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DAMAGE DEVELOPMENT IN BOLTED COMPOSITES WITH CLEARANCE SUBJECTED TO PRELOAD

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Abstract

In this study, a damage development process of glass-epoxy laminated composite bolted-joints with bolt/hole clearance under preload moments was investigated. To observe the effects of joint geometry and stacking sequence on the bearing strength and damage mode, parametric studies were performed experimentally. Two different geometrical parameters that were the edge distance-to-hole diameter ratio (E/D) and plate width-to-hole diameter ratio (W/D) were considered. Hence, E/D and W/D ratios were selected from 1 to 5 and 2 to 5, respectively. In the meantime, the preload moments on the specimens were also applied as 0, 3 and 6 Nm. Due to observing material parameters effect on damage development, composite laminated plates were stacked three different orientations as $[0^o/0^o/60^o/-60^o]_s$, $[0^o/0^o/60^o/60^o]_s$ *and* $[0^o/0^o/30^o/-30^o]_s$. *In addition, the experiments were performed under a clearance for the diameters of the bolt and the circular hole for 5 and 6 mm, respectively. Experimental results point out that failure mode and bearing strength related to damage development are strictly influenced from both material parameters and geometrical parameters. Furthermore, if the preload moments are applied to bolted-joints, the damage mechanism is completely affected from its increasing values.*

Keywords: Bolted composites, failure analysis, damage development, fiber reinforced composites.

1. Introduction

Fiber reinforced composite materials have been widely used in aircraft and space structures because of their high specific modulus and high specific strength. Since the use of composites has become popular in recent years, 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, not by its basic structures [1]. Bolts, pins or rivets have been used extensively 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 owing to their heterogeneity and anisotropy [4].

Tong [5] has studied 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 have been also used to validate an existing model. Two extreme diametral fit positions, with a positive or negative bolt hole-to-washer clearance, have been also examined. Meola et al. [6] have studied an experimental investigation on an innovative Glare Fiber Reinforced Metal Laminate (FRML) with the aim to characterize its strength and behavior in the case of mechanical joints. Several specimens have been 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, have been analyzed in both non-destructive and destructive ways. Icten and Sayman [7] have determined failure load and failure mode in an aluminum-glass-epoxy sandwich composite plate, with a circular hole, which was subjected to a traction force by a pin, experimentally. Hamada and Maekawa [8] have studied failure analysis of quasi-isotropic carbon epoxy laminates both numerically and experimentally. Kovacs et al. [9] evaluated moment-rotation diagrams and cyclic parameters, which define and characterize the failure modes. The details of the specimens, the loading history and the testing procedure were discussed. Sayman et al. [10] studied a failure analysis to determine bearing strengths of mechanically fastened joints with single bolt in glass-epoxy laminated composite plates. Sen and Sayman [11] carried out an experimental failure analysis of two serial bolted composite plates. The laminated composite plates were produced from eight laminas. The bearing strengths and failure modes were obtained. Whitworth et al. [12] have carried out an analysis to evaluate the bearing strength of pin-loaded composite joints. The analysis involved using the Chang-Scott–Springer characteristic curve model and a two-dimensional finite element analysis to estimate the stress distribution around the fastener hole. Lin and Lin [13] have studied stresses around a pin-loaded hole in symmetrically stacked composite laminates of finite size using a two-dimensional direct boundary element method. Effects of friction and clearance between the pin and hole edge on the stresses have been obtained for also geometric compatibility and force constraint between the pin and the plate were enforced. Characterization of joint damage in bolted composite laminates is complicated because of the large number of parameters involved [14]. Therefore, according to literature review results, many papers have been found deal with damage analysis of composite bolted-joints as mentioned before. However, applied preload moments, to the authors' knowledge, have not been utilized for such a study.

In this study, an experimental failure analysis was performed to determine damage development in glass fiber reinforced-epoxy laminated composite bolted-joints with clearance between bolt and hole diameter. Additionally, experiments were carried out for applied preload moments variously. Besides, the effects of the stacking sequences and a variety of geometrical parameters of composite specimens on damage behavior and bearing strengths were also considered.

2. Materials and Methods

2. 1. Problem Statement

Consider a laminated composite rectangular plate of length L+E and width W with a circular hole of diameter D and also the diameter of bolt d, as shown in Figure 1. Because of the creating a clearance, bolt and bolt/hole diameters were also fixed at constant values of 5 and 6 mm, respectively. The hole was at a distance E, from the free edge of the plate. A bolt was located at the center of the hole and a uniform tensile load P was performed to the plate. The load was also parallel to the plate plane and was symmetric with respect to the centerline. It was preferred to attain bearing strength and damage mode. To observe the effects of joint geometry and stacking sequence on the bearing strength and damage mode, parametric studies were performed experimentally. For this reason, two different important parameters were also considered for bolted-joint of laminated composites. One of them was geometric parameters. Therefore, edge distance-to-hole diameter ratio, E/D, were selected as from 1 to 5, whereas the plate width-to-hole diameter ratio, W/D, were chosen as from 2 to 5, respectively. In other words, two different geometrical parameters were investigated. Besides, other important consideration was material parameter. For this purpose, laminated composite plates were stacked as three different stacking sequences differ from each other as $[0^o/0^o/60^o/-60^o]_s$, $[0^o/0^o/60^o/60^o]_s$ and $[0^o/0^o/30^o/-30^o]_s$ during the production process. These orientations were also expressed in Table 1. Thus, each laminated composite plate was created to stick eight laminas onto together under press and heat, symmetrically. At the end of the production, each laminated plate had a nominal thickness of 3 mm at a volume fraction of 60%. The various preload moments were carried out as 0, 3 and 6 Nm during the experimental procedure, due to observing different preload effect on failure mode and bearing strength, as the main goal of this study. The experiments were also carried out in tension mode on the Instron-1114 Tensile Test Machine at a crosshead speed of 0.5 mm/min. The bolted-joint arrangement is illustrated in Figure 2, schematically. The lower edge of the specimen clamped and loaded from the steel bolt by stretching the specimens as seen in this figure. The load versus bolt displacement curves for all composite configurations were drawn via a computer connected to test machine. Damage development of bolted joints in laminated composite plates under tensile loads generally occurs in four basic modes as cleavage mode, net-tension mode, shear-out mode and bearing mode [7, 15-18]. Schematic view of these damage modes are shown in Figure 3. Besides, combinations of these damage modes are possible in practical applications. To determine the strength of single bolt loaded composite specimens, the bearing strength can be defined as,

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

wherein P, D and t are characterized as applied tensile load, bolt hole diameter, and average thickness of laminated composite plate, respectively.

