EFFECT OF ORIENTATION OF GLASS FIBER MAT IN EPOXY MATRIX ON MECHANICAL PROPERTIES

By

Md. Kamal Miah

DEPARTMENT OF INDUSTRIAL AND PRODUCTION ENGINEERING

BANGLADESH UNIVERSITY OF ENGINEERING ANDTECHNOLOGY

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CERTIFICATE OF APPROVAL

The thesis titled "EFFECT OF ORIENTATION OF GLASS FIBER MAT IN EPOXY MATRIX ON MECHANICAL PROPERTIES ", Submitted by Md. Kamal Miah, Student No: 100508008F, Session: October-2005, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of **Master of Engineering in Industrial and Production Engineering** on April 1, 2008.

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Associate Professor
Depart of Industrial and Production Engineering
Bangladesh University of Engineering and Technology, Dhaka

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Professor
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Bangladesh University of Engineering and Technology, Dhaka

Dr. Abdullahil Azeem — Member
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Bangladesh University of Engineering and Technology, Dhaka

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Date: 08/04/2008

MD. KAMAL MIAH

This dissertation is dedicated to my parents and brother

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NOMENCLATURE

Abbreviations

DTL	Delamination Thresold Load
DCB	Double Cantilever Beam
ENF	End Notch Flexural
CAI	Compression After Impact
FRP	Fiber Reinforced Plastic
V_f	Volume Fraction of Fiber
V_m	Volume Fraction of Matrix
E_c	Young modulus of Unidirectional Fiber Composite
E_f	Young Modulus of Fiber
E_m	Young Modulus of Matrix
FRC	Fiber Reinforced Composite
SMA	Shape Memory Alloys
f_p	Factor of Distribution of fiber Orientation
GFRP	Glass Fiber Reinforced Plastic
G_{IC}	Shear Modulus of Type I Composite
G_{IC}	Shear Modulus of Type I Composite
SHPB	Hopkinson Pressure Bar
RTM	Resin Transfer Molding
CFRP	Carbon Fiber Reinforced Plastic
DGEBPA	Diglycidyl Ether of Bisphenol-A
DER	Diglycidyl Ether Resin
CSM	Chopped Strand Mat
RM	Woven Roving Mat
RPC	Reinforced Polymer Composite
ASTM	American Society for Testing and Materials.

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Abstract

High performance composites are currently being used in the marine, automotive, aerospace and defense industries. These industries demand materials with properties that are similar or better than conventional metals at a fraction of the weight. The design of composite structures is challenging due to the complex mechanical behavior of the structures and the number of design variables involved. A composite laminate is typically formed from a number of fiber-reinforced layers having directional properties. Basically, for each layer of the laminate, the design variables are the choice of material system, thickness and orientation of the layers.

The objective of this research work was to evaluate the effects of glass fiber mats (CSM and RM) orientation and the dimensions (3D) of orientation on the mechanical properties in compare with epoxy matrix and other types of orientations by testing under tensile loading system. A die was designed prior to manufacture the composite samples and the samples were prepared as per ASTM standards. An Instron machine was used for tensile loading test. All specimens were tested to failure in order to characterize the effect of maximum strain on failure strength of the material. The fiber volume fractions (FVFs) of all types of composite specimen were measured in a conventional method.

Experimental values were obtained for tensile modulus, maximum stress, and the strain at maximum stress in all three directions. It was experimentally found that Composite of 3D orientation of CSM provided 81.46% higher strength, whereas other horizontal orientations of CSM with and without woven roving mat provided 43.73%, 52.53% and 56.2% higher strength over epoxy matrix. The 3D oriented GFR composite also absorbed 114.15% and 153.05% higher energy than epoxy matrix both to initiate crack and to fracture respectively. Whereas other types of horizontally oriented GFR composites absorbed 85.69%, 76.0%, 35.23% and 93.37%, 91.84%, 39.11% higher energy than epoxy matrix both to initiate crack and to fracture respectively. The 3D oriented GFR composite was, therefore, more toughened than other types of composites.

CHAPTER 1

INTRODUCTION

In the technologically advanced era that we currently live in, there is a growing demand for cheaper and more durable materials for a variety of applications. Previously metals and metal alloys were used to manufacture anything and everything from paper clips to skyscrapers. Then plastics were discovered and a revolution began where plastics started replacing metal components, for example, gears, bearings, etc. Plastics are easier to mould into complex parts as well as being lighter than their metal counterparts and just as durable. Initially plastics were expensive, but as their application and demand in everyday life increased, the manufacturing costs of plastic components decreased.

The use of plastic components are limited to low end applications such as food containers and dustbins due to their relatively low strength. High end applications such as automotive, marine and aerospace structures still required the use of metals and their alloys. Thus there was a need for a strong yet lightweight material and composite materials were developed.

Reinforcement of plastics by fibers has been employed successfully for over fifty years as means of improving the mechanical properties of the manufactured products. Combining high-modulus, high-strength fibers with a polymeric matrix produces a composite material with higher stiffness and strength, and lower thermal-expansion coefficient. The reinforcing fibers can be introduced either in a continuous (long) or discontinuous (short) form. While continuous fibers provide greater relative improvement of the mechanical properties, they also significantly complicate composite-material processing. Short-fiber composites, on the other hand, can be easily manufactured by automated, and hence more economical, methods [1].

Recent research work has targeted to evaluate the effects of orientations of glass fiber mats on the mechanical properties of polymer-based composite produced by HLU methods.

1.1 BACKGROUND

In antiquity, mechanical properties were often the decisive factor in materials selection. Today, they still limit the size of our bridges and skyscrapers, and the performance of our airplanes. The second part of the twentieth century has seen significant developments in our understanding of fundamental material science, and thus also of the mechanical performance of materials. This understanding has generated profound changes in the field, leading to new families of materials, new concepts, and wide ranging improvements in the mechanical behavior and in all other properties of materials. In our energy-conscious society, materials and structures are required to be more performant, lightweight, and cheap. The best answer to these requirements is often provided through the powerful concept of reinforcement of a "matrix" material with a second-phase dispersion (particles, fibers). This concept was already known to our ancestors. Indeed, the book of Exodus provides an often quoted reference to straw-reinforced clay bricks prepared by the Hebrews, and plant fibers in pottery artefacts were used early on in Central and South America. In these early examples however, the aim was to prevent cracking of the brittle material rather than reinforcement. The concept of reinforcement of materials by a second-phase solid is omnipresent in nature as well, from human bones (hydroxyapatite platelets within a collagen fibrillar matrix) to fingernails and rhinoceros horn (both consist of keratin fibers dispersed in a protein matrix), to the various types of wood (cellulosic fibers in a lignin matrix). A more subtle concept related to reinforcement in nature concerns the hierarchical microstructures (including the various degrees of symmetry), which so far have only partially been applied to synthetic composites, and a promising future seems to lie ahead for the observation of (and lessons to be learned from) the reinforced structures that appear in nature, a field commonly termed biomimetics.

It is an interesting fact that many natural forms of reinforcement possess a nanometric dimension whereas most current synthetic composites include fibers in the micrometer range. Expected benefits of such "miniaturization" would range from a higher intrinsic strength of the reinforcing phase (and thus of the composite) to more efficient stress transfer, to possible new and more flexible ways of designing the mechanical properties of yet even more advanced composites. First these arguments are reviewed, and then the concept of stress transfer leading to the principle of reinforcement is discussed. This is followed by specific materials aspects and by a short account of possible future forms of reinforcement [2].

Although many definitions of "composites" are available, they can be described as materials comprised of two or more constituents with very distinct compositions, structures and properties separated by an interface. The aim in producing composites is to combine different materials in a single device with properties that cannot be obtained from the individual components. Therefore composites for optical, structural, electrical, opto-electronic, chemical and other applications are easily found in modern devices and systems. During the past 30 years, there has been a substantial development of composites for structural applications. The main support of this tendency is the possibility of producing composites with high mechanical properties and low density that can replace traditional materials such as steel and wood. The combination of high performance polymers with high modulus-high strength ceramic or polymer fibers allowed the production of composites with a group of properties per weight superior than those of steel, aluminum and others [3].

Another important feature of composites is that they can also be easily designed to fit in a specific application due to the capability of having their properties tailored by changing one of a series of variables. Some of these variables are the type, concentration, size, shape and orientation of the constituents. Among these variables, the shape and the orientation of the reinforcing agent are the components of recognized importance in the design of composites. The influence of the aspect ratio of short fibers on the properties of composites is well documented and dictates the overall stress transferability phenomenon. Free fiber ends do not contribute to stress transfer. Stress is built progressively from the fiber ends up to a certain length (fiber critical size) where the stress transferred to the fibers reaches the characteristic maximum value for a specific system [3].

Structural composites are engineering materials made of oriented reinforcing fibers dispersed in a metallic, ceramic or polymer matrix. The use of composites moved forward in components of aircrafts and space structures due mainly to project flexibility, easy processing, lower density (0 ~ 2 g.cm^{-3}), as well as high mechanical strength and modulus. That matcher the requirements of the structures during service [4, 5]. This turns the composites particularly attractive as substitutes of the metallic alloys for high demanding aeronautical and space applications [4].

The aim of this work is to evaluate the effect of fiber mat orientation on the properties and mechanical behavior of composites. . However, the properties of composites depend on other factors, such as the molding techniques, fiber orientation and cure cycles.

1.2 OBJECTIVES

The core objective of this research work is to evaluate the effect of orientation of glass fiber mat and the dimension of orientation in epoxy matrix on mechanical properties. Mechanical characterization was carried out on coupon specimen sandwich plates manufactured by hand lay up process. In addition, comparison of performance is made based on parameters like manufacturing methods, fiber architecture, resin etc. To achieve the main objective, the following steps are also the integral parts of this research objective:

1. Manufacturing GFRP plates using hand lay-up in conjunction to compression molding.
2. Preparing coupon specimen from plates manufactured by open hand lay up (HLU) process.
3. Conducting tension tests on coupon specimens to find mechanical properties as per ASTM standard.
4. Comparing stress-strain behavior of different fiber architecture, effect of 3D reinforcement of glass fiber mats etc.

1.3 ORGANIZATION OF THESIS

Chapter 1: general Introduction and background on plastics, reinforced composites and their comparative discussion over conventional materials and detailed objectives of the research work.

Chapter 2: highlights literature data available on GFRP composites and description of previous research works done over GFR composites.

Chapter 3: Summary of constituent materials and manufacturing methods used for fabrication of composites. Constituent materials include fiber and resin matrix with their detailed description. Further, brief information about each manufacturing method used is provided. Steps involved in coupon specimens' preparation are listed in the end.

Chapter 4: Describes about composite specimens manufacturing method used is provided. Steps involved in composite specimens' preparation are die design; molding process and sample specimen preparation are also described.

Chapter 5: Describes the testing machine and the experiments conducted for mechanical characterization at specimen level. In addition, step wise procedure of each test method is listed followed by equations and plots required for property determinations.

Chapter 6: It contains comprehensive summary of results and data analysis for various test methods. Stress-strain and load-deflection behaviors are thoroughly studied with tabular and graphical presentations. Effect of various parameters is discussed.

Chapter 7: Detailed results and their relations are discussed. Result predictions are then compared with experimental data for various orientations.

Chapter 8 Conclusions and recommendations for future work are presented.

CHAPTER 2

LITERATURE REVIEW

This chapter focuses on critically reviewing of available literature on mechanical properties of fiber reinforced polymer composites as well as the constituent materials such as fiber and matrix. Some of the previous research works over fiber reinforced composites were also described briefly.

2.1 INTRODUCTION

The evolution of composite material has replaced most of the conventional material of construction in automobile, aviation industry etc. Fiber reinforced composites have been widely successful in hundreds of applications where there was a need for high strength materials. There are thousands of custom formulations, which offer FRPs a wide variety of tensile and flexural strengths. When compared with traditional materials such as metals, the combination of high strength and lower weight has made FRP an extremely popular choice for improving a product's design and performance [6].

2.2 FIBER REINFORCED COMPOSITES

Fiber reinforced composite components consist of rigid fibers embedded in a comparatively soft matrix. The fibers can be directional or non-directional, long or short. The matrix joins together the individual fibers so as to make them resistant to shear forces. In general, the mechanical properties of the matrix are significantly poorer than those of the fibers. Owing to the differing fiber directions of orientation, fiber composite structures exhibit an anisotropic or in some cases quasi-isotropic behavior. Three main groups of composites can be distinguished with respect to the type of matrix material:

- Polymer Matrix Composites: The most common composite materials, mostly used for light weight structural applications.

- Metal Matrix Composites: Used for special applications. e.g. for engine parts in the automotive industry, for which high temperature performance with low thermal distortion and specific tribological properties, e.g. wear resistance, are required.
- Ceramic Matrix Composites: Used in high temperature applications such as brake discs and heat shields.

For a given combination of strength, stiffness and energy absorption capacity, parts made of fiber reinforced composites are often lighter than if they were made of conventional lightweight construction materials, and they are therefore mainly applied in load bearing structures. The other main advantage is design freedom in particular for shell-like structures, e.g. dome-shaped components.

The following are the design parameters for polymer matrix composites:

- Type of fiber and matrix: The properties of the fibers and the matrix and the adhesion between the two components determine the properties of the composite material.
- Fiber volume fraction: Since the fibers mainly determine the strength and the stiffness of the part high fiber volume fractions must be achieved for load bearing structures. The manufacturing processes mainly give limitations, e.g. flow stop due to low permeability for liquid composite molding processes.

- Length and orientation of fibers: Stiffness, strength and crashworthiness can be increased by using longer fibers and orienting them parallel to the direction of loading.

Although significant improvements have been made over the last 30 years to the fiber materials as well as those of the polymer matrix, polymer matrix composites have failed to make the breakthrough to application in mass production. The reasons are as follows:

- Designing is not straightforward because of the anisotropy of the material and the difficulty of characterizing its mechanical properties.
- Material and manufacturing costs are high.

- The necessary quality control procedures are both complex and difficult to apply.
- There is no effective standard method for repairing the components.
- There is a limited plan or system for recycling the material.

Thus fiber reinforced composite materials have not been able to oust conventional lightweight building materials. Nevertheless fiber composite technology has been used successfully in two areas. These areas differ, especially in terms of product quality and costs:

- Hi-tech applications such as aerospace, leisure and sports, where the market will bear a high price to save weight. The main requirement in this area is high rigidity in conjunction with the lowest possible weight.
- Low-tech laminates such as glass-fiber reinforced polyester laminates that can be used for prototypes, hand production in small lots or efficient automated processes like chopped fiber spray or filament winding of simple geometries. Possible applications are in producing silos, ship hulls or hang-on parts for automotive use.

In recent years the automotive industry has showing increasing interest in composite technologies. In particular, fiber-reinforced composites seem to have an advantage over conventional lightweight materials such as aluminium or magnesium for making structural and semi-structural parts for sport and luxury cars in small and medium production runs. For this scale of production the low tooling costs compared to those for conventional steel parts more than offsets the higher operating cost, and the greater design freedom allows the manufacture of highly integrated structures that replace assemblies of smaller parts [7].

2.3 MECHANICAL PROPERTIES OF FRP COMPOSITES

Mechanical properties of FRP composite are dependent upon the ratio of fiber and matrix material, the method of manufacture, the mechanical properties of the constituent materials, and the fiber orientation in the matrix. Mechanical properties of glass fiber composites manufactured by different fabrication methods are shown in tables below.

Table 2.1: Typical mechanical properties of glass fiber composites manufactured by different fabrication methods [8]

Method	Tensile Strength (MPa)	Tensile Modulus (GPa)	Flexural Strength (MPa)	Flexural Modulus (MPa)
Hand Lay-up	62-344	4-31	110-550	6-28
Spray-up	124-335	6-12	83-190	5-9
RTM	138-193	3-10	207-310	8-15
Filament winding	550-1380	30-50	690-1725	34-48
Pultrusion	275-1240	21-41	517-1448	21-41

Table 2.2 Properties of chopped strand glass fiber reinforced composites [9]

Property	In chopped strand mat
Glass content	25-45
Softening or melting point ^0C	750-800
Specific gravity	1.4-1.6
Tensile strength, MPa	76-160
Tensile modulus, MPa	5.6-12
Flexural strength, MPa	140-260
Flexural modulus, MPa	6.9-14
Compressive strength, MPa	120-180

Mechanical properties also depend on reinforcement forms-continuous. aligned fibers: woven fabric; and aligned or randomly distributed discontinuous fibers. In unidirectional fiber composites, fibers are straight and parallel. They are considered orthotropic materials because they have two orthogonal planes of symmetry. To estimate extensional Young's modulus for unidirectional fiber composites, the following relationship between moduli of matrix and fiber can be used:

$$E_l = V_f E_f + V_m E_m \quad \text{Eq. (2.1)}$$

Where V_f and V_m denote volume fractions of fiber and matrix, respectively [10]. Modulus in transverse direction and shear moduli in the 1-2 and 1-3 planes (1-, 2-, and 3- directions denote longitudinal, width, and thickness. respectively) are strongly dependent of the fiber distribution.

The stress-strain behavior of FRP composites has almost linear relationship; and they do not yield plastically. However, non-linearity can also be observed due to formulation of small crack in resin; fiber buckling in compression; fiber debonding; viscoelastic deformation of matrix. fibers, or both. Therefore, yield point in composite materials denotes the departing from linearity in stress-strain relationship. The axial tensile and compressive strengths are dominated by fiber properties because they carry most of the axial load. Their stiffness is higher than that of matrix. The other strength values, which are often lumped into transverse strength properties, are influenced primarily by matrix strength characteristics, fiber-matrix interfacial bond strength, and the internal stress concentration due to voids and proximity of fibers. When fiber breaks under tensile load, the matrix resists the displacement by shear stress on lateral surface of the fibers. In compression, matrix helps stabilize the fibers, preventing them from compressive buckling at low stress level.

