INVESTIGATION OF DAMAGED GLASS FIBER REINFORCED POLYMER COMPOSITES IN 3-POINT BENDING

A Thesis report submitted
in partial fulfillment of the requirements
for the award of degree of

Master of Engineering
in
CAD/CAM & Robotics

Submitted By

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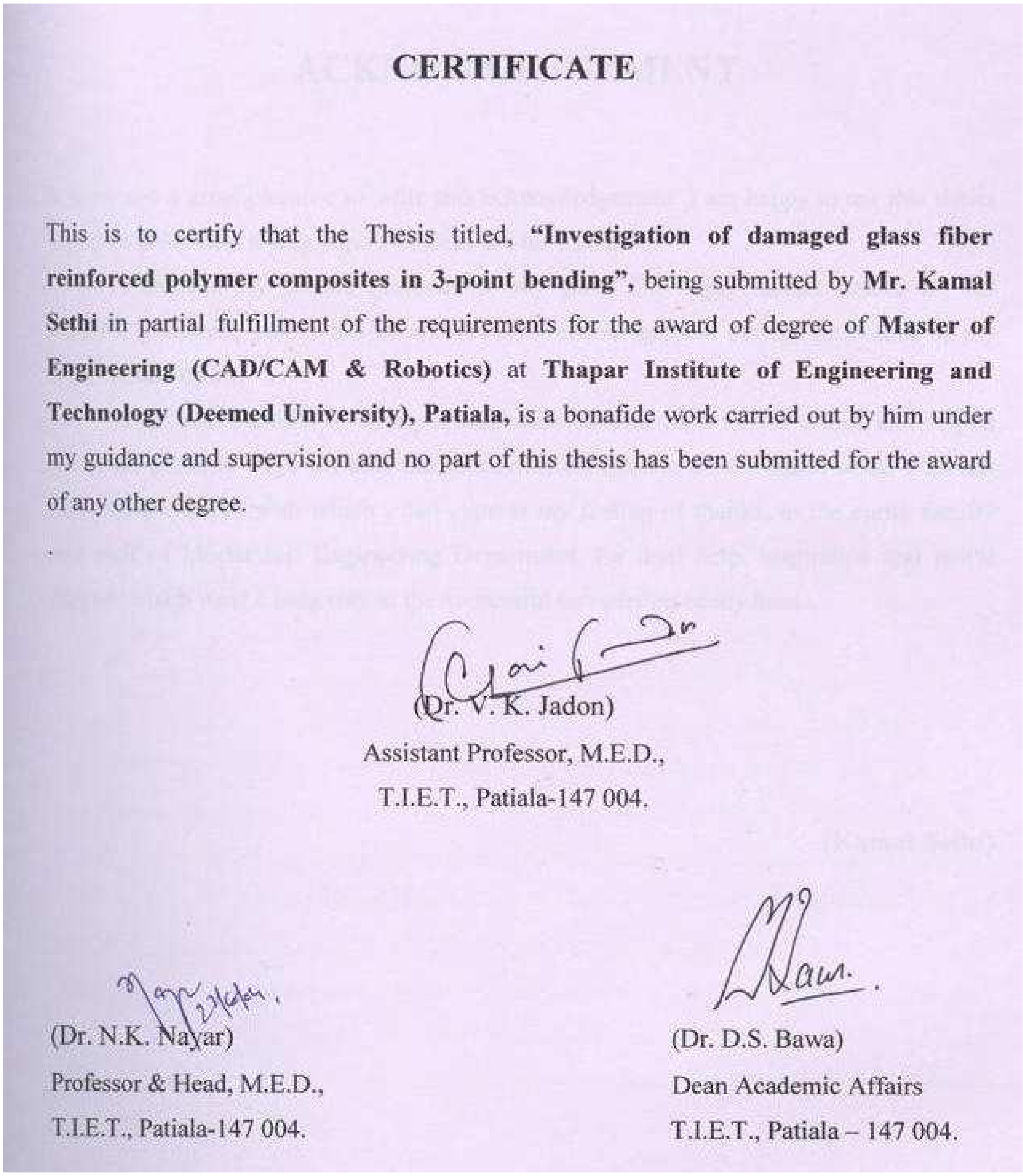

CERTIFICATE

This is to certify that the Thesis titled, **"Investigation of damaged glass fiber reinforced polymer composites in 3-point bending"**, being submitted by **Mr. Kamal Sethi** in partial fulfillment of the requirements for the award of degree of **Master of Engineering (CAD/CAM & Robotics)** at **Thapar Institute of Engineering and Technology (Deemed University), Patiala,** is a bonafide work carried out by him under my guidance and supervision and no part of this thesis has been submitted for the award of any other degree.

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It gives me a great pleasure to write this acknowledgement. I am happy to see this thesis report in print after a long period of time and hard labour.

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ABSTRACT

Composites materials are used in almost all aspects of the industrial and commercial fields in aircraft, ships, common vehicles, etc. Their most attractive properties are the high strength-to-weight ratio and high stiffness-to-weight ratio. However, these materials also have some problems such as fiber breakage, matrix cracking and delamination. Matrix cracks and fiber breakages play an important role in laminates under tensile load. However, delamination is the critical parameter for laminates under compression and one of the most common failure modes in composite laminates. Delamination may be formed due to a wide variety of foreign object impact damage, poor fabrication process, and fatigue from environment cycle.

In the present study, an experimental work was carried out to determine the ultimate breaking load using flexure tests of damaged, 90-degree glass fiber-reinforced, laminated composites loaded in 3-point bending. E-glass/epoxy composites were manufactured to fabricate the specimens, using Hand lay-up technique. The laminated composites were prepared, with lateral and longitudinal multiple delaminations and broken fiber strands. The delamination length of the manufactured specimen was fixed to 15.5% of the global beam length. Tests were carried out on laminated beams with $[90^\circ{}_{20}]$ and $[90^\circ{}_{32}]$ stacking sequence. The influence of various defects on the residual strength of the defected laminated composites was examined using the load verses displacement graphs. The results show that, the increase in the number of lateral multiple delaminations and broken fiber strands significantly reduces the residual ultimate strength of the laminated composites.

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1 – COMPOSITE MATERIALS

1.1 INTRODUCTION

It is a truism that technological development depends on advances in the field of materials. One does not have to be an expert to realize that a most advanced turbine or aircraft design is of no use if adequate materials to bear the service loads and conditions are not available. Whatever the field may be, the final limitation on advancement depends on materials. Composite materials in this regard represent nothing but a giant step in the ever-constant endeavor of optimization in materials.

A composite material is a heterogeneous solid consisting of two or more different materials that are mechanically or metallurgic-ally bonded together. The word "composite" means, "consisting of two or more distinct parts." Thus, a material having two or more distinct constituent materials or phases may be considered a composite material. It is only when the constituent phases have significantly different physical properties and thus the composite properties are noticeably different from the constituent properties that we have come to recognize these materials as composites. The constituents are combined at a macroscopic level and are not soluble in each other. Each of the various constituents retains its identity in the composite and maintains its characteristic structure and properties. There are recognizable interfaces between the materials. One constituent is called the reinforcing phase and the one in which it is embedded is called the matrix. The reinforcing phase material may be in the form of fibers, particles and flakes. The composite material, however, generally possesses characteristic properties such as high strength-to-weight ratio, high stiffness-to-weight ratio, high temperature performance, corrosion resistance and hardness, which are not possible to obtain with the individual components.

The concept of composite materials is a familiar one even to those not acquainted with theoretical aspects of composites technology. Finely ground wood, silica or chalk is added to plastic molding materials largely to make them cheaper; crushed rock aggregate is used in concrete partly to reduce the cost per unit weight of the material and partly to improve its compressive strength; the blending of air or gas with metals, plastics or cements results in foamed products of low density. The purpose in each of the above-mentioned cases is to optimize material properties by the process of combination. In engineering practice, as indeed in nature, it is common principle that two or more components may be profitably combined to form a composite material to make best use of the favorable properties of the components while simultaneously mitigating the effects of some of their les desirable characteristics. The principle applies to all kinds of properties – physical, chemical and mechanical – and a concomitant benefit of making composites is that the density and perhaps the cost of the product is often less. Examples of composites include carbon black in rubber, concrete reinforced with steel, epoxy reinforced with glass/graphite fibers etc. Naturally, found composites include wood where the lignin matrix is reinforced with cellulose fibers and bones, in which the matrix made of minerals, are reinforced with collagen fibers.

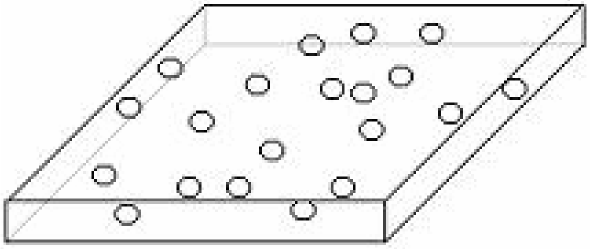
Practically everything is a composite material in this world. Thus, a common piece of metal is a composite (polycrystalline) of many grains. Therefore, we must agree on an operational definition of composite material. We shall call a material that satisfies the following conditions a composite material:

1. It is manufactured (i.e., naturally occurring composites, such as wood, are excluded).
2. It consists of two or more physically and/or chemically distinct, suitably arranged or distributed phases with an interface separating them.
3. It has characteristics that are not depicted by any of the components in isolation.

1.2 CLASSIFICATION OF COMPOSITE MATERIALS [12]

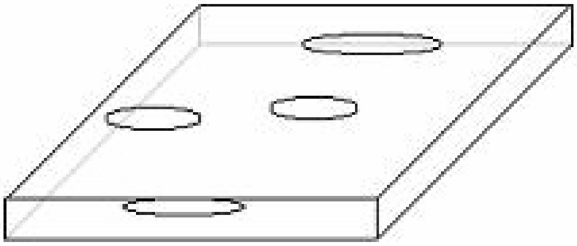
Composites are classified by the geometry of the reinforcement – particulate, flake and fibers – or by the type of matrix – polymer, metal, ceramic and carbon.

Particulate composites consist of particles immersed in matrices such as alloys and ceramics. They are usually isotropic since the particles are added randomly. Particulate composites have advantages such as improved strength, increased operating temperature and oxidation resistance etc. Typical examples include use of aluminum particles in rubber, silicon carbide particles in aluminum and gravel, sand & cement to make concrete.



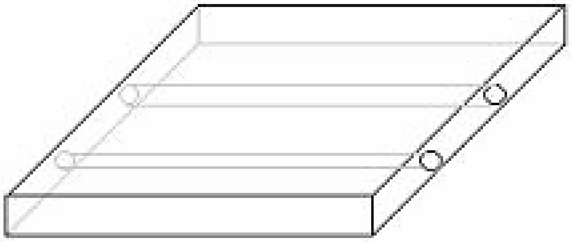
Particulate Composites

Flake composites consist of flat reinforcements of matrices. Typical flake materials are glass, mica, aluminum and silver. Flake composites provide advantages such as higher strength and low cost. However, flakes cannot be oriented easily and only a limited number of materials are available for use.



Flake Composites

Fiber composites consist of matrices reinforced by short (discontinuous) or long (continuous) fibers. Fibers are generally anisotropic and examples include carbon and aramids. Examples of matrices are resins such as epoxy, metals such as aluminum and ceramics such as calcium-alumino silicate. The fundamental units of continuous fiber matrix composite are unidirectional or woven fiber laminas. Laminas are stacked on top of each other at various angles to form a multidirectional laminate.



Fiber Composites

Polymer Matrix Composites (PMCs)

The most common advanced composites are polymer matrix composites. These composites consist of a polymer (e.g. epoxy, polyester, urethane) reinforced by thin-diameter fibers (e.g. glass, graphite, aramid). For example graphite/epoxy composites are approximately five times stronger than steel on a weight-for-weight basis. The reasons why they are the most common composites include their low cost, high strength and simple manufacturing principles. The main drawbacks of PMCs include low operating temperatures, high coefficient of thermal, moisture expansion, and low elastic properties in certain directions. Applications of PMCs range from tennis racquets to the space shuttle.

Metal Matrix Composites (MMCs)

MMCs have a metal matrix. Examples of matrices in such composites include aluminum, magnesium and titanium. Typical fibers include carbon and silicon carbides. Metals are mainly reinforced to increase or decrease their properties to suit the needs of design. For example, the elastic stiffness and strength of metals can be increased, while large coefficients of thermal expansion and thermal and electrical conductivities of metals can be reduced by the addition of fibers such as silicon carbide.

MMCs are mainly used to provide advantages over monolithic metals such as steel and aluminum. MMCs have several advantages over PMCs, like, higher elastic properties, high service temperature, insensitivity to moisture, and better wear & fatigue resistance. Reinforcing metals with fibers reduce ductility and fracture toughness.

