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Research Article

Investigation of the Effect of Fiber Reinforcement on Adhesively Repaired Composite Plates

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ABSTRACT

In this study; fiber reinforcement effect on the circular hole perforated adhesively patch repaired woven glass fiber reinforced composite plates investigated with experimental study. The 8 layered woven glass fiber reinforced composite plates were using as composite plates and external patch. The fiber reionforcement angle of composite and external patch were changed as 0º, 15º, 30º and 45º. The circular hole in the center of composite plate was repaired with external patch and Loctite 9466 adhesive. The failure load was determined with static tensile tests. The repair performance was compared with un-perforated and un-repaired composite plates failure strength. As a result of the experimental studies; it was determined that the applied repair treatment increased the failure loads by 34% to 102% compared to notched plates. In addition, it was determined that the change in the patch fiber reinforcement angle was more effective on the failure loads. The largest failure loads were obtained for the plate repaired with a 30º fiber reinforcement angle patch compared to the notched plates.

1. INTRODUCTION

Composite materials are produced for their intended use and purpose. In addition to their advanced properties, they have complex mechanical properties compared to conventional materials. For this reason, their production is quite expensive and requires special manufacturing techniques. When they are failure as a result of some external factors, repairing them instead of replacement can offer more economical solutions. However; due to their complex mechanical properties, it is also very difficult to repair them compared to traditional metallic materials. It is especially important to maintain the mechanical properties of continuous fiber reinforced thermoset based composite materials during repair processes or to repair them with appropriate methods in terms of working performance. The reinforcement angles of the fibers that provide the strength of such composites are selected and optimized depending on the strength states such as bending, tension or torsion to which the material is exposed. In case of failure, the continuity of the material structure may be disrupted as the fibers that provide strength are failure. In addition, in order to maintain the aerodynamic structure of high-speed vehicles such as air and sea vehicles, the repair process must be designed. It is a common practice to repair composite materials by using patches and adhesives on the outside. During these processes, the layer arrangement and the selection of the appropriate fiber reinforcement angle affect the performance of the repair processes. Repair with adhesives using composite plates has been the subject of many studies in the literature [1-14]. In these studies, the effects of single side repair [1-9], double side repair [10-14], single and double side repair [14] on the failure load using composite patches were investigated using numerical and experimental methods. In the studies; repair of composite plates with circular hole in the center [2, 5, 6, 8, 20-14], repair of plates with edge notches [1, 3, 14, 15], center [7] and edge crack [4, 9] repair was investigated. Albedah et al. [1] investigated the effects of single side repair of aluminum plates with V-notch on the edge on fatigue life using composite patches. The negative effects of increasing the patch thickness on the failure load were reported by Tse et al. [2], while the relationship between load and fiber reinforcement direction was emphasized by Mohamed et al. [3] emphasized that there is a relationship between load and fiber reinforcement direction. Aminallah et al. [4] found that geometrically modified plates, when reinforced with composite patches, caused a significant reduction in J-integral values and increased fracture resistance. Yashiro et al. [5] reported that variable stiffness patches increase the debonding initial strain by reducing bending deformation in the end regions, resulting in later debonding and higher load carrying capacity. Huang and Haftka [6] suggested in their study that fiber orientation optimization significantly increases the load carrying capacity. Aabid et al. [7] investigated the effect of patch and adhesive thickness on the repair of 2024 aluminum plates using boron/epoxy, while Du et al. [8] investigated the repair of titanium foils with carbon fiber reinforced PEEK prepregs. Kaman and Çetişli [9] investigated the effects of edge-notched graphite/epoxy composite and patch on stress intensity factor. They determined that increasing the fiber reinforcement angle decreases the KI mode. Cheng et al. [10] used carbon/epoxy composite and patches and found that the patches with fiber reinforcement angle [45/-45] had the highest failure loads. Liu and Wang [11] emphasized in their study that the failure loads are reduced for adhesive thickness values of 0.3 mm and larger. Kuswaha et al. [12] emphasized that patch fiber reinforcement angle variation has a positive effect on failure loads. Gong et al. [13] investigated the effect of patch arrangement on the strength of composite plates with a circular hole in the center and repaired from the outside using patch and adhesive by experimental and numerical methods. They stated that the patch fiber reinforcement angle and layer arrangement were effective on the repair strength. Çelik et al. [14] investigated the effects of fiber reinforcement angle on the patch and adhesive repair strength of composite plates with central and edge notches. They determined that the lowest repair strength for all notch types was obtained for 45° fiber reinforcement angle. Turan [15] investigated the effect of patch fiber reinforcement angle on joint strength in lap adhesive joints in composite plates. He determined that the fiber reinforcement angle is highly effective on the joint strength and that the patch with 15° fiber reinforcement angle has the highest joint strength, especially at low lap length. In the studies, it is generally concluded that the repair process increases the strength at certain rates and the mechanical properties of the patch are important.

