Failure analysis of pin joints in glass-epoxy nanoclay composite laminates

Dissertation

Submitted in partial fulfilment of the requirement for the award of degree of

Master of Engineering

in

CAD/CAM Engineering

Submitted

by

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July 2014

Certificate

This is to certify that the dissertation entitled **"Failure analysis of pin joints in glass-epoxy nanoclay composite laminates"**, is an authentic record of my own work carried out as requirements for the award of degree of Master of Engineering in CAD/CAM from Thapar University, Patiala, under the guidance of Dr. Haripada Bhunia (Associate Professor, Chemical Engineering Department) and Dr. Jaswinder Singh Saini (Assistant Professor, Mechanical Engineering Department).

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Abstract

Fiber reinforced composite materials have been gaining wide application in aircraft submarine and spacecraft constructions. These applications require joining composites either to composites or to metals. Most commonly, joints are formed using mechanical fasteners. Therefore, suitable revealing methods for the failure strength would help in selecting the appropriate joint size in a given application. The objective of the present study is to investigate the effect of joint geometry on strength of pin-loaded glass-epoxy nanoclay nanocomposite laminates experimentally and numerically. Composite laminates were prepared using press moulding technique at 150 ^{0}C. Specimens were made according to ASTM standards. Geometric parameters that were investigated during analyses; the distance from the free edge of plate to the diameter of the first hole (E/D) ratio, width of the specimen to the diameter of the holes (W/D) ratio. Both the experimental and analytical results were compared. The Results showed that the pin hole farthest from the free edge is subjected to the highest stress. It can also be seen that geometric parameters such as E/D and W/D ratios are crucial for pinned laminated composite joints.

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1.1 Composite

Composite materials, often called as composites or composition materials are engineered or naturally occurring materials made from two or more materials with significantly different physical or chemical properties which remain separate and distinct at the macroscopic or microscopic level within the finished structure. Some examples of basic composites include concrete (cement mixed with sand and aggregate), reinforced concrete (steel rebar in concrete), and fiberglass (glass strands in a resin matrix). A common example of composite materials would be disc brake pads, which has hard ceramic particles embedded in soft metal matrix. Another example can be found in shower stalls which are made of fiberglass. Required properties of composites are high stiffness and high strength, low density, stability at high temperature, good thermal and electrical conductivity, resistance to corrosion, increased wear resistance etc.

Composites are made up of individual materials referred to as constituent materials. There are two classifications of constituent materials: matrix and reinforcement. At least one share of each type is required. The reinforcement provides their special mechanical and physical properties to enhance the matrix properties. A composite provides material properties different from its individual constituent materials, while the large variety of matrix and reinforcement materials allows the designer of the product or structure to choose an optimum combination. In matrix-based structural composites, the matrix serves mainly two purposes, holding the reinforcement phases in place and deforming so that the stresses can be distribute among the constituent reinforcement materials under applied force. The anatomy of composite is shown in Fig. 1.1.

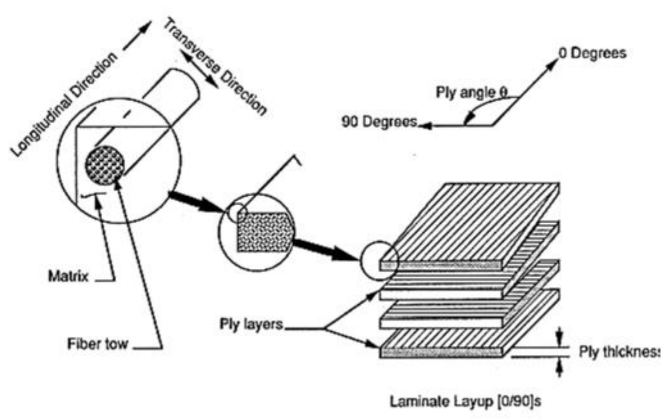


Fig. 1.1 Composite anatomy

1.2 Components of Composite Materials

Matrix Phase: Bulk materials such as metals, ceramics and polymers.

Reinforcement: fibers and particulates such as glass, carbon, Kevlar, silicon carbide, boron, ceramic, metallic and aggregate.

Interface: bounding surface where discontinuity occurs whether physical, mechanical, chemical etc.

1.2.1 Matrix

The matrix is the material into which the reinforcement is embedded, and is totally continuous. This means that there is a way through the matrix to any point in the material, two different materials joined together. In various structural applications, the matrix is usually made of lighter metal such as aluminum, magnesium, or titanium, and provides support for the reinforcement. In applications of high temperature, cobalt and cobalt-nickel alloy matrices are common.

1. The primary phase, having a continuous character.
2. Usually more ductile and less hard phase.
3. Holds the reinforcing phase and shares a load with it.

Properties of a Matrix:

The needs or desired properties of the matrix which are important for a composite structure are as follows:

- Less moisture absorption.
- Low shrinkage.
- Low thermal expansion coefficient.
- Good flow characteristics so that it can pass through the fiber bundles completely and eliminates voids during the compacting/curing process.
- Reasonable strength, modulus and elongation (elongation should be greater than fiber).
- Must be able to transfer load to fibers.
- Strength at elevated temperature.
- Low temperature capability.
- Excellent chemical resistance.
- Should be easily processable into the final composite shape.
- Dimensionally stable.

As the load is mainly carried by the fibers, the overall elongation of the composite material is governed by the elongation to failure of the fibers that is usually 1-1.5%. A necessary property of the matrix is that crack should not be formed. The job of the matrix in a composite material will vary depending on how the composite is being stressed. For example, in compressive loading case, the matrix does not allow the fibers to buckle and is, therefore, a very crucial part of the composite since without it; the reinforcement could carry no load. On the other hand, a bundle of fibers could sustain high tensile loads in the direction of the fibers without a matrix. The matrix plays a minor role in the tensile load-carrying capacity of a composite structure.

Factors considered for Selection of Matrix:

In selecting matrix material, following factors may be taken into consideration:

- The matrix must have a mechanical strength corresponding with that of the reinforcement *i.e.* both should be compatible. Thus, if strength of the fiber used as the reinforcement is high then there is no point of using a low strength matrix, which will not transmit stresses efficiently to the reinforcement.
- The matrix must stand up to the environmental conditions, viz., temperature, humidity, exposure to UV radiations, exposure to chemical atmosphere, abrasion by dust particles, etc.
- The matrix should be easy to use in the selected fabrication process.
- Life expectancy.
- The composite must be cost effective.

1.2.2 Reinforcement

The reinforcement material is embedded into the matrix. The reinforcement does not always aids purely structural task (reinforcing the compound), but is also used to enhance physical properties such as resistance to wear, coefficient of friction or thermal conductivity. The reinforcement can be either continuous, or discontinuous. Discontinuous composites may be isotropic, and can be processed with standard manufacturing techniques, such as forging, rolling or extrusion.

1. Second phase (or phases) is embedded in the matrix in a discontinuous form,
2. Usually stronger than the matrix, therefore it is also called as reinforcing phase.

Reinforcements for the composites can be fibers, fabrics particles or whiskers.

a) Fiber Reinforcement: Fibers are the most important class of reinforcements, as they meet the desired conditions and transfer strength to the matrix ingredients influencing and changing their properties as required. Glass fibers are the first known fibers used to reinforce various materials. Ceramic and metal fibers were afterward found out and put to extensive use, to contribute composites stiffer more resistant to heat. Fibers lack ideal performance due to various factors. The performance of a fiber reinforced composites is estimated by its shape, length and orientation, composition of the fibers and the mechanical properties of the matrix.

b) Glass fibers: Over 90% of the fibers used in reinforced plastics are glass fibers, as they are less costly, easy to manufacture and possess high strength and stiffness with respect to the plastics with which they are to be reinforced. Their low density, chemically resistant, insulation capacity is other bonus characteristics, although the one big disadvantage in glass is that it is sensitive to break when subjected to high tensile stress for a long time. However, it remains does not break at higher stress-levels in lesser time frames. This property represents the effective strength of glass especially when glass is expected to bear loads for many months or years continuously.

c) Metal fibers: As reinforcement, metal fibers possess many advantages. They can be easily produced using various manufacturing processes and has more ductility; they are less sensitive to surface damage and possess good strength and resistance to temperature. However, weight and problem of reacting each other through alloying mechanisms has major disadvantage. Ceramic fibers improve largely in performance when a fine metal outline is used with refractory ceramics by improving their thermal shock and impact resistance properties.

1.2.3 Interface

It has characteristics that are not portrayed by any of the component in isolation. The interface is a bounding surface where a discontinuity occurs, whether physical, mechanical, chemical etc. The matrix material should “wet” the fiber. Coupling agents are used to improve wettability. Good “wetted” fibers increase the interface surfaces area. To obtain required properties in a composite, the load should be effectively shared from the matrix to the fibers through the interface. This means that the interface must be large and should have good adhesion between fibers and matrix. Performance of Composite depends on:

1. Properties of matrix and reinforcement.
2. Size and dispersion of constituents.

3. Shape of constituents.
4. Type of interface between constituents.

1.3 Advantages of Composite

- High resistance to fatigue and corrosion deterioration.
- High ‘strength to weight’ ratio. Weight savings are significant ranging from 25-45% of the weight of conventional metal components.
- Due to good reliability, there are very less inspections and repairs of structures.
- Improved resistance to dents is normally achieved. Composite panels do not damage as easily as thin gage sheet metals.
- Composites offer enhanced torsional stiffness. This means high whirling speeds, less number of intermediate bearings and supporting structural elements. The overall part count, manufacturing and assembly costs are thus reduced.
- Greater resistance to impact damage.
- Composites are dimensionally stable *i.e.* they have low thermal conductivity and low coefficient of thermal expansion. Composite materials can be tailored to comply with a broad range of thermal expansion design requirements and to minimize thermal stresses.
- The improved weatherability of composites in a marine environment as well as their corrosion resistance and durability reduce the down time for maintenance.
- Close tolerances can be obtained without machining.
- Material is reduced because composite parts and structures are frequently built to shape rather than machined to the required configuration, as is common with metals.

1.4 Disadvantages of Composites

- High cost of raw materials and fabrication.
- Composites are brittle than wrought metals and thus are more easily damaged.
- Transverse properties can be weak.
- Matrix is weak, therefore, toughness is low.
- Reuse and disposal may be difficult.
- Repair may introduce new problems.
- Materials require refrigerated transport and storage and have limited shelf life.

- Hot or cold curing takes time.
- Analysis is very difficult.
- Matrix is subject to environmental degradation.

1.5 Classification of Composites

Composites are commonly classified with respect to Matrix and Reinforcement constituents.

Classification made with respect to the Matrix constituent

The classification made with respect to the matrix phase is as follows:-

1. Polymer-matrix composites (OMCs).
2. Metal-matrix composites (MMCs).
3. Ceramic-matrix composites (CMCs).

Various types of matrices as discussed above have been shown below in Fig. 1.2.

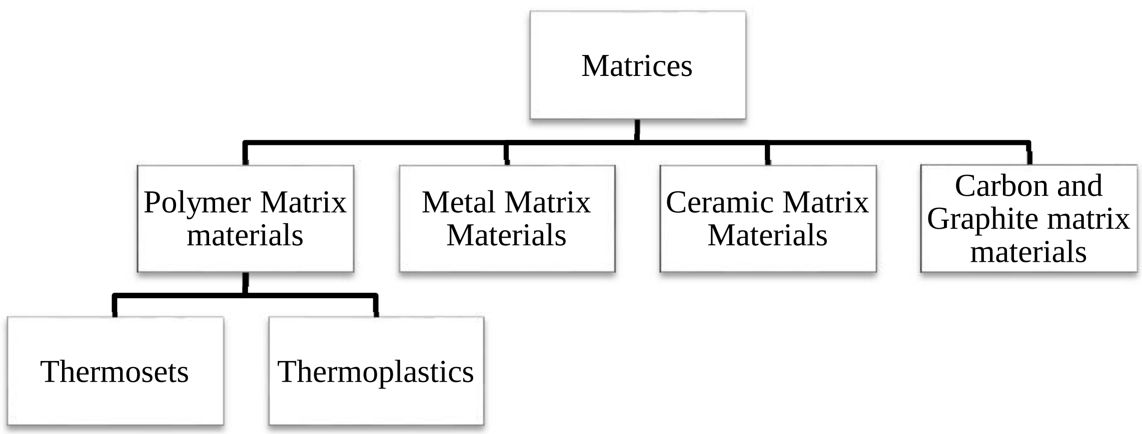


Fig. 1.2 Classifications with respect to the matrix constituent

1.5.1 Polymer Matrix Materials

Polymers make ideal materials as they can be treated easily, possess lightweight, and required mechanical properties. It follows, therefore, that high temperature resins are lagely used in aeronautical applications. Two main kinds of polymers are thermosets and thermoplastics:-

(a) Thermosets

Thermosets have cross-linked or network structures with covalent bonds with all molecules. They do not soften but disintegrate on heating. Once solidified by cross-linking process they cannot be reshaped.

Common examples are epoxies, polyesters, phenolics, ureas, melamine, silicone, and polyimides. Fig.1.3 shows some kinds of thermosets.