Table 1. Stacking sequence of laminated composite plates

Group number	Stacking sequence	Average thickness (mm)	Total number of lamina
1	$[0^o/0^o/60^o/-60^o]_s$	3	8
2	$[0^o/0^o/60^o/60^o]_s$	3	8
3	$[0^o/0^o/30^o/-30^o]_s$	3	8

Table 2. 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

2. 2. Production of the Composite Plates

Glass fiber reinforced-epoxy laminated composite plates that were produced in Izoreel Firm in Izmir used in experiments. Firstly, all composite laminates lay-up were covered with a release film to prevent the lay-up from bonding to the mold surface. After that resinimpregnated fibers were placed in the mold for curing. The press generated the temperature and pressure required for curing. The mould was closed down to give the nominal thickness. The glass fiber/epoxy material was cured at 120 ^{o}C under a pressure of 0.2 MPa. Then this temperature was held constant for 4 hours for the first phase. Next, the temperature was decreased to 100 ^{o}C and held constant for 2 hours for the second phase. Later than the second phase, the laminates were cooled to room temperature. Finally, laminated plate removed from press and cut to specimen dimensions. The last thickness of composite specimens had an average thickness of 3 mm. The fiber volume fraction of the glass-epoxy laminated composite plate was measured as 60 %.

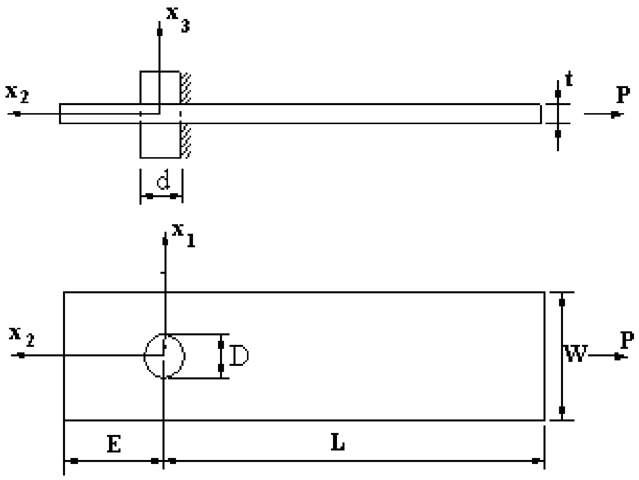

Fig. 1. Geometry of a bolted composite specimen

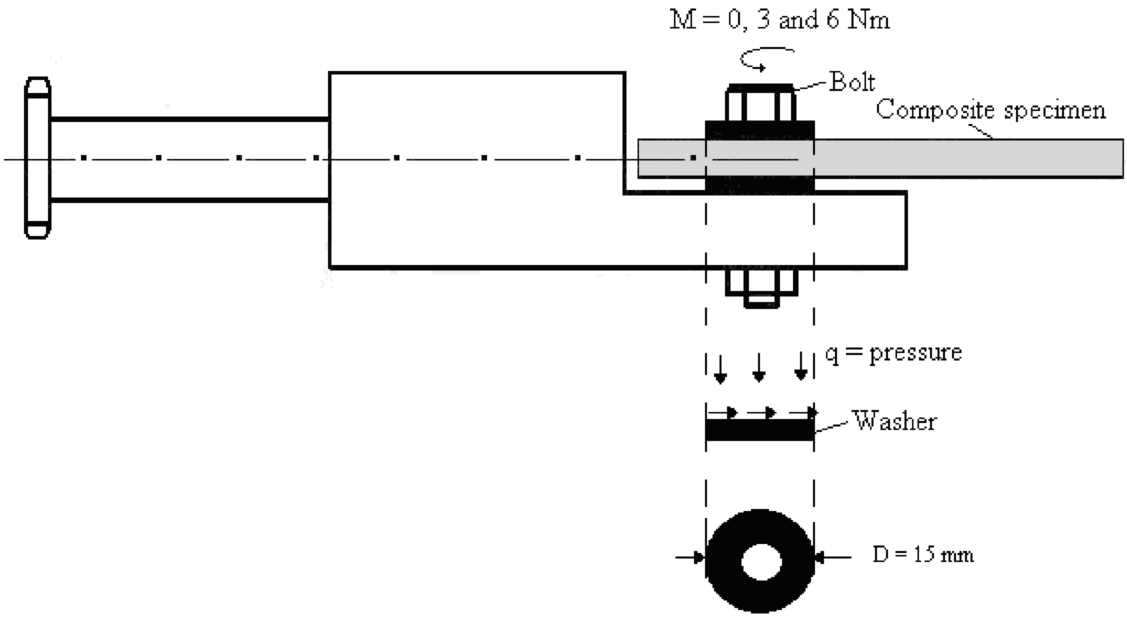

Fig. 2. Bolted-joint test fixture

2. 3. Determination of Mechanical Properties

Some mechanical tests were carried out to measure the mechanical properties of glass fiber reinforced-epoxy laminated composite material using standard test methods in literature related to composite science and technology [18-20]. During the determination of mechanical properties, to define of coordinate system is very important. Therefore, the schematic view of a unidirectional fiber reinforced lamina with global and material coordinate systems is illustrated in Figure 4 [21]. To measure E_1, ν_{12} and X_t, a rectangular specimen whose a fiber direction coincides with the loading direction was taken and two strain gauges perpendicular to each other were stuck on. One of them was in a fiber direction the other in the transverse direction. The specimen was loaded step by step via an Instron-1114 Tensile Test Machine. For all steps, ε_1 and ε_2 were measured and recorded by an indicator. By using these strain values E_1 and ν_{12} were computed from the linear part of the load-displacement curve. X_t was estimated by dividing the ultimate force by the cross-sectional area of the tested specimen. The compressive failure strength was measured in the direction of fibers.

