bearing strengths is obtained very lower than those in other  $E/D$  ratios, so  $E/D=1$  is observed the weakest geometrical parameters.
- The magnitudes of bearing strengths are fully influenced from stacking sequences of laminated composite plates.
- The stacking sequence of (0°/0°/45°/45°)<sub>s</sub> laminated plate is seemed well than other orientations used in this investigation.
- The (60°/60°/-60°/-60°)<sub>s</sub> oriented plate is observed the weakest plates tested in this study.

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