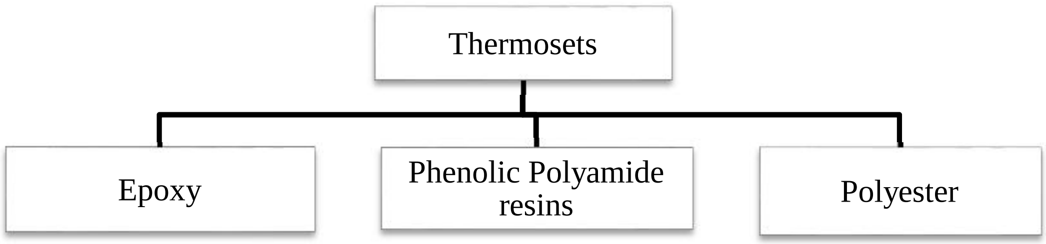


Fig. 1.3 Various types of thermosets

Direct condensation polymerization followed by rearrangement reactions to form heterocyclic entities is the method generally used to produce thermoset resins. Water, a product of the reaction, in both methods, prevents production of void-free composites. These gaps have a negative effect on properties of the composites in terms of strength and dielectric properties.

Epoxy resins are largely used in filament-wound composites and are compatible for moulding prepress. They are stable to chemical attacks and are excellent adherents having slow shrinkage during curing and no emission of gases. These benefits, however, make the use of epoxies rather expensive. Also, they cannot be expected above a temperature of 140ºC. Use in high technology areas where temperatures are higher, as a result, is ruled out.

Polyester resins on the other hand are quite accessible, cheap and find use in a wide range of fields. Liquid polyesters are stored at room temperature for number of months, sometimes for years and the addition of a catalyst can treat the matrix material within a very less time. They are used in automobile and structural applications.

(b) Thermoplastics

Thermoplastics consist of linear or branched chain molecules which has strong intramolecular bonds and weak intermolecular bonds. Their shape can be altered by application of heat and pressure. At high temperature they can be changed into any shape. Examples include polyethylene, polypropylene, polystyrene, nylons, polycarbonate, polyacetals, polyamide-imides, polyether ether ketone, polysulfone, polyphenylene sulfide, polyether imide. Fig.1.3 shows the types of thermoplastics.

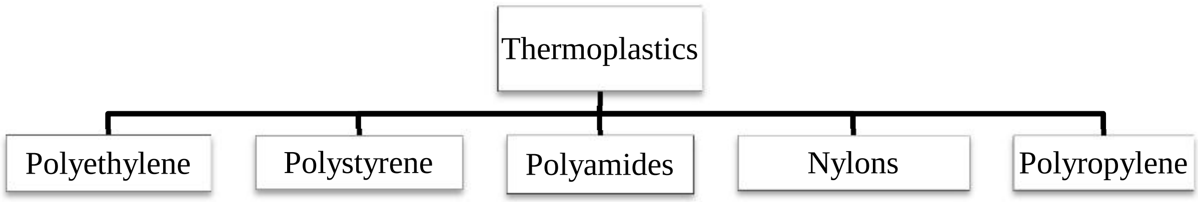


Fig. 1.4 Types of thermoplastics

A small amount of shrinkage and the tendency of the shape to maintain its original form are also to be accounted for. But reinforcements can change this condition too. The advantage of thermoplastics systems over thermosets are that there are no chemical reactions involved, which often result in the release of gases or heat. Manufacturing is limited by the time required for heating, shaping and cooling the structures.

Thermoplastics resins are sold as moulding compounds. Fiber reinforcement is apt for these resins. Since the fibers are randomly dispersed, the reinforcement will be almost isotropic. However, when subjected to moulding processes, they can be aligned directionally.

There are a few options to increase heat resistance in thermoplastics. Addition of fillers increases the heat resistance. At elevated temperatures the strength of all thermoplastic composites starts decreasing.

1.5.2 Metal Matrix Materials

Metal matrix composites are those in which matrix material is made of metals and reinforcing material can be anyone. High strength, fracture toughness and stiffness are the properties better than those offered by their polymers. Most metals and alloys could be used as matrices and they need reinforcement materials which have to be stable over a range of temperature and non-reactive with others too. However the guiding aspect for the choice depends essentially on the matrix material. Light metals are used as matrix for temperature application.

Most metals and alloys form good matrices. However, practically, the choices for low temperature applications are not many. Only light metals are responsive, with their low density as an advantage.

Aluminium, Titanium and magnesium are the most popular matrix metals currently in use, which are particularly useful for aircraft applications. If metallic matrix materials have to offer high strength, they require high modulus reinforcements. The strength-to-weight ratios of resulting composites can be higher than most alloys.

Most metals, ceramics and compounds can be used with matrices of low melting point alloys. With increase in the melting temperature of matrix materials, the reinforcement material has to be selected carefully.

1.5.3 Ceramic Matrix Materials

Ceramics are solid materials which has very strong ionic bonding in general and in very few cases covalent bonding. High melting points, good resistance to corrosion, stable at elevated temperatures and high compressive strength, makes ceramic-based matrix materials best for applications that requires a structural material that doesn't give up at temperatures above 1500ºC. Naturally, ceramic matrices are the best choice for high temperature applications.

A material is reinforcement to make use of the high tensile strength of the fiber, to enhance the load bearing capacity of the matrix. The use of reinforcement with high modulus of elasticity may take care of the problem to some extent and presents pre-stressing of the fiber in the ceramic matrix is being increasingly resorted to as an option.

When ceramics have a higher thermal expansion coefficient than reinforcement materials, the resultant composite is unlikely to have a superior level of strength. In that case, the composite will develop strength within ceramic at the time of cooling resulting in microcracks extending from fiber to fiber within the matrix. Microcracking can result in a composite with tensile strength lower than that of the matrix.

Classification made with respect to Reinforcement constituent

Reinforcements for the composites can be fibers, fabrics particles or whiskers. Fibers are usually characterized by one very long axis with other two axes either often circular or near circular. Particles have no specific orientation and so does their shape. Whiskers have a specific shape but are small both in diameter and length as compared to fibers. Fig. 1.5 shows types of reinforcements in composites.

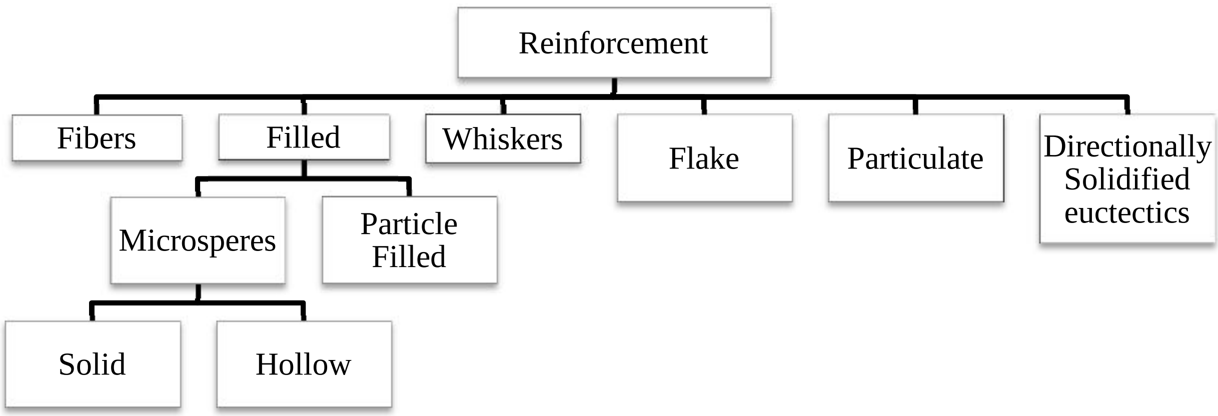


Fig. 1.5 Classification with respect to reinforcement constituent

(i) Fiber Reinforcement

Fibers are the most important class of reinforcements, as they meet the desired conditions and transfer strength to the matrix ingredients influencing and changing their properties as required. Glass fibers are the first known fibers used to reinforce various materials. Ceramic and metal fibers were afterward found out and put to extensive use, to contribute composites stiffer more resistant to heat. Fibers lack ideal performance due to various factors. The performance of a fiber reinforced composites is estimated by its shape, length and orientation, composition of the fibers and the mechanical properties of the matrix.

Unidirectional loading is found in few structures and hence it is wise to give a mix of orientations for fibers in composites particularly where the load is expected to be the heaviest. The strength of the fiber in any one of the three directions would, therefore be $\frac{1}{3}$rd the unidirectional fiber composite, assuming that the volume percentage is equal in all three axes. Short fibers with proper orientation composites that use glass, ceramic or multi-purpose fibers can be endowed with considerably higher strength than those that use continuous fibers. Small fibers are also known to their theoretical strength. The continuous fiber constituent of a composite is often joined by the filament winding process in which the matrix infuse fiber wrapped around a mandrel shaped like the part over which the composite is to be placed, and equitable load distribution and favorable orientation of the fiber is possible in the finished product. However, winding is mainly known for fabrication of bodies of revolution and the occasional irregular, flat surface. Most fibers in use currently are solids which are easy to produce and handle, having a circular cross-section, although a few non-conventional shaped and hollow fibers show signs of capabilities that can improve the mechanical qualities of the composites.

Given the fact that the vast difference in length and effective diameter of the fiber are assets to a fiber composite, it follows that greater strength in the fiber can be obtained by smaller diameters due to minimization or total elimination of surface of surface defects.

(ii) Laminar Composites

Laminar composites are found in as many combinations as the number of materials. They can be described as materials comprising of layers of materials bonded together. These may be of several layers of two or more metal materials occurring alternately or in a determined order more than once, and in as many numbers as required for a specific purpose.

Pre-painted or pre-finished metal whose primary advantage is elimination of final finishing by the user is the best known metal-organic laminate. Several combinations of metal-plastic, vinyl-metal laminates, organic films and metals, account for up to 95% of metal-plastic laminates known. They are made by adhesive bonding processes.

(iii) Flake Composites

Flakes are often used in place of fibers as can be closely packed. Metal flakes that are in close contact with each other in polymer matrices can conduct electricity or heat, while mica flakes and glass can resist both. Flakes are not costly to produce and usually cost less than fibers.

Glass flakes usually create notches or cracks around the edges, which weaken the final product. They are also resistant to be lined up parallel to each other in a matrix, causing uneven strength. They are usually set in matrices, or more simply, held together by a matrix with a glue-type binder. Depending on the end-use of the product, flakes are present in small quantities or occupy the whole composite.

Flakes have various benefits over fibers in structural applications. Parallel flakes filled composites provide uniform mechanical properties in the same plane as the flakes. Flake composites have a higher theoretical tensile modulus of elasticity than fiber reinforced composites. They are relatively cheaper to produce and can be handled in small quantities.

(iv) Filled Composites

Filled composites outcomes from addition of filer materials to plastic matrices to replace a portion of the matrix, enhance or change the properties of the composites. The fillers also increase strength and reduce weight. Fillers produced from powders are also considered as particulate composite. In the open matrices of a porous or spongy composite, the formation is the natural result of processing and such matrices can be strengthened with different materials. Metal impregnates are used to improve strength or tolerance of the matrix. Metal casting, graphite, powder metallurgy parts and ceramics fall in this class of filled composites. In the honeycomb structure, the matrix is not naturally formed, but specifically designed to a predetermined shape.

Fillers may be the main component or an additional one in a composite. The filler particles may be irregular structures, or have precise geometrical shapes like polyhedrons, short fibers or spheres. The final composite properties can be affected by the shape, surface treatment, blend of particle types, size of the particle in the filler material and the size distribution.

(v) Particulate Reinforced Composites

Microstructures of metal and ceramics composites, which show particles of one phase scattered in the other, are known as particle reinforced composites. Square, triangular and round shapes of reinforcement are very common, but the dimensions of all their sides are observed to be more or less equal.

The dispersed size in particulate composites is of the order of a few microns and volume concentration is greater than 28%. The difference between particulate composite and dispersion strengthened ones is, thus, oblivious. The mechanism used to strengthen each of them is also different. The dispersed in the dispersion-strengthen materials reinforces the matrix alloy by arresting motion of dislocations and needs large forces to fracture the restriction created by dispersion.

Three-dimensional reinforcement in composites offers isotropic properties, because of the three systematical orthogonal planes. Since it is not homogeneous, the material properties acquire sensitivity to the constituent properties, as well as the interfacial properties and geometric shapes of the array. The composite’s strength usually depends on the diameter of the particles, the inter-particle spacing, and the volume fraction of the reinforcement. The matrix properties influence the behavior of particulate composite too.

1.6 Glass Fiber Reinforced Polymer (GFRP)

Glass fibers are among the most versatile industrial materials known today. They are produced from raw materials, which is available in unlimited supply. They show useful properties such as hardness, transparency, chemically resistant, stable, as well as desirable fiber properties such as flexibility, strength and stiffness.

The basic raw materials for fiberglass products are a variety of natural minerals and manufactured chemicals. The major constituents are silica sand, limestone, and soda ash. Other ingredients may be alumina, borax, nepheline syenite, magnesite, and kaolin clay. Silica sand is used as the glass former, soda ash and limestone helps in lowering the melting temperature. Other ingredients are used to improve other properties, such as borax for chemical resistance. Waste glass, also called cullet, is also used as a raw material. The raw materials are weighed carefully in exact quantities and thoroughly mixed together (called batching) before being melted into glass.

