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Failure response of single bolted composite joints under various preload

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In this study, an experimental failure analysis is performed to calculate bearing strength of single bolted joints in laminated composites reinforced unidirectional glass fibers. The main goal of this study is to determine the failure behaviour of bolted composite joints under various preload moments as 0, 2.5 and 5 Nm. Furthermore, two different geometrical parameters that are the edge distance-to-hole diameter ratio (*E*/*D*) and plate width-to-hole diameter ratio (*W*/*D*) are investigated. For that reason, *E*/*D* and *W*/*D* ratios are selected from 1 to 5 and from 2 to 5, respectively. Besides, the effect of orientation angle of laminated plates is considered. Therefore, four different ply orientations are selected as $[30^o]_4$, $[45^o]_4$, $[60^o]_4$ and $[90^o]_4$. The experimental results show that the magnitudes of bearing strengths in single bolted composite joints are strictly influenced from increasing value of applied preload moments, changing of *W*/*D* and *E*/*D* ratios and also ply orientations.

Keywords: Bearing strength, Failure analysis, Fiber reinforced composites, Laminated plates, Bolted joints

Modern aviation, defense and marine structures require high strength, lightweight composite materials to realize the full potential of recent technological advances. High strength ensures durability and lightweight adds to the increase in payload[1]. The design of the composite joints has become a very important research area, since the structural efficiency of the composite structure is determined by its joints, not by its basic structures[2]. Among the different techniques for joining structural members, mechanical fastening through a pin or bolt is a general preference because of low cost, simplicity, and facilitation of disassembly for repair[3]. Contrasting 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].

A review of the research and development of strength analysis of bolted joints can be found in a previous study[5]. Tong[6] studied an experimental examination 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. Hamada and Maekawa[7] studied a failure analysis of quasi-isotropic carbon epoxy laminates both numerically and experimentally. Meola *et al.*[8] studied an experimental investigation on an innovative glare fiber reinforced metal laminate with the aim to characterize its strength and behaviour in the case of mechanical joints. 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. Icten and Sayman[9] examined 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. Liu *et al.*[10] investigated mechanical joints with combinations of various composite thicknesses and pin diameters. Composite material made of woven glass fabric and phenolic matrix was investigated. Sixteen joint configurations based on four composite thicknesses and four pin diameters were examined. Both experiments and finite element analysis were conducted in that study. Pakdil *et al.*[11]

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studied the effect of preload moments on failure response of glass-epoxy laminated composite single bolted-joints with bolt/hole clearance. To find out the effects of bolted-joint geometry and stacking sequence of laminated plates on the bearing strength and failure mode, parametric analysis were performed, experimentally. Sayman *et al.*[12] investigated an experimental failure analysis to determine the bearing strengths of mechanically fastened joints with single bolt in glass-epoxy laminated composite plates. The effects of different geometrical parameters on failure behaviours were also examined. Ataş *et al.*[13] aimed to study failure load and modes of laminated glass-polyester composite plates with two parallel circular holes, which were subjected to traction forces by two rigid pins. The behaviours of pin loaded composite plates were observed both experimentally and numerically with different geometries and fiber orientations.

The published studies so far on mechanically-fastened joints present experimental results on the effect of the stacking sequence, geometric properties, clearance between the hole and the pin, and the degree of lateral clamping pressure exerted by the bolt[14]. In literature many papers were found deal with failure analysis of composite bolted or pinned-joints. However, applied preload moments have been rarely utilized for such a study.

In this study, the bearing strengths depending on *E*/*D* and *W*/*D* ratios have been obtained on glass fiber reinforced epoxy laminates, experimentally. Since the knowledge of the bearing strength would help in selecting the appropriate joint dimension in a given application. Furthermore, 0, 2.5 and 5 Nm preload moments were applied since it is desired to find out the effects of increasing values of preload moments on composite bolted joint. The unidirectional glass fiber reinforced epoxy composite material was produced and its mechanical properties were determined from standard tests[15-17].

Characterization of Bolted Joint Problem

The geometry and loading conditions of the bolted composite specimen is shown in Fig. 1. As seen in this figure, consider a laminated composite rectangular specimen of length (*L*+*E*) and width (*W*) with a circular bolt hole of diameter (*D*). The hole diameter (*D*) and specimen length (*L*) are fixed at a constant value of 5 and 70 mm, respectively. The average thickness (*t*) of the specimen is 1.6 mm. The hole is at a distance *E*, from the free edge of the plate. The bolt is assumed rigid and located at the centre of the hole and a uniform tensile load *P* is applied to the specimen. The load is parallel to the specimen and is symmetric with respect to the centerline. Bolt strength is very high compared with that of the composite specimen. Therefore, the failure of the bolt has been ignored. Edge distance-to-hole diameter (*E*/*D*) and width-to diameter (*W*/*D*) ratios in the specimen are designed from 1 to 5 and 2 to 5, respectively. To estimate the strength of the single bolt loaded composite specimens, the static bearing strength can be written as,

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

wherein *P*, *D* and *t* are defined as applied tensile load, bolt hole diameter and thickness of the laminated composite specimen, respectively.

Because of the investigating failure modes and bearing strengths of the various composite specimens, four different laminated plates are considered. The stacking sequences of unidirectional laminates are oriented as $[30°]_4$, $[45°]_4$, $[60°]_4$ and $[90°]_4$. In other words, each laminated plate are arranged to stick onto together four unidirectional laminas, symmetrically. The geometries and configurations of the specimens are given in Table 1. A unidirectional fiber reinforced lamina with global and material coordinate systems[18] is also shown in Fig. 2. The 0° direction in the stacking notation denotes the x-axis or loading direction.