In this study, the effect of fiber reinforcement angle on the failure loads of woven glass fiber/epoxy composite plates with a circular hole in the center was investigated experimentally. The main objective is to gain a clearer understanding of the effects of fiber reinforcement angle in repair processes using patches and adhesives. The study basically consists of two parts. In the first part, composite plates with 0°, 15°, 30° and 45° fiber reinforcement angles were repaired using 0° fiber reinforcement angle patches. In the second part, composite plates with 0° fiber reinforcement angle were repaired using 0°, 15°, 30° and 45° fiber reinforcement angle patches and adhesive on one and two sides. In order to evaluate the performance of the repair processes, the results obtained were compared with the failure loads of unrepaired composite plates without holes. The results are presented in tables and graphs.

2. Experimental Study

In the experimental study, 8-layer woven glass fiber reinforced epoxy resin composite plates and Loctite 9466 adhesive were used. The patches used in the repair processes were cut from the same composite plates. Composite plates were produced by hand lay-up and hot-pressing technique using 250 gr/m^2 woven glass fiber and at a rate 20/80 epoxy resin. The plates supplied from Izoreel™ (İzmir, Türkiye) company are 2 mm thick and 30 mm wide. A 10 mm diameter circular hole was drilled in the center of the 180 mm long plates on a drill bench. Composite patches were cut in 30 mm length and 30 mm width and used. Figure 1 shows the problem description and geometrical properties.

The specimens were manufactured in the laboratories of the Dicle University Mechanical Engineering at room temperature conditions. The surfaces to be repaired were roughened with 300 grit sandpaper and cleaned with a cotton cloth and acetone. During the bonding process, the adhesive thickness was selected as a constant 0.2 mm

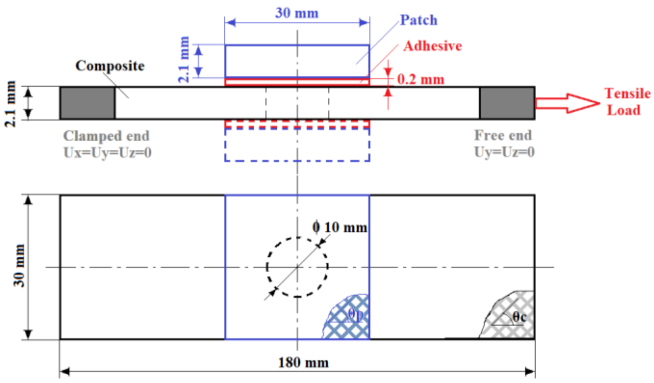

Figure1. Boundary conditions and Definitions of problem [13, 14].

In order to keep the adhesive thickness constant, the bonding processes were carried out on molds obtained from the 3D printer. For the consistency of the experimental results, three of each specimen were produced. The experiments were performed on an Instron BS8801 tensile testing machine at a tensile speed of 1mm/min. The experiments were continued until the specimen broke and the load value obtained when the specimen broke was accepted as the ultimate failure load. Figure 2 shows the specimen and experimental setup.

Figure 2. Manufactured specimens and experimental setup.

In the experimental study, the changes in fiber reinforcement angles of the composite plate and patch were investigated. The number of specimens and fiber reinforcement angle variations are presented in Table 1.

