

**Comparative Study of nanofillers content on failure modes
and strength of pin jointed unidirectional glass reinforced
epoxy 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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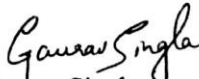
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Certificate

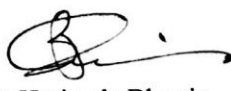
This is to certify that the dissertation entitled “ Comparative Study of nanofiller content on failure modes and strength of pin jointed unidirectional glass reinforced epoxy composite laminates ”, is an authentic record of my own work carried out as requirements for the award of degree of Master of Engineering in CAD/CAM Engineering from Thapar University, Patiala, under the guidance of Dr. Jaswinder Singh Saini (Assistant Professor, Mechanical Engineering Department) and Dr. Haripada Bhunia (Professor, Chemical Engineering Department).

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Abstract

The objective of the present study is to investigate and compare the effect of joint geometry on strength of pin loaded with two different nano particles which are nanoclay and nanoTiO₂ filled glass epoxy composite laminates after optimizing the weight percent of nano particles experimentally and numerically. Mechanical Properties of the composite material are obtained using ASTM Standards whereas numerical study is performed by means of ANSYS finite element analysis program. Laminates were prepared using hand layup technique at 150 0C. Single hole pin loaded specimens were tested for their tensile strength and the distance from the free edge of specimen to the diameter of the first hole (E/D) ratio, width of the specimen to the diameter of the holes (W/D) ratio evaluated. The influence of the joint geometry parameters on the strength of the pin loaded composites was investigated.

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1.1 Composites

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). The properties of composites includes 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.

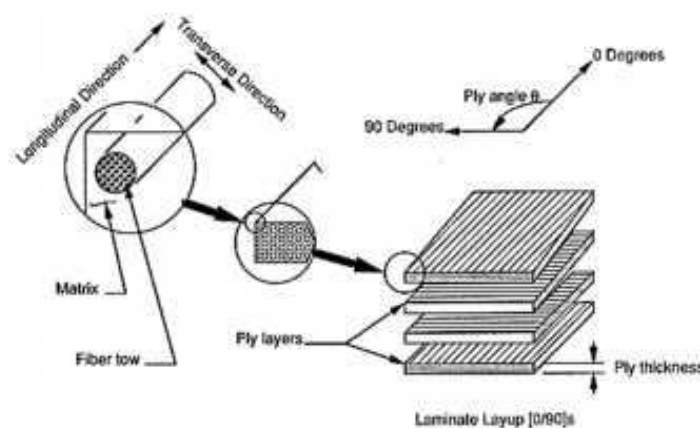


Fig. 1.1 Composite Anatomy (Karakazu , 2006).

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.

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

- **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.

- **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

The advantages of the composites are as follows:

- 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

The disadvantages of the composites are as follows:

- 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 (PMCs).
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.

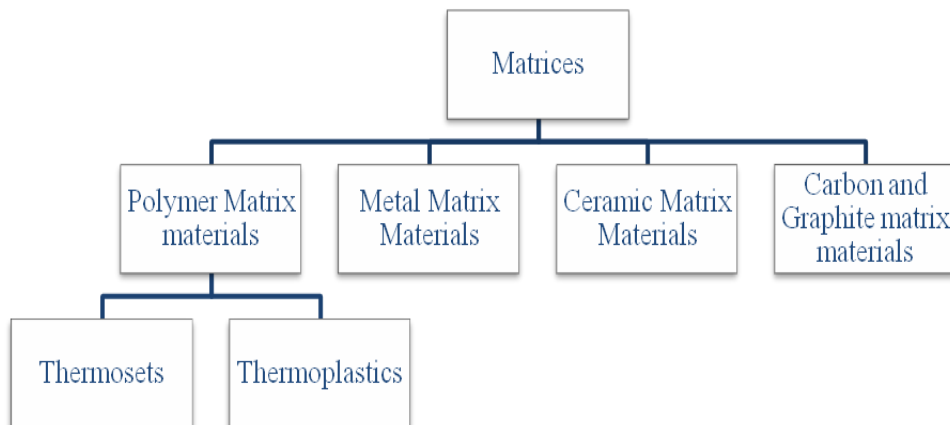


Fig. 1.2 Classifications with respect to the matrix constituent

1.5.1 Polymer Matrix Materials

Polymers make ideal materials as they can be treated easily, possess lightweight, and possesses mechanical properties. 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.

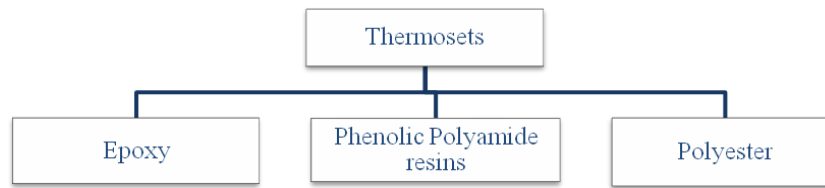


Fig. 1.3 Various types of thermosets

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 140°C. 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.

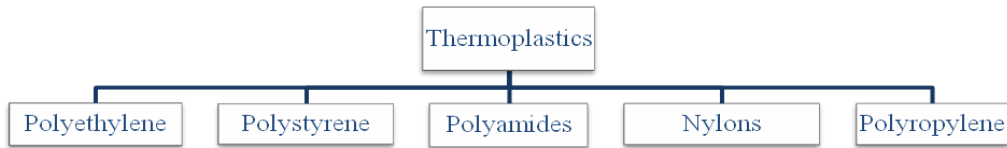


Fig. 1.4 Types of thermoplastics

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 1500°C. 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.

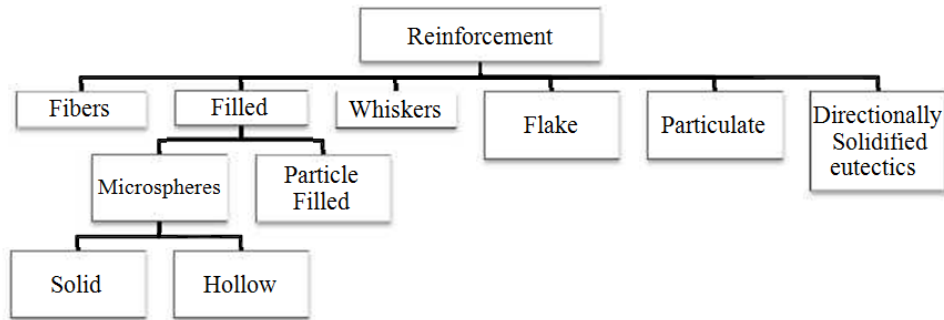


Fig. 1.5 Classification with respect to reinforcement constituent

(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.

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 filler 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.

1.7 Joints in composite structures

Unfortunately, it is seldom possible to produce a part without joints due to the limitations of material size, ease of manufacturing or transportation and the need for access. But mechanical fastened joints are usually weak points in structures due to complicated stress field in the locality of the hole. They are prone to high stress concentrations which occur around and in the locality of the hole and are often the cause of sudden failure in composite structures containing joints [Aluko (2011)]. The high stress concentration reduces the efficiency of the joint along with the redistribution of stresses near the discontinuities [Kishore *et al.* (2009)]. Because of the intricate stress field near the hole area, which causes a reduction of load capacity of composite structure. While increasing the efficiency of the composite structure, the operational force continues to rise, the load carried by each fastener joint increases accordingly. Hence, this increases the chances of failure.

It has been observed experimentally that mechanical fastened joints fail under three basic mechanisms: net-tension, shear-out and, bearing (in addition, combinations of these mechanisms are often given separate names). Typical damage caused by each mechanism is shown in Figure 1.6.