1.6.1 Advantages of Glass Fibers

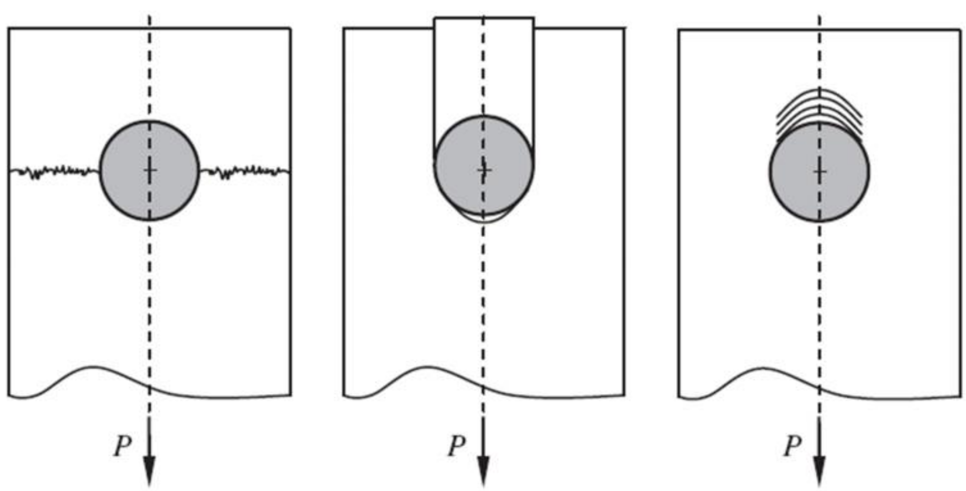
- Expected lifespan - over 100 years.
- The reduction in constant load from its own weight allows either improving its effective load-carrying capability.
- Quick installation: The installation process consists of bridge deck assembly and on-site mounting - the bridge is opened for traffic within no more than 1-5 weeks. For bridges having large blocks, the bridge deck can be mounted within no more than a few hours.
- This technology is environment friendly as the bridge is prefabricated, does not require scaffolding and negates any construction site contamination.
- Minimal operating and maintenance costs for many years - GFRP Composite bridge structures are resistant to climate effects, do not get corroded or degrade in quality and only require repainting once in a decade.
- All-year-round construction regardless of climate conditions.

1.7 Joints in composite structures

In the last decade, composite materials are being 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. Fiber-reinforced composites offer the most reliable engineering materials in automotive, marine and aircraft industrial engineering applications due to their outstanding mechanical properties, like impact resistance, high durability, low coefficient of friction and thermal expansion, ability to provide higher load bearing capability in the directions of high loading, flexibility in design capabilities and relatively low density.

The applications usually require the joining of composites either to other composites or to metals. 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. But these joints are usually weak points in structures due to complicated stress field in the vicinity of the hole. They are susceptible to high stress concentrations which occur around and in the vicinity of the hole and are often the cause of unexpected failure in composite structures containing joints [**Aluko** (2011)]. The high stress concentrations reduce the efficiency of the joint along with the redistribution of stresses near the discontinuities [**Kishore** *et al.* (2009)]. Because of the complicated stress field near the hole area, they often causes a reduction of load capacity of composite structure. Further, in pursuit of increasing efficiency of the structure, the operational load continues to grow, the load carried by each fastener increases accordingly. This increases probability of failure.

The literature shows that there are five basic failure modes for composite mechanical joints: net tension, shear out, bearing, tear out and cleavage [**Pisano** *et al.* (2012)], shown in Fig. 1.6.



(a) *Net-tension* (b) *Shear-out* (c) *Bearing*

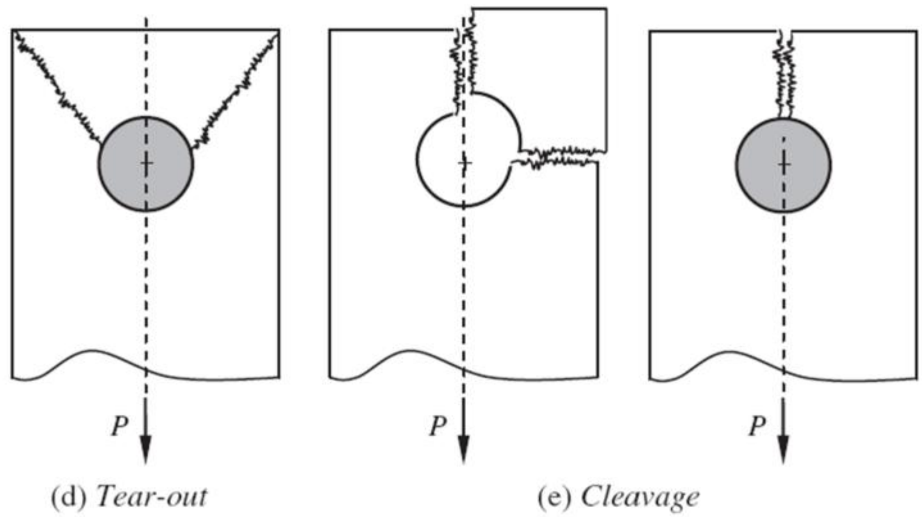


Fig. 1.6 Common failure modes in composite plates [**Pisano** *et al*. (2012)]

Studies show that the failure behaviors of mechanical joints can be affected by many parameters, such as the geometric dimensions, material properties, laminate lay-up, ply orientation, and fit, whether clearance or interference, between the pin and the hole **Aktas** and **Dirikolu** (2004) grouped the parameters into following different types:

- **i. Material parameters:** fiber types and form, resin type, fiber orientation, laminate stacking sequence, etc.
- **ii. Geometry parameters:** specimen width (W) or ratio of width to hole diameter (W/D), edge distance (E) or ratio of the edge distance to hole diameter (E/D), specimen thickness (t), hole size (D), and pitch for multiple joints.
- **iii. Fastener parameters:** fastener type, fastener size, clamping area and pressure, washer size and hole size and tolerance.
- **iv. Design parameters:** loading type (tension, compression, fatigue, etc.), loading direction, joint type (single lap, double lap), geometry (pitch, edge distance, hole pattern etc.), environment and failure criteria.

The present work deals with the failure analysis of pin joint based on the geometry parameters *i.e.* specimen width to hole diameter (W/D) and edge distance to hole diameter (E/D), keeping the material parameters constant.

Numbers of researchers have worked on the failure analysis of pinned joints in polymer composites. A brief review of such work is discussed in the following paragraphs.

Aslan *et al.* (2001) examined the effects of woven fiber, specimen width-to-hole diameter ratio (W/D), and the ratio of edge distance to hole diameter (E/D) on the bearing strength of woven laminated composites. Glass/epoxy composites were manufactured under pressure by moulds at 120^0C. The mechanical properties and strengths of the composites were obtained experimentally. The glass/epoxy woven composites were loaded through pins. Single-hole pin-loaded specimens were tested for their tensile response and W/D and E/D ratios were evaluated. Failure propagation and failure type were observed on the specimens. The experimental results show that the ultimate load capacity was increased by increasing W and E. However, increasing the E/D ratio beyond 2 and increasing the W/D ratio beyond 3 have an insignificant effect on the ultimate load capability of the connection.

Okutan (2002) determined the failure of mechanically fastened fiber-reinforced laminated composite joints. Mechanical properties and strengths of the composite were obtained experimentally. Tests have been carried out on single pinned joints in [0/90/0] and [90/0/90] laminated composites. A parametric study considering geometries was performed to identify the failure characteristics of the pin-loaded laminated composite. Data obtained from pin-loaded laminate tests were compared with the ones calculated from a Finite Element Model. Damage accumulations in the laminates were evaluated by using Hashin's failure criteria.

Okutan and Karakuzu (2003) investigated the response of pin-loaded laminated composites. Tensile tests were performed on E/glass-epoxy composites for two different ply orientations such as [0/45] and [90/45]. For each ply orientation, 20 different geometries were chosen. The major focus of the study was to characterize the failure mechanisms and to evaluate the effect of geometric dimensions on the bearing, shear-out and net-tension strengths of pinned joints. The specimens were tested to find first and final failure load. Comparisons were made between the experimental and numerical results.

McCarthy *et al*. (2005) studied the effects of bolt–hole clearance on the mechanical behaviour of bolted composite (graphite/epoxy) joints. The joint type studied was single-bolt, single-lap, which is a standard test configuration in both a civilian and a military standard for composite joints.
Experimental results of surface strains and joint stiffness were compared with Finite Element parameter study involving variations in mesh density, element order, boundary conditions, analysis type and material modeling. The model had the ability to capture three-dimensional effects such as secondary bending and through-thickness variations in stress and strain

Icten *et al.* (2006) determined the failure mode and the failure load of mechanically fastened joints in woven kevlar epoxy composite plates. Two-dimensional finite element was performed to predict damage initiation, progression and strength of joints. Hashin, Hoffman and Maximum Stress criteria were used in this failure analysis. Experiments were performed to find the failure load and to predict the failure mode. Parametric studies were also carried out to evaluate the effect of joint geometry on this analysis. Comparisons were made between the experimental and numerical results.

Baba (2006) investigated the effects of joint geometry and fiber orientation on the failure strength and failure mode in a pinned joint laminated composite plate. Behavior of pin-loaded laminated composites with different stacking sequence and different dimensions was observed experimentally. Single-hole pin-loaded specimens were tested for their tensile response and width-to hole diameter (W/D) and edge distance-to-hole diameter (E/D) ratios were evaluated. A series of experiments was performed with six different material configurations ($[0/45]_s$ –$[90/45]_s$, $[0/90/0]_s$–$[90/0/90]_s$ and $[90/0]_{2s}$–$[45]_{2s}$), in all, over 120 specimens. All the connections tested showed that the fiber orientations have a definite influence on the position around hole circumference at which failure initiated. Net-tension failure occurred for specimens that had small width and large end distance. When the width was increased, the specimens which had small end distances failed in the shear-out modes. When the end distance was increased, bearing failure developed in addition to shear-out failure. The experimental results showed that the ultimate load capacities of E/glass–epoxy laminate plates with pin connection were increased by increasing W and E.

Karakuzu *et al.* (2008) investigated various failure mode, failure load and bearing strength in a laminated woven glass-vinylester composite plate with two parallel circular holes which were subjected to traction forces by two parallel rigid pins. The behaviors of pin loaded composite plates with various dimensions were observed both experimentally and numerically. The edge distance-to-hole diameter (E/D), the distance between two holes-to-hole diameter (M/D) were selected as parameters. The numerical study was performed by using Finite Element software, LUSAS 13.6. Hashin failure criteria were used to obtain failure load and failure mode.

Karakuzu *et al.* (2008) investigated the effects of geometrical parameters such as the edge distance-to-hole diameter ratio (E/D), plate width-to-hole diameter ratio (W/D), and the distance between two holes-to-hole diameter ratio (M/D) on the failure loads and failure modes in woven-glass–vinylester composite plates with two serial pin-loaded holes, experimentally and numerically. In the numerical analysis, the Hashin failure criterion was used in order to determine failure loads and failure modes. LUSAS commercial Finite Element software was utilized during the analysis. The numerical and experimental results showed that the ultimate load capacity of woven-glass–vinylester laminates with pin connections increased by increasing the ratios of E/D, W/D, and M/D.

Sen *et al*. (2008) determined the failure mode and bearing strength of mechanically fastened bolted-joints in glass fiber reinforced epoxy laminated composite plates, experimentally. Two different geometrical parameters *i.e.* the edge distance-to-hole diameter ratio (E/D) and plate width-to-hole diameter ratio (W/D) were considered. For the purpose, E/D ratio was selected from 1 to 5, whereas W/D ratio was chosen from 2 to 5. To determine material parameters effect, laminated plates were stacked as three different group which are $[0/0/45/-45]_s$, $[0/0/45/45]_s$ and $[0/0/30/30]_s$, symmetrically. In addition, the preload moments were applied as 0, 3 and 6 Nm. Results showed that failure modes and bearing strengths considerably increased with increased preloads. Furthermore, when the material and geometrical parameters of composite bolted-joints were changed, the failure behavior and bearing strengths changed.

Uddin and Sun (2008) studied the strength of unidirectional glass/epoxy composite with silica nanoparticle enhanced matrix. A commercially available standard DGEBA epoxy with silica nanoparticles (Nanopox F 400) was used as the matrix to make fiber composites. The silica nanoparticles in Nanopox were grown in situ via a sol–gel process resulting in a concentration of 40 wt% which was later diluted to 15 wt% particle loading. TEM images showed very uniform dispersion of silica nanoparticles with a size distribution of about 20 nm. Compression test revealed a substantial improvement (40%) in elastic modulus of the modified epoxy. Inclusion of silica nanoparticles dramatically increased the longitudinal compressive strength and moderately increased the longitudinal and transverse tensile strengths.

Aktas *et al.* (2009) investigated failure load and failure mode of glass-epoxy composite plates with single and double parallel pinned-joints experimentally and numerically. Two variables were investigated during analyses; the distance from the free edge of 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. The numerical study was performed using ANSYS. Yamada-Sun failure criterion was used for failure analyses. The results showed that the pin hole farthest from the free edge is subjected to the highest stress.

Atas (2009) presented a step-by-step procedure for transforming an orthogonal fabric into a non-orthogonal fabric with small weaving angles. Four different stacking sequences were chosen for comparison, considering ratios of W/D to be 3, 4 and E/D to be 1, 2, and 3. It was concluded that using layers with identical orientations may result in undesirable severe damage modes and small load carrying capacities in mechanically fastened joints of woven fabric composites with small weaving angles.

Kishore *et al.* (2009) investigated various failure modes and failure loads for multi-pin joints in unidirectional glass fiber/epoxy composite laminates by Finite Element Analysis and validating the results with the experimental work. In multi-pin joints, the effect of variation in pitch-to-diameter ratio (P/D) is also important, in addition to side width-to-diameter (S/D) and edge-to-diameter (E/D) ratios. A two-dimensional Finite Element model was developed using ANSYS software. Tsai–Wu failure criteria associated with material property degradation was used in the analysis to predict failure load and to differentiate failure modes. Experimental and Finite Element analysis results showed that it is very important to consider the effect of E/D, S/D and P/D ratios in designing multi-pin joints.

