Failure Analysis of Unidirectional Composite Pinned-Joints

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Abstract: **The objective of the study is to investigate the effects of geometrical and physical parameters on failure loads unidirectional composite laminates by finite element analysis. The failure load of for a single pin hole, parallel pin hole and multi-pin holes. Three different distance variables were investigated during analysis the ratio of free edge distance to the outer holes/pin diameter (E/D = 2, 3, 4, 5), the ratio of longitudinal distance between the holes/pin diameter (G/D = 2, 3, 4, 5), and the ratio of transverse distance between the parallel holes/pin diameter (W/D = 2,3, 4, 5) ratios. Yamada-Sun failure criterion was used for failure analysis. The results from finite element analysis showed that it is very important to consider the effect of E/D, G/D and W/D ratios in design of single, double and multiple joints. The results showed that the pin hole farthest from the free edge is subjected to the highest stress.**

Keywords: **Composites, ANSYS Workbench, Pin Loaded joints, parallel pinned joints, multiple pin joints.**

1. Introduction

In advanced engineering fields such as aerospace engineering, composites have found applications because of their high strength/weight ratios. A study of joining methods for composite materials became an important research area. Notably the mechanical joint always requires fastener holes. fastener joining is the most widely used method of assembling of structural elements

Joints present potential problem regions to the designers due to stress concentrations, and therefore, the strength of such a structure is dependent on the strength of its joints. Among them, Alaattin Aktas [1] have studied the failure loads and failure modes of composite specimens with single and double parallel holes which are subjected to reaction force by two rigid pins are investigated experimentally and numerically, and unidirectional laminates are examined that minimum failure load is obtained W/D = 2 (E/D is constant) and E/D = 2 (W/D is constant). Maximum failure load is obtained when E/D and W/D is equal to 4, and greater than these points. Alaattin Aktas et al [2] have studied the effect of stacking sequence of carbon-epoxy composite laminates, with $[0/45/45/90]_S$, and $[90/45/45/0]_S$ configuration, on pinned-joint. They found, for both configurations, that the bearing strength reaches their maximum value at W/D = 4 and E/D = 4 geometric configurations. Nanda Kishore et al. [3] Investigated the failure analysis of glass fiber epoxy composite laminates using the FEM analysis and experimental for multiple pin joints. Failure loads and failure modes of composite laminates are analyzed by Varying the P/D ratios. Alaattin Aktas [4] investigated the failure loads and failure modes of a one and two serial pin joints are analyzed experimentally and numerically, Minimum failure load is obtained when *W/D*=2 (*E/D*=4) and *E/D*=2 (*W/D*=4). Maximum failure load is obtained when *E/D* and *W/D* is equal to 4. Kadir Turan et al [5] the effects of joint geometry and fiber orientation on the failure loads and failure modes, parametric studies were performed experimentally and numerically using the mechanical APDL programing and examine the Hashin Failure Criteria. B. Okutan [6] investigated E glass epoxy for two different ply orientations such as $[0/45]_s$ and $[90/45]_s$ For each ply orientation, 20 different geometries were chosen, bearing stress and shear stress of specimens are analyzed by both experiential and numerically. The shear strength of single-hole joints has been shown to be strongly dependent on the ply orientations within the laminate and the edge distance. the effect of a change in the ratio of edge distance to diameter is of about 66% loss in strengths. Buket Okutan et al [7] Investigated experimental and numerical analysis for E/glass–epoxy composites, for a single pin hole. A parametric study considering geometries was performed to identify the failure characteristics of the pin-loaded laminated composite. Failure modes are calculated by finite element analysis. Shear stress and net tension of single hole joints is strongly dependent on the ply orientation. R. Karakuzu et al [8] Studied The failure behavior of glass–epoxy laminated composite plates fabricated from stacking sequence $[0/90/\pm45]_S$ subjected to a traction force by three-pins. Varying the G/D, W/D and E/D ratios observed that failure modes of the first and second pin holes are the same for all specimens but sometimes different from the third pin hole. Bearing mode and shear out mode are observed the specimens are damaged in bearing mode which is the most desired mode. The failure load increases with increasing E/D ratio. B.G. Kiral et al [9] investigated the effect o f clearance and interference fit of pin joints. Three-dimensional finite element models are created using ANSYS software. Non-linear contact analyses are performed to examine the effects of the clearance and interference for different ratios of the edge distance-to-hole diameter (E/D) and plate width-to-hole diameter (W/D). It is observed that interference for all pin-loaded joint configurations is beneficial. Manjeet Singh et al [10] studied the effect of ply orientation of a unidirectional glass epoxy nanoclay laminates. Nanoclay filler with 1, 2, 3, 4 and 5 wt% were added in the epoxy for the said orientations to prepare the pin joints. the geometric parameter i.e. W/D and E/D ratios. Net-tension and shear-out failure modes occur with small W/D and E/D values, respectively. Bearing failure is desirable as it is progressive. The bearing mode of failure occurs for W/D and E/D ratios to be greater than 4. Bu¨ lent Murat Ic et al [11] investigated the failure strength and failure mode of a pinned-joint carbon–epoxy composite plate of arbitrary orientations. A computer program developed for such an analysis is used to calculate the failure load, the failure mode, and the propagation of failure of plate with different fiber orientation, different material properties and different geometries. B. Okutan Baba [12] investigated the effect of joint geometry and fiber orientation on the failure strength and failure mode in a pinned joint laminated composite plate. The ultimate load capacities of E/glass–epoxy laminate plates with pin connection are increased by increasing W and E. This study is the continuity of the previous work of Aktas et al [1]. in which, the authors compared the single and parallel pin joints experimentally and numerically. However, in this study, the effects of *E/D* and *W/D* ratios on failure mode and failure load are investigated furthermore, continuation for multiple joints. The numerical investigation was performed utilizing ANSYS Workbench. Yamada-Sun failure criterion is used to obtain failure load of the laminated plates.