In discontinuous fiber composites, the orientation of fibers depends on relative sizes of fibers and part, resulting in 2- or 3-dimensional fiber orientations. In addition to factors affecting the properties of unidirectional composite, fiber length and diameter often affect the properties of discontinuous composite. Variability is apparent in discontinuous composites because fiber orientation and volume fraction are difficult to control in manufacturing process. In general. fiber volume fraction for discontinuous fiber composites tends to be lower than that for continuous and fabric composite, hence lower mechanical properties. The following equations can be used to estimate the Young's modulus of discontinuous fiber composite.

For parallel discontinuous, $E_c = \phi_c V_f E_f + (1 - V_f) E_m$ Eq. (2.2)

$$\phi_c = 1 - \frac{\tanh(p)}{p}$$

$$p = \frac{2l}{d}\left(\frac{G_m}{E_f}\right)^{1/2}\left(\frac{-1}{\ln(v_f)}\right)^{1/2}$$

where d and l are bulk diameter and length of fibers, respectively [10].

For 3-and 2-dimensional random discontinuous fiber, there are 1/3 and 1/6 coefficients in front of the fiber contribution term.

Region with significant amount of fiber curvature is likely to be the source of part failure because of their low strength properties. However, strength of discontinuous fiber composites is difficult to predict than that of continuous composites due to complexity of fiber orientation. There are three potential causes of failure of FRP composite. First, failure can be caused by error in the design process of FRP composite material or structure built from FRP composite. Second, error during fabrication and processing of FRP composite can cause failure Third, failure can be caused by fracture, which depends on type and orientation of fiber reinforcement [10].

One area that the weight efficiency and controllable properties of the FRC are crucial is the aerospace industry. This is because much portions of the structure in aircraft structures designed to be load carrying capacity components are made of thin flat or curved panels. Examples of these components are aircraft stabilizers, fuselage sections, missile nose and body sections. These components are subjected to both mechanical loads such as lateral pressure and edge compression loads and thermal load. As these loads are responsible for failures such as yielding and buckling failure.

it is important to study the state of stress beside other behaviors such as vibration, buckling and post buckling of FRC plates [11].

2.4 ENERGY ABSORPTION UNDER TENSION

When a force is applied to a material there is work done in the sense that a force moves through a distance (the deformation of the material). This work is converted to elastic (reconvertible) energy absorbed in the creation of new surfaces at the cracks in the material and surfaces [12].

Traditionally metals are used in many applications for their good energy absorption; however, the design often tends to be heavy. Linked to a demand for lightweight and fuel efficiency in vehicles there is a move toward the use of composite components. Properly designed composites can absorb a significantly greater amount of energy per unit mass than metals [13-16]. Metals tend to absorb energy by local plastic deformation; whereas composites exhibit more complex mechanisms. Most composite materials are brittle and absorb energy via a combination of fracture mechanisms such as matrix cracking, delamination and fiber breakage [17].

2.5 STRUCTURAL BEHAVIOR OF FRC

The structural behaviors of FRC can be optimized by using the correct combination of FRC parameters such as lamination angle, number of layers, aspect ratios etc. However the improvement based on this optimization procedure is rather fully utilized. One method that can give improvement to structural behaviors is by employing passive treatment such as using structural stiffeners. This however can override the weight efficiency advantage obtained from using the FRC. Researchers in the last decade have turn to new material technology such as the smart materials as an active treatment for improving structural behaviors of FRC plates.

Shape memory alloys (SMA) composite is either a polymer matrix composite or a metal-matrix composite that has the structural integrity of the composite material [18]. Most importantly the constraint of the matrix allows the generation of the high recovery stress that no conventional materials can provide [19].

2.6 EFFECTS OF FIBER ORIENTATION ON COMPOSITE PROPERTIES

An important characteristic that all composite parts have in common is the effect of fiber orientation on the final properties of the part. The properties of the part in the direction of fiber orientation and transverse to it are significantly different [20]. The graph in Figure 2.1 demonstrates this effect. It is clear that the elastic modulus is much higher when a stress is applied in the direction of fiber orientation than when it is applied transverse to it. Mayer (1993) [21] claims that there is progressive damage to the material at stresses below the ultimate. The first sign of damage is transverse fiber debonding through separation between the resin and fiber perpendicular to the load direction. This occurs typically at 0.3% strain and a stress level of about 30% of the tensile strength.

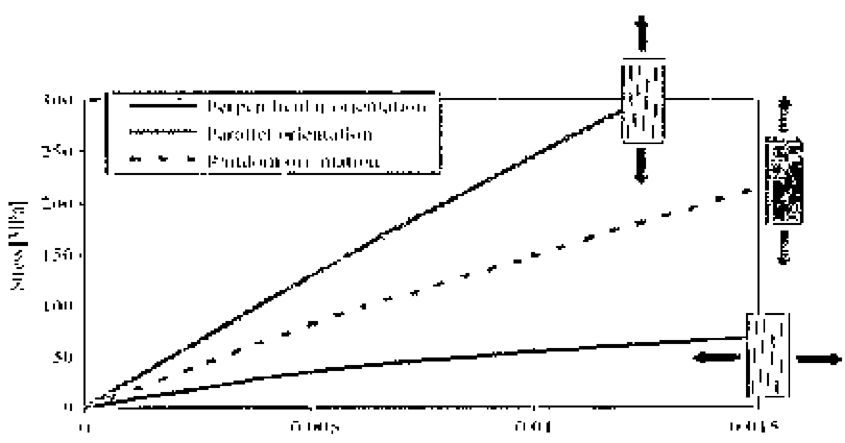


Figure 2.1 Stress-strain graphs with fibers oriented in the direction of strain and transversal to strain [20].

A single parameter f_p can be used to present the distribution of fiber orientations. This condition holds true when all the fiber are all in parallel planes as in thin layers. When all orientations are equally likely, this parameter becomes 0 and when all the fibers are perfectly aligned along a reference direction, f_p becomes 1. When the fibers are all aligned at right angles to the reference direction, f_p is -1[22]. The variations of f_p properties from 0 to 1 are represented in Figure 2.2.

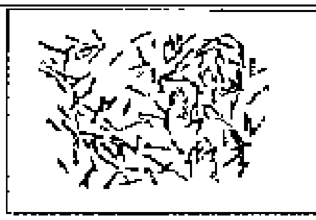
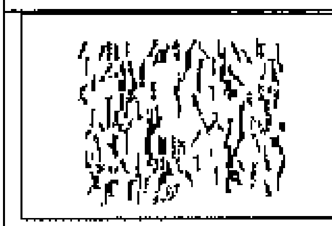
	f_p=0.0 random orientation of fiber.
	f_p=0.3"slightly"aligned orientation of fiber.
	f_p=0.6"moderately"aligned orientation of fiber.
	f_p=0.9"highly"aligned orientation of fiber.

Figure 2.2 Variation of *fp* properties correspondingly from 0 to1 [22].

The strength of a fiber composite clearly depends upon the orientation of the applied load with respect to the direction in which the fibers are oriented as well as upon whether the applied load is tensile or compressive. The following sections present a discussion of failure mechanisms and composite constituent property relations for each of the principal loading conditions [23].

Given the orientation of fibers in most of the composites currently used. entirely in the plane of the laminate, panel edges are particularly sensitive to loads, which cause in-plane and out-of-plane shear stresses [24–28]. The rupture of the link between plies, interlaminar cracking, is more commonly known as delamination. This mode of rupture is important for many marine structures and frequently defines the useful limit of these materials. The risk of delamination is also critical in many aeronautical applications, particularly after impact, and has been the object of many studies [29].

Impact loads are often present in marine structures (slamming due to wave loading and more concentrated impacts (dropped object, floating object impact) [30]. Sellars [31] has studied the conditions, which define slamming as a violent impact of water on the lower hull. The duration of slamming is very short, measured as milli-seconds [32] Military vessels, such as anti-mine vessels, may also be loaded by explosions, either underwater or air blast. As a result of their low interlaminar strength transverse impact loading can cause cracks and delamination in composites and stiffener debonding [31]. During impact, the energy absorbed can create a large damaged zone (matrix cracking, fiber breakage, fiber debonding and delamination). This damage can cause a reduction in strength and residual stiffness without visible degradation of the component [28, 33- 34].

2.7 EFFECT OF STACKING SEQUENCE

While highly orthotropic stacking sequences may be optimal with respect to global loading and stiffness based design, stress concentrations as high as 7 or 8 have been determined for orthotropic laminates containing holes. Laminate stacking sequence allows the designer to tailor laminates for applied loads and this possibility has been used extensively in the design of composite joints. Stacking sequence has been shown to influence the strength of joints significantly with respect to both strength and failure mode. Collings [35] in his earlier work on joints in CFRP discovered that while stacking sequences had a lesser effect on shear-out and net-section strengths, bearing strengths were sensitive to stacking sequence. Subsequent research has shown that all failure modes are dependent on stacking sequence. Arnold [36] and Hamada [37] expressed the importance of 0^0 plies on the bearing strength with Hamada proposing that the strength was dependent on the degree of interlaminar fracture versus fiber buckling in the 0^0 plies. The pseudo-clamping effect obtained through employing plies at 90^0 to the load direction at the outer surfaces, has been shown both experimentally [36, 38, 39] and numerically [38, 40] for both glass fiber reinforced plastic (GFRP) and CFRP laminates.

Applying 90^0 plies at the outer surface acts in reducing interlaminar normal stresses and impedes delamination. In contrast to much of the published literature, Hamada [38] found that the highest joint strengths were achieved through adopting outer 0^0

plies in his study of the effects of stacking sequence on the strength of quasi-isotropic laminates.

It has also been reported [41] that plies of similar orientation should be dispersed throughout the laminate and not 'blocked' in order to achieve higher bearing strength. Thus the most efficient laminates, considering all possible failure modes, have a dispersed [90. / ± 45. /0]s quasi-isotropic stacking sequence. Cross-ply laminates have been studied in tension by Marshall [31] and in bending by Chen and Lee [29] with both authors in consensus that [90.*n*/0.*n*].*s* laminates exhibit higher ultimate joint strength compared to [0.*n*/90.*n*].*s* laminates.

2.8 STITCHED/3-DIMENSIONAL LAMINATES

Delaminations in impacted laminates are mainly the result of low through-the-thickness shear strength. The reason for this is that the fibers in traditional laminates are only oriented two dimensionally; there are no fibers running through-the-thickness which can carry τxz, τyz or σz stresses that result from transverse impacts. Therefore one way that researchers have attempted to improve impact performance is by placing fibers in the z-direction of laminate. The preferred method of placing fibers through the thickness is stitching.

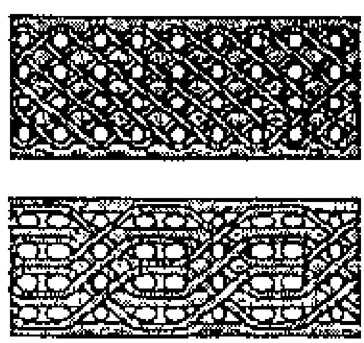


Figure 2.3 Different Stitching Patterns [42]

To fully understand just how the stitching affects the behavior of a composite one must first understand the basic mechanics behind a stitched composite and more specifically how a delamination crack propagates in a stitched composite. A study by Sharma and Sankar. 1995 [43] examined mode I and mode II crack propagation of composites with different stitch densities. It was found for mode I crack propagation that stitches first debond from the surrounding resin and then fracture as the crack propagates. The propagation of a mode I crack for a traditional 2-D laminate in a double cantilever beam (DCB) was gradual and steady. The separation of the layers advanced progressively as the ends were pulled apart; the stitched composite's crack front on the other hand progressed intermittently as individual stitches fractured. For mode II crack propagation the unstitched laminate experienced a sudden catastrophic failure while the stitched composite had steady crack propagation. Both the G_{IC} and G_{IIC} values were higher for stitched composites and increased with increased stitch density.

The improved G_{IC} and G_{IIC} values that stitched composites displayed in the end notch flexural (ENF) and double cantilever beam (DCB) have led researchers to the conclusion that stitching would reduce delamination area and improve residual strength. These assumptions have borne themselves out as can be seen in the following studies [44-49]. From these studies many common trends emerge. The first and most significant of these trends has to do with the amount of damage that accumulates in stitched composites as compared to baseline specimens. The DTL is higher in stitched specimens than in baseline laminates. In baseline laminates a large load drop immediately follows the DTL whereas in the stitched specimens the load has a saw tooth profile of small load drops and increases after the DTL. This saw tooth appearance is the result of the progressive fracture of stitches as the delamination crack tip propagates along a ply interface. The stitches therefore absorb the impact energy through strain and fracture, restrict the growth of the delamination crack tip and eventually arrest the propagation of the delamination much sooner than in traditional laminates. This has the overall effect of significantly reducing the delamination area of an impacted specimen. The stitched composite is also stiffer after the DTL than the baseline laminate with the load increasing to a higher maximum load at a lower deflection than in baseline laminates. The density of the stitching also affects the impact performance of specimens. Generally the rule is that the higher the stitch density the better the impact behavior but there does seem to be an optimum stitch density for impact performance. Damage accumulates, as the stitches get closer together: the needle must move or break the main 2-D fibers, which cause not only fiber fracture but also distortion of the original fiber architecture that can affect the load carrying capacity of the laminate. Therefore for stitch densities above the optimum density damage and discontinuity introduced into the fiber architecture overshadows the strength gained by an increased number of fibers.

The virgin and residual strength of a stitched composite, as with traditional laminates, is dependent upon the type of loading that it is subjected to. The virgin tensile capacity of a stitched specimen is actually lower than that of an equivalent non-stitched laminate. The reason for this is the aforementioned fiber damage and architecture distortion that takes place as a consequence of the stitching process. The distortion of the fibers reorients them in a different pattern than was originally intended and produces voids, which are filled by resin causing stress concentrations within the laminate itself. The result is that the virgin tensile capacity decreases with an increase in stitch density. The increase in post-impact residual tensile capacity of stitched laminates is only marginal at best. The real advantage of stitching comes with the compression after impact (CAI) strength. This comes about because CAI strength, as mentioned above, is driven largely by the stability of the laminate. To optimize the CAI capacity of a composite the aforementioned optimum stitch density should be used. The stitching not only reduces the initial delamination area it also restricts the resulting sub laminates from buckling individually and helps the laminate ct as a whole. This comes about from the stitching that crosses the ply interfaces improving the IC value and restricting the delamination crack tip from propagating and making the sub-laminates less stable. This greatly increases the stability of the laminate as a whole and improves he overall buckling capacity. The orientation of the stitching can also play a role in the residual strength of a laminate. For optimum capacity the stitching should be aligned with the direction of the load to reduce the fiber damage and distortion in the direction of the load.

2.9 PREVIOUS WORKS

2.9.1 Research Works on Tensile Loading of FRP

The behavior of the fiber-reinforced composite materials has been experimentally studied in many aspects mostly under tensile and strain rates has been experimentally studied in many aspects mostly under tensile and compressive load by the Split

Hopkinson Pressure Bar (SHPB) method, as it gives the properties of the test materials over a wide range of strain rates [50- 52].

In attempt to determine the mechanical properties of composite materials under dynamic tensile loads, a review of technique was given by Harding and Welsh [53]. In the standard tensile version of Kolsky bar apparatus the input loading bar become the weigh bar tube within which the output bar slides freely. Dynamic stress strain curves for unidirectionally reinforced carbon epoxy composite in which failure occurs in less than 30 μs at a mean strain rate of about 400 s^{-1} and for woven reinforced glass/epoxy composites with the time to failure approach 100 μs and the average strain rate was around 1000 s^{-1}were presented and their validity was established by the authors.

Toward this objective, pardo and batiste [54] performed tension tests of unidirectional E-glass/polyester composite specimens on a Schenck high strain rate hydraulic test machine to investigate the effect of strain rate on the tensile strength of material.
Hayes and Adams [55] conducted various tests at various tests speeds and load levels to characterize the tensile impact behavior and rate sensitive materials properties of unidirectional glass/epoxy and graphite/epoxy composites.

Peterson and pantano [56] tested five different materials and ultimate strength; failure strains and effective modulii for each material were investigated as function of strain rate under dry and wet test conditions. The authors got a different type of results here in terms of failure strains for the materials tested.

Barre and Chotard [57] studied the tensile dynamic behavior of glass fiber reinforced polyester and phenolic resins in order to find the effects of strain rate on the mechanical properties of composite materials produced by resin transfer molding (RTM) and pultrusion processes and had the results that the dynamic elastic modulus and strength increased by a ratio and the shear modulus measured with off-axis and ±45 coupons produce different effects.

Staab and Gilat [58] studied that maximum normal stress experienced by glass/epoxy angle-ply laminates is higher for dynamic than for quasi-static loading conditions. But fibers dominate the laminate properties in case of high rate loading. Authors also mentioned that the failure patterns change with fiber orientations.

On the basis of the loading unloading tests, energy analysis of unidirectional fiber reinforced epoxy under tensile impact, Yuanming and Xing [59] proposed a coated fiber bundle model and it can be used for other unidirectional brittle fiber reinforced resins.

