FAILURE BEHAVIOR OF TWO PARALLEL PINNED/BOLTED COMPOSITE JOINTS

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ABSTRACT

In this study, the failure behavior of two parallel pinned/bolted composite joints was investigated, experimentally. The laminated composite plates were produced from glass fibers and epoxy matrix. During the tests, various joint geometries and ply orientations were considered to decide the optimum joint geometry and suitable stacking sequence of the laminated composite plates for two parallel pinned/bolted joints. For these reasons, the distance from the free edge of the plate to hole diameter ratio (E/D) was changed from 1 to 5, the distance between two parallel holes to hole diameter ratio (K/D) was selected as 2 and 5, the distance from the lateral edge of the plate to hole diameter ratio (N/D) was taken as 2 and 3. The laminated plates were composed from 8 laminas to stuck onto together with three different orientations as $[0°_2 / 30°_2]_s$, $[0°_2 / 45°_2]_s$ and $[0°_2 / 60°_2]_s$. The experiments involved both pinned and bolted joint. Experimental results indicate that failure behaviors of pinned/bolted composite joints are strictly influenced from both orientations of laminated plates and geometrical parameters.

Keywords : Failure behavior, Bolted joints, Pinned joints, Bearing strength, Failure mode.

1. INTRODUCTION

The use of fiber reinforced composites has become popular in recent years. Therefore, the construction of the composite joints has become a very important research area because the structural efficiency of the composite structure is determined by its joints, rather than its basic structures [1]. Bolts, pins or rivets have been used widely in these applications for transferring load between the structural components [2]. Among the different techniques for joining structural members, mechanical fastening through a pin or bolt is a common selection due to low cost, simplicity, and facilitation of disassembly for fix [3]. Opposing to many metallic structural parts, for which the strength of the joints is mainly governed by the shear and tensile strengths of the pins or bolts, composite joints present specific failure modes due to their heterogeneity and anisotropy [4]. Nonetheless, bolted joints require holes to be drilled in the structure; large stress concentration tends to grow around the hole, which can severely reduce the overall strength of the structure [5].

Meola *et al*. [6] conducted an experimental investigation on an innovative Glare Fiber Reinforced Metal Laminate (FRML) to characterize its strength and joint behavior. Several specimens were fabricated 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. Kovacs *et al*. [7] considered moment-rotation diagrams and cyclic parameters, which define and characterize the failure modes. The details of the specimens, the

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loading history and the testing procedure were evaluated. Pakdil *et al*. [8] investigated the effect of preload moments on failure response of glass-epoxy laminated composite single bolted-joints with bolt/hole clearance. To determine the influences of single bolted-joint geometry and stacking sequence of laminated plates on the bearing strength and failure mode, a parametric analysis was performed, experimentally. Sayman *et al*. [9] experimental determined the bearing strengths depending on various E/D and W/D glass fiber reinforced epoxy laminates joined by single bolt. Since the knowledge of bearing strength helps determine the appropriate joint size in a given application. The effects of various preload moments were also analyzed for single bolted composite joints.

Ataş *et al*. [10] obtained failure load and failure modes of laminated glass-polyester composite plates with two parallel circular holes, which were subjected to traction forces by two rigid pins. The failure behaviors of pin loaded composite plates were observed both experimentally and numerically for different geometries and fiber orientations. Tong [11] carried out an experimental investigation on the effect of non-uniform bolt-to-washer radial clearance on bearing failure of bolted joints under different clamping forces with various lateral constraints. The experimental results were also used to validate an existing model. Two extreme diametral fit positions, with a positive or negative bolt hole-to-washer clearance, were also considered. Chang *et al*. [12] presented a method for calculating the failure strengths and failure modes of composite laminates containing a pin loaded hole for materials exhibiting nonlinearly elastic behavior. Numerical results, generated using a nonlinear finite element scheme, were compared to data. Riccio and Marciano [13] performed an experimental investigation in single-lap bolted composite joints in order to point out the effect of geometrical and material characteristics on the damage onset and propagation under tensile loading conditions. Firstly, static tensile tests were performed on single-lap joints for different bolt diameters and different interfaces. Then, non-destructive ultrasonic evaluations were conducted at intermediate load levels and at final failure in order to illustrate the real onset and evolution of failure inside the joints in terms of fibers and matrix breakage.

