FAILURE ANALYSIS OF DOUBLE PIN-LOADED HOLES IN GLASS FIBRE REINFORCED POLYMER COMPOSITE LAMINATES

Dissertation

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By

Paramdeep Singh
(Roll No. 801481015)

Under the Supervision of

Dr. Jaswinder. S. Saini
Assistant Professor
Department of Mechanical Engineering

Dr. Haripada Bhunia
Professor
Department of Chemical Engineering

Department of Mechanical Engineering
Thapar University
Patiala-147004, Punjab

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Declaration

This is to certify that dissertation entitled, "**Failure analysis of double pin-loaded holes in glass fibre reinforced polymer composite laminates**" submitted by me in partial fulfillment of the requirements for the award of Masters of Engineering Degree in CAD/CAM Engg. at Thapar University, Patiala is an authentic work carried out by me under the supervision and guidance of Dr. J.S. Saini, Assistant Professor, Department of Mechanical Engineering and Dr. Haripada Bhunia, Professor, Department of Chemical Engineering, Thapar University, Patiala.

Date: 15/07/2016

Paramdeep Singh

Roll No. 801481015

It is certified that the above statement made by the student is correct to the best of our knowledge and belief.

Dr. J. S. Saini 15/7/16
Assistant Professor
Department of Mechanical Engineering

Dr. Haripada Bhunia
Professor
Department of Chemical Engineering

Countersigned by:

Dr. S. K. Mohapatra
Head & Sr. Professor
Department of Mechanical Engineering

Dr. S. S. Bhatia
Dean, Academic Affairs
Thapar University, Patiala

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Paramdeep Singh

Paramdeep Singh

Abstract

The effect of geometric parameters on the bearing strength for double pin joints prepared from glass fibre reinforced polymer composites was studied experimentally and numerically. The types of configurations *i.e.* serial and parallel, were studied in the present work. In case of serial pin joint laminates, the parameters varied were the distance from the free edge of the specimen to the diameter of the nearest hole (E/D) ratio, width of the specimen to the diameter of the hole (W/D) ratio, and the distance between the two holes to the diameter of the hole (P/D) ratio. The parameters varied in case of parallel pin joint laminates were the distance from the transverse free edge of the specimen to the diameter of the hole (E/D) ratio, the distance from the longitudinal free edge of the specimen to the diameter of the nearer hole (K/D) ratio, and the distance between the two holes to the hole diameter (P/D) ratio. Taguchi method has been applied to reduce the experimentation time and cost. The results were validated numerically using progressive damage method and the characteristic curve method. Tsai – Wu failure criteria was used along with the numerical method for the failure prediction.

The results suggested that the serial pin joint laminate with the configuration of E/D= 4, W/D= 4 and P/D= 5 and the parallel pin joint laminates with the configuration of E/D= 4, W/D= 3 and P/D= 5 have given the best bearing strength. The ANOVA technique has suggested that E/D ratio is the most significant factor for the bearing strength of the double pin joints.

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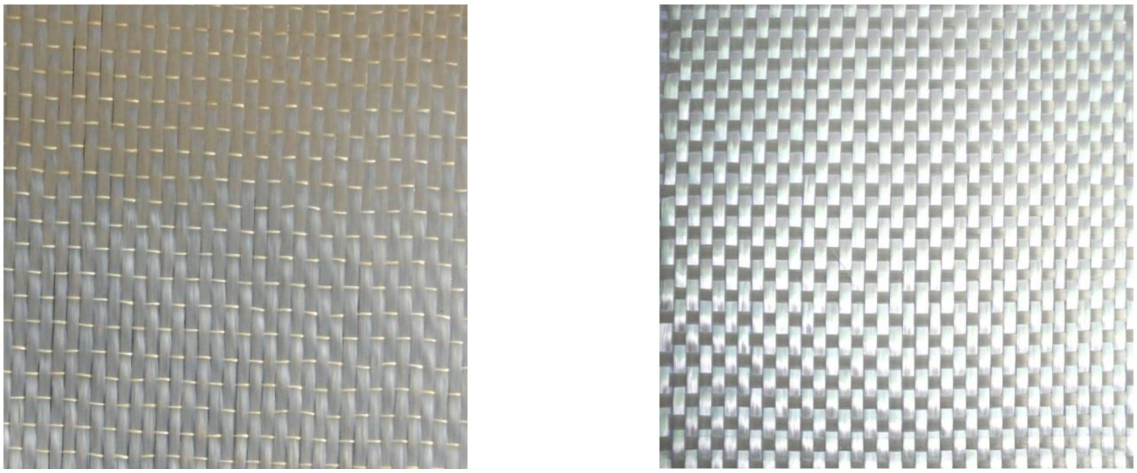
Chapter 1 Introduction

The present era is in high demand of materials with high strength to weight ratio for their requirement in automobiles, aircrafts, buildings, bridges etc. to increase their strength without much increase in their weight. Exhaustive research is being carried out worldwide for finding out such new materials. Till now conventional metals and their alloys were the principal materials used in the industry for this purpose due to their high strength, low cost, ease of moulding and other treatment processes to play with their strength. But these materials have certain drawbacks, though not serious ones as compared to their services. Major drawbacks are low strength to weight ratio and less resistance to corrosion. But this extensive research has led to discovery of a new set of non- conventional materials, which have solved the major drawbacks of conventional materials. Fibres are leading in this set which have very high strength as compared to their weight and are corrosion resistant, with high cost being a compromise. But when these fibres are reinforced with certain polymers, the material formed shows fabulous improvement in its mechanical properties. The further improvement in its properties is observed when a small percentage of nano-fillers is added to it and such compounds formed are called fibre reinforced polymer nano-composites.

1.1 Polymer Composites

Composites are obtained by combining two or more materials with each material having its own distinct chemical, physical and mechanical properties, but finally providing us with more strength than each of the constituent material individually. These constituent materials can be categorized as matrix and reinforcement, where matrix is the continuous phase, and the reinforcement is the distributed phase. Reinforcement can be particulate or fibrous. Fibres can be continuous or discontinuous, which can be distinguished on the basis of their aspect ratio, with continuous fibres having much longer aspect ratio as compared to the discontinuous fibres. Continuous fibres have more volume as compared to matrix whereas discontinuous fibres have lesser volume as compared to the reinforcement. Continuous reinforcements can be further classified on the basis of their orientation as unidirectional, woven and roving. Fig. 1.1 shows the types of reinforcements that can be used in the composite materials.

Commonly used fibres are carbon and glass fibres. Matrix can be a metal, ceramic or polymer. The matrix serves its purpose by acting as a medium of stress transfer among the reinforcement and by keeping the fibres oriented [1].



(a) Unidirectional fibre (b) Woven fibre

Figure 1.1: Types of continuous fibre reinforcements

Polymer composites are those materials in which the reinforcement is the fibre and the matrix phase is the polymer. Polymer matrix can be a thermoset or a thermoplastic. The composites mostly are anisotropic in nature as they have different properties in different directions. Considering the case of unidirectional fibre reinforced composites, they would have higher value of Young's Modulus along the direction of fibres, and lesser value in the other two normal directions. Such materials which have different magnitude of the properties in the principal directions are said to be orthotropic materials, which is a sub category of anisotropic materials.

1.2 Joints in composites

The composites find a wide range of applications in fields such as automotive, civil, marine etc. These composites need to be joined with each other components, metals etc. Otherwise also, to get ease in transportation of material, it is always comfortable to manufacture various parts which can be joined together as per requirement.

These can be joined either by adhesively bonded joints or by mechanically fastened joints. Mechanical fastening of joints can be done by use of pins, rivets or bolts. In adhesively bonded joints, the load is transferred through the surfaces in contact under adhesive bonding, whereas, in the mechanically fastened joints, the load is transferred through the fasteners used in the joints. In most of the cases, the mechanical joints are preferred to adhesive joints due to reasons such as ease of assembling and disassembling, ease of manufacturing, high load bearing capacity and high reliability. The holes are to be drilled in the composite for mechanical joints. These holes weaken the composite which can lead to the failure of the joint. So, it is very important to study the stresses caused due to the joints in the design of the structure, to make it safe and efficient.

1.3 Design of mechanically fastened joints

In the present work, the focus is on the behaviour of laminates after the application of load through the fasteners. To make the analyses simple, pins are used as fasteners in the present work. A large number of applications require single pin joints as the fasteners. The study of failure modes and their causes is important in order to make the pin- joint efficient. The design of the plates with the single pin and the plates with double pin are discussed below on the basis of the strength criteria.

- **Plates with single pin joints**

The plates with single pin joints are subjected to failure by any of the modes discussed below.

1. Net tension mode of failure

This type of failure occurs, when the laminate tears off along the line perpendicular to the direction of application of load. Such type of failure occurs when the width to hole - diameter ratio of the specimen is less. The plate with the net tension mode of failure is shown in Fig. 1.2.

Figure 1.2: Net tension mode of failure in plate with single pin-joint

If w is the width of the plate, d is the diameter of the hole, t is the thickness of the plate, P_t is the failure load of the member, then the net tension strength (σ_t) of the plate can be calculated by using Eqn. (1.1).

$$P_t = (w - d) \times t \times \sigma_t \quad (1.1)$$

2. **Shear out mode of failure**

This mode of failure is quite common in the laminates with smaller edge to hole - diameter ratio. The hole widens in the direction of application of load and the area ahead of the hole moves out, as the load increases. The plate with the shear out mode of failure is shown in Fig. 1.3.

Figure 1.3: Shear out mode of failure in plate with single pin-joint

The shearing strength of the plate (τ_s) can be given by Eqn. (1.2)

$$P_s = 2 \times \tau_s \times E \times t \quad (1.2)$$

Where E is the distance between the hole and the transverse edge and P_s is the failure load of the plate. Multiplication factor of 2 is used in the equation, as double shear takes place.

3. **Bearing mode of failure**

The bearing mode of failure occurs when the plate fails to bear the crushing force offered by the pin. As a result the hole widens in the direction of application of the load. This mode is the most desired form of failure because of its non- catastrophic nature. If the laminate has sufficient edge distance and width, it will tend to fail only by bearing mode. The bearing strength (σ_b) of the plate is given by Eqn. (1.3).

$$P_b = d \times t \times \sigma_b \quad (1.3)$$

Where P_b is the failure load, d is the diameter of the hole and t is the thickness of laminate. The plate with the bearing mode of failure is shown in Fig. 1.4.

Figure 1.4: Bearing mode of failure in plate with single pin-joint

But there are numerous applications which require a greater load to be carried by using the plate of same dimensions. If the single pin joint laminate is replaced by the double pin joint laminate, the load carried by the laminate also increases significantly. So, the present work focuses on the laminates with the double pin joints. The double pin joint laminates also fail by the same failure modes, but the load carried before the failure is more than that in case of single pin joint laminates.

A double pin joint may fail due to the following modes:

1. The plate may tear off along the line of pin holes and this mode is generally referred to as failure due to net tension.
2. The plate may fail due to shear out between the hole and the edge along the line perpendicular to the edge.
3. The plate may not be able to resist the bearing pressure between the pin and the hole and the failure occurred is said to be bearing failure.

There is possibility of the failure of laminate due to any of these modes, depending on, in which mode the respective stress first approaches the ultimate stress of the laminate. In this case, the strength of plate is determined and the joints are designed according to the pre-determined strength of the plate. The design of the joints is discussed below considering each possible mode of failure.

1. Net tension mode of failure

As can be seen from the Fig. 1.5, it is clear that the split occurs along the line perpendicular to the longitudinal edges. It generally occurs, when the distance between the hole and the longitudinal edge is very small.

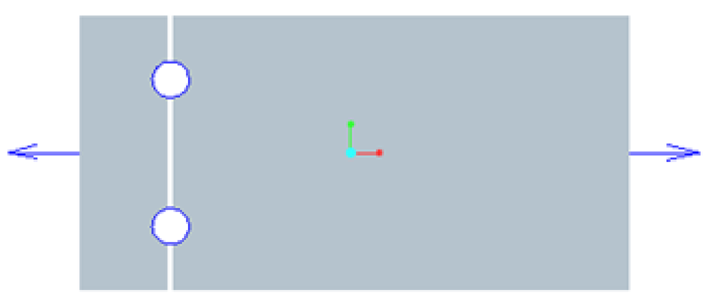


Figure 1.5: Net tension mode of failure in plate with double pin joint

If w is the width of the plate, d is the diameter of the holes, t is the thickness of the plate, P_t is the failure load of the member, then the net tension strength (σ_t) of the plate can be calculated using Eqn. (1.4).

P_t = (w – 2.d) × t × σ_t (1.4)

2. Shear out failure

Such failure occurs when the split occurs along the line travelling from the hole towards the transverse edge. In such cases the material ahead of the hole moves out with the increase of the load. The plate with the shear out mode of failure is shown in Fig. 1.6.

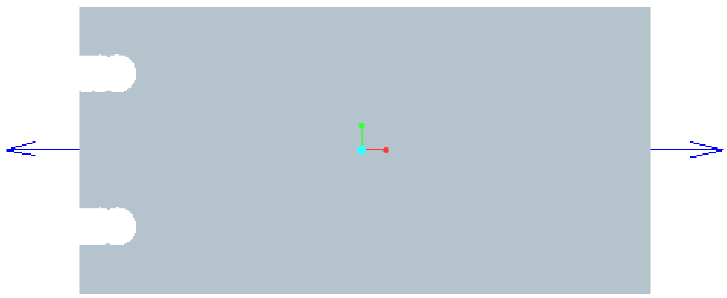


Figure 1.6: Shear out mode of failure in plate with double pin joint

The shearing strength of the plate (τ_s) can be given by Eqn. (1.5)

P_s = 2 × τ_s × 2 × E × t (1.5)

Where E is the distance between the hole and the transverse edge and P_s is the failure load of the plate.

3. Bearing mode of failure

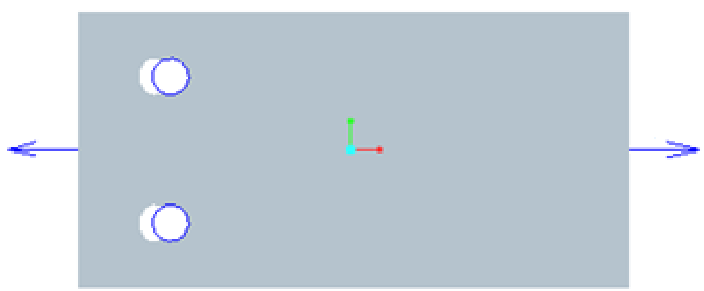


Figure 1.7: Bearing mode of failure in plate with double pin joint

Such type of failure occurs when the plate fails to resist the crushing force exerted by the pin. In such failures the hole widens in the direction of the force applied. Bearing strength (σ_b) of the plate with two holes is given by Eqn. (1.6).

$$P_b = 2 \times d \times t \times \sigma_b \qquad (1.6)$$

where P_b is the failure load of the plate, 2 is the number of holes, d is the diameter of the hole and t is the thickness of the plate. The plate with the bearing mode of failure is shown in the Fig.1.7.

It is worthy to note that the bearing failure is the most desired form of failure, as it generally depicts the highest strength of the joint. Bearing failure is a non-catastrophic form of failure, whereas net tension and a shear out are a catastrophic form of failure. Shear out failure is considered as a type of bearing failure, the difference being that, the region of the part ahead of the hole also moves out as the load increases.

1.4 Factors affecting the strength of the plate-

In general, the following factors affect the strength of the plate, that need to be considered during the safe design of the plate with the holes, held with the mechanical fasteners.

1. Material used in the plate will decide its strength. For the fibre reinforced polymer composites, type of fibre used, type of resin employed will affect the strength of the laminate.
2. The geometric parameters like pitch of the holes, edge to hole distance, width of the plate etc. will also affect the strength
3. Type of fastener used such as rivets, nut-bolt or pins will also decide the strength of the plate.
4. Some miscellaneous factors like environmental conditions, type of loading and direction of loading will also play a significant role in deciding its strength.