Ceramic Matrix Composites (CMCs)

CMCs have a ceramic matrix such as alumina, calcium alumino silicate reinforced by fibers such as carbon or silicon carbide. Advantages of CMCs include high strength, hardness, high service temperature limits for ceramics (1500 ° C), chemical inertness and low density. Reinforcing ceramics with fibers, such as silicon carbide or carbon, increases their fracture toughness because it causes gradual failure of composite. CMCs are finding increased application in high temperature areas where MMCs and PMCs cannot be used. Typical applications include cutting tool inserts in oxidizing and high temperature environments.

Carbon-Carbon Composites (CCCs)

CCCs use carbon fiber in a carbon matrix. CCCs are used in very high temperature environments of up to 3315 ° C, and are 20 times stronger and 30% lighter than graphite fibers. Reinforcement of a carbon matrix allows the composite to fail gradually, and gives advantages such as ability to withstand high temperatures, low creep at high temperatures, low density, good tensile and compressive strengths, high fatigue resistance and high thermal conductivity. The main uses of CCCs are Space shuttle nose cones; Aircraft brakes and Mechanical fasteners needed for high temperature applications.

1.3 MECHANICAL ADVANTAGE OF COMPOSITE MATERIALS

Two parameters are commonly used to measure the relative mechanical advantage of composite materials. One parameter is called the specific modulus and is defined as the ratio between the Young’s modulus (E) and the density (ρ) of the material. The other parameter is called the specific strength and is defined as the ratio of the strength (σ ult) and the density of the material (ρ), that is

$$\text{Specific modulus} = \frac{E}{\rho}$$

$$\text{Specific strength} = \frac{\sigma ult}{\rho}$$

The two ratios are high in composite materials. For example, the strength of a graphite/epoxy unidirectional composite is same as that of steel, but the specific strength is three times that of steel. What does this mean to a designer? Take the simple case of a rod designed to take a fixed axial load. The rod cross section of graphite/epoxy would be only one third that of steel. This reduction in cross-sectional area and mass translates to reduced space requirements and lower material and energy costs.

On a first look, fibers such as graphite, aramid and glass have a specific modulus several times that of metals, such as steel and aluminum. This gives a false impression about the mechanical advantages of composites because they are made not only of fibers, but are combines with a matrix; and matrices generally have lower modulus and strength than fibers. Is the comparison of the specific modulus and specific strength parameters of unidirectional composites to metals now fair? The answer is no for two reasons. First, unidirectional composite structures are acceptable only for carrying simple loads such as uniaxial tension. In structures with complex requirements of loading and stiffness, composite structures including angle plies will be necessary. Second, the strength and elastic moduli, of unidirectional composites, perpendicular to the fibers are far less.

Moreover, specific modulus and specific strength are not the only mechanical parameters used for measuring the relative advantage of composites over metals. Consider compression of a column, where it may fail due to buckling. The Euler buckling formula gives the critical load, at which a long column buckles, as

$$P_{cr} = \frac{\pi^2 EI}{L^2}$$

Where, P_{cr} = critical buckling load (N)

E = Young's modulus of column (N/m²)

I = second moment of area (m^4)

L = length of beam (m)

.

If column has a circular cross-section, the second moment of area is,

$$I = \frac{\pi d^4}{64}$$

In addition, the mass of rod is,

$$M = \frac{\rho \pi d^2 L}{4}$$

Since the length 'L' and the load 'P_{cr}' are constant, we find the mass of the beam as,

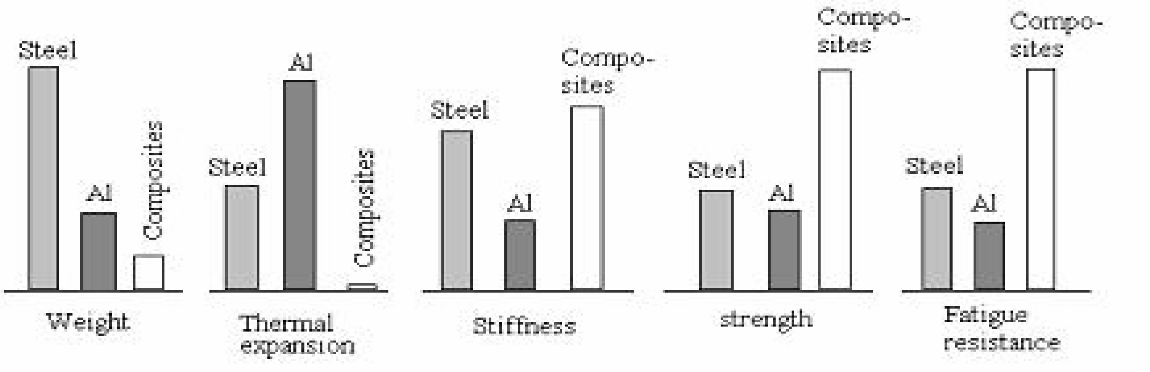
$$M = 2L^2 \rho \left(\frac{P_{cr}}{\pi E}\right)^{\frac{1}{2}}$$

This means that the lightest beam for specified stiffness is one with the highest value of $\frac{E^{\frac{1}{2}}}{\rho}$.

1.4 ADVANTAGES AND DISADVANTAGES OF COMPOSITES OVER METALS

Monolithic metal and their alloys cannot always meet the demands of today's advanced technology. Different composite material made by combining several materials can meet the performance requirements. Here are some advantages of composite materials:

- Dimensionally stable in space during temperature changes. Composites such as graphite/epoxy satisfy this requirement.
- Good corrosion resistance.
- An outstanding feature of some of composites is high strength to weight ratio. In aircrafts, use of composites saves the fuel by lowering the overall mass.
- Another outstanding feature, which makes composites advantageous over metals, is controlled anisotropy; this means the desired ratio of property values in different directions can be easily varied.
- Composite materials have improved strength, stiffness, and fatigue and impact resistance.
- Other advantages include ease of processing and structural forms that are otherwise inconvenient or impossible to manufacture.



Comparison between conventional monolithic materials and composite materials

Everything has its own advantages and disadvantages, and composites are no exception. Few disadvantages of composites are:

- High cost of fabrication of composites is one of critical issue. For example, a part made of graphite/epoxy composites may cost up to 10 to 15 times the material costs.
- Mechanical characterization of a composite structure is more complex than that of a metal structure. Unlike metals, composite materials are not isotropic, that is,

their properties are not the same in all directions. Therefore, they require more material parameters.

- Composites do not have a high combination of strength and fracture toughness as compared to metals.
- Repair of composites is not a simple process as compared to metals. Sometimes critical flaws and cracks in composite structures may go undetected.
- Composites do not necessarily give higher performance in all the properties used for material selection. Composites show better strength than metals but lower values for other material selection parameters, such as – toughness, join ability and affordability.

1.5 AREAS OF APPLICATION

Many composite materials are stronger than steel, lighter than aluminum and stiffer than titanium. They offer low thermal conductivity, good heat resistance, good fatigue life, low corrosion rates and adequate wear resistance. For these reasons, they have become well established in a number of major areas.

Aircraft: The advantage of weight reduction, by preferring composites to metal parts, has led to the increase in the use of composites in aircraft industry. Composites are used for making rudders, elevators, landing gear doors, panels, floorings and helicopter rotor blades.

Space: Two factors, high specific modulus and strength, and dimensional stability during large changes in temperature in space make composites the material of choice in space applications. Examples include payload bay doors in space shuttle and space shuttles' remote manipulator arm, which deploys and retrieve payloads, are made from graphite/ epoxy composites.

Sporting goods: Graphite/epoxy is replacing metals in golf club shafts, tennis racquets, ice hockey sticks, ski poles and bicycles mainly to decrease the weight. Composites also allow frames to consist of one piece that improves fatigue life and avoids the stress concentration found in metallic frames at their joints.

Medical devices: Applications here include glass/epoxy lightweight facemasks for epileptic patients, artificial portable lungs made of graphite-glass/epoxy so that a patient can be mobile and X-ray tables made of graphite/epoxy.

Automotive: Automotive applications of polymer matrix composites include fiberglass body and glass/epoxy composite leaf springs. Composite leaf springs have a fatigue life of more than five times that of steel and give a smoother ride than steel leaf springs. By weight, about 8% of today's automobile parts- including bumpers, body panels and doors- are made of composites. Metal matrix composites are finding use now in automotive engines and gas turbine engines for their high strength and low weight than their metal counterparts.

Commercial: Commercial applications include pressure vessels for chemical plants, garden tools and artificial limbs, which are lighter than traditional metal or wooden limbs, and hence are suitable for physically challenged people.

1.6 REVIEW OF LITERATURE

Recently, a considerable amount of research effort regarding the delamination damage has been expended due to its importance in operational conditions. One-dimensional problems for models with a single delamination were investigated by a large number of researchers. Sunghee Lee, Taehyo Park and George Z. Voyiadjis [1] performed vibration analysis of multi-delaminated beams. Experiments were performed on composite beams with lateral and longitudinal multiple delaminations. The results showed that multiple delaminations significantly affect the dynamic characteristics of composite laminated beams.

T. Kevin O'Brien, Arun D. Chawan, Ronald Krueger and Isabelle L. Paris [2] did the transverse tension fatigue life characterization through flexure testing of composite materials. The transverse tension fatigue life of glass-epoxy and carbon-epoxy was characterized using flexure tests of 90-degree laminates loaded in 3-point and 4-point bending.

D. M. Hoyt, Stephen H. Ward and Pierre J. Minguet [3] had applied a combined strength and fracture analysis approach to typical bonded joint configurations found in rotorcraft structures. The analysis uses detailed 2-D non-linear finite element models of the local bond line. A strength-of-materials failure criterion is used to predict critical damage initiation loads and locations. A fracture mechanics approach is used to predict damage growth and failure under static and cyclic loads based on test data for static fracture toughness and crack growth rate.

T. Kant, and K Swaminathan [4] presented analytical formulations and solutions to the static analysis of simply supported composite and sandwich plates based on a higher order refined theory developed by the first author. The theoretical model presented herein incorporates laminate deformations which account for the effects of transverse shear deformation, transverse normal strain/stress and a nonlinear variation of in-plane displacements with respect to the thickness coordinate – thus modeling the warping of transverse cross-sections more accurately and eliminating the need for shear correction coefficients. In addition, a few higher order theories and the first order theory were also considered for the evaluation. The comparison of the present results with the available elasticity solutions and the results computed independently using the first order and the other higher order theories. After establishing the accuracy of present results for composite and sandwich plates, new results for the stretching–bending coupling behaviors of anti-symmetric sandwich laminates.

A numerical and experimental study was carried out by Buket Okutan [5] to determine the failure of mechanically fastened fiber-reinforced laminated composite joints. E/glass–epoxy composites were manufactured to fabricate the specimens. Mechanical properties and strengths of the composite were obtained experimentally. 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 combined with the proposed property degradation model.

S.Y. Zhang, P.D. Soden and P.M. Soden [6] studied the inter laminar shear fracture of chopped strand mat glass fiber-reinforced polyester laminates both experimentally and analytically. Lap shear (double-grooved) specimens were used to measure the inter laminar shear strength and the cracking mechanism was studied using photomicrography. The finite element method was used to calculate the stress distribution along the shear surface and the mixed-mode stress distribution along the shear surface. The length of the shear surface was found to have a significant effect on the results. Based on the experimental and analytical results, the validity of the British Standard for GRP pressure vessels (BS4994, 1973) was evaluated.

Raimondo Luciano, and Raffaele Zinno [7] presented a quasi-brittle damage model for composite material to analyze progressive failure in composite structure. A rate independent constitutive law is expressed in term of three damage parameters by using several polynomial failure criteria and suitable micromechanical models. In particular, the material stiffness reduction is computed by the proposed damage model and the number of global degrees of freedom is reduced by using “clusters of lamina”. Finally, both numerical and experimental data available in literature are compared with the results obtained by the proposed numerical procedure.

Okenwa I. Okoli, Ainullotfi Abdul-Latif [8] conducted a study to ascertain the relationship between the predicted and experimental data of the impact response of a reinforced composite laminate. The FEA was used to simulate impact behavior of glass fiber reinforced composites. High strain rate properties obtained by the extrapolating results of experiments conducted at low to intermediate strain rate were used in FEA of simple three-point bend beam impact. Three point bend impact tests were performed on the laminates, and comparisons were made of the results predicted from this analysis and actual impact test data.