Liftshtz and Leber[60] investigated interlaminar tensile strength and modulus of two material systems namely PW E-glass/epoxy and unidirectional carbon epoxy of 30-32 mm thick plates and found that both strength and modulus were rate sensitive and increase with loading rates.

Hou and Ruiz [61] tested CFRP T300/914 laminates and found that specimens remained virtually linear elastic up to failure and tensile modulus and strength in 0^0 direction were rate dependent and tests on ±45 specimens gave non-linear stress strain stress curves.

Majzoobi and Saniee [52] used the high rate tensile testing apparatus called "Instron testing machine" for testing of R2000 Glass/Epoxy specimens and observations showed that there is significant increase in failure strength and reduction in failure strain in dynamic tests compared to the static tests. Also the rate of the increase of stress versus strain slowed down as ply angle increased.

Shenoi and Makarov [62] dealt with experimental investigation of unidirectional glass fiber-reinforced composite materials to determine the mechanical properties of Unidirectional E-Glass/Epoxy composites. The conclusion from the results here was also the same that there was significant increase in ultimate strength and modulus of the material.

2.9.2 Research Works on Fiber Orientation in Composites

Research carried out by Hull [62] shows that fiber lay-up of $0\text{-}90^0$ of glass/epoxy is better than $\pm 45^0$ by 40%. Similarly the difference with respect to glass/polymer is about 50%. Another study by Farley [63] on glass/epoxy, carbon/epoxy and

Kevlar/epoxy composite with respect to the fiber orientation showed significant difference when these materials were subjected to energy absorption trends. Further studies conducted by Hamada et al [64] showed that hybrid reinforced composites with both carbon and dyneema fibers/epoxy had a decrease in their energy absorption capability with an increase in fiber orientation to the longitudinal axis of the tube. Another study of varying angle orientation of lay up done by Berry [65] on woven glass fabric/polyester showed that composites with the warp and weft directions of 45^0 to the tensile axis was 30% less when compared to composites with warp and weft direction parallel to the axial 0^0 and hoop 90^0 directions. This is due too more fracture and material deformation.

Ramakrishna et al [66] studied composites with fiber orientations of 0^0, $+5^0$, $+10^0$, $+15^0$, $+20^0$. $+25^0$, and $+30^0$ with respect to the axis of the composites. He determined that the specific energy absorption capability of the composite is a function of the angle of the fiber orientation.

Thus from all the above mentioned studies we can say that the angle or ply orientation is inversely proportional to the length of the longitudinal cracks. This results due to the increase of fracture toughness with increase in the angle, which in turn resists the growth of the crack. Thereby resulting in higher energy absorption for the composite material.

2.10 SUMMARY OF LITERATURE REVIEW

From the literature of the reinforced composites and the previous research works of different researchers, it was found that the mechanical properties and the structural behavior of the reinforced composites greatly depend on several factors such as

1. Manufacturing process: Hand lay up, Spray up, RTM, Filament Winding. Pultrusion etc.
2. Type of reinforcement: Glass fiber, carbon fiber, Kevlar etc
3. Type of orientation:0^0,90^0,45^0, random orientation, unidirectional, bi-directional, stitch and sequence of orientation etc.
4. Loading system: Tensile, transverse, bending and compression etc.

It was also evident that orientation of fiber and the dimension of orientation are the important factors for superior mechanical properties of reinforced composites. The type of orientation of reinforcing fibers largely influences strength, modulus, stiffness, toughness and absorption energy etc. But few researchers did work on it and no researcher worked specially on the 3D orientation of reinforcing glass fiber mat.

CHAPTER 3

MATERIALS USED AND MANUFACTURING PROCESS

This chapter deals with a brief description of constituent materials such as type of matrix, fiber, classification, and composition, emphasizing the constituent material properties and their individual contribution towards properties of composites. Also, an overview on the some of the manufacturing techniques available is discussed. Further, details of the types of mats and resins, and processing methods employed for fabrication is provided.

3.1 CLASSIFICATION OF POLYMER MATRICES

Polymer matrices typically are of two types: thermoplastic and thermosetting polymers. Thermoplastic polymers have the ability to regain their original state upon addition of heat i.e., above the glass transition temperature. While, thermosetting polymers undergo chemical reactions during curing which cross-linking of the polymer molecules takes place. Once cross-linked, thermosets become permanently hard and simply undergo chemical decomposition under excessive heat.

3.2 USE OF THERMOSET COMPOSITES

Even though thermoplastic resin have many advantages such as longer shelf life, higher strain to failure, ability to be repaired, reshaped and reused, use of thermoplastics introduces problem of fiber penetration into the matrix, high matrix viscosity causing dealignment of reinforcing fibers, as well as void formation within the final composite product. Thermosetting polymers, on the other hand, have greater abrasion resistance and
dimensional stability compared to thermoplastic polymers. Hence, for the past few decades, fiber reinforced composite materials are being fabricated using thermosetting matrices.

Thermosetting resins include epoxies, polyamides, phenolics, polyesters, vinyl ester etc. One of the most generally used thermosetting materials is epoxy resin.

3.2.1 Epoxy Resin

Epoxy resins are a high strength polymer with low viscosity, which allows good wetting

of the fibers. The ability to infuse under low pressure helps to prevent fiber misalignment during processing. Also, these resins exhibit low shrink rate reducing the tendency of internal stresses and especially large shear stresses of the bond between epoxy and fibers after curing [67]. They offer good adhesion to the substrate which leads to high resistance at the fiber/matrix interface and, consequently, high mechanical properties as shown in the table 3.1 below.

Table 3.1 Typical Properties of Cast Epoxy Resin (at 23^{0}C) [68]

Specific gravity	1.2-1.3
Tensile Strength, MPa (psi)	55-130 (8000-19000)
Tensile modulus, GPa (10^6 psi)	2.75-4.10 (0.4-0.595)
Poisson's ratio	0.2-0.33
Coefficient of thermal expansion, 10^{-6} m/m per ^{0}C (10^{-6} in./in. per ^{0}F)	50-80 (28-44)
Cure shrinkage, %	1-5

However, their main drawback is slow processing, compared to other resin types such as polyester, due to their comparatively higher viscosity and longer gel times [69].

There are a variety of epoxy formulations available for composite structures. The most common basic epoxy resin is derived from the reaction of bisphenol-A with epichlorohydrin. It is called the diglycidyl ether of bisphenol-A (DGEBPA or epi-bis types) [70]. American trademarks for this type resin include DER- 332 (Dow) and Epon 828 (Shell). The general structure of the epoxy is shown in Fig. 3.1. Such epi-bis epoxies are liquid at room temperature, others have increased viscosity, and some are solids that melt at about 150^0 C (302" F). Generally, the higher the melting point of the epoxy, the less curing is needed. Cured properties of the various epi-bi resins are similar. However, toughness increases as the melting point of the unreacted epoxy is increased.

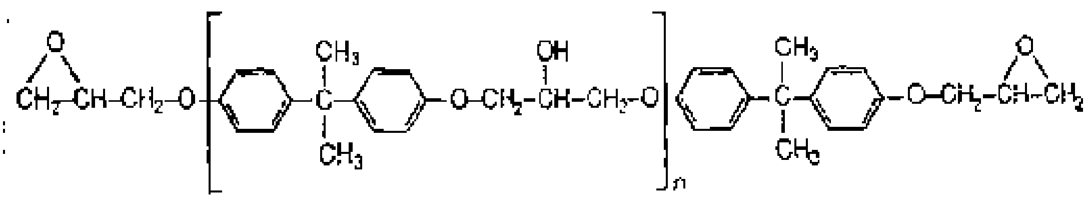


Fig 3.1. Epoxy Structure

3.2.2 Resin/Hardener systems

Resin systems are usually composed of two parts; namely resin and hardener, or cross-link agent, which initiates the curing reaction. The choice of resin/hardener system depends on the application, the process selected and the properties required. For difficult large parts, a slow hardener will be preferred in order to allow the resin to fully impregnate the reinforcement before gel initiation. In general, Cycloaliphatic diamines such as isphoronediamine, bis-p-aminocyclohexylmethane and 1, 2-diaminocyclohexane is used as epoxy resin curing agents for both ambient- and heat-cure epoxy resin systems. While they have advantages such as epoxy resin hardeners (light colors and good chemical resistance), they have the disadvantage of slow cure at low temperatures. In this research, bis-p-aminocyclohexylmethane, which is commercially available. used to harden epoxy resin both in ambient and heat cure temperature. In this study bis-p-aminocyclohexylmethane was used as hardener in resin mix cure at ambient temperature.

3.2.3 Fiber types

In composites materials, fibers are used to reinforce the matrix. A large variety of types
exist offering a wide range of mechanical characteristics, such as high strength, high stiffness and relatively low density. In this work, E-glass fibers were investigated; table 3.2 presents their main mechanical and physical properties.

Table 3.2: Typical properties of E-glass and carbon fibers [69] [71] [72].

Properties	E-Glass		Carbon	
	[122][80]	[100]	[92][80]	[100]
Density [g/c^3]	2.60	2.55-	1.75	1.75
Young's modulus E_{11} [GPa]	82	2.60	237	240
Transverse modulus E_{22} [GPa]	72	85	22	-
Poisson's ratio v_{12}	0.22	-	0.3	-
Longitudinal tensile strength [GPa]	2.6	-	3.93	4.0
Elongation to failure [%]	3.4	3.44	1.7	1.67
Coefficient of thermal expansion [$K^{-1}x10^{-4}$]	4.8	4.8	-0.4	-0.5

3.2.3.1 Glass fiber

Glass fibers are obtained from a compound of silica (SiO2) to which metal oxides are added. As shown in figure 3.2, these two constituents are melted together at a temperature of 1500°C. The molten raw materials are then fed into bushings of several

hundred holes, from which filaments are drawn and cooled with water before finally being combined as strands and wound on a forming package.

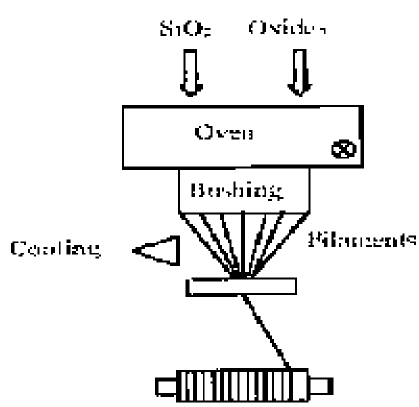


Figure 3.2 Manufacture of glass fibers (reproduction of [69].

Usually, glass filaments are wider than carbon filaments; their diameters are in the range
of 5μm to 24μm. Also, as for carbon fibers. a surface treatment such as an aqueous solution can be applied. Glass fibers are preferably used for low cost applications requiring relatively high tensile strength properties. However, their use is limited due to low stiffness, low fatigue, and poor resistance to environmental conditions. For these reasons, they will be used in low and medium performance composite applications. The composition of glass can be varied depending on the requirement of the end product. Some of the different glass compositions available are E-glass, S-glass, C-glass, A-glass, D-glass, L-glass, and M-glass. E-glass is mostly used due to its low-alkali Composition and superior insulation properties.

3.2.4 Reinforcement Forms

As the glass filaments are extremely fragile, they are supplied in a wide variety of reinforcement forms, such as strands, rovings, yarns, milled fiber, chopped strands, continuous or chopped mats, woven fabrics, braided fabrics, knitted fabrics etc. Materials
used for reinforcements are designed to serve the fabrication process and end product requirements[69].

3.2.4.1 Unidirectional

Tapes, rovings, tow sheets, are considered as unidirectional fibers. Fibers are aligned parallel to each other in one direction or another direction, and have maximum performance along the aligned direction. Unidirectional fabrics are also available wherein
the majority of fibers run in one direction (warp), while polyester or Kevlar thread or some other low-grade material is made to run in the other direction (weft) in order to hold
the warp fibers in position. Usually. the contribution of weft fibers is negligible. Typically, the density of unidirectional fabrics is very low; hence requires more lay-ups for most of the applications.

3.2.4.2 Multidirectional Fabrics

Multidirectional fabric based laminate composites are replacing unidirectional laminates primarily due to better performance in different directions. In multidirectional type of plies, fibers can take different forms of architecture such as woven, stitched (knitted), or braided.

- **Stitched Fabrics**

Stitched fabrics are one of the mostly used fabrics in structural applications, as they are non-crimped, and also provide better orientation with the increase in the lay-up. They are produced by assembling the layers of aligned fibers. The fiber orientations available are 0, 90, and ± 45 direction. The whole lay-up is then sewn together, allowing high modulus in tension and bending.

- **Continuous Strand Mats (CSM)**

Continuous strand mats are made from fiber glass strands randomly looped fibers, are held together with a binder. It has good wet-out (in case of thermosets), tailored to different shapes, and has good physical properties. Though CSM is used for variety of applications, it is used in combination with woven rovings, woven fabric, stitched fabric etc, to gain adequate stability and for better desirable properties. They assist in obtaining desired properties mainly in transverse direction of the end-product. Owing to all the above, in this study, multidirectional E-glass fabrics were used. For comparison purposes, unidirectional, cross ply, tri-directional with CSM, and quadridirectional with and without CSM were the stitched fabrics utilized. A continuous strand mat is produced by randomly oriented fiber reinforcement being placed together [73].

Figure 3.3 Continuous Strand Mat (CSM)

3.3 DESCRIPTION OF REINFORCEMENT

Fabrics used for this study were continuous chopped strand mats (CSM) and roving cloths (RC) glass fiber.

The sample specimens used to examine to determine mechanical properties of four different types of reinforcement are described in the table and figures below.

Table 3.3 Types and reinforcement of composite samples

Sample Type	Sample ID	Fiber Type	Reinforcement Type	
A	TLA	Chopped strand mats (CSM)	CSM/CSM/CSM/CSM+CSM (Vertical)	Four horizontals with vertical layer
B	TLB	Chopped strand mats	CSM/CSM/CSM/CSM+CSM	Five horizontal layers
C	TLC	Chopped strand mats and roving cloth (RC)	CSM/CSM/RC/CSM+CSM	Four horizontals with one roving cloth
D	TLD	Chopped strand mats and roving cloth	CSM/RC/CSM/RC/CSM	Four horizontals with one roving cloth