Chapter 2 Literature Review

In the recent era, where the engineering has reached at a very advanced stage, the need of new set of materials with high strength to weight ratio has become one of the major needs in the engineering fields. For this purpose, the fibre reinforced polymer composites have become one of the favourite choices of the researches. But practically, their application would require mechanically fastening these composites with each other or with other metals during their application. So this would require the use of one of the mechanical fastening techniques. In the present work, pins have been used as mechanical fasteners, due to their advantages of making the experimental and numerical analysis simple. However use of the mechanical fasteners lead to arise of one major problem *i.e.* stress concentration around the holes, thus leading to reduced load carrying capacity of the plate. Though this complicated stress distribution around the holes is dependent on several parameters such as material properties, laminate lay-up, ply orientation and geometric parameters, here the study is confined only to the effect of geometric parameters on the behavior of pin joints. The following section gives a brief review of the literature on mechanical joints.

2.1 Literature Review

Okutan [2] made a numerical and experimental analysis to determine the fibre reinforced polymer composites having pin loaded joints for their failure. Single pin jointed laminates were prepared for two different orientations of glass fibre *i.e.*, $[0°/90°/0°]_s$ and $[90°/0°/90°]_s$. The geometric parameters were also varied for the laminates which included E/D ratio and W/D ratio. The specimens were tested for their bearing strength by applying the tensile load on the laminates, parallel to the 0° direction of the fibre. The numerical analysis for the same configuration of FRP laminates was carried out by the progressive damage technique, using the Hashin failure criteria as the failure theory. Analysis was done by applying the incremental load in steps, where analysis was done at each step until the convergence was obtained. The results suggested that the bearing mode of failure for the $[0°/90°/0°]_s$ configuration was for E/D ratio greater than 3 and shear out for E/D less than 3. The bearing strengths in case of $[90°/0°/90°]_s$ was dependent on the W/D ratio. It was observed that the specimens showing the bearing mode of failure had the numerical results close to the experimental results.

Karakuzu *et al.* [3] conducted a study to experimentally and numerically determine the effect of variation of geometric parameters on the failure load, failure mode and bearing strength of the fibre reinforced polymer composite laminates having the serial pin joints. The reinforcement was the glass fibre and the matrix used was vinylester epoxy. The geometric parameters that were varied are: edge distance to hole diameter (E/D) ratio, plate width to hole diameter ratio (W/D), and the distance between the holes to hole diameter ratio (M/D). Firstly, the laminates were prepared with all the possible combinations of geometric parameters as E/D, W/D and M/D were varied from 2 to 5, 1 to 5 and 2 to 5 respectively, thus leading to preparation of 80 samples in all. These samples were subjected to tensile load in a 20 kN loading capacity tensile testing machine and this tensile load was resisted by the rigid pins thus arising out the stresses in the laminate. The load was applied to each sample until the pin displacement of 6 mm at a crosshead speed of 0.5 mm/min. Load vs. displacement graphs were obtained and were analyzed. The numerical study was performed in LUSAS finite element software. The failure criteria used was the Hashin failure criteria. Brick elements having 16 nodes were used. The element shape was hexahedral with quadratic interpolation order. Radial boundary conditions were used to simulate the pin. The results have suggested good agreement between the experimental and numerical results. It was clear from the observations that the failure load was highly dependent on the E/D ratio as it increased significantly with the increase in the E/D ratio. The minimum value of failure load was observed at E/D = 1 and maximum at E/D = 5. Net tension mode of failure was highly dependent on the W/D ratio. Lower the value of W/D ratio, higher the chances of the failure by net tension mode. Shear out failure mode did not occur at the inner hole in any case, but it occurred at the outer hole only for E/D=1.

Karakuzu *et al.* [4] investigated the woven glass/ vinyl ester composite plates with the double parallel pin joints for its failure load, failure mode and the bearing strengths. The position of the holes were varied for each plate by bringing the variation in the geometric parameters, namely edge distance to the hole diameter (E/D), distance between the hole to the hole diameter (M/D), and the distance from the longitudinal edge to the hole nearer to that edge (K/D). both experimental and the numerical analyses were performed on the specimens. The objective of the study was to study the effect of the variation of the geometric parameters E/D, M/D and K/D ratio on the failure load and the failure mode of the FRP laminates, whose values were varied from 1 to 5, 2 to 4 and 2 to 5 respectively. Experiments were conducted on 20 kN loading capacity with a crosshead speed of 0.5 mm/min where tensile load was applied to the plate until the displacement of the pin would occur by 10 mm. Numerical analysis was done on the LUCAS finite element software. Brick laminates with 16 nodes per element were used for analysis. 3D Hashin failure criteria was used as the failure theory. Radial boundary condition was used to simulate the pin. Shear out mode of failure was obtained for laminates with E/D =1. Bearing and net tension mode were observed for the laminates with M/D=2, K/D=2 and E/D>1. Bearing strength values were found to be highly dependent on E/D ratio.

Nanda *et al.* [5] conducted an experimental and a numerical study on glass fibre/epoxy composite laminates with three and four multi pin joints. The geometric parameters were varied in both types of laminates. In three pin joints, the variable geometric parameters were pitch distance to hole diameter ratio (P/D), width of specimen to hole diameter ratio (S/D), and distance between the edge and hole to hole diameter ratio (E/D). The glass fibre/epoxy laminates were prepared in an orientation of [45°, -45°, 0°]. Hole diameter was kept as 4 mm. E/D was varied as 2, 3, 4 and 5, S/D as 2, 2.5, 3.5, 4 and P/D as 3, 4, 5, 6. The numerical analyses with Tsai- Wu failure criteria were run on ANSYS software with the two dimensional model of specimen. Quadrilateral elements had been chosen for meshing. Radial boundary condition was employed to simulate the pin and the displacement boundary condition was given to simulate incremental loading. The results obtained from the numerical analyses were in good agreement with the results obtained from experiment. The results suggested that the damage had initially been caused due to bearing mode at smaller values of load, and this damage had expanded side-wards towards the edge. It was concluded that the factor having maximum influence on the failure load and failure mode was P/D ratio, but only up to P/D=6. Keeping P/D =6, the critical failure load was observed at E/D=3.

Aktas *et al.* [6] conducted an experimental and a numerical study on the fibre reinforced polymer composite plates with single and double parallel pin joint laminates. The results were analyzed in terms of failure loads and failure modes. The geometric parameters, namely the distance from the free edge of the plate to the diameter of the first hole (E/D) ratio and width of the specimen to the diameter of the hole (W/D) ratio were varied as 2, 3, 4 and 5. The mechanical properties of the prepared laminates were tested according to ASTM D953-D. The load was applied to the FRP plate which was resisted by the pin inserted in it. The experiments were performed with all the combination of geometric parameters. These results were verified numerically. The numerical analysis was done on the ANSYS software with Yamda Sun as failure criteria. Radial boundary conditions were used to simulate the pin. Characteristic curve method was used for failure analysis.

The experimental results were in good agreement with the numerical results. The maximum failure load for both single and double parallel pin joint laminates was found at E/D= 4 and W/D= 4. Bearing mode of failure was found to occur in the laminates with E/D ≥ 4 and W/D ≥ 4 and net tension occurs for the W/D = 2 and E/D = 4. Shear out occured at E/D= 2 and W/D=4.

Aktas [7] made an experimental as well as a numerical study to determine and compare the failure load and failure mode of single and two serial pin joint FRP laminates subject to tensile load. In the study of serial pin joint laminates, two geometric parameters are varied, namely, distance from free edge of the plate to the diameter of the first hole (E/D) ratio, and the width of the specimen to the diameter of the holes (W/D) ratio. Mechanical properties of the laminates were determined using ASTM D 953. E/D ratio was varied as 2,3,4 and 5 keeping W/D as 4, whereas W/D was varied as 2,3,4 and 5 keeping E/D ratio as 4. The specimen was subjected to tensile load with step by step increment at a speed of 1.5 mm/min until rupture with a 50 kN loading capacity UTM machine. Numerical study was performed in ANSYS software. Yamda-Sun failure criteria was used as a failure criteria. To obtain the failure mode, characteristic curve method was used. The characteristic curve was defined by Eqn. (2.1)

$$R_c(\theta) = D/2 + R_{OT} + (R_{OC} - R_{OT}) \cos \theta \tag{2.1}$$

Where D is the diameter of the hole, R_{OT} is the characteristic length for tension, R_{OC} is the characteristic length for compression, and θ is the failure angle. The results of the experiment and the numerical analysis found that the maximum failure load occured at the E/D=4 and W/D =4. Moreover maximum failure load was observed at the hole at the farther end from the edge and the failure initiation started at the same hole itself. Failure mode was observed as bearing mode at all cases except for W/D=2 and E/D= 2.

Feo *et al.* [8] conducted a numerical analysis on the fibre reinforced polymer composite plates having the bolted joints, with the number of bolts varying in the rows as well as in the columns, to investigate the stress distribution around the holes. The results obtained from the numerical analysis were verified using the experimental results.

The numerical analysis was performed in a commercial software Strauss 7. Brick elements were used to model the joints. Contact between the plate and the bolt were defined using the point contact elements. Double overlap joints were considered for the analysis. The prepared models were subjected to the tensile loading such that the load was applied to exterior plates keeping the internal plate fixed. The results were measured in terms of shear stress distribution. The results led to the conclusion that the load distribution among the bolts was unequal due to various factors like varying bolt position, bolt torque, bolt hole clearance etc. Moreover, it was concluded that the joints with the number of rows of bolts and number of bolts in each row must not be greater than four.

Pisano *et al.* [9] conducted a numerical study on the fibre reinforced polymer composites with pin joints. A total of 130 laminates were analyzed with three different configurations *i.e.*, three pin joints, two pin joints with serial configuration, and two pin joints with parallel configuration. The pin joints in case of serial and parallel arrangements were further varied in their configuration by varying their geometric parameters. These variable geometric parameters in case of serial arrangement were ratio of the width of the specimen to the hole diameter (W/D) ratio, distance between the first and the second hole to the diameter of the hole ratio (M/D) and distance from the longitudinal edge and the hole to the hole diameter ratio (E/D). Similarly in case of parallel pin joint laminates, the geometric parameters that were varied are the distance between the transverse edge and the holes to the hole diameter ratio (E/D), distance between the holes to the hole diameter ratio (G/D), and the distance between the longitudinal edge and the nearest hole to the hole diameter ratio (K/D). The numerical analysis was conducted by using \ Linear Matching Method (LMM) and Elastic Compensation Method (ECM). The limit analysis numerical procedures were used to find the upper bound and the lower bound to real peak load values obtained from the experiment conducted on these FRP laminates. The failure theory used was the Tsai-Wu failure criteria. These limit analysis procedures were run in the Fortran main program. Isoparametric shell elements with 16 nodes per element were used. Contact type boundary condition was given to simulate the pin. Tensile load was applied to the plates, which was resisted by the pin.

Pisano *et al.* [10] conducted a numerical study to verify the failure modes in woven glass fibre/epoxy laminates with multi-bolted joints, whose results were obtained in an experimental study conducted by Karakuzu *et al.* [3, 4] The Linear Matching Method (LMM) was used in order to conduct the FEM analysis. The program was written in Fortran. A finer mesh was employed at the region around the hole. The LMM technique was used to obtain the upper bound to the real peak load value obtained in the experiment. The different configurations used to prepare the bolted joints in the laminates were those with three bolted joints, laminates with double serial bolted joints and with double serial parallel joints. The geometric parameters were varied in case of the serial and parallel bolted joints thus leading to preparation of 130 specimens in all. 45 specimens with the three bolted joints were tested with E/D varying from 1 to 5, G/D from 3 to 5, and F/D being varied as 2, 4 and 6. Similarly, the FRP laminates with serial pin joints were tested by varying the geometric parameters namely, W/D, M/D and E/D and the FRP laminates with the parallel bolted joints were tested by varying the geometers namely, K/D, M/D and E/D. The analyses were successful in their ability to recognize each type of failure. The numerical results were in good agreement with the experimental results.

Zhang *et al.* [11] conducted a numerical study to perform the progressive damage analysis based characteristic length method on the multi bolted composite joints to detect their failure load and failure modes. The specimens prepared had the carbon fibre as reinforcement in the epoxy and were prepared with double and four bolted joints. The progressive damage analysis was done to know the characteristic lengths whose values were also obtained experimentally. Analyses were conducted using two different failure criteria which included Hashin failure criteria and Yamda Sun failure criteria. ABAQUS software was used for analysis. The characteristic pints were obtained on the basis of the failure index obtained from the concerned failure theory. The characteristic lengths obtained numerically with different failure criteria were closer to the values obtained from PDA. Failure modes were recognized by observing that whether the failure index of tensile characteristic point or the failure index of compressive characteristic point reaches unity.

Arun *et al.* [12] made a study to determine the failure load and failure mode of fibre reinforced polymer laminates with the filler material as well as without the filler material. TiO_2 and ZnS were used as filler materials, whose volume percentage was varied as 1%, 2% and 3%. Moreover the laminates had different number of bolts which varied as 2, 3 and 4 in each case *i.e.*, laminates with the filler material and laminates without the filler material. The results had suggested that the FRP laminates with 2 bolt configuration had failed due to the bearing mechanism, because crushing was noticed in the hole region in the direction of the applied load. The laminates with 3 bolt configuration had been found to fail due to the combined effect of the bearing and net tension, as the 2 bolts in the front had failed due to net tension but the third hole behind them had failed by the bearing mode. It was further observed that the laminate with the 4 bolt configuration had failed due to the cleavage failure, which is considered as a cause of the bearing failure. Further it was noticed that on addition of nano-filler to the epoxy resin, the laminates with all type of bolt configuration had shown significant increase in the failure load values, but only upto 2% of total volume. With further increase in the volume percentage of this filler, the strength was found to decrease

Nerilli *et al.* [13] conducted a study to model the progressive damage of fibre reinforced composite plates with single and double bolted joints, with two different stacking sequences of $[0°]_{4s}$ and $[90°]_{4s}$. Three different types of laminates based on glass fibre, basalt fibre, and carbon fibre were analyzed with single and double pin holes in each case. These fibres were reinforced into epoxy resin. Pin holes were replicated as bolted joints for numerical study. Numerical analysis of these laminates was conducted using the progressive damage model using the displacement incremental approach. Failure theory used was the biaxial strength criteria proposed by Huang. The degradation rule was based on the reduction of elastic stiffness by some factor as per the model, on occurrence of damage of fibre/matrix. The results were measured in terms of failure loads in each case, whose values were compared to each other. The failure load values of double bolted joints were greater than that in case of single bolted joints. Moreover it was analyzed that right pin in case of double bolted joint plate carries more load as compared to the left pin. It was about 65% of total load in case of GFRP and BFRP and about 75% in case of CFRP. While observing the failure modes, it was noticed that the laminates with a stacking sequence of $[0°]_{4s}$, failed due to bearing mechanism, with maximum damage on the right pin, whereas the laminates with the stacking sequence of $[90°]_{4s}$ failed due to combined effect of net tension and bearing.

Singh *et al.* [14, 15, 16] conducted experimental studies to analyze the effect of ply orientation on and the filler content on the failure load and failure mode of the glass fibre reinforced polymer nanocomposite with single pin hole. The geometric parameters of the laminates, namely E/D ratio and W/D ratio have been varied where E/D is the distance between the edge and the hole to the hole diameter ratio and W/D ratio is the width to the hole diameter ratio. The nanofillers used were Cloisite 30 B and TiO_2. The nanofiller content was varied from 0% to 5% by weight in each case. The orientation of glass fibre sheets considered for comparison were [0°/45°/0°], [0°/90°/0°] and [0°/45°/90°].