2 – FIBER REINFORCED COMPOSITES

2.1 INTRODUCTION

A fiber is a slender, threadlike structure whose length is much greater than its cross-sectional dimensions. Glass fibers are the earliest known fibers used to reinforce materials. Fibers, because of their small cross-sectional dimensions, are not directly usable in engineering applications. Therefore, they are embedded in matrix materials to form fibrous composites. The matrix serves to bind the fibers together, transfer loads to the fibers, and protect them against environmental attack and damage due to handling.

Fibrous composites can be broadly classified as single-layer and multi-layer (angle-ply) composites. “Single layer” composites may actually be made from several distinct layers with each layer having the same orientation and properties, and thus the entire laminate may be considered a “single-layer” composite. Most composites used in structural applications are multilayered; that is, they consist of several layers of fibrous composites. Each layer or lamina is a single layer composite, and its orientation is varied according to design. When the constituent materials in each layer are the same, they are called simply laminates. Hybrid laminates refer to multilayered composites consisting of layers made up of different constituent materials.

Reinforcing fibers in a single-layer composite may be short or long compared to its overall dimensions. Composites with long fibers are called continuous-fiber-reinforced composites and those with short fibers, discontinuous-fiber-reinforced composites. A further distinction is that a discontinuous-fiber composite can be considered to be one in which the fiber length affects the properties of the composite. In continuous-fiber-reinforced composites it may be assumed that the load is directly applied to the fibers and that, the fibers in the direction of load are principal load-carrying constituent. Thus, the principal purpose of a matrix is not to be a load-carrying constituent but essentially to bind the fibers together and protect them. The failure mode of such composites is also generally controlled by the fibers.

The continuous fibers in a “single-layer” composite may be aligned in one direction to form a unidirectional composite. Such composites are fabricated by laying the fibers parallel and saturating them with resinous material, such as polyester or epoxy resin, which holds the fibers in position and serves as the matrix. Such forms of pre-impregnated fibers are called prepregs. The unidirectional composites are very strong in the fiber direction but are generally weak in the direction perpendicular to the fibers. The continuous reinforcement in a single layer may also be provided in a second direction to provide more balanced properties. The bidirectional reinforcement may be provided in a single layer in mutually perpendicular directions as in a woven fabric. The bidirectional reinforcement may be such that the strengths in two perpendicular directions are approximately equal.

The orientation of short or discontinuous fibers cannot be easily controlled in a composite material. In most cases, the fibers are assumed randomly oriented in the composite. Different areas of a single molding can have quite different fiber orientations. Short fibers, sometimes referred to as chopped fibers, may be sprayed simultaneously with a liquid resin against a mold to build up a reinforced plastic structure. Alternatively, chopped fibers may be converted to a lightly bonded preform or mat that can be later impregnated with resin to fabricate single-layer composites. The chopped fibers lie generally parallel to the surface of the mold and are randomly oriented in planes parallel to the surface. Therefore, properties of a discontinuous-fiber-reinforced composite can be isotropic; that is, they do not change with direction within the plane of the sheet. The two outstanding features of oriented fibrous composites are their high strength: weight ratio and controlled anisotropy. Controlled anisotropy means that the desired ratio of property values in different directions can be easily varied. For example, in a unidirectional composite, longitudinal strength: transverse strength ratio can be easily changed by changing the volume fraction of fibers.

2.2 FIBER FACTORS CONTRIBUTING TO THE PERFORMANCE OF A COMPOSITE [12]

Following fiber factors contribute to the mechanical performance of a composite:

Length: The fibers can be either long or short. Long continuous fibers are easy to orient and process, while short cannot be controlled fully for proper orientation. Long fibers provide many benefits over short fibers. These include impact resistance, low shrinkage, improved surface finish and dimensional stability. However, short fibers have few flaws and therefore have higher strength.

Orientation: Fibers oriented in one direction give very high stiffness and strength in that direction. If the fibers are oriented in more than one direction, such as in a mat, there will be high stiffness and strength in the directions of the fiber orientations. However, for the same volume of fibers per unit volume of the composite, it cannot match the stiffness and strength of the unidirectional composites.

Shape: The most common shape of fibers is circular because handling and manufacturing them is easy. Hexagon and square shaped fibers are possible but their advantages of strength and high packing factors do not outweigh the difficulty in handling and processing.

Material: The material of the fiber directly influences the mechanical performance of a composite. Fibers are generally expected to have high elastic modulus and strengths. This expectation and cost have been key factors in graphite, aramids and glass dominating the fiber market for composites.

Diameter: Fibers have a high aspect ratio (length: diameter ratio). The main reasons for using a thin diameter of fibers are the following:

1. Materials have actual strengths, which are several magnitudes, lower than the theoretical strength. This difference is due to the inherent flaws in the material. Removing these flaws can increase the strength of the material. As the fibers become smaller in diameter, it reduces the chances of an inherent flaw in the material.
2. For higher ductility and toughness, and better transfer of loads from the matrix to fiber, composites require larger surface area of the fiber-matrix interface. For the same volume fraction of fibers in a composite, the area of the fiber-matrix interface is inversely proportional to the diameter of the fiber and is proved as follows. Assume a lamina consisting of 'N' fibers of diameter 'D'. The fiber-matrix-interface area

   $$A = NADL$$

   If one replaces the fibers of diameter 'D' by fibers of diameter 'd', then the number of fibers 'n' to keep the fiber volume the same would be

   $$n = N\left(\frac{D}{d}\right)^2$$

   Then, the fiber-matrix interface area would be

   $$A = nAdL$$

   $$= \frac{N\pi D^2 L}{d}$$

= 4 (Volume of fibers) / d

This implies that for a fixed fiber volume in a given volume of composite the area of fiber-matrix interface is inversely proportional to the diameter of the fiber.

3. Fibers able to bend without breaking are required in manufacturing of composite materials, especially for woven fabric composites. Ability to bend increases with a decrease in the fiber diameter and is measured as flexibility. Flexibility is defined as the inverse of bending stiffness and is proportional to the inverse of the product of the elastic modulus of the fiber, and the fourth power of its diameter.

2.3 VARIOUS FIBERS USED IN COMPOSITES

Fiber	**Advantages**	**Drawbacks**
Glass (Most common fiber used in PMCs)	High strength, low cost, high chemical resistance, good insulating properties	Low elastic modulus, poor adhesion to polymers, sensitivity to abrasion, low fatigue strength
Graphite (Common in aircraft components)	High specific strength and modulus, low coefficient of thermal expansion, high fatigue strength	High cost, low impact resistance, high electrical conductivity
Metal	Easy production, high strengths, temperature resistance	Poor tolerance of high temperatures, high weight
Alumina (Aluminum oxide) fibers	Offers good compressive strength, high melting point (2000 °C)	Low tensile strength
Boron-tungsten fibers (Boron coated tungsten filament)	High stiffness, high strength	Low modulus of elasticity
Aramid	Low density, high tensile strength, low cost, high impact strength	Low compressive properties, degradation in sunlight

In addition to the above-mentioned fibers, Silicon-carbide fibers and Quartz & Silica fibers are also used as to reinforce composite materials.

2.4 GLASS FIBERS

Glass fibers are the most common of all reinforcing fibers for polymer matrix composites. For structural composites, the two commonly used types of glass fibers are E-glass and S-glass, because of their relative low cost. The E in E-glass stands for electrical as it was designed for electrical applications. The S in S-glass stands for higher content of silica. It retains its strength at high temperatures as compared to E-glass and has higher fatigue strength. It is used mainly for aerospace applications. The difference in the properties is due to the composition of E-glass and S-glass fibers. Other types available commercially are C-glass (C stands for corrosion) used in chemical environments such as storage tanks and A-glass (A stands for appearance) used to improve surface finish. Combination types such as E-CR glass (E-CR stands for electrical and corrosion resistance), and AR-glass (AR stands for alkali resistance) also exist. The main disadvantage of glass fibers is their poor adhesion to polymer matrix resins, particularly in the presence of moisture. This poor adhesion requires the use of chemical (silane) coupling agents on the surface of fibers.

Manufacturing: Glass fibers are made generally by drawing from a melt. The melt is formed in a refractory furnace at about 1400 °C from a mixture, which includes sand, limestone and alumina. The melt is stirred and maintained at a constant temperature. The melt passes through as many as 250 heated platinum alloy nozzles of about 10-µm diameter, where it is drawn into filaments of needed size at high speeds. These fibers are sprayed with an organic sizing solution before they are drawn. The sizing solution is a mixture of binders, lubricants, and coupling and antistatic agents; binders allow filaments to be packed in strands, lubricants prevent abrasion of filaments, and coupling agents give better adhesion between the inorganic glass fiber and the organic matrix. Fibers are then drawn into strands and wound on a forming tube. Strands are groups of more than 204 filaments. The wound array of strands is then removed and dried in an oven to remove any water or sizing solutions.

Glass composition: Glass fibers are amorphous solids. Chemically, glass is composed primarily of a silica (SiO_2) backbone in front of ($–SiO_4–$) tetrahedra. Modifier ions are added for their contribution to glass properties and manufacturing capability.

Compositions of E-glass and S-glass fibers [9]

Material	(% Weight) E-glass	 S-glass
Silicon oxide	54.30	64.20
Aluminum oxide	15.20	24.80
Ferrous oxide	–	0.21
Calcium oxide	17.20	0.01
Magnesium oxide	4.70	10.27
Sodium oxide	0.60	0.27
Boron oxide	8.0	0.01
Barium oxide	–	0.20
Miscellaneous	–	0.03

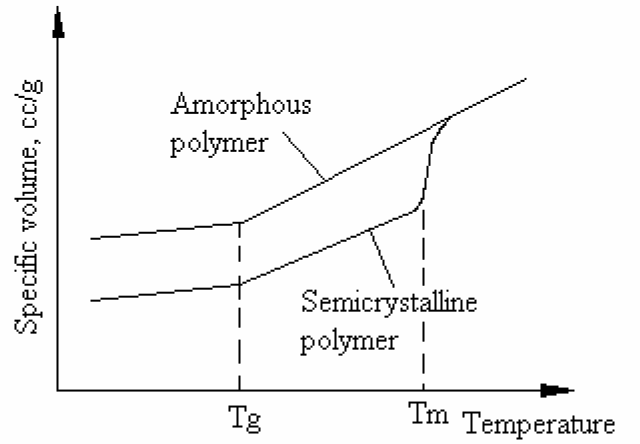
Properties of E-glass and S-glass fibers [9]

Property, units	E-glass	S-glass
Density, g / cm^3	2.54	2.59
Tensile strength, MPa	3448	4585
Elastic modulus, GPa	72.4	85.5
Range of diameter, µm	3–20	8-13

2.5 POLYMER MATRIX MATERIALS

Polymers (commonly called plastics) are the most widely used matrix material for fiber composites. Their chief advantages are low cost, easy processibility, good chemical & resistance. On the other hand, low strength, low modulus, and low operating temperatures limit their use. Two main kinds of polymers are thermosetting polymers and thermoplastic polymers. The polymers that soften or melt on heating, called thermoplastic polymers, consist of linear or branched-chain molecules having strong intra molecular bonds but weak intermolecular bonds. Melting and solidification of these polymers are reversible and they can be reshaped by application of heat and pressure.

They are either semi crystalline or amorphous in structure. Examples include polyethylene, polystyrene, nylons, polycarbonate & polyamides. Thermosetting plastics have cross-linked or network structures with covalent bonds between all molecules. They do not soften but decompose on heating. Once solidified by a cross linking (curing) process, they cannot be reshaped. Common examples of thermosetting polymers include epoxy, polyesters, phenolics & melamine. The temperature limitations of a thermoplastic depend on whether it is semi crystalline or amorphous. Thermosetting plastics have amorphous structures, but thermoplastics may be either semi crystalline (they are never 100% crystalline) or amorphous. The amorphous state is characterized by a glass transition temperature (T_g) only, while the semi crystalline polymer has a crystalline melting point (T_m) as well as a glass transition temperature. These transition temperatures are shown in figure as measured by specific volume changes with temperature.