Osman (2010) investigated the bearing strength behavior of pinned joints of glass fiber reinforced composite filled with different proportions of Al_2O_3 particles, as a function of filler loading and joint geometry. The weight fractions of the filler in the matrix were 7.5, 10 and 15%. Single-hole pin-loaded specimens of each composite material were tested in tension. The results showed that the bearing strength of glass fiber reinforced epoxy composites pinned joints was associated with the filler content and geometric parameters. The increase of the Al_2O_3 particle loading in the matrix improved the bearing strength of the composites. The highest bearing strengths were obtained for composite specimens with 10 wtz. % Al_2O_3 particle content. Further increase in the Al_2O_3 particle content in the matrix resulted in decrease of the bearing strength, but remains above that of the unfilled glass reinforced epoxy composites.

Wei *et al.* (2011) studied the effect of SiO_2 nanoparticles modified epoxy on the basalt fiber rovings. The SiO_2 nanoparticle–epoxy composite coating gave rise to a significant increase in the tensile strength of the basalt fibers as compared with the pure epoxy coating, and also the coating endowed the basalt fiber with a promising interfacial property in the basalt fiber reinforced resin matrix composite. The coating modification was an effective way in improving the mechanical properties of basalt fibers and the properties of basalt fiber/epoxy resin composites.

Aktas (2011) studied the failure modes and failure loads of woven glass epoxy composite plates. The plates with one and two serial pinned joints were analyzed numerically and experimentally. Two variables were investigated during analysis; the distance from the free edge of 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. The result showed that the maximum failure load was obtained at E/D and W/D ratios to be 4.

Ondurucu *et al.* (2012) investigated damage development process of glass–epoxy laminated composite pinned-joints. To determine the effects of joint geometry and stacking sequence on the bearing strength and damage mode, experimental studies were carried out. Two different geometrical parameters *i.e.* the edge distance-to-hole diameter ratio (E/D) and plate width to hole diameter ratio (W/D) were considered. E/D and W/D ratios were selected from 1 to 5 and 2 to 5, respectively. By observing the effect of material parameters on damage development, composite laminated plates were stacked as two different orientations [0/90/0] and [90/0/90]. A total of 144 specimens with nine different geometries were tested to obtain the experimental strength and failure mode.

Lingaraju *et al.* (2012) studied the behavior of pin loaded laminated composite plates with different dimensions experimentally. The aim was to investigate the stress, failure load and failure mode in laminated glass epoxy/polystyrene composite plates with one circular hole. The hole of the plate was subjected to a traction force by rigid pin. The analysis was then extended to find the effect of varying K/D and W/D. It was observed that the strength of the specimen increases with the increase in K/D and W/D to an extent and then becomes constant. W/D has a greater effect on the mode of failure.

Ilic *et al.*(2012) used Finite Element Method to determine the stress distribution around the fastener hole. Tsai-Wu initial failure criterion was used to analyze joint failure. Attention was paid to pin-load distributions and its effect on the load level of failure and its location. The influence of stacking sequences of layered composites containing pin-loaded holes was also investigated. Special attention was paid to failure load and mode analyses in composites with stacking sequence [0/+45/-45/90].

Irisarri *et al.* (2012) used Finite Element modeling for strength prediction, and especially bearing strength prediction, of mechanically fastened joints in CFRP laminates. Delamination onset and propagation was explicitly taken into account in the model by means of cohesive elements. The ply behavior was described through a viscoelastic model combined with a progressive damage approach. A multi-model calculation strategy was developed to reduce the calculation costs. Prediction of the proposed model was compared to both bearing tests and open-hole tests results.

For further validation, numerical predictions were also compared to filled-hole tensile tests and bearing/bypass interaction tests. The obtained results demonstrated the capability of the proposed model to capture the material and stacking sequence effects on the joint behaviour and strength, as well as the influence of the geometrical dimensions of the joint.

Pisano *et al.* (2012) studied the prediction of the failure mechanism of pinned joints in composite laminates. Upper and lower bounds to the collapse (failure) load multiplier of statically loaded joints, fastening orthotropic laminates in plane stress conditions, were worked out via a limit analysis numerical procedure carried out at lamina level. Such a layer-by-layer approach, taking into account the actual stacking sequence of the laminate, was able to tackle the addressed problem with very good accuracy so resulting in an effective design tool. A large number of experimental data, detected on real prototypes and available in the relevant literature, were considered to validate the proposed procedure.

Sharma *et al. (2012)* studied the effect of modified epoxy with nanoclay cloisite 30B (at 1, 3 and 5 wt% of resin) on the unidirectional glass fibers. The nanocomposites were characterized by X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM). XRD results show that the interlayer spacing between the clay platelets increased significantly indicating that the polymer was able to intercalate between the clay layers. The mechanical properties were measured by carrying out tensile, hardness and flexural tests and values were compared with those found for fiber reinforced neat epoxy composites. The tests show that an addition of nanoclay up to 3 wt% increases tensile strength and micro-hardness and there is a decrease in values with further clay addition up to 5 wt%.

Khashaba *et al.* (2013) studied the influence of specimen stacking sequences on the mean bearing strength, mean ultimate failure stress, failure displacement and bearing stiffness. Four configurations were studied: $[0/90]_{2s}$, $[15/-75]_{2s}$, $[30/-60]_{2s}$, and $[45/-45]_{2s}$. The results showed that the apparent bearing stiffness was qualitatively agreed with the predicted Young's modulus. Specimens with $[0/90]_{2s}$ stacking sequence had the maximum failure displacement and ultimate failure stress compared with the other stacking sequences. On the other hand, specimens with $[45/45]_{2s}$ stacking sequence have the maximum failure displacement and bearing capacity based on the first-peak criterion.

Qin *et al.* (2013) revealed the effect mechanisms of different fasteners on mechanical behaviors of composite bolted joints. Double-lap composite joints joined by protruding head or countersink fasteners were focused on and their mechanical behaviors were characterized. Differences in the joint strength, stiffness and failure mode between protruding head joint and countersink joint were depicted experimentally. Further comprehensive understanding of the fastener effects was provided by Finite Element Analysis, which embraced net-fit, clearance-fit and clearance-fit with preload cases and considered the influences of contact models. For composite joints with protruding head or countersink fasteners, the changes of contact area, fastener bending, local deformation and stress distributions around fastener hole were detailed analyzed based on the numerical results.

2.1 Problem Formulation

Fiber reinforced composite materials have been gaining wide application in aircraft submarine and spacecraft constructions etc. These applications require joining composites either to composites or to metals. Most commonly, joints are formed using mechanical fasteners. Therefore, suitable revealing methods for the failure strength would help in selecting the appropriate joint size in a given application. From the literature review it is seen that various parameters have to be study to find the strength of pin joints. Moreover very less amount of work is reported on the effect of addition of filler particles on the strength of pin joints. Hence the present work deals with the development of nanocomposites using nanoclay (Cloisite 30B) as filler material. Thereafter the developed material is used to prepare the samples for the pin joints. These pin joints are then analyzed both experimentally and numerically.

2.2 Objectives

The specific objectives are:

1. Preparation of epoxy based unidirectional glass fabric nanocomposite laminates.
2. Preparation of pin joint samples based upon optimized nanomaterial.
3. Failure analysis of single pin joints for unfilled and filled glass epoxy nanocomposite laminates.

The following section gives the details of different materials used, methodology followed and different apparatus used for the experimentation in the present work.

3.1 Materials

3.1.1 Resin

Materials used for the preparation of the laminates were epoxy, hardener, accelerator and glass fabric. The epoxy used 'L-12' also known as Lapox is DGEBA (Di Glycidyl Ether of Bisphenol-A). K-12 hardener and K-13 accelerator were used. Resin *i.e* (epoxy, hardener and accelerator) were supplied by Atul Ltd., Gujarat, India (www.atul.co.in).The properties of epoxy, Hardener and accelerator are shown in Table 3.1, 3.2 and 3.3.

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	cPs	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)	Flexural Strength (N/mm^2)	Compressive Strength (N/mm^2)	Impact Strength (KJ/mm^2)	Co-efficient of Liner Thermal($^oK^{-1}$)
L-12(100)+K-12(100)+K-13	1.80-1.85	70-90	15000-16000	100-120	190-210	4-7	28-32 x 10^{-6}

3.1.2 Glass Fabric

Unidirectional glass fabric used as reinforcing agent was supplied by the Owens Corning India Pvt. Ltd, Mumbai (www.owenscorningindia.com). It was Advantex Unidirectional 1200 gsm fabric as shown in Fig.3.1. Mechanical and physical properties of unidirectional glass fabric are shown in Table 3.4 and 3.5. Weaving characteristics and specifications of glass fabric are shown in Table 3.6 and 3.7.

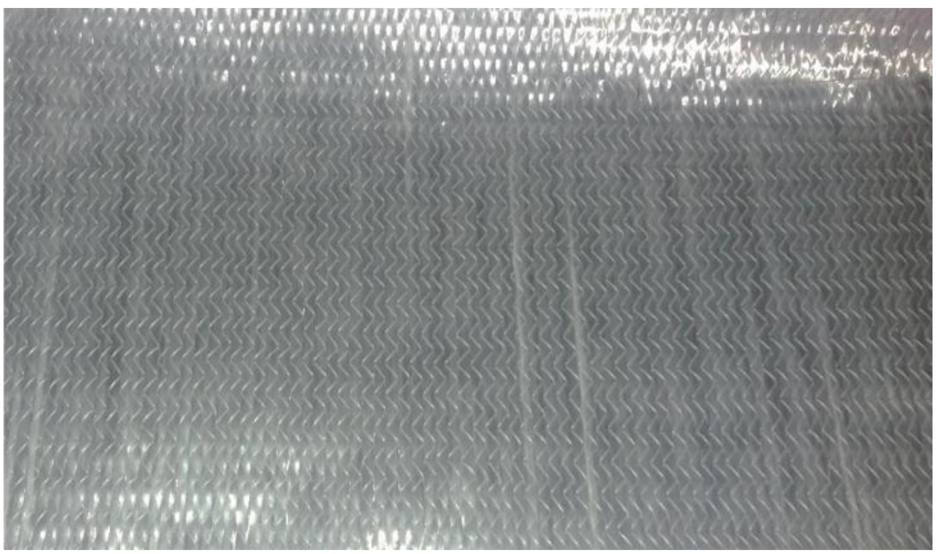


Fig. 3.1 Glass Fabric

Table 3.4 Mechanical properties of unidirectional fabric

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 unidirectional fabric

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

Table 3.6 Weave characteristics of glass fabric

Layer	Nominal	Tex	Yarns/cm	Filament	Roving type	Test method
0^0	1150	2400	4.72	17	ADVANTEX/SE 1500	ISO 1889
90^0	50	300	3.93	17	ADVANTEX/SE 1500	ISO 1889
Chopped strands	50	35		13	ADVANTEX / CS 495-2400 TEX	ISO 1889
Stitching	15	180			PES	ISO 3374
Total aerial weight	1265 +/-3% gm/m^2 , incl. stitching					
Stitch pattern	Tricot					
Stitch gauge	E-7					
Glass type	Advantex					

Table 3.7 Glass fabric specifications

	Specifications			**Actual**			**Test method**
	Min	Normal	Max	Min	Normal	Max	
Weight uniformity(gr/m^2)	1198	1262	1325	1250	1269	1280	ISO 3374
Width	54.5	55	55.5	54.8	55	55.2	ISO 5025
Stitch length	4.8	5	5.2	5	5	5	Calibrated scale
Moisture	0	0.03	0.05	0.08	0.14	0.19	Moisture

3.1.3 Nanoclay

Nanoclay Cloisite 30B was used and it was supplied by the Connell Bros. Company Pvt. Ltd., Mumbai, India (www.connellbrothers.com). Cloisite 30B is a natural montmorillonite modified with a quaternary ammonium salt. Cloisite 30B is an additive for plastics to improve various physical properties such as reinforcement is shown in Table 3.8.

Table 3.8 Physical properties of Cloisite 30B

Sr.No.	Composition	Moisture	Typical dry particle size (μm)	Color	Packed bulk density (g/l)	Density (g/cm^3)	X ray results (nm)
1	Alkyl quaternary ammonium salt bentonite	<3%	<10	Off white	365	1.98	d_{001} = 1.85

3.1.4 Acetone

Acetone is an important solvent with molecular formula $(C_3H)_2CO$ and has been used to concentrate the mixture of epoxy and nanoclay. It was supplied by the Loba Chemie Pvt. Ltd, Mumbai (http://www.lobachemie.com/).

3.2 Methods

3.2.1 Material processing and sample preparation

Laminates were prepared using DGEBA based epoxy resin as matrix and glass fiber as reinforcement. There are several methods for the preparation of laminates but the one used in the present work was using compression moulding technique. After in-depth study of the literature the procedure for the laminates preparation is given below.

3.2.1.1 Addition of nanoclay in epoxy resin

Epoxy resin and nanoclay were mixed in the ratio as per the standard procedure. After the hardener and epoxy resin were properly mixed, accelerator was added to the solution to accelerate the process. Mass ratio in terms of parts per hundred of fiber is given in Table 3.9.