Table 1 Mechanical Properties of Epoxy Carbon UD (230 GPa) Prepreg

Properties	Symbol	Magnitude
Elastic modulus of Longitudinal direction(MPa)	E_1	121000
Elastic modulus in transverse direction(MPa)	E_2	8600
Shear modulus	G_{12}	4700
Poisson's ratio	v_{12}	0.27
Longitudinal tensile strength (MPa)	X_t	2231
Longitudinal compressive strength (MPa)	X_c	1082
Transverse tensile strength (MPa)	Y_t	29
Transverse compressive strength (MPa)	Y_c	100
Shear strength (MPa)	S	60

Table 2 Mechanical Properties of Epoxy E-Glass UD

Properties	Symbol	Magnitude
Elastic modulus of Longitudinal direction(MPa)	E_1	45000
Elastic modulus in transverse direction(MPa)	E_2	10000
Shear modulus	G_{12}	5000
Poisson's ratio	v_{12}	0.3
Longitudinal tensile strength (MPa)	X_t	1100
Longitudinal compressive strength (MPa)	X_c	675
Transverse tensile strength (MPa)	Y_t	35
Transverse compressive strength (MPa)	Y_c	120
Shear strength (MPa)	S	80

Table 3 Mechanical Properties of Epoxy S-Glass UD

Properties	*Symbol*	*Magnitude*
Elastic modulus of Longitudinal direction(MPa)	E_1	50000
Elastic modulus in transverse direction(MPa)	E_2	8000
Shear modulus	G_{12}	5000
Poisson's ratio	v_{12}	0.3
Longitudinal tensile strength (MPa)	X_t	1700
Longitudinal compressive strength (MPa)	X_c	1000
Transverse tensile strength (MPa)	Y_t	35
Transverse compressive strength (MPa)	Y_c	120
Shear strength (MPa)	S	80

2. Problem definition

In this study, three types of pin joint plates are analyzed. One has single, other has two parallel holes and other has multiple holes as shown in Fig. 1a, b, and c, respectively. The specimen with single hole of diameter D is located along the centerline of the plate (Fig. 1a). The center of the hole is located a distance E from one end. A uniform tensile load P is then applied to the plate, and this load is resisted by a rigid pin. The load is parallel to the plate and is symmetric with respect to the centerline. The specimens are of two parallel holes, which are located a distance E from one free edge and W/2 from the other. The distance between the two parallel holes is taken 24 mm (Fig. b). The specimen with multiple holes of diameter First and second pins are symmetric according to the centerline of the specimen by a distance of 24 mm and are located a distance E from the free edge of the specimen. The distance between any parallel pin and the nearest longitudinal edge is taken as W/2. The third hole is located along the centerline of the plate at a horizontal distance G from the first and second pins. A uniform tensile load P was applied to the specimen which was supported by three-pins with different arrangements (Fig c). All the circular holes have the same diameter of 6.5 mm and the thickness of the plate is 3.14 mm.

Two parameters investigated in single hole specimen

E/D -The ratio of edge distance-to-hole/pin diameter, it has been varied from 2 to 5.

W/D- The ratio of the width of the specimen to the diameter of the holes, it has been varied from 2 to 5.

Two parameters investigated in Two parallel hole specimen

E/D -The ratio of edge distance-to-hole/pin diameter, it has been varied from 2 to 5.
W/D- The ratio of the width of the specimen to the diameter of the holes, it has been varied from 2 to 5.