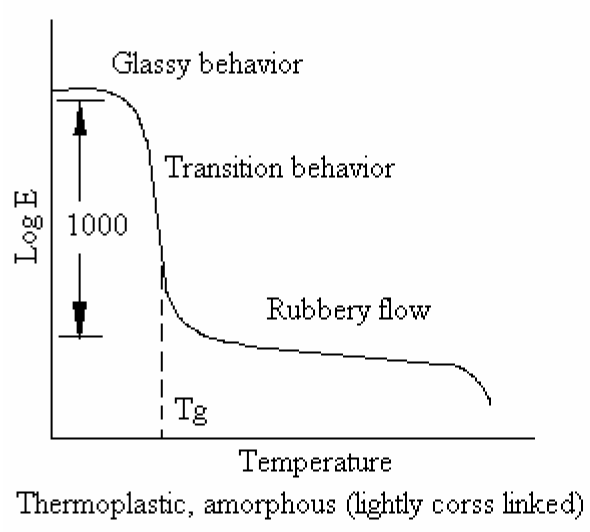


Specific volume versus temperature behavior of amorphous and semicrystalline polymers

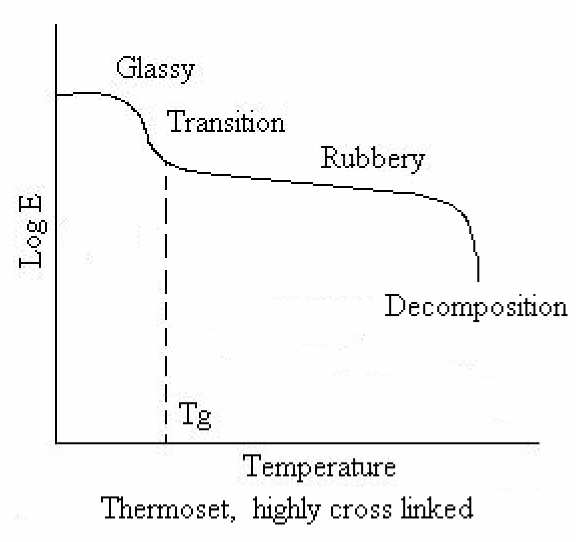
The temperature for processing of thermoplastics is governed by either the melt temperature or glass transition temperature. For example, an amorphous thermoplastic must be molded well above its T_g in order to sufficiently reduce its melt viscosity.

An understanding of the effect of these temperatures on the mechanical behavior of polymers is best seen by the behavior of modulus of elasticity (E) with temperature. An amorphous thermoplastic (e.g., polystyrene, polycarbonate) has a significant change of mechanical properties at the glass transition temperature. Hence, maximum use temperatures must be less than the glass transition temperatures. A thermoset (e.g., epoxy, polyester, phenolic) has a much-reduced change in properties at the glass transition temperature because of its high degree of cross-linking.

Variation of elastic modulus of polymers with temperature



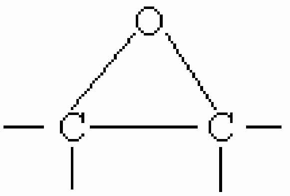
Thermoplastic, amorphous (lightly corss linked)



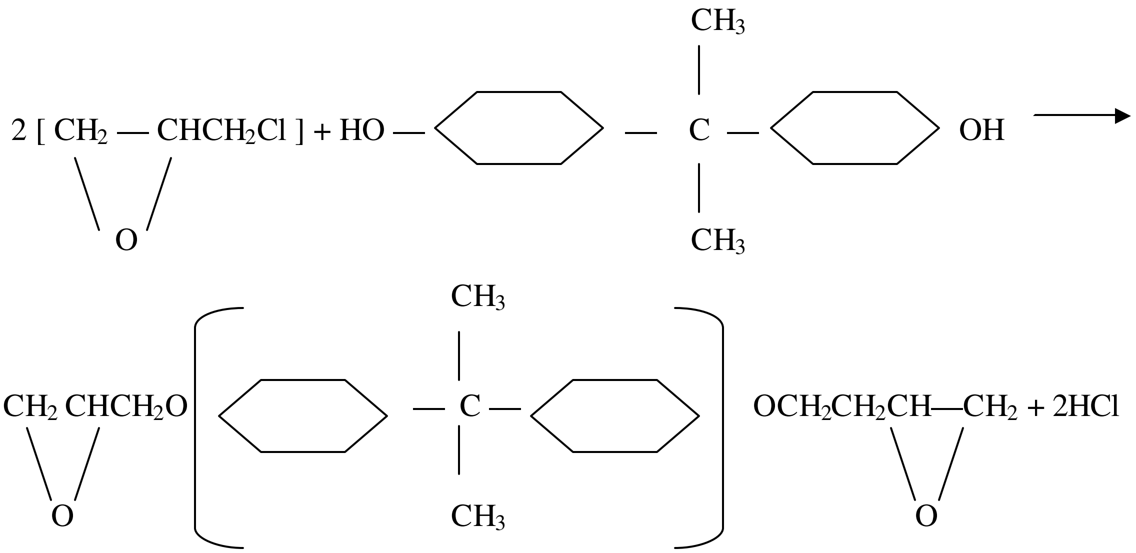
Thermoset, highly cross linked

2.6 EPOXY RESINS [9]

Epoxy resins are low-molecular-weight organic liquids containing a number of epoxide groups, which are three-membered rings with one oxygen and two carbon atoms:



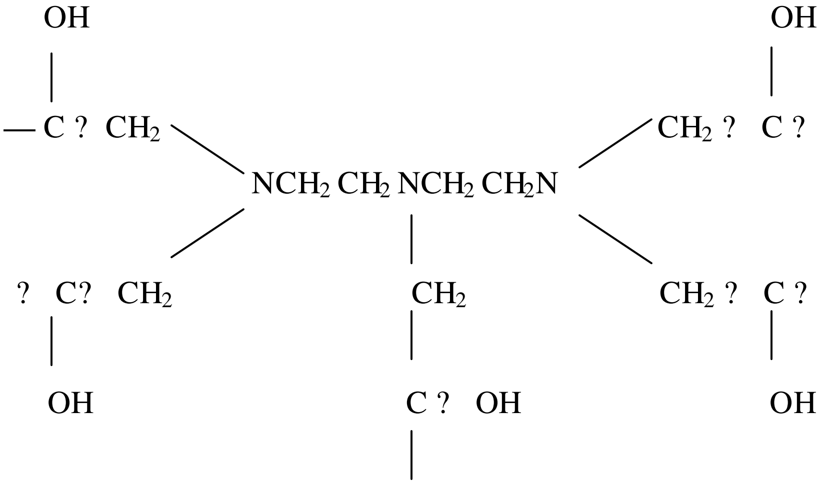
The most common process for producing epoxies is the reaction of epichlorohydrin with bisphenol-A amino or acid compounds, and cross-linking is obtained by introducing chemicals that react with the epoxy and hydroxy groups between the adjacent chains. The chemical reaction to form the epoxy resin prepolymer is as shown below:



The epoxy resin is a viscous liquid, and the viscosity is a function of the degree of polymerization *n*. Each epoxy molecule is end-capped with the epoxy group. A curing agent is mixed into the liquid epoxy to polymerize the polymer and form a solid network crosslinked polymer. For example, diethylene triamine [used at 10 pph (parts per hundred)] achieves rapid cure at room temperature.

Diethylene triamine : $NH_2(CH_2)_2NH(CH_2)_2NH_2$

Five molecules of epoxy can react with each amine molecule through the active hydrogen on the nitrogen atom. A segment of fully cured structure is as follows:



This reaction does not produce a by-product, but does produce heat accompanied with chemical shrinkage.

Epoxy systems, can be cured at room temperature, but quite often heat is added to accelerate and improve suring. The choice of curing agent dictates whether a room-temperature or elevated-temperature cure is required. The properties of a cured epoxy resin depend on the chemical composition of the epoxy prepolymer, which can be greatly modified, as well as the curing agent molecule.

Properties of cast epoxy resins (at 23 °C)

Density, g/cm3	1.2 – 1.3
Tensile strength, Mpa	55 - 130
Tensile modulus, Gpa	2.75 – 4.10
Water absorption, % in 24 h	0.08 – 0.15

Epoxy systems are superior to polyesters particularly with regard to adhesion with a wide variety of fibers, moisture resistance and chemical resistance.

2.7 FABRICATION OF THERMOSETTING RESIN MATRIX COMPOSITES [9]

Thermosetting resin systems, by chemical reaction become hard when cured, and further heating does not soften them – the hardening is irreversible. During curing they undergo a chemical change or reaction called polymerization, the linking of ”monomers or prepolymers” to form ” network polymers.” This reaction is accompalished in the presence of catalysts or curing agents usually selected to give a desired combination of time and temperature to complete the reaction suitable for a particular product.

Fabrication processes for thermosetting resin matrix composites can be broadly classified as wet forming processes abd processes using premixes or prepegs. In the wet forming processes, the final product is formed while the resin is quite fluid and the curing process is usually completed in one step. Compounding (combining fibers and matrix) is done during forming. The wet processes include hand lay-up, filament winding, autoclave forming, pultrusion and resin transfer molding.

Hand Lay-up Technique

The hand lay-up technique is the simplest and the most commonly used method for the manufacture of both small and large reinforced products. A flat surface, a cavity (female) or a positive (male) – shaped mold, made from wood, metal, plastics, reinforced plastics, or a combination of these materials may be used. Fiber reinforcements and resin are placed manually against the mold surface. Thickness is controlled by the layers of materials placed against the mold. This technique, also called contact lay-up, is an open-mold method of molding thermosetting resins in association with fibers. A chemical reaction initiated in the resin by a catalytic agent causes hardening to a finished part.

The following operations are involved in a typical hand lay-up process:

Mold Preparation : This is one of the most improtant functions in the molding cycle. If it is done well, the molding will look good and separate from the mold easily. After the desired finish has been attained, several coats of paste wax are applied for the purpose of mold release.

Gel Coating : When good surface appearance is desired, the first step in the open-mold processes is the application of a specially formulated resin layer called the gel coat. It is applied first to the mold and thus becomes the outer surface of the laminate when complete. The gel coating may be painted on, or air-atomized with gravity or pressure feeding.

Hand Lay-up : After properly preparing the mold and gel coating it, the next step in the molding process is material prepartion. In hand lay-up, the fiberglass is applied in the form of chopped strand mat, cloth or woven roving. Premeasured resin and catalyst (hardener) are then throughly mixed together. The resin mixture can be applied to the glass either outside of or on the mold. To ensure complete air removal and wet-out, rollers are used to compact the material against the mold to remove any entrapped air. The resin-catalyst mixture can be deposited on the glass via a spray gun, which automatically meters and combines the ingredients.

Filament winding

Filament winding is a technique used for the manufacture of surfaces of revolution such as pipes, tubes and cylinders and is fequently used for the construction of large tanks and pipework for the chemical industry. Fibers are impreganted with a resin by drawing them through an in-line resin bath (wet winding) or prepegs (dry winding) are wound over a mandrel. Wet winding is inexpensive and lets one control the properties of the composites. Dry winding is cleaner but more expensive and hence quite uncommon. Depending on the desired properties of the product, winding patterns such as hoop, and helical can be developed. The product is then cured with or without heat and pressure. Mandrels are made of wood, aluminum, steel or plaster depending on the application.

Autoclave Forming

This method of manufacturing is used with composites available as prepegs. First a peel ply made out of nylon or cellophane coated with Teflon is placed on the mould. Tefolon is used for the easy removal of the part while the peel ply achieves a desired finish whihc is smooth and wrinkle free. Replacing Teflon by mold-releasing powders and liquids can also accomplish removal of the part. Prepegs of the required number are laid up one ply at a time either by automated means or by hand. Each ply is pressed to remove any entrapped air and wrinkles. The lay-up is sealed at the edges to form a vacuum seal. Now one establishes the bleeder system to get rid of the volatiles and excess resin during the heating and vacuum process which follows later. The bleeder system consists of several bleeder sheets made of glass cloth. These are placed ont he edges and on the top of the lay-up. Then vacuum connections are placed over the bleeders and the lay-up is bagged. A partial vacuum is developed to smoothen the bag surface. The whole assembly is put in an autoclave where heat and pressure are applied with an inert gas such as nitrogen. The vacuum system is kept functioning to remove volatiles during the cure cycle and to keep the part conformed to the mold. The cure cycle may last more than 5 hr.

Pultrusion

Pultrusion is an automated process for manufacturing compsite materials into continuous, constant-cross-section profiles. This technique has some similarities to aluminum extrusion. In pultrusion, however, the product is pulled from the die rather forced out by pressure. A large number of profiles such as rods, tubes and various structural shapes can be produced using appropriate dies. The pultrusion process generally consists of pulling continuous rovings and/or continuous glass mats through a resin bath or impregnator and then into performing fixtures where the section is partially shaped and excess resin and/or air are removed. Then it goes into a heated die where the section is cured continuously. The basic pultrusion machine consists of the following elements: (1) creels, (2) resin bath or impregnator, (3) heated dies, (4) puller or driving mechanism, and (5) cut-off saw. The pultrusion process is most suitable for thermosetting resins that cure without producing a condensation by-product (polyester and epoxy).

Resin Transfer Molding (RTM)

A low viscosity resin such as polyester or epoxy resin is injected under low pressure into a closed mold which contains the fiber preform. The resin flow is stopped and the part is allowed to cure. The cure is done either at room temperature or at elevated temperatures. The later is done if the part is to be used for high temperature application.