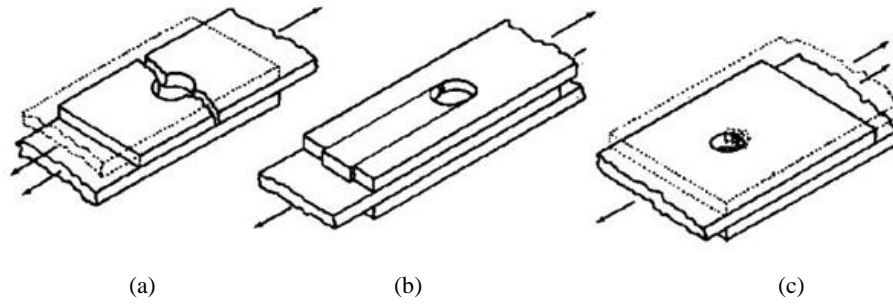


Fig. 1.6 Common failure modes in composite plates (Aktas and Dirikolu,2004)

(a) Tension Failure (b) Shear Out Failure (c) Bearing out Failure

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.

Numbers of researchers have worked on the behaviour of polymeric nanocomposites when nano filler content is added to study the strength of different mechanical joints. A concise review of the present research work is discussed in the following paragraphs.

2.1 Literature Review

Aslan et al. (2001) investigated ratio of various geometrical parameters width-to-hole diameter ratio (W/D) and edge distance to hole diameter (E/D) on the bearing strength of woven laminated composites. Glass fiber epoxy based laminated composite were processed under the pressure by moulds at 120⁰C. The mechanical characteristics and the endurance of the composites were obtained experimentally. The glass fiber reinforced epoxy composites were loaded through pin joints. Single-hole pin-loaded samples were tested for their tensile behavior whereas W/D and E/D ratios were evaluated. Failure propagation and different failure modes were analysed on the samples. The experimental study shows that the ultimate load carrying capacity was increased with increasing W and E. However, raising the E/D ratio beyond 2 and W/D ratio beyond 3 had an trivial effect on the ultimate load carrying ability.

Okutan (2002) determined the analysis of fiber-reinforced laminated composite mechanically fastened joints. Mechanical properties and the bearing strength of the glass reinforced fiber epoxy composites were obtained by performing tests. Various experimental tests have been carried out on pinned joints with stacking sequence of [0⁰/90⁰/0⁰] and [90⁰/0⁰/90⁰] laminated composites. A parametric investigation considering geometries was performed to classify the failure characteristics of the pin-loaded laminates. Results obtained from experiments were compared with a Finite Element Model using Hashin's failure criteria.

Okutan and Karakuzu (2003) examined the behavior of single pin-loaded epoxy based laminates. Tensile test was carried on glass epoxy composites for different layups such as [0⁰/45⁰] and [90⁰/45⁰]. For each layups, 20 different geometries were picked. The major focus of the research was to evaluate the effect of geometric parameters on the

different failure modes. The samples were tested to find start and end failure load conditions. Comparison was done both experimentally and numerically.

McCarthy et al. (2005) studied the effects of clearance of bolt-hole on the mechanical behavior of bolted laminate joints. The joint type was single-bolt, single-lap while testing. Experimental study was compared with Finite Element parameter involving changes in various entities i.e boundary conditions, analysis type, element order, material modeling and mesh density.

Icten et al. (2006) on mechanical joints investigated the various failure modes and the failure loads on woven kevlar epoxy laminates. 2D finite element model was performed to analyse failure and strength of joints. Different failure criterion was adopted (Hashin, Hoffman and Maximum Stress criteria) in this failure analysis. Experiments study was conducted to predict the different failure modes and strength carrying capacity. Parametric study was also carried out to evaluate the effect of joint geometry. Comparisons of both experimental and numerical results was carried out in the further study.

Baba Okutan(2006) concluded the effects of joint geometry and different fiber orientation on the failure strength and modes of failure in a pinned joint laminates. Behavior of pin-loaded laminates with different layups and different dimensions was observed. Single pin- loaded samples were investigated and tested for their tensile response and geometric parameters were also evaluated. When the end distance was increased, bearing failure occur in addition to shear whereas when width increases, sample fails in shearing mode only.

Karakuzu et al. (2008) examined propagation of various failure load, bearing strength and failure modes in composite plate with two parallel symmetric holes which were subjected to gripping forces by two parallel stiffed pins. The characteristic of pin loaded laminated plates with various geometries were analysed experimentally and analytically. The distance of edge to hole diameter(E/D) and hole-to-hole diameter (M/D) were kept as significant parameters. Hashin failure criteria adopted to know the exact variations of failure load and failure modes.

Karakuzu et al. (2008) compared the effects of geometrical entities i.e ratio of E/D, W/D, (M/D) on the failure loads and different modes in composite plates reinforced with glass failure with two serial pin-loaded holes, experimentally and analytically. Research was carried out using Hashin failure criterion which further compared with the results obtained from FEM software LUSAS. Results showed the ultimate load carrying capacity of laminates with pin connections increases by increasing the geometrical parameters i.e E/D, W/D, and M/D.

Sen et al. (2008) determined the bearing strength of mechanically fastened bolted-joints of laminates filled with epoxy and glass fiber reinforcement. Geometrical parameters *i.e.* the edge distance-to-hole diameter ratio (E/D) was selected from 1 to 5, whereas W/D ratio was chosen from 2 to 5. To find materialistic variations in laminates, plates were layed up as three different categories which are $[0^0/0^0/45^0/-45^0]_s$, $[0^0/0^0/45^0/45^0]_s$ and $[0^0/0^0/30^0/30^0]_s$, symmetrically. In addition to this, preload moments were applied as 0, 3 and 6 Nm. Results obtained showed that the bearing strength considerably increases with increased preloads. Study was further carried out by changing material and geometrical parameters of composite bolted-joints.

Uddin and Sun (2008) performed experiment on the strength of unidirectional glass fiber composite with silica nanoparticle in epoxy. DGEBA epoxy with silica nanoparticles was used as the matrix to make reinforced fiber laminates. Images obtained by TEM showed very consistent dispersion of silica nanoparticles having distributed size of 20 nm. Compression test was carried out which revealed a substantial growth (40%) in elastic. Inclusion of silica nanoparticles increased the longitudinal compressive strength whereas no significant effect was observed on longitudinal and transverse tensile strengths.

Aktas et al. (2009) examined failure characteristic of single and double parallel pinned-joints. Two variables were investigated during analyses i.e E/D ratio and W/D ratio. The analytical study was performed using FEM software ANSYS in which Yamada-Sun failure criterion was adopted. The experimental and analytical analysis were compared in which the pin hole farthest from the free edge was subjected to the highest stress concentration was observed.

Atas (2009) presented a step-by-step process for conversion of an orthogonal fabric into a non-orthogonal fabric with small weaving angles. Four different stacking layups were adopted for comparison of W/D to be 3, 4 and E/D to be 1, 2, and 3. It was further proved that by adopting layers with same orientations resulted in undesirable severe modes of failure whereas load carrying capacity decreases with small weaving angles in mechanically fastened joints.

Kishore et al. (2009) investigated on various modes of failure and failure load for multi-pin joints in unidirectional glass epoxy composite laminates. To study failure modes and load using FEM Model, the results with the experimental study were compared. In multi-pin joints, the effect of pitch-to-diameter ratio (P/D), side width-to-diameter (S/D) and edge-to-diameter (E/D) ratios were investigated. 2D Finite Element model was developed using ANSYS software in which Tsai–Wu failure criteria was used to predict failure load and modes of failure. Experimental and analytical results compared which showed the importance of all geometric parameters while designing multi-pin joints.

Osman (2010) investigated the behavior of single pinned joint of glass epoxy fiber reinforced laminates filled with Al₂O₃ particles in different proportions. Single-hole pin-loaded samples were investigated in tension. The results showed that the bearing strength of fiber epoxy laminated pinned joints was closely linked with the filler content and geometric parameters. The increase of nanofiller content in the matrix improved strength upto a certain limit. The highest bearing strength was obtained with 10 wt.% of Al₂O₃ content. Further increase in the nanofiller content in the matrix resulted in decrease of bearing strength, when compared to unfilled glass reinforced epoxy composites.