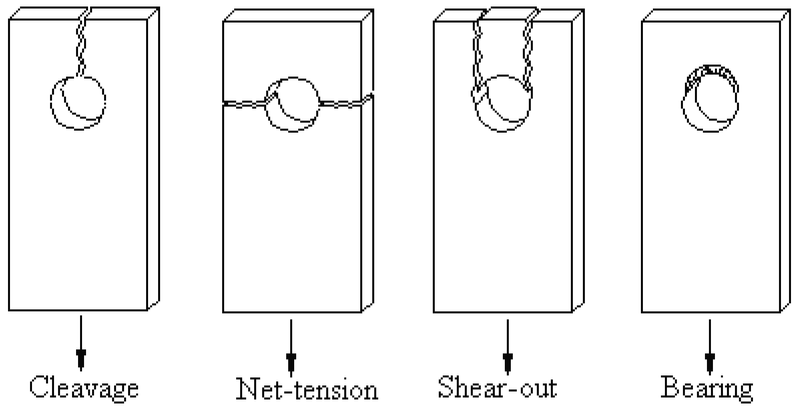

Fig. 3. General damage modes in bolted composite plates

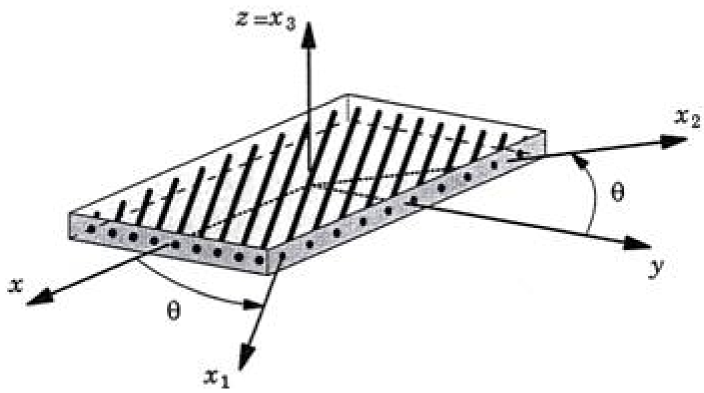

Fig. 4. Defining of global and material coordinate systems for a lamina [21]

To determine the shear modulus G_{12}, a test specimen whose principal axis is on 45° was considered and a strain gauge was stuck on loading direction of the lamina. The specimen was also loaded step by step using the test machine and G_{12} was calculated by measurement of the strain in the tensile direction ε_x [19]. Iosipescu test method [7, 18 and 20] was also chosen to determine the shear strength S. Schematic view of Iosipescu test fixture is illustrated in Figure 5.

The dimensions of the test specimen were chosen as a=80 mm, b=20 mm, c=12 mm and t=3 mm. A compressing testing was performed to the test fixture. In damage process, S was computed using Equation (2);

$$S = \frac{P_{max}}{t\,c} \tag{2}$$

where P_{max} was the failure force. The mechanical properties of the glass fiber reinforced-epoxy laminated composite material are presented in Table 2.

3. Results and Discussion

For every kind of composite specimen, two tests were conducted and average bearing strength values were obtained. Besides, each of bolted-joint was loaded up to the bolt displacement arriving 7 or 8 mm from the initial position. It can be seen in Figure 6, four types of load versus displacement curves were observed after the tensile tests. If the laminate contains nearly all 0^o fibers, cleavage damage mode is also possible in some specimens (Figure 6a). Load-displacement curves are linear until a sudden lost of applied load, approximately. The load usually reaches this value between 0.4 mm and 0.9 mm displacements. A number of specimens break away suddenly at this point. This damage mode is named as net tension (Figure 6b). For a quantity of specimens, the load decreases with rising bolt displacement and specimens tear. This damage mode is called as shear out (Figure 6c). For an amount of specimens, the load then increases with growing damage and reaches the ultimate point. Then, the load decreases with growing damage zone. Nevertheless, the specimen continues to hold up loading. Since damage region reaches 3-4 mm from the free edge of the composite specimen in the loading direction, after that the specimen breaks off unexpectedly. This damage mode is also classified as bearing (Figure 6d). In addition, pictures of damage modes in tested specimens (Figure 6) are formed as similar in literature (Figure 3). In the meantime, even if the bolt joints carry on bearing load later than the first peak, the constructer must guarantee that the bolted-joint configuration never reaches the first peak. As bolted joints cannot be getting better its joint properties next this peak. From a safe design position, a bearing failure is more advantageous than either a cleavage, net tension or shear-out damages.

Damage modes of tested composite specimens for Group 1, 2 and 3 are presented in Tables 3, 4 and 5, respectively. As seen in these tables, four types of damage modes are observed as mentioned previously. Damage modes change related to vary of geometric parameters, which are both E/D and W/D ratios and increased value of the applied preload moments.

During the experiments, usually three basic damage modes consisting on net tension, shear out and cleavage are observed with small E/D and W/D ratios, whereas the other connections are bearing mode or mixed mode. The cleavage damage modes occur for only Group 1 specimens (Table 3). When E/D =1 damage mode changes from net tension, cleavage or shear-out to bearing or mixed mode by increasing W/D ratio. Besides, increasing values of the preload moments cause mixed modes those are consisted bearing damage, especially. It is known that a bearing damage is more advantageous than either net tension, cleavage or shear-out damage modes for a safe joint. Therefore it is said that increasing of preloads is suitable for supplying bearing damage mode of bolted-joint structures.

