Failure and Stress Analysis of Glass Fiber Reinforced Laminated Composite Pinned Joints

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Abstract: In this study, behavior of pin-loaded glass fiber reinforced with polyethylene laminated composites with different stacking sequence and different dimensions has been observed experimentally and stress analysis was performed using ANSYS software. The aim is to investigate stresses, failure strength and failure mode of composite laminates containing a pin loaded hole, when the material exhibits linear elastic behavior. The logical methodology for modeling the joint problem uses the two major steps: failure analysis and stress analysis. Failure analysis is done experimentally and stress analysis is done by using ANSYS software. To investigate and verify to the analytical predictions of mechanical behavior, and to observe the failure characteristics of the pin-loaded composites, a series of experiments were performed with eight different material configurations, in all, over 36 specimens. The edge distance-to-hole diameter ratios and width-to-hole diameter ratios of plates were changed. For this part of study, layered composite materials were manufactured in our Institute. The stress distribution around the hole in pin-loaded glass-fiber with polyethylene laminate was performed, and in addition, ANSYS was performed to compare effects of different boundary conditions used to simulate the pin load on stress distributions around the hole.

Keywords: ANSYS Software, Composite, Pinned Joints, Stress & Failure Analysis

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1 INTRODUCTION

Composite materials are commonly used in structures that demand a high level of Mechanical performance. Their high strength to weight and stiffness to weight ratios has facilitated the development of lighter structures, which often replace conventional metal structures. Due to strength and safety requirements, these applications require joining composites either to composites or to metals. Although leading to a weight penalty due to stress concentration created by drilling a hole in the laminate, mechanical fasteners are widely used in the aerospace industry. In fact mechanically fastened joints (such as pinned joints) are unavoidable in complex structures because of their low cost, simplicity for assembly, and facilitation of disassembly for repair [1-3].

Quinn & Matthews have studied experimentally the effect of stacking sequence on the pin bearing strength in glass fiber reinforced plastic [4]. The results suggested that placing the 900 layer (normal to the applied load) at or next to the surface increases the bearing strength [4]. Collings has discussed the effects of variables such as ply orientation, laminate thickness and bolt clamping pressure [5]. Collings has also tested CFRP for a range of laminate configurations and hole sizes, and investigated the relation between joint strength and W/D, E/D and t/d [6]. Kim et al. developed a two-dimensional finite element model for load distribution of multi-fastener joints [7]. A similar model was used by Chutima et al. to investigate the stress distribution and load transfer in multi-fastened composite joints utilizing the I-DEAS software [8].

2 JOINTS IN COMPOSITE STRUCTURES

The structures essentially consist of an assembly of single elements connected to form a load transmission path. Joints in components or structures incur a weight penalty, are a source of failure and cause manufacturing problems; whenever possible, therefore, a designer will avoid using them. Unfortunately, it is rarely possible to produce a construction without joints due to limitations on material size, convenience in manufacture or transportation and the need for access. All connections or joints are potentially the weakest points in the structures so can determine its structural efficiency. To make useful structures, consideration must be given to the way structural components are joined together [9].

The introduction of fiber-reinforced composites has been a major step in the evolution of airframe structures. Compared with conventional aluminium alloys, optimized use of composites can result in significant weight savings. Additionally, composites have many other important advantages, including improvement formability and immunity to corrosion and fatigue damage. From the joining viewpoint a very important advantage of composite construction is the ability to form large components, thus minimizing the number of joints required [10].

3 FAILURE ANALYSIS

In this chapter, the first component is to perform model of a failure analysis. The fundamental of methodology for prediction of laminate strength is the knowledge of stress state in each lamina. However, because of anisotropic and heterogeneous nature of composite materials, failure modes occur that require new analyses quite unlike those for isotropic homogenous materials. In particular, for a laminated composite, failure of one layer does not necessarily imply failure of the entire laminate; the laminate may, in fact be capable of sustaining higher loads despite a significant change in stiffness [11].

To analyze the strength of any laminated composite, strength theories are required. Failure analysis is a tool for predicting the strength of a laminated composite, containing several plies with different orientations, under complex loading conditions using strength data obtained from uniaxial tests of unidirectional plies and strength theories.

There are numerous failure criteria for composite materials as a direct result of the complex nature of observed failure phenomena. These criteria are only useful if they can be incorporated into a progressive damage analysis, which usually means that they must be compatible with a finite element formulation.