Wei et al. (2011) investigated the effect of SiO₂ nanofiller epoxy on the basalt fiber. The silica nanofiller–epoxy laminate coating gave rise to a significant increase in the tensile strength of the basalt fibers when compared to neat epoxy coating with a promising interfacial property in the basalt fiber reinforced resin matrix composite. The nanofiller added to neat composite improved the mechanical characteristics of basalt fibers.

Aktas (2011) investigated the modes of failure and failure loads of glass composite

epoxy laminates. The laminated plates with one and two serial pinned joints were observed numerically and experimentally. Study of Geometric parameters E/D and W/D ratio were carried out. The result after conducting the study showed that the maximum failure load was obtained at E/D and W/D ratios to be 4.

Ondurucu et al. (2012) investigated damage propagation of glass–epoxy laminated composite pinned-joints. To find the effects of joint geometry and stacking of laminates on the bearing strength and failure mode, experimental work were carried out. E/D and W/D ratios were selected from 1 to 5 and 2 to 5, respectively. By analyzing the effect of material parameters on damage initiation, composite laminated plates were stacked as one on another using different orientations $[0^0/90^0/0^0]$ and $[90^0/0^0/90^0]$. A total of 144 samples with nine different geometries were manufactured and tested to find the experimental strength and modes of failures.

Lingaraju et al. (2012) studied the characteristics of pin loaded laminates with different geometrical parameters. The aim of the research was to investigate the failure modes, failure load and stresses on pinned hole. The hole of the plate was subjected to a gripping force by stiffed pin. The analysis was further carried out to find the effect of varying K/D and W/D ratio. It was analyzed that the strength of the samples increases with the increase in K/D and W/D ratio to certain extent and then becomes stable.

Ilic et al. (2012) used FEM model to find the stress distribution around the pinned hole using Tsai-Wu initial failure criterion. Test was carried out to study the load distributed around the hole. The influence of stacking of layups $[0^0/45^0/90^0]$ and $[0^0/+45^0/-45^0/90^0]$ on pin laminates was investigated to determine the various modes of failure.

Irisarri et al. (2012) used FEM package for predicting strength in CFRP laminates. Delamination was taken into account in the model by means of cohesive elements. The ply characteristic was described through a viscoelastic model combined with a progressive damage technique. Prediction of the proposed model was compared to both bearing tests and open-hole tests results. Numerical study were also done to filled-hole tensile tests and bearing/bypass interaction tests. The obtained results showed the capability of the defined model to capture the material and stacking layup effects on the

joint characteristic, as well as the influence of the geometrical parameters on the joint.

Pisano et al. (2012) performed on various failure mechanism of pinned joints in glass fiber based laminates. Orthotropic fastened laminates in plane stress conditions were observed via a limit analysis numerical procedure carried out at lamina level. Layer-by-layer approach considering the actual stacking sequence of the laminate, was able to withstand the addressed problem with very fine accuracy. A large number of experimental results detected on actual prototypes were analysed to validate the defined procedure.

Sharma et al. (2012) studied the effect of epoxy with nanoclay cloisite 30B (at 1, 3 and 5 wt.% of resin) on the unidirectional glass fibers. The nanocomposite laminates were analysed using X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM). XRD showed that the interlayer spacing between the clay increased drastically indicating that the polymer was able to withstand between the clay layers. The mechanical properties were calculated by carrying out flexural, hardness tensile tests and values were compared with neat epoxy composites. The tests showed addition of nanoclay up to 3 wt.% increases tensile strength and micro-hardness whereas decrease in values with further clay addition up to 5 wt.%.

Qin et al. (2013) revealed the effect of different fasteners on mechanical behaviors of bolted joints. Double-lap composite joints joined were analysed and their mechanical behavior were investigated. Differences in the joint withstand capability, stiffness and mode of failures between protruding head joint were depicted. The fastener effects like clearance-fit, embraced net-fit with material parameters were observed using FEM. The changes of contact area, local deformation, distribution of stresses and bending of fasteners were detailed analyzed based on the numerical results.

Khashaba et al. (2013) investigated the influence of specimen stacking layup on the strength, failure displacement, bearing stiffness and mean ultimate stress. Four configurations were taken into account $[0^0/90^0]_{2s}$, $[15^0/-75^0]_{2s}$, $[30^0/-60^0]_{2s}$, and $[45^0/-45^0]_{2s}$. The results obtained showed that the apparent bearing stiffness was qualitatively agreed with the predicted Young's modulus. Samples with $[0^0/90^0]_{2s}$ stacking orientation had the ultimate failure stress and maximum failure displacement compared with the other stacking sequences whereas orientation $[45^0/45^0]_{2s}$ have the maximum failure

displacement and bearing capacity based on the first-peak criterion.

2.2 Gap in Literature

From the literature review it is seen that various geometric parameters were studied 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 nano composites using nanoclay (Cloisite 30B) and nanoTiO₂ as filler material. The distribution of tensile stress by keeping the stacking sequence [0⁰/45⁰/90⁰], varying geometrical parameters to increase the strength of joint by reducing the stress concentration near the holes. Thereafter, Comparative study was carried out to investigate the strength both experimentally and numerically.

2.3 Objectives

The specific objectives are:

1. Preparation of epoxy based unidirectional glass fabric composites laminates with or without filler content. The nanofiller used are nanoclay and nanoTiO₂ whereas reinforcement used is Glass Fiber.
2. Preparation of pin joint samples with different geometrical parameters based upon optimized nanomaterial.
3. Testing of mechanical properties.
4. Determination of different failure modes and bearing strength of single pin joints for unfilled and filled glass epoxy nanocomposite laminates.
5. Numerical analysis of the samples using FEM.

The following chapter gives the details of various materials used, different apparatus used and methodology followed for the experimentation in the present study.

3.1 Materials

3.1.1 Resin

Materials used while manufacturing of the composite laminates were epoxy mixed with hardener and accelerator known as resin matrix. DGEBA (Di Glycidyl Ether of Bisphenol-A) based epoxy also known as Lapox, K-12 hardener and K-13 accelerator were used. Resin *i.e* (epoxy, hardener and accelerator) were purchased from Atul Ltd., Gujarat, India (www.atul.co.in). The properties of epoxy, Hardener and accelerator are shown in Table 3.1 and 3.2.

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 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)	Coefficient of Liner Thermal (°K ⁻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

Reinforcement in the present work used is Unidirectional glass fabric Advantex 1200 gsm was purchased from the Owens Corning India Pvt. Ltd, Mumbai (www.owenscorningindia.com). Mechanical and physical characteristics of unidirectional glass fabric are shown in Table 3.3 and 3.4.

Table 3.3 Mechanical properties of unidirectional fabric Advantex

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

Table 3.4 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

3.1.3 Nanoclay

Nanoclay (Cloisite 30B) was adopted as first nanofiller which was purchased from the Connell Bros. Company Pvt. Ltd., Mumbai, India (www.connellbrothers.com). Nanoclay is a natural montmorillonite tailored with a quaternary ammonium salt. Nanoclay is an additive for plastics which improves its various properties. The physical and chemical properties of the nanoclay are shown in Table 3.5.

Table 3.5 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 NanoTiO₂

TiO₂ nanoparticle is second nanofiller content which is white solid inorganic substance. It also improves the various properties of the composites. Table 3.6 shows the various physical properties of nanoTiO₂. It was purchased from Degussa Company, Frankfurt, Germany.

Table 3.6 Physical properties of NanoTiO₂

Material	Particle Size	Purity	Morphology	True Density(g/cm ³)	Color
Nano TiO ₂	15nm	99.8%	Spherical	4.26	white

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 various methods for preparing the laminates but hand layup technique is used in the present work. After in-depth study of the literature the procedure for the laminates preparation is given below.

3.2.1.1 Addition of nanofiller in epoxy resin

Resin and nanofiller 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.