Table 3. Damage modes of Group 1 specimens, $[0^o/0^o/60^o/-60^o]_s$

W/D	**E/ D**	**Preload moments**		
		0 Nm	**3 Nm**	**6 Nm**
2	1	C	C	C
	2	C	C	C
	3	B	B+N	B+N
	4	B	B+N	B+N
	5	B	B+N	B+N
3	1	S	S	S
	2	B+C	B+C	B+C
	3	B	B+C	B+C
	4	B	B+C	B+C
	5	B	B	B
4	1	S	S	S
	2	B+C	B+C	B+C
	3	B	B+C	B+C
	4	B	B	B
	5	B	B	B
5	1	S	S	S
	2	B+C	B+C	B+C
	3	B	B+C	B+C
	4	B	B	B
	5	B	B	B

C: Cleavage mode, N: Net-tension mode, S: Shear-out mode, B: Bearing mode

The effects of E/D ratio on the bearing strength for all groups are shown in Figure 7 depending on W/D ratio and applied preload moments. This figure points out that the magnitude of bearing strengths increase by rising both W/D and E/D ratios. When E/D=1, the geometrical parameter is not strong, especially.

Besides, when the value of preload is raised, the magnitude of bearing strengths increased. In general, the magnitudes of bearing strengths under applied preload moments as 3 and 6 Nm are calculated higher than without preload moments. The smallest values of bearing strengths are usually estimated for Group 2 specimens both without preload moments and under various preload moments.

Table 4. Damage modes of Group 2 specimens, $[0^o/0^o/60^o/60^o]_s$

W/D	**E/ D**	**Preload moments**		
		0 Nm	**3 Nm**	**6 Nm**
2	1	N	N	B+N
	2	N	N	B+N
	3	N	N	B+N
	4	N	N	B+N
	5	N	B+N	B+N
3	1	N	N	B+N
	2	N	B+N	B+N
	3	N	B+N	B+N
	4	N	B+N	B+N
	5	N	B+N	B+N
4	1	S	N	B+N
	2	B+N	B+N	B+N
	3	B+N	B+N	B+N
	4	B+N	B+N	B+N
	5	B+N	B+N	B+N
5	1	S	S	B+N
	2	B+N	B+N	B+N
	3	B+N	B+N	B+N
	4	B+N	B+N	B+N
	5	B+N	B+N	B+N

N: Net-tension mode, S: Shear-out mode, B: Bearing mode

Table 5. Damage modes of Group 3 specimens, $[0^o/0^o/30^o/-30^o]_s$

W/D	**E/ D**	**Preload moments**		
		0 Nm	**3 Nm**	**6 Nm**
	1	N	N	N
	2	N	N	N
2	3	N	N	N
	4	N	N	N
	5	N	N	N
	1	N	N	B+N
	2	N	N	B+N
3	3	N	N	B+N
	4	N	B+N	B+N
	5	N	B+N	B+N
	1	S	S	B+S
	2	B	B+N	B+N
4	3	B	B+N	B+N
	4	B	B+N	B+N
	5	B	B+N	B+N
	1	S	S	B+N
	2	B	B+N	B+S
5	3	B	B+N	B+N
	4	B	B+N	B+N
	5	B	B+N	B+N