3 – SPECIMEN PREPARATION AND EXPERIMENTATION

The objective of the research reported herein is to study the effect of various defects on the strength of composite laminates, loaded in 3-point bending. Composite laminates made from 90-degree unidirectional E-glass roving / epoxy, having fiber breakage & delamination defects, were tested in 3-point bending to determine their ultimate breaking load. Composite specimens were prepared by Hand Lay-up Technique, as it is a relatively cheaper and easier method of composite preparation, when compared to other composite fabrication methods.

3.1 SPECIMEN PREPARATION

The selected specimen material was a fiberglass roving/epoxy (GFRP) composite, because of its widespread application in naval, automotive and aerospace industry. The use of fabrics is particularly attractive due to their reduced manufacturing costs and increased resistance to (impact) damage. Further, its transparency facilitates visual inspection for damage. The delaminated and fiber broken specimen were made by Hand Lay-up technique. The laminates were cured using manufacturers recommended cure cycle. The stacking sequence of the laminated beams are $[90^\circ{}_{20}]$ and $[90^\circ{}_{32}]$. The length, width and thickness of the cured 20-ply laminate are 152 mm, 25 mm and 2.9 mm, and that of 32-ply laminate are 152 mm, 25mm and 5.1 mm respectively. The composite has a fiber weight fraction of approximately 76 %. The delamination length of the manufactured specimen was fixed to 15.5% of the global beam length (˜ 24 mm) in the present study.

3.1.1 RAW MATERIAL

The laminates were made from fiberglass roving (E-glass), consisting of 18 strands, and Araldite LY 556/ Hardener HY 951 system. The density, thickness and width of the fiberglass roving are 1.3334 x 10^{-3} g/mm^3, 0.2 mm and 25 mm respectively.

Fiberglass Roving

The resin used, Araldite LY 556, is an unmodified liquid epoxy resin based on Bisphenol A. Along with Hardener HY 951 (aliphatic primary amine) it provides a low-viscosity, solvent free room temperature curing laminating system. By varying the hardener content from 10 to 12, the reactivity of the system can be adapted to suit the processing and curing conditions. Due to the very low cure shrinkage, Araldite LY 556 / Hardener HY 951 based glass fiber laminates are dimensionally stable and practically free from internal stresses. The laminates have excellent water resistance.

Araldite LY 556

Viscosity	at 25°C	mPa.s	10,000 – 12,000
Density	at 25°C	g/cc	1.15 - 1.20
Vapour Pressure	at 25°C	Pa	< 0.01

Hardener HY 951

Viscosity	at 25°C	mPa.s	10 – 20
Density	at 25°C	g/cc	0.97 - 0.99
Vapour Pressure	at 100°C	Pa	˜ 390

Mixing Ratio

Araldite LY 556	100 parts by weight
Hardener HY 951	10 - 12 parts by weight

Properties of the mix

Viscosity at 25°C	: 1,700 mPa.s
at 40°C	: 650 mPa.s
Gel time at 25°C	: 40 – 60 minutes
at 40°C	: ~ 20 minutes

Curing Schedule

Temperature, ° C	25	60	80	100
Duration, hr	24 - 48	4 – 8	2 – 4	1 - 4

3.1.2 MOLD PREPARATION

A mold, having a cope and drag, was prepared from mild steel plates to fabricate the specimen. The length, width and thickness of the cope are 275 mm, 275 mm and 22 mm, and that of drag are 275 mm, 250 mm and 8.5 mm respectively. The benefit of selecting a thick plate for the cope is an increased pressure on the composite specimen, due to the self-weight of the cope. The plates were grinded using a surface grinder to attain the desired surface finish. A good surface finish on the inside surface of cope and drag results in an equally good surface finish on the surface of the specimen. Finally, six holes, four at the corners of the cope and two near the side edges of the cope, of 12 mm diameter each were drilled for the nut-bolt assembly. The tightening of the nuts, results in an increased pressure on the specimen, which removes any air bubbles present and squeezes the excess epoxy/hardener mixture.

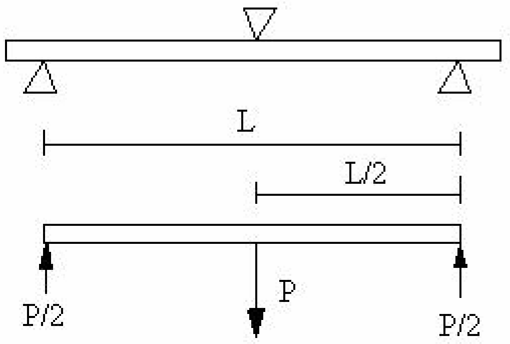
3.1.3 HAND LAY-UP TECHNIQUE

Firstly, a layer of cellophane was placed on the drag to avoid the spoiling of the grinded surface and for the easy removal of the cured laminate. Pre measured resin and hardener, 60:6 grams for $[90^\circ{}_{32}]$ laminate and 40:4 grams for $[90^\circ{}_{20}]$ laminate were thoroughly mixed together and applied on the fiberglass rovings using a brush. Defects were created either by inserting a layer of cellophane of required length, between the fiberglass rovings, or by cutting the strands of the fiberglass rovings. To ensure complete air removal, rollers were used to compact the stack of fiberglass rovings against the mold to remove any entrapped air, but that, only after placing another layer of cellophane over the stack. Lastly, the cope was placed in the proper position and nuts were tightened to apply the pressure. The laminates were allowed to cure, at room temperature, for a period of 24 hours. Cured laminates were cut to dimensions by an air-cooled circular saw.

Fabricated specimen

3.2 EXPERIMENTATION

An experimental investigation was carried out to determine the ultimate breaking load of the defected laminates subjected to bending. The laminates were tested in 3-point bending, on a FIE (India) make Universal Testing Machine, having maximum load capacity of 10 Tonnes. Gripping, buckling and end tabbing are not issues for this test.



Three-point bending test

A beam subjected to bending moment and shear force undergoes certain deformations. The material of the member offers resistance or stresses against these deformations. A bending moment bends a member. The stresses introduced by bending moment are called bending stresses. In a beam, the bending moment is balanced by a distribution of bending stress. The top side is under compression while the bottom surface is under tension. The mid-plane contains the neutral layer which is neither stretched nor compressed and is subjected to zero bending stress. The line of intersection of the neutral layer with the cross-section of the beam is called as the neutral axis. According to Flexure formula:

$$\frac{M}{I} = \frac{E}{R} = \frac{\sigma}{y}$$

Where, M= Bending moment

I = Moment of Inertia about neutral axis

E=Young's Modulus of beam material

R=Radius of curvature of neutral surface

s =Bending stress

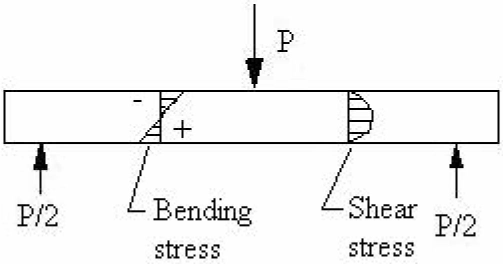
y=Distance of layer from neutral axis

Therefore, $\sigma = \frac{E}{R} y$

At neutral axis y = 0; s = 0

At extreme fiber y = maximum; s = maximum

Hence, the stress intensity in any layer is proportional to the distance of the layer from the neutral layer.



Stresses in a beam under three-point loading

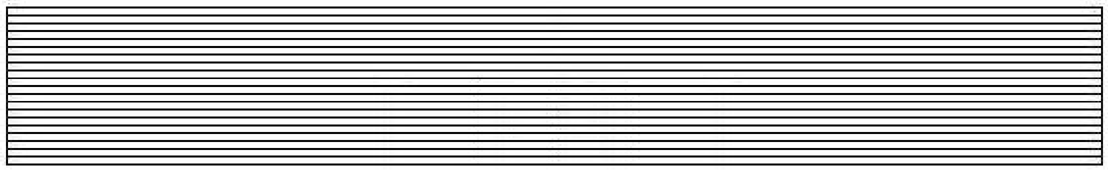
The inter-laminar shear stress is maximum at the beam center. The stress state is highly dependent on the span-to-thickness ratio. Beams with small span-to-thickness ratio are dominated by shear. The short span, three-point bending test is commonly used for inter–laminar shear strength determination. Beams with long spans fail in tension or compression.

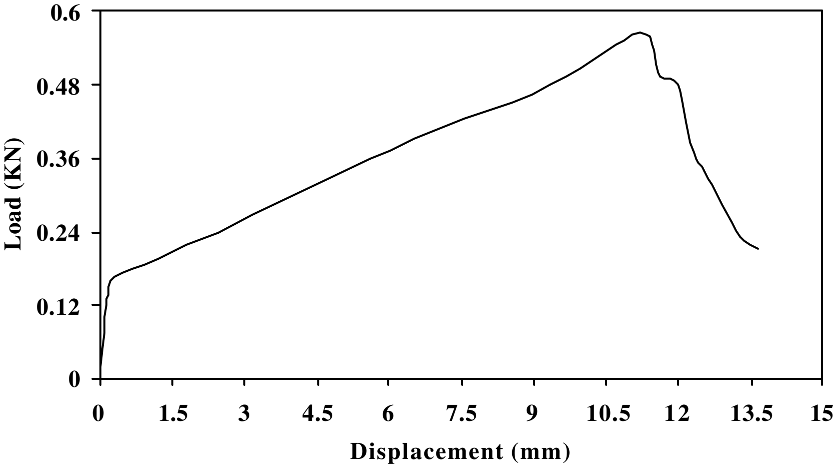
A tested / fractured specimen

4 – RESULTS AND DISCUSSION

Damaged composite laminates, with [90° $_{20}$] and [90° $_{32}$] stacking sequence were tested in 3-point bending and a load verses displacement graph was plotted. The load was applied up to the point of fracture. The behavior of defected composites was obtained from the load/displacement graphs. Varied defects, viz. totally consistent length delamination, longitudinal and lateral multiple delmainations, and broken fiber strands were intentionally introduced in the laminated composite specimens. In all but one specimen, the area of delamination was kept constant. It was observed that with the increase in the area of delamination, number of lateral multiple delaminations and broken fiber strands the ultimate breaking load of the specimen went on decreasing. Graphs 1 to 15 show the behavior of various specimens tested.