The major consideration of this study is to determine the failure mechanisms under various

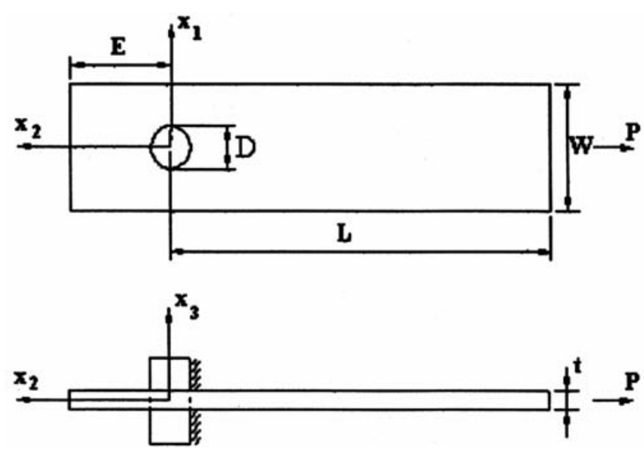

Fig. 1—Geometry and loading of the bolted composite specimen

preload moments as 0, 2.5 and 5 Nm. Since, joining by mechanical fasteners is common practice in the assembly of structures and since joint failure can lead to premature failure of the structure, joint strength is an important property in any design[19]. The torque wrench was used for creating of the preload moments. There are in common three main failure modes; net tension, shear out and bearing as defined in Fig. 3. Net tension and shear out modes are catastrophic and result from excessive tensile and shear stresses, whereas bearing mode is local damage and progressive, and related to compressive failure. Net tension and shear out failures can be avoided by increasing the end distance (*E*) and width (*W*) of the structural part for a given thickness, nevertheless bearing failure cannot be avoided by any modification of the geometry. In addition, combinations of these failure modes are possible in practice[9,17,19].

Table 1—Lay-ups and geometries of the composite specimens

Lay-up	*t* (mm)	*D* (mm)	*E*/*D*	*W*/*D*	Total number of laminas
$[30°]_4$	1.6	5	1,2,3,4,5	2,3,4,5	4
$[45°]_4$	1.6	5	1,2,3,4,5	2,3,4,5	4
$[60°]_4$	1.6	5	1,2,3,4,5	2,3,4,5	4
$[90°]_4$	1.6	5	1,2,3,4,5	2,3,4,5	4

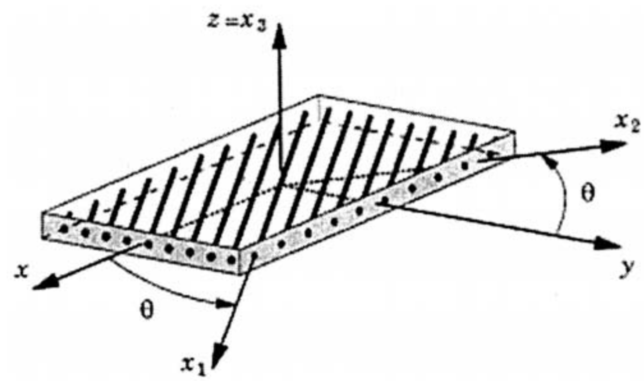

Fig. 2—A unidirectional fiber reinforced lamina with global and material coordinates

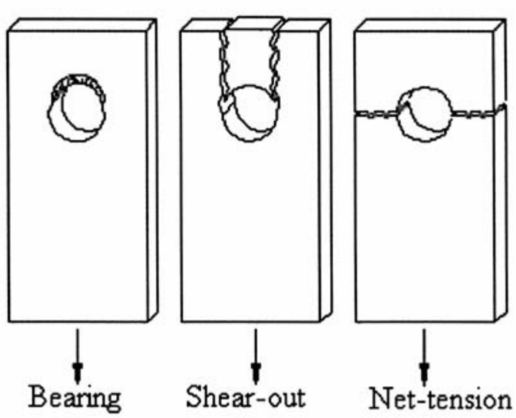

Fig. 3—Failure modes in bolted composite laminates

Production of Composite Plate

The glass fiber unidirectional reinforced epoxy laminates used in this study were produced in Izoreel Composite Isolate Materials Company in Izmir. All laminated composite plates were produced E-glass fiber and epoxy resin using press-mould technique. Epoxy CY225 and hardener HY225 were mixed in the mass ratio of 100:80 for matrix material. A hand roller was used to compact plies and take away entrapped air that could later lead to voids or layer separations. Firstly, all composite laminates lay-up were covered with a release film to prevent the lay-up from bonding to the mold surface. Then, resin-impregnated 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°C under a pressure of 0.2 MPa. Followed by this temperature was held constant for 4 h for the first phase. After that, the temperature was decreased to 100°C and held constant for 2 h for the second phase under the mentioned pressure. Later than the second phase, the laminates were cooled to room temperature. Finally, laminated plate removed from press and cut to specimen dimensions. In addition, each laminated plate was manufactured to stick four laminas onto together under press and heat, symmetrically. At the end of the production process, the average thickness of the laminated composite plate was measured as 1.6 mm. Volume fraction of the glass fiber was measured approximately 55%.

Experimental Procedure

The experiments were performed in tension mode on the Instron-1114 Tensile Test Machine at a crosshead speed of 0.5 mm/min. The composite bolted joint arrangement is shown in Fig. 4, schematically. The lower edge of the specimen clamped and loaded from the steel bolt by stretching the specimens as seen in Fig. 1. During the experiments, the load versus bolt displacement curves for all composite configurations were drawn via a computer that was connected to test machine.