Table 3.9 Nanoclay-resin formulation as per hundred parts of resin

Sr.No.	Clay wt%	Parts per hundred of resin		
		Resin	Fiber	Clay
1	1	100	152.04	1.01
2	2	100	152.04	2.04
3	3	100	152.04	3.09
4	5	100	152.04	5.26

3.2.1.2 Stirring of epoxy-clay mixture in homogenizer

After the nanoclay was added to the epoxy in required proportion, stirring with homogenize was done for 15 minutes as per the procedure for proper mixing of the solution.

3.2.1.3 Stirring of epoxy-clay mixture in sonicator after homogenization

After the stirring with homogenizer, sonication of the mixture was done for 15 minutes for proper dispersion of clay content in the epoxy resin.

3.2.1.4 Addition of hardener and accelerator in epoxy-nanoclay mixture

After sonication process, keeping hardener to resin ratio 1:1, add hardener and accelerator to the epoxy-nanoclay mixture. The mixture should be kept under homogenization for 15 minutes for insuring proper mixing. Resin is prepared for laminated composites.

3.2.1.5 Formation of Laminate Layers

Glass fabric was cut into the required sizes with a cutter. Placing the first layer of the glass fiber on the Teflon sheet, resin was applied on it with a brush and then second layer was placed on it, following this procedure the laminate was formed with three layers of glass fiber. The hand roller was used to remove any entrapped air particles between the layers so that laminates can properly stick to each other. The formulation and geometric parameters of the laminates are given in Table 3.10.

3.2.1.6 Curing

After the laminate layers were prepared, they are properly bonded to each other with the help of compression moulding. Laminate was cured at room temperature for 24 hours.

3.2.1.7 Fabrication of Composite Plate

After the curing at room temperature, laminates were finally made with the hydraulic press. Teflon sheets were used to avoid sticking of the glass fiber with the mould. Mould of square shape having cavity of required shape was used. Laminated plate was held at constant pressure of 120 MPa and temperature of 150^{o}C for 2 hours for the curing process and then the composite plate was cooled to room temperature at the same pressure. The thickness of the plate obtained was 2mm.

Table 3.10 Formulation and geometrical parameters of glass/epoxy nanoclay laminates

Sr. No.	Sample code	Fabric orientation	Number of plies	Weight fraction %		
				Resin	**Fiber content**	**Nanoclay**
1	MC0	[$0^0/45^0/90^0$]	3	40	60	0
2	MC1	[$0^0/45^0/90^0$]	3	39.52	60.08	0.40
3	MC2	[$0^0/45^0/90^0$]	3	39.36	59.84	0.80
4	MC3	[$0^0/45^0/90^0$]	3	39.20	59.59	1.21
5	MC5	[$0^0/45^0/90^0$]	3	38.86	59.09	2.05

3.3 Testing

3.3.1 Tensile test

The tensile tests were performed at 25 ± 2 ^{0}C on a Zwick-Roell Universal Testing Machine – Model Z010, Zwick-Roell, Germany, according to ASTM D3039 standard. The grip to grip separation of the samples having 138 mm gauge length was 238 mm at the start position. A crosshead speed of 2 mm/min was maintained. At least 3 specimens of each blend were tested and the average values were reported.

3.3.2 Shear test

The shear tests were performed at 25 ± 2 ^{0}C on a Zwick-Roell Universal Testing Machine – Model Z010, Zwick-Roell, Germany, according to ASTM D5379 standard. A crosshead speed of 2 mm/min was maintained. At least 3 specimens of each blend were tested and the average values were reported.

The Iosipescu test specimen, shown in Fig.3.2, was tested using Iosipescu test fixture, shown in Fig. 3.3. The specimens were placed in Iosipescu test fixture in which the specimen was centered using the alignment pin and lightly clamped with the adjustable wedges. Then the load was applied to the specimen.

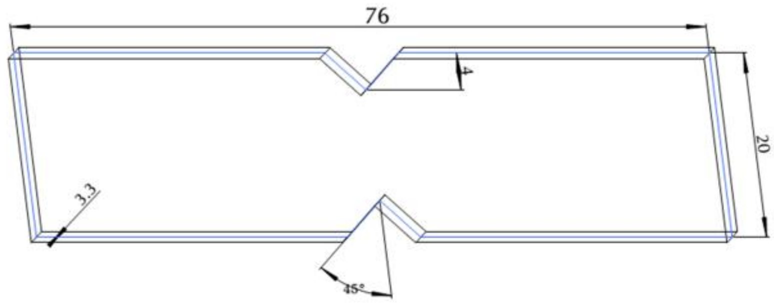


Fig. 3.2 Geometry of the Iosipescu shear test specimen

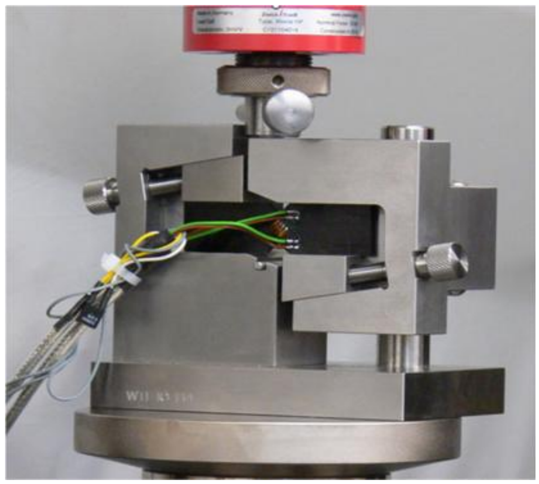


Fig. 3.3 Iosipescu Test fixture

3.3.3 Flexural tests

The flexural tests were performed at 25 ± 2 ^{0}C on a Zwick-Roell Universal Testing Machine – Model Z010, Zwick-Roell, Germany, according to ASTM D7264 standard. The standard span-to-thickness ratio is 40:1, the standard specimen thickness and width was 2 mm and 7 mm respectively. The flexural tests were run at a crosshead movement rate of 1 mm/ min. At least three samples were tested for each sample from which the mean values were reported.

For a test sample, the flexural strength (σ_F), modulus (E_F) and strain to failure (ε_F) are given by equations (3.1), (3.2) and (3.3).

$$\sigma_F = \frac{3\times P_{max}\times L}{2\times b\times h^2} \quad \text{when } L/h \leq 16 \qquad (3.1)$$

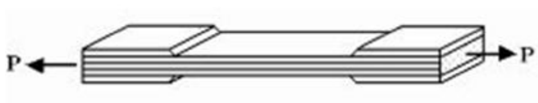
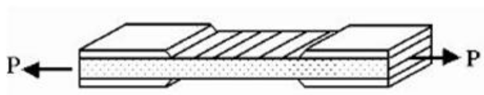
$$E_F = \frac{m \times L^3}{4 \times b \times h^3} \tag{3.2}$$

$$\varepsilon_F = \frac{6 \times D \times h}{L^2} \tag{3.3}$$

Where L, b and h are the span (Length), width and depth of the sample, m is the slope of the tangent to the initial straight-line portion of the load–deflection curve, D is the maximum deflection before failure, and P_{max} is the maximum load encountered before failure.

Table 3.11 shows summary of geometry and ASTM standards which were used. In Table 3.11, E_1, E_2 are the Longitudinal Young's Modulus and G_{12} are Shear Modulus.

Table 3.11 Properties and ASTM standards

Determinable Property	Symbol	Geometry	ASTM standard
Longitudinal or Tensile Modulus	E_1 (MPa)		ASTM D3039
Transverse Modulus	E_2(MPa)		ASTM D3039
Shear Modulus	G_{12}(MPa)		ASTM D 5379

3.4 Pin Joint Geometry

In the study, plate (length L, width W, thickness t) made of glass fiber-reinforced unidirectional plies with a single circular hole to have a rigid pin is used. The ply orientation of the laminate is [0^o/45^o/90^o]. The geometry of composite plate is shown in Fig. 3.4. A hole of diameter D (4 mm) 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 on 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.

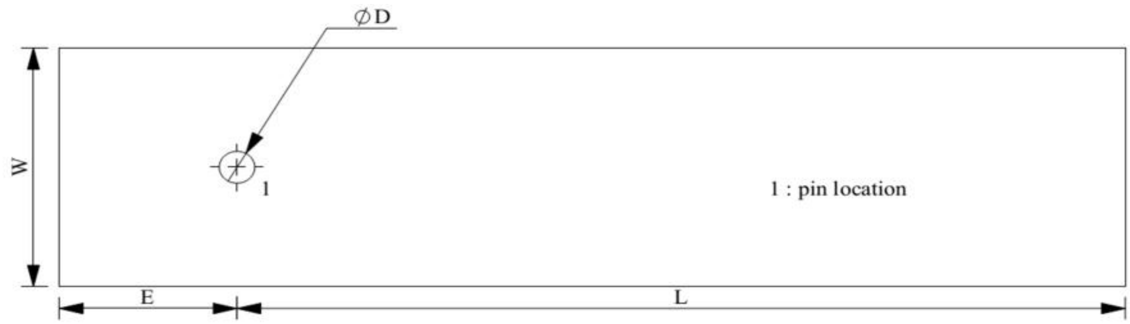


Fig. 3.4 Geometry of composite plate with hole

The samples with different E/D and W/D ratios are given in Table 3.12.

Table 3.12 Geometries of samples to be tested

		Diameter of Hole(mm)	**E(mm)**	**W**	**Thickness(mm)**	**Length from hole to edge(mm)**	**Layup**
E/D =2	W/D=2	4	8	8	2	100	$[0^0/45^0/90^0]$
	W/D=3	4	8	12	2	100	$[0^0/45^0/90^0]$
	W/D=4	4	8	16	2	100	$[0^0/45^0/90^0]$
	W/D=5	4	8	20	2	100	$[0^0/45^0/90^0]$

		Diameter of Hole(mm)	**E(mm)**	**W**	**Thickness(mm)**	**Length from hole to edge(mm)**	**Layup**
E/D =3	W/D=2	4	12	8	2	100	$[0^0/45^0/90^0]$
	W/D=3	4	12	12	2	100	$[0^0/45^0/90^0]$
	W/D=4	4	12	16	2	100	$[0^0/45^0/90^0]$
	W/D=5	4	12	20	2	100	$[0^0/45^0/90^0]$

		Diameter of Hole(mm)	**E(mm)**	**W**	**Thickness(mm)**	**Length from hole to edge(mm)**	**Layup**
E/D =4	W/D=2	4	16	8	2	100	$[0^0/45^0/90^0]$
	W/D=3	4	16	12	2	100	$[0^0/45^0/90^0]$
	W/D=4	4	16	16	2	100	$[0^0/45^0/90^0]$
	W/D=5	4	16	20	2	100	$[0^0/45^0/90^0]$

		Diameter of Hole(mm)	E(mm)	W	Thickness(mm)	Length from hole to edge(mm)	Layup
E/D =5	W/D=2	4	20	8	2	100	$[0^0/45^0/90^0]$
	W/D=3	4	20	12	2	100	$[0^0/45^0/90^0]$
	W/D=4	4	20	16	2	100	$[0^0/45^0/90^0]$
	W/D=5	4	20	20	2	100	$[0^0/45^0/90^0]$

The samples as per the ASTM D3039 standards were prepared with different wt %age of nanoclay *i.e.* 1, 2, 3, 5, to find their mechanical properties. The optimum wt %age of nanoclay was decided on the basis of maximum strength achieved. Thereafter the pin joint samples were prepared as per the Table 3.12 for the achieved optimum value of wt %age of nanoclay in epoxy glass fiber laminates. The strength of these samples was compared with the neat (without nanoclay) epoxy glass fiber laminates.

Tests have been carried out on single pinned joints in 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 laminate edge and width are discussed.

4.1 Mechanical properties of composite laminates

The results obtained by conducting tensile and shear tests on prepared nanoclay laminates using Universal Testing Machine are shown in Table 4.1.

Table 4.1 Mechanical properties of neat glass fiber/epoxy composite laminates

Sr. No.	Sample Code	Tensile Modulus (N/mm^{2})		Shear Modulus (G_{11}) N/mm^2	Poisson Ratio
		MD (±SD)	TD (±SD)		
1	MLC0	17400(±500)	6200(±500)	3100	0.3

*MD is Machine or Longitudinal Direction and TD is Transverse Direction.

Thereafter nanoclay in the wt % of 1, 2, 3 and 5 were added to the laminates to find out the change in properties. The results obtained for various compositions of nanoclay are shown in Fig. 4.1.

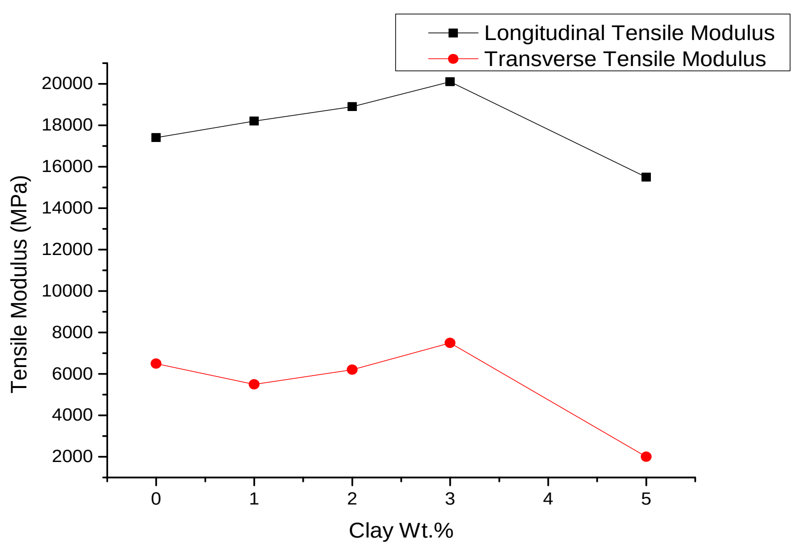


Fig. 4.1 Tensile modulus vs. weight percentage of nanoclay

It can be observed from Fig. 4.1 that at 3% wt. of nanoclay, the laminates show maximum value of Young's Modulus. Table 4.2 shows the mechanical properties of glass/epoxy nanoclay nanocomposite laminates.