3.2.1.2 Stirring of epoxy-nanofiller mixture in homogenizer

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

3.2.1.3 Stirring of epoxy- nanofiller mixture in sonicator after homogenization

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

3.2.1.4 Addition of hardener and accelerator in epoxy-nanofiller mixture

After sonication process, keeping the control hardener to resin ratio as 1:1, accelerator and hardener were added to the epoxy- nanofiller blend. The blend was 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 with desired orientation, resin was applied on sheet with a brush and then second layer of fiber with selected orientation 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 air entrapped between the layers so that laminates can properly stick to each other. The geometric parameters and formulation of the

laminates are given in Table 3.7.

3.2.1.6 Curing

After the laminate layers were prepared, they were properly bonded to each other with the help of compression moulding. Laminate were cooled and cured at room temperature for one day.

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°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 3.7 Formulation and geometrical parameters of glass/epoxy nano filler laminates

Sr. No.	Sample code	Fabric orientation	Number of plies	Weight fraction %		
				Resin	Fiber content	Nano Filler
1	MC0	[0°/45°/90°]	3	40	60	0
2	MC1	[0°/45°/90°]	3	39.52	60.08	0.40
3	MC2	[0°/45°/90°]	3	39.36	59.84	0.80
4	MC3	[0°/45°/90°]	3	39.20	59.59	1.21
5	MC4	[0°/45°/90°]	3	39.04	59.36	1.65
6	MC5	[0°/45°/90°]	3	38.86	59.09	2.05

3.3 Testing

3.3.1 Tensile test

The tensile tests as per ASTM D3039 standard were carried out at 25 ± 2 °C on a Zwick-Roell Universal Testing Machine Germany. The grip to grip separation of 138 mm and gauge length of 238 mm of the samples were taken at the start position. A crosshead speed of 2 mm/min was maintained throughout the testing. At least three samples of each mixture were manufactured and tested. The average values of the

samples were taken for the results.

3.3.2 Shear test

The shear tests as per ASTM D5379 standard were performed at 25 ± 2 °C on a Zwick-Roell Universal Testing Machine – Model Z010, Zwick-Roell, Germany,. A crosshead speed of 2 mm/min was maintained. At least three samples of each mixture were manufactures and further tested. After that the average values of these samples were reported.

The Iosipescu test sample was fabricated and cut according to the dimension, shown in Fig.3.1. It was further tested using Iosipescu test fixture shown in Fig.3.2. The specimens were placed in Iosipescu test fixture in which the sample was centered using the alignment pin and lightly clamped with the adjustable wedges. Then the load was applied to the specimen.

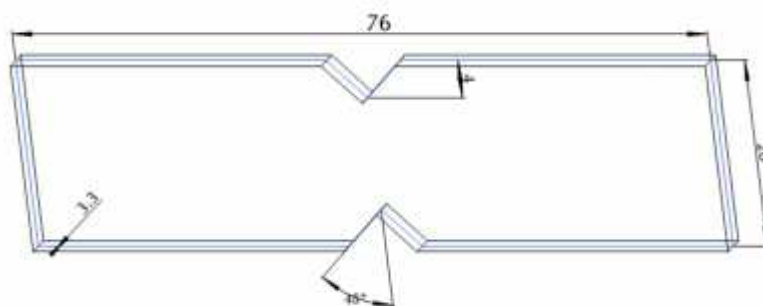


Fig. 3.1 Geometry of the Iosipescu shear test specimen



Fig. 3.2 Iosipescu Test fixture

3.3.3 Flexural tests

The flexural tests according to ASTM D7264 standard were carried out at 25 ± 2 °C on a Zwick-Roell Universal Testing Machine. The standard span-to-thickness ratio was 40:1, the standard specimen thickness and width were 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).


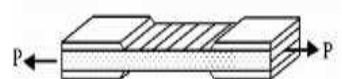

$$\sigma_F = \frac{3 \times P_{\max} \times L}{2 \times b \times h^2} \quad \text{when } L/h \leq 16 \quad (3.1)$$

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

$$\varepsilon_F = \frac{6 \times D \times h}{L^2} \quad (3.3)$$

Where L, b and h are the span (Length), width and depth of the sample, P_{\max} is the maximum load encountered before failure, D is the maximum deflection before failure, m is the slope of the tangent to the initial straight-line portion of the load–deflection curve. Table 3.8 shows the summary of geometry and ASTM standards which were used.

Table 3.8 Properties and ASTM standards

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

Mechanical properties of composite laminates with a ply orientation of $[0^0/45^0/90^0]$ and different geometrical parameters were found to investigate the effect of nanofiller contents.

4.1 Mechanical properties of composite laminates

The results obtained by conducting tensile and shear tests on prepared nano particle 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.	Young's Modulus (N/mm ²)		Shear Modulus (N/mm ²)	Poisson Ratio
	Longitudinal Direction (±SD)*	Transverse Direction (±SD)		
1	17400(±500)	6200(±500)	3100	0.3

Nanofiller contents in the wt.% of 1, 2, 3, 4 and 5 were added to the epoxy based reinforced laminates to find out the varying properties. The results obtained for a range of compositions of nanoparticles are shown in Fig. 4.1.

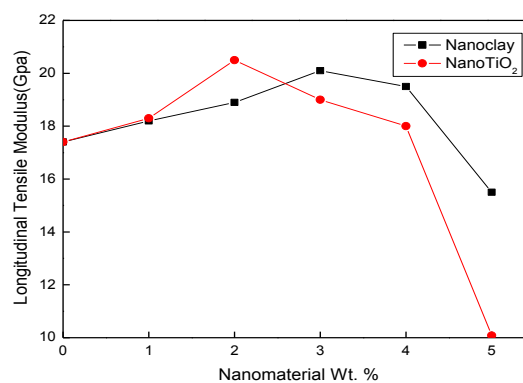


Fig. 4.1 Tensile modulus vs. weight percentage of nanomaterial

It can be seen from Fig. 4.1 that at 2 wt.% of nanoTiO₂ and 3 wt.% of nanoclay, the laminates show maximum value of Tensile Modulus. Table 4.2 shows the different mechanical properties of glass/epoxy reinforced with 3 wt.% of nanoclay and 2 wt.% of nanoTiO₂ composite laminates.

Table 4.2 Mechanical properties of glass fiber/epoxy nanocomposite laminates

Sr. No.	Nanomaterial	Young's Modulus (MPa)		Shear Modulus (Mpa)
		Longitudinal Direction (\pm SD)	Transverse Direction (\pm SD)	
1	Cloisite-30B	20100 (\pm 500)	7500 (\pm 500)	3300
2	TiO ₂	20000(\pm 500)	4500(\pm 500)	1200

4.2 Flexural Test

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

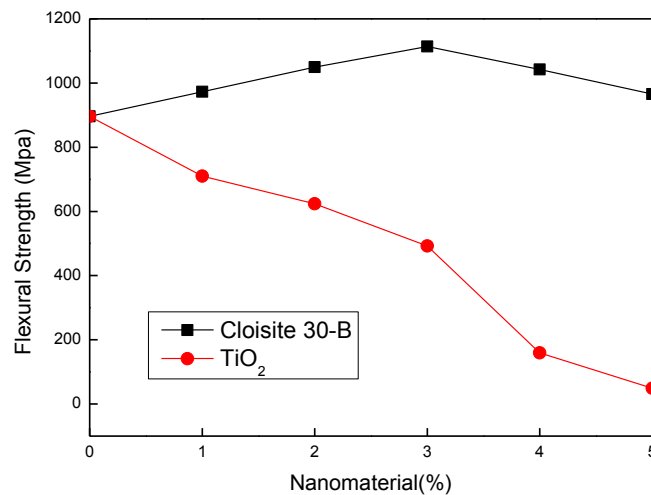


Fig. 4.2 Flexural strength vs. wt % of nano material

As can be seen from Fig. 4.2, there is a significant rise in the flexural strength at 3 wt.% of nanoclay. A 24% improvement in strength of specimen with 3 wt.% nanoclay loading was observed when compared with neat epoxy. 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. However there is a decrease in the flexural strength due to nanoTiO₂. The decrease in the flexural properties is due to reduced interfacial properties in the presence of TiO₂ particles.