In this study, an experimental work was undertaken to investigate the failure response of two parallel pinned/bolted composite joints. The laminated composite plates were produced from glass fibers and epoxy matrix. The effects of the stacking sequences and a number of geometrical parameters of composite specimens on failure behavior were investigated.

2. MATERIALS AND METHODS

Consider a laminated composite rectangular specimen of length $L + E$ and width W $(K + 2N)$ with two parallel circular hole of diameter D, as illustrated in Fig. 1. The diameters of each hole and length were fixed at constant values of 5 and 90mm, respectively. The centre of each hole was positioned at a distance E, from

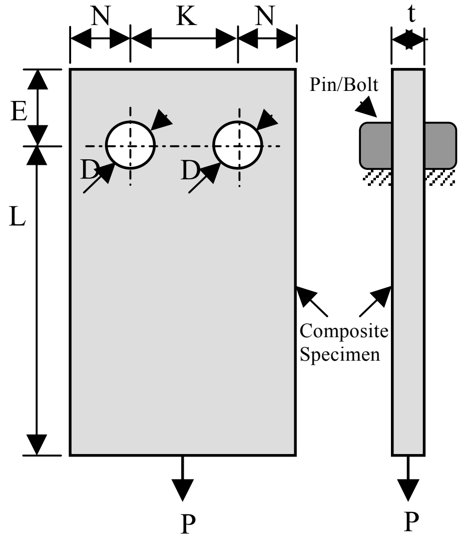

Fig. 1 Geometry of a tested composite specimen

the free edge of the plate. A steel pin/bolt was located at the center of the hole and a uniform tensile load P was applied to the specimen. The load was also parallel to the plate plane and was symmetric with respect to the centerline. This configuration was preferred to achieve bearing strength and damage mode. To investigate the effects of joint geometry and stacking sequence on the failure behavior, parametric studies were carried out experimentally. Briefly, two different main parameters were considered for two parallel pinned/bolted joint of laminated composites. One of them was geometric parameters. Therefore, the distance from the free edge of the specimen to hole diameter ratio (E/D) was designed from 1 to 5, the distance between two parallel holes to hole diameter ratio (K/D) was planned as 2 and 5 and the distance from the lateral edge of the specimen to hole diameter ratio (N/D) was considered as 2 and 3. Each laminated composite plate was created by sticking a total of eight laminas arranged in four groups made from two laminas. Two of the groups of two laminas were then laminated at an angle of $[0°_2 / 30°_2]_s$. Finally, the two main groups of four laminas were laminated together, symetrically, thus forming a balanced composite plate. The same process was repeated for the following angles of $[0°_2 / 45°_2]_s$ and $[0°_2 / 60°_2]_s$ thus creating a total of 3 samples. The lamination process took place under pressure and heat. The final nominal thickness of each laminated plate was 3mm at a volume fraction of 60%. Furthermore, glass fiber reinforced-epoxy laminated composite plates were produced locally in Izmir, Turkey. The detailed production process of laminated composites was explained in a previous study [8]. Similarly, determination of mechanical properties of composite material after the production process can also be found in the same reference. The mechanical properties of the glass fiber reinforced-epoxy laminated composite material are presented in Table 1 [8].