Table 4.2 Mechanical properties of glass fiber/epoxy nanoclay nanocomposite laminate

Sr. No.	**Sample Code**	**Tensile Modulus (N/mm^{2})**		**Shear Modulus (G_{11}) N/mm^2**	**Poisson Ratio**
		MD (±SD)	**TD (±SD)**		
1	MLC3	20100 (±500)	7500 (±500)	3300	0.32

4.2 Flexural Test

The results obtained by conducting Three Point Flexural tests on prepared glass/epoxy nanocomposites at different nanoclay wt% are shown in Fig. 4.2.

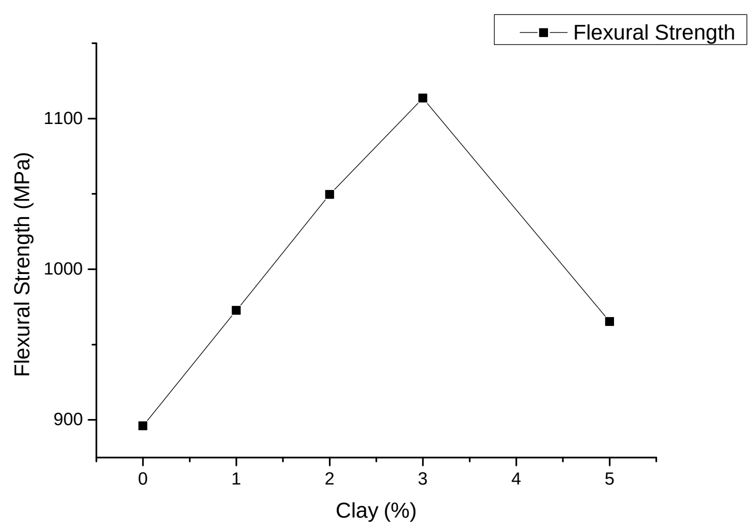


Fig. 4.2 Flexural strength vs. wt % of nanoclay

As can be seen from Fig. 4.2, the addition of nanoclay increases the Flexural Strength. A significant rise in the Flexural Strength was seen at 3 wt% of nanoclay. With the 3 wt% of nanoclay loading, 24% improvement in strength of specimen was observed when compared with neat Epoxy nanocomposites. The enhancement in the flexural properties is attributed to the improved interfacial properties responsible for transfer of stresses and elastic deformation in the presence of nanoclay particles.

4.3 Test results of glass/epoxy pin joints configuration for unfilled and filled samples

Tests were conducted on pin joint configuration of glass/epoxy nanocomposites with unfilled (no nanoclay) and at achieved optimum nanoclay percentage (*i.e.* 3% wt.) obtained from the results of the tensile tests. Experimental results for pin joints configuration are discussed in the following sections.

4.3.1 Results of neat glass/epoxy composite laminates

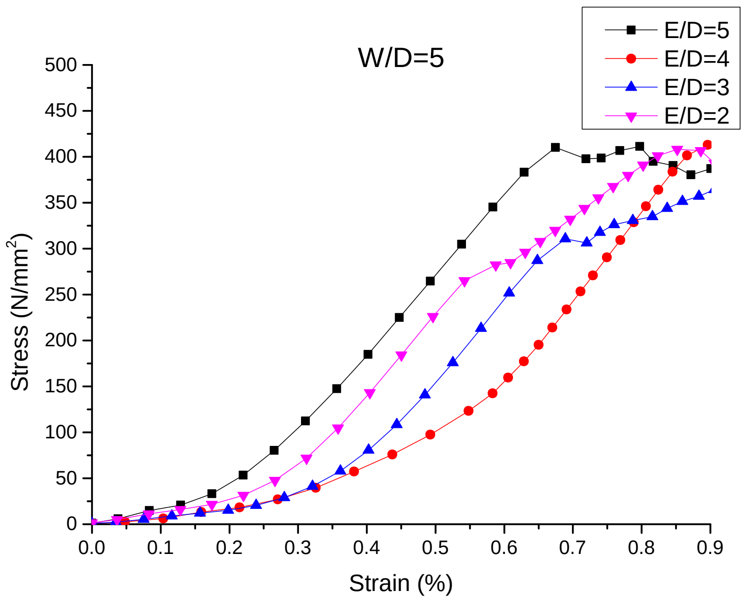


Fig. 4.3 Stress vs. Strain curves of pin joints for nanoclay 0% at W/D=5

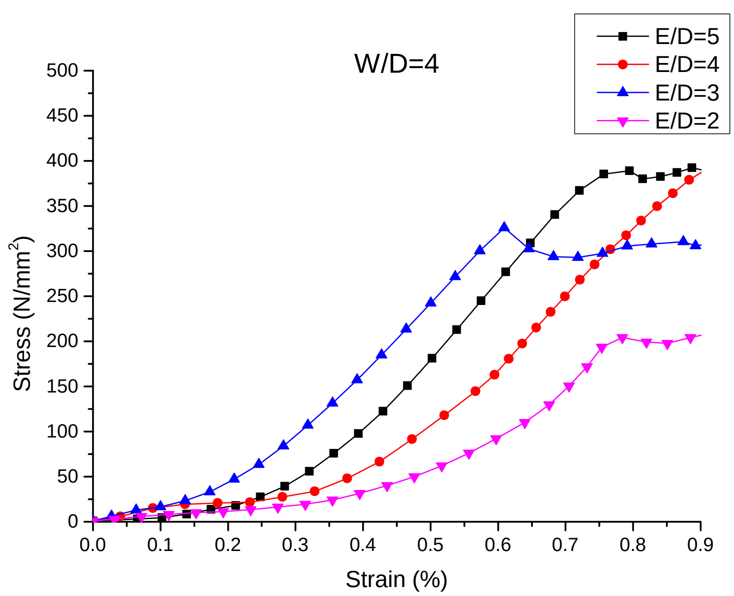


Fig. 4.4 Stress vs. Strain curves of pin joints for nanoclay 0% at W/D=4

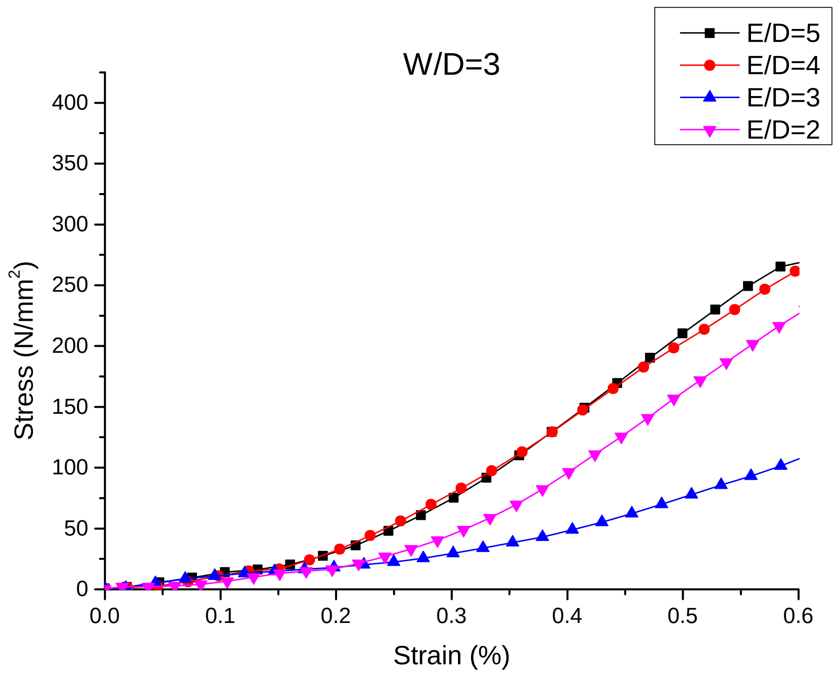


Fig. 4.5 Stress vs. Strain curves of pin joints for nanoclay 0% at W/D=3

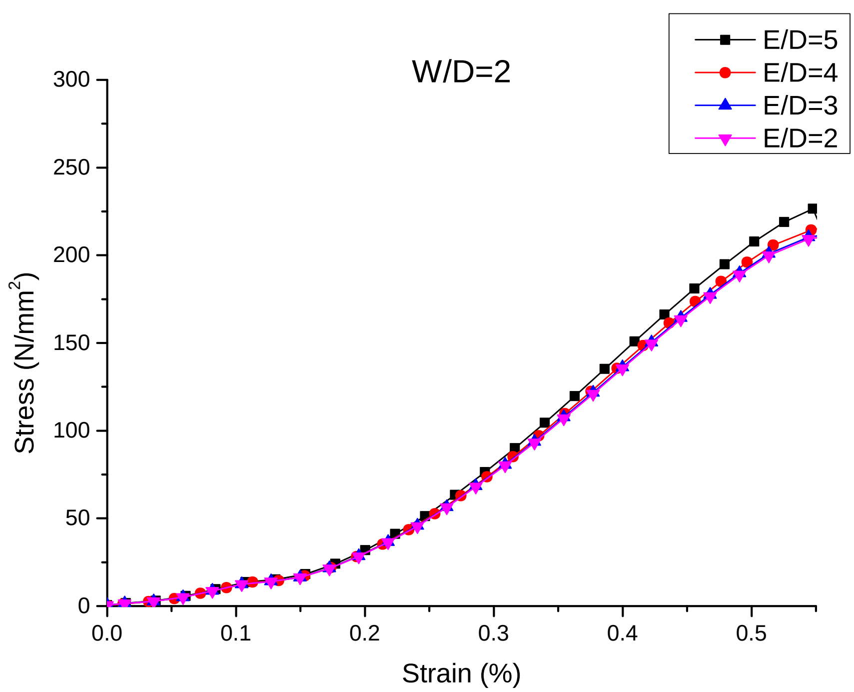


Fig. 4.6 Stress vs. Strain curves of pin joints for nanoclay 0% at W/D=2

From the above results it is seen that the results of E/D=4 and E/D=5 and at any W/D ratio does not have much difference so we can take E/D=4 as the optimum ratio for pin joint configuration. Also, the bearing strength of the joints increases with increase in W/D or E/D ratios. When E/D and W/D ratios have larger values the joint has maximum strength. Net-tension and shear-out failure modes occur with small W/D and E/D values, respectively. Joint failure with the net-tension and shearing modes is catastrophic, immediate and without warning and results from excessive tensile and shear stresses. However, bearing damage is gradual and is related to compressive failure.

4.3.2 Results of single pin joint glass/epoxy nanocomposites at 3% by wt of nanoclay

It is seen that nanoclay enhances the mechanical properties of the glass/epoxy composites. Hence the pin joint testing of glass/epoxy laminates at 3% of nanoclay was carried out. The results are given in Table 4.3. The graphical plots of these results are shown in Fig. 4.7 to 4.10.

Table 4.3 Mechanical properties of pin joint glass/epoxy nanoclay laminates

Sr.No.	Sample code	W/D ratio	E/D ratio	Ply orientation	Ultimate Strength (MPa)	Strain (%)
1	PM1C3	5	5	$[0^0/45^0/90^0]$	510	0.75
2	PM2C3	5	4	$[0^0/45^0/90^0]$	495	0.86
3	PM3C3	5	3	$[0^0/45^0/90^0]$	467	0.78
4	PM4C3	5	2	$[0^0/45^0/90^0]$	482	0.65
5	PM5C3	4	5	$[0^0/45^0/90^0]$	520	0.72
6	PM6C3	4	4	$[0^0/45^0/90^0]$	475	0.82
7	PM7C3	4	3	$[0^0/45^0/90^0]$	412	0.85
8	PM8C3	4	2	$[0^0/45^0/90^0]$	385	0.813
9	PM9C3	3	5	$[0^0/45^0/90^0]$	423	0.73
10	PM10C3	3	4	$[0^0/45^0/90^0]$	360	0.79
11	PM11C3	3	3	$[0^0/45^0/90^0]$	349	0.82
12	PM12C3	3	2	$[0^0/45^0/90^0]$	359	0.77
13	PM13C3	2	5	$[0^0/45^0/90^0]$	229	0.85
14	PM14C3	2	4	$[0^0/45^0/90^0]$	179	0.57
15	PM15C3	2	3	$[0^0/45^0/90^0]$	228	0.77
16	PM16C3	2	2	$[0^0/45^0/90^0]$	192	0.72