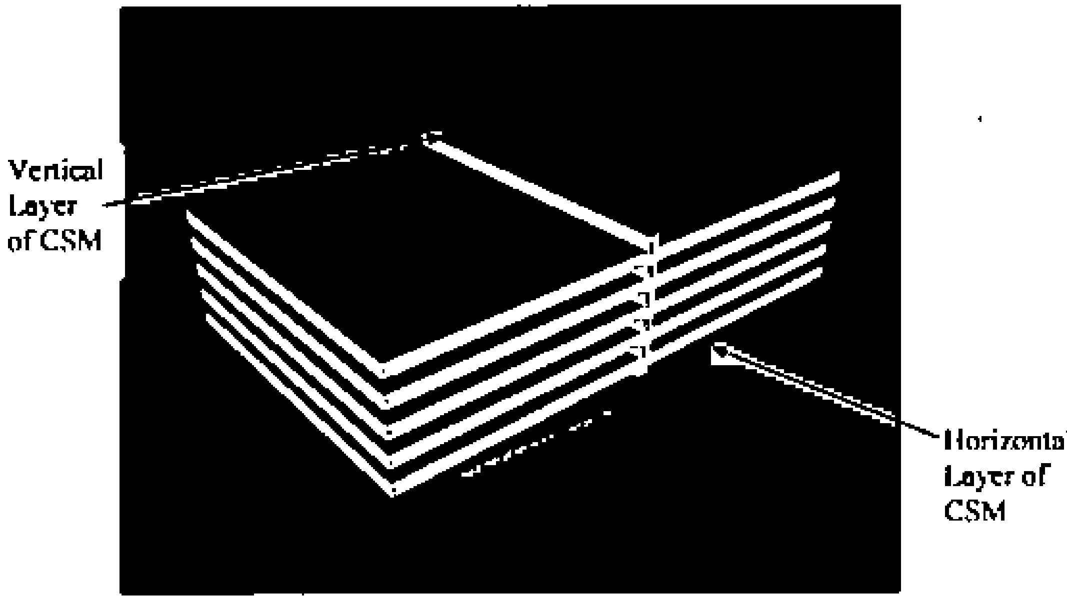


Figure 3.4 Glass fiber mat reinforcement of Type A (TLA) composite sample

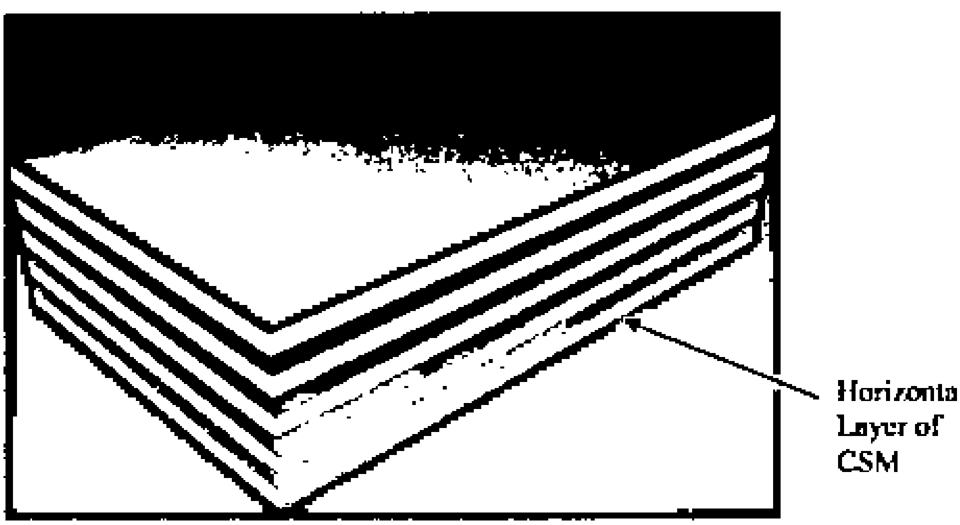


Figure 3.5 Glass fiber mat reinforcement of Type B (TLB) composite sample

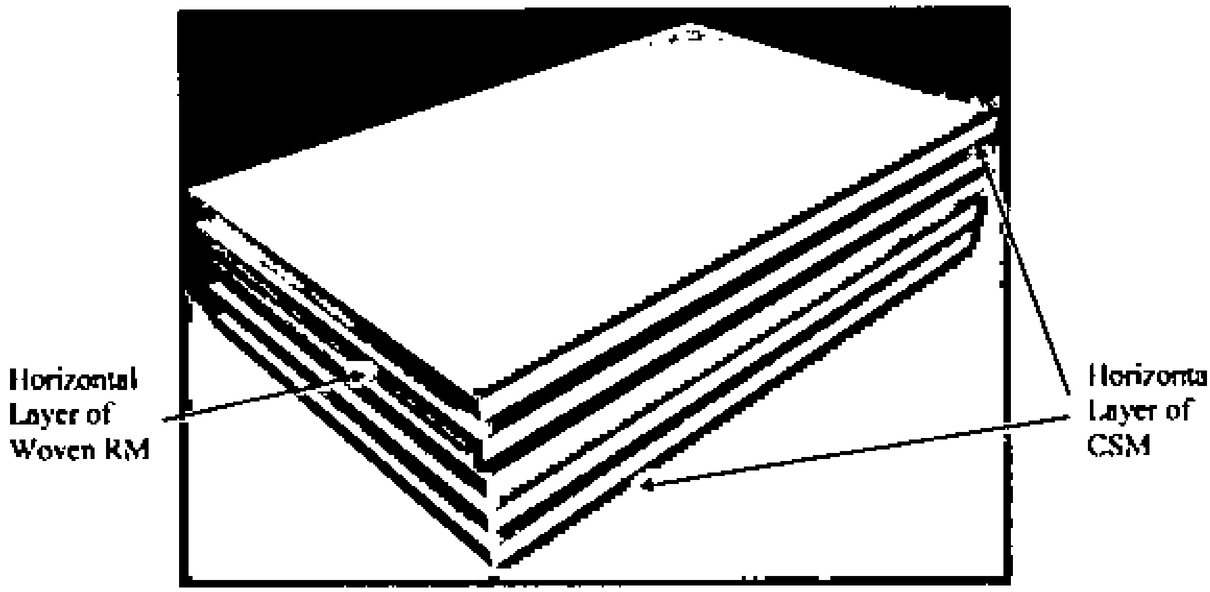


Figure 3.6 Glass fiber mat reinforcement of Type C (TLC) composite sample

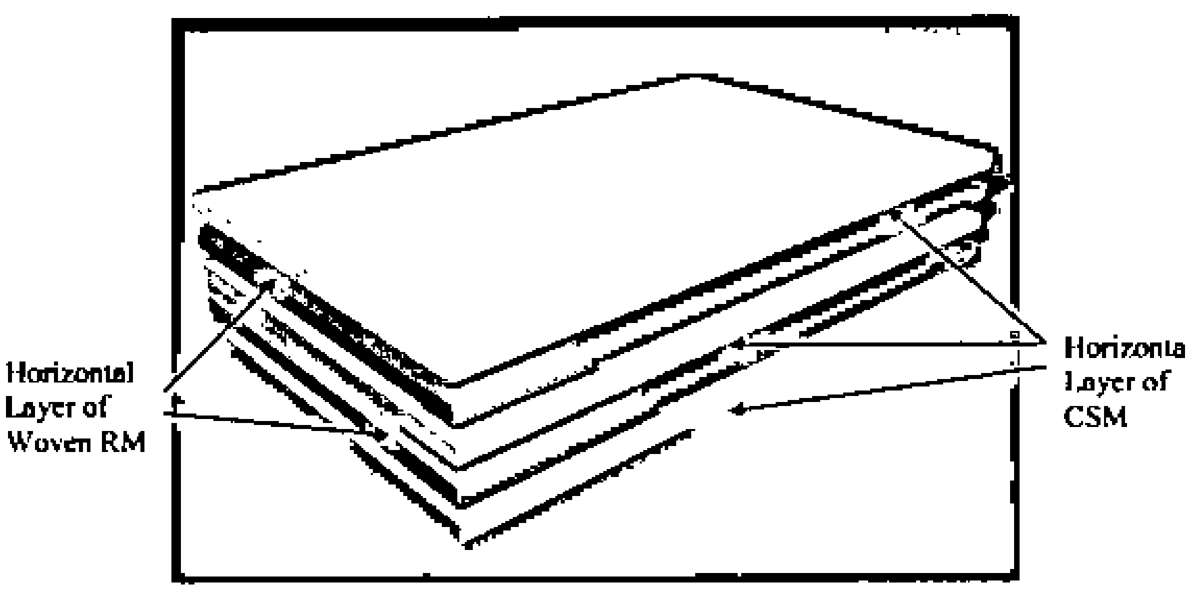


Figure 3.7 Glass fiber mat reinforcement of Type D (TLD) composite sample

3.4 MANUFACTURING PROCESS

There are wide varieties of manufacturing processes practiced starting from hand lay up technique to automated mass production systems like filament windings, etc. The manufacturing processes are classified as open mold process, and closed mold process.

3.4.1 Open Mold Process

Includes spray-up or hand lay-up processes. These are the simplest and oldest processes. Each ply is either sprayed with resin or brushed on the top and bottom of the fabric, thus wetting out the laminate. In order to remove excess resin, a squeeze is used after laying up the fabric.

3.4.1.1 Hand Lay-Up.

Hand lay-up is one of the most common low-to-medium volume RPC production processes. It typically involves manual application of general polyester liquid resins to reinforcement, such as glass fiber mats or woven roving, that are laid against the smooth surface of an open mold. Serrated rollers or squeegees drawn across the preparation help to release any air that may be entrapped in the reinforcement material. Chemical curing, often induced by a catalyst additive, hardens the resin and reinforcement into a structural form that is exceptionally strong for its weight. The resin offers a uniform matrix for the reinforcing material in much the same way that concrete does when used in conjunction with reinforcing bars made of steel [74].

The mold is the primary piece of equipment necessary for the hand lay-up process, as Figure 3.8 illustrates. Prior to hand lay-up production, the mold (which is often itself a composite) is sprayed with a tinted gel-coat and allowed to partially cure. The gel-coat side of the final product takes on the color of the pigment used to tint the gel-coat and has a smooth surface and decorative finish, much like that provided by high quality paint. The appearance and texture of the other side is rough and abrasive, unless corrective measures, such as applying a tightly woven sail cloth to the back surface prior to curing, or sanding the back-surface after curing are performed. In most applications of hand lay-up, only a single finished side is required. [74]

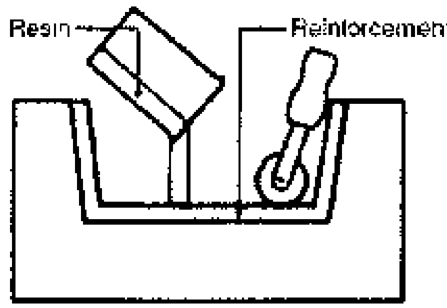


Figure 3.8. Hand Lay-up Processing [74]

3.4.2 Closed Mold Process

Includes resin transfer molding, pultrusion, vacuum bag molding, compression molding, injection molding, autoclave molding, filament winding etc. These processes take place in a closed chamber. The liquid resin or prepreg form may be handled manually or pumped into the container for the curing step.

3.4.2.1 Compression Molding Process

This is the oldest and most commonly used process in automobile industry. Typically, a compression mold is a vertically orientated hydraulic press consisting of two platens and the force. The mold in the shape of the part to be molded is to be placed in between the two platens, where it is compressed (under pressure) depending on the part geometry. The mold is closed under pressure, compressing the material for several hours until it is cured (in this study). The curing is done either at elevated temperature or room temperature. At elevated temperatures, the heat of the mold softens the resin under pressure and forms the shape of the mold.

For this study, hand lay-up in conjunction with compression molding process was used for the fabrication of composite plate. This process produces a composite plate with uniform thickness, good fiber wet-out and negligible porosity. Schematic diagram of compression molding process used for the fabrication of composite plate is shown in Figure 3.9.

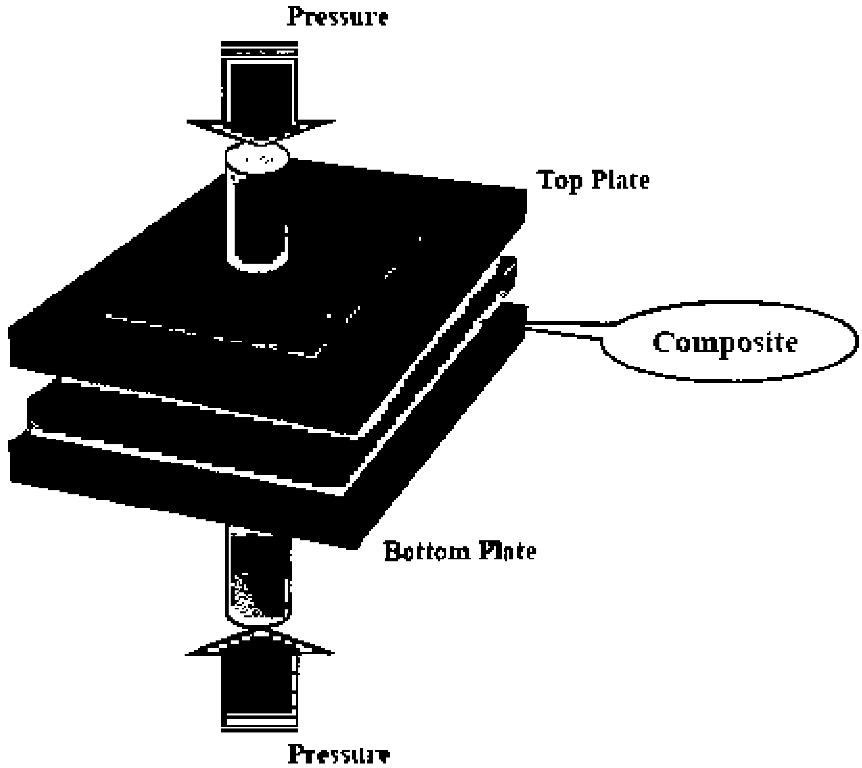


Figure 3.9 Schematic Diagram of Compression Molding Process

For each of these processes, the chosen composite materials, including all resins, reinforcements, filler, and additives, are compressed into a desired shape in a matched die by keeping a suitable amount of load approximately 100kgs. The composite feedstock is then held in place while the resin matrix quickly cures into its permanent hardened shape. Significant differences among these processes determine their suitability for a given application. The following sections offer brief descriptions of each of the main high-volume molding processes. [74]

CHAPTER 4

EXPERIMENTAL PROCEDURE

In this chapter, the design and manufacturing process for the molding die and the test specimens are described. The manufacturing process was carried out at departmental machine tools laboratory. The dimensions of the test specimens and method of testing used in this research were determined using the American Society for Testing and Materials (ASTM) standards.

The tensile specimens were designed in accordance with ASTM D3039 standard [12]. According to the standard, the specimen should be a "dog bone" shape. ASTM standard D3039 [11] is the standard for polymer matrix composites. The dog bone shape was chosen to ensure that the samples would break in the gauge area. D3039 cautions that samples should be individually molded or if cut from a panel care must be taken to avoid a rough finish from the cut or delamination as a result of poor cutting methods.

4.1 DIE DESIGN

The method used to create the test coupons was to use a compression molding process, a panel about 30cm by 30cm was created and the specimens were cut from the panel. This is accomplished using a mold shown in Figure 4.1 to figure 4.3.

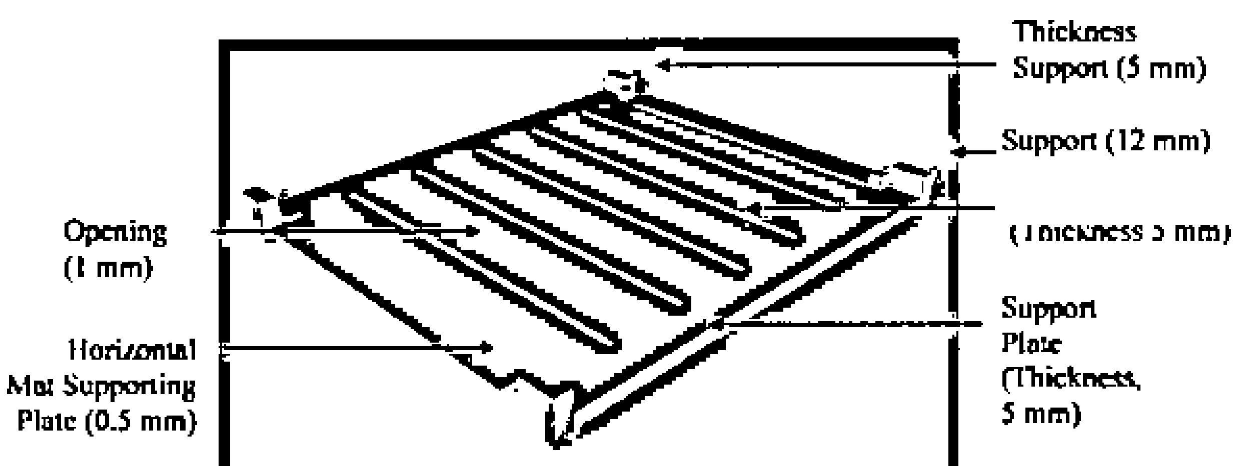


Figure 4.1 Bottom part of Mold for 3D reinforcement of fiber (First Approach)

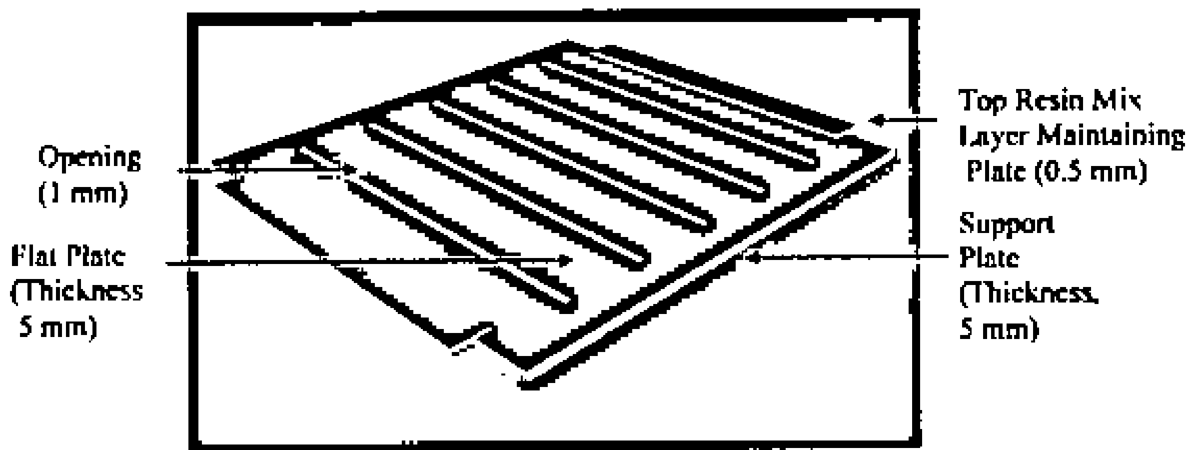


Figure 4.2 Top part of Mold for 3D reinforcement of fiber (First Approach)

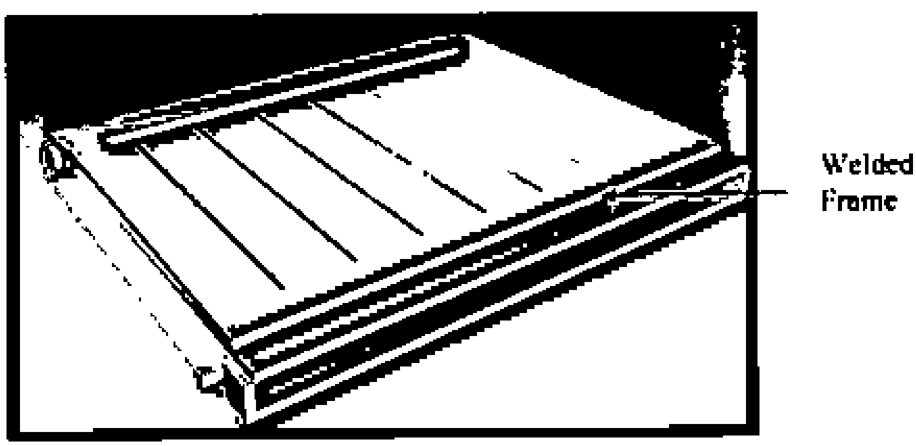


Figure 4.3 Complete Mold for 3D reinforcement of fiber (First Approach)

Several approaches were adopted to make a die before molding of composites (as seen in the Appendix A). The die is designed specially for vertical reinforcement of fiber mats. The die consists of two parts; the base and the upper cover. Stainless steel sheet with the plane surface of different thickness was used in different approach.

Several problems appear during molding of composites by these dies.