N: Net-tension mode, S: Shear-out mode, B: Bearing mode

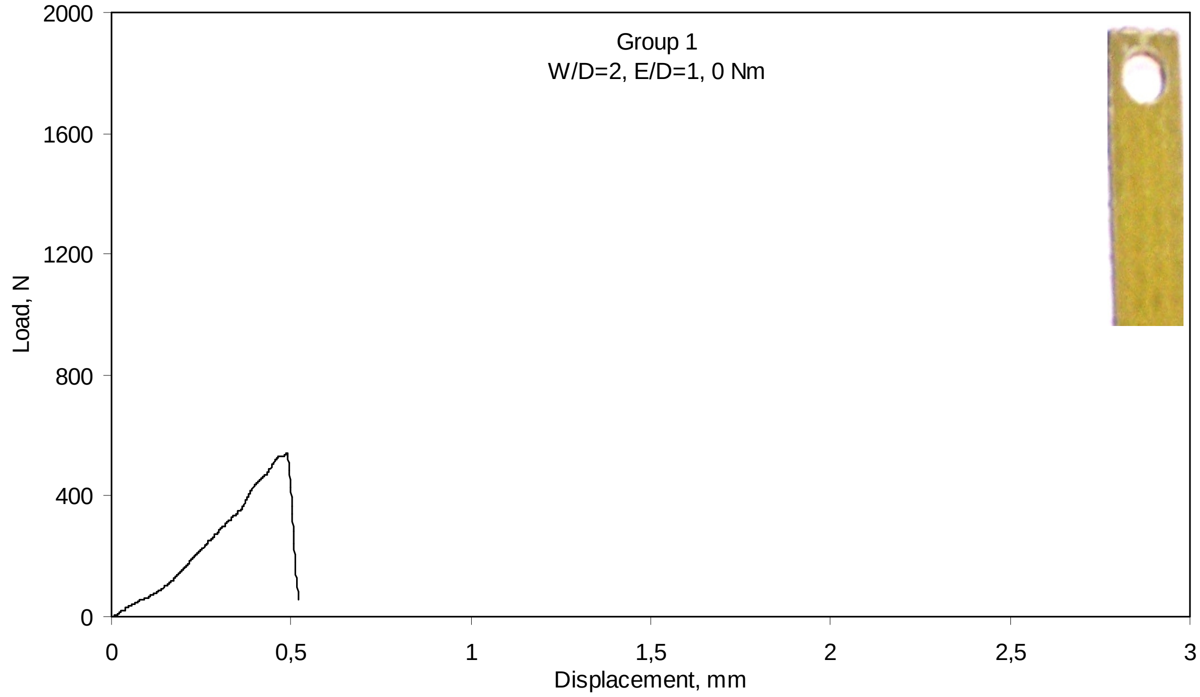

Fig. 6. Damage modes in experimental study
a) Cleavage damage mode

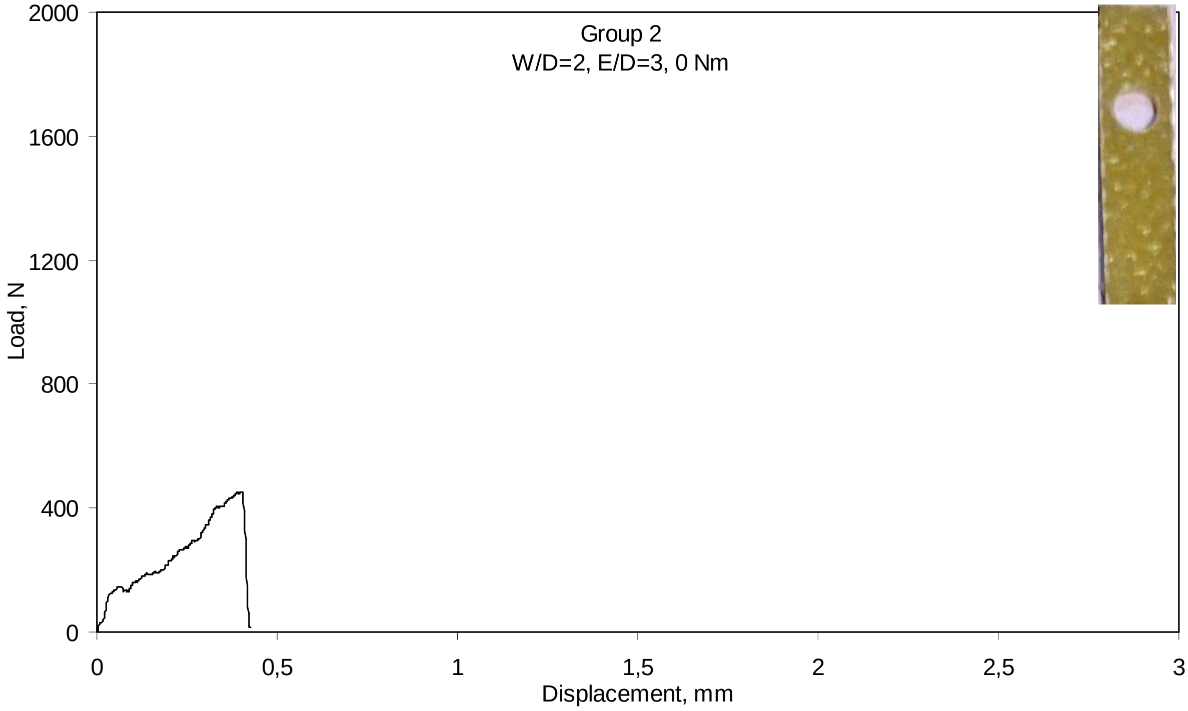

Fig. 6. Damage modes in experimental study
b) Net-tension damage mode

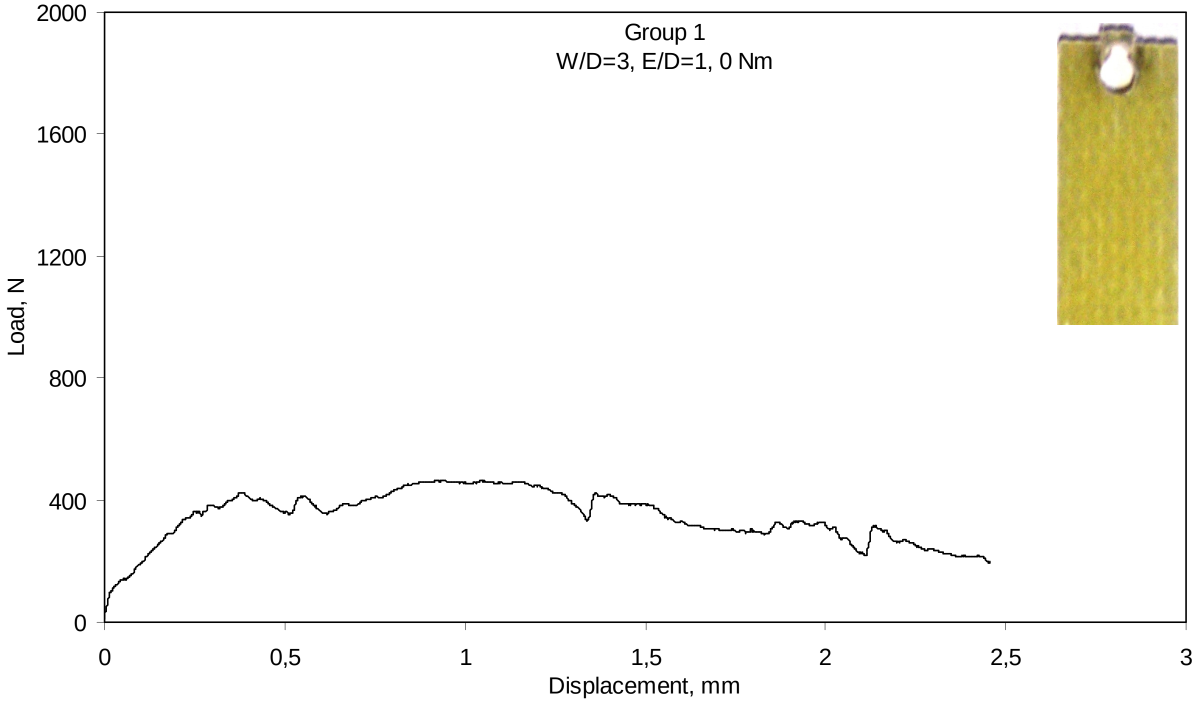

Fig. 6. Damage modes in experimental study
c) Shear-out damage mode

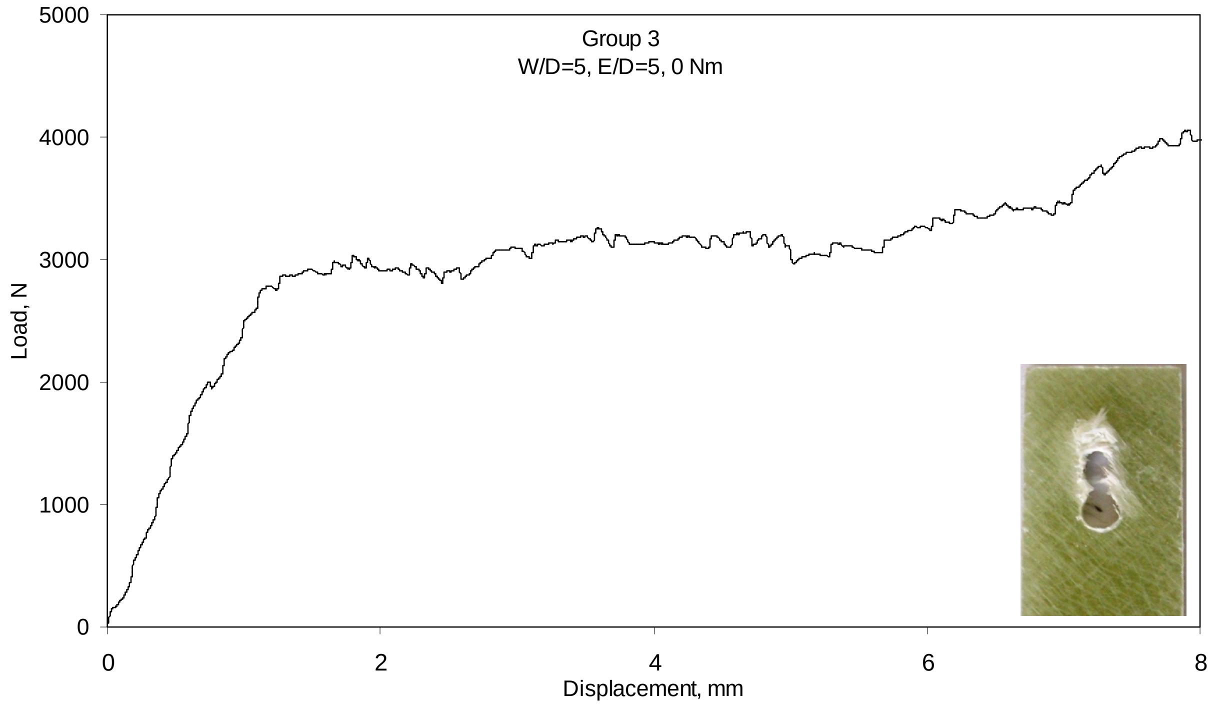