Each bolted joint was loaded up to the bolt displacement arriving 6 or 8 mm from the initial position. Furthermore, for each type of composite specimen, two tests were conducted and average bearing strength values were calculated. Mechanical tests were carried out to measure the material properties of glass fiber reinforced epoxy laminated composite plates using standard test methods[15-17]. Determined mechanical properties of composite material are given in Table 2.

To measure E_1, ν_{12} and X_t, a rectangular specimen whose 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 by an Instron-1114 Tensile Test Machine. For all steps, ε_1 and ε_2 were measured by an indicator. By using these strains E_1 and ν_{12} were obtained. X_t was estimated by dividing the ultimate force by the cross-sectional area of the test specimen. Longitudinal modulus and Poisson's ratio was also calculated from the linear part of the load-displacement curve. The compressive failure strength was measured in the direction of fibers. To measure the shear modulus G_{12}, a 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 obtained by measurement of the strain in the tensiledirection ε_x[15].

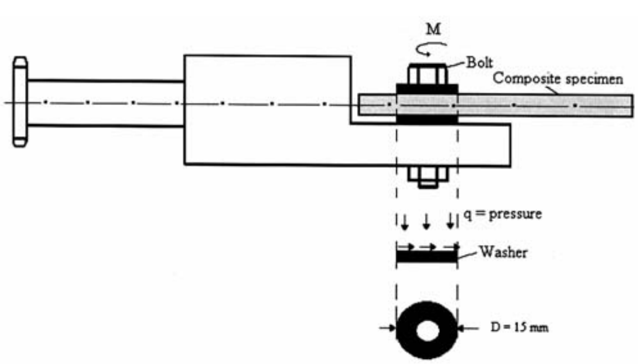

Fig. 4—Schematic testing fixture of bolted joint

To determine the shear strength S, the Iosipescu testing technique, which is known an effective method, was preferred[16]. Schematic presentation of Iosipescu test fixture and the dimensions of the tested specimen are shown in Fig. 5. The sizes of the specimen were prepared as a=80 mm, b=20 mm, c=12 mm and t=1.6 mm. A compressive test was applied to the test fixture. In damage process, S was computed from

$$S = \frac{P_{max}}{t\,c} \quad \ldots(2)$$

here $P_{\max}$, t and c are the applied load, specimen thickness and distance between the notches, respectively.

Table 2—Mechanical properties of composite material

Elastic modulus for fiber direction, E_1 (MPa)	45100
Elastic modulus for transverse direction, E_2 (MPa)	14400
Shear modulus, G_{12} (MPa)	2550
Poisson ratio, ν_{12}	0.25
Axial strength, X_t=X_c (MPa)	687
Transverse strength as tensile, Y_t (MPa)	65
Transverse strength as compressive, Y_c (MPa)	146
Shear strength, S (MPa)	55
Fiber volume fraction, V_f (%)	55

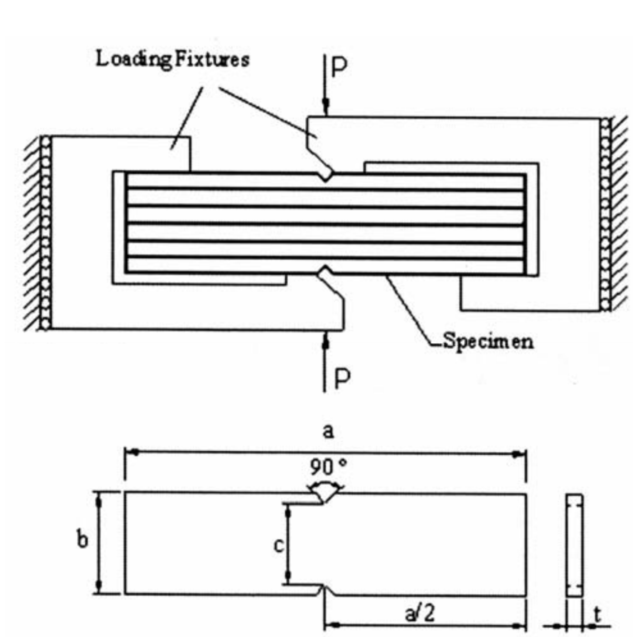

Fig. 5—Iosipescu test fixture and dimensions of the specimen

Results and Discussion

There are in common three main failure modes; net tension, shear out and bearing as defined in Fig. 3, schematically. In this experimental study, these failure modes are also observed. Typical failures of tested composite specimens without any preload are shown in Fig. 6, as example. It can be seen in this figure that the net-tension failure modes are occurred for low *E*/*D* and *W*/*D* ratios, especially. Besides, shear-out and bearing failure modes are formed for bigger ratios of *E*/*D* and *W*/*D*. When *E*/*D*=5 and *W*/*D*=5 failure modes are bearing $[30°]_4$, $[45°]_4$ and $[60°]_4$ laminated specimens (Figs 6a, b and c). The shear-out failure modes is also possible for *W*/*D*=5 ratios, if *E*/*D* ratio is chosen as 1 or 2. However, all $[90°]_4$ laminated specimens are damaged as net-tension (Fig. 6d). It seems that the failures of $[90°]_4$ specimens are come into being as matrix failures; the fibers is not almost to carry any load. Consequently, the failure modes are only net-tension in spite of higher values of *E*/*D* and/or *W*/*D*. It is known that the net-tension failure mode is not desired for any safe design. Therefore, $[90°]_4$ specimens are seen as the weakest type of laminated composite plates tested in