2.2 Conclusion from literature review

Effect of geometric parameters namely distance between transverse edge and its nearest hole to hole diameter ratio, distance between longitudinal edge to its nearest hole to hole diameter ratio, width of laminate to hole diameter ratio and distance between holes to hole diameter ratio is studied. Three modes of failure are observed that are responsible for the failure *i.e.* net tension, shear out and bearing mode of failure.

In order to reduce the number of specimens and the experimentation cost, Taguchi method can be applied. It will reduce the specimen count on the basis of availability of factor- level combination to construct the orthogonal array.

The effect of geometric parameters on the failure mode and failure load of fibre reinforced polymer composite laminates with double pin joint will be studied. Both serial and parallel configurations of pin joints in the laminates will be analyzed. For this purpose the numerical analyses will be done with the characteristic curve method besides using the progressive damage model, which has already given satisfactory results for the single pin joint laminates.

Chapter 3 Experimentation

3.1 Materials used

The materials used in the experimentation are described below along with their properties.

- ***Resin***

The resin was prepared by mixing the epoxy, hardener and accelerator in the proper ratio.

a) Epoxy: The epoxy was Lapox L12, whose chemical name is Di glycidyl ether of Bisphenol-A.

b) Hardener: The hardener used was K12.

c) Accelerator: The accelerator used was K13.

Epoxy, hardener as well as accelerator were supplied by Atul Ltd., Gujarat, India. Table 3.1, 3.2 and 3.3 shows the physical, processing and mechanical properties of resin respectively.

Table 3.1: Physical properties of resin

Description	Density (g/cm^3)	Viscosity (mPa.s)
Epoxy(L-12)	1.1-1.2	9000-12000
Hardener(K-12)	1.15-1.25	150-230
Accelerator(K-13)	0.88-0.92	<10

Table 3.2: Processing properties of resin

Property	Resin: Hardener: Accelerator	Initial Mix Viscosity	Minimum Curing Schedule
Condition	-	@40^{0}C	-
Unit	w/w	cP	Hours
value	100:100:0.1-2	450	120^{0}C/2h 160^{0}C/(1/2)h

Table 3.3: Mechanical properties of resin

Description	Specific Gravity	Tensile Strength (N/mm^2)	Elastic Modulus in Tension (N/mm^2)	Compressive Strength (N/mm^2)	Co-efficient of Liner Thermal ($^oK^{-1}$)	Thermal Conductivity (W/m^ok)
L-12(100) + K-12(100) + K-13	1.80-1.85	70-90	15000-16000	190-210	28-32 x 10^{-6}	0.25

- ***Glass fibre***

The glass fibre as a reinforcement was unidirectional 'Advantex' glass fibre, whose supplier was Owens Corning India Pvt. Ltd, Mumbai. The mechanical and physical properties of the glass fibre are shown in the Table 3.4 and 3.5 respectively.

Table 3.4: Mechanical properties of glass fibre

Description	Tensile strength (N/mm^2)	Tensile modulus in tension (GPa)	Elongation at breaking load (%)
Glass fabric	3100-3800	80-81	4.6

Table 3.5: Physical properties of glass fibre

Description	Fiber type	Density(g/cm^3)	Area density (gsm)	Refractive index
Glass fabric	Advantex	2.62	1200	1.560-1.562

3.2 Preparation of laminates

To prepare a single laminate, 60 gm of resin was weighed in the beaker and the hardener was added to the beaker keeping the ratio of resin to hardener as 1:1 by weight. 2.5 gm of accelerator was added into the resin and hardener mixture. The mixture was then stirred thoroughly with the help of the glass rod. Now taking a Teflon sheet of size slightly larger than the size of the glass fibre sheet, the epoxy resin was applied to the Teflon sheet with the help of brush. A sheet of glass fibre was kept on the Teflon sheet at 0° orientation and the epoxy resin was applied to it. Then the glass fibre sheet was placed on the first sheet at 90° orientation and epoxy resin was applied to it followed by placing the third sheet of glass fibre above the second sheet at an orientation of 0°, with the application of epoxy resin on the third fibre sheet too.

These laminates were left to cure at room temperate for minimum 24 hours. Then they were subjected to compression in a hydraulic press at a maximum temperature of 180°C and under a constant load of 120 kN for 2 hours. These laminates were then cut with the help of diamond cutter as per the required dimensions.

3.3 Mechanical properties of the laminate

The laminates prepared both with and without clay were tested for their mechanical properties. The tensile and compressive testing was done according to the ASTM D3039 [17], while the shear testing was done according to ASTM D5379 [18]. The properties determined from the concerned tests are given in Table 3.6 while their values are given in Table 3.7.

- **Tensile and compressive test**

The standard referred to for tensile and compressive testing was ASTM D3039. According to this standard, a prismatic thin flat strip of the concerned material is required to be prepared according to the dimensions mentioned in the standard. This strip is then required to be loaded in the testing machine and then subjected to the tensile or compressive force as required.

Both longitudinal and transverse tests for tension and compression were conducted according to the ASTM D3039 standard. The tests were performed on Zwick- Roell Universal Testing Machine- Model Z010, Zwick- Roell, Germany. A cross head speed of 2mm/min was fixed. In the longitudinal test, the load was applied in the direction parallel to the direction of fibre alignment whereas in the transverse tensile test, the load was applied in the direction perpendicular to the direction of fibre alignment. Tests were performed on three specimens and the average of three tests was considered. The schematic diagram of tensile and compressive testing to obtain the longitudinal properties are shown in Fig. 3.1 and Fig. 3.2 respectively.

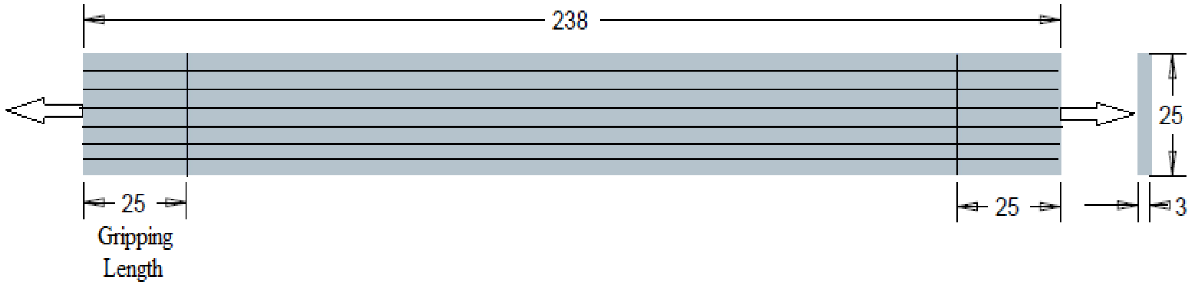


Figure 3.1: Specimen for tensile testing to obtain longitudinal properties

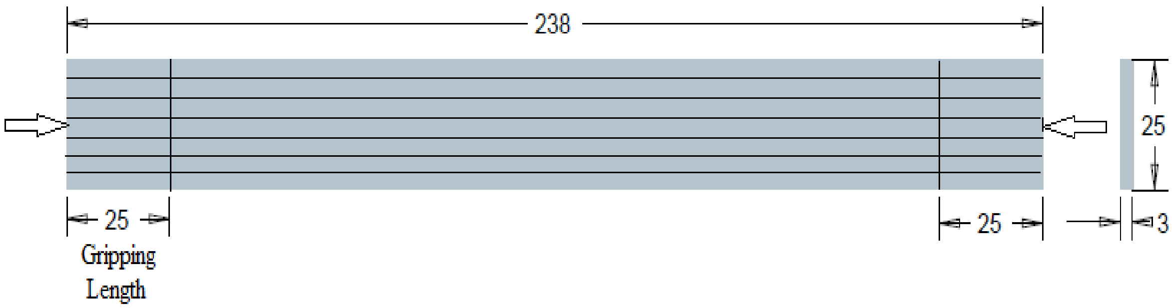


Figure 3.2: Specimen for compressive testing to obtain the longitudinal properties

- **Shear test**

The shear test was performed following the guidelines given by ASTM D5379. According to this standard, it was required to prepare the flat rectangular strip having the V- notches that are located symmetrically at the center of the specimen. The schematic diagram of the shear test specimen is shown in the Fig. 3.3.

The shear tests were performed on a Zwick Roell Universal Testing Machine- Model Z010, Zwick Roell, Germany. The sample was loaded in the machine in such a way that it was aligned in the axial direction of shear loading. The strain gauges were attached along two axes in the middle of the sample between the top and bottom V- notches in order to measure the strain. A cross head speed of 2 mm was maintained. Three specimens were tested and the average result of the three specimens was considered.

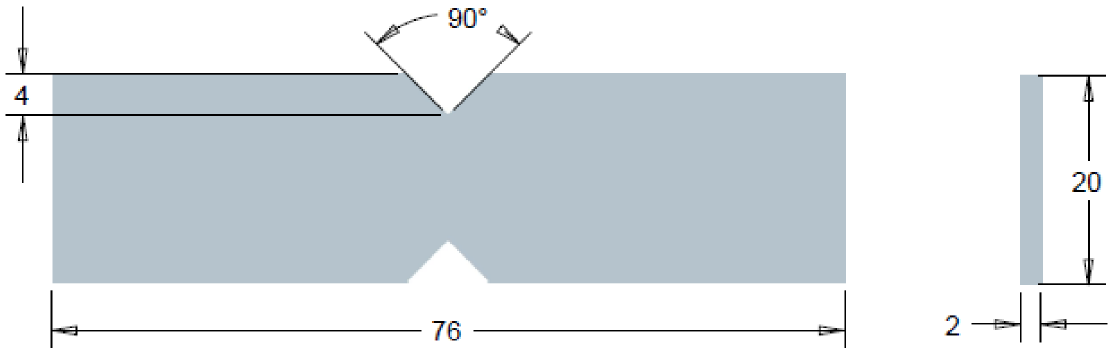


Figure 3.3: Specimen prepared for the shear test

Table 3.6: Properties determined from the respective tests

Test conducted	**Properties determined**
Tensile test in longitudinal direction	Longitudinal strength in tension (X_t), Longitudinal tensile modulus (E_1), Poisson ratio (ν_{12})
Tensile test in transverse direction	Transverse strength in tension (Y_t), Transverse tensile modulus (E_2)
Compressive test in longitudinal direction	Longitudinal strength in compression (X_c),
Compressive test in transverse direction	Transverse strength in compression (Y_c)
Shear test	Laminate shear strength (S)

Table 3.7: Mechanical properties of FRP laminates

Mechanical Property	**Symbol (Units)**	**Magnitude**
Longitudinal Modulus	E_1 (MPa)	12809.23
Transverse Modulus	E_2 (MPa)	7802.23
Laminate Shear Strength	S (MPa)	155.68
Longitudinal Strength in Tension	X_t (MPa)	390.76
Transverse Strength in Tension	Y_t (MPa)	255.98

Poisson Ratio	ν_{12}	0.32
Longitudinal Strength in Compression	X_c (MPa)	324.11
Transverse Strength in Compression	Y_c (MPa)	224.45

3.4 Application of Taguchi method

- ***Need of Taguchi method***

In the present study, the laminates of glass fibre reinforced polymer nanocomposites are prepared with double holes. The configuration *i.e.* serial and parallel were selected for the present study. These two configurations are shown in Fig. 3.4 and Fig. 3.5 respectively. The geometric parameters were varied in both the configurations resulting into need of preparation of large number of specimens for the testing. Geometric parameters that were varied in case of serial hole configuration are E/D, W/D and P/D ratio, where E is the distance between the free edge of the specimen and the first hole, W is the width of the specimen, P is the distance between the two holes and D is the diameter of the holes. In case of parallel hole configuration the geometric parameters varied were E/D, P/D and K/D ratio, where E is the distance between the free edge and the holes, P is the distance between the holes and K is the distance between the side edge and the hole nearer to it. All the geometric parameters in case of serial hole configuration were varied from 2 to 5, whereas in case of parallel hole configuration the geometric parameters E/D and P/D were varied from 2 to 5 and K/D was varied from 1 to 4. In both the configurations, there were three independent parameters with four different combinations. So, the total number of factors in each case is three with four levels of each factor. Hence the number of specimens required to be prepared according to the full factorial design for each case would be 4^3 *i.e.* 64. So it would require a total of 128 samples for both the cases. Making too many specimens would utilize large amount of material which already has high cost and would require ample time. So, to reduce the number of samples, Taguchi method was implemented in the present work.

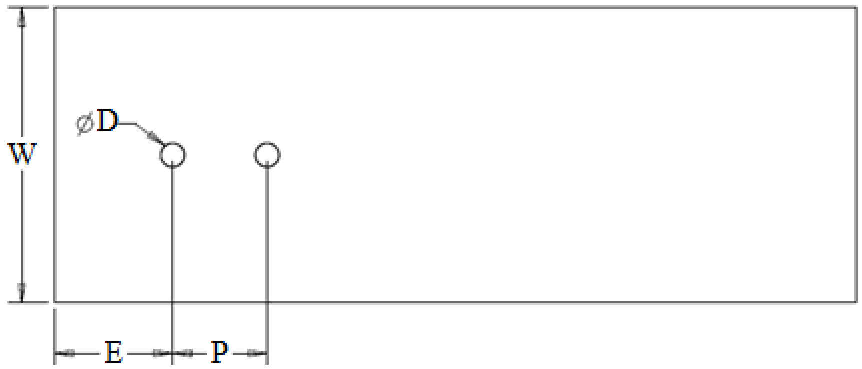


Figure 3.4: Laminate with holes in serial

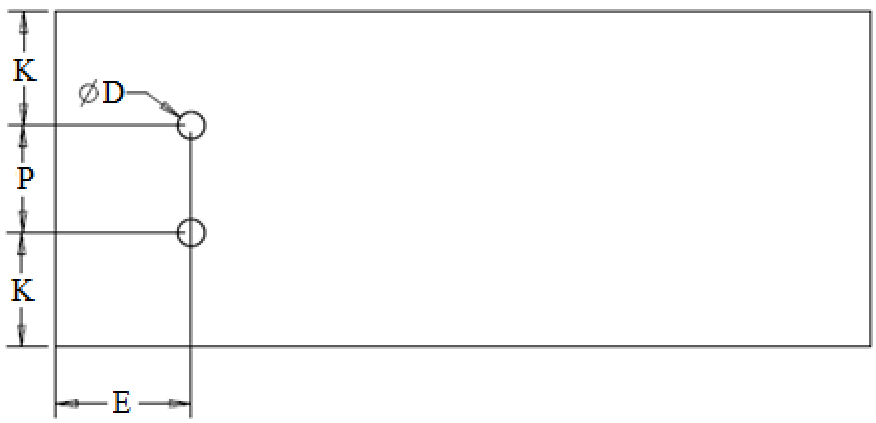


Figure 3.5: Laminates with holes in parallel

- ***Selection of Orthogonal array*** [19]

Taguchi method has a set of specially designed tables which reduce the total number of experiments to be conducted to a very small number, by selecting only a few combinations of factor and level for conducting the experiments. Orthogonal arrays are selected on the basis of the total number of factors and levels of each factor in the available problem. The degrees of freedom is the main criteria of selection of the orthogonal array and the rule says that the degrees of freedom of the problem must be less than or equal to the degree of freedom of the orthogonal array selected. The availability of the orthogonal array with the required factor- level combination must be available. In the present study L16 orthogonal array has been selected, because the degree of freedom of the orthogonal array which is 15 for L16 is greater than the degree of freedom of the current problem which is 9 in this case. L16 denotes that a total of 16 trials have to be run with 16 different combinations of factor and level.

The orthogonal array was generated in the MINITAB software, which automatically gave the 16 factor-level combinations to be considered for experimentation. The possible combinations for both serial and parallel configurations are given in Table 3.8.