The main problems are;

- There was a little possibility to place malate paper for easy release of molded composite plate.
- The sealing problem of liquid resin mix.
- Air voids entrapping.

At the final approach, a die consisting of three parts i.e., the base plate consisting of four holes at the four corners, the upper plate and a frame of rod iron is prepared to mold composite. The plates are made of stainless steel and are with slightly greater dimensions than the required molded composite plate as shown in the figure 4.4 to figure 4.8 below.

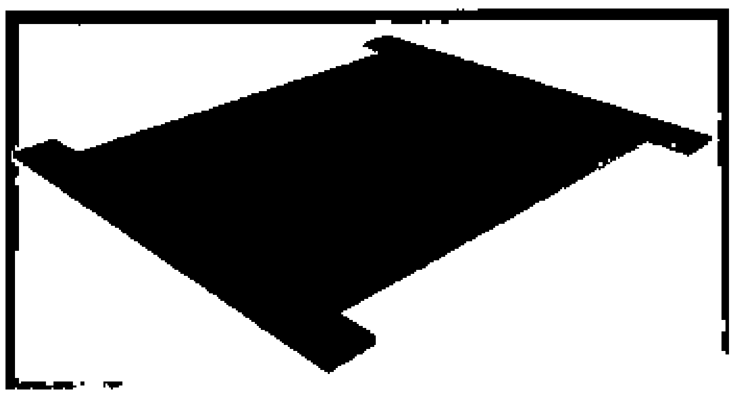


Figure 4.4 Bottom part of mold for 3D reinforcement of fiber (Final Approach)

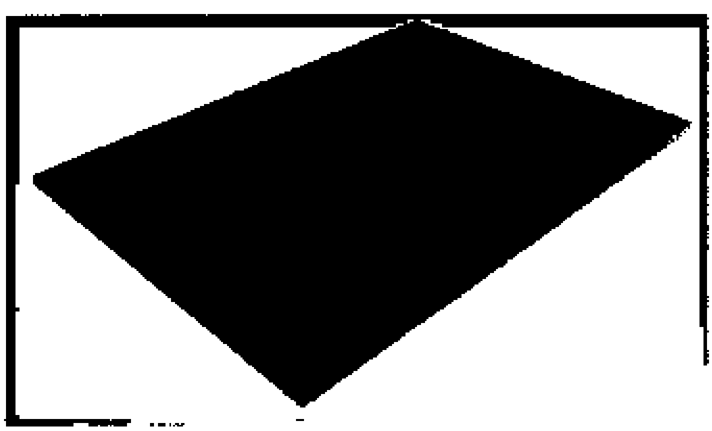


Figure 4.5 Top part of Mold for 3D reinforcement of fiber (Final Approach)

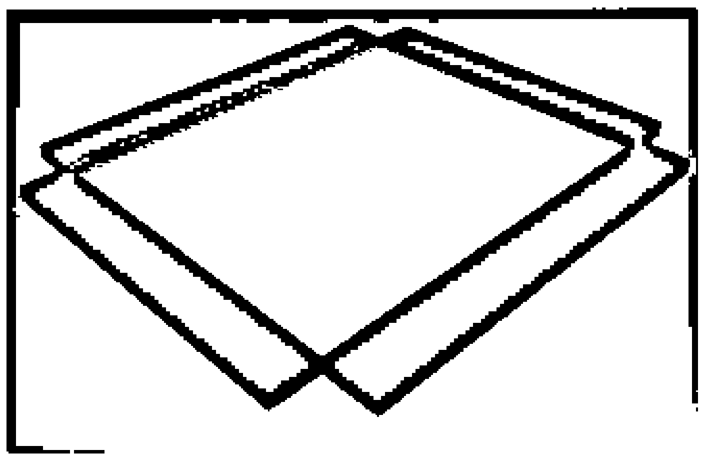


Figure 4.6 Flat bar for maintaining constant thickness of molded composite plate (Final Approach)

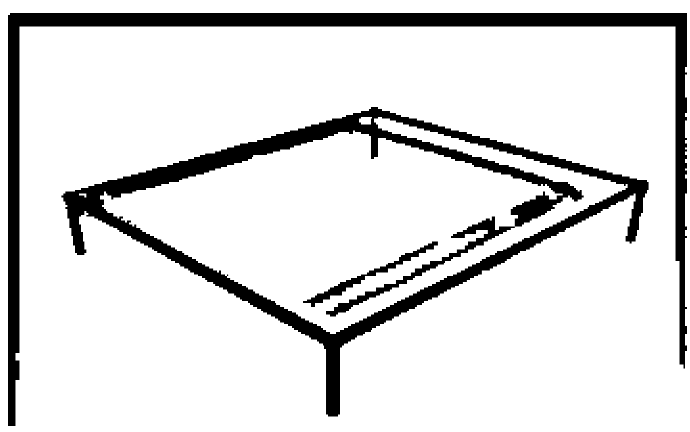


Figure 4.7 Rod Iron frame for vertical orientation of glass mat (Final Approach)

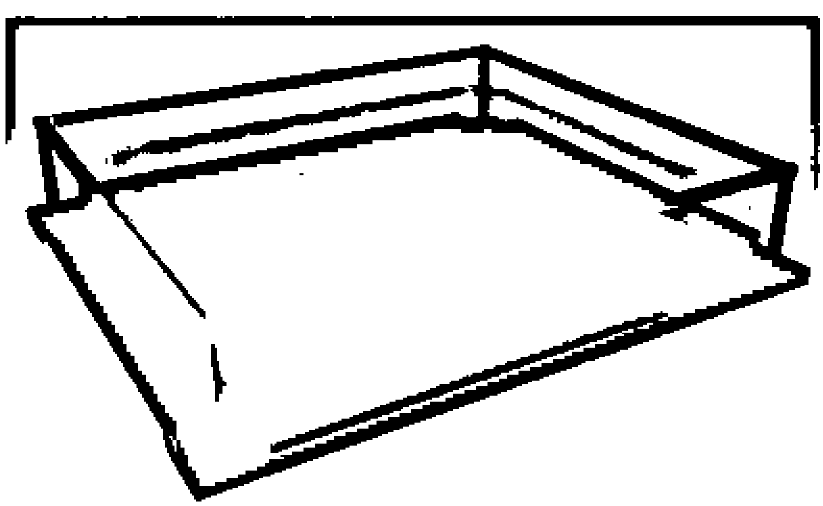


Figure 4.8 Complete Die for Creating Large Flat Composite plates (Final Approach)

There are four stands of same length (6 cm) welded at the four corner of the rectangular rod iron frame so that the frame can seat on the base plate. Four stainless steel bars are provided to keep the accurate thickness of molded composite plates. The bars are of nearly same length of the base plate and adjusted to the outer sides of the base plate. The bars are of 25 mm wide and 4.6 mm thick. The rod iron frame is kept separate and it is removed after molding. Malate paper was used to separate the molded composite plates easily from the mold. It was applied as an inside layer of both (top and bottom) parts. The advantage of the final die as appeared in the figure 4.5, was that all types of orientation of fiber in any direction mat were possible. Since the parts were separable, it was easy to compress the mold with a desirable after the end of molding.

4.2 MOLDING PROCESS

As a first step. both parts were wrapped with papers tightly so that clean, smooth and plane surfaces can be provided. The malate papers for both parts were cut with slightly greater dimensions than the mold plates and one paper was place on the top of the bottom flat surface and wrapped with the plate. The use of Malate paper prevents the resin from

sticking on to its surface while curing, so the composite can be easily removed from the

mold. Four steel bars in wrapped with paper were placed firmly with the help of tap around the bottom wrapped such that the desired rectangular area to make a mold was obtained

The areal density of each type of fiber mats was measured and noted for fiber volume fraction analysis. The fiber mats of both types (CSM and RM) were cut approximately 300 mmX260mm (length X width). Proper care was taken when handling the glass fiber mats, so as to avoid damage and distortion of fibers. For manufacturing of 3D reinforced composite samples, the CSM was cut slightly larger than the dimension of the composite plate from which sample specimens were cut and the vertical layer mat for this type was also cut with the same dimension of thickness of the molded 3D reinforced composite samples. Clean and non-sticky brush and serrated rollers were used in order to coat resin on the mat. Epoxy resin was then initially weighed and poured into a beaker and mixed with initiator in appropriate proportions (20: 3) as per material safety and data sheet, where the quantity depends on the size of the plate prepared. The resin/hardener mix was agitated properly prior to apply.

Initially resin mix was applied on the malate sheet using brush. A layer of mat was then placed on top of resin mix layer. The serrated roller was used to ensure proper wet out and compaction, and removal of any entrapped air in the mat. Then a second layer of resin mix was placed on top of the first layer, and the above procedure was repeated up to five layers of mats. In case of 3D composite, the vertical layer of CSM was clipped by two longitudinal sides with the rod iron bar (as seen in the figure 4.2). Several vertical layers of CSM were clipped to prepare 8/9 samples from the molded composite plate. An appropriate amount of resin was poured on the last top layer. It was then covered with a malate sheet and, the flat top plate of stainless steel was placed on the top to ensure a good flat surface. The whole set up was placed on a flat plane surface and was loaded with a weight of approximately 100 kgs and kept for 24 hours, until it was cured at room temperature. After room temperature curing, the molded plates were cured in a woven at the constant temperature approximately 100^0C for 5 hours. About 40 composite plates with different fiber architectures and thickness were prepared using the above compression molding process.

Procedure for the manufacturing of composite plate was carried in a fume hood with exhaust system. Gloves, respiratory mask and glasses were used for safety purposes.

4.3 SPECIMEN PREPARATION

Four different types of test specimens were prepared for this test. The final product (composite plates) obtained by using hand lay up molding process has uneven edges due to resin oozing out during compression. Hence, the edges of the molded plates were trimmed off. The excess vertical ribs of the CSM in the 3D molded composite plate were machined off with the milling operation as can be seen in figure A7 (Appendix-A). The plates were cut into sample specimens using round power saw, depending on the dimensions required for tension test. The edges of the samples were made smooth with the help of grinding operation and polishing with emery papers. Sample specimens prepared from the plates were dog bone in shape and cut in longitudinal direction as per ASTM 3039 standard specifications using carbide tipped band saw. The geometry and shape of the sample specimen is appeared in the figure 4.3 below.

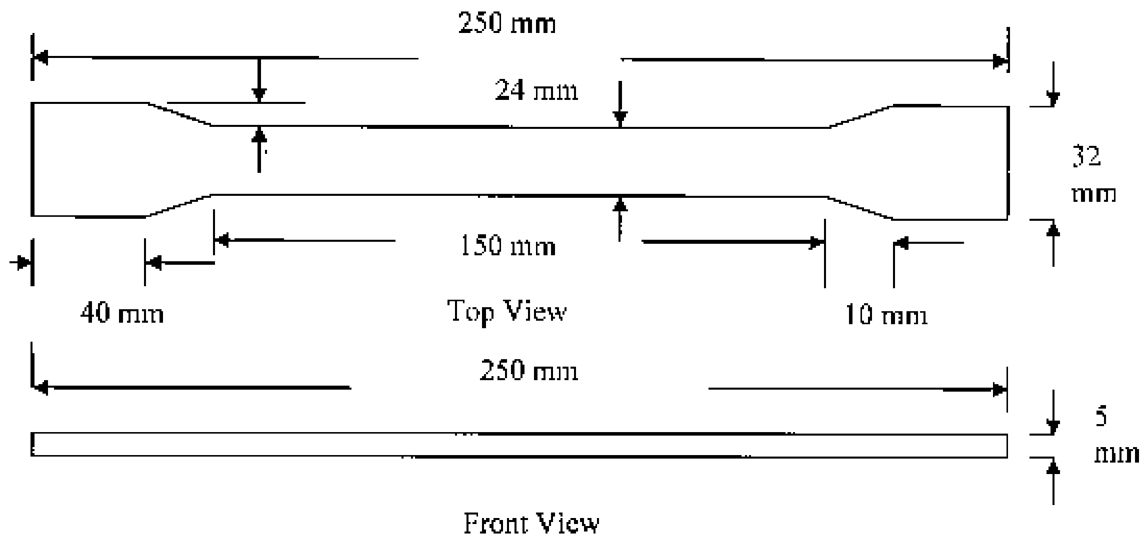


Figure 4.9 Geometry of Specimen

The fiber architecture, manufacturing and dimensions of each specimen used and the type of testing were carried out in the laboratory of the university. All of the specimens of different types were manufactured with a thickness of around 5mm.

Specimens were labeled in accordance with the type of testing, fiber architecture and specimen number. The required dimensions such as width, thickness and gage length were measured at various locations using digital Vernier calipers and average value was considered and noted for calculation and analysis of results.

4.4 EXPERIMENTATION

The mechanical testing mainly includes tension test. Tension test was performed on coupon level samples. The tensile test of different types specimen manufactured for mechanical characterization was carried out by using Instron Model3369 servo-hydraulic material testing machine at the materials and metallurgy laboratory in the university. Additionally, physical property characterization such as fiber content was tested manually at the departmental laboratory. The testing equipments used and procedure are briefly discussed in the next sections.

4.4.1 INSTRON MODEL 3369 SERVO-HYDRAULIC MATERIAL TESTING SYSTEM

Instron-3369 has a maximum load capacity of 50-kN (11 kip) and is used to conduct broad range of testing such as compression, tension, bending, shear, and fatigue. The applied load rate is uniformly maintained by electronic control panel. Typical equipment
setup is shown in Figure 4.2. Some of the important components of Instron System are
listed below.

- Strength-Testing Machine
- Hydraulic System
- Control Tower
- Control Console

This equipment was used to carry out bending tests on coupon sample. For all bending
test samples, dimensions were approximately kept constant. The samples used were of the average dimensions 250mm(L)x32mm(W)x5mm(t). Load and deformation data were collected.

The unit consists of a two-column load frame with a movable crosshead. Auxiliary hydraulic lift cylinders regulate the position of the crosshead. Hydraulic column clamps
fix the crosshead in the desired position. A load cell is mounted on the crosshead. The force applied to the specimen is sensed by in-built strain gage type load cell placed on the
stationary top cross-head, wherein the analog signals from the load cell are amplified and
converted into a digital signal. The machine is operated by the control module of the

computer, where the readings are displayed and are saved and stored for analysis using IX version software. The displacement is determined from grip position. The data were evaluated for mechanical properties.

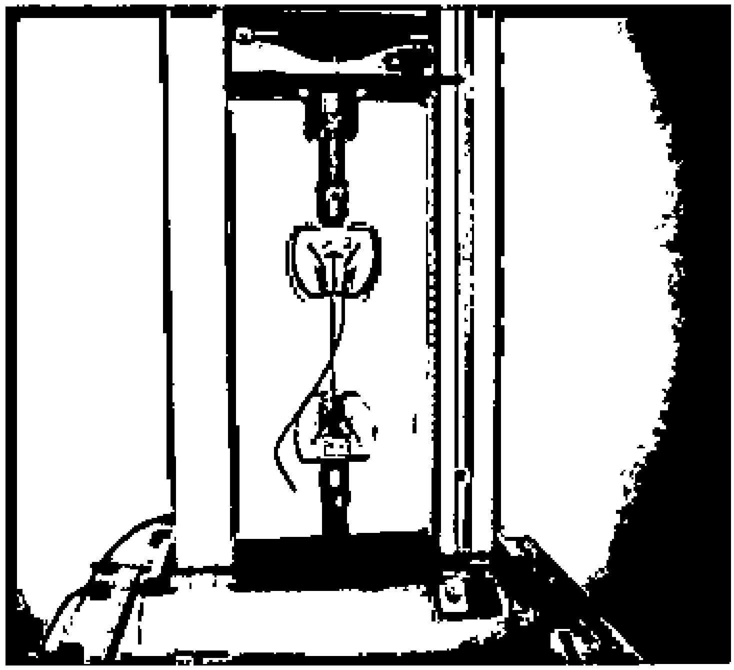


Figure 4.10 Instron Model 3369 Servo-hydraulic Material Testing System

4.4.2 TESTING METHODOLOGIES

GFRP sample specimens were subjected to tension loads, to determine the mechanical properties. Axial tension tests were conducted on GFRP laminates manufactured by hand lay up method. This test determines tensile strength and modulus. All the tests were carried out as per ASTM D3039 standard. The specimens subjected to tension test were of the size 250mm x32mm. Thickness of test specimen varied from 3.5mm to 5.5mm, depending on manufacturing method. A minimum of 24 hours curing time was allowed for the bonding agent to fully cure before testing the samples. Strain gages were mounted axially along the length of specimen. All the tension test specimens were tested with Instron 8501 Machine by maintaining loading rate nearly constant. Data of load versus strain were recorded. These data were then reduced for stress versus strain curve. The slope of linear portion of stress versus strain plot is referred to as modulus of elasticity, a measure of stiffness of a material. Results and comparison for different sets of sample are summarized in Chapter 5.

Coupon specimens with different fiber orientation (symmetric and non-symmetric), manufacturing method (hand lay up), resin matrix (epoxy) were tested in longitudinal direction. Standard procedure listed by ASTM D3039, was followed for all the samples. All tension specimens were tested in Instron 3369 Machine.

4.4.2.1 Stepwise Procedure for Tension Tests

I. Width and thickness of test samples were measured at three different locations. Cross sectional area was calculated from average width and thickness.

II. Tension specimens were centrally aligned between the jaws ensuring uniform force distribution.. During the test, loading rate was manually maintained constant. All the samples were tested till failure.