4 STRESS ANALYSIS

In this chapter, the second component of model information is given about the finite element formulation and Macro mechanical behavior of lamina and laminate, where the theoretical bases of the model are explained. The purpose of a joint is to transfer load between the two parts being joined. As a result of this load transfer there will be a stress variation in the components in the joint region. In most cases, an accurate understanding of the stress distributions in the joint is one of the critical ingredients. Although other methods of analysis may identify the origin and mode of failure, stress analysis most often provides a quantitative explanation for the cause of failure.

Stress analysis procedures for composite materials are complex issue. In order to utilize the full potential of the specific strength of composite materials, we must know accurate maximum stress and shear distributions.

5 EXPERIMENTAL DETAILS OF SINGLE PINNED HOLES IN COMPOSITES

Tests have been carried out on single pinned joints in multi-directional glass-fiber reinforced epoxy for a range of laminate configurations and specimen geometry. For single-hole joints the strengths have been obtained experimentally; the effects of variables such as ply orientation, laminate edge and side distances were discussed in the light of the results:

Problem Statement:

In this study, plate (length L, width W, thickness t) made of N fiber-reinforced unidirectional plies with a single circular hole filled with a rigid pin is used. The ply orientation of the laminate is symmetric. The geometry of composite plate is shown Fig 1, where a hole of diameter D is located along the centerline of the plate at a distance E from one end of the plate. A uniformed tensile load P is applied to the plate and the rigid pin, supported outside the laminate, resists this load. Load is parallel to the plate and is symmetric with respect to the centerline. Hence the load cannot create bending moments about the x, y, and z-axes.

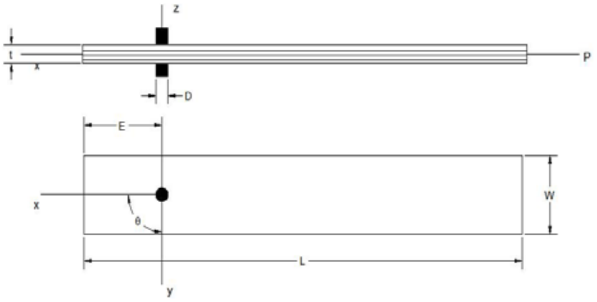

Fig. 1 Geometry of a composite plate

Material Selection and Laminate Manufacture:

The fiber-reinforced composite material used in this study was produced at V.R Siddhartha Engineering College at Vijayawada. Three different laminate configurations 0/±45; ±45 0/90 were fabricated anticipating that the significance of fiber orientation and interaction effects of mixed fiber orientations on the strength could be determined. Other reason of selecting these lay-ups was to observe variety of failure modes.

All laminates balanced about the mid-plane both to prevent thermal distortion during manufacture and to eliminate bending and twisting under tension. All laminates were made from E glass fiber and unsaturated polyester using hand-layup technique. For matrix material, accelerator (cobalt) and hardener (mkp) were mixed in the mass ratio of 3:2 the resin and hardener mix was applied to the fibers.

Fibers were coated with this mix. Subsequent plies were placed one upon another as required orientations. A hand roller was used to compact plies and remove entrapped air that could later lead to voids or layer separations. The mold and lay-up were covered with lease fabric. Once the matrix and fibers are combined, it is necessary to apply the proper temperature and pressure for specific periods of time in order to produce the fiber reinforced structure. For this purpose, resin-impregnated fibers were placed in the mold for curing. The press generates the temperature and pressure required for curing.

Specimen Preparation and Testing Procedures:

In designing a joint to satisfy strength requirements and to suppress undesirable failure modes, it is important to select proper parameters. It is recommended to design the joint such that it fails in a bearing mode because this failure is non-catastrophic. In contrast to bearing failure, the net-tension and the shear-out failure modes are catastrophic and should be avoided in design [12-14]. Thus it is desirable to optimize the bearing strength in the design process with respect to various geometric parameters, such as edge distance E, plate width W, hole diameter D. The hole diameter (D) was fixed at a constant value of 5 mm.

In this study, for each type of laminate the values of edge distance E, and specimen width W were varied to produce each of the three primary modes of failure. The ratio of width to diameter, W/D, was 2, 3, 4, and 5. The distance from the centre of the pin-loaded hole to the free end, E, was 1, 2, 3, 4, 5 times the hole diameter; that is, the edge distance to diameter E/D, ratio was 1, 2, 3, 4, and 5. The geometries and configurations of the specimens used in this study were summarized in below Table 1.