During the present experimental study, similar specimens were tested both as pinned and bolted joints. When the bolt was used, different preload moments were also performed on the specimen via a nut and a

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washer before the tensile tests. The magnitudes of preload moments were 3 and 6Nm. Nevertheless, application of preload moments was not possible for pinned joints because of using a pin only. The experiments were also carried out in tension mode on the Instron-1114 Tensile Test Machine at a crosshead speed of 0.5mm/min. The arrangements of two parallel pinned and bolted joints are schematically shown in Fig. 2. The lower edge of the specimen was clamped and loaded from the steel pin or bolt by stretching the specimens as seen in this figure. The load versus bolt displacement curves for all composite configurations were plotted by a computer connected to test machine. The static bearing strength of two parallel mechanical fasteners is [14];

$$\sigma_b = \frac{P}{2.\,D.\,t} \tag{1}$$

wherein, t is the thickness of the tested specimen. According to some previous studies, the four basic failure modes are observed in laminated composite plates, if mechanical fasteners are used as joint component [8-15]. The tensile loads are generally applied to the composite joint and it causes failure modes named as cleavage mode, net-tension mode, shear-out mode and bearing mode. Schematic view of these failure modes are plotted in Fig. 3. Nonetheless, combinations of these failure modes are observed in many practical applications.

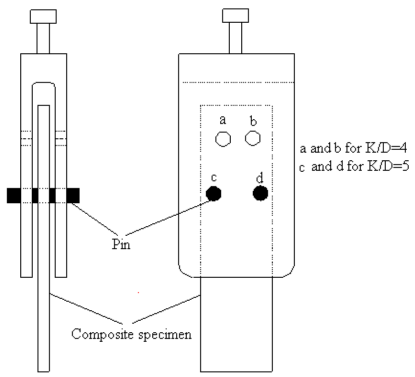
3. RESULTS AND DISCUSSION

During the experiments, for every type of composite specimen, three tests were conducted and average bearing strength values were calculated. In addition, each of mechanically-joint was loaded up to the fastener displacement arriving 6 or 8mm from the initial position, if any catastrophic failure was not occurred. The load-displacement curves of $[0°_2/ 45°_2]_s$ are plotted in Fig. 4 pinned some specimens as example. According to this figure, the shear out failure mode is created between 1 and 2mm pin/bolt displacement in Fig. 4(a). Bearing/Cleavage mixed failure mode is observed after 2mm displacement in Fig. 4(b). When full bearing failure mode is occurred, the load carrying capacity of the joint is decreasing after 6mm displacement. Therefore, the fastener displacement is determined as 6 or 8mm.

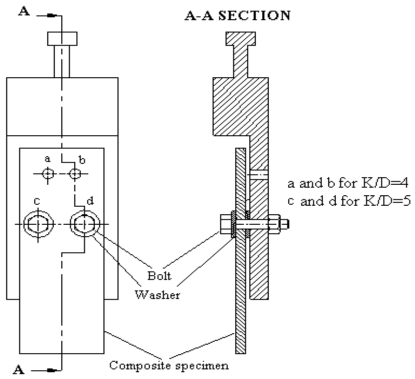
Failure mode of each type of tested specimen was determined to observe both three damaged specimens and its load-displacement curves plotted during the tests using computer. Failure modes of $[0°_2/ 30°_2]_s$, $[0°_2/ 45°_2]_s$ and $[0°_2/ 60°_2]_s$ specimens are offered in Tables 2 ~ 4, respectively. As seen in these tables, two main types of failure modes were observed as called shear-out (S) and bearing (B), although the mixed failure mode was seen in some specimens as the combination of bearing and cleavage (BC). With the symmetry of parallel fastener and careful recreation of the tensile load condition, the same failure mode was created in two parallel holes. The net-tension of failure mode was not observed in any specimen, since the occurrence of net- tension failure mode was prevented with the selection of suitable geometrical parameters of specimens in the present study. It is known that the net-tension failure mode is a catastrophic failure [16]. This failure mode causes to decrease load carrying capacity of the joint and any load is not carried by the joint after the occurrence of the net-tension failure mode [8]. Meanwhile, some little E/D ratios cause cleavage failure mode. This failure mode is also catastrophic like net-tension. The pure cleavage mode is not observed in any specimen, but it occurs with bearing failure in this study. The immediate drop of the load is clearly seen from Fig. 4(b), when cleavage failure mode is created. In other words, after the occurrence of cleavage failure mode the joint can not any higher load according to before. Some previous studies pointed out that this failure mode occurred for small specimen width, for example $W/D = 2$, [8-10,14].