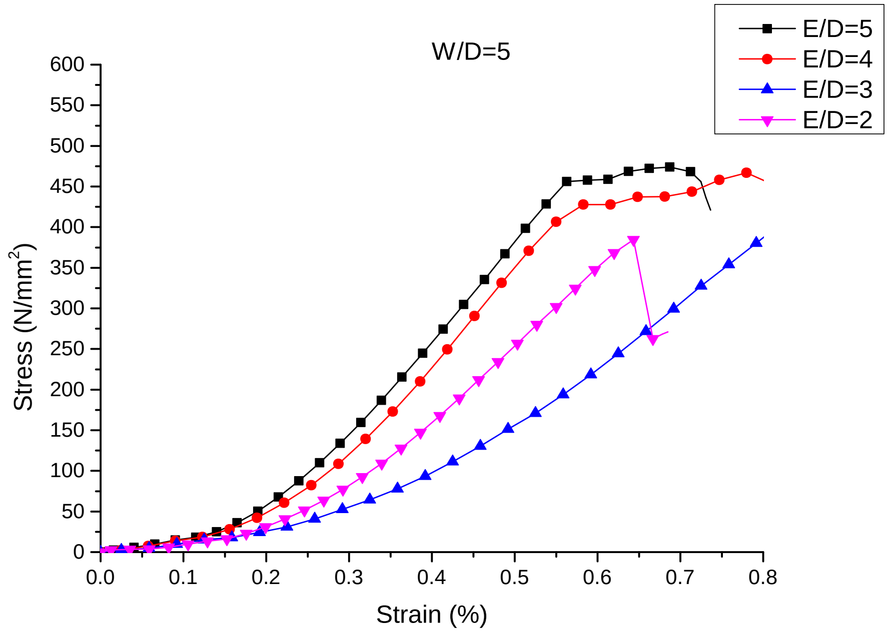


Fig. 4.7 Stress vs. Strain curves of pin joints for nanoclay 3% at W/D=5

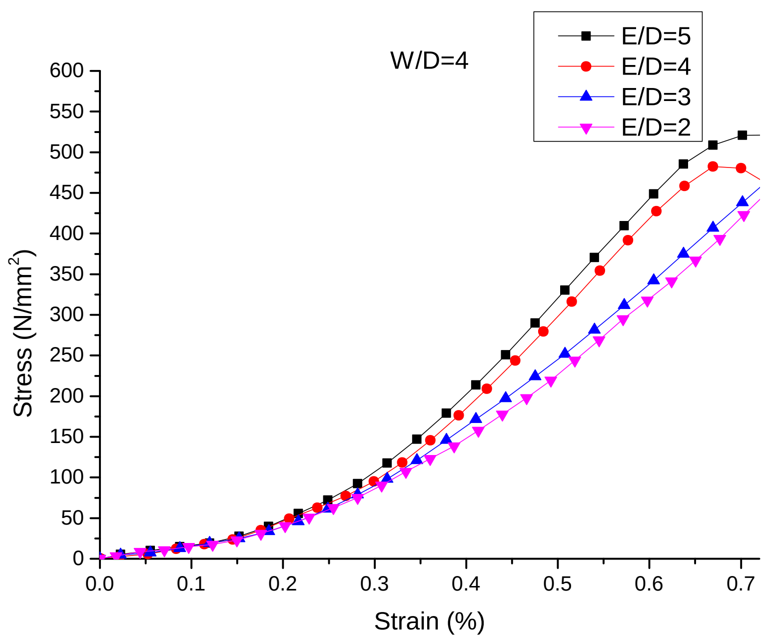


Fig. 4.8 Stress vs. Strain curves of pin joints for nanoclay 3% at W/D=4

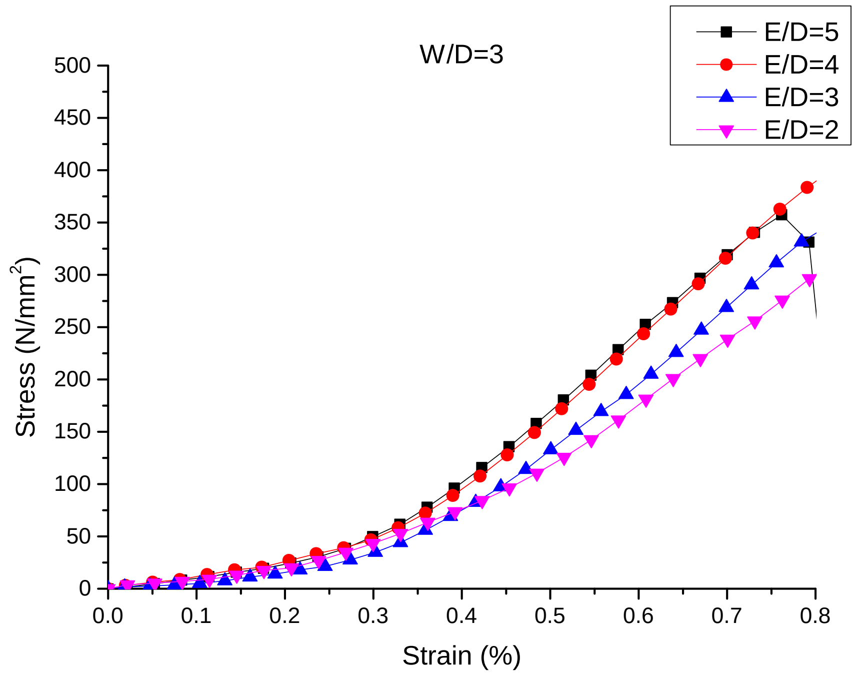


Fig. 4.9 Stress vs. Strain curves of pin joints for nanoclay 3% at W/D=3

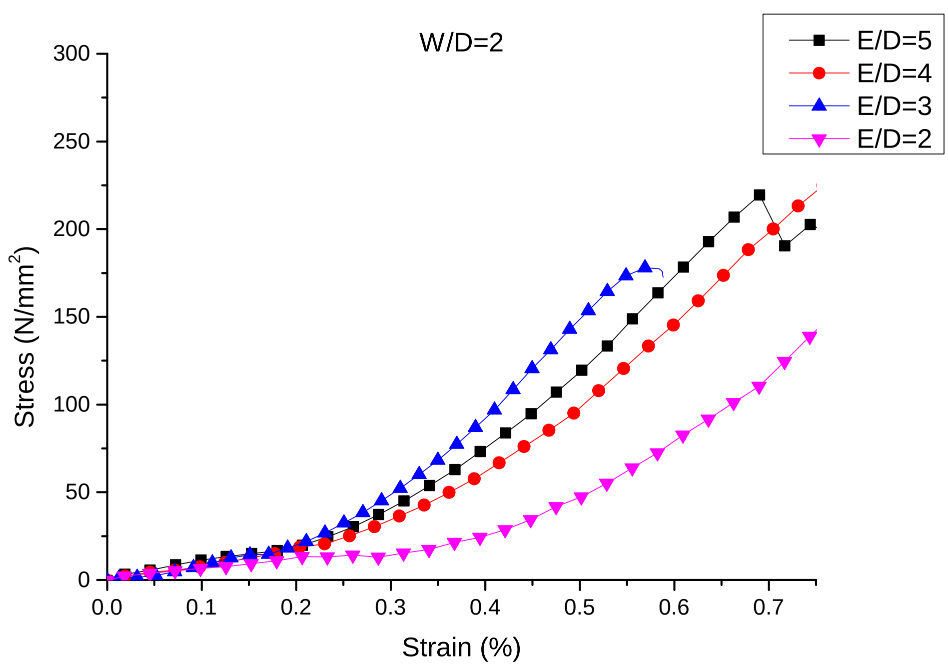


Fig. 4.10 Stress vs. Strain curves of pin joints for nanoclay 3% at W/D=2

From the above results it is seen that the nanoclay increases the strength of the pin joints. Also, the bearing strength of the joints increases as W/D or E/D ratios increase. When E/D and W/D ratios have larger values the joint has maximum strength. Net-tension and shear-out failure modes occur with small W/D and E/D values, respectively. Joint failure with the net-tension and shearing modes is catastrophic, immediate and without warning which results from excessive tensile and shear stresses. However, bearing damage is progressive and is related to compressive failure. From the results, it can be concluded that E/D ratio 4 and 5 does not have much difference in their strengths.

4.4 Numerical analysis

Finite Element Method is a very versatile tool which can be used for analysis of composites. Number of researchers has used this tool for the analysis of different composites.

4.4.1 Finite element modeling

The geometry of the plate investigated in this study was shown in Fig. 3.5. The ply orientation is symmetric with respect to the z = 0 plane. A rigid pin is inserted into the hole. Perfect bonding between each ply and frictionless contact are assumed. The composite plate is loaded with an in-plane load P for the pinned joint.

4.4.2 Geometric modeling and meshing

Geometric model was made in the ANSYS 14.5 with the standard dimensions. Model was meshed using quadrilateral elements. High density mesh was used at the high stress concentration areas. The meshed model is shown in Fig. 4.11.

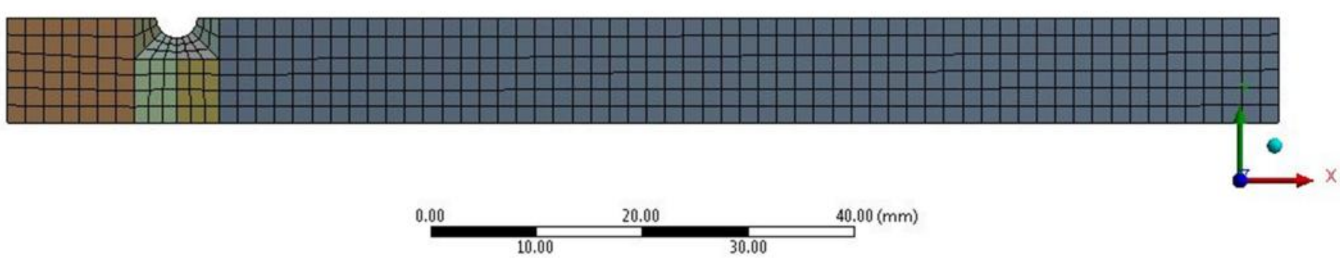


Fig. 4.11 Meshing of the model

4.4.3 Boundary conditions and loading

Radial displacement boundary conditions were applied semi circularly, to nodes around the hole where the pin will contact the composite. These nodes are free tangentially. Composite is loaded gradually in the form of displacements from one end. Radial and symmetric boundary conditions are shown in Fig.4.12.

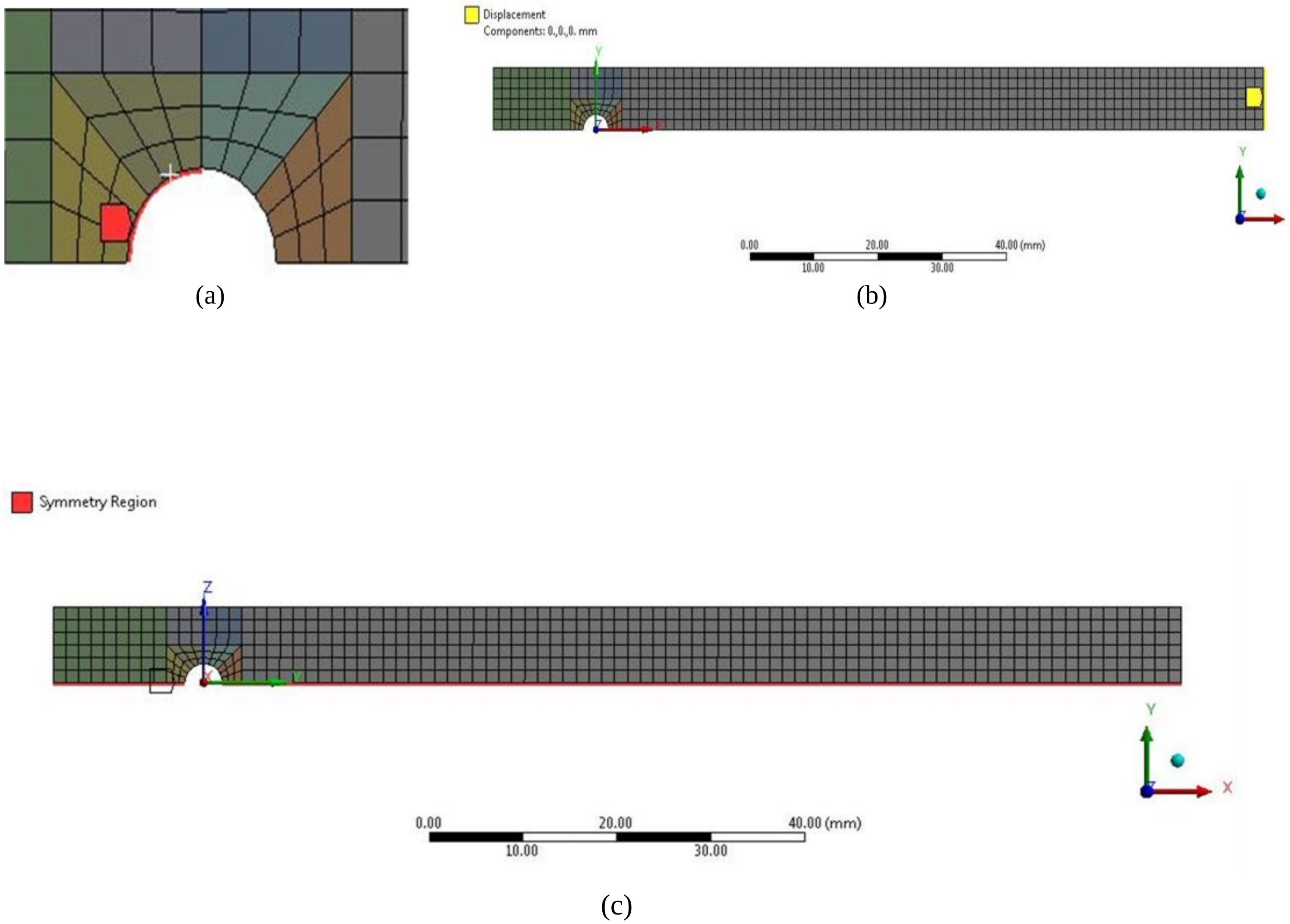


Fig. 4.12 (a) Radial boundary conditions (b) Displacement (c) Symmetric boundary conditions

Finite Element Analysis was carried out on the glass/epoxy pin joint samples and it was found that the unfilled (with no nanoclay) specimens fails early and was not able to sustain large values of stresses but the specimens having 3% nanoclay content was able to sustain larger stress values and shows very good correlation with experimental results. Fig. 4.13 and 4.14 shows the stress distribution around the hole for optimum W/D and E/D ratios *i.e.* 4 for unfilled and filled (3 % wt.) respectively.