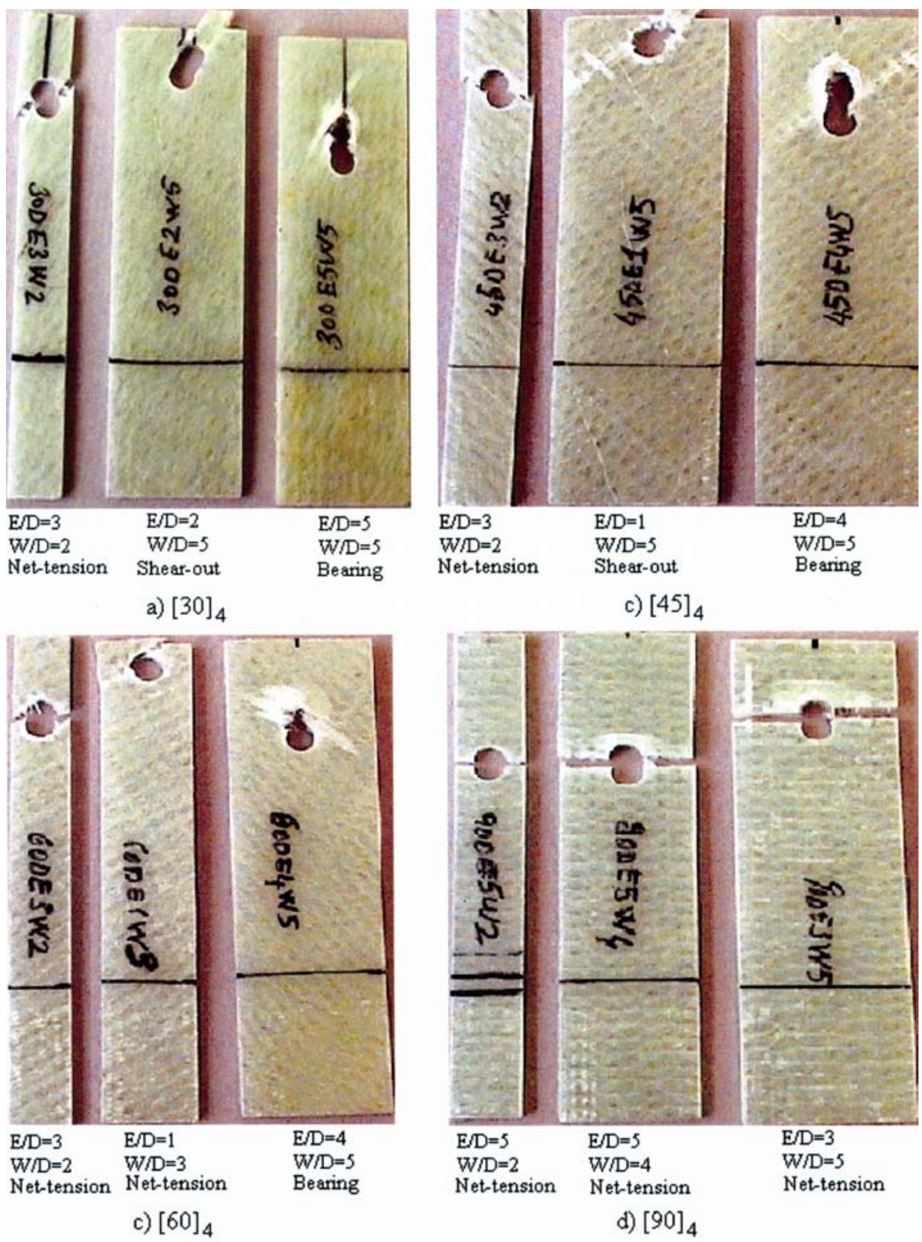

Fig. 6—Typical failures of tested composite specimens

this study. Furthermore, bearing failure mode is more acceptable than other failure modes in bolted-joints. Hence, *W*/*D*=2 and *E*/*D*=1 ratios should not be selected for unidirectional reinforced and bolted composite plates by a designer.

The effect of *E*/*D* ratio on the bearing strength for $[30°]_4$, $[45°]_4$, $[60°]_4$ and $[90°]_4$ laminated plates are given in Figs 7-10, respectively. Each figure is drawn depending on *W*/*D* ratio from 2 to 5 and applied preloads. First of all, it is seen clearly in these figures that the magnitudes of bearing strengths increase by increasing of *E*/*D* ratio. Besides, the bearing strengths also increase, when *W*/*D* ratio is raised. Furthermore, when the applied value of preload is increased, the bearing strengths rise, generally. Consequently, the minimum values of bearing strengths are obtained under 0 Nm preloads, whereas the maximum values are usually calculated under 5 Nm preloads. But maximum values of it are computed when the preload is applied as 2.5 Nm for some specimens. For instance, when *W*/*D*=5 the bearing strengths under 2.5 Nm preload moment are higher than 5 Nm preload moment for $[60°]_4$ specimens except only *E*/*D*=2. The preload moment produces the friction force which is caused by the normal pressure on the washer, nut and specimen. Besides, load carrying capacity does not vary linear versus to preload moments. As a result, it is said that increased values of preloads provide a better structure design according to load carrying capacity of bolted composite plates. This result is preferred for a stronger structure.

As seen in Figs 7-10, the magnitude of bearing strengths for $[30°]_4$ laminated specimens are calculated higher than other laminated plates. For example, the maximum value of it is computed as 524 MPa for *E*/*D*=4 and *W*/*D*=5 under 5 Nm preload (Fig. 7), while the minimum values of it are calculated as 25 MPa for $[90°]_4$ oriented specimens under 0 Nm preload when *E*/*D*=4 and *W*/*D*=2 (Fig. 10). Therefore, $[30°]_4$ laminated plates are stronger than other laminated plates investigated in this study. In addition, the bearing strengths for $[90°]_4$ specimens are obtained lower than other laminated specimens for all geometrical parameters and preload conditions. Accordingly the $[90°]_4$ laminated plates are weakest than other laminated plates.