Table 1 The lay-ups and geometries of glass-fiber reinforced polyester samples tested

Layup	t (mm)	D (mm)	E/D	W/D
0/90/0/90	12	5	3,4,5,6	4,5,6
45/-45/45/-45	12	5	3,4,5,6	4,5,6
0/45/0/45	12	5	3,4,5,6	4,5,6

The test specimen consisted of a rectangular strip of laminate of constant thickness t, width W and length of approximately 150 mm, with the 0 ply fiber axis parallel to the length. Each end of the specimen was prepared with a single circular hole of diameter D= 5 mm, centrally placed with respect to the width and at a pre determined distance from the end. The tolerance on hole diameter was such that to allow a ‘precision run’ fit to be obtained between loading pin and hole.

For each of three ply orientations, 12 different geometries were used. The experiments were performed in tension mode on universal testing machine, equipped with a chart to record the load-extension behavior of the specimen. A double-lap, single-steel-pin joint was considered for experimental model. The end of specimen was placed in wedge grips. The steel pin was inserted into the hole of the specimen. The other end of the specimen passed through a specially manufactured fork fitting attached to the testing machine crosshead. The load was applied to the specimen by means of loading pin. The 0^0 fiber direction was aligned with the direction of the load.

6 EXPERIMENTAL RESULTS

In the following subsections, the experimental results for three different configurations (as shown in Table 1) of pin-loaded composite laminates are presented (Figs. 2-13). The general behavior of all the composites mentioned above was obtained from the load/displacement chart record from the testing machine. Because the appropriate value of joint strength depends upon the failure load, failure loads in deterministic sense were measured and presented as below.

0/90/0/90 LAMINATED PINNED JOINTS:

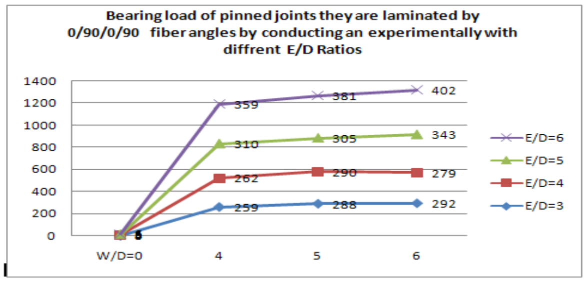

Fig. 2 The effect of edge distance to diameter ratio on bearing load (kg) at failure for [0/90/0/90] laminates

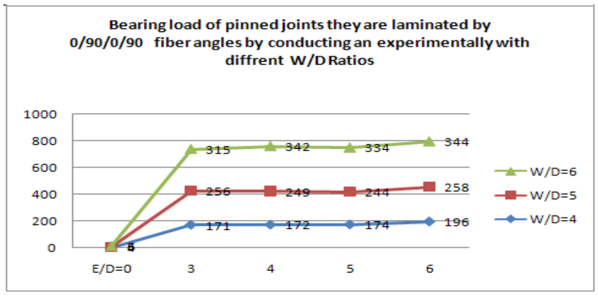

Fig. 3 The effect of width to diameter ratio on the bearing load (kg) at failure for [0/90/0/90] laminates

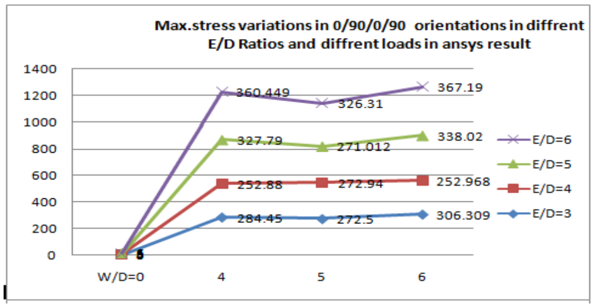

Fig. 4 The effect of width to diameter ratio on the Max stress (kg/mm^2) at failure for [0/90/0/90] laminates

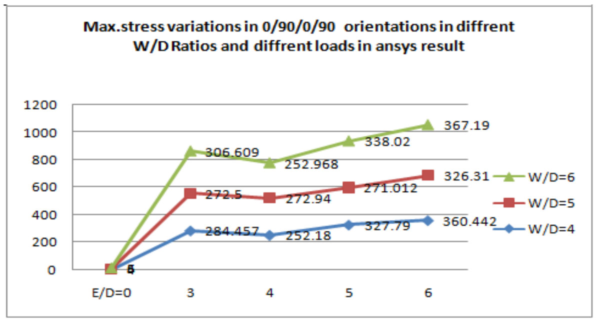

Fig. 5 The effect of edge distance to diameter ratio on the Max stress (kg/mm^2) for [0/90/0/90] laminates

45/-45/45/-45 LAMINATED PINNED JOINTS:

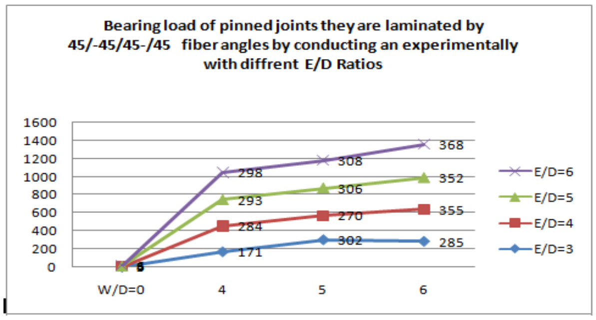

Fig. 6 The effect of edge distance to diameter ratio on bearing load (kg) at failure for [45/-45/45/-45] laminates

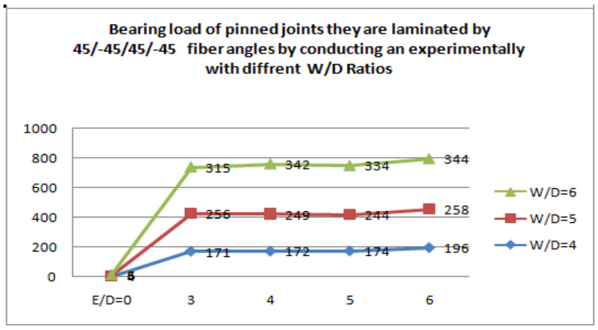

Fig. 7 The effect of width to diameter ratio on bearing load (kg) at failure for [45/-45/45/-45] laminates

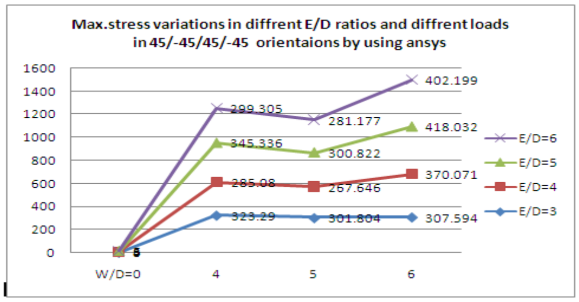

Fig. 8 The effect of edge distance to diameter ratio on maximum stress (kg/ mm^2) for [45/-45/45/-45] laminates

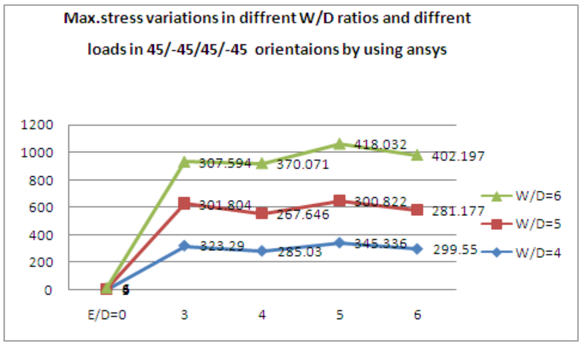

Fig. 9 The effect of width to diameter ratio on maximum stress (kg/ mm^2) for [45/-45/45/-45] laminates

0/45/0/45 LAMINATED PINNED JOINTS:

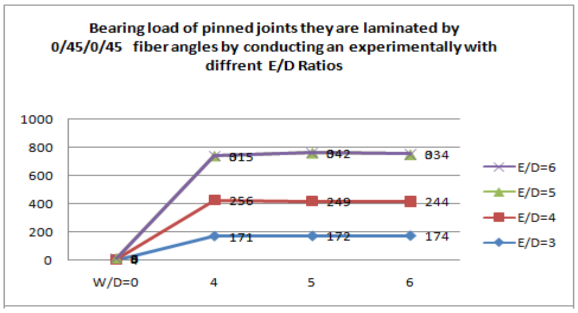

Fig. 10 The effect of edge distance to diameter ratio on bearing load (kg) at failure for [0/45/0/45] laminates

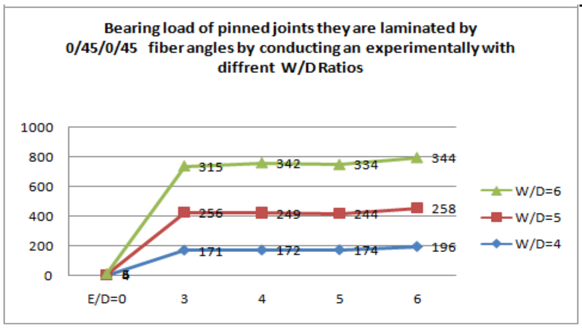

Fig. 11 The effect of width to diameter ratio bearing load (kg) at failure for [0/45/0/45] laminates