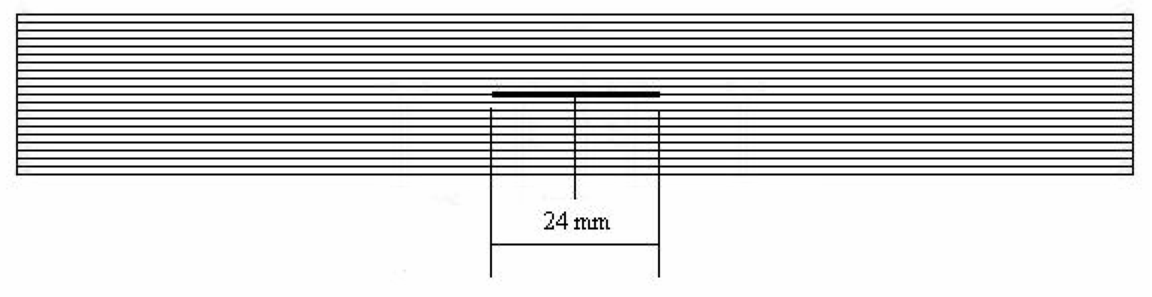
<u>Specimen – 1</u>

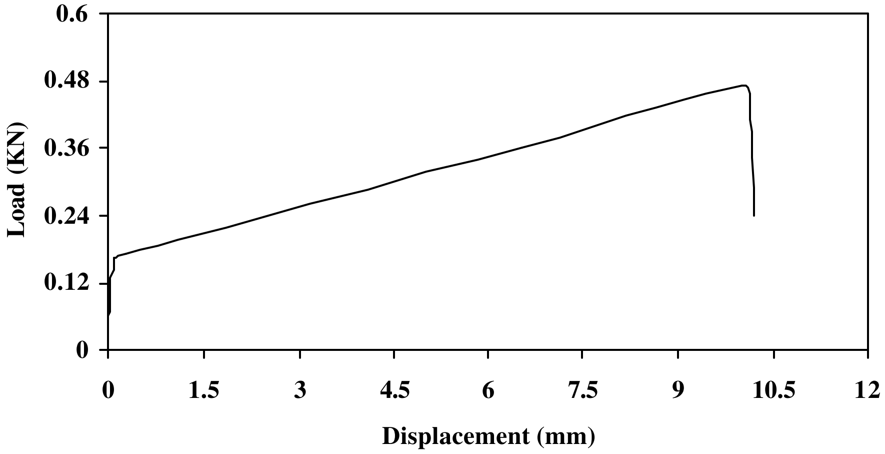




Graph – 1 [90° $_{20}$] specimen with no defect

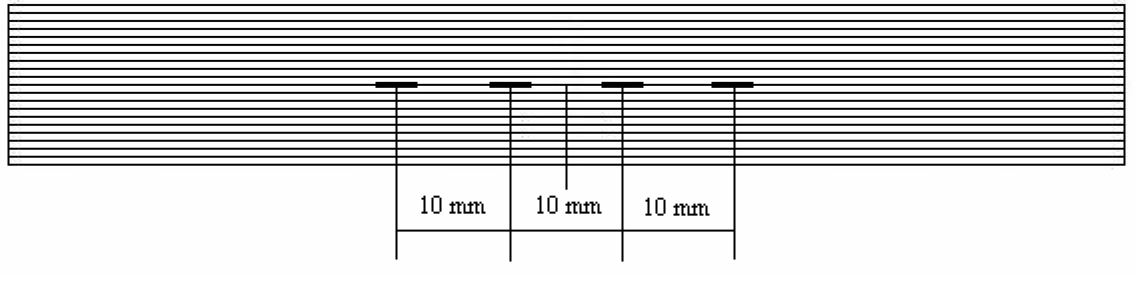
Specimen – 2



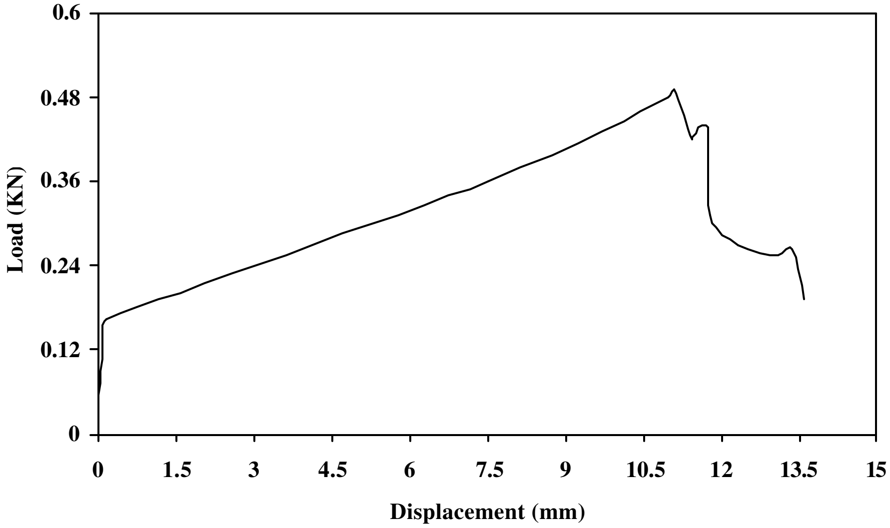


Graph – 2 [90° $_{20}$] specimen with totally consistent delamination length

Specimen – 3



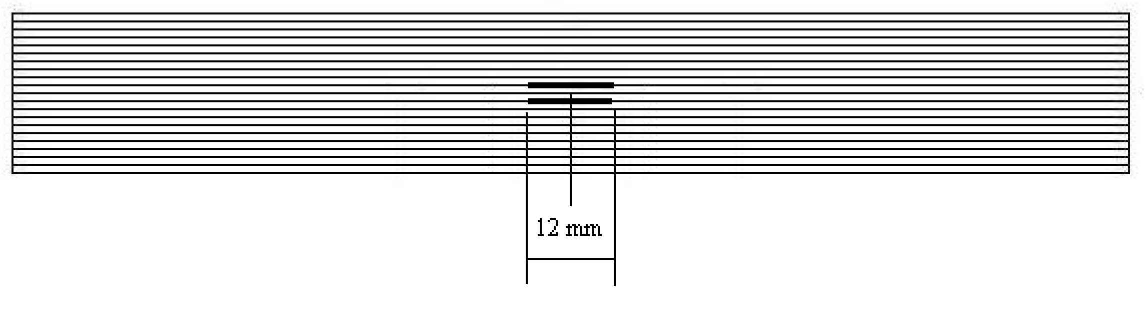
Delamination length = 6 mm x 4

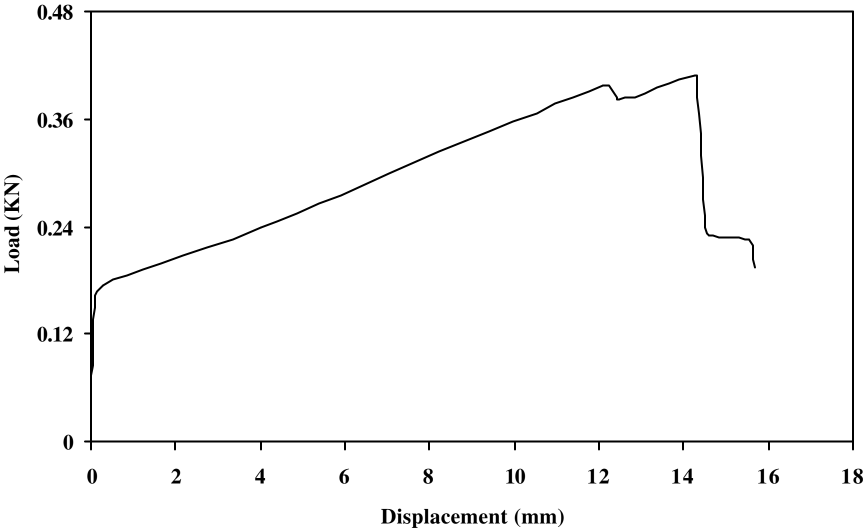


Graph – 3 [90° $_{20}$] specimen with longitudinal multiple delaminations

Graphs 1, 2 and 3, show that the load required for the failure of the specimen, which is a measure of the residual ultimate strength, decreases due to the delamination defect. When compared to the ultimate breaking load corresponding to the specimen-1, the totally consistent delamination length in specimen-2 decreases the ultimate breaking load required by 15.93 %. The longitudinal multiple delaminations in specimen 3, also have the same effect of decreasing the ultimate breaking load required, but to a slightly lesser extent. The ultimate breaking load required for specimen-3 decreases by 15.04 % when compared to specimen-1.

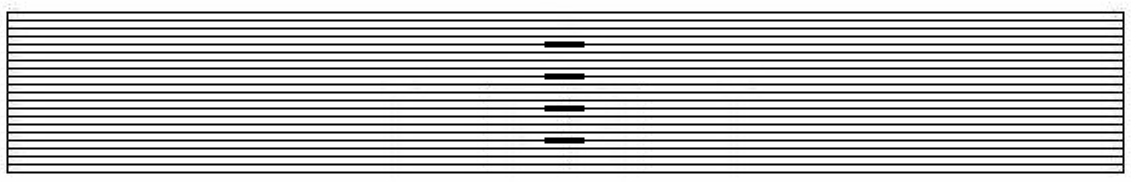
Specimen – 4



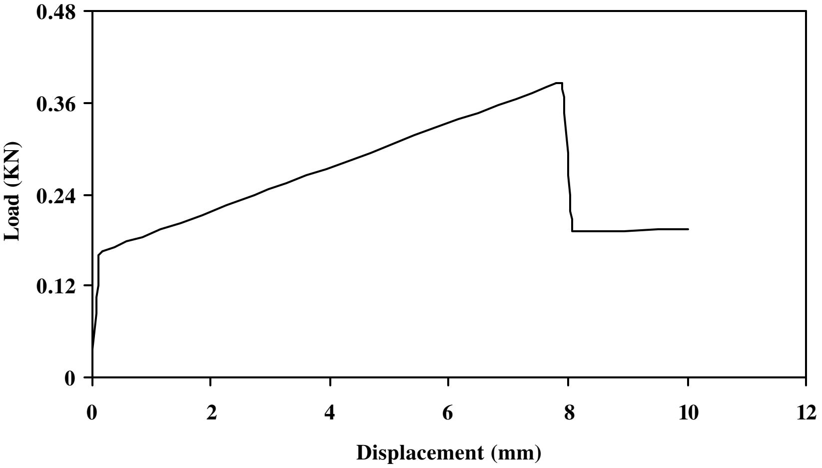


Graph – 4 [90° $_{20}$] specimen with lateral multiple delaminations

Specimen – 5

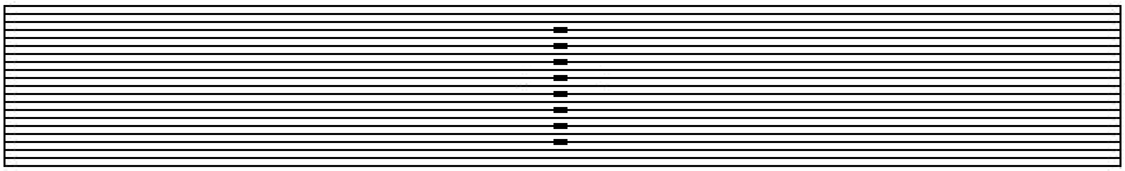


Delamination length = 6 mm x 4

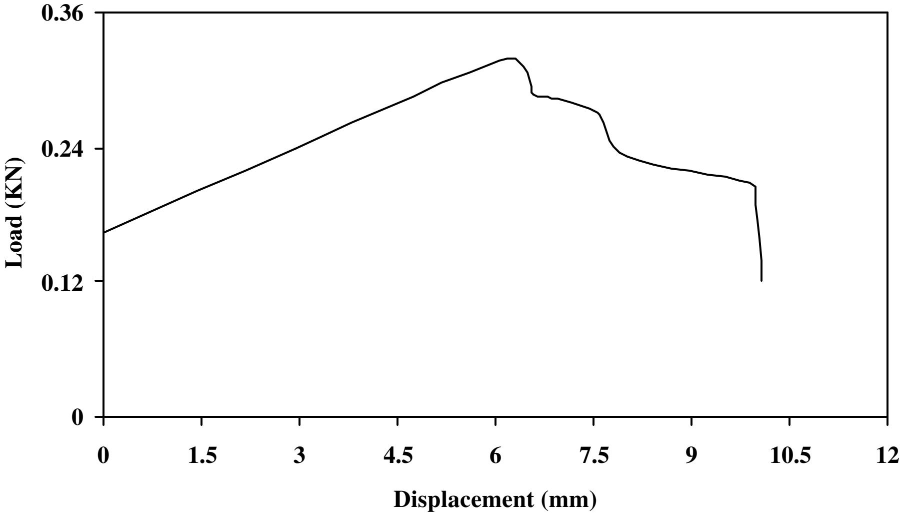


Graph – 5 [90° $_{20}$] specimen with lateral multiple delaminations

Specimen – 6



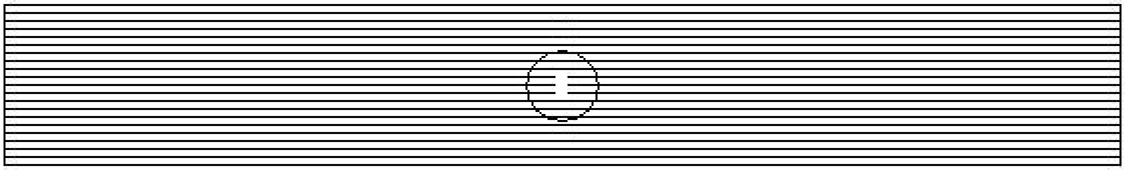
Delamination length = 3 mm x 8



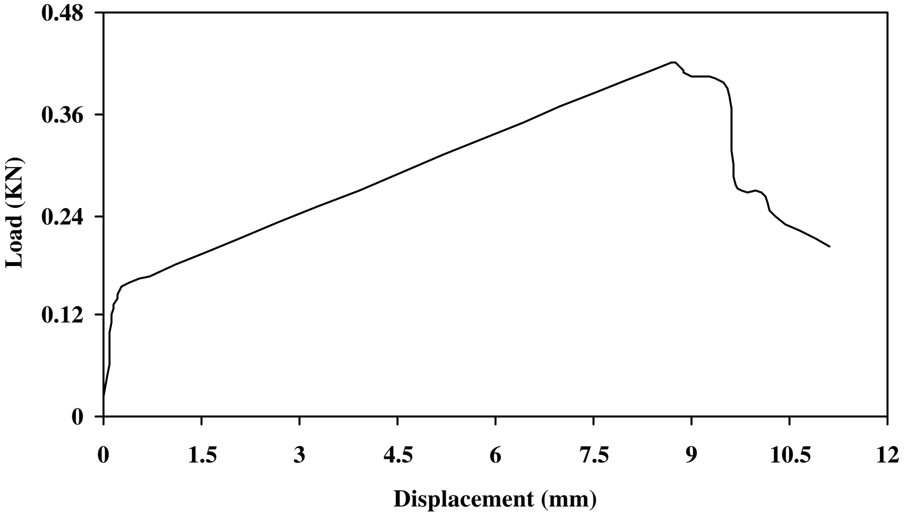
Graph – 6 [90° $_{20}$] specimen with lateral multiple delaminations

Graphs 4, 5 and 6, show that the ultimate breaking load required for the specimen decreases with the increase in the number of lateral delaminations. The increase in the number of lateral delaminations, firstly from 2 to 4 and then to 8, decreases the ultimate breaking load required for the specimen-4, 5 and 6 by 27.43 %, 31.85 % and 43.36 % respectively, when compared to specimen-1.