Three parameters investigated in Multiple hole specimen

E/D -The ratio of edge distance-to-hole/pin diameter, it has been varied from 2 to 5.
W/D- The ratio of the width of the specimen to the diameter of the holes, it has been varied from 2 to 5.
G/D- The ratio of longitudinal distance between the holes/pin diameter, it has been varied as 2 to 5.

Table 4 Geometries of pin joint samples

G/D ratio	W/D ratio	E/D ratio	D (mm)	E (mm)	W (mm)	Thickness (mm)	Length of the hole to edge (mm)
2	2	2	6.5	13	13	3.14	100
	3	3	6.5	19.5	19.5	3.14	100
	4	4	6.5	26	26	3.14	100
	5	5	6.5	32.5	32.5	3.14	100
3	2	2	6.5	13	13	3.14	100
	3	3	6.5	19.5	19.5	3.14	100
	4	4	6.5	26	26	3.14	100
	5	5	6.5	32.5	32.5	3.14	100
4	2	2	6.5	13	13	3.14	100
	3	3	6.5	19.5	19.5	3.14	100
	4	4	6.5	26	26	3.14	100
	5	5	6.5	32.5	32.5	3.14	100
5	2	2	6.5	13	13	3.14	100
	3	3	6.5	19.5	19.5	3.14	100
	4	4	6.5	26	26	3.14	100
	5	5	6.5	32.5	32.5	3.14	100

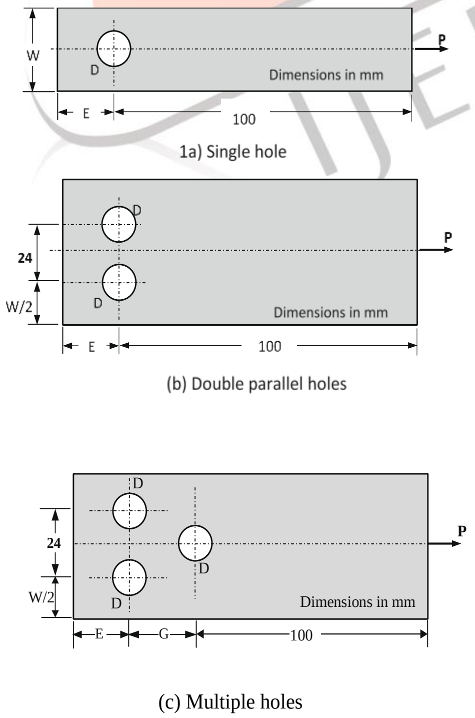


Fig. 1. The geometry of the single, double and multiple pinned-joints.

3.Numerical Study

In order to determine the failure loads, a failure criterion must be applied. In this investigation, the Yamada-Sun failure criterion is used. The criterion is quadratic theory. Involving the shear stress (τ_{12}) and the longitudinal stress (σ_1) along the fibers, and the following criterion for laminate failure is proposed

$$\left(\frac{\sigma_1}{X}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 = e^2 \quad e \geq 1 \text{ failure } e < 1 \text{ no failure} \qquad (1)$$

Where (σ_1) is longitudinal stress along the fibers, X is longitudinal tensile strength of ply, τ_{12} is shear stress along the fibers and S is the rail shear strength. The failure criterion (Eq. 1) only predicts whether the pin joint failed or not.

4.Finite element Analysis

Ansys Workbench finite element package has been used in the numerical analyses. Whether or not a joint fail under a given condition is determined by the finite element analysis as follows:

The geometry of the problem is modeled for single hole, serial holes and multiple pin holes using the design modular Workbench 18.1, geometry and material with respect to x-axis and displacements in y-direction is zero. The stresses (σ_x, σ_y and τ_{xy}) are calculated using the finite element method. Size of the mesh is 0.5 mm. In order to simulate the rigid pins, radial displacement constraints were used on the left-hand sides of the holes as shown in Fig 3. Shows the boundary conditions and meshing of the composite laminate it is similar boundary conditions is applied to the parallel hole pin joints and multiple pin joints.

ACP Pre- provides the ability to use Look-up Tables to define the state of user-defined fields in composite analysis.

A static structural analysis determines the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed; that is, the loads and the structure's response are assumed to vary slowly with respect to time.