III. Data were recorded for load versus strain variation during the test. Experimental values of tensile strength and stiffness were calculated.

Data analysis and results are discussed in detail in Chapter 5.

4.4.2.2 Tension Test Calculations

Tensile strength $\sigma_{ult} = P_{ult}/wt$

Tensile modulus $E_{ss} = \sigma/\varepsilon$

Where,

P - Applied load on the specimen (kgs)

w - Average width of specimen (mm)

t - Thickness of specimen (mm)

A = W x T = Cross-sectional area of the specimen (mm^2)

Ess – Calculated from slope of elastic zone of Stress Vs. Strain curve

4.5 FIBER CONTENTS

As strength of composite typically is in direct proportion with fiber content, a quantitative measure of fiber content is essential. There are many standard methods to determine FVF for FRP composites specified by ASTM such as ASTM D3171.In this research work, non-destructive method is applied. In order to determine fiber content in the composite sample, Areal density of each type of glass fiber mat is measured. Each type of composite sample contains five horizontal layers of glass fiber mats. The average dimensions of sample were measured with help of Vernier caliper. A layer of dry mat of each type of glass mat with the same dimensions of sample is measured. As a layer of CSM is reinforced vertically with other five horizontal layers and positioned longitudinally at the middle of the 3D composite sample architecture, this layer is also measured with nearly accurate dimensions of the respective sample. The weight of a sample of each type was then measured. With these quantities, fiber content was calculated.

4.5.1 Fiber Volume Fraction Calculations

Length of Specimen - L in mm

Width of Specimen - W in mm

Thickness of Specimen - T in mm

The surface area of the sample-LW mm^2

Average area of a horizontal layer of mat-A_{fH} mm^2

Average area of a vertical reinforced layer of mat-A_{fV} mm^2

Areal density of glass fiber mat-w_f gm/cm^2

Areal density of CSM-0.06 gm/cm^2

Areal density of roving mat (RM)-0.046 gm/cm^2

Density of glass fiber – ρ_f in gm/cc (2.552 gm/cc) (Barbero, 1998)

Density of epoxy resin –ρ_m in gm/cc (1.2 – 1.3 gm/cc)

Average weight of the CSM–0.1 gm/cm2

Average weight of the Roving mat per sq.mm-0.08 gm/cm^2

Average weight of sample – Ws in gm

Number of Horizontal layer-N_H

Number of Vertical layer-N_V

Fiber Volume Fraction, $v_f = \frac{W_f/\rho_f}{W_f/\rho_f + (1-w_f)/\rho_m}$

Where, V_f represents the weight percentage of fiber volume content present in the composite sample.

Sample Calculations:

Sample type-B

Sample ID-TLB

Number of layers-5

L = 25.00 cm

W = 3.2 cm

T = 0.5 cm

ρ_f = 2.552 g/cc

ρ_m= 1.2 gm/cc

Ws = 48 gm

$Wf = [(N_H A_{fH} + N_V A_{fV}) \times w_f]_{CSM} + [(N_H A_{fH} + N_V A_{fH}) \times w_f]_{RM} = 15.04$ gm Eq. (4.1)

So, V_f=21.08%

4.6 STRAIN ENERGY UNDER TENSILE LOADING

Strain energy per unit volume is obtained by calculating the area under the load-elongation curve in order to get the strain energy of the specimen. About 40 coupons were tested in tension direction i.e., longitudinal direction. From each test, stress-strain or load deflection curves were generated to determine the mechanical properties of glass fiber reinforced composites. Descriptive statistics of the experimental data including modes of failure, and development of theory based on the data are detailed in Chapter 5.

CHAPTER 5

EXPERIMENTAL RESULTS AND DISCUSSION

5.1 INTRODUCTION

In this chapter, a detailed analysis of experimental data is presented. As described earlier, specimens were subjected to tension test as per ASTM D3039, standards. In addition, a summary of stress-strain behavior and load-deflection behavior is presented and tabulated. Test results of coupon laminate and sandwich panel are shown in subsequent sections.

5.2 SPECIMEN LEVEL

Composite laminates of different glass fiber mat orientation were tested for their mechanical properties. Sample specimens with desired dimensions were prepared for testing under tension. Stress-strain curves are then plotted to obtain tensile stress and tensile modulus. Similarly, load deflection behavior was plotted for the tension response.

5.3 TENSION TEST

Composites specimens prepared for this study differed in their fiber and fiber orientation method. Objective of this test was to compare the effect of various parameters on tensile properties of composite materials manufactured by hand lay up (HLU) methods. Stress-strain behavior is shown for each set of specimen. Tensile stress and tensile modulus are then calculated and tabulated for each of test.

5.4 DETAILS OF LAMINATES

Fiber architectures considered for this study are:

Type A: 3-D orientation of chopped strand glass fiber mat consisting of 5 horizontal layers and one vertical 1 layer with 90^0 positions of horizontal layers.

5HCSM-1VCSM (Longitudinal)

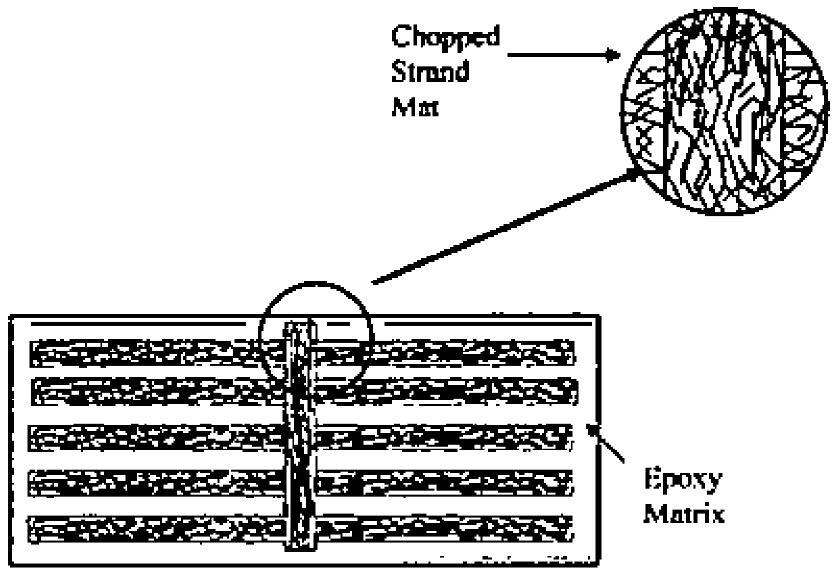


Figure 5.1 Type A 3-D, 5HCSM-1VCSM (Longitudinal)

Type B: 5 horizontal layers of chopped strand glass fiber mat. This is designed as "B" 5CSM (Longitudinal)

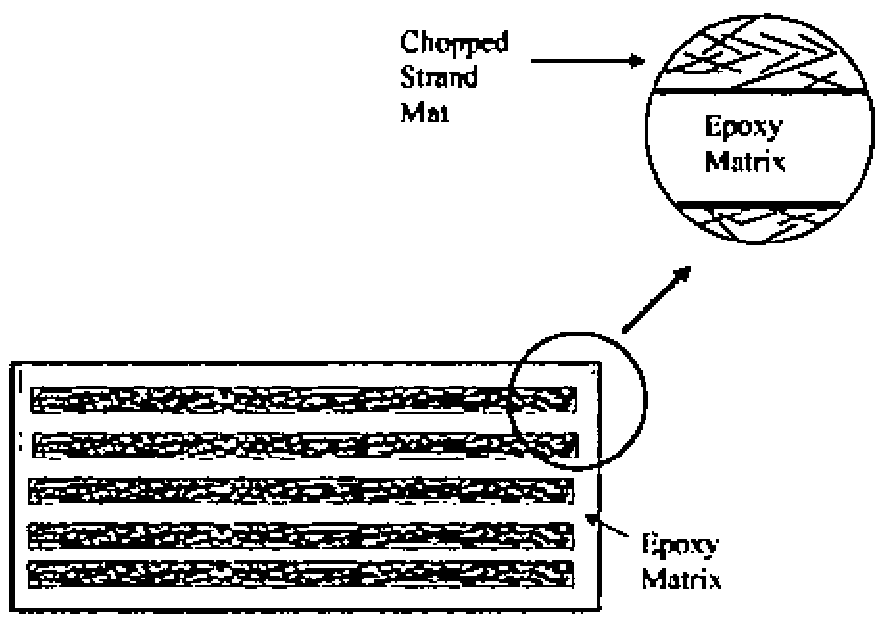


Figure 5.2 Type B (TLB), 5HCSM (Longitudinal)

Type C: 5 horizontal layers of chopped strand glass fiber mat consisting of 1 roving mats. CSM/CSM/RM/CSM/CSM (Longitudinal)

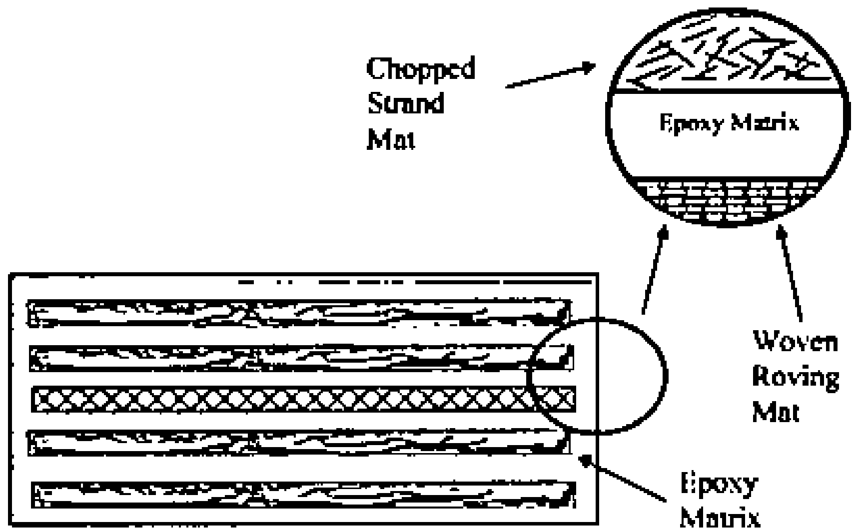


Figure 5.3 Type C (TLC), 4HCSM-1HRM (Longitudinal)

Type D: 5 horizontal layers of chopped strand glass fiber mat consisting of 2 roving mats, CSM/RM/CSM/RM/CSM (Longitudinal)

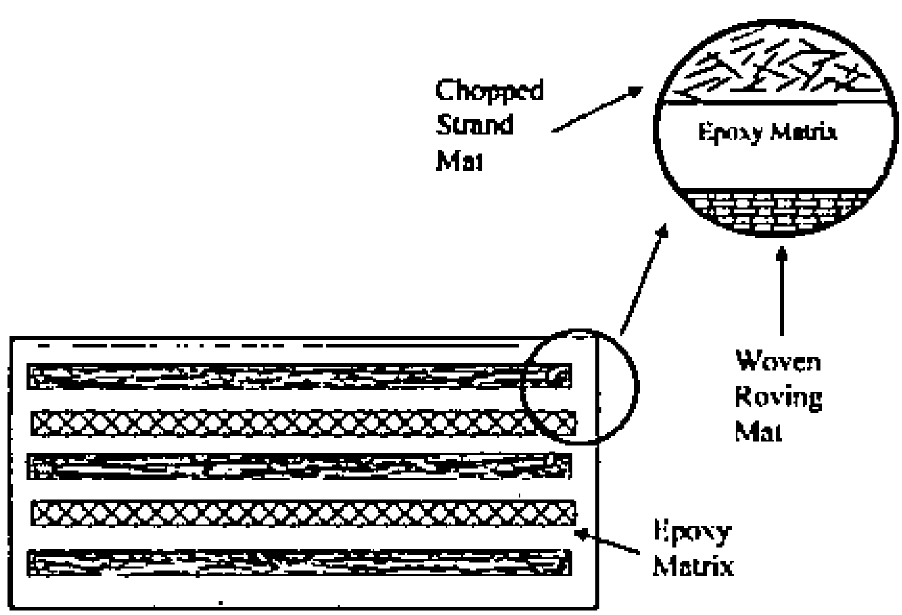


Figure 5.4 Type D (TLD), 3HCSM-2HRM (Longitudinal)

Type R: Composite sample of cured resin/hardener mix for base mechanical properties.

All the sample composites were fabricated with epoxy resin using hand lay up molding process.

5.5 TENSION TEST DATA ANALYSIS

Over 40 specimens with different fiber architectures and thicknesses were tested in longitudinal direction. Samples are labeled according to the type of fabric, specimen number, direction of loading, and thickness. For instance, sample labeled as TLA1 implies, Tension test of composite specimens in longitudinal direction (in terms of sample preparation), sample number being 1.The test was done at room temperature.

Zero degree unidirectional laminates of 5mm thick were fabricated. Stress-strain curve of each unidirectional composite coupon specimen under tension in longitudinal direction is shown in Figure and tabular form. The stress-strain curve for each type of sample composite is in almost same manner. It is seen that, the stress-strain curve is separated into two portions such as elastic region and plastic region. The mechanical characteristics such as strength, modulus of elasticity, plasticity, stress-strain relationships of each type of sample are described both in tabular and in graphical form below.

5.5.1 Properties in Elastic Region

Table 5.1 Tension test results for glass/epoxy composites

Sample Type	Sample ID	Avg. Width (m) ($\times10^{-3}$)	Avg. Thickness (m) ($\times10^{-3}$)	Area (m^2) ($\times10^{-6}$)	Yield point Load P (kN)	Yield Stress σ (MPa)	Modulus E (GPa)	Yield Strain $\mu\varepsilon$	Fiber Cont. (%)
R	TLR	23.46	3.87	90.72	1.429	15.752	2.594	6.067	
B	TLB	24.20	5.62	136.0	2.909	21.388	3.864	5.535	21.081
C	TLC	23.88	5.10	122.0	2.615	21.436	3.676	5.833	19.862
D	TLD	23.70	4.25	101.0	2.376	23.520	4.768	4.933	19.975
A	TLA	23.88	4.57	109.0	2.532	23.227	3.168	7.333	22.229