Table 1 Mechanical properties of laminated composite material

E_1 (MPa)	E_2 (MPa)	G_{12} (MPa)	ν_{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



(a) Two parallel pinned composite joint



(b) Two parallel bolted composite joint

Fig. 2 Schematic view of test equipments (for $K/D = 5$)

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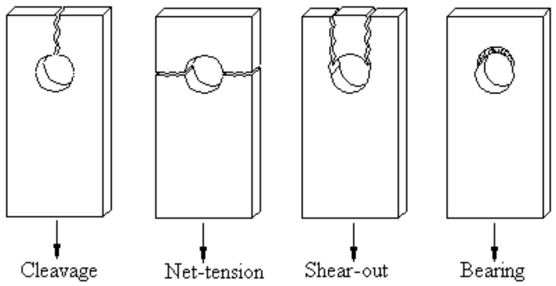
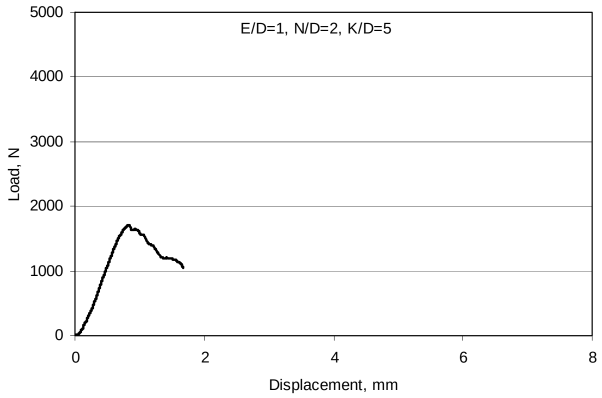
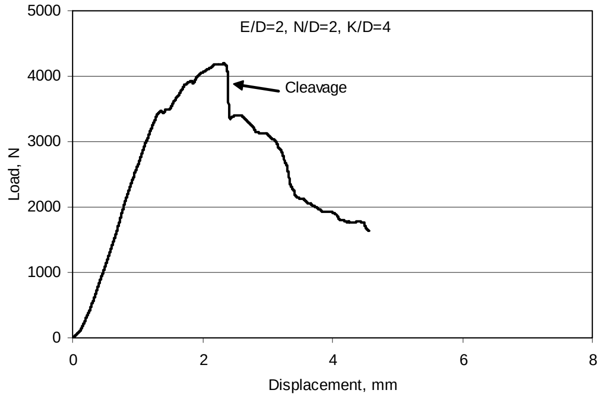


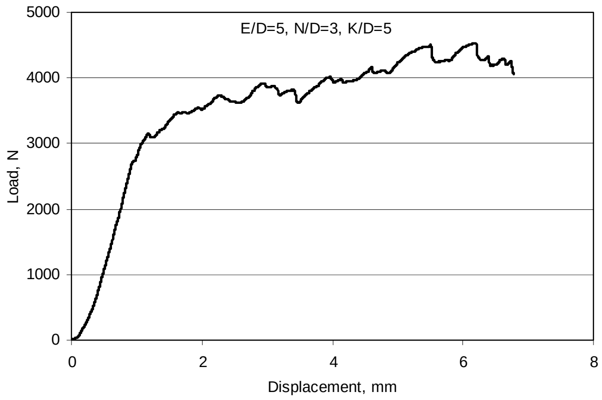
Fig. 3 General failure modes in mechanically fastened composite plates