Fig. 6. Damage modes in experimental study
d) Bearing damage mode

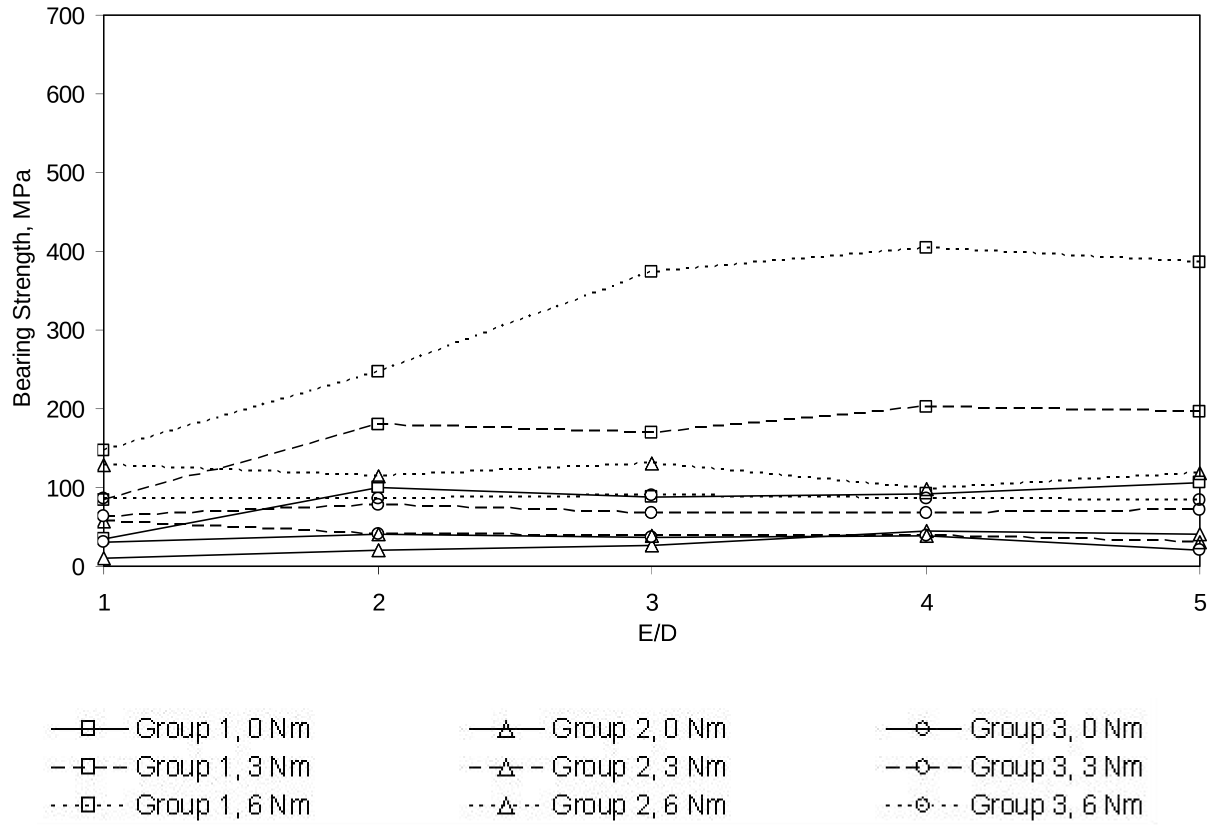

Fig. 7. The effect of E/D ratio on the bearing strength for Groups 1, 2 and 3
a) W/D=2

If a comparison is done between all specimens without preloads, bearing strengths are obtained for Group 3 higher than Groups 1 and 2 specimens. However, when W/D=2 for Group 1, bearing strengths are higher than other specimens without preloads.