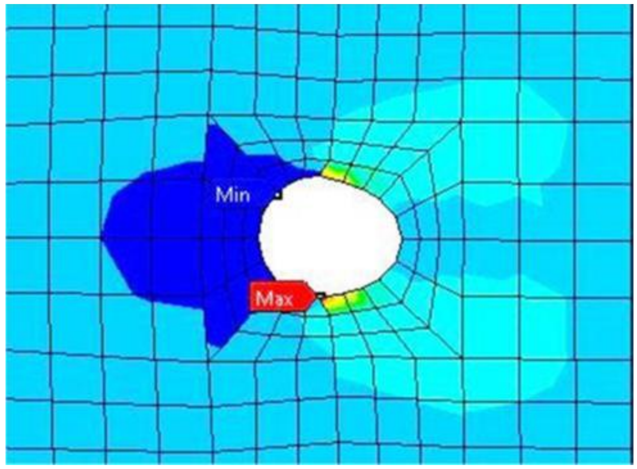


Fig. 4.13 Stress distribution around hole at nanoclay 0% for W/D=4 and E/D=4

From the Fig. 4.13 it can be seen that specimen starts failing with the bearing failure. The stresses increases with increase in load and the failure mode starts changing from bearing to shearing. Dark blue colour represents the change in failure mode from bearing to shearing. Bearing failure mode is the desired mode for the failure of the specimen. So at E/ D =4 and W/D=4 specimen undergoes bearing failure mode.

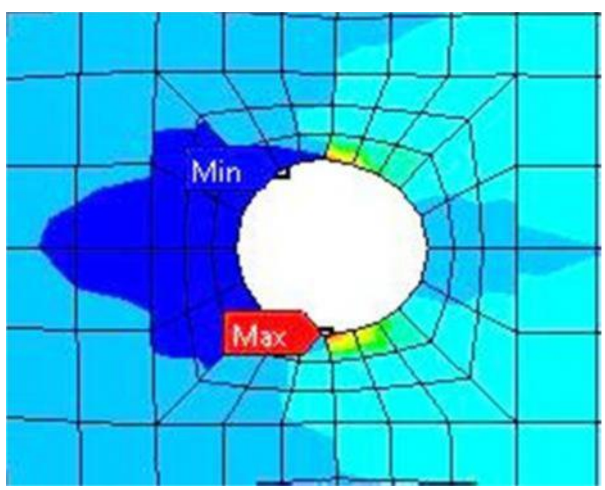


Fig. 4.14 Stress distribution around hole at nanoclay 3% for W/D=4 and E/D=4

From the Fig. 4.14 it can be seen that specimen starts failing with the bearing failure mode. The stresses increase with increase in load. The failure mode starts changing from bearing to shearing as the dark blue colour represents the change in mode from bearing to shearing. It can be seen from the above two figures that the deformation around the hole is very less in the samples made with nanoclay contents as compared to the unfilled ones.

4.5 Comparison of Finite Element Analysis and Experimental results

From the above results it can be seen that the optimum strength for glass/epoxy nanoclay nanocomposites comes at E/D=4 for any W/D ratios *i.e.* 2, 3, 4, 5. FEM tool is used to investigate the failure analysis at E/D=4 and various W/D ratios. Comparisons between FEA and experimental results have been shown in the Fig. 4.15 to 4.18.

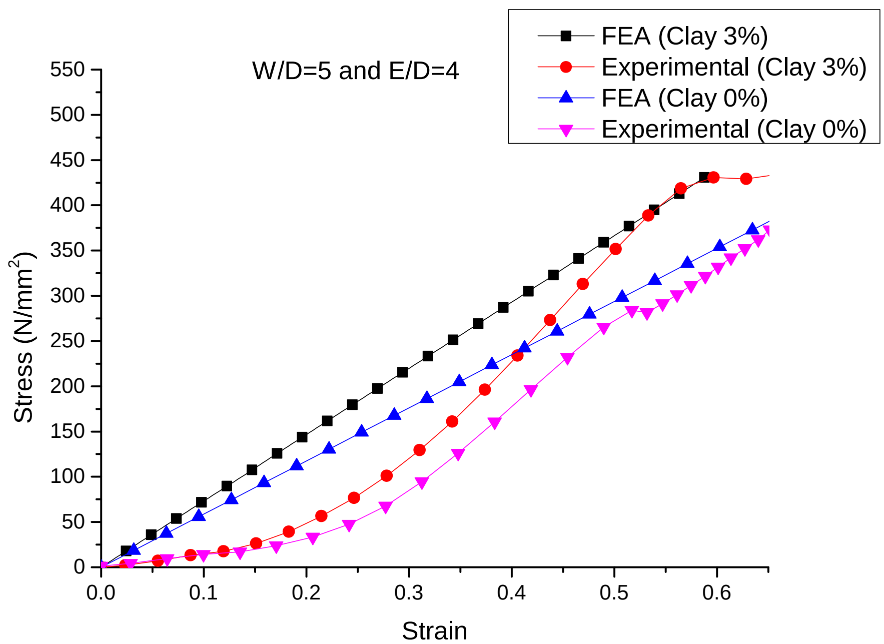


Fig. 4.15 Experimental vs. FEA results of pin joints at nanoclay 0% and 3%

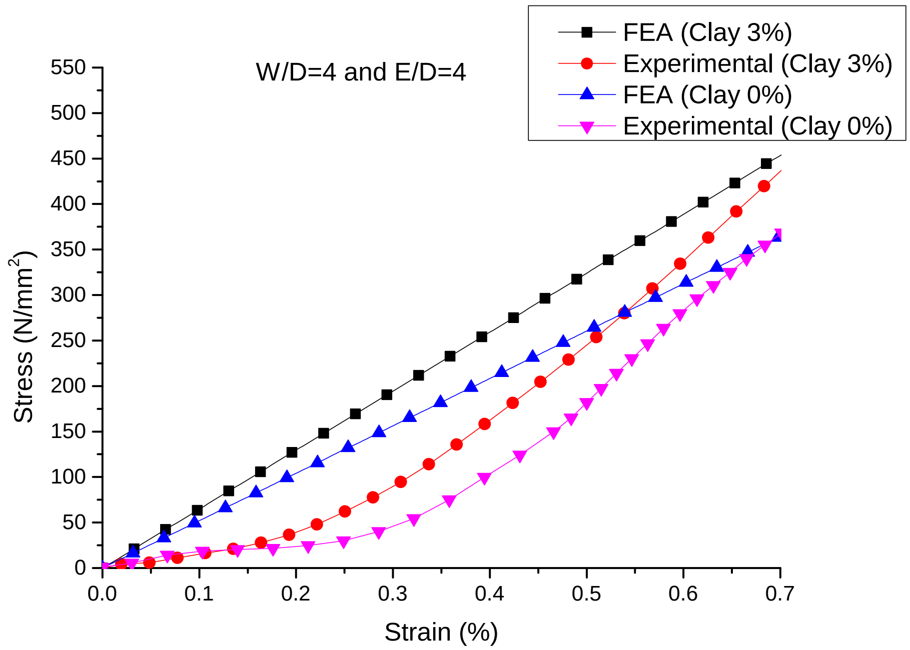


Fig. 4.16 Experimental vs. FEA results of pin joints at nanoclay 0% and 3%

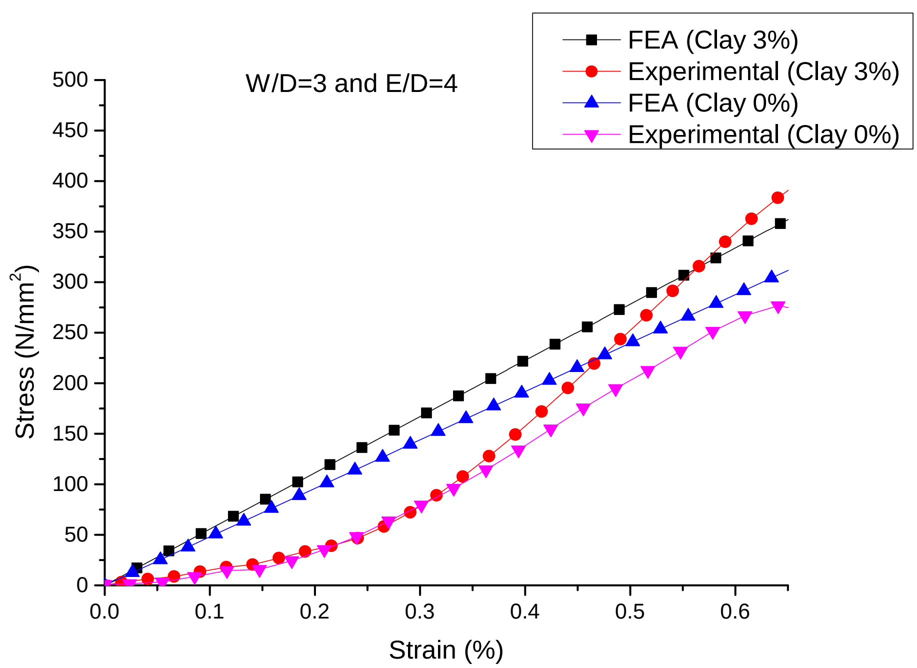


Fig. 4.17 Experimental vs. FEA results of pin joints at nanoclay 0% and 3%

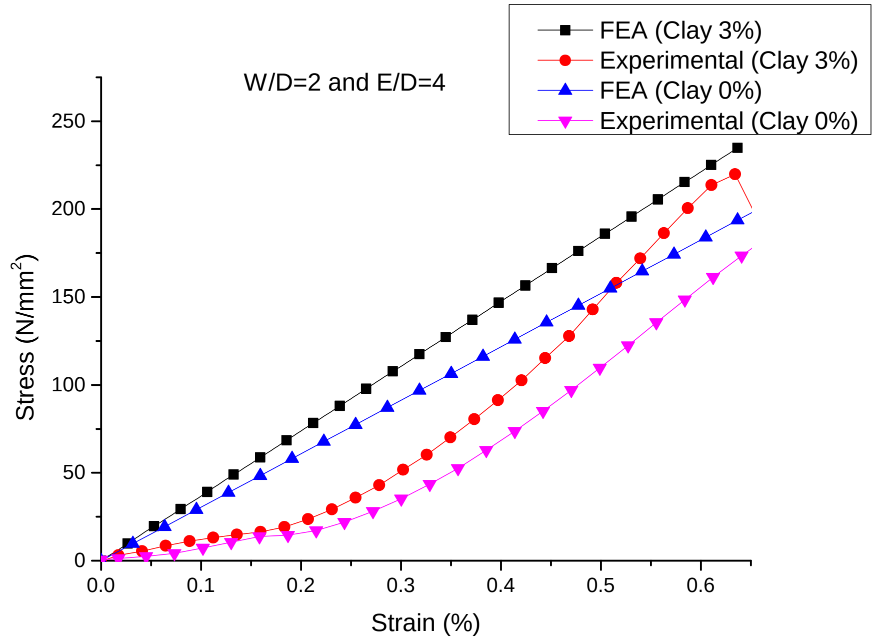


Fig. 4.18 Experimental vs. FEA results of pin joints at nanoclay 0% and 3%

Above results show that there is fairly good correlation between experimental and numerical results. The difference in experimental and FEA results can be due to the material processing *i.e.* proper layer orientation, proper curing and the material non linearity.

5.1 Conclusion

In the present work, the failure strengths of pin-loaded glass epoxy nanoclay laminates have been investigated experimentally and numerically. The major focus of the study was to characterize the failure mechanisms and to evaluate the effect of geometric dimensions on the strength of pinned joints.

Based on the experimental and numerical results the following observations are made:

1. The present work shows a definite dependence of strength of joints on joint geometry and the nanoclay wt %. Maximum strength has been obtained at 3% wt. of nanoclay. The Tensile Strength of nanoclay glass/epoxy nanocomposites laminates specimen was increased with the increasing wt% of Nanoclay with maximum tensile modulus at 3 wt% of Nanoclay. This strength is around 20% higher than neat glass/epoxy composite laminates. However, the strength decreases with further increase in the nanoclay content.
2. Ultimate strengths are sensitive to W/D and E/D values in a larger range compared to the laminate tensile strength. Increasing the end distance increased the bearing strength of the joint until a critical end distance was reached; any increase of the end distance beyond that value did not result in a corresponding increase in the strength of the joint. Pin bearing strength decreases with decreasing W/D ratio. As the width of the specimen decreases, there is a value where the failure changes from the bearing to net-tension failure mode. Maximum strength is reached when the edge distance ratio E/D is equal to or greater than 4, and the side distance ratio W/D is equal to or greater than 4. Critical E/D and W/D ratios are 2.
3. In net-tension and shear-out failure, the reduction in load is both greater and more sudden. But in bearing failure there is gradual reduction in load. Therefore, joints that fail in the bearing mode are stronger and safer joints.

5.2 Future scope

The present work can be extended further in the following ways:-

1. Effect of different nanofiller materials in varying compositions can be studied.
2. Different techniques can be used for composite preparation.
3. Multi pin joint analysis can be done.

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