Table 3.8: Orthogonal array generated in MINITAB

Experimental run	**For serial hole configuration**			**For parallel hole configuration**		
	E/D	**W/D**	**P/D**	**E/D**	**K/D**	**P/D**
1	2	2	2	2	1	2
2	2	3	3	2	2	3
3	2	4	4	2	3	4
4	2	5	5	2	4	5
5	3	2	3	3	1	3
6	3	3	2	3	2	2
7	3	4	5	3	3	5
8	3	5	4	3	4	4
9	4	2	4	4	1	4
10	4	3	5	4	2	5
11	4	4	2	4	3	2
12	4	5	3	4	4	3
13	5	2	5	5	1	5
14	5	3	4	5	2	4
15	5	4	3	5	3	3
16	5	5	2	5	4	2

- ***Mechanical testing of pin joints***

After the preparation of the laminates, they were tested for their failure load and failure mode on a UTM machine with the specifications given in the previous section.

A fixture was prepared in such a way so as to hold the samples of all combinations of geometric parameters obtained in the orthogonal array. The fixture prepared is as shown in the Fig. 3.6.

Figure 3.6: Fixture for double pin joint laminates

In the UTM testing, the fixture was held in the lower jaw, while the laminate was held in the upper jaw positioned by the pins passing through the laminate holes and the corresponding fixture holes. The laminate was pulled in the upward direction by the movable upper jaw, when the command was given the computer to the UTM machine. The crosshead speed of 2mm was maintained. The results were obtained in terms of load vs. displacement in the computer connected to the UTM machine. The UTM used is shown in the Fig. 3.7.

Figure 3.7: UTM machine

The test for each configuration has been performed for three times and the average values were considered. The experimental run for all the configurations were conducted and are shown in Table 3.9 and 3.10.

Table 3.9: Results of serial hole configuration

Experimental run	E/D	W/D	P/D	Average Resisting Force (N)	S/N ratio (dB)
1	2	2	2	940	59.4626
2	2	3	3	1830	65.2490
3	2	4	4	2930	69.3374
4	2	5	5	3040	69.6575
5	3	2	3	3590	71.1019
6	3	3	2	3950	71.9319
7	3	4	5	4560	73.1793
8	3	5	4	4620	73.2928
9	4	2	4	4690	73.4235
10	4	3	5	4930	73.8569
11	4	4	2	4750	73.5339
12	4	5	3	5110	74.1684
13	5	2	5	4590	73.2363
14	5	3	4	4730	73.4972
15	5	4	3	5080	74.1173
16	5	5	2	4440	72.9477

Table 3.10: Results of parallel hole configuration

Experimental run	E/D	K/D	P/D	Average Resisting Force (N)	S/N ratio (dB)
1	2	1	2	470	53.4420
2	2	2	3	1390	62.8603
3	2	3	4	2380	67.5315
4	2	4	5	2590	68.2660
5	3	1	3	2090	66.4029
6	3	2	2	2910	69.2779
7	3	3	5	3700	71.3640
8	3	4	4	3380	70.5783
9	4	1	4	3510	70.9061
10	4	2	5	3890	71.7990
11	4	3	2	4300	72.6694
12	4	4	3	4380	72.8295
13	5	1	5	3260	70.2644
14	5	2	4	3640	71.2220
15	5	3	3	4410	72.8888
16	5	4	2	4310	72.6895

- ***Signal to noise ratio*** [19]

The Taguchi method was further extended to know the configuration at which the best results were obtained. For this purpose, the mean effect and the Signal to Noise ratio was obtained for each of the 16 factor-level combination. The signal is the effect of factor change on the response of the quality characteristic and noise is the effect of uncontrollable factors on the response of quality characteristic in the experiment. Quality characteristic is a means of defining the performance of the product in any experiment. It is measured in terms of its units and the direction of desirability. There are three possible directions of desirability:

a) Larger is better

b) Smaller is better

c) Nominal is better

In the present case the quality characteristic is the bearing strength whose units are 'Newton' and the direction of desirability is 'Larger is better'.

So, S/N ratio serves its purpose for selection of the optimum levels of factor by allowing the user to interpret the results on the basis of two main aspects: results with least deviation of the average value from the target value and the results with least variation around the target value. S/N ratio is preferred in an experiment with multiple repetitions for the same trial condition and it is calculated from the mean square deviation given by Eqn. (3.1).

$$S/N = -10 \log_{10} (MSD) \quad (3.1)$$

where MSD is the mean square deviation of the quality characteristic from the target value.

The mean square deviation is calculated differently for the different categories of quality characteristic *i.e.* larger is better, smaller is better and nominal is better. Mean square deviation (MSD) for the three characteristics are given by Eqn. (3.2) to (3.4).

For smaller is better:

$$MSD = (y_1^2 + y_2^2 + y_3^2 + \ldots)/n \quad (3.2)$$

For nominal is better:

$$MSD = ((y_1 - m)^2 + (y_2 - m)^2 + \ldots)/n \quad (3.3)$$

For bigger is better:

$$MSD = (1/y_1^2 + 1/y_2^2 + 1/y_3^2 + \ldots)/n \quad (3.4)$$

where y_1, y_2, …. and so on are the results *i.e.* quality characteristics. The levels for each of the factors are always selected at which the value of S/N ratio is maximum irrespective of the category of quality characteristic chosen.

The plots of mean of S/N ratio for each factor at all levels for serial and parallel pin hole laminates as obtained in MINITAB are shown in the Fig. 3.8 and Fig. 3.9.

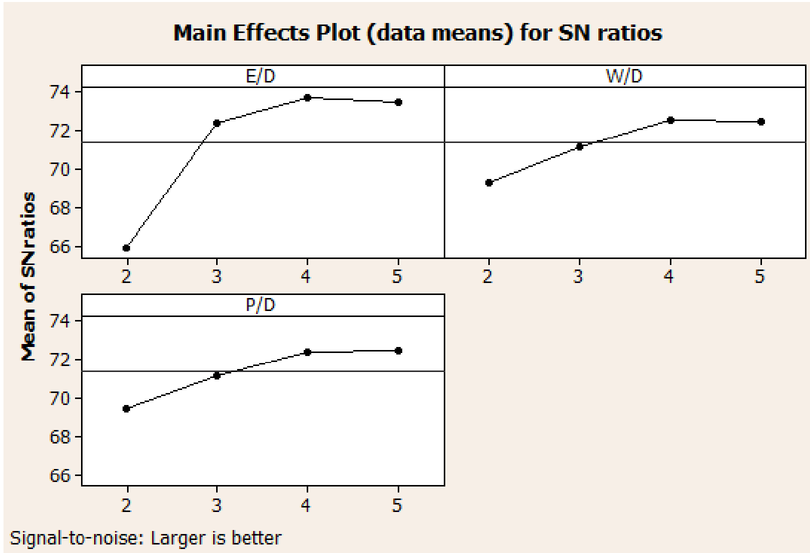


Figure 3.8: Mean of S/N ratios for serial hole laminates

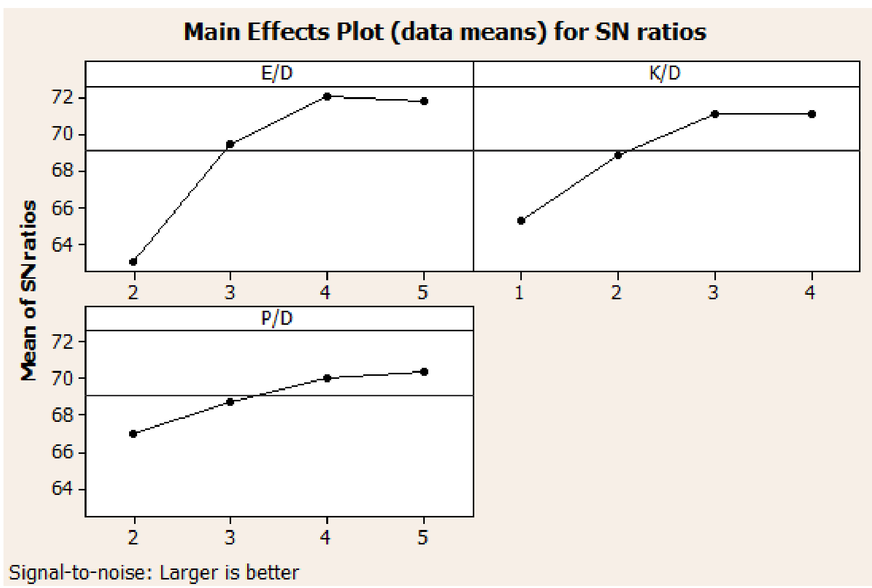


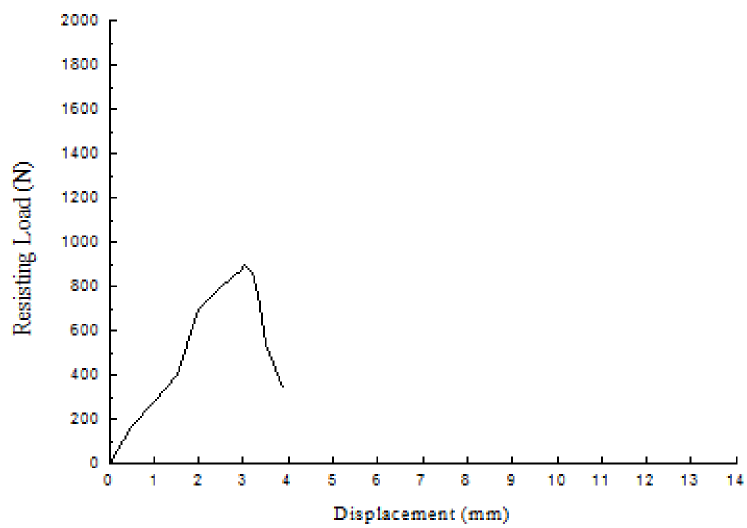
Figure 3.9: Mean of S/N ratios for parallel hole laminates

From the Fig. 3.8 for the serial hole laminates, the maximum value of mean of S/N ratio for E/D, W/D and P/D occurred at 4, 4 and 5 respectively. While from the Fig. 3.9 for the parallel hole laminates, the maximum value of mean of S/N ratio for E/D, K/D and P/D occurred at 4, 3 and 5 respectively. So the best results for the serial pin joint laminates would be obtained at E/D=4, W/D =4 and P/D =5, whereas for the parallel pin joint laminates, the configuration with E/D=4, K/D =3 and P/D =5 would give the optimum value of bearing force of the laminates.

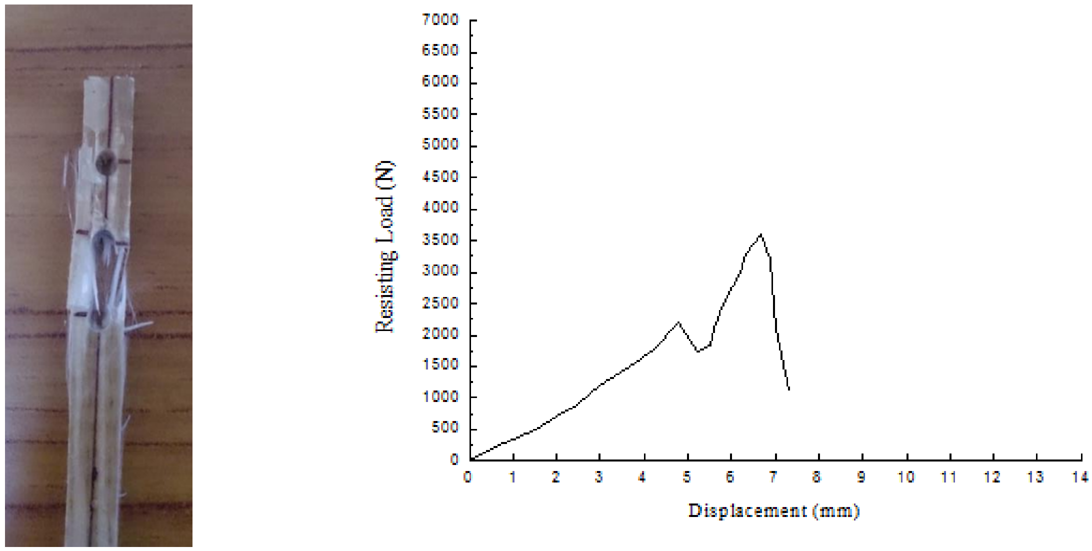
3.5 Modes of failure

The fibre reinforced composites may fail due to one of the failure modes which includes bearing mode, net tension mode, shear out mode or combination of any of the two modes. In the bearing mode, the load carried by the laminate increases almost linearly upto a certain limit and then it decreases to small extend followed by the zig zag curve with almost constant value of load for certain displacement. In the net-tension mode, the load carried by the laminate increases linearly up to a specific value and then it suddenly decreases after that point. The failure by net tension is highly catastrophic in nature. In the shear-out mode, the load vs displacement graphs shows a few peaks before the sudden failure of the laminate. Of all these failure modes, the bearing mode of failure is highly desirable, because of its non-catastrophic nature. [3, 4]

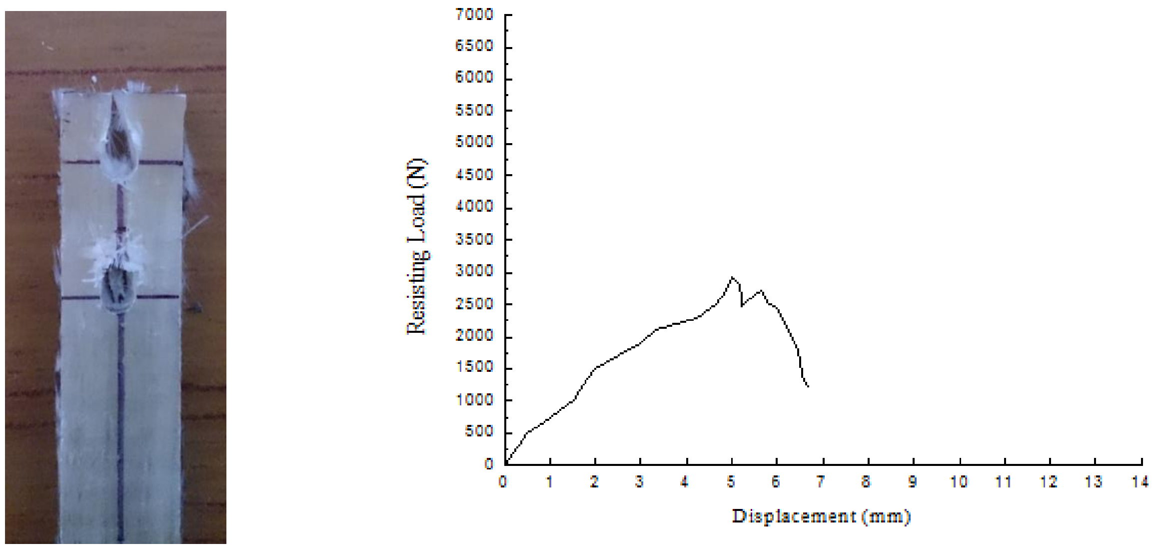
These failure modes were identified by the graphs obtained after UTM testing for both serial and parallel pin joint laminates. The actual images of some of the laminates along with the resisting load vs. displacement graphs obtained after testing are shown in Fig. 3.10.