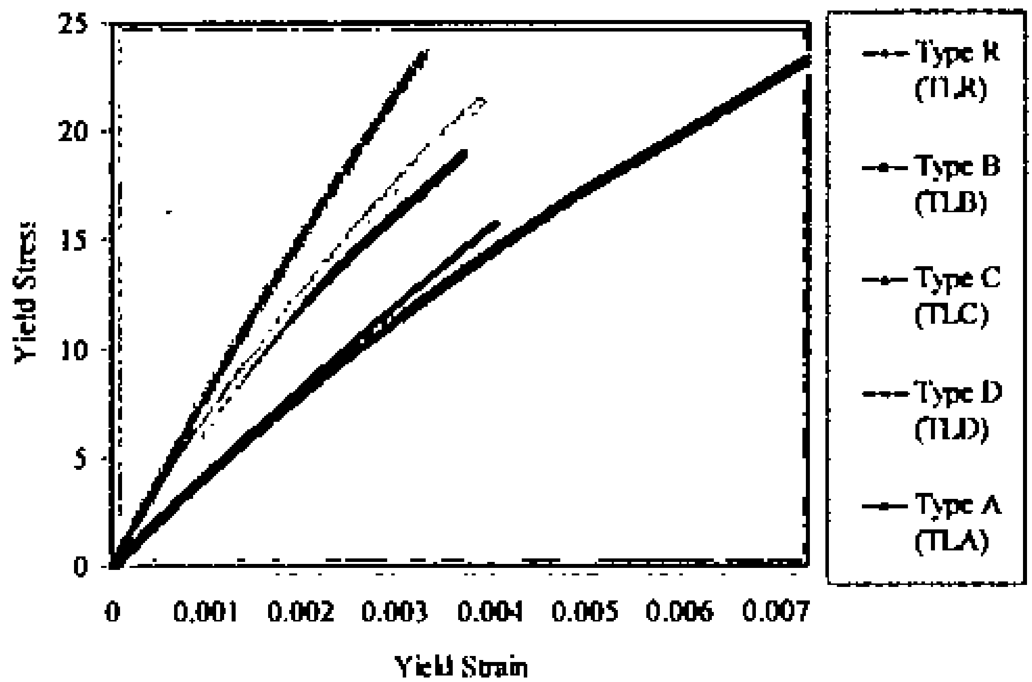


Figure 5.5 Stress-Strain of different sample composite in Elastic region

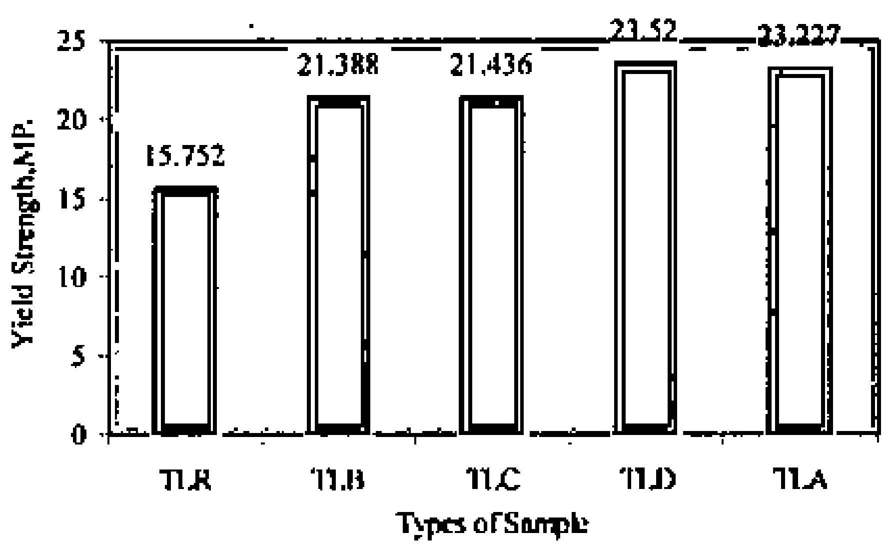


Figure 5.6 Yield Stress of different types Sample

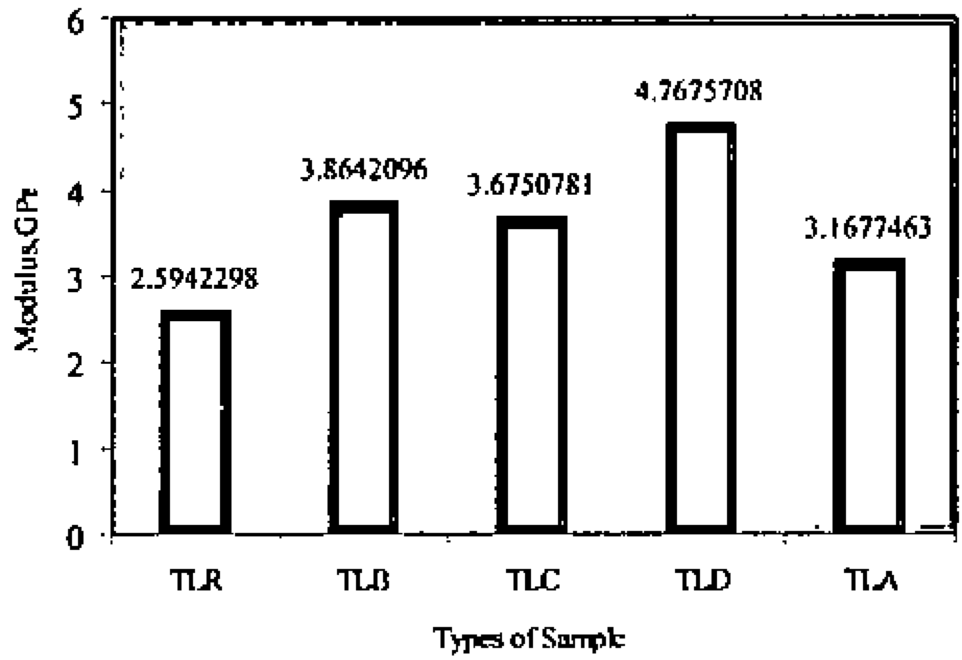


Figure 5.7 Modulus of Elasticity of different types Sample

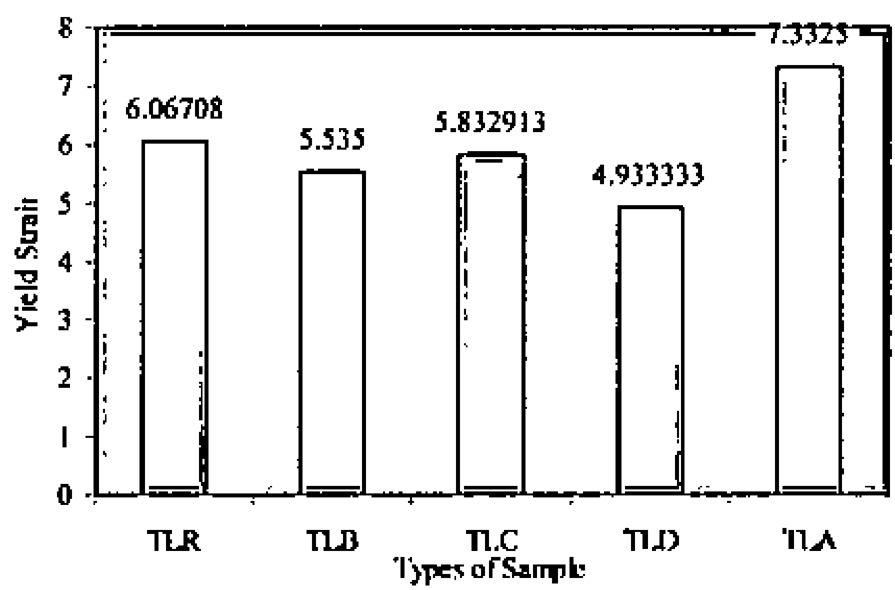


Figure 5.8 Yield Strain of different types Sample in Elastic region

It is revealed from table 5.1 and figure 5.5, that the stress-strain of all types of composite samples, except type A (TLA), is almost linear up to the yield Point. Type A (TLA) provided slightly non-linear viscoelastic form. Type A composite sample (TLA) took larger energy to initiate crack and hence had greater yield strain as appeared in figure 5.8. This was happened due to the larger shear stress and discontinuous architecture of fiber mats. The shear stress of type A (TLA) under tensile loading distributed among the horizontal layers of CSM and this shear stress was then transferred to the vertical layer of CSM. The type D (TLD), on the other hand, had lower yielding strain as appeared in figure 5.8.In case of type D (TLD), crack initiated in matrix earlier than type A (TLA). Though there was a combined reinforcement of continuous RM along with CSM, the earlier yield point of type D (TLD) occurred due to poor wet ability of RM and non-homogeneous bonding of fiber matrix interfaces. The woven RM was also not so porous as CSM. But the yield stress and the modulus of type A (TLA) composite sample is lower than type D (TLD) as found in figure 5.6 and 5.7.

5.5.2 Properties in Plastic Region

Table 5.2. Tension test results for glass/epoxy composites

Type	Avg. Width (m) $(\times 10^{-3})$	Avg. Thickness (m) $(\times 10^{-3})$	Area (m^2) $(\times 10^{-6})$	Max. Load P (kN)	Elongation (m) $(\times 10^{-3})$	Max. Stress σ (MPa)	Modulus E_{ut} (GPa)	Strain At Max. Load mε	Fiber Cont. (%)
R	23.46	3.87	90.72	4.917	4.53	54.20	1.794	30.20	
B	24.20	5.62	136.0	10.595	4.12	77.90	2.787	27.47	21.08
C	23.88	5.10	122.0	10.085	4.35	82.67	2.854	28.97	19.86
D	23.70	4.25	101.0	8.55	3.67	84.66	3.465	24.43	19.98
A	23.88	4.57	109.0	10.72	5.49	98.35	2.689	36.58	22.23

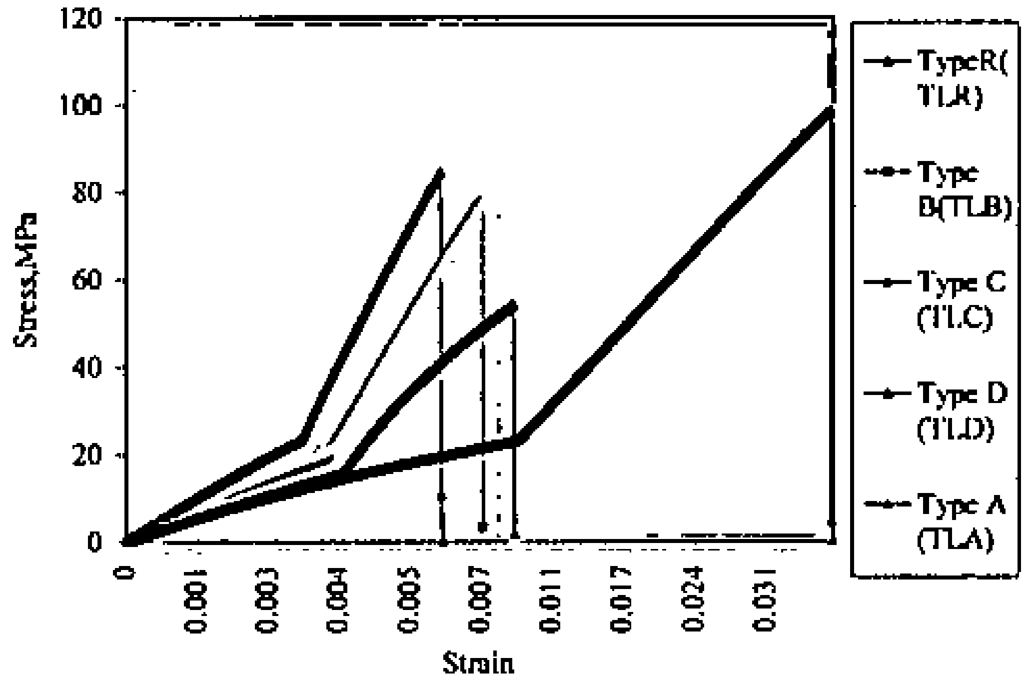


Figure 5.9 Stress-Strain properties of different types Sample in Plastic region

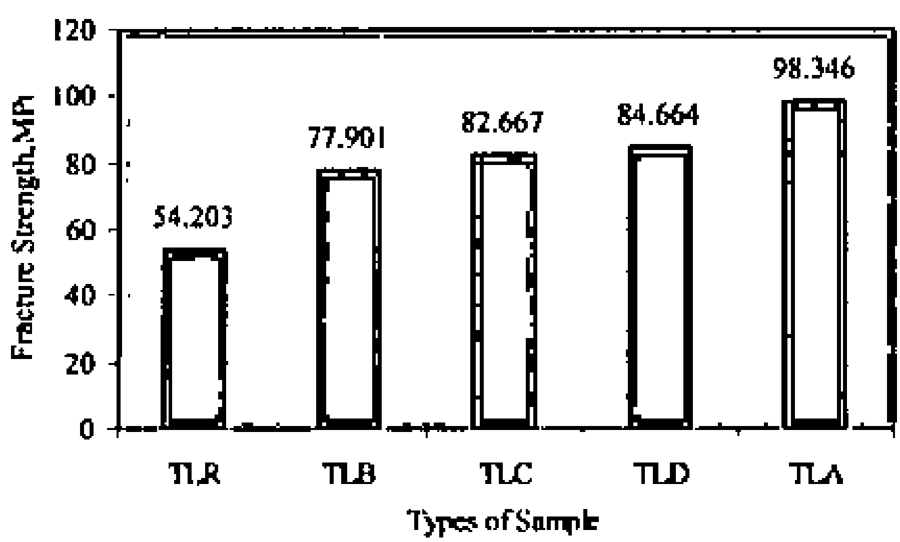


Figure 5.10 Fracture Strength of different types Samples

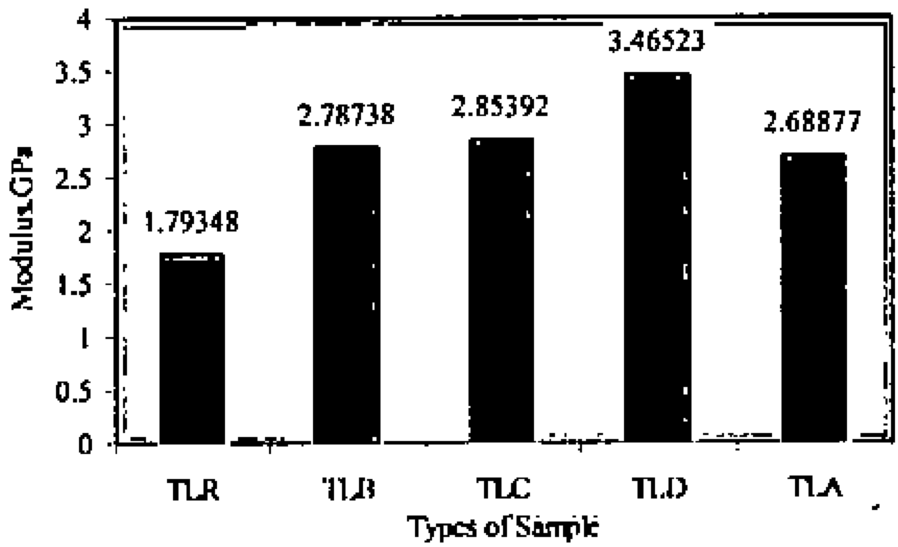


Figure 5.11 Modulus in plastic region of different types Sample

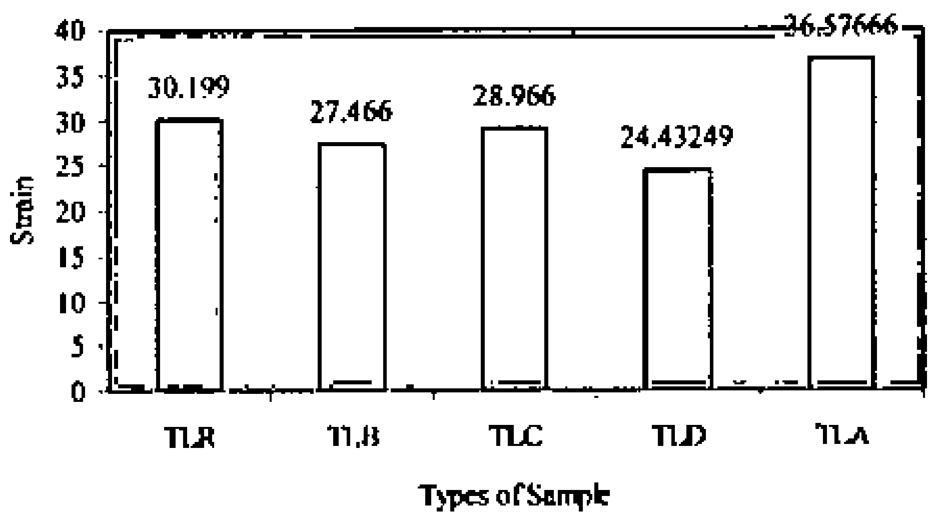


Figure 5.12 Fracture Strain of different types Sample in Plastic region

Since the stress of all composites increased proportionally with the strain up to the fracture point due to the contribution of the fiber strength and appeared as linear manner, the slope of the stress-strain was referred as plastic modulus in the plastic region. The ultimate strength of the composites was also referred as fracture strength. This was because that the composites were failed suddenly by reaching fracture point. As can be seen from the Figure 5.9, the stress-strain is also linear almost to the fracture load. From table 5.2, it is found that the type A (TLA) had the maximum stress (fracture) beyond the yield point. After the yield point, type A (TLA), like other composites showed brittleness in nature, as can be appeared in figure 5.9. But those composite samples were fractured at different level of elongation and strain and TLA has higher fracture strain which are revealed in figure 5.12.The modulus of type A (TLA) is lower than type D (TLD) due to higher fracture strain that can be seen in figure 5.12.

5.5.3 Energy absorption calculation

Table 5.3. Crack initiating energy (Elastic region)

Types of sample	Sample ID	Crack initiating load, (kN)	Elongation (x 10^{-3}) (m)	Absorbed energy (J)	Fiber content (%)
R	TLR	1.428987	0.91	0.650	
B	TLB	2.908828	0.83	1.207	21.081
C	TLC	2.615235	0.875	1.144	19.862
D	TLD	2.375512	0.74	0.879	19.975
A	TLA	2.531780	1.1	1.392	22.229

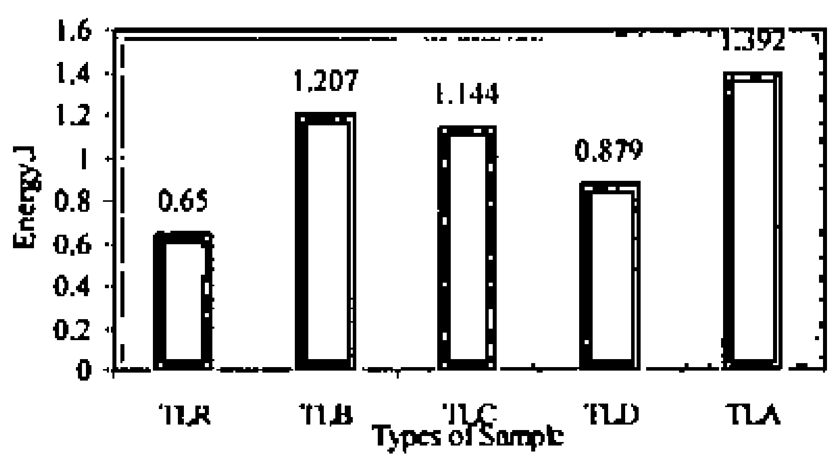


Figure 5.13 Crack initiating energy absorption of different types of sample.

Table 5.4. Fracture energy (Plastic region)

Types of sample	Crack initiating load. (kN)	Fracture load. (kN)	Elongation ($\times 10^{-3}$) (m)	Absorbed fracture energy (J)	Fiber content (%)
R	1.42899	4.917	3.619788	11.48557	
B	2.90883	10.5946	3.28965	22.21078	21.081
C	2.61524	10.085	3.469963	22.03468	19.862
D	2.37551	8.55	2.92487	15.97785	19.975
A	2.53178	10.7197	4.386625	29.06464	22.229

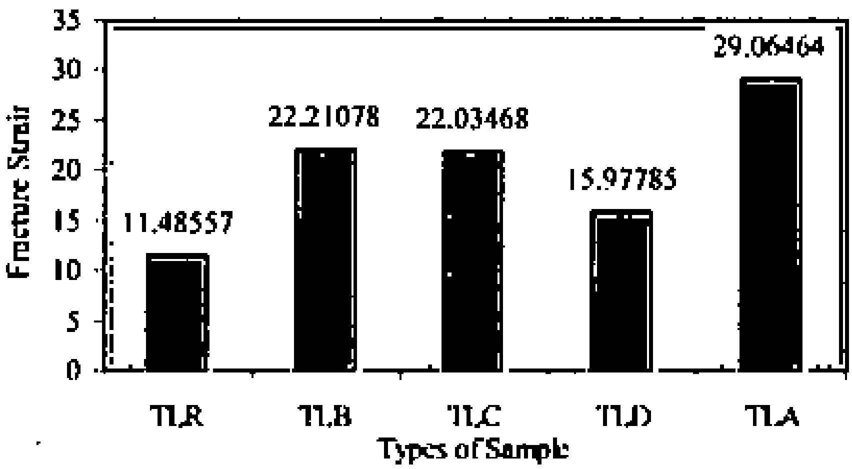


Figure 5.14 Fracture energy absorption of different types of sample.