4.3 Pin Joint Geometry

In the present work, composite plate with length L, width W, thickness t, made of glass fiber-reinforced laminates with a single circular drilled hole was tested. The

rigid pin is inserted into the hole. The ply orientation of the laminate is to be kept standardized $[0^\circ/45^\circ/90^\circ]$ according to the literature studied. The geometry of composite plate is shown in Fig. 4.3. A hole of diameter D fixed as 4 mm was located along the centre line of the composite plate at a distance E from one end of the plate. A constant tensile load P is applied on the plate and the rigid pin which is supported outside the laminate, resists this load. Load is along the fibers reinforced in the plate and is symmetric with respect to the middle line.

Bearing stress, σ_b is defined by equation (4.1)

$$\sigma_b = \frac{P_{\max}}{D.t} \quad (4.1)$$

Where P_{\max} is the applied maximum load, D is the hole diameter and t is the specimen thickness.

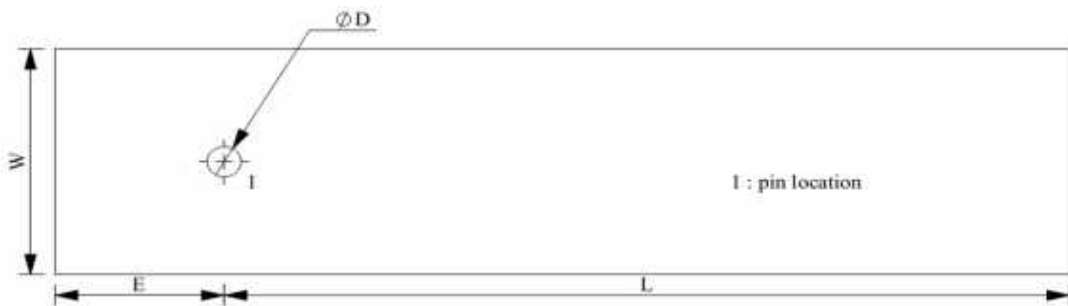


Fig. 4.3 Geometry of composite plate with hole

The samples with different E/D and W/D ratios are given in Table 4.3. The thickness of the plate is 2 mm, and length from hole to edge is 100 mm.

Table 4.3 Geometries of samples to be tested

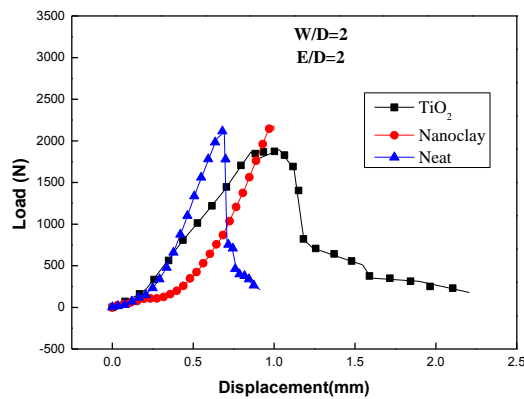
Geometric Parameters	Diameter of Hole (mm)	Layup	E(mm)	W/D			
				2	3	4	5
E/D=2	4	$[0^\circ/45^\circ/90^\circ]$	8	8	12	16	20
E/D=3	4	$[0^\circ/45^\circ/90^\circ]$	12	8	12	16	20
E/D=4	4	$[0^\circ/45^\circ/90^\circ]$	16	8	12	16	20
E/D=5	4	$[0^\circ/45^\circ/90^\circ]$	20	8	12	16	20

The samples manufactured and tested as per the ASTM D3039 standards with different wt.% of nanofillers *i.e.* 1% to 5% to find their mechanical properties. The optimum wt.% of nanoclay and nanoTiO₂ was decided on the basis of highest strength achieved. Thereafter the pinned joint samples were prepared for that achieved optimum value of wt.% of nanofillers in epoxy laminates whose achieved strength is greater. The strength of these samples was compared with the neat (without nanofillers) epoxy glass fiber laminates.

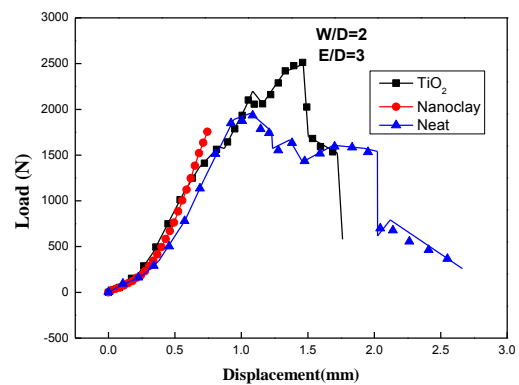
4.4 Test results of glass/epoxy pin joints configuration for unfilled and filled samples

Tests were conducted on pin joint configuration of glass/epoxy nanocomposites with unfilled (no nanoparticles) and at achieved optimum nanoclay percentage (*i.e.* 3 wt.%) and nanoTiO₂ (*i.e.* 2 wt.%) obtained from the results of the tensile tests.

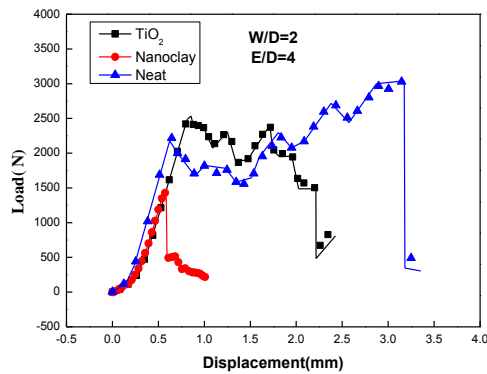
4.4.1 Comparative study of strength for neat glass/epoxy composite laminates with the addition of two different nano materials



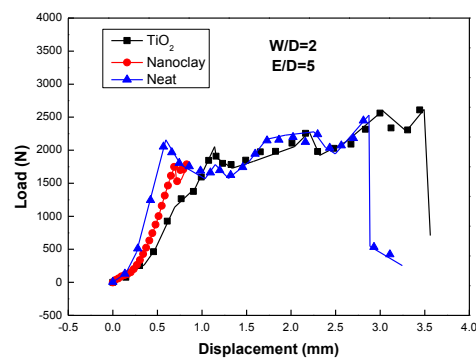
(a)



(b)



(c)



(d)