(a) Shear-out failure mode



(b) Bearing/Cleavage failure mode



(c) Bearing failure mode

Fig. 4 Load-displacement curves for pinned $[0_2°/45_2°]_s$ specimens

Table 2 Failure modes of $[0°_2 / 30_2]_s$ specimens

N/D	*E/D*	*K/D*	Joint Type		
			Pinned (0Nm)	Bolted (2.5Nm)	Bolted (5Nm)
2	1	4	S	S	S
		5	S	S	S
	2	4	BC	BC	BC
		5	BC	B	B
	3	4	B	B	B
		5	B	B	B
	4	4	B	B	B
		5	B	B	B
	5	4	B	B	B
		5	B	B	B
3	1	4	S	S	S
		5	S	S	S
	2	4	BC	BC	BC
		5	BC	BC	BC
	3	4	B	B	B
		5	B	B	B
	4	4	B	B	B
		5	B	B	B
	5	4	B	B	B
		5	B	B	B

Table 3 Failure modes of $[0°_2 / 45_2]_s$ specimens

N/D	*E/D*	*K/D*	Joint Type		
			Pinned (0Nm)	Bolted (2.5Nm)	Bolted (5Nm)
2	1	4	S	S	S
		5	S	S	S
	2	4	BC	BC	BC
		5	BC	BC	BC
	3	4	B	B	B
		5	B	BC	BC
	4	4	B	B	B
		5	B	B	B
	5	4	B	B	B
		5	B	B	B
3	1	4	S	S	S
		5	S	S	S
	2	4	BC	BC	BC
		5	BC	BC	BC
	3	4	B	B	BC
		5	B	B	B
	4	4	B	B	B
		5	B	B	B
	5	4	B	B	B
		5	B	B	B

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Table 4 Failure modes of $[0°_2 / 60_2]_s$ specimens

N/D	E/D	K/D	Joint Type		
			Pinned (0Nm)	Bolted (2.5Nm)	Bolted (5Nm)
2	1	4	S	S	S
		5	S	S	S
	2	4	BC	BC	BC
		5	BC	BC	BC
	3	4	BC	BC	BC
		5	B	BC	BC
	4	4	B	B	B
		5	B	B	B
	5	4	B	B	B
		5	B	B	B
3	1	4	S	S	S
		5	S	S	S
	2	4	BC	BC	BC
		5	BC	BC	BC
	3	4	BC	BC	BC
		5	BC	BC	BC
	4	4	B	B	B
		5	B	B	B
	5	4	B	B	B
		5	B	B	B

In the present study, failure modes changed in relation to the geometrical parameters. When $E/D = 1$, the shear-out failure mode was observed for all tested specimens. The mixed failure mode also occurred, when $E/D = 2$ and 3, generally. Nevertheless, the full bearing failure modes were usually observed, when the E/D selected as 3, 4 or 5. The failure modes differ from each other in terms of orientations of the composite specimens (Tables 2-4). Besides, increasing values of the preload moments caused to change of failure modes, especially. On the other hand, the occurrence of failure mode was changed depending on joint type, namely either pinned or bolted. Briefly, it is known that a bearing failure is more advantageous than either net tension, cleavage or shear-out failure modes for a safe composite joint, but the failure mode alone is not only enough to determine the safety for a composite joint. The effects of E/D ratio on the bearing strength for all tested specimens are shown in Fig. 5 depending on geometrical parameters, N/D and K/D ratios, stacking sequences of laminated plates, $[0°_2 / 30°_2]_s$, $[0°_2 / 45°_2]_s$ and $[0°_2 / 60°_2]_s$, and joint type in terms of applied preload moments. According to this figure, firstly, the values of bearing strengths increase by the increasing of E/D and K/D ratios. Furthermore, the results indicate that for $K/D = 4$ or 5, no significant effect on bearing strength of laminate with a pinned joint, especially.