The effect of *E*/*D* ratio on the bearing strengths for 0, 2.5 and 5 Nm applied preloads related to varying of orientation angle are plotted in Figs 11-13, respectively. It is seen that in these figures, the magnitude of bearing strengths without preload

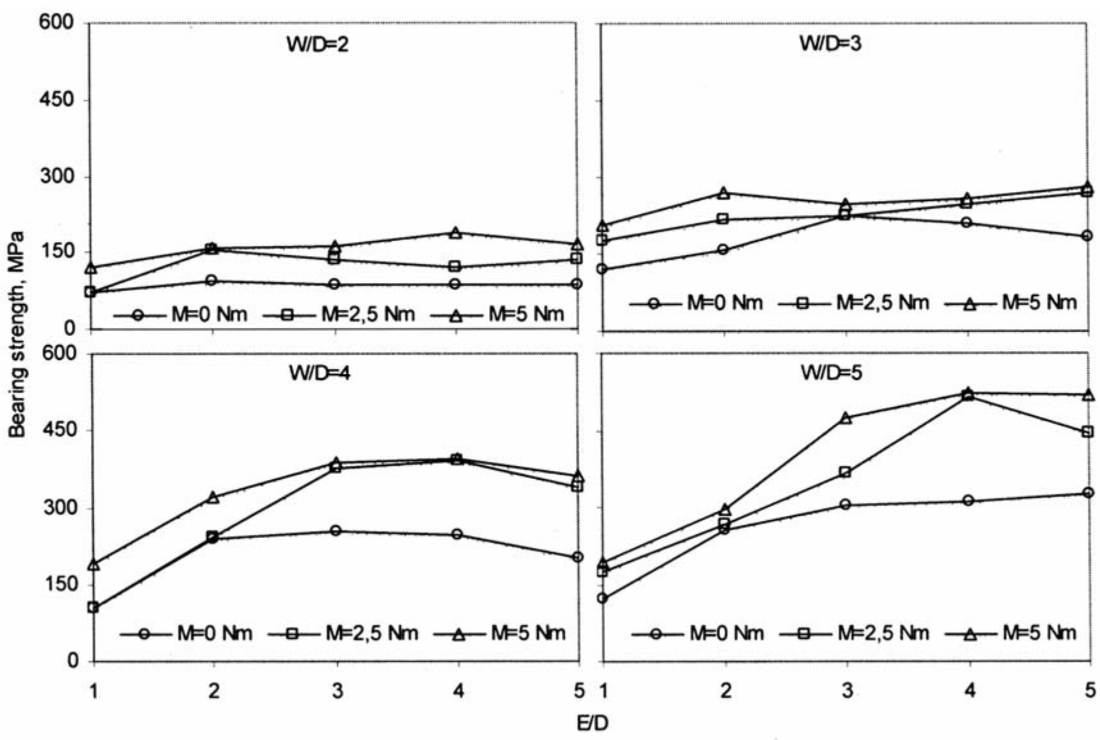

Fig. 7—Effect of *E*/*D* ratio on the bearing strength of $[30^o]_4$ specimens for *W*/*D* = 2 to 5

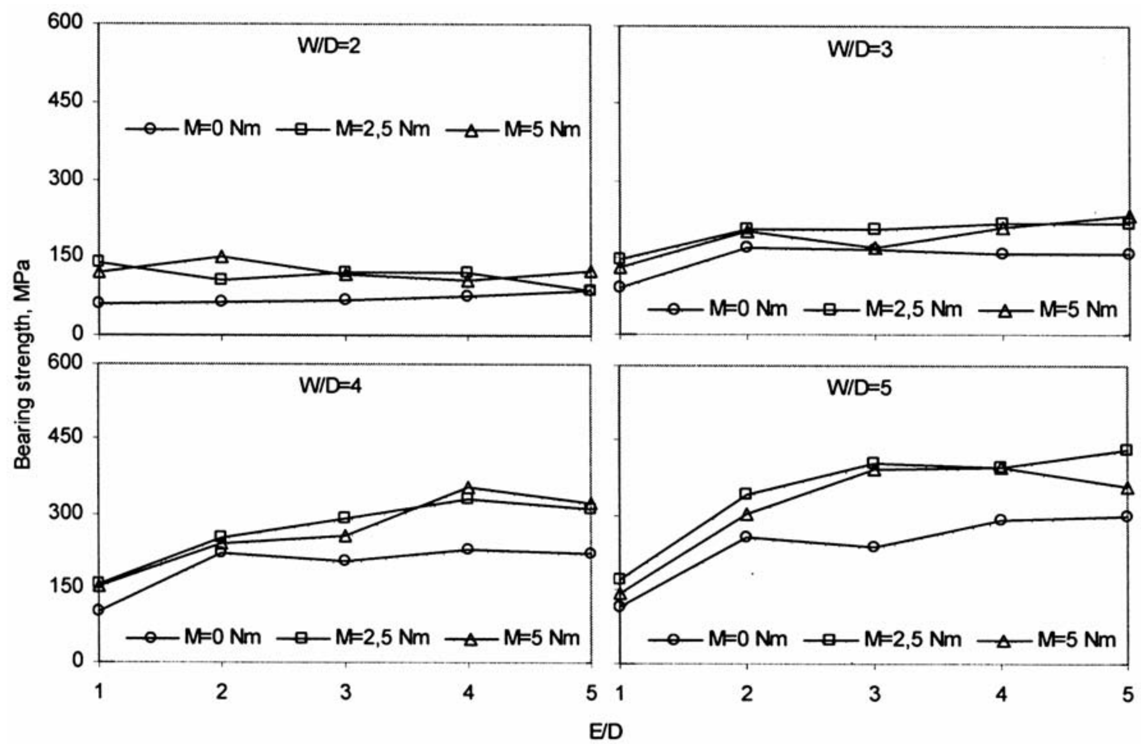

Fig. 8—Effect of *E*/*D* ratio on the bearing strength of $[45^o]_4$ specimens for *W*/*D* = 2 to 5