Fig. 4.4 Load vs. Displacement curves of pin joints for $W/D=2$

(a) $E/D=2$ (b) $E/D=3$ (c) $E/D=4$ (d) $E/D=5$

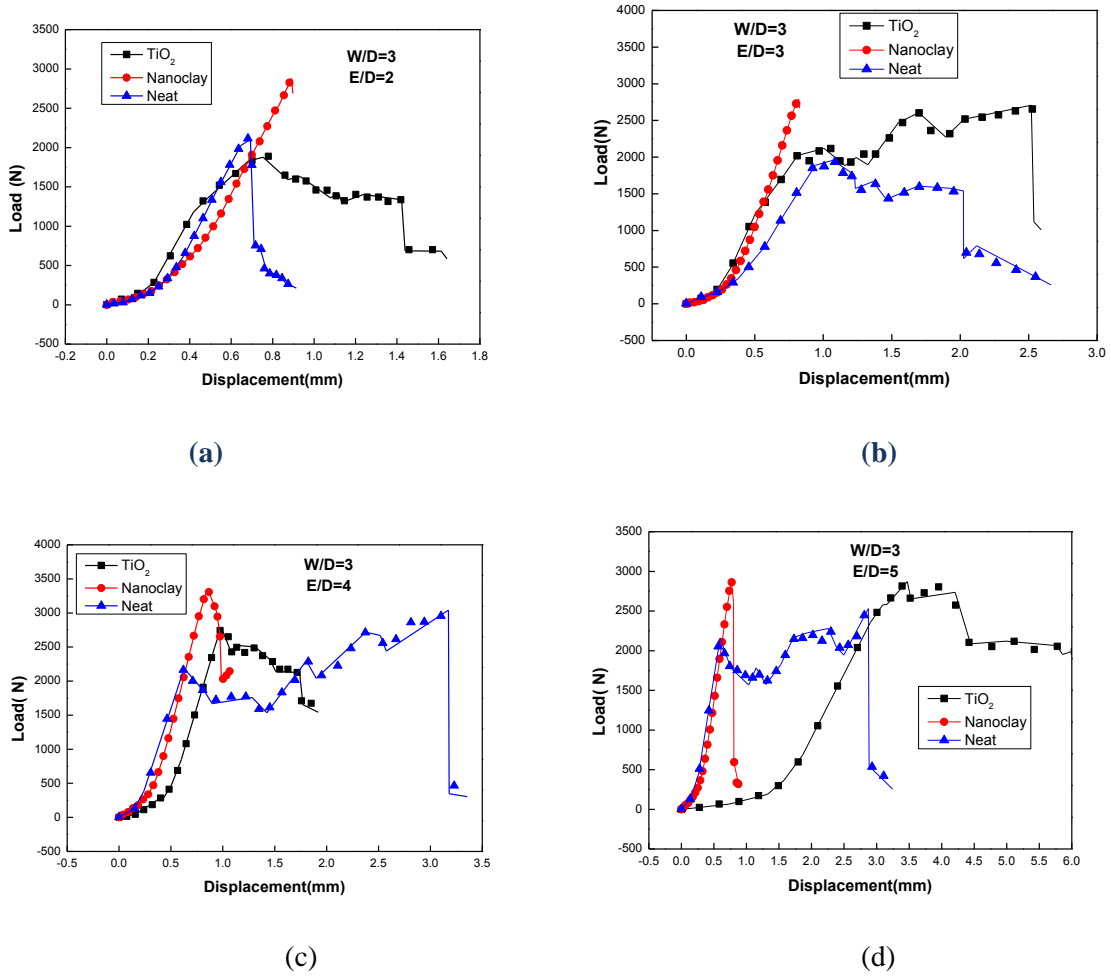
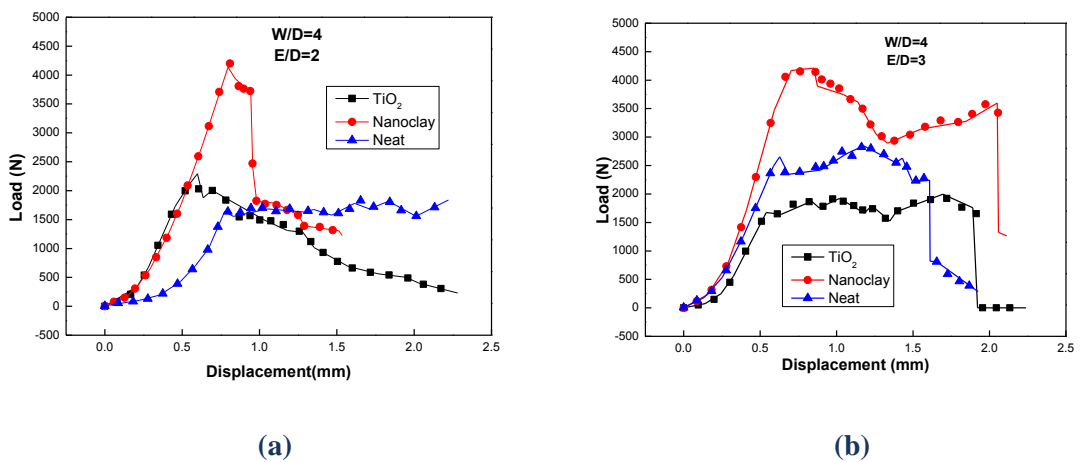
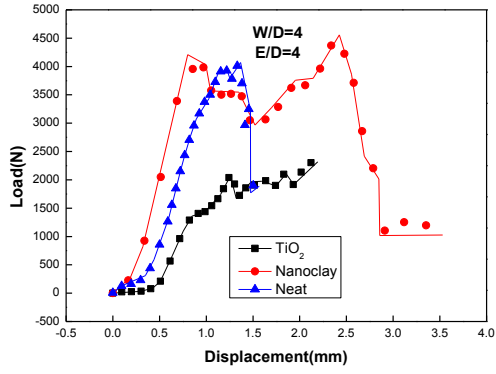


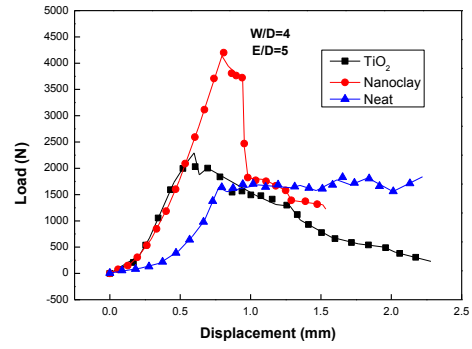
Fig. 4.5 Load vs. Displacement curves of pin joints for $W/D=3$

(a) $E/D=2$ (b) $E/D=3$ (c) $E/D=4$ (d) $E/D=5$





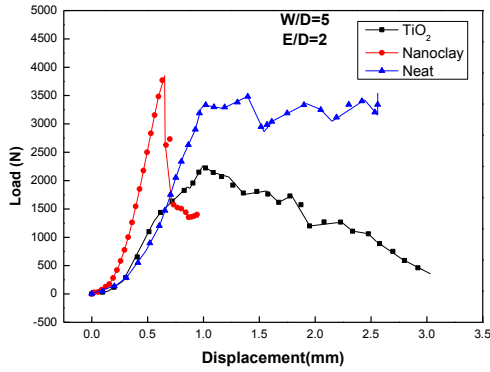
(c)



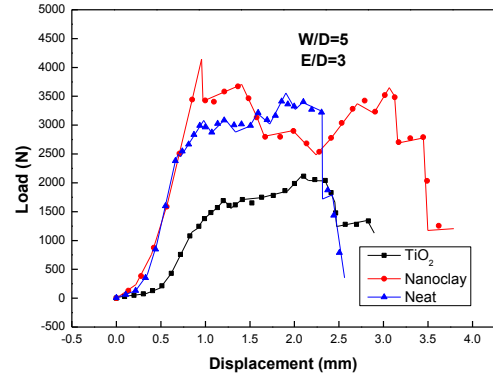
(d)

Fig. 4.6 Load vs. Displacement curves of pin joints for W/D=4

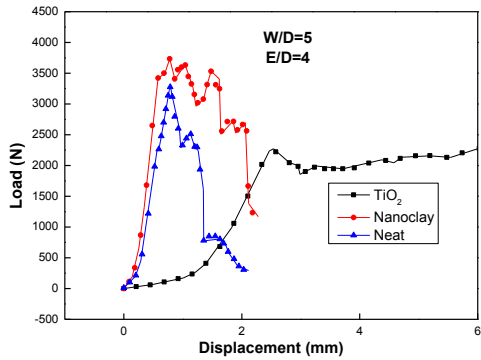
(a) E/D=2 (b) E/D=3 (c) E/D=4 (d) E/D=5



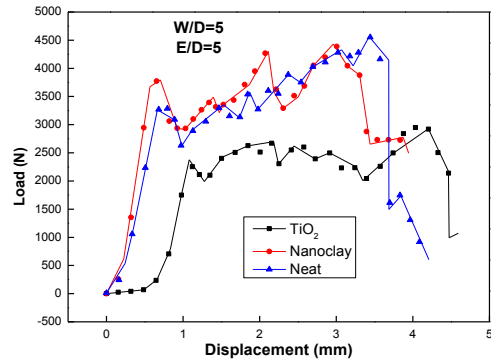
(a)



(b)



(c)



(d)

Fig. 4.7 Load vs. Displacement curves of pin joints for W/D=5

(a) E/D=2 (b) E/D=3 (c) E/D=4 (d) E/D=5

The different failure modes as predicted from the curves shown in Fig. 4.4 to 4.7 are given in Table 4.4.