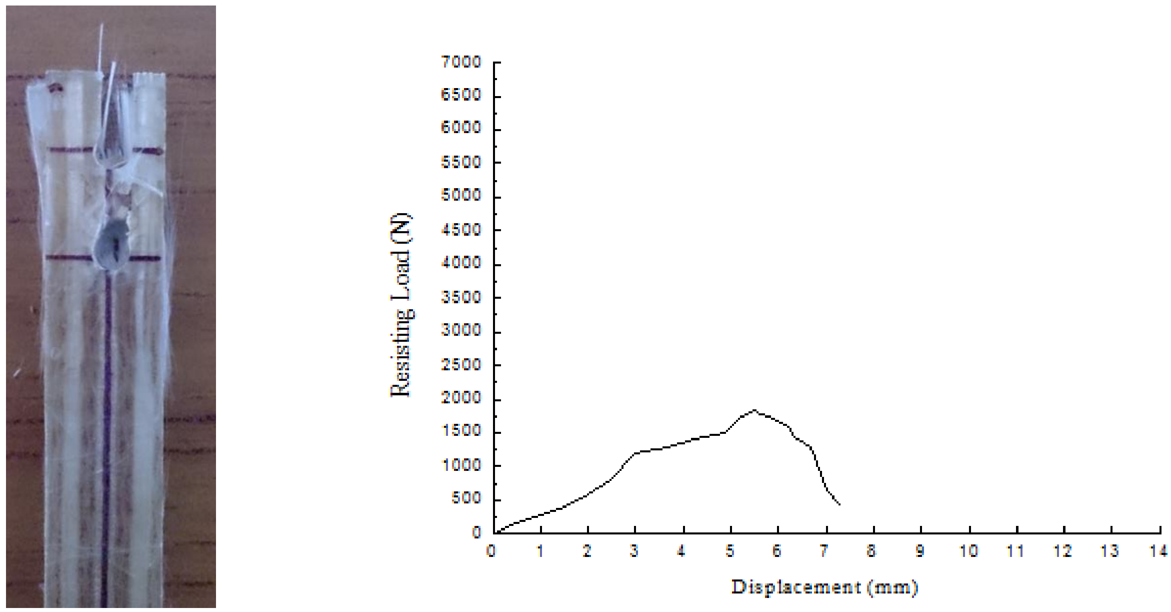
(a) E/D= 2, W/D= 2, P/D= 2 with net-tension mode of failure



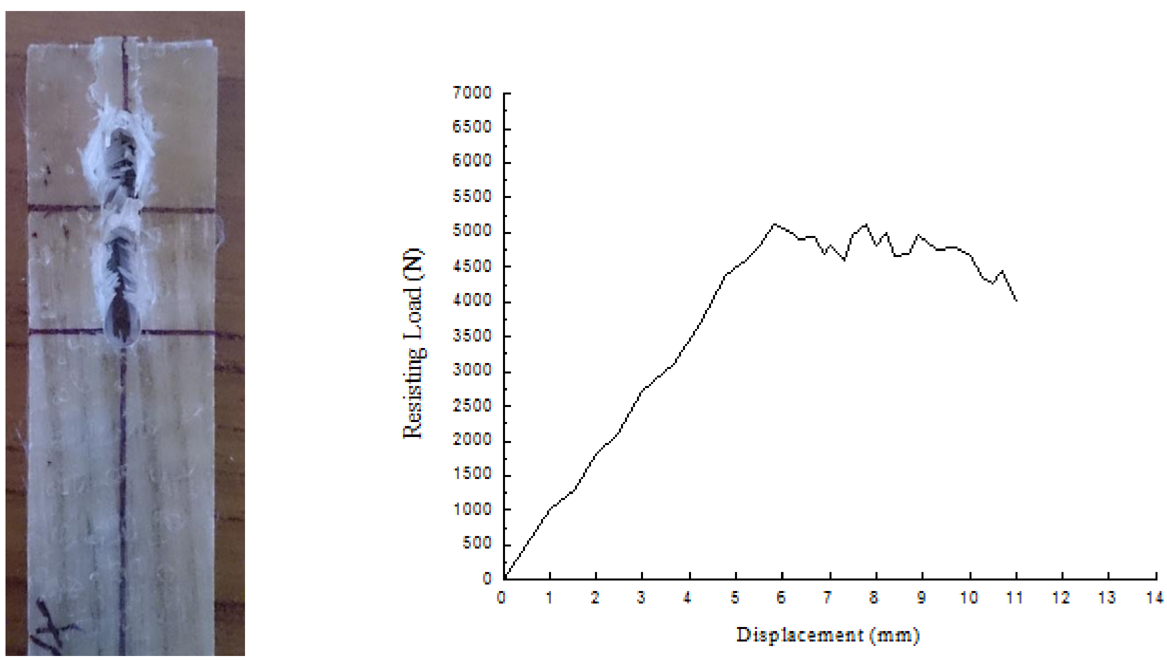
(b) E/D= 3, W/D= 2, P/D=3 with net-tension mode of failure



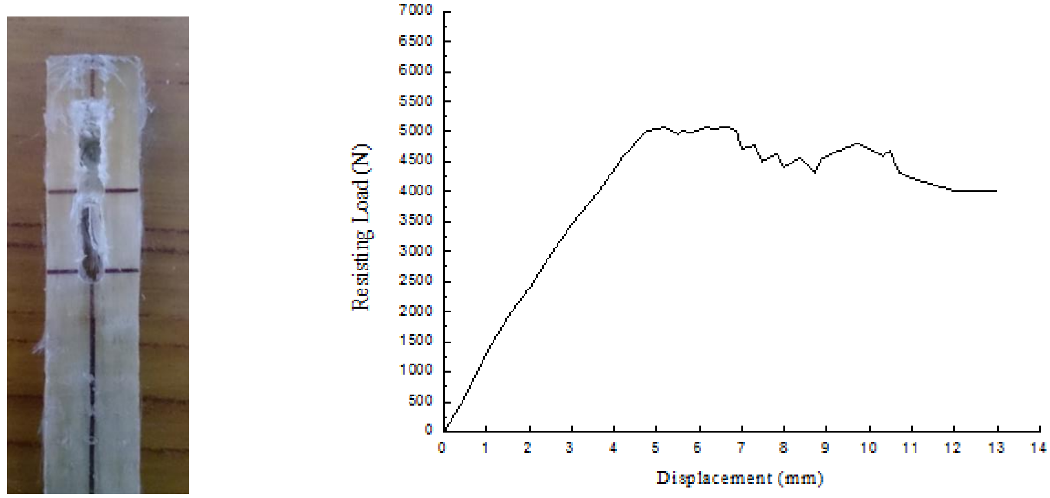
(c) E/D= 2, W/D= 4, P/D=4 with shear out mode of failure



(d) E/D= 2, W/D= 3, P/D= 3 with shear out mode of failure



(e) E/D= 4, W/D= 5, P/D= 3 with bearing mode of failure

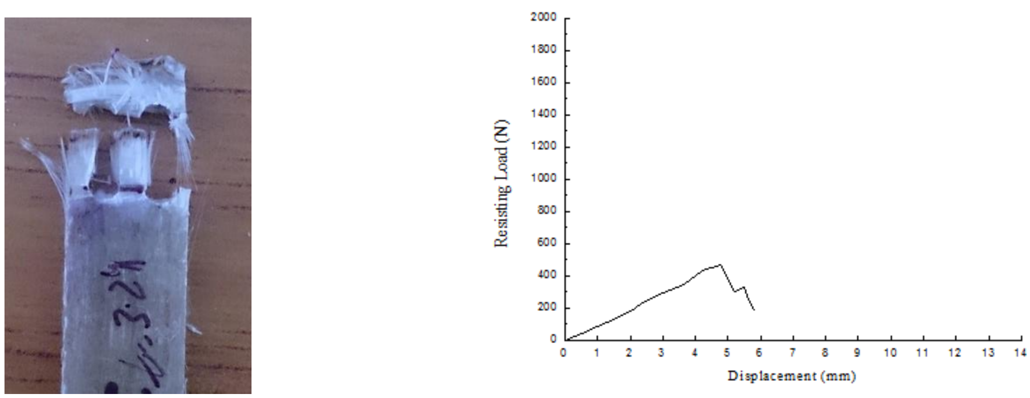


(f) E/D= 5, W/D= 4, P/D= 3 with bearing mode of failure

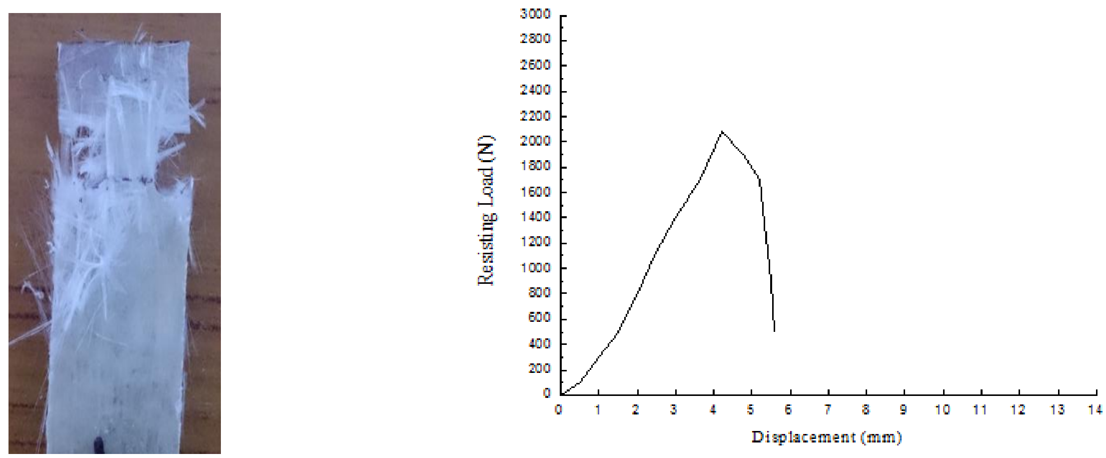
Figure 3.10: Plots of resisting load vs. displacement for serial pin joint laminates

From the Fig. 3.10 it is clear that net tension mode of failure is observed in the laminates with smaller value of W/D *i.e.* laminates having very small width, because they have less net cross-sectional area to resist the tensile load. The laminates with smaller edge length are more prone to shear out mode of failure. The laminates which have larger width and edge length generally fail by the bearing mode, which is the most desired mode of failure, due to its non- catastrophic nature. Hence the laminates for the serial pin must be designed in such a way that they have sufficient edge length and width to avoid the net tension and shear out mode of failure.

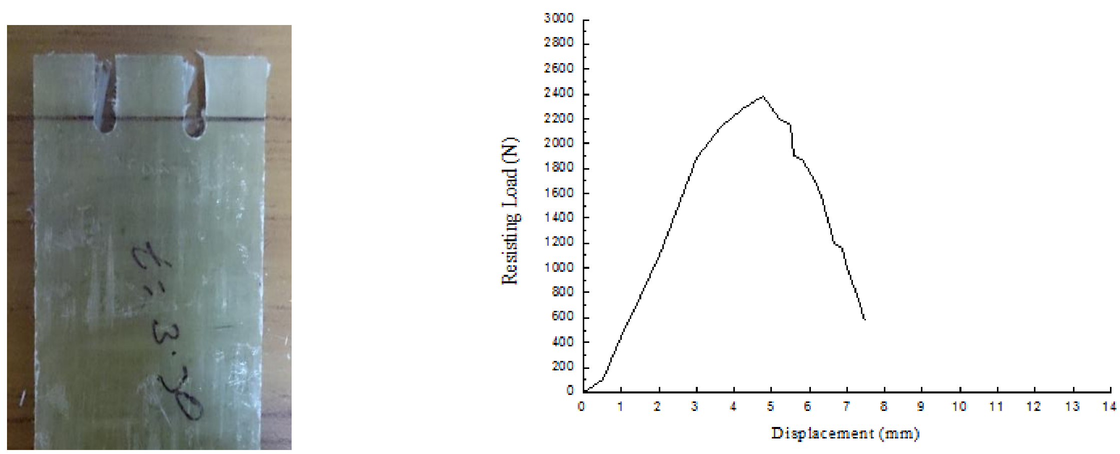
The actual images of some of the laminates with the parallel pin joints along with their plots of resisting load vs. displacement obtained after UTM testing are shown in Fig. 3.11.



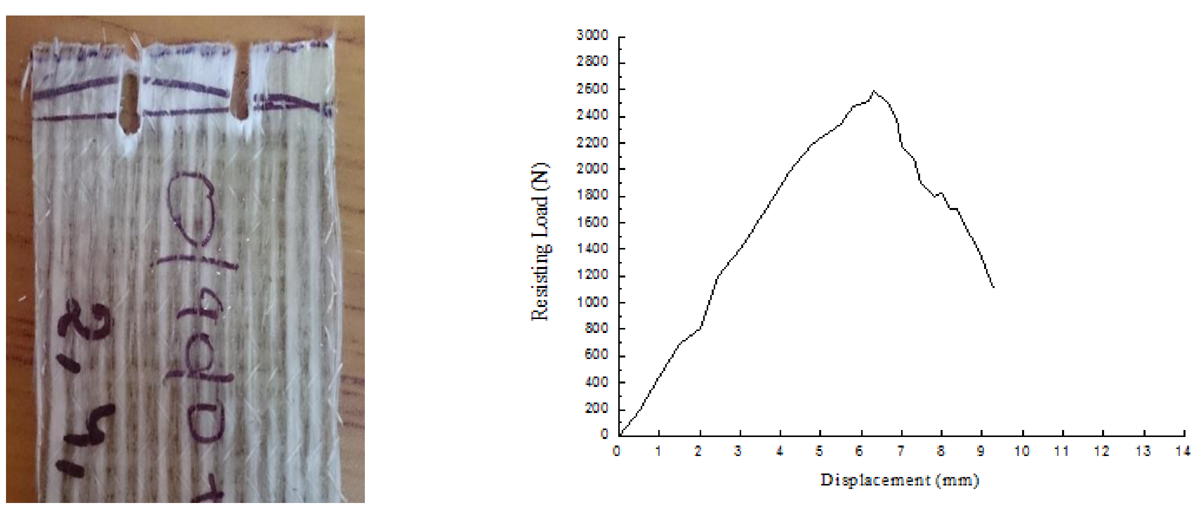
(a) E/D= 2, K/D= 1, P/D= 2 with net tension mode of failure



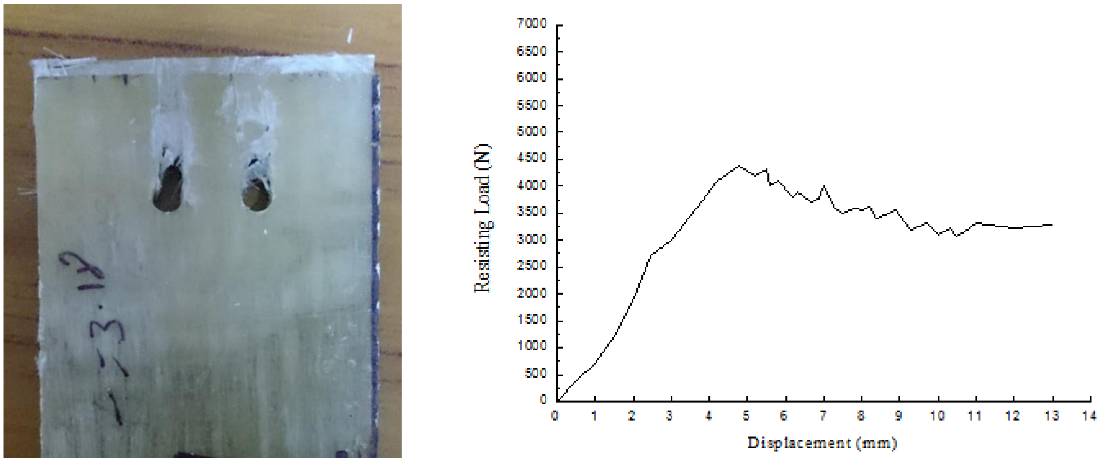
(b) E/D= 3, K/D= 1, P/D= 3 with net tension mode of failure



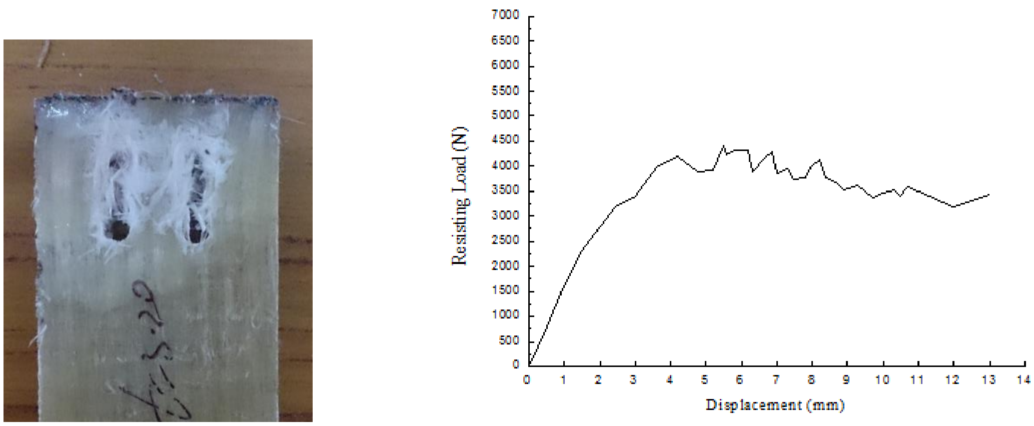
(c) E/D= 2, K/D= 3, P/D= 4 with shear out mode of failure



(d) E/D= 2, K/D= 4, P/D= 5 with shear out mode of failure



(e) E/D= 4, K/D= 4, P/D= 3 with bearing mode of failure



(f) E/D= 5, K/D= 3, P/D= 3 with bearing mode of failure

Figure 3.11: Plots of resisting load vs. displacement for serial pin joint laminates

It can be seen from Fig. 3.11 that the laminates with the smaller E/D ratio fail by the shearing mode, whereas the laminates with the smaller value of K/D ratio fail by the net- tension mode. The laminates which have sufficient edge length and side edge distance fail by the bearing mode which is the desired mode due to its non – catastrophic nature. So, the laminate should be designed in such a way that it has sufficient edge length (E) and side edge distance (K) in order to avoid the net tension and the shear out mode of failure.