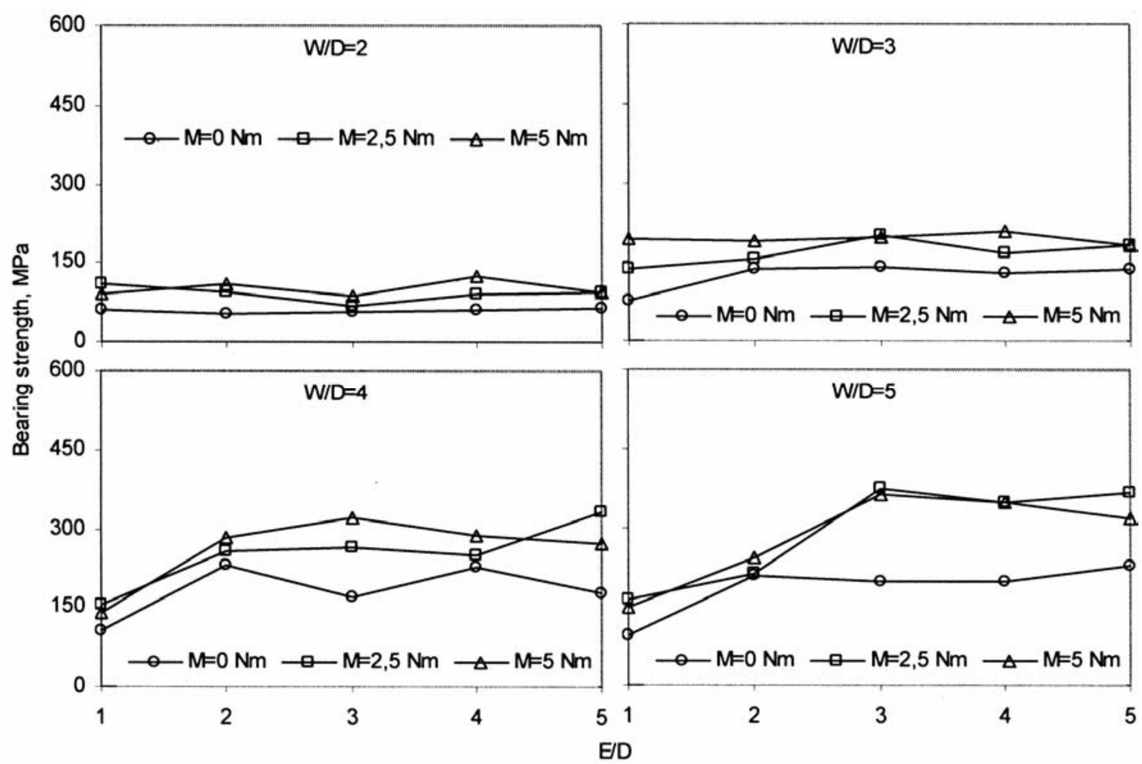

Fig. 9—Effect of *E*/*D* ratio on the bearing strength of $[60^o]_4$ specimens for *W*/*D* = 2 to 5

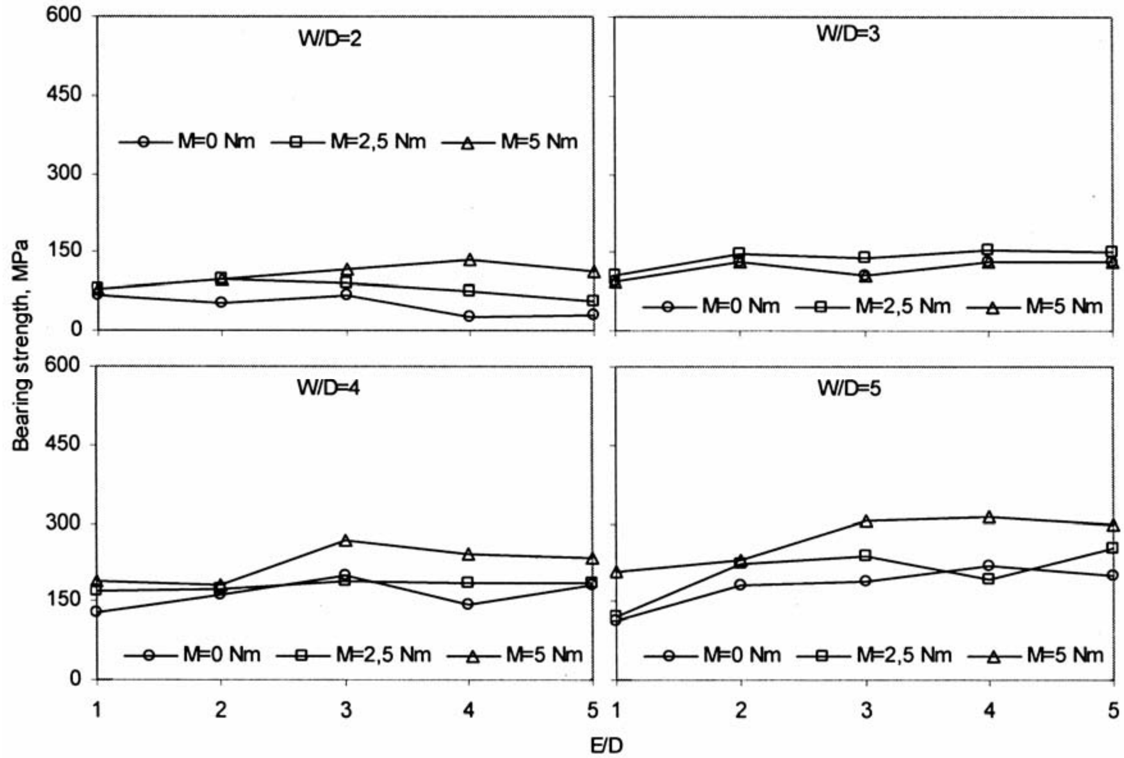

Fig. 10– Effect of *E*/*D* ratio on the bearing strength of $[90^o]_4$ specimens for *W*/*D* = 2 to 5