Table 4.4 Failure Modes in Pin Joint Glass Epoxy reinforced composite laminates

Nanomaterial at maintained ratios	W/D=2		W/D=3		W/D=4		W/D=5	
	Clay	TiO ₂	Clay	TiO ₂	Clay	TiO ₂	Clay	TiO ₂
E/D=2	N	N	N	N	S	S	S	S
E/D=3	N	N	N	N	B+S	B+S	B+S	B+S
E/D=4	N	N	B+N	N	B	B+S	B	B+S
E/D=5	N	N	N	B+N	B	B	B	B

*N: Net Tension S: Shearing B: Bearing

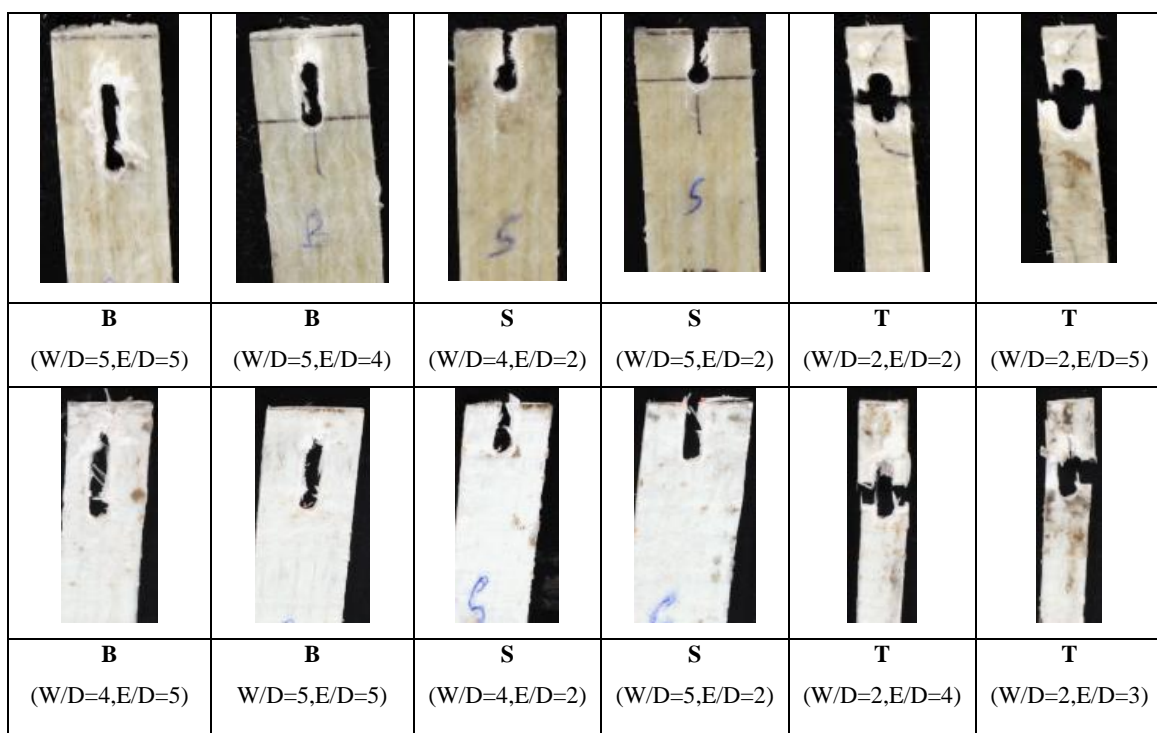


Figure 4.8 Actual images of failure modes in the specimens

It can be seen from Fig. 4.3 to 4.6 that the bearing strength of the joint increase as W/D or E/D ratio increases. When W/D and E/D ratios have larger values, bearing mode of failure occurs. 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 any warning. These failures results from excessive tensile and shear stresses. Bearing failure is often considered as the desirable mode because it usually gives a higher strength. Other modes of failure should be avoided through proper design of the joint geometry and composite material itself. The different

failure modes in the composite are given in Table 4.3 with their actual image in fig. 4.8. From Fig. 4.4 to 4.7 , it can be seen that the bearing mode of failure occurs for $W/D \geq 4$ and $E/D \geq 4$ for samples prepared using nanoclay, whereas the samples prepared using nanoTiO₂ have the bearing mode of failure for $W/D \geq 4$ and $E/D \geq 5$. It is seen that the addition of nanoclay enhances the bearing strength as compared to that of nanoTiO₂ at all the W/D and E/D ratios.

4.5 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.

4.5.1 Finite element modeling

The geometry of the plate investigated in this study was shown in Fig. 4.3. 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.

4.5.2 Geometric modeling and meshing

Geometric model was made in ANSYS 14.5 software package 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. 4.9.

Stress and strains are related using Equation (5)

$$\{\sigma\} = [D] \{\epsilon^e\} \quad (5)$$

With,

$$[D]^{-1} = \begin{bmatrix} 1/E_x & -\nu_{xy}/E_x & -\nu_{xz}/E_x & 0 & 0 & 0 \\ -\nu_{yx}/E_y & 1/E_y & -\nu_{yz}/E_y & 0 & 0 & 0 \\ -\nu_{zx}/E_z & -\nu_{zy}/E_z & 1/E_z & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{xy} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{yz} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{xz} \end{bmatrix}$$

Where,

E and ν are the Young's Modulus and Poisson's ratio in the respective direction.

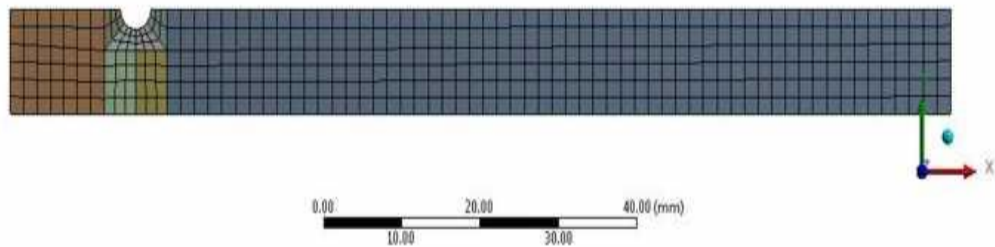


Fig. 4.9 Meshing of the model

4.5.3 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.4.10.