3.6 Confirmation tests

The bearing load value for the configurations of serial and parallel pin hole laminates obtained in the Taguchi method were estimated using the Eqn. (3.5).

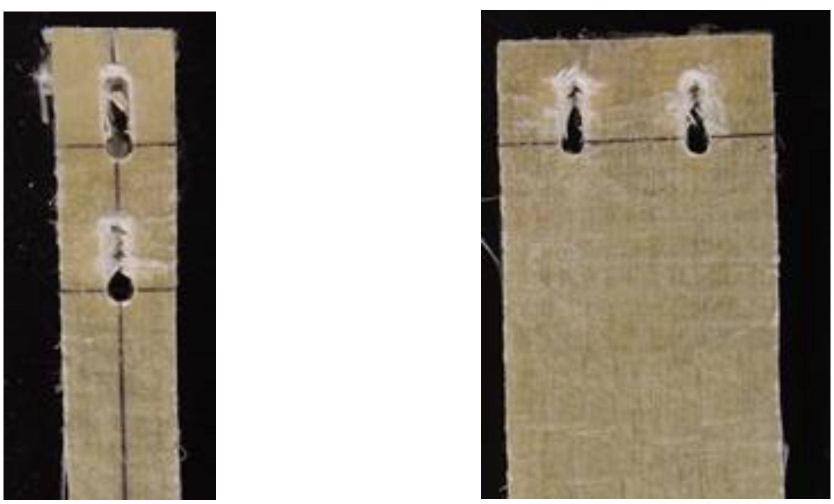
$$F_{opt}^2 = \frac{1}{10^{\left(\frac{-S/N_{opt}}{10}\right)}} \quad (3.5)$$

where the value of S/N_{opt} is the optimum value of S/N ratio and it was calculated for the serial pin hole laminate with configuration E/D = 4, W/D = 4 and P/D = 5 using the Eqn. (3.6)

$$S/N_{opt} = S/N_{mean} + S/N_{E/D4} - S/N_{mean} + S/N_{W/D4} - S/N_{mean} + S/N_{P/D5} - S/N_{mean} \quad (3.6)$$

Where S/N_{mean} is the mean of S/N ratio for all trials, $S/N_{E/D4}$ is the value of S/N ratio for E/D = 4, $S/N_{W/D4}$ is the value of S/N ratio for W/D = 4, $S/N_{P/D5}$ is the value of S/N ratio for P/D = 5.

After obtaining the configurations that can deliver the best results in terms of bearing strength for both serial and parallel pin joint laminates, the confirmation tests were conducted on the obtained configurations. The laminates with the serial pin joint having the configuration of E/D= 4, W/D= 4 and P/D= 5 and parallel pin joint having the configuration of E/D 4, K/D= 3 and P/D= 5 were prepared and tested for their bearing strength. Both the laminates after the testing have been shown in the Fig. 3.12.



(a) **(b)**

Figure 3.12: Laminates prepared for (a) serial pin holes with E/D= 4, W/D= 4 and P/D= 5 and (b) parallel pin holes with E/D= 4, K/D= 3, P/D= 5

3.7 Application of ANOVA technique

After conducting the experiments, the results were analyzed to find out the following:

1. Percentage influence of each factor on the results of experiments.
2. Influence of each factor on the response of quality characteristic on getting its level changed. [19]

In this case the two way ANOVA technique has been applied due to number of factors greater than two and number of levels greater than one. The ANOVA table had been automatically generated in the MINITAB software, from where the results were analyzed easily. F-test in the table helps to judge the factor which has more effect on the change in the response of quality characteristic, when its level changes. Percentage contribution signifies the extent of contribution of the factor in the response of quality characteristic. The complete table of ANOVA for serial and parallel pin hole laminates is shown in Table 3.11 and Table 3.12 respectively.

Table 3.11: ANOVA table for serial pin joints

Source	DF (Degree of Freedom)	Sum of square	Mean square	F	Contribution (%)
E/D	3	162.45	54.149	15.89	69.23
W/D	3	28.02	9.338	2.74	11.94
P/D	3	23.73	7.909	2.32	10.11
Residual Error	6	20.45	3.408	-	8.71
Total	15	234.64	-	-	100

From the above table it is clear that the E/D ratio has contributed maximum towards the bearing strength of serial pin jointed laminates, with W/D and P/D contributing significantly lesser as compared to E/D ratio. Moreover the F-test conducted at 95% confidence level has shown that the E/D ratio effects the bearing strength significantly when E/D value changes as compared to W/D and P/D ratio.

Table 3.12: ANOVA table for parallel pin joints

Source	DF (Degree of Freedom)	Sum of square	Mean square	F	Contribution (%)
E/D	3	211.24	70.414	10.35	56.76
K/D	3	91.60	30.534	4.49	24.61
P/D	3	28.48	9.493	1.40	7.65
Residual Error	6	40.83	6.805	-	10.96
Total	15	372.15	-	-	100

In the case of parallel pin joints, the E/D ratio again has a major contribution on the results but the contribution of K/D can't be ignored because it has 24% contribution on the bearing force of laminate, which is very significant. The F-test shows that E/D has more effect on the change in the bearing force of the parallel pin jointed laminates as its level gets change.

In the present study ANSYS 16 has been used to conduct the analysis of the fibre reinforced composite laminates using the progressive damage model and the characteristic curve method.

4.1. Progressive damage model

It is a model, commonly used to study the progression of damage in composite laminates. It is required to select the damage evolution law for this model. Two types of damage evolution laws are available in ANSYS

a) Material Property Degradation Method
b) Continuum Damage Mechanics Method

Material Property Degradation method instantly degrades the properties of the element by step reduction of the stiffness matrix, once the failure in that element is detected. Hence, it is a step function *i.e.* it either considers the element as damaged or undamaged. The element with the damage status as '0' refers to 'undamaged' while the damage status as '1' refers to 'damaged'. With the further increase of the load, the damage progresses into other elements. Whereas in case of Continuum Damage Mechanics Method, the damage progression is studied in each element. In order to decide the limit, at which the failure is needed to be declared, a failure criteria is needed. Commonly used failure criteria include maximum stress criteria, maximum strain criteria, Hashin criteria and Tsai- Wu criteria [20, 21].

Each damage initiation criteria has its certain mathematical equations, which define the failure of the material. Once the failure at any element is detected as per the conditions of the damage initiation criteria during the analysis, its properties are degraded. The damage then advances to the other elements according to the damage evolution law.

In the present case, the damage evolution law used is the Material Property Degradation Method and the failure initiation criteria used within this method is the Tsai- Wu failure criteria. It decides the failure of the element by calculation of failure index. After the detection of failure index damage evolution law plays its role by degrading its properties.

For all the observations in the present work, equivalent stresses were considered to analyze the results, because for the uniaxial state of stress, the equivalent stress is the actual stress [22].

- **Tsai - Wu Failure Criteria**

The Tsai Wu polynomial failure theory was used as a 'damage initiation criteria' to find the failure load. This failure theory is given by Eqn. (4.1).

$$\mathrm{F}_1\sigma_1 + \mathrm{F}_2\sigma_2 + \mathrm{F}_{11}\sigma_1^2 + \mathrm{F}_{22}\sigma_2^2 + \mathrm{F}_{66}\sigma_6^2 + 2\mathrm{F}_{12}\sigma_1\sigma_2 = \mathrm{FI} \tag{4.1}$$

The values of F_1, F_2, F_{11}, F_{22}, F_{66} and F_{12} depend on the certain physical properties of the composite. These are calculated by using Eqn. (4.2) to (4.7). These physical properties include transverse tensile strength, longitudinal tensile strength, transverse compressive strength, longitudinal compressive strength and shear failure strength. σ_1 is the maximum principal stress, σ_2 is the minimum principal stress and σ_6 is the maximum shear stress at a point corresponding to an intermediate load while the application of gradual load [23].

$$F_{11} = \frac{1}{X_t X_c} \tag{4.2}$$

$$F_1 = \frac{1}{X_t} - \frac{1}{X_c} \tag{4.3}$$

$$F_{22} = \frac{1}{Y_t Y_c} \tag{4.4}$$

$$F_2 = \frac{1}{Y_t} - \frac{1}{Y_c} \tag{4.5}$$

$$F_{66} = \frac{1}{S^2} \tag{4.6}$$

$$F_{12} = -0.5\sqrt{F_{11}F_{22}} \tag{4.7}$$

If $FI < 1$; there is no failure in the composite laminate

If $FI \geq 1$; there is failure in the composite laminate

4.1.1 Finite element modelling

The steps involved in the analysis of the laminate for the serial pin joint laminate with the configuration of E/D= 4, W/D= 4 and P/D= 5 and the parallel pin joint laminate with the configuration of E/D= 4, K/D= 3 and P/D= 5 have been discussed below.

- ***Engineering data***

  A new custom material named ‘advantex epoxy’ was introduced and all the properties that were obtained by the testing were assigned to it in the ‘engineering data’.

- ***Geometry***

  A two dimensional model was generated, whose thickness was given as 3mm. The geometry was sliced as per the requirements of meshing and application of boundary condition. All the sliced parts, which generated 27 faces were connected to each other by the edges using the ‘connect’ tool. Hence all the parts had merged to give a single surface.

- ***Meshing***

  In the laminate with serial pin joint, face meshing was employed at all the 27 faces of the body. Face meshing was employed, as it gave more uniform meshed surface, specifically around the hole. Quadrilateral elements were selected to mesh the geometry. A total of 1503 elements and 1684 nodes were generated after meshing. The meshed surface in serial pin joint laminate is as shown in Fig. 4.1.

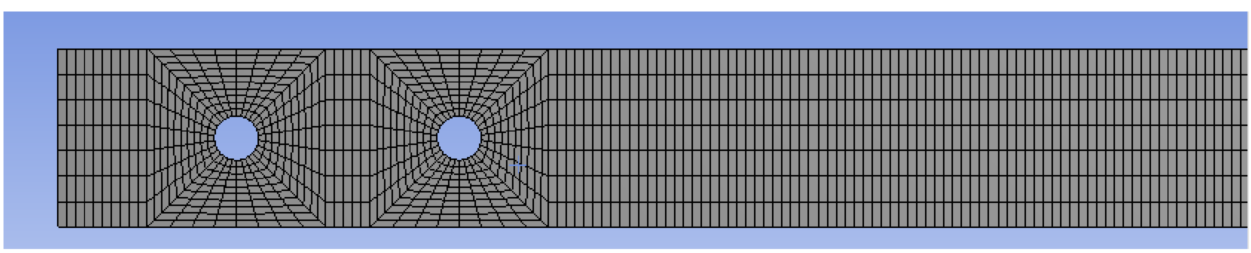


Figure 4.1: Mesh generated on the serial pin hole specimen with E/D= 4, W/D= 4 and P/D= 5

In the parallel pin joint laminate, face meshing was done on 22 faces created after slicing. The number of nodes generated were 1576 and the number of elements were 1473. The meshed geometry of parallel pin joint laminate is as shown in Fig. 4.2.

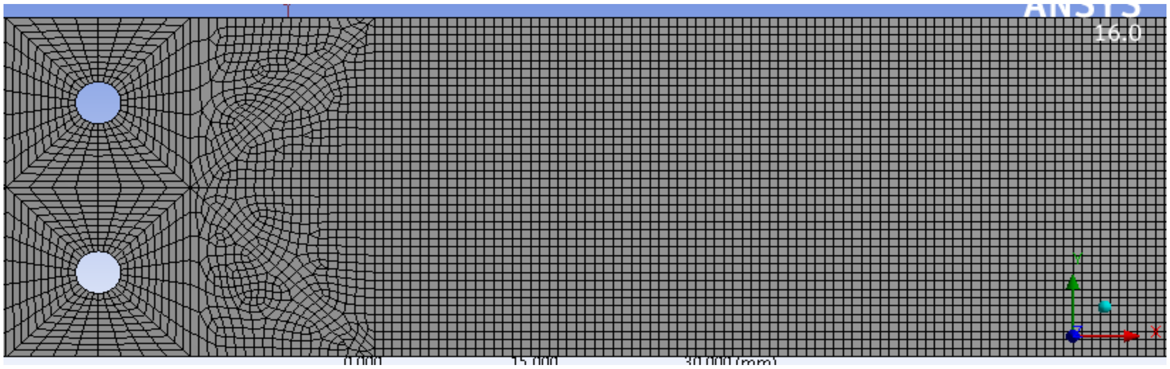
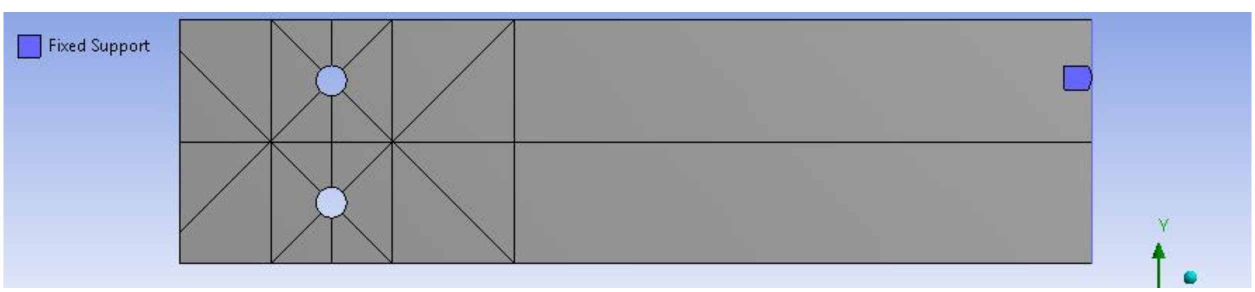


Figure 4.2: Mesh generated on the parallel pin hole specimen with E/D= 4, K/D= 3 and P/D= 5

- ***Boundary conditions***

  Force with magnitude of 8000N was applied perpendicular to the cross section. This value of force was arbitrarily selected on the basis of observation from the experimental results where all the specimens failed at a load value significantly less than 8000N. Its increment was given in 10 steps. Fixed support was given at the opposite cross section. The fixed support in the serial and parallel pin joint laminate is as shown in the Fig. 4.3.