TABLE I
NAME AND QUANTITY OF EACH TYPE SPECIMEN USED IN THE EXPERIMENTAL STUDY

Plate	CFRA (°)			
	0	15	30	45
Un-Rep.	3	3	3	3
Str.Plate	3	3	3	3
SL-R	3	3	3	3
DL-R	3	3	3	3
	PFRA(°)			
	0	15	30	45
SL-R	3	3	3	3
DL-R	3	3	3	3

The composite fiber reinforcement angle variation is referred to as CFRA, the patch fiber reinforcement angle variation is referred to as PFRA, the plate repaired on one side is referred to as SL-R, the plate repaired on two sides is referred to as DL-R, the composite plate with circular holes is referred to as Un-Rep. and the plate without circular holes is referred to as Str.Plate. The load and strain values obtained as a result of the experimental study were recorded and graphs were drawn. The largest load value in the graphs was considered as the ultimate failure load of the specimen.

2. Results and Discussion

Figure 3 showed that the obtained load and extension graphs at the end of the experimental study. When the graphs in Figure 3 are evaluated, the change in PFRA and CFRA is manifested by the change in elongation values.

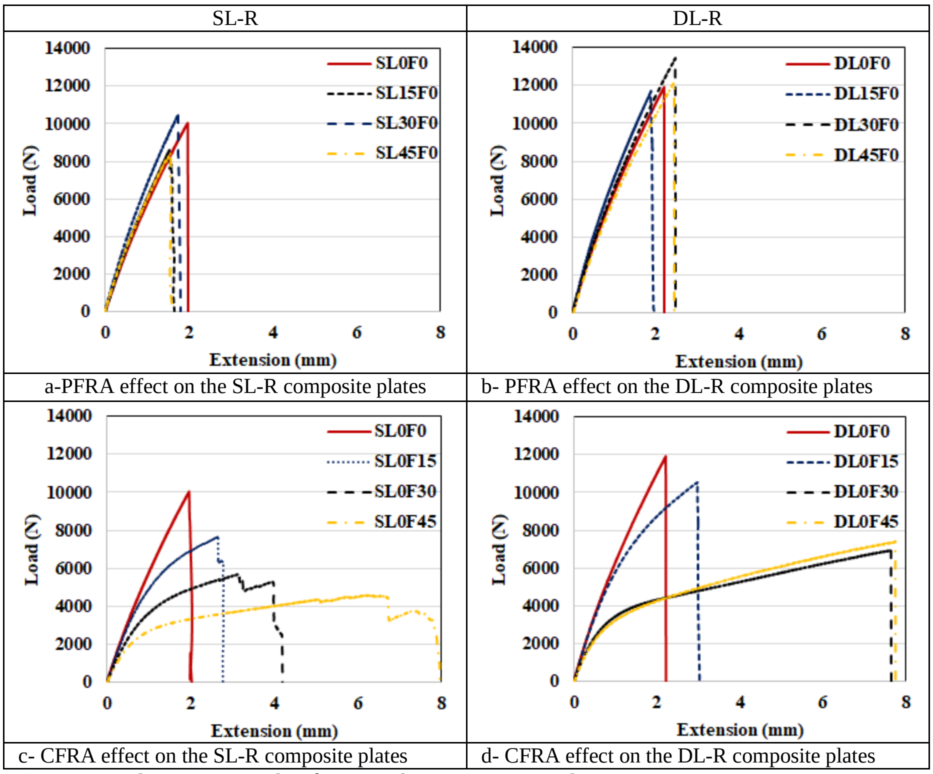

Figure 3. Load-extension graphs of SL-R and DL-R composite plates

It was determined that the change in PFRA was not very effective on extension for both repair types. In the case of CFRA change, it was determined that the extension values increased depending on the fiber reinforcement angle change. It is seen that the highest failure load value is obtained as 13184 N for the DL-R specimen with state of 30° PFRA. The lowest failure load value is obtained as 4200 N for the SL-R specimens with state of 45° CFRA.

3.1. Effect of plate fiber reinforcement angle variation on failure behavior

In order to investigate the effects of CFRA variation, the PFRA was selected as 0°, 15°, 30° and 45° for single and double side repair processes, keeping the PFRA 0 ° constant. Figure 4 shows the graph of the effects of CFRA variation on failure load.

Figure 4 shows that the failure loads for all parameters decrease with increasing fiber reinforcement angle of the composite plate. The highest failure load values for DL-R and SL-R are 11910 N and 10255N for composite plates with 0° fiber reinforcement angle, respectively. The lowest failure load values were determined as 5915 N and 4644 N for composite plates with 45° fiber reinforcement angle, respectively.