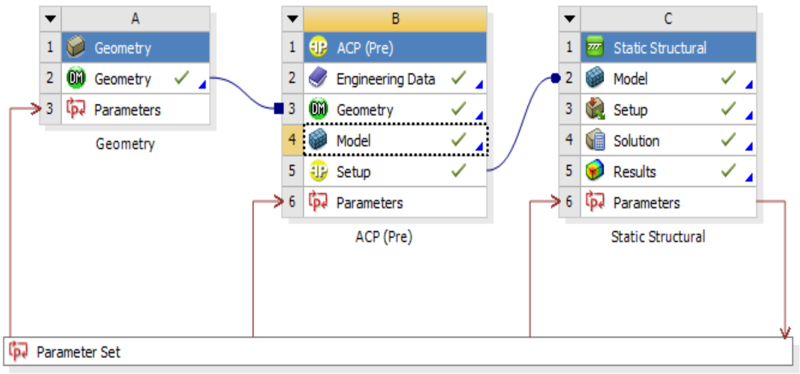


Fig 2 Interface of Ansys workbench.

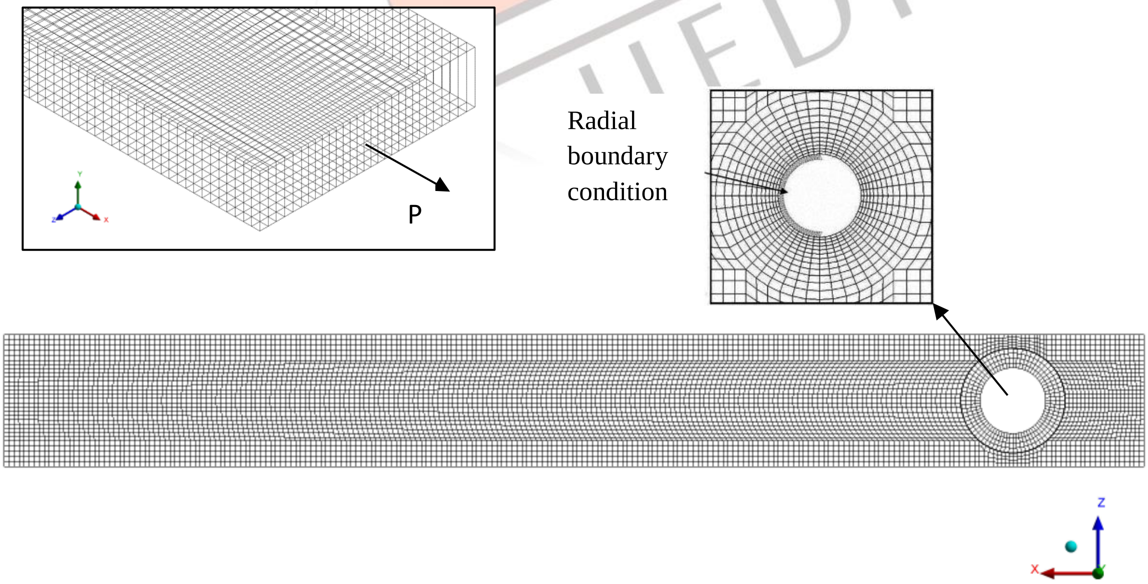


Fig 3 mesh and its boundary condition of single hole.

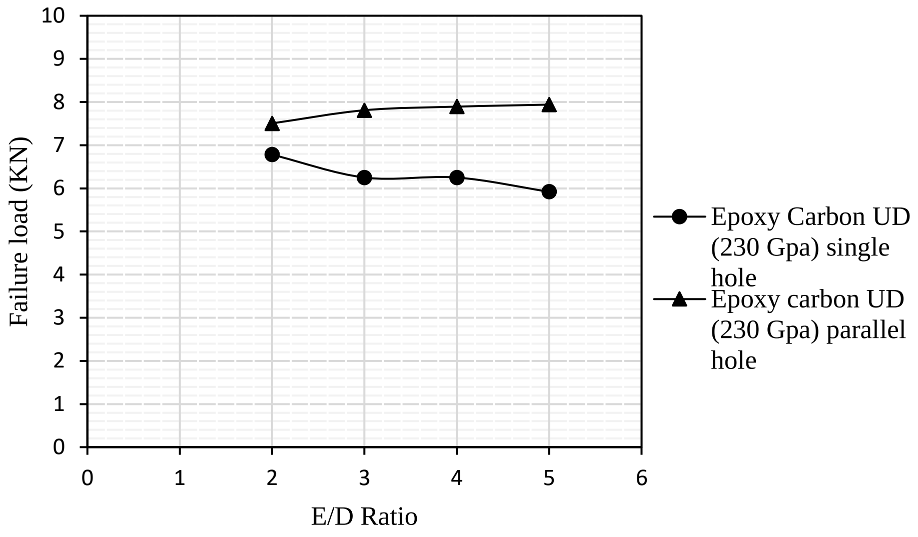


Fig 4 The effect of E/D ratio on failure load for single and double pinned-joints.