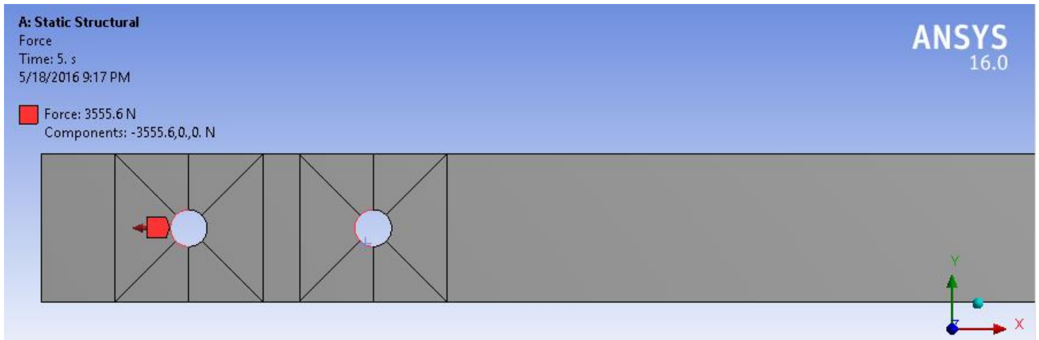
(a) Serial pin joint laminate



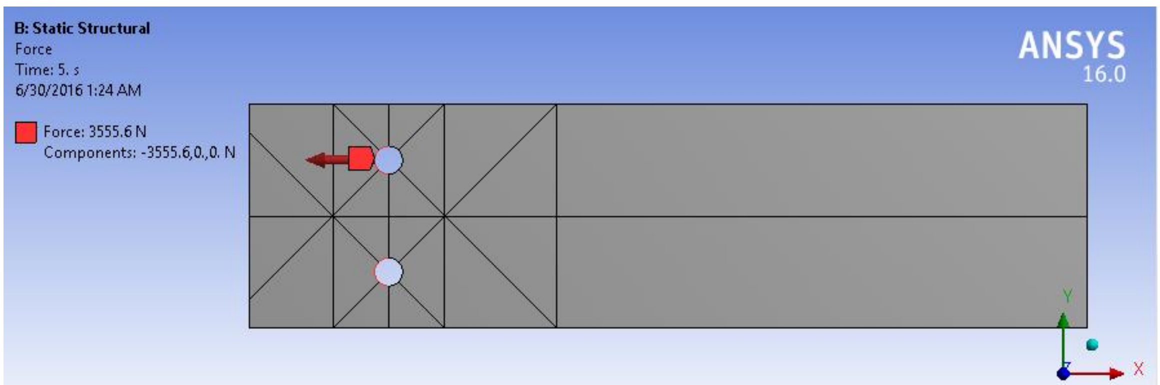
(b) Parallel pin joint laminate

Figure 4.3: Fixed support given on the end shown with blue colour

The magnitude and the location of the force for serial and parallel pin joint laminate configuration at the time of 5 seconds is as shown in the Fig. 4.4.



(a) Serial pin joint laminate



(b) Parallel pin joint laminate

Figure 4.4: Force given on the hole edges shown with red colour

4.1.2 Analysis of results

The study of results obtained by the application of progressive damage model was restricted only to the following areas:

a) Determining the stress value at which the failure initiated in the laminate.

b) Determining the stress value at which the laminate failed completely.

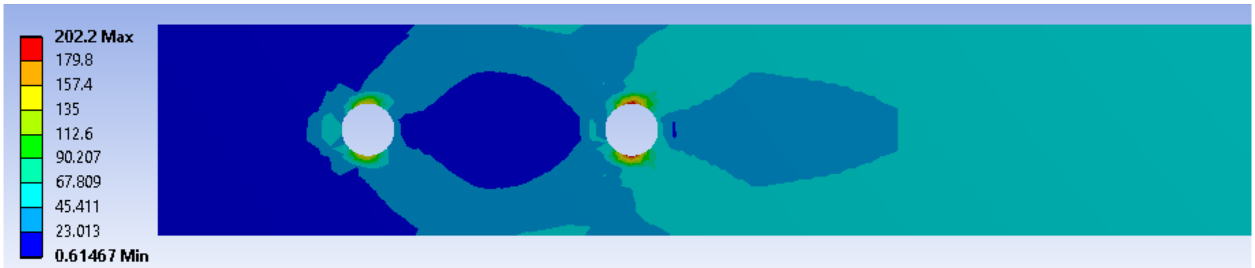
In order to determine the stress value at which the failure initiated, the magnitude of stress at the time, when the damage status became equal to unity was observed from the report generated after analysis run.

The stress magnitude at the point of the failure of the laminate was found from the graph of the equivalent stress vs. time obtained after the completion of the analysis. The maximum value of stress at the elastic limit (σ_f) was considered as the failure stress of the laminate. The values of stress corresponding to the time of damage initiation and the failure of the laminate for serial and parallel pin joint laminates are shown in Table 4.1.

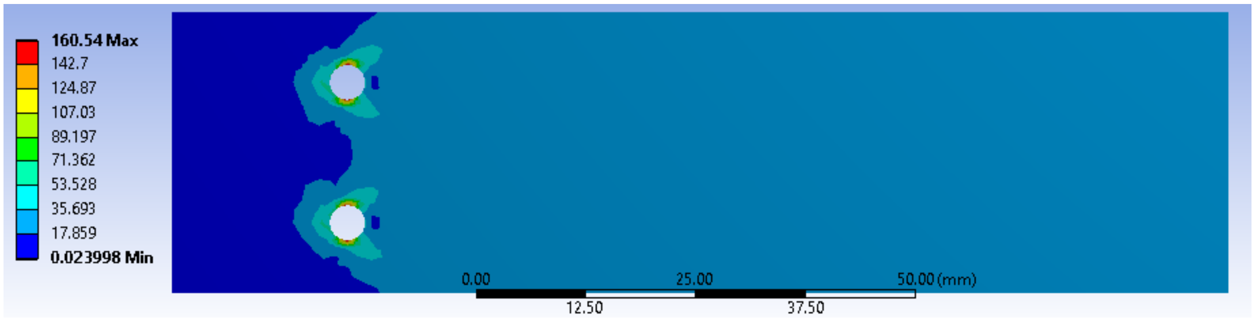
Table 4.1: Equivalent stresses at the time of damage initiation and laminate failure for serial and parallel pin joint laminate

Type of laminate configuration	Damage stage	Time (in seconds)	Equivalent stress (in MPa)
Serial	Damage initiation	2.9	202.2
	Laminate failure	6.2	526.62
Parallel	Damage initiation	3.2	160.54
	Laminate failure	6.8	495.76

The geometric models of the equivalent stress distribution for the serial and parallel pin joint laminate at the time of damage initiation is shown in Fig. 4.5, while the equivalent stress distribution for the serial and the parallel pin joint laminate at the time of failure is shown in the Fig. 4.6.

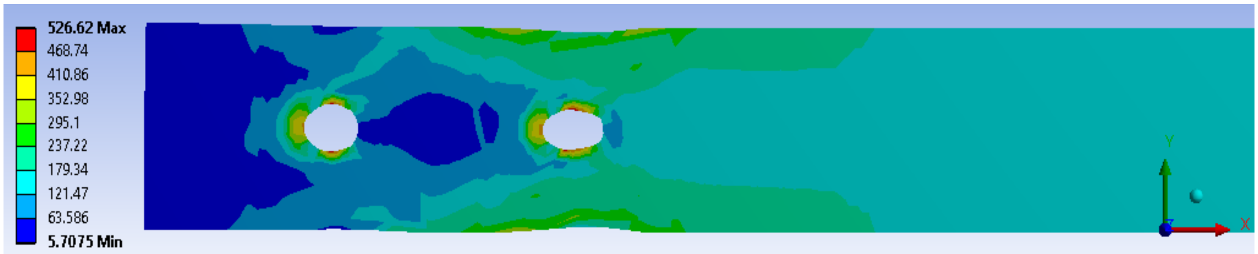


(a) Serial pin joint laminate (E/D= 4, W/D= 4 and P/D= 5)

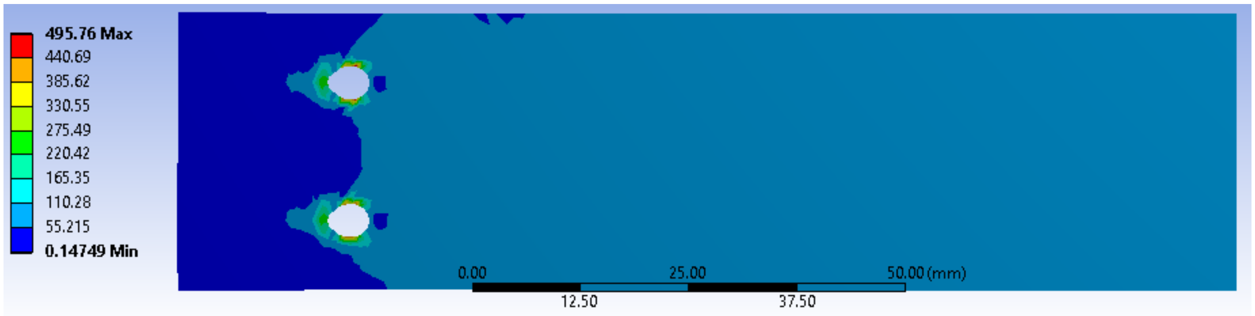


(b) Parallel pin joint laminate (E/D= 4, K/D= 3 and P/D= 5)

Figure 4.5: Equivalent stress distribution at the time of damage initiation



(a) Serial pin joint laminate (E/D= 4, W/D= 4 and P/D= 5)



(b) Parallel pin joint laminate (E/D= 4, K/D= 3 and P/D= 5)

Figure 4.6: Equivalent stress distribution at the time of laminate failure

The magnitude of failure (P_f) load of the laminate was determined by using the Eqn. (4.8).

$$P_f = \sigma_f \times d \times t \tag{4.8}$$

Where d is the diameter of the hole and t is the thickness of the plate.

The failure load for serial pin joint laminate came out to be 6319.44 N, while for the parallel pin joint laminate, it came out to be 5949.12 N.

The value obtained from the progressive damage model is almost equal to the value obtained from the experiment performed.

4.2 Characteristic curve method

Characteristic curve is an artificial curve that is made with the help of characteristic lengths determined by the joint tests namely bearing test and tensile test. The bearing test is conducted to determine the compressive characteristic length, while the tensile test is conducted to determine the tensile characteristic length. The distance from the edge of the hole to this point where the equivalent stress becomes equal to the mean bearing stress is called the characteristic length in compression (R_{oc}), while the distance from the hole edge to the point where the equivalent stress is equal to the mean tensile strength is called the characteristic tensile length (R_{ot}). The schematic diagrams for both bearing and tensile tests are shown in the Fig. 4.7 (a) and (b) respectively [24, 25].

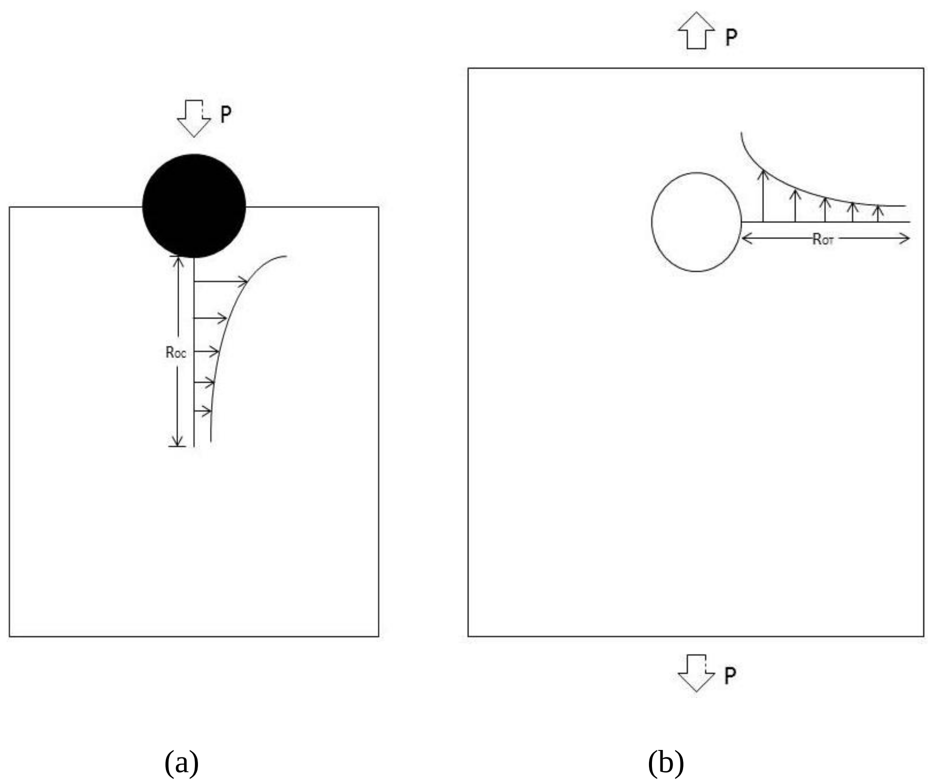


Figure 4.7: Schematic representation of joint tests for finding characteristic lengths: (a) bearing test (b) tensile test

The curve is drawn using the Eqn. (4.9) with the determined value of characteristic lengths.

$$R_c = d + R_{ot} + (R_{ot} - R_{oc}) \cos \theta \quad (4.9)$$

Where R_{oc} is the characteristic length in compression, R_{ot} is the characteristic length in tension, d is the diameter of the hole and θ is the angle measured clockwise or anti-clockwise from the direction of applied load. It can be measured clockwise as well as anticlockwise due to the symmetry of the curve around the base line. The failure modes are detected on the basis of location of maximum value of failure index on the characteristic curve. The failure modes can be distinguished as follows:

$0^{\circ} \leq \theta \leq 15^{\circ}$: Bearing failure

$30^{\circ} \leq \theta \leq 60^{\circ}$: Shear-out failure

$75^{\circ} \leq \theta \leq 90^{\circ}$: Net-tension failure

Here the characteristic curve method has been applied to the serial configuration of E/D= 4, W/D= 4 and P/D= 5. The analysis had been done separately to find both the characteristic lengths.

4.2.1 Methodology used to draw a characteristic curve

In order to draw the characteristic curve, the characteristic lengths were required which were found out by conducting numerical analysis for each characteristic length.

- ***Characteristic length in compression***

The laminate with the configuration for E/D= 4, W/D= 4 and P/D= 5 had been modelled in the ANSYS and the force (P) of 8000N had been applied to both the holes in compression. Load of any arbitrary magnitude could be applied here, as it would vary the characteristic lengths proportionately and hence the corresponding value of equivalent stresses. The bearing strength of the specimen had been calculated according to the Eqn. (4.10)

Mean bearing strength = $\mathrm{P}/(d \times t)$ (4.10)

where d is the diameter of the hole and t is the thickness of the laminate.

Then the probe was used to locate the point ahead of the hole along the X axis where the equivalent stress was equal to the mean bearing strength.