Specimen – 7

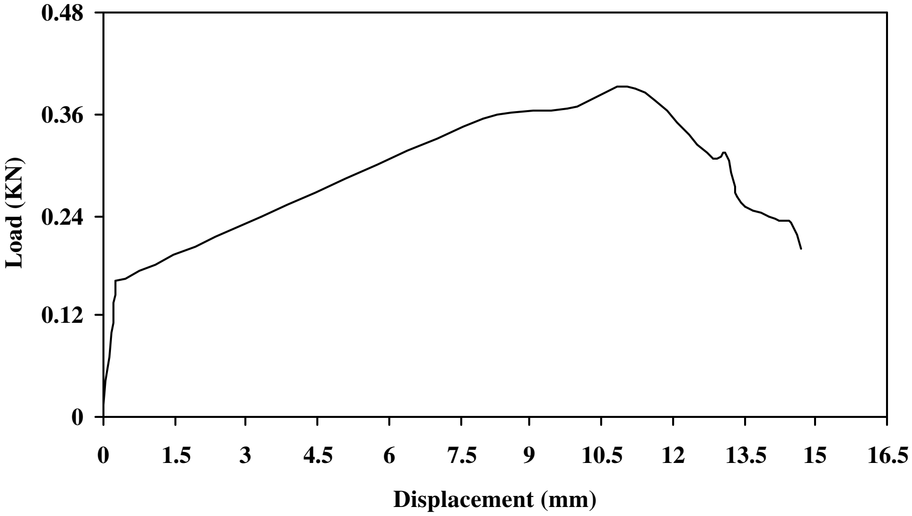


Fiber strand breakage at the mid-span



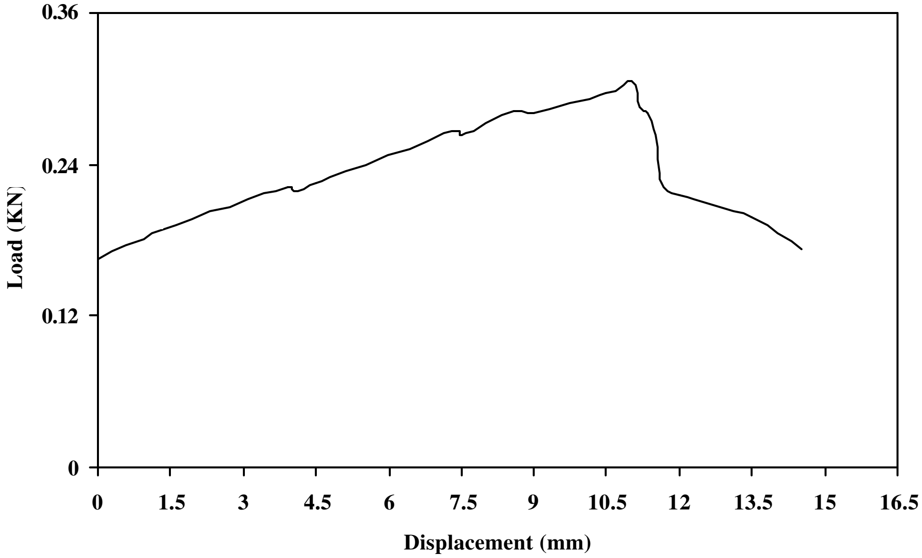
Graph –7 [90° $_{20}$] specimen with 2 broken fiber strands each in 4 layers

Specimen – 8



Graph –8 [90° $_{20}$] specimen with 4 broken fiber strands each in 4 layers

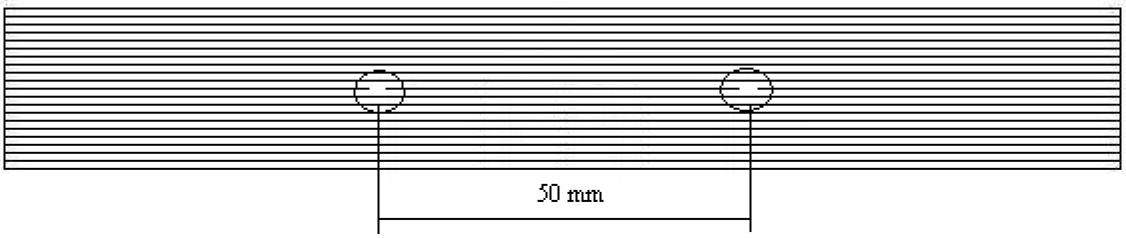
Specimen – 9

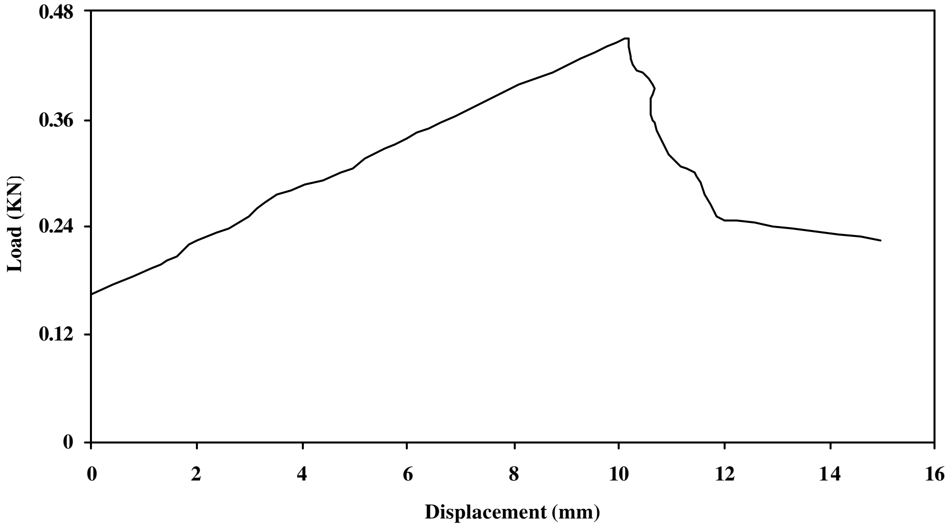


Graph –9 [90° $_{20}$] specimen with 6 broken fiber strands each in 4 layers

Graphs 7, 8 and 9 show that, with the increase in the number of broken fiber strands, firstly from (2 x 4) to (4 x 4) and then to (6 x 4), decreases the ultimate breaking load required for the specimen-7, 8 and 9 by 25.66 %, 30.97 % and 46.01 % respectively, when compared to specimen-1.

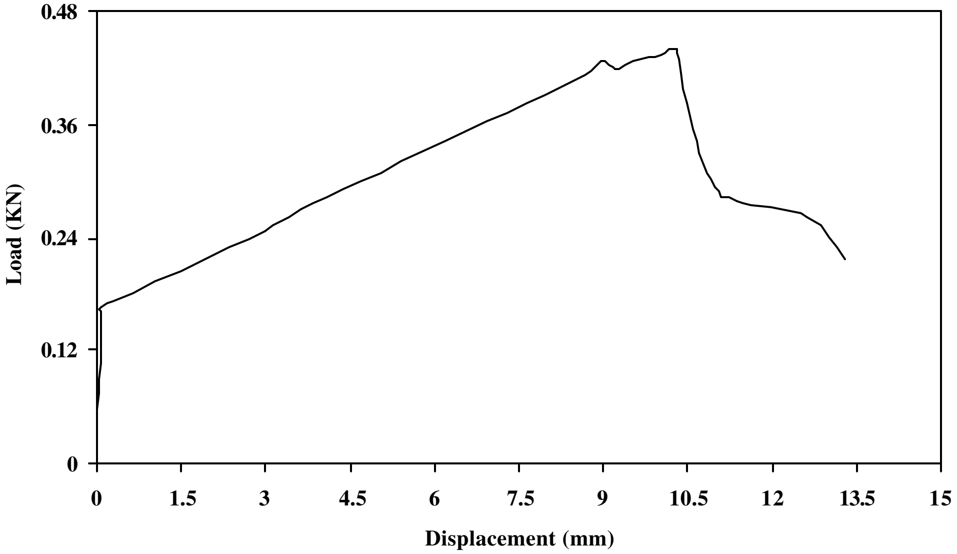
Specimen – 10





Graph –10 [90° $_{20}$] specimen with (2 x 2) broken fiber strands each in 2 layers

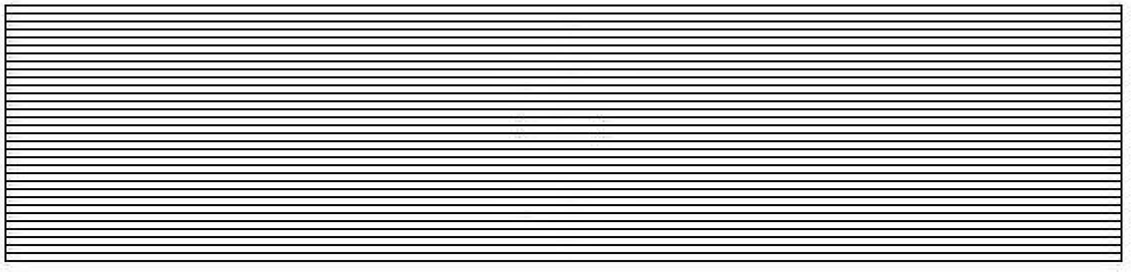
Specimen – 11

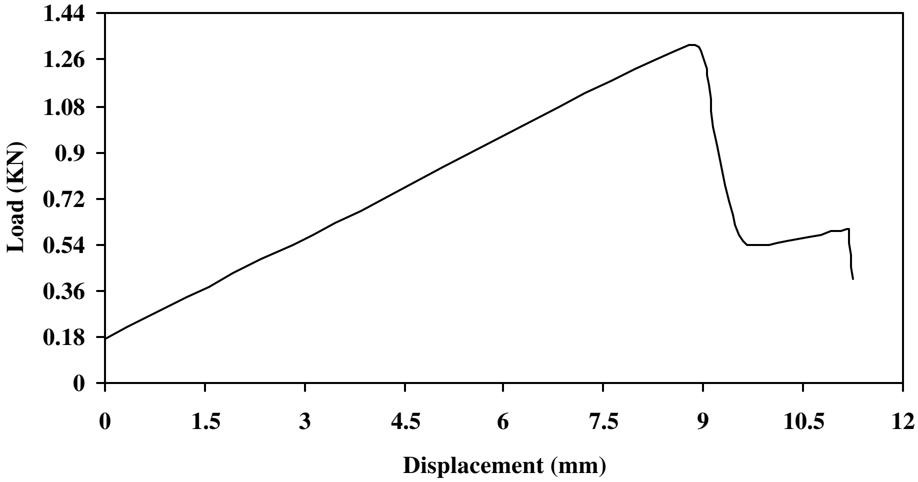


Graph –11 [90° $_{20}$] specimen with (4 x 2) broken fiber strands each in 2 layers

Graphs 10 and 11 when compared with graphs 7 and 8, show that the breakage of fiber strands at an offset from the mid-span, as done in the specimens-10 and 11, has less severe effect on the residual ultimate strength of the specimens. Though the number of broken fiber strands is same for the specimens-7 and 10, and specimens-8 and 11, the decrease in the ultimate breaking load required for the specimens-10 and 11 is only 20.35 % and 22.12 % respectively, when compared to specimen-1.