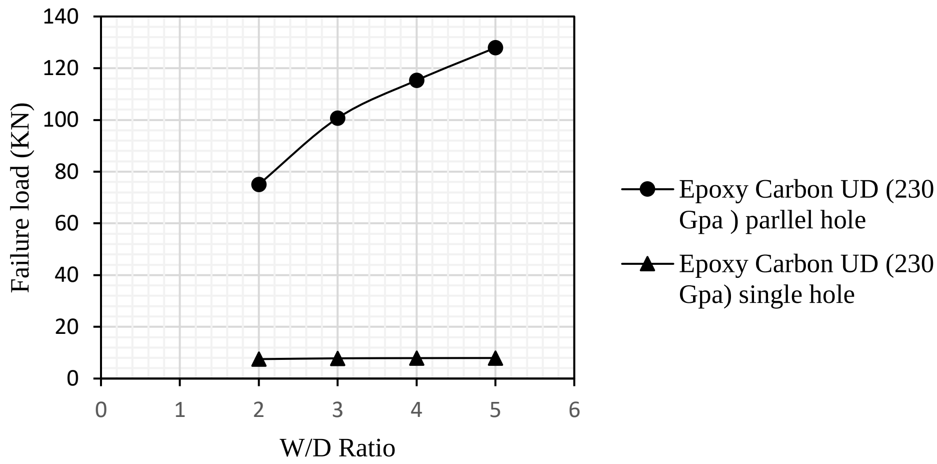


Fig 5 The effect of W/D ratio on failure load for single and double pinned-joints.

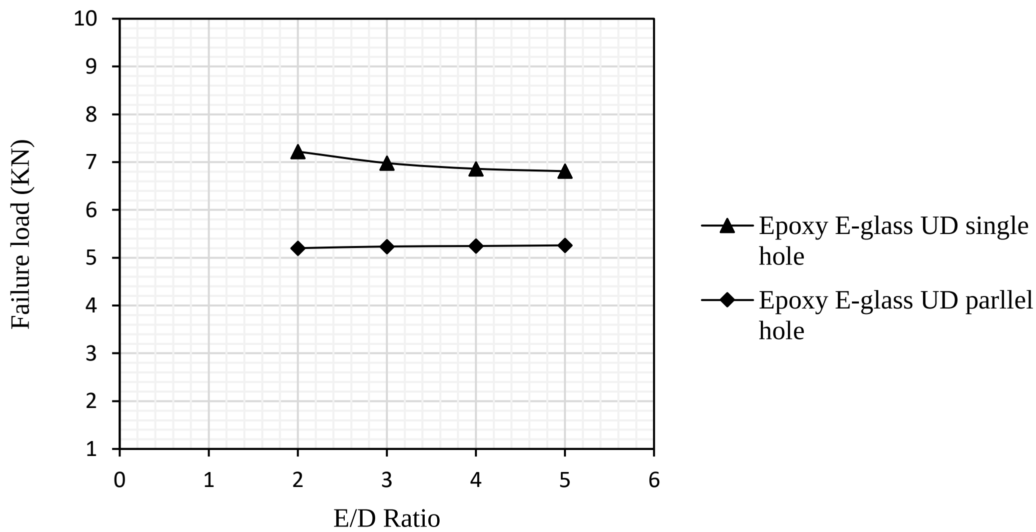


Fig 6 The effect of E/D ratio on failure load for single and double pinned-joints.

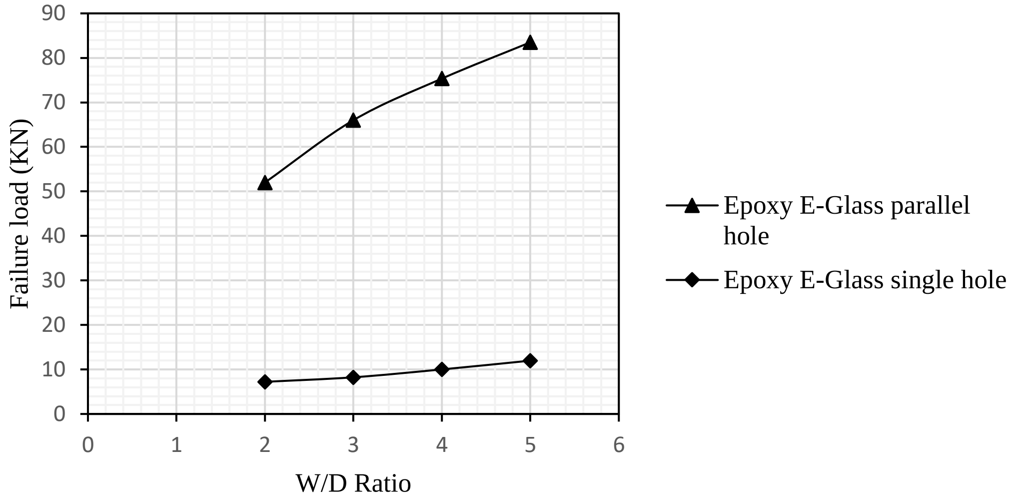


Fig 7 The effect of W/D ratio on failure load for single and double pinned-joints.