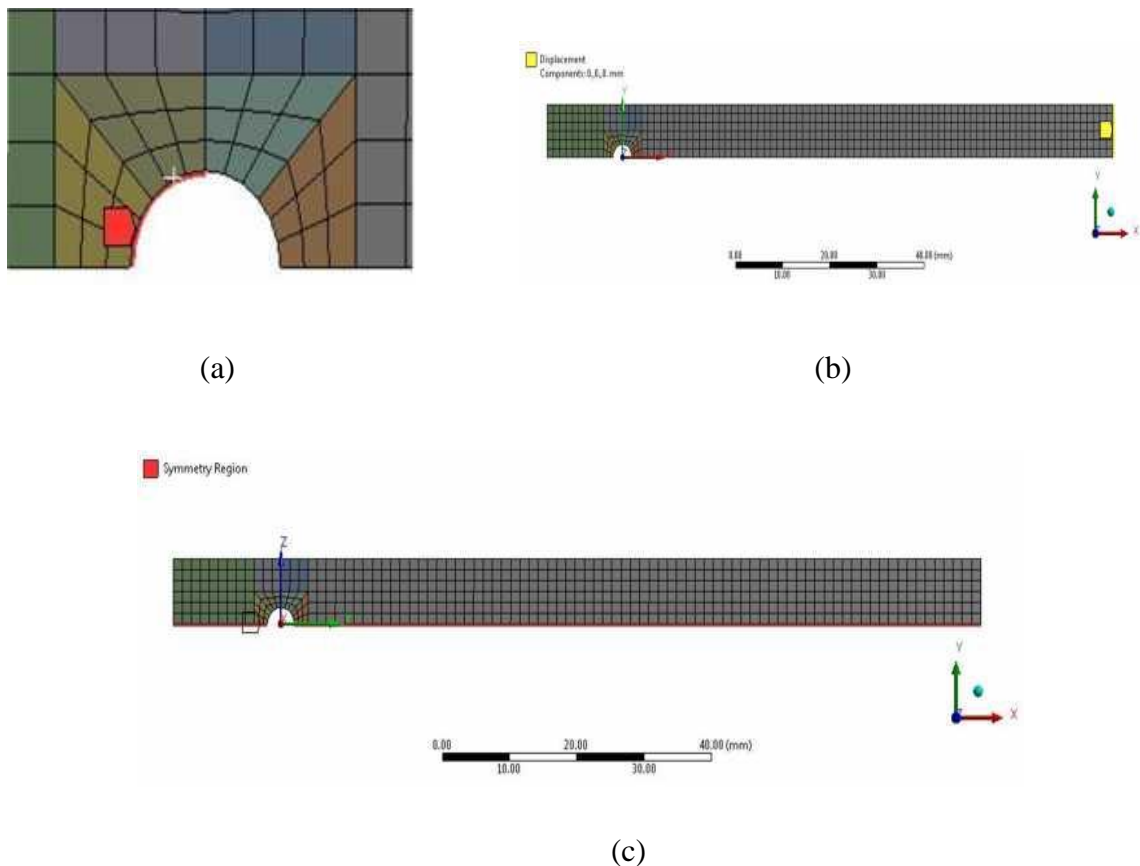


Fig. 4.10 (a) Radial boundary conditions (b) Displacement (c) Symmetric boundary conditions

Finite element analysis results for filled and unfilled composites are shown in Fig. 4.11. It can be seen that the bearing strength is more in composites with nanoclay as compared to the neat specimen. The specimen with nanoTiO₂ has bearing strength even less than the neat specimen.

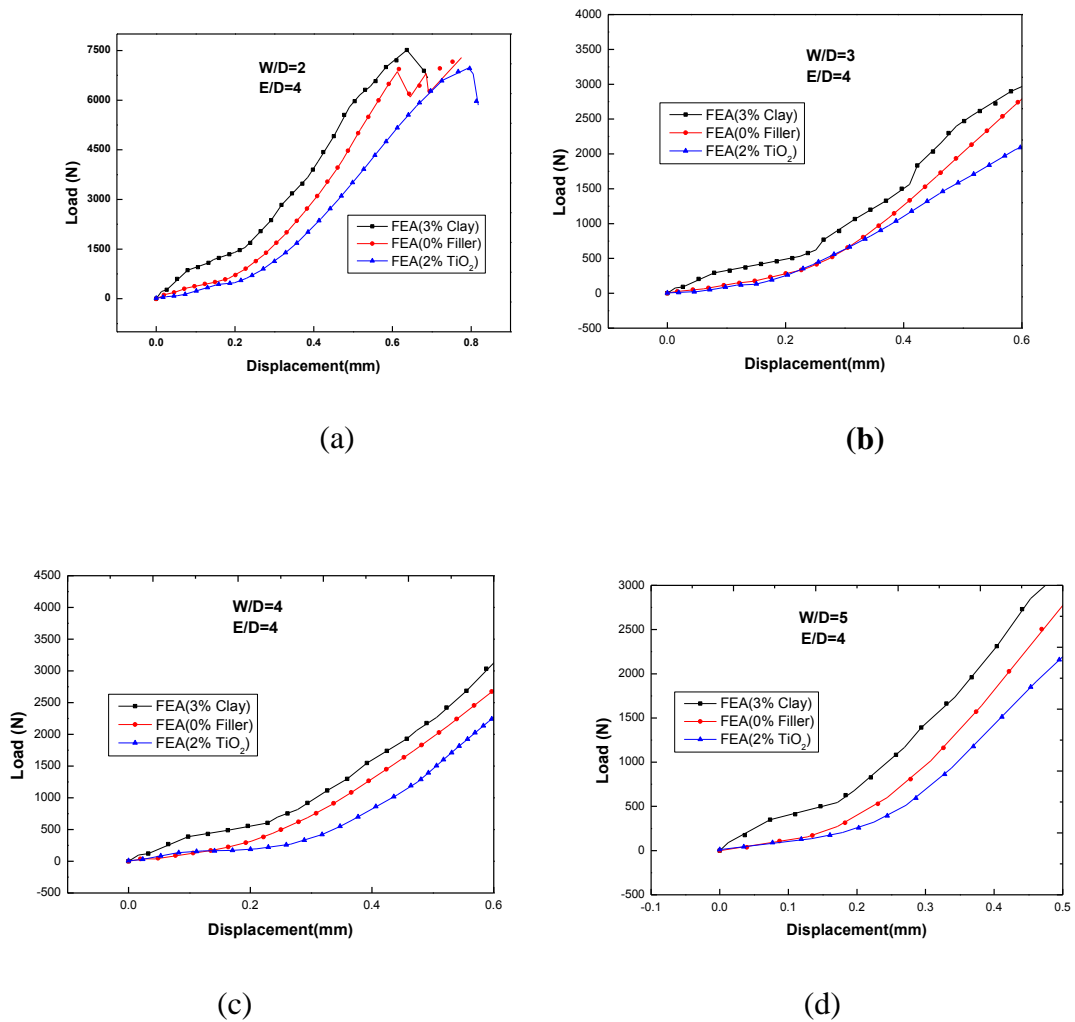


Fig. 4.11 FEA Comparison of pin joints at 0%, 2% TiO₂ and 3% nanoclay

(a) W/D=2 (b) W/D=3 (c) W/D=4 (d) W/D=5

Table 4.5 shows that the numerical results which match fairly with the experimental results.

Table 4.5: Percentage Error in Experimental and Numerical Results

S. No.	Geometrical Parameter	Experimental (kN)	Numerical (kN)	Percentage error (%)
1	W/D=4, E/D=4(Neat)	4.00	4.11	2.81
2	W/D=4, E/D=4 (Nanoclay)	4.55	4.51	0.1
3	W/D=4, E/D=5(NanoTiO ₂)	3.12	3.27	4.6

5.1 Conclusion

The major focus of the study was the comparative study of nanoparticle fillers content and their influence on the various modes and strength of glass fiber reinforced epoxy composites pin joints.

Based on the numerical and experimental investigation, the following observations are made:

1. The load carrying capacity of laminates increases due to addition of nanofiller content upto a certain limit. Higher loading capacity has been obtained at 3 wt.% of nanoclay which is approximately 19% higher than neat glass/epoxy composite laminates. The loading capacity decreases with further increase in the nanoclay content above 3 wt.%.
2. Higher loading capacity has been obtained at 2 wt.% of nanoTiO₂ which is less than neat glass/epoxy composite laminates. With addition of nanoTiO₂, loading capacity of laminated epoxy composites at 2 wt.% is maximum. But with the further increase in the content of nanoTiO₂, degradation of the inter laminar bonding of fiber and resin occurs which leads to fall in its load bearing strength.
3. Laminates of Pin Joint can withstand higher loads and give the progressive failure which is desirable when it falls due to bearing. The bearing failure is obtained for geometrical parameters *i.e* $W/D \geq 4$ and $E/D \geq 4$ for nanoclay, whereas for nanoTiO₂, the bearing mode of failure occurs for $W/D \geq 4$ and $E/D \geq 5$.
4. The experimental work when compared with that of numerical study, shows fairly good correlation with each other.

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 or methodologies used for the preparation of composites can be adopted.
3. Multi pin joint analysis can be done.

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