The maximum values of bearing strengths are computed for Group 1 specimens under 6 Nm preload moment except some E/D=1 and 2 ratios. When E/D=3, 4 and 5, the bearing strengths for Group 1 are extremely high others. Furthermore, the maximum value of bearing strengths is computed as 689.72 MPa for Group 1 specimen under 6 Nm preload, when E/D and W/D are equal 5. Briefly, Group 2 specimens are seen the weakest stacking sequence from other stacked specimens, since the magnitude of bearing strengths are calculated smaller than other groups for all conditions associated with applied preload and without preload moments, generally.

However, the best ply orientation is seemed as Group 3, if any preload is not carried on joint. Nonetheless, when M=3 and 6 Nm, the best oriented specimens are appear as Group 1 according to selected ply orientations in this study. In addition, the better stacked composite plate is also possible in other studies.

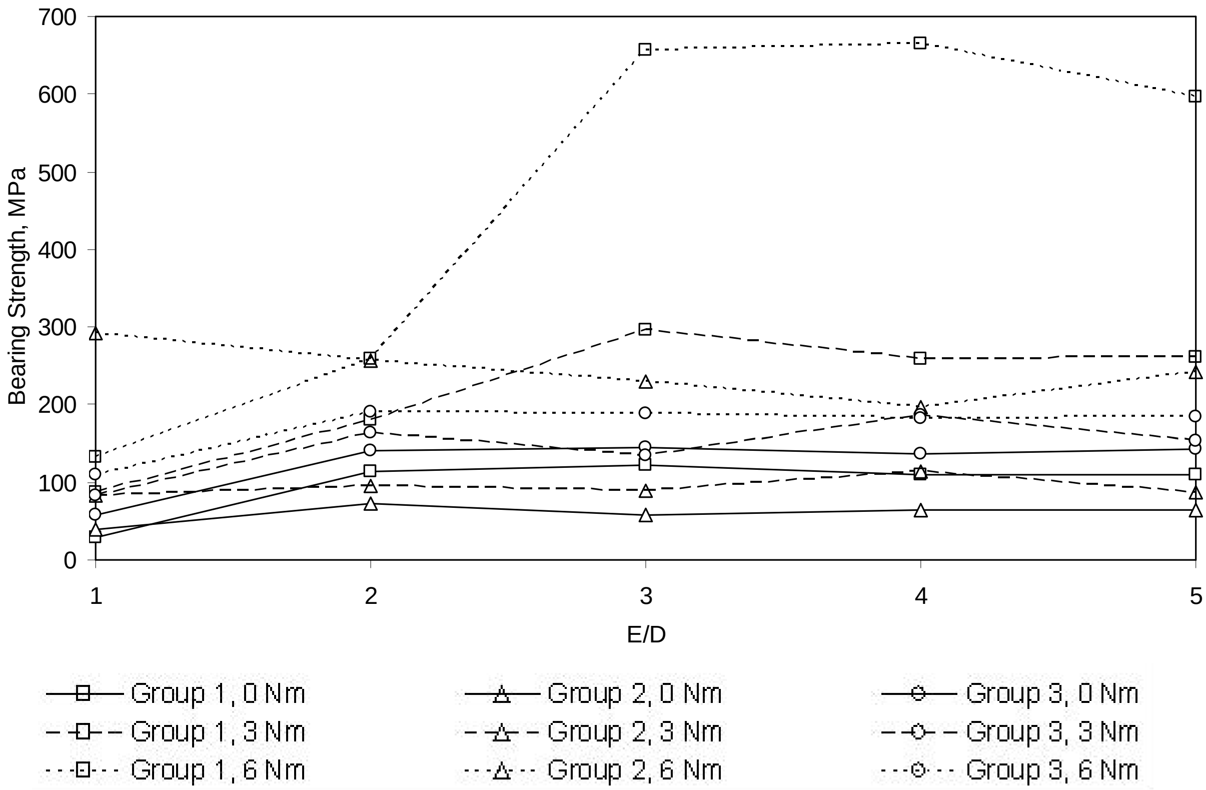

Fig. 7. The effect of E/D ratio on the bearing strength for Groups 1, 2 and 3
b) W/D=3