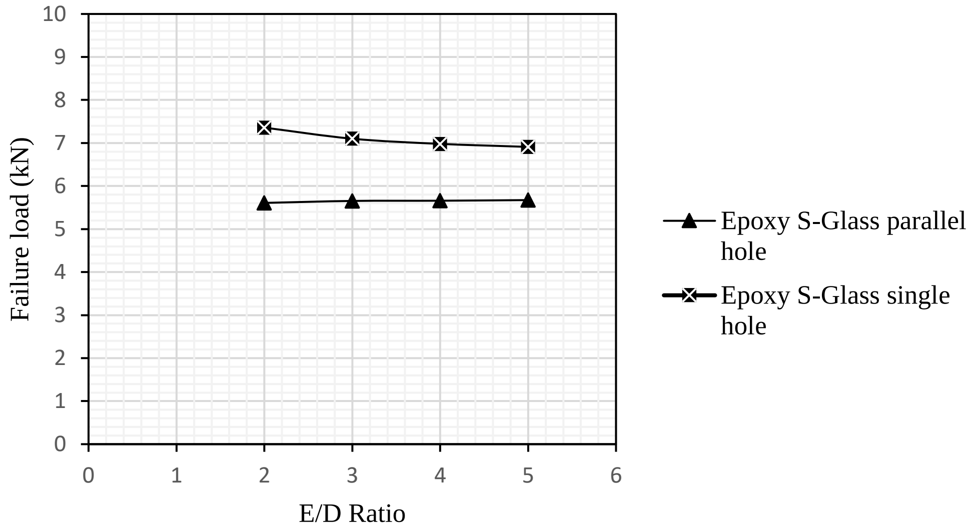


Fig 8 The effect of E/D ratio on failure load for single and double pinned-joints.

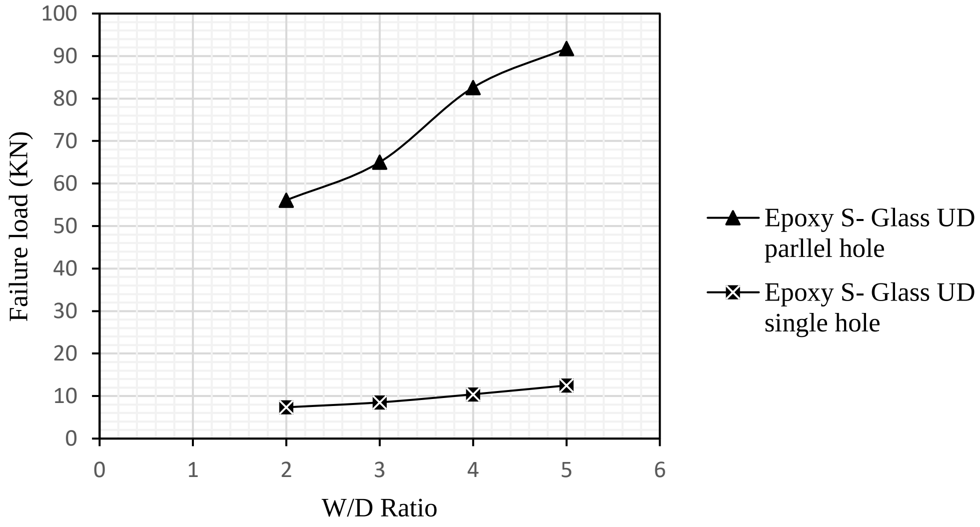
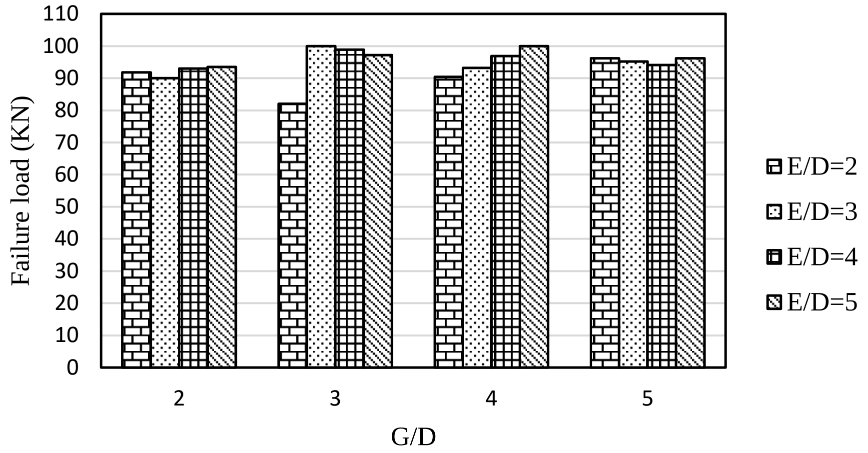


Fig 9 The effect of W/D ratio on failure load for single and double pinned-joints.