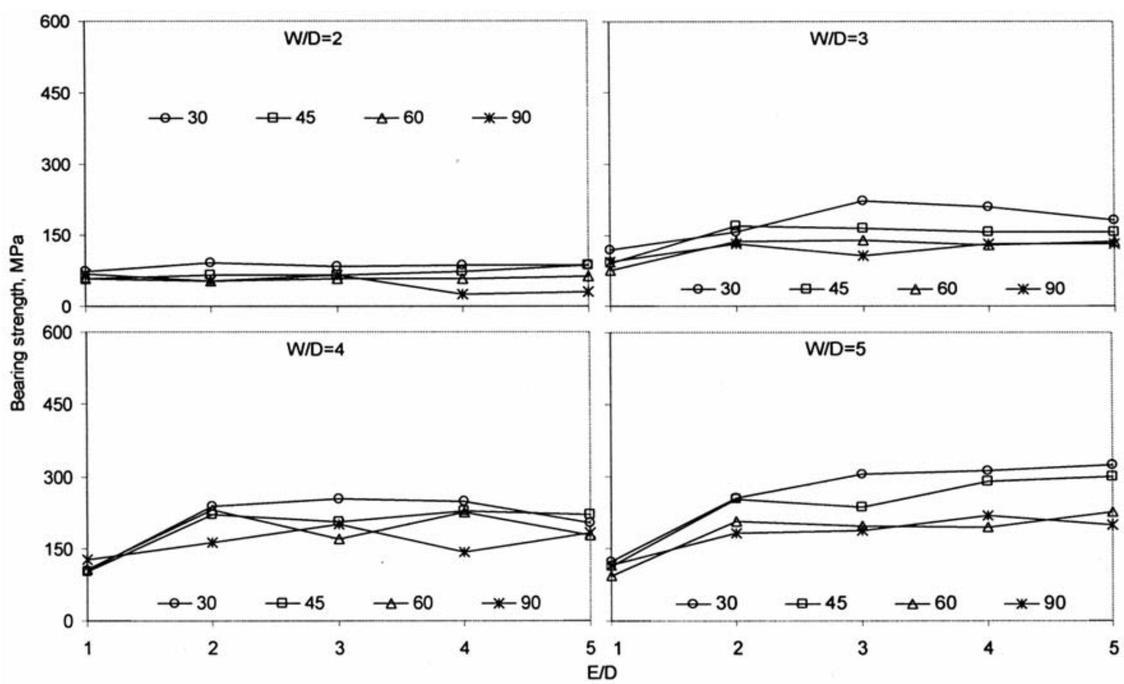

Fig. 11—Effect of *E*/*D* ratio on the bearing strength depending on orientation angle under 0 Nm preload specimens

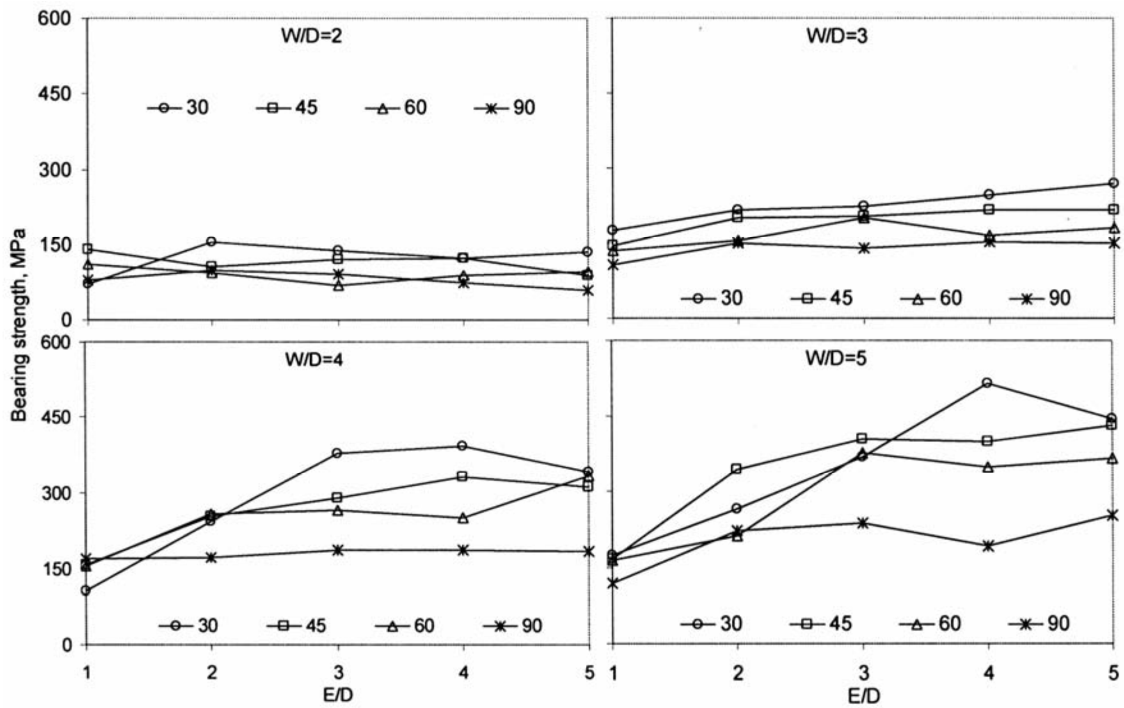

Fig. 12—Effect of *E*/*D* ratio on the bearing strength depending on orientation angle under 2.5 Nm preload specimens