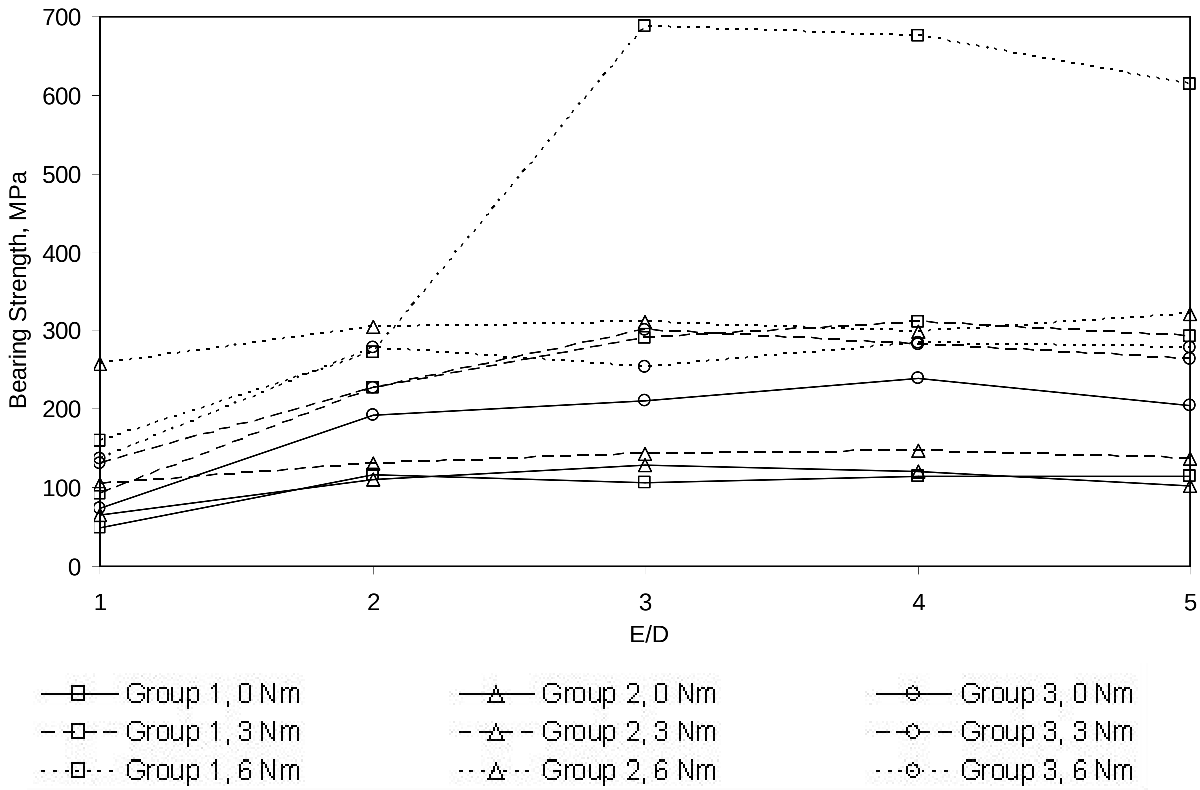

Fig. 7. The effect of E/D ratio on the bearing strength for Groups 1, 2 and 3
c) W/D=4

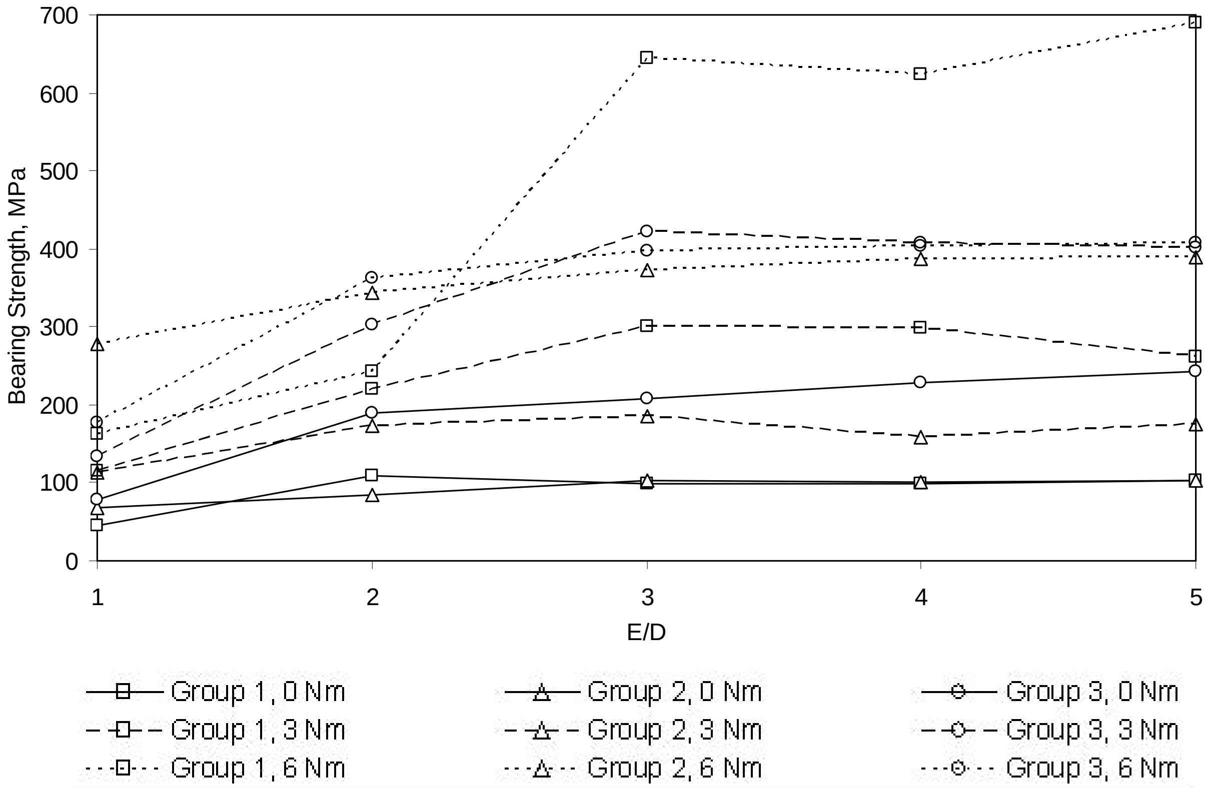

Fig. 7. The effect of E/D ratio on the bearing strength for Groups 1, 2 and 3
d) W/D=5

4. Conclusions

In this study, an experimental investigation was performed to obtain the magnitude of bearing strength and damage behavior of composite bolted-joint with clearance and also under various preload moments. During the tests, one of the parameters is changed while the others are held constant. Furthermore, the effects of ply-orientation on damage improvement are considered. According to the experimental study results, some important points can be concluded that:

1. The magnitude of bearing strength increases by increasing the edge distance to diameter ratio (E/D) and/or width to diameter ratio (W/D).

2. When E/D ratio is equal to or greater than 3, bearing or mixed damage modes come into being generally. It is known that mixed or bearing damage is the best convenient mode because of carrying load capacity.

3. When E/D=1, the damage mode usually occurs as net tension, cleavage or shear out. Therefore, this geometrical parameter is the weakest.

4. The best ply orientation is seem as Group 3, $[0^o/0^o/30^o/-30^o]_s$, if any preload is not applied on joint. However, the best laminated plates is appear Group 1, $[0^o/0^o/60^o/-60^o]_s$, under both 3 and 6 Nm preload moments according to selected orientations in this study.

5. The weakest stacking sequence is observed as Group 2, $[0^o/0^o/60^o/60^o]_s$, in selected and investigated plates.

6. The magnitude of bearing strength under 0 Nm preload is smaller than under 3 and 6 Nm preloads. This means that increasing of applied preload moments increases the magnitude of bearing strength.

7. Increasing of preloads is seen very convenient for a safe bolted-joint configuration due to the providing bearing mode and high values of bearing strengths.

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