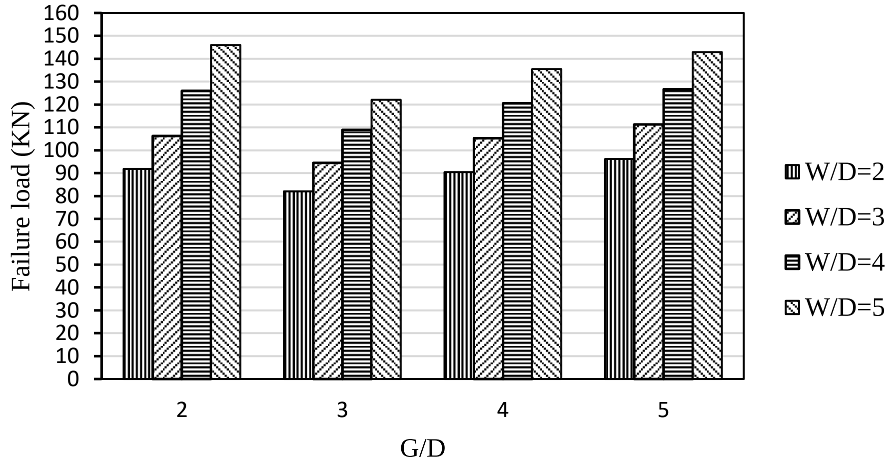


Fig 10 Epoxy Carbon UD (230 GPa) The effect of failure G/D ratio on failure load for multiple pinned-joints

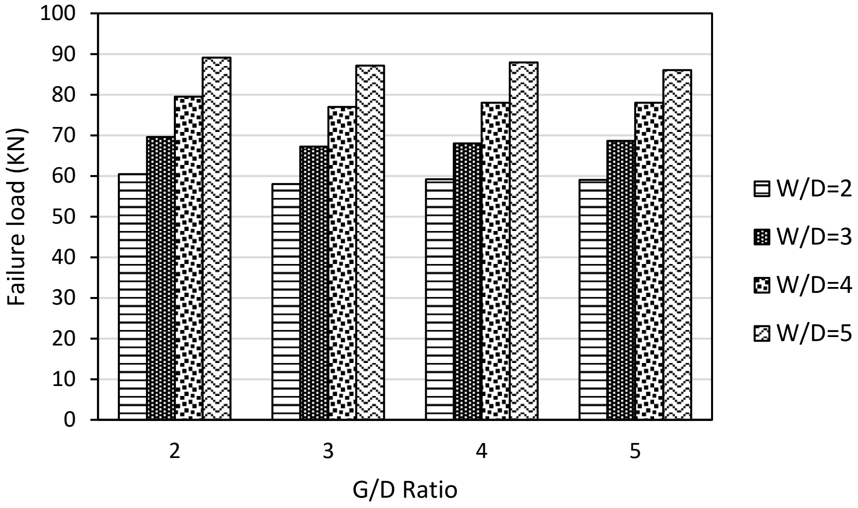
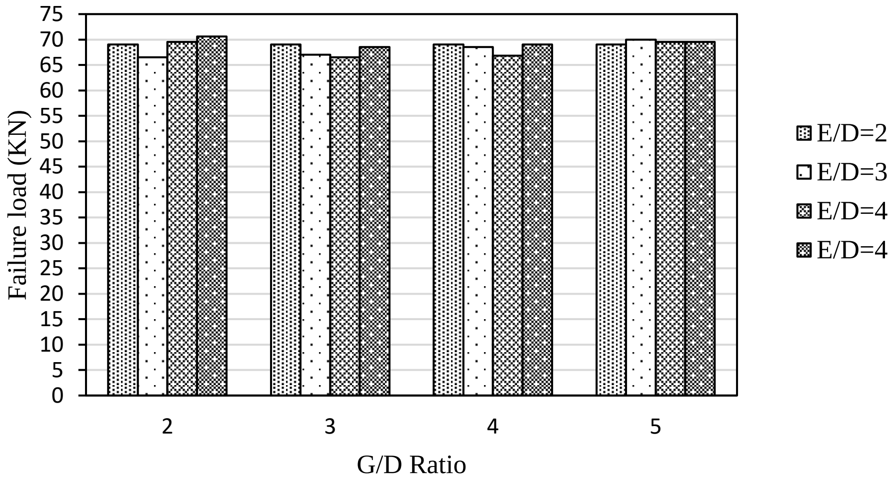


Fig 11 Epoxy E-Glass The effect of G/D ratio on failure load for multiple pinned-joints.