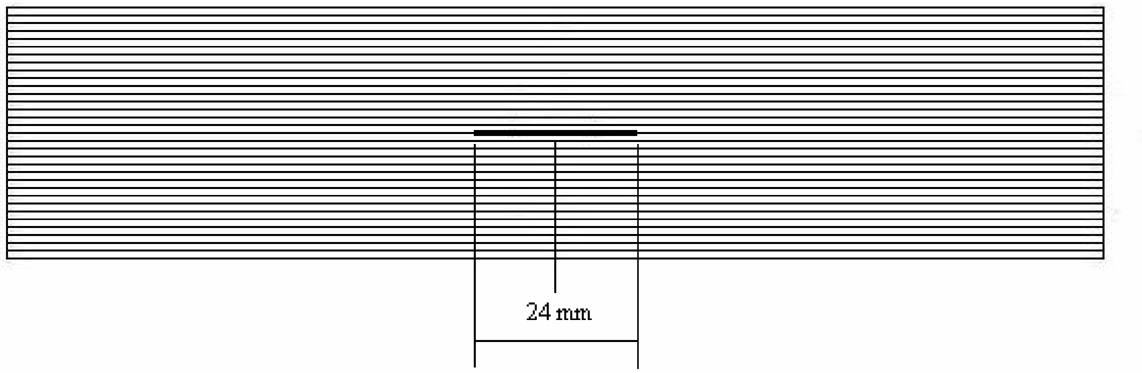
Specimen – 12



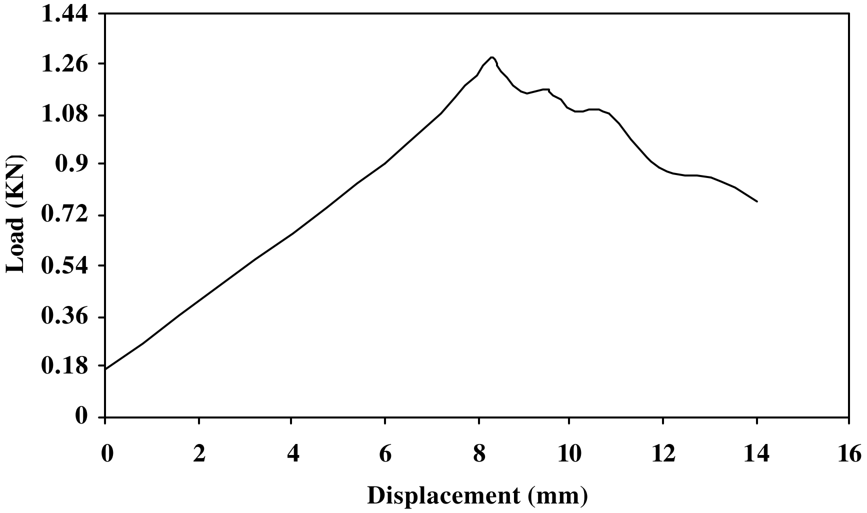


Graph –12 $[90^\circ_{32}]$ specimen with no defect

Specimen – 13

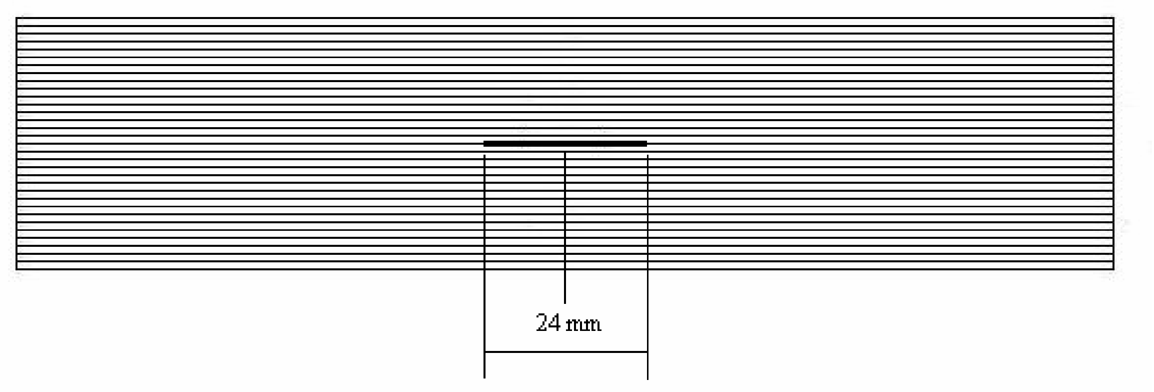


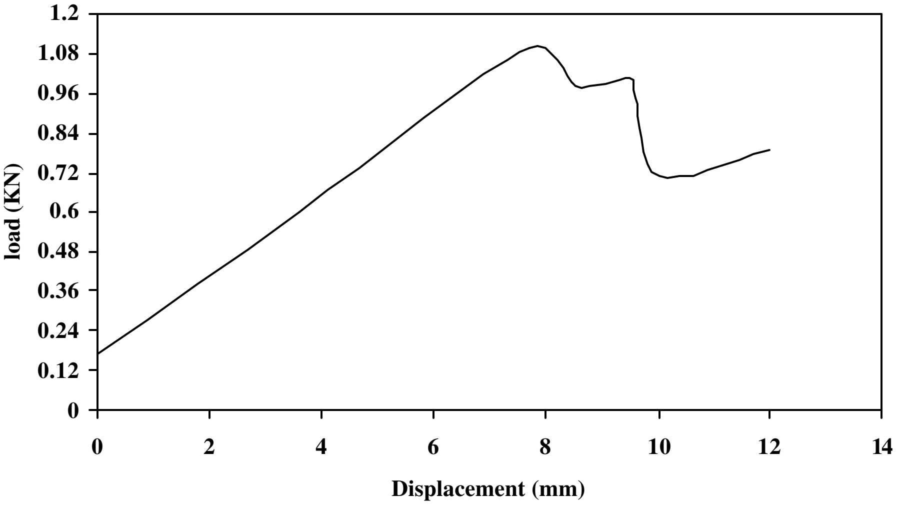
Delamination width = 12.5 mm



Graph–13 [90° $_{32}$] specimen with totally consistent delamination length & 12.5 mm width

Specimen – 14

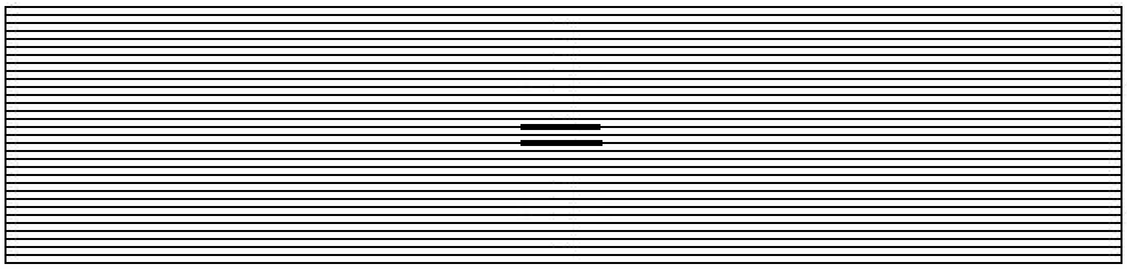




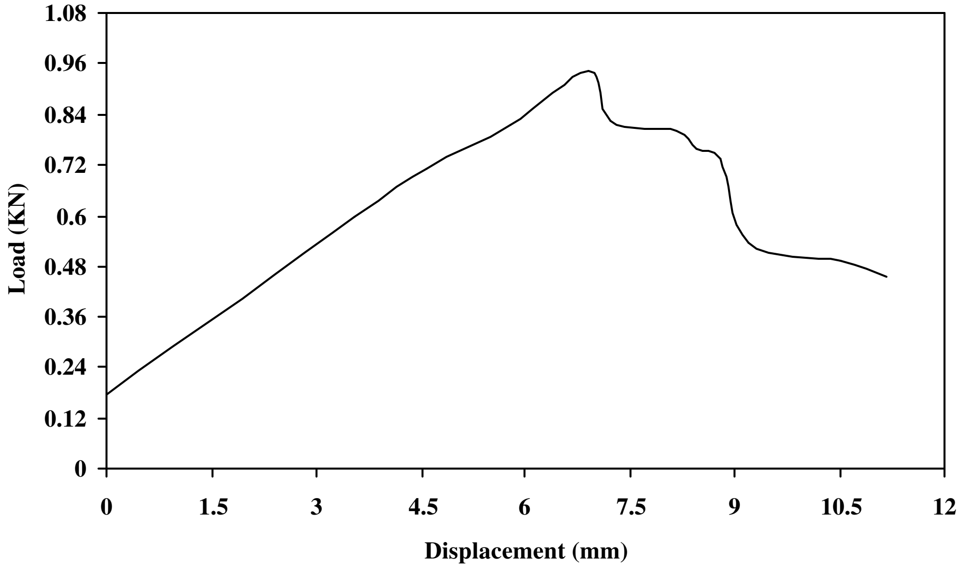
Graph – 14 [90° $_{32}$] specimen with totally consistent delamination length & 25 mm width

Graphs 12, 13 and 14 show that, with the increase in the area of delamination from (24 x 12.5 mm ^{2}) to (24 x 25 mm ^{2}) in specimens-13 and 14, the ultimate breaking load required decreases by 2.66 % and 16.73 %, when compared to specimen-12.

Specimen – 15



Delamination length = 12 mm x 2



Graph – 15 [90° $_{32}$] specimen with lateral multiple delaminations

Graph 15 shows that the lateral multiple delaminations decrease the ultimate breaking load largely, as compared to the totally consistent delamination length. The ultimate breaking load required for the specimen-15 decreases by 28.13 %, when compared to specimen-12.

TABLE – 1 SPECIMEN DEFECTS AND EXPERIMENTAL RESULTS

Specimen number	Composite stacking sequence/ Defect type	Delamination Length (mm) / Width (mm)	Delamination placement	Number of strands broken/Layer number	Ult. load, (KN)	Displacement at Ult. load, (mm)
1.	$[90^{\circ}{}_{20}]$				.565	11.2
2.	$[90^{\circ}{}_{20}]$ / Dl	24 / 25	10 / 10		.475	10.0
3.	$[90^{\circ}{}_{20}]$ / Dl	(6 x 4) / 25	10 / 10		.480	11.0
4.	$[90^{\circ}{}_{20}]$ / Dl	(12 x 2) / 25	1-9 / 10,11 / 12-20		.410	14.3
5.	$[90^{\circ}{}_{20}]$ / Dl	(6 x 4) / 25	1-4 / 5-8 / 9-12 / 13-16 / 17-20		.385	7.8
6.	$[90^{\circ}{}_{20}]$ / Dl	(3 x 8) / 25	1-3 / 4,5 / 6,7 / 8,9 / 10,11 / 12,13 / 14,15 / 16,17 / 18-20		.320	6.2
7.	$[90^{\circ}{}_{20}]$ / FB			2 Strands / 9-12	.420	8.7
8.	$[90^{\circ}{}_{20}]$ / FB			4 Strands / 9-12	.390	11.2
9.	$[90^{\circ}{}_{20}]$ / FB			6 Strands / 9-12	.305	11.0
10.	$[90^{\circ}{}_{20}]$ / FB			(2 x 2) Strands / 10,11	.450	10.1
11.	$[90^{\circ}{}_{20}]$ / FB			(4 x2) Strands / 10,11	.440	10.3
12.	$[90^{\circ}{}_{32}]$				1.315	8.8
13.	$[90^{\circ}{}_{32}]$ / Dl	24 / 12.5	16 / 16		1.28	8.3
14.	$[90^{\circ}{}_{32}]$ / Dl	24 / 25	16 / 16		1.095	7.7
15.	$[90^{\circ}{}_{32}]$ / Dl	(12 x 2) / 25	1-15 / 16,17 / 18-32		.945	6.9

Dl = Delamination

FB = Fiber Breakage

CONCLUSION AND SCOPE FOR FUTURE WORK

CONCLUSION

An experimental study was conducted to determine the residual strength of defected glass fiber-reinforced laminated composites loaded in 3-point bending. The findings suggest that:

- The increase in the area of delamination results in decreasing the ultimate strength of composite laminates.
- As compared to longitudinal multiple delaminations, lateral multiple delaminations have more severe effect on the ultimate strength of laminated composites.
- For the same area of delamination, the ultimate strength of laminated composites decreases with the increase in the number of delaminations in the lateral direction.
- For the same number of broken fiber strands, the ultimate strength of a composite laminate decreases with the placing of broken strands near the point of application of load.

SCOPE FOR FUTURE WORK

Composite materials have problems such as fiber breakage, matrix cracking and delamination. The present work involves the investigation of damaged, unidirectional glass fiber-reinforced, laminated composite specimens in 3-point bending, with the specimens having broken fiber strands and delamination defects. In order to reach to a substantial conclusion, regarding the strength prediction of damaged composites; further comprehensive investigations may be carried out, considering the following:

- Composites having both lateral and longitudinal multiple delaminations.
- Composites having cracks in the matrix.
- Composites with different fiber orientations.
- Composites with particulates and flakes as reinforcements.
- Study of the behavior of composites subjected to tensile and fatigue loading.

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