It is seen that these results are consistent with the values obtained for Str.Plate and Un-Rep. plates. This shows that the CFRA is determinant on the failure load values considering that the PFRA is 0° and constant.

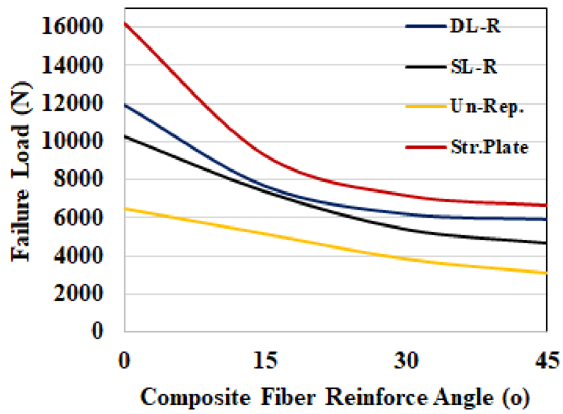

Figure 4. Composite plate reinforced angle change effect on the failure loads

More detailed evaluations of the experimental study results shown in Figure 4 are presented in Table 2. The increase ratio used in this table (INC.R) indicates the strength increase ratio of SL-R or DL-R composite plates compared to Un-Rep. composite plates. According to Table 2, it is determined that the failure loads obtained for SL-R and DL-R plates are between 92% and 40% higher than the Un-Rep. plates. The failure loads of DL-R plates were calculated to be 26% to 11% lower than Str.Plate. Similarly, the failure loads of SL-R plates were calculated to be 36% to 20% lower.

TABLE II
EXPERIMENTAL DETAILS OF CHANGING OF COMPOSITE FIBER REINFORCED ANGLE EFFECT ON THE FAILURE LOAD (FOR PATCH REINFORCED ANGLE CONSTANT AS 0^{O})

	DL-R			SL-R			Un-Rep.		Str.Plate	
CFRA (º)	F.L. (N)	St.Dev. (%)	Inc.R. (%)	F.L. (N)	St.Dev. (%)	Inc.R. (%)	F.L. (N)	St.Dev. (%)	F.L. (N)	St.Dev. (%)
0	11910.82	6.85	83.18	10255.82	5.39	57.73	6502.22	4.25	16243.49	3.14
15	7654.57	4.10	48.49	7356.32	3.48	42.70	5155.01	6.35	9293.94	6.58
30	6186.05	5.04	62.06	5363.57	7.44	40.52	3817.03	3.54	7188.04	2.45
45	5915.46	7.49	92.49	4644.14	8.52	51.12	3073.16	8.72	6663.47	4.12

CFRA: Composite fiber reinforced angle, F.L.: Failure Load, Inc.R.: Increasing rate, St.Dev.: Standart deviation.

3.2. Effect of patch fiber reinforcement angle variation on failure behavior

In order to investigate the effects of PFRA on repair strength, the patch fiber reinforcement angle was selected as 0º, 15º, 30º and 45º while the plate fiber reinforcement angle was kept 0º and constant. Figure 5 shows the graph of the effects of PFRA variation on failure load. The details of the effects of CFRA change on the failure load are presented in Table 3. According to Table 3; it is determined that the failure loads obtained for the plates repaired on the double side are 15% to 25% higher than the plates repaired on the single side. It is seen that the single side repair process is 15% to 25% lower than the composite plate without notch and 15% to 25% higher than the composite plate with notch. As can be seen from Figure 5, it is seen that the change in the PFRA leads to quite different results on the failure loads. According to the PFRA, it is understood that 30º fiber reinforcement angle causes the highest failure loads for both repair types. The highest failure load values for DL-R and SL-R were determined as 13184 N and 10544 N for composite plates with 30º fiber reinforcement angle, respectively. The lowest failure load values were 11645 N and 8725 N for composite plates with 15º fiber reinforcement angle, respectively.