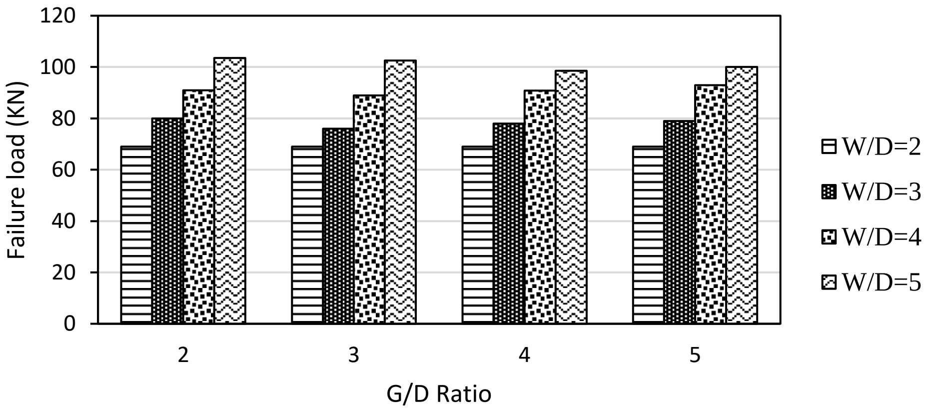


Fig 12 Epoxy S-Glass The effect of G/D ratio on failure load for multiple pinned-joints

Results and discussion

Failure loads of composite specimens with single hole, double parallel holes and multiple holes which are subjected to reaction force by rigid pins are investigated numerically. In order to obtain the optimum geometry for three cases, the ratio of free edge distance to the outer holes/pin diameter (E/D), the ratio of longitudinal distance between the holes/pin diameter (G/D), and the ratio of transverse distance between the parallel holes/pin diameter (W/D) ratios are investigated by using finite element analysis. In the above show in figs the failure loads of composite materials.

Failure load

In serial case, the maximum failure load was calculated numerically from the procedure described in the finite element analysis section, the percentage of the hole far from the free edge of specimen. From Fig 4 observed the failure load for a single hole pin joint loads with respect to (E/D) ratio of edge distance to the outer holes/pin diameter for single and parallel holes around 40% difference in single and parallel hole pin joints. When *E/D* is equal to 2 and 4, the failure loads takes its minimum and maximum value, respectively. An interesting result is that the failure load for the parallel holes is less than the single hole.

Conclusions

In present paper, failure strength of Epoxy Carbon UD 230 (GPa), Epoxy E-Glass, Epoxy S-Glass composite plates with single, double parallel, multiple pinned joints has analyzed numerically. Three different distance variables were investigated during analysis the ratio of free edge distance to the outer holes/pin diameter (E/D = 2, 3, 4, 5), the ratio of longitudinal distance between the holes/pin diameter (G/D = 2, 3, 4, 5), and the ratio of transverse distance between the parallel holes/pin diameter (W/D = 2,3, 4, 5) ratios. The numerical study was performed by means of ANSYS Workbench program. Hence ANSYS Workbench program helps to optimize the joint design and predict failure before conducting experiments thereby saving cost and time in carrying out the tests.

The following results are found from the numerical results:

In case of multiple pin holes:

- The ratio G/D increases from 2 to 5, its slope decreases with increasing W/D and E/D ratios. Maximum failure load is obtained at E/D=4, G/D=4 and W/D=4.
- Epoxy Carbon UD, E/D ratio is constant by varying the G/D ratio the minimum failure load at G/D=3 and maximum failure load at G/D=5.
- In this case of multiple joints epoxy carbon has high strength when compared to Epoxy E-glass and Epoxy S-Glass. In some cases, E/D ratio of E-Glass is better than Epoxy Carbon.

In case of double parallel pin holes

- Epoxy carbon UD, E/D proportion is differed starting with 3 on 5 the effect of double parallel pin holes get good results compared to single hole.
- S-Glass UD, E-Glass UD geometries of the specimen E/D is kept constant varying W/D ratio.

In case of single pin hole

- Minimum failure load is obtained W/D = 2 (E/D is constant) and E/D = 2 (W/D is constant).
- Maximum failure load is obtained when E/D and W/D is equal to 4, and greater than these points.

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