This case is clearly seen for E/D ratios. The weakest geometrical parameter is determined as $E/D = 1$, since the bearing strengths are significantly smaller than other E/D ratios. This mean that the load carrying capacity of the joint is not safe when $E/D = 1$. As mentioned previously, the selection of this particular geometrical parameter had also caused shear-out failure mode in the joint area. The shear-out failure mode is also a catastrophic failure, because cannot the joint carry any load after this type of failure. In real applications, any designer should avoid to use the following geometrical parameters: $E/D = 1$ and 2, particularly. Furthermore, the magnitudes of bearing strengths for pinned composite joints were lower than bolted composite joints for all orientations. It is calculated understand that the load carrying capacity of two parallel bolted joint is higher than two parallel pinned joint, since the nut, washer and bolt system carries a part of the load. The bolted joint provide an extra pressure on the specimen, this pressure is increased by increasing applied preload moment. Therefore, the bad effect based on holes was decreased using the washer in bolted joints. The bearing strengths for $[0°_2 / 45°_2]_s$ and $[0°_2 / 60°_2]_s$ pinned joint specimens are very close to each other, whereas bearing strengths for $[0°_2 / 30°_2]_s$ specimens were obtained higher than other orientations except for $E/D = 1$. In other words, the $[0°_2 / 30°_2]_s$ oriented plates were stronger than $[0°_2 / 45°_2]_s$ and $[0°_2 / 60°_2]_s$ plates when joined by two parallel pins. Similarly, when a bolted joint was used, the values of bearing strengths for $[0°_2 / 30°_2]_s$ specimens became higher than others except for $E/D = 1$. Briefly, $[0°_2 / 30°_2]_s$ specimens load to the stronger stacking sequence when compared to other stacked specimens investigated presently, since the magnitudes of bearing strengths were calculated higher than other orientations for both pinned and bolted joint. Meanwhile, the maximum value of the bearing strengths is 453,54MPa for $[0°_2 / 30°_2]_s$ bolted plates when it has ratios of $N/D = 3$ and $K/D = 4$. In bolted joints, it was clearly seen that applied preload moments caused to increase the magnitude of bearing strengths, generally. Therefore, the bearing strengths obtained under 2,5Nm applied preload moment were lower than 5Nm. It can be clearly said that the applied preload moments increased the load carrying capacity of two parallel bolted composite joint.

Additionally, the photographs of some tested $[0°_2 / 30°_2]$ composite specimens are shown in Fig. 6 as examples of observed specific failure modes. This figure points out that the occurrence of failure modes was similar in each parallel fastener hole of two parallel pinned/bolted composite joints, since a good loading condition on the specimens were achieved during the experiments, successfully. Another important result from this figure is that, the failure modes were strictly influenced from the geometrical parameters used, because the failure mode changed from shear-out to mixed (bearing + cleavage) or bearing when the E/D ratio increased from 1 to 3, respectively. It is concluded that, the catastrophic failure modes of two parallel pinned/bolted composite joints can be prevented by using higher values of E/D ratio.