- ***Characteristic length in tension***

The laminate with the same configuration was subjected to the tensile load of 8000 N on the edge applied symmetrically along the X axis. The mean tensile strength was calculated using the Eqn. (4.11)

Mean tensile strength $= \dfrac{\mathrm{P}}{(\mathrm{w}-\mathrm{d})\times \mathrm{t}}$ (4.11)

Where w is the width of the plate, d is the diameter of the hole and t is the thickness of the laminate. The probe was used to locate the point from the edge of the hole in the transverse direction where the equivalent stress is equal to the mean tensile strength. After finding the values of the characteristic lengths, the characteristic curve equation was used to draw the characteristic curve by varying the angle θ from 0 to 90° and then mirroring the curve as desired.

4.2.2 Calculation of failure index (FI)

The following methodology had been adopted in order to obtain the values of failure index for all the nodes lying on the characteristic curve. The methodology involved determination of maximum principal stress (σ_1), minimum principal stress (σ_2) and maximum shear stress (σ_6). Then the calculations for failure index for all the nodes lying on the characteristic curve were done using the Tsai- Wu failure polynomial.

- ***Determination of principal stresses and maximum shear stress***

The reference numbers of node on the characteristic curve were noted down from the solution file in the ANSYS and the results of maximum principal stress, minimum principal stress and maximum shear stress were exported from the ANSYS. The values of principal stresses and shear stresses for the required node numbers already noted down were sorted out. The analysis for the minimum principal stresses for the serial configuration is shown in the Fig. 4.8.

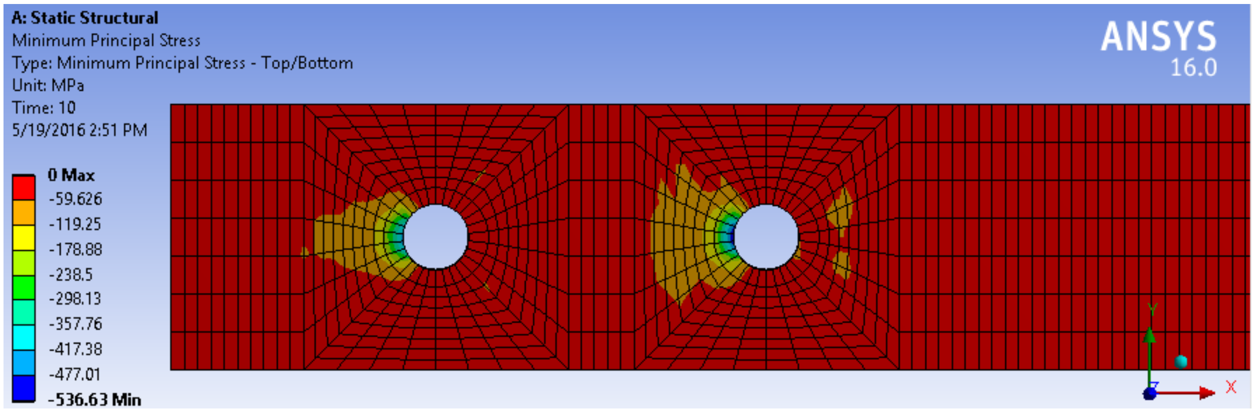


Figure 4.8: Minimum principal stress being detected on the characteristic curve

- ***Calculation of failure index from Tsai- Wu polynomial***

The values of σ_1, σ_2 and σ_6 sorted out were substituted in the formula of failure index given by Tsai- Wu polynomial for each node of both inner and outer hole. A program was created in MATLAB to reduce the calculation time of failure index for each configuration. The maximum value of failure index was considered for load optimization at the respective holes. The maximum value of failure index for the serial pin joint laminate was at the inner hole with a value of 0.64. For the parallel pin joint laminate, its maximum value was 0.64. The maximum failure index for the serial and the parallel pin hole configuration are shown in the Fig. 4.9 and Fig. 4.10 respectively.

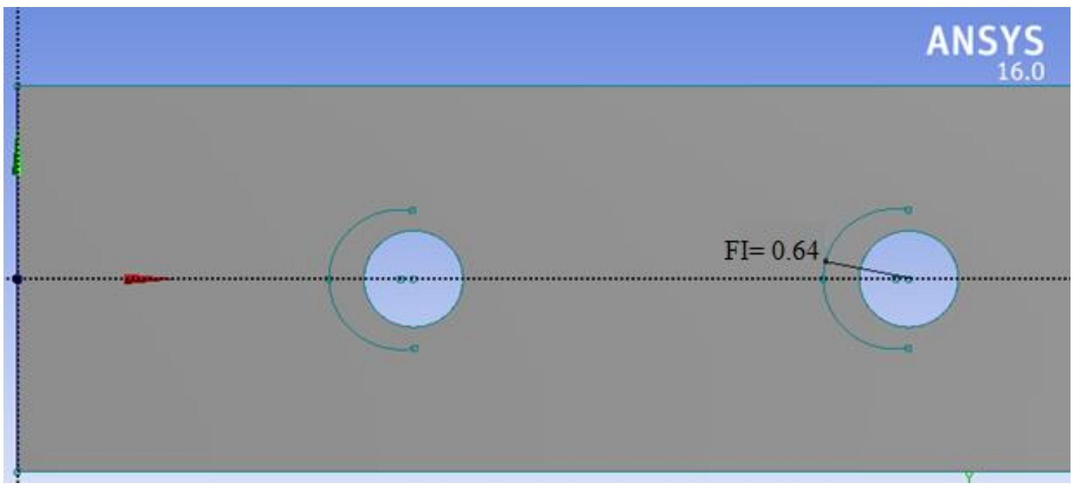


Figure 4.9: Failure index for serial pin on characteristic curve

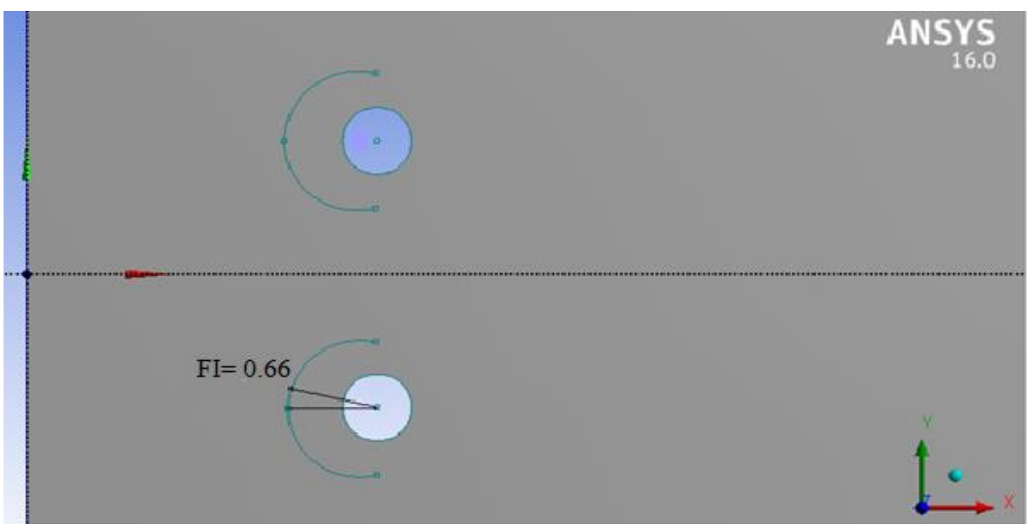


Figure 4.10: Failure index for parallel pin on characteristic curve

4.2.3 Optimum value of failure load

The optimum value of failure load was calculated using the Eqn. (4.12).

$$F_{opt} = F/FI \qquad (4.12)$$

Where F was the force carried at the inner hole for serial pin joint laminate and either of the holes for the parallel pin joint laminate. [15]

The value of force 'F' for the serial pin joint laminate was calculated using the equivalent stress distribution between the two holes at any time during the analysis at their respective characteristic curves. The higher value of load was observed at the outer hole. Hence the maximum failure index calculated at the outer hole was used to obtain the value of the optimum failure load. The value of force 'F' for the parallel pin joint laminate was directly taken as 4000N, because the load is always equally distributed in the laminate with parallel pin joint, subjected to uniaxial loading.

- For serial pin joint laminate with configuration of E/D = 4, W/D = 4 and P/D = 5

  Corresponding to load of 8000 N:

  $\sigma_{eq.\ at\ inner\ hole}$= 337.6 MPa

  $\sigma_{eq.\ at\ outer\ hole}$= 329.06 MPa

  The ratio of stresses at the inner and the outer hole gave the load distribution at both the holes.

  F= Larger of $[F_{inner\ hole}\ , F_{outer\ hole}]$

  F= Larger of [4094.72 N, 3905.28 N]

  F= 4094.72 N

  F_{opt} = 6398 N

- For parallel pin joint laminate with configuration of E/D = 4, K/D = 3 and P/D = 5

  F= 4000N

  F_{opt} = 6060.6 N

4.2.4 Failure mode of laminates

The mode of failure is easily determined by finding the angle of location of maximum failure index from the horizontal on the characteristic curve. The following inequalities given by the characteristic curve method are used to find the mode of failure.

$0^{\circ} \leq \theta \leq 15^{\circ}$: Bearing failure

$30^{\circ} \leq \theta \leq 60^{\circ}$: Shear-out failure

$75^{\circ} \leq \theta \leq 90^{\circ}$: Net-tension failure

The angle of the node containing the maximum failure index was determined by using the 'equation of slope for two known points' given by Eqn. (4.13). The coordinates of the node of maximum failure index and the center of the hole were found by exporting the coordinates of the nodes' file into the excel file.

$$\tan \theta = (y_2 - y_1)/(x_2 - x_1) \quad (4.13)$$

where x_1, y_1 are the coordinates of the center of the hole and x_2, y_2 are the coordinates of the node with the maximum failure index lying on the characteristic curve.

The value of θ for the serial pin joint laminate with the configuration of E/D = 4, W/D = 4 and P/D = 5 was 12.5°, thus giving the bearing mode of failure for it. The value of θ for the parallel pin joint laminate was 11° with the configuration of E/D = 4, K/D = 3 and P/D = 5, giving the bearing mode of failure for it too.

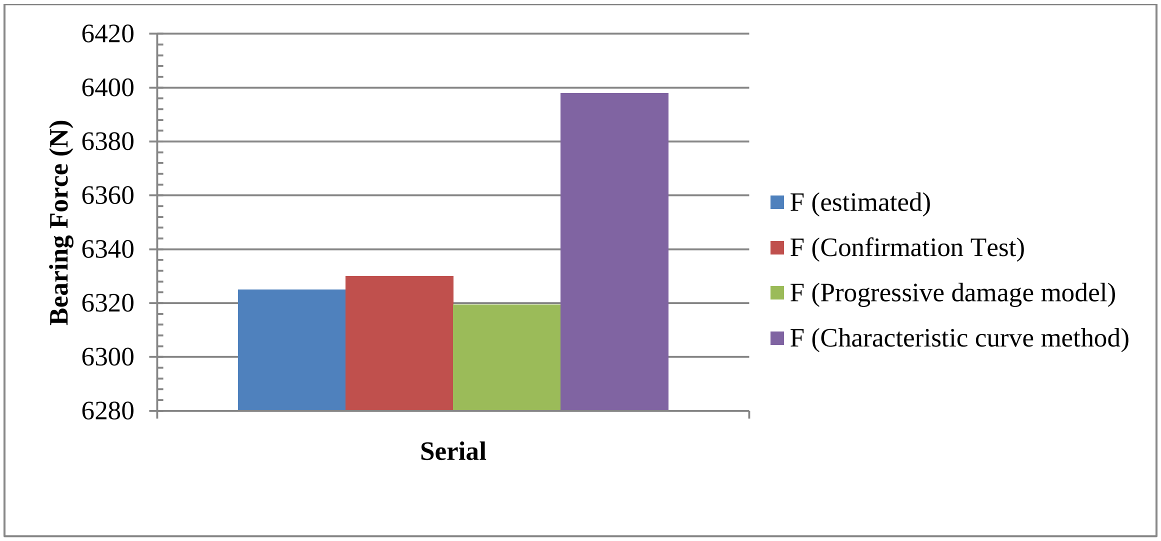


Figure 4.11: Comparison of results for serial pin joint laminates with E/D = 4, W/D = 4 and P/D = 5

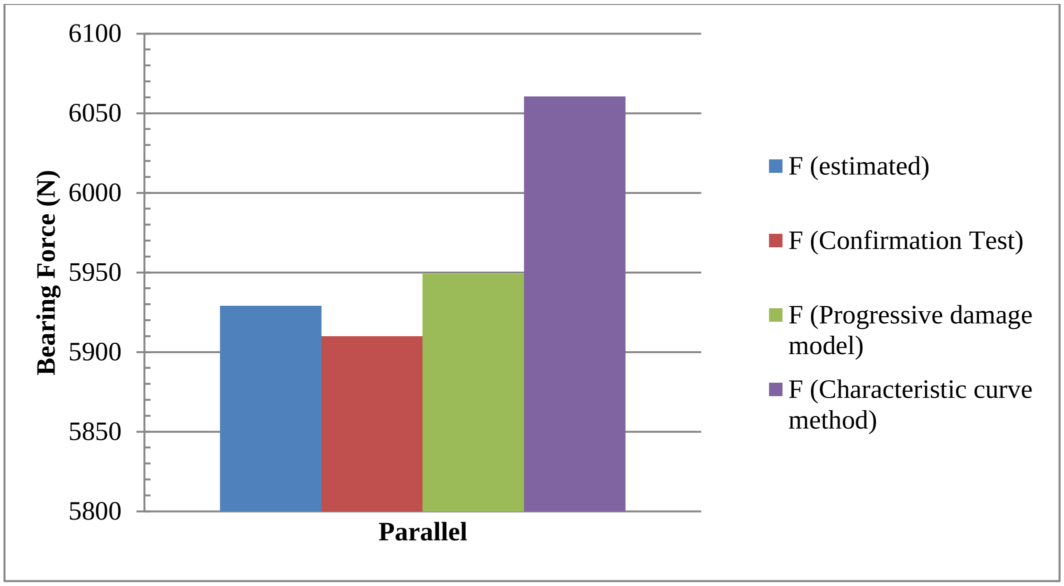


Figure 4.12: Comparison of results for parallel pin joint laminates with E/D = 4, K/D = 3 and P/D = 5

The results obtained with estimation formula, experimentation and with numerical methods *i.e.* progressive damage model and characteristic curve method are compared in Fig. 4.11 and 4.12 for the serial and parallel pin joint configuration respectively.

Chapter 5 Conclusion

In the present work, experimental and numerical study has been conducted on the polymer nanocomposites reinforced with glass fibre to obtain the optimum geometric parameters giving the highest bearing strength of the laminates in the double pin holes. The following conclusions have been drawn from the results obtained.

5.1 Conclusion

1. The maximum bearing strength for the serial pin joint laminates has been obtained at E/D= 4, W/D= 4 and P/D= 5 and the mode of failure has been observed as the bearing mode. This is due to the fact that as the E/D ratio increases, the chances of shear out failure decreases and as the W/D ratio increases, the chance of failure due to net tension decreases.
2. The maximum value of the bearing strength for the parallel pin joint laminates is obtained at E/D= 4, K/D= 3 and P/D= 5 with the bearing mode of failure at both the holes. This is again due to the fact that the shear out failure mode and net tension failure are rarely observed at E/D> 3 and K/D> 3 respectively.
3. E/D is the most significant factor for the bearing strength of the laminates in both the configurations as given by ANOVA Method.
4. Taguchi method is very effective in reducing the number of specimens required to be made for analysis and provide very reliable results on the basis of S/N ratio for each trial.
5. The Progressive Damage Analysis and the Characteristic Curve Method were applied for the numerical analyses of the failure strengths of the pin joints, whose results were in good agreement with the experimental results.

5.2 Future Scope

The present work can be studied in the following dimensions:

1. Different nano- materials can be used to increase the strength of the laminates.
2. The study can be extended to laminates with three or four pin joints.
3. Hygrothermal effects can be taken into consideration while analyzing the laminates for their failure.
4. Other mechanical joints can be used for the study.

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