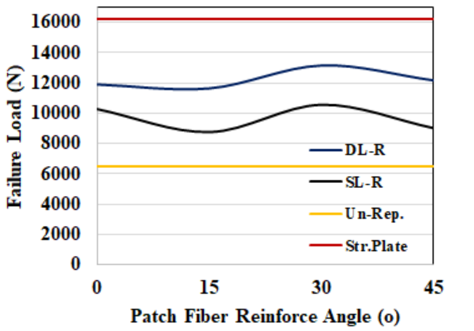

Figure 5. Patch reinforced angle change effect on the failure loads

It is known that there is an inverse relationship between fiber reinforcement angle and composite plate strength. It was strikingly evident that the load transferred from the adhesive to the patch in the bonding joints was influenced by the deformation along with the load transferred to the patch. Although the highest deformation capability is for the 45º fiber reinforcement angle, it has the lowest strength as shown in Figure 4 plate strength values. More detailed evaluations of the experimental results shown in Figure 5 are presented in Table 3.

TABLE III.
EXPERIMENTAL DETAILS OF CHANGING OF COMPOSITE FIBER REINFORCED ANGLE EFFECT ON THE FAILURE LOAD (FOR PATCH REINFORCED ANGLE CONSTANT AS 0^{O})

	DL-R			SL-R			Un-Rep.		Str.Plate	
PFRA (º)	F.L. (N)	St.Dev. (%)	Inc.R. (%)	F.L. (N)	St.Dev. (%)	Inc.R. (%)	F.L. (N)	St.Dev. (%)	F.L. (N)	St.Dev. (%)
0	11910.82	16.85	83.18	10255.82	5.39	57.72	6502.22	4.25	16243.49	3.14
15	11645.32	23.98	79.09	8725.13	6.91	34.18	6502.22	4.25	16243.49	3.14
30	13184.03	9.28	102.76	10544.88	22.54	62.17	6502.22	4.25	16243.49	3.14
45	12183.71	5.25	87.37	8986.09	9.26	38.20	6502.22	4.25	16243.49	3.14

PFRA: Patch fiber reinforced angle, F.L.: Failure Load, Inc.R.: Increasing rate, St.Dev.: Standart deviation.

The table 3 show the increase ratios of the failure loads of repaired specimens compared to the failure loads of Un-Rep. plates. According to Table 3; it is determined that the failure loads obtained for single and double side repaired plates are 102% to 34% higher than the unrepaired plates. The failure loads of DL-R plates were calculated to be 28% to 18% lower than Str.Plate. Similarly, the failure loads of SL-R plates were calculated to be 46% to 35% lower. Kuswaha et al.[12] reported that 45º fiber reinforcement angle increased the failure loads up to 67% compared to 0º fiber reinforcement angle, while Gong et al. [13] reported an increase of up to 90% for the same fiber reinforcement angle. In the study conducted by Turan [15], it was stated that 15º fiber reinforcement angle increased the adhesion joint by 45% for single side and 15% for double side connection compared to 0º. This is supported by other studies in the literature on fiber reinforcement angle variation [12-15]. This situation supports the consistency and scientificity of the study.

4. Conclusions

In this study, the effect of fiber reinforcement angle variation on the failure loads of composite plates repaired using SL-R and DL-R was experimentally investigated. In the study, the variation of PFRA for fixed CFRA and the variation of CFRA for fixed PFRA value were analyzed. The results obtained are listed in items.

- It was determined that the failure loads of the composite plates with circular holes increased by 34% to 102% as a result of the repair applied.
- As a result of the SL-R process, the increase in failure loads compared to the Un-Rep. increased the failure loads at rates ranging from 34% to 62%, while this ratio was between 48% and 102% in the DL-R process.
- For all parameters; it was determined that the failure loads obtained as a result of the repair operations were lower than the failure loads of the Str.Plate. It was determined that the repaired composite plate failure loads can approach the failure loads of the Str.Plate by a maximum of 11% and a minimum of 46%.
- As a result of the composite PFRA, it was determined that the failure loads decreased in accordance with the fiber reinforcement angle of the plate and the patch did not have much effect.
- It was determined that the PFRA variation was quite determinant on the failure loads. Especially when a patch with a fiber reinforcement angle of 30^o was used, it was determined that the failure loads of the plates repaired from SL-R and DL-R were the highest.
- It is seen that fiber reinforcement angle is important in the repair of composite materials by adhesive and patch. when the results obtained are evaluated together with the literature, the importance of the highest bond strength is understood. designers should act with an appropriate optimization.

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BIOGRAPHIES

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