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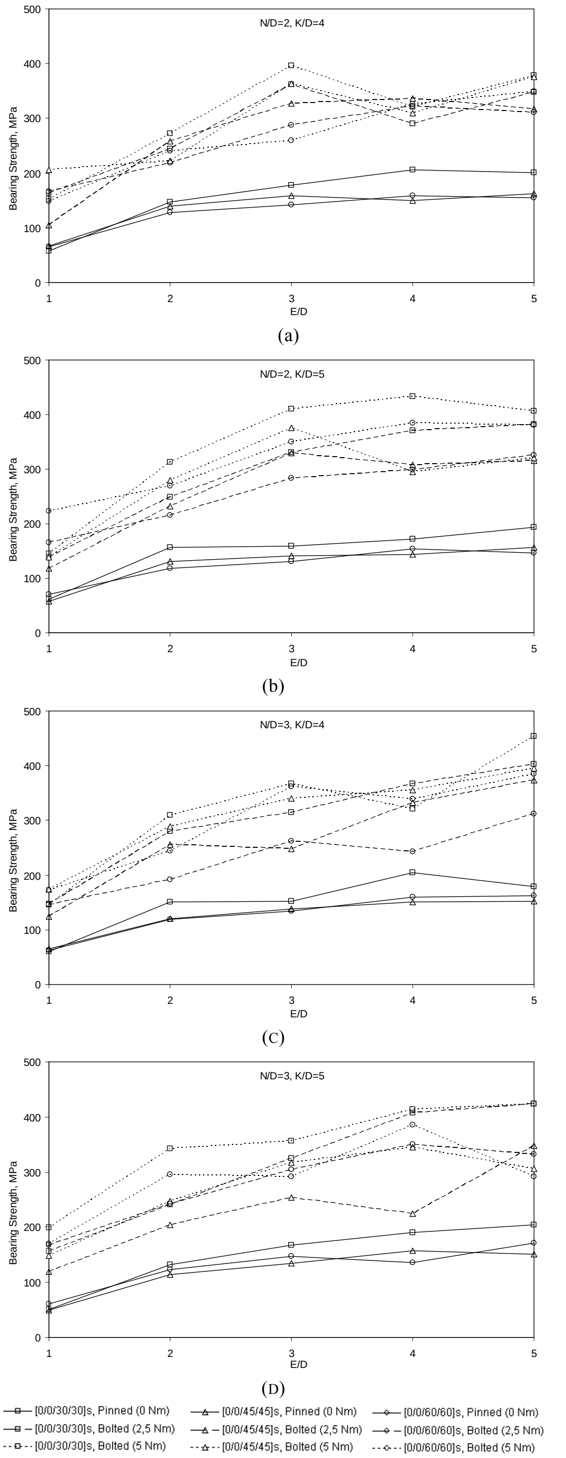

Fig. 5 The effect of *E*/*D* ratio on the bearing strength

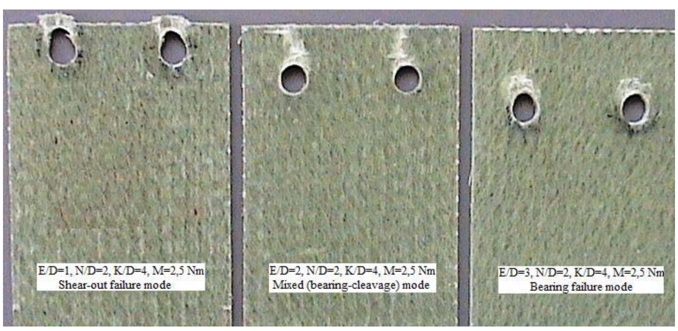

Fig. 6 The photographs of some tested $[0°_2 / 30°_2]_s$ composite specimens

4. CONCLUSIONS

In this study, an experimental investigation was performed to observe failure behavior of two composite joints; parallel both pinned and bolted composite joints. The effects of some geometrical parameters and applied preload moments on failure response were analyzed. During the tests, one of the parameters was changed while the others were held constant. Additionally, the effects of ply-orientations on failure improvement were considered. According to the experimental study results, some important remarks can be concluded as,

1. The magnitude of bearing strength increases by increasing the edge distance to diameter ratio (*E*/*D*).
2. When *E*/*D* = 1, the failure mode occurs as shear out. Therefore, this geometrical parameter is the weakest because it causes the catastrophic failure.
3. When *E*/*D* ratio is equal to or greater than 2, mixed or bearing damage modes occur generally. It is known that bearing and mixed damage is the best convenient mode due to load carrying capacity.
4. The best ply orientation is seem as $[0°_2 / 30°_2]_s$ in this study. Nevertheless, the better stacked composite plate is also possible in other studies.
5. The bolted joint is more suitable than pinned joint. If it is possible, the bolted joint should be preferred by the designer for any real application.
6. The magnitude of bearing strength under the applied preload moment of 2,5Nm is smaller than that of 5Nm. This means that increasing the applied preload moments increases the magnitude of bearing strengths in bolted joints.

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