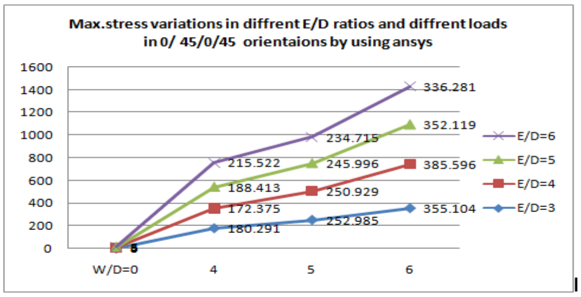

Fig. 12 The effect of edge distance to diameter ratio on maximum stress (kg/ mm^2) for [45/-45/45/-45] laminates

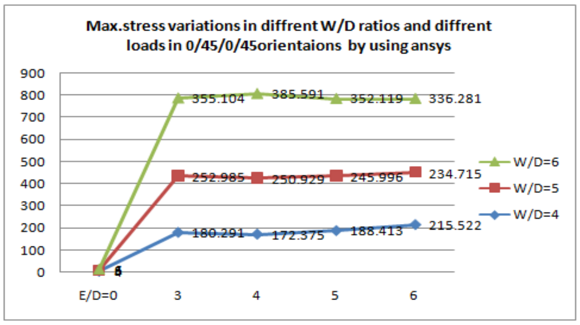

Fig. 13 The effect of width to diameter ratio on maximum stress (kg/ mm^2) for [0/45/0/45] laminates

Failure Analysis:

In this investigation, when laminated composite plates were loaded to final failure, two basic failure modes shear-out and bearing failure were observed for different geometric dimensions and ply lay-ups shown in the above figures. All the connections tested showed signs of bearing damage in the vicinity of the pin hole after failure, where damage occurred in the laminate area adjacent to the loaded half of the hole. A study of the failed specimens reveals that the fiber orientations have a definite influence on the position.

Stress Analysis:

As might be expected from knowledge of the in-plane shear strength of multidirectional laminates, the shear strength of single-hole joints has been shown to be strongly dependent on the ply orientations within the laminate and edge distance. The stress analysis was performed using ANSYS software where the results are shown in Figs 4, 5, 8, 9, 12, and 13.

Specimen Strength and Effect of Geometry:

The bearing strength of single-hole pinned joints has been shown to be dependent on two main variables; geometric dimensions and ply orientation. In general, discussion of the effect of E/D or W/D ratio on pin bearing strength has to be combined with a consideration of the related failure. The failure mode changes from the bearing to net-tension or shear-out with decreasing W/D and E/D ratios.

Changing in this mode is associated with a considerable drop in load-carrying capacity. The effect of changing width and end distance demonstrate clearly that both distances must be above a minimum value for the full bearing strength to be developed; these minima are seen to depend on lay-up. The “plateau” regions of the curves of bearing strengths versus E/D and W/D ratios correspond to bearing failure and the “knee” to the change in mode.

From the Figs. 2, 3, 6, 7, 10, and 11, it can be seen that increasing the end distance increased the bearing strength of the joint until a critical end distance was reached; any increase of the end distance over that value did not result in a corresponding increase in the strength of the joint. As may be seen, pin bearing strength decreases with decreasing W/D ratio. As the width of the specimen decreases, there is a point where the mode of failure changes from the bearing to net-tension, and the specimen fails across the width.

The effect of ply orientations on bearing strength is shown in Figs. 2, 3, 6, 7, 10, and 11. There is a little difference between the bearing strengths of [±45] and [0/90/] laminates, each achieving a mean value of about 318 MPa. There is a small reduction in the bearing strength realized in [90/0]2s laminates (mean strength of about 306.14 MPa), a further reduction for [0/45] laminates (mean value of 260 MPa).

7 CONCLUSIONS

This study is an attempt to further understand the failure characteristics of pinned joints where the prediction of both failure mode and ultimate load is the most important objective. Such a capability would allow synthesis rather than analysis to be used in the future design of fastener joints. In this study, the stresses, and failure modes of different composite laminates were investigated when the material exhibits linear and non-linear elastic behavior.

To investigate and verify to the analytical predictions of mechanical behavior, and to observe the failure characteristics and failure propagation of the pin-loaded composites, a series of experiments were performed under in-plane shear in static loading conditions. From the results presented on linear and non-linear two-dimensional modeling and tests of mechanically fastened joints, the following points of discussion are summarized

1. In glass fiber laminates, in different E/D ratios the carrying bearing load are increasing gradually. In the same way, maximum stress and shear stress are increasing gradually except for some geometry.
2. Ultimately observing three lay-ups and different E/D and W/D ratios, finally it is concluded that 0/90/0/90 layup is the best orientation in all dimensions.

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