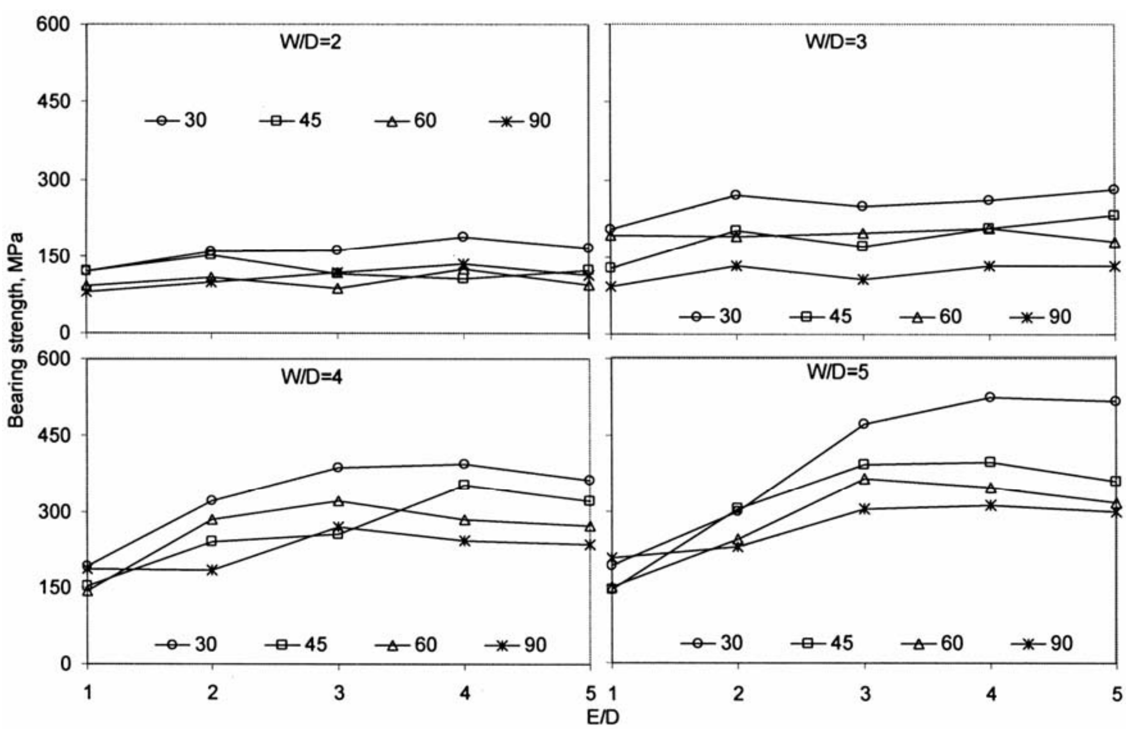

Fig. 13—Effect of *E*/*D* ratio on the bearing strength depending on orientation angle under 5 Nm preload specimens

moments are obtained lower than 2.5 and 5 Nm preload conditions for each laminated plates and all geometrical parameters. It is also mentioned previously, the bearing strengths for $[30°]_4$ laminated specimens are higher than other laminated plates. Besides, it is calculated for $[90°]_4$ specimens lower than other plates. These explanations are also valid generally, but the bearing strengths can be computed differently for some geometrical parameters. For example, when *E*/*D*=1 and *W*/*D*=4 under 2.5 Nm preload moment, the minimum value of bearing strengths is occurred for $[30°]_4$ specimens, whereas the maximum values are estimated $[90°]_4$ specimens (Fig. 12).

When *W*/*D* is held constant, the bearing strengths for *E*/*D*=1 are calculated very lower than other *E*/*D* ratios, generally. It is said that when *E*/*D*=1, the design is very weakest in comparison with other *E*/*D* ratios. The *E*/*D* ratio should be selected as 3, 4 and/or 5 during any real bolted composite applications. In other words, the designer have to avoid from selecting *E*/*D*=1, especially.

Conclusions

In this study, an experimental failure analysis was carried out in single bolted glass reinforced-epoxy laminated composite plates. Bearing strengths and failure modes were investigated for different geometrical parameters and stacking sequences under various preloads. The following conclusions can be derived from experimental study:

(i) Bearing strengths of the composite specimens are increases by increasing both *E*/*D* and *W*/*D* ratios.

(ii) When *E*/*D* = 1, the bearing strengths is obtained lower than those in other *E*/*D* ratios. Therefore, *E*/*D*=1 is observed as the weakest geometrical form.

(iii) Bearing strengths under 0 Nm preload are calculated lower than both 2.5 and 5 Nm preloads.

(iv) In general, the maximum values of bearing strengths are obtained under 5 Nm preload except for some geometrical parameters under 2.5 Nm preload. It is said that increasing of preloads is very suitable for a safe structure because of providing high bearing strengths and bearing mode.

(v) The magnitudes of bearing strengths are completely influenced from stacking sequences of laminated composite plates.

(vi) The stacking sequence of $[30°]_4$ laminated plate is seemed well than other orientations, whereas $[90°]_4$ laminated plate is the weakest selected in this investigation.

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