Table 5.5. Total energy absorption of different types of Sample

Types	Crack initiating load. (kN)	Fracture load. (kN)	Elongation ($\times 10^{-3}$) (m)	Absorbed energy (Elastic region) (J)	Absorbed fracture energy (Plastic region (J)	Total energy absorption (J)	Fiber cont (%)
R	1.429	4.917	4.53	0.65	11.486	12.136	
B	2.909	10.595	4.12	1.207	22.211	23.418	21.081
C	2.615	10.085	4.345	1.144	22.0345	23.179	19.862
D	2.376	8.55	3.665	0.879	15.978	16.857	19.975
A	2.532	10.72	5.487	1.392	29.065	30.457	22.229

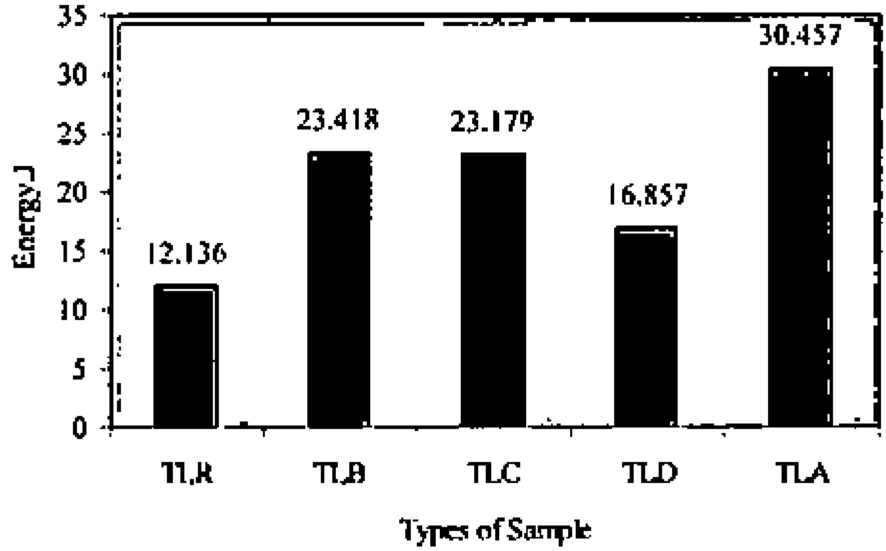


Figure 5.15 Total energy absorption of different types of sample

Initialization of crack either in fiber or matrix depends on energy absorption that can be calculated from the yield load and the respective elongation. Type A (TLA) composite sample absorbed higher energy to initiate crack as it is appeared in table 5.3 and figure 5.13. Type B (TLB) and type C (TLC) absorbed nearly same amount of energy in this regard.

The fracture energy and the total energy absorbed by each types of composite sample provided the similar trend of result of elastic region and TLA composite sample herein absorbed higher energy as it is seen in table 5.4, 5.5 and figure 5.14 to 5.15.

5.5.4 Points where change of slope occurred

The curve is a bilinear curve (Figure 5.5 and Figure 5.9), which implies that there is only one location where the change of slope mainly occurs. Herein, point where change of slope occurred is defined as the yield point. Beyond the yield point, the elongation and the strain rate of type A (TLA) decrease with respect to the loads and stresses. The first change of slope location point in the slope is hypothesized to be due to matrix micro cracking of layers and the specimen still remained intact with matrix micro cracks until sudden fracture of the samples into two parts. Since all of the composites failed at the pick point of the load, the ultimate strength of the composite was referred as fracture strength. After the failure, the load suddenly dropped. The first modulus was obtained up to the point where first change of slope occurred was referred as elastic modulus. The plastic modulus was obtained at the fracture point.

5.6 CORRELATIVE EFFECT OF STRENGTH, STRAIN AND MODULUS

A load bearing device or component must not distort so much under the action of the service stresses that its functions did not impair, nor must it fail by rupture, through local yielding may be tolerable. Therefore, high modulus and high strength, with ductility, is the desired contribution of attributes. But, in case of polymer matrix composite, it is difficult to provide all of the properties in the desired level.

The properties such as stress, strain and modulus provide relationships among each other. As the modulus is defined by the ratio of stress and strain, the modulus of the materials directly depends on the stress and strain of the materials. In this thesis work, a combined effect of stress and strain was found. These correlative effects are described with the help of graphical presentation.

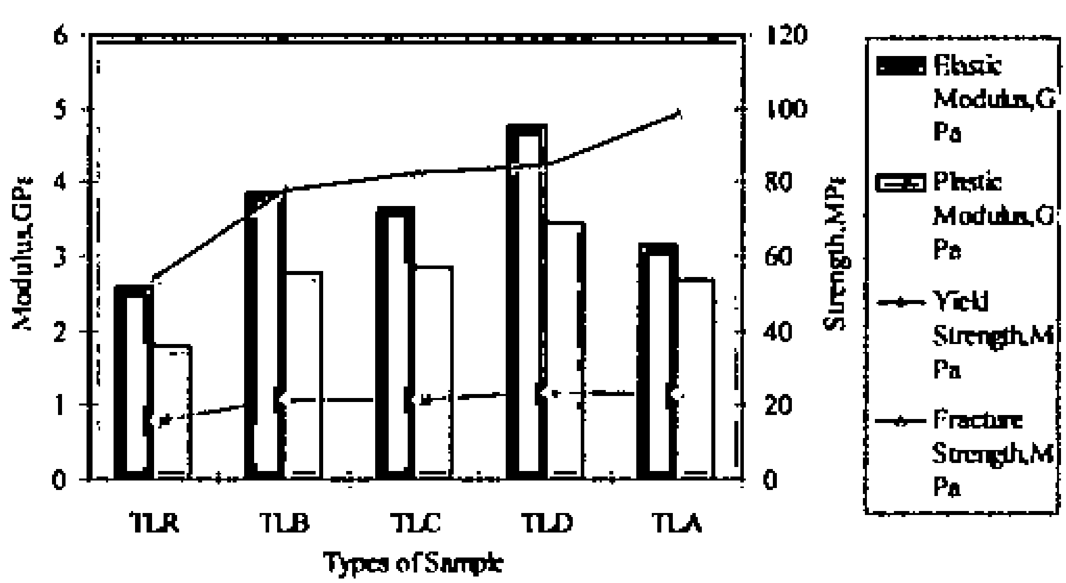


Figure 5.16 Modulus-Strength relationships of different types of sample

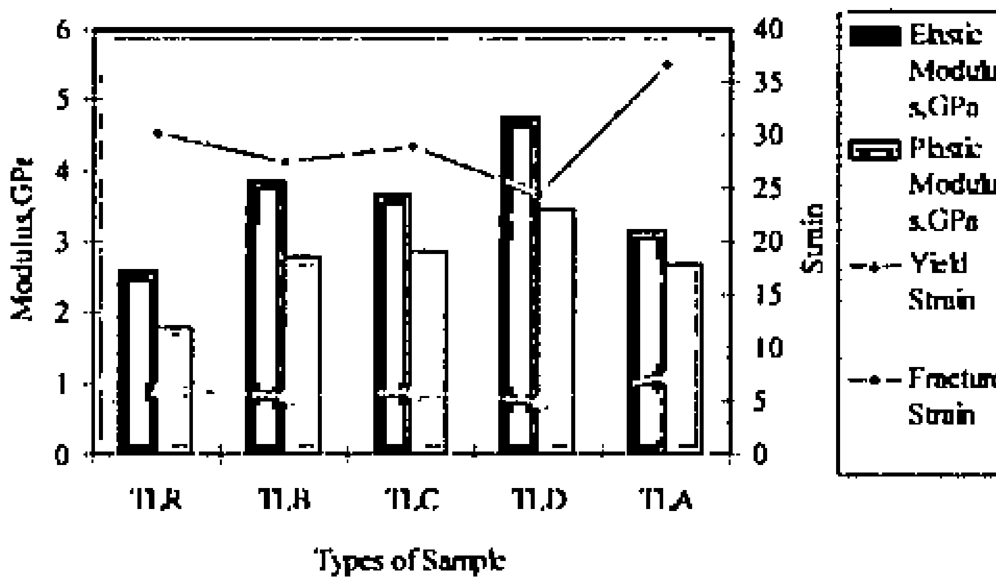


Figure 5.17 Modulus-Strain relationships of different types of sample

As seen in the figure 5.16 and 5.17, the modulus of each type of composite is higher in the elastic region than plastic region. This is because of lower strain rate with respect to stress in elastic region, which can be referred as stiffness. The modulus of sample composite TLD is higher due to higher stress and lower strain whereas the modulus of sample composite TLA is lower than TLD due to higher strain. The yield strength of both TLA and TLD is approximately same. But the fracture strength of TLA is higher than any other types and it is gradually increased with the strain. It is evident that TLA provided ductile nature in both regions. This is due to the vertical reinforcement of CSM. It is therefore found that the ductility of the GFR composite can be improved by the addition of vertical reinforcement of glass fiber mat in the fiber architecture.

5.7 EFFECT OF ENERGY ABSORPTION ON MODULUS

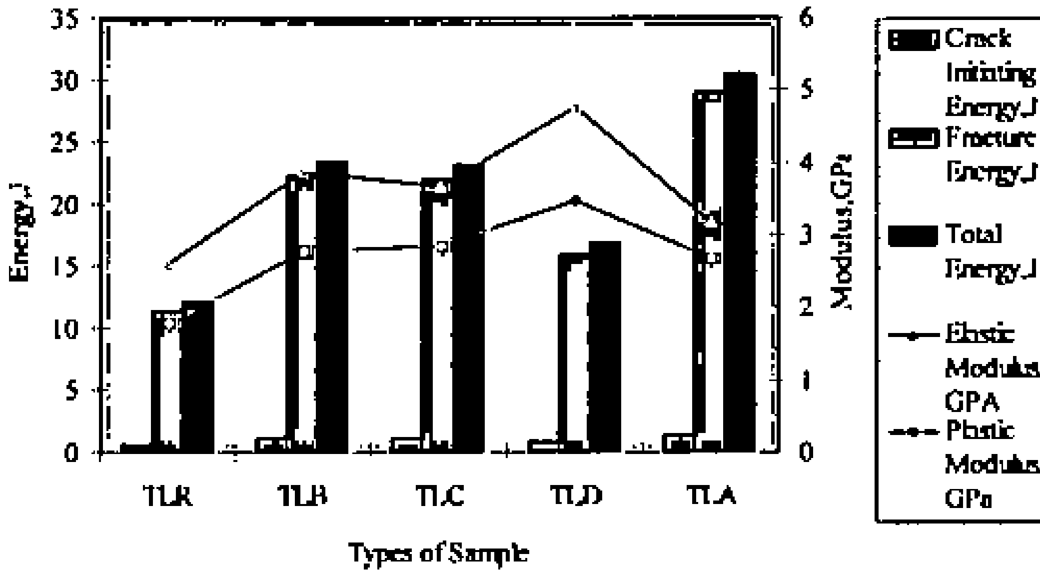


Figure 5.18 Energy-modulus relationships of different types of sample

As the stress of type A (TLA) was increased faster than stress beyond the yield point, the absorption of energy is increased with the increasing of area under stress-strain, which is revealed in figure 5.18; that is why, the modulus of type A (TLA) is not increased. In case of type D (TLD), as the stress-strain ratio is higher due to lower strain rate, the area under stress-strain curve is smaller than that of A (TLA) and hence D (TLD), absorbed lower energy than others. It is therefore found that the modulus of the composite (thermoset) is retarded with the increasing of absorption of energy.

5.8 EFFECT OF ENERGY ABSORPTION ON STRENGTH

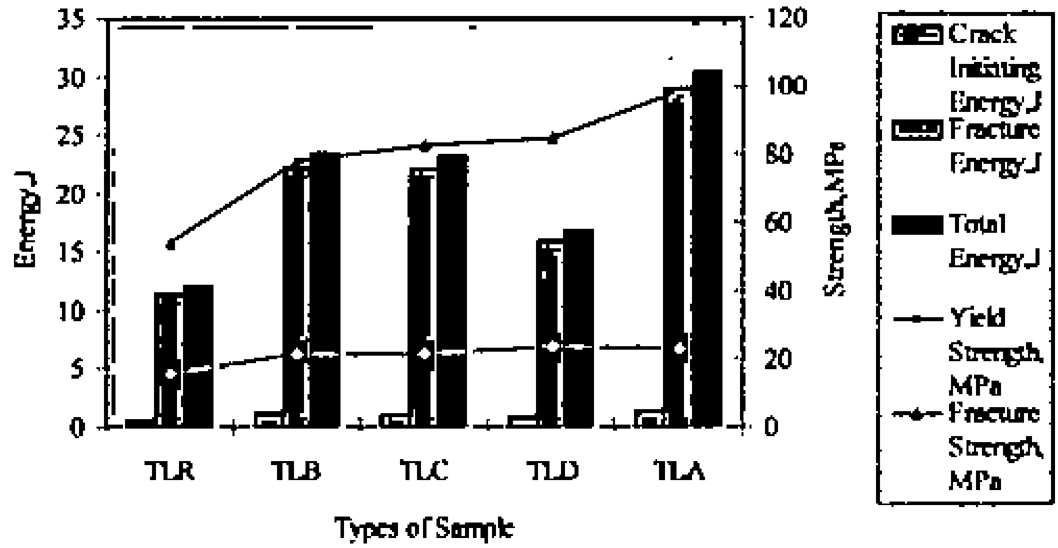


Figure 5.19 Energy-Strength relationships of different types of sample

Since the absorption of energy is calculated from the area under stress-strain curve, the amount of energy absorbed for strain is directly proportional to the stress and the strain causes due to loading. As the strain of type A (TLA) is increased with the increasing of stress, the absorbed energy of A (TLA), in either region, is increased higher than other types of composite, which can be appeared in figure 5.19.In case of type D (TLD), the energy absorption is lower due to lower strain. The absorption of energy is also referred as the toughness of the composite material.

5.9 EFFECT OF ENERGY ABSORPTION ON STRAIN

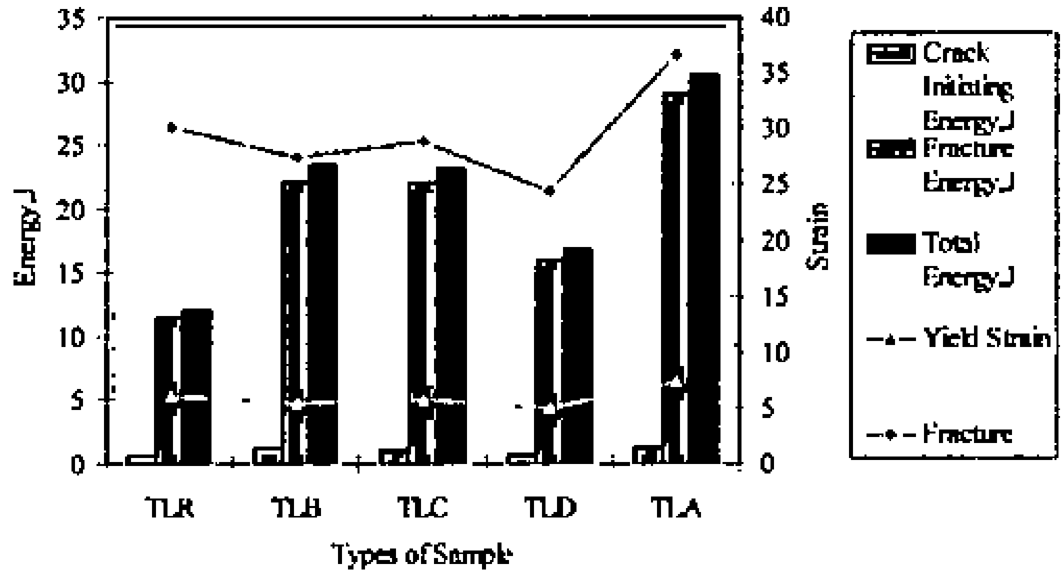


Figure 5.20 Energy-Strain relationships of different types of Sample

The strain of the composite affects both the modulus and absorption of energy. The absorption of energy to resist fracture under certain load is proportional to the strain, as revealed in the figure 5.20

5.10 EFFECT OF ORIENTATION

Based on the results, it is evident that the direction of the orientation and types of glass fiber mat affected the tensile properties of the GFR composite significantly. The main focus of this project was to evaluate the effects of 3D orientation of glass fiber mat on mechanical properties of composite. It was observed that vertical orientation of CSM increase the tensile strength and strain energy while decreasing of modulus. The modulus of GFR composite can be increased by addition of roving mat.

5.10.1 Strength

From the experimental results of the sample composite, it was observed that the yield strength of type A, B, C and D was improved by 47.45%, 35.78%, 36.08% and 49.31% respectively over epoxy matrix and the fracture strength of type A, B, C and

D was also increased by 81.46%, 43.73%. 52.53% and 56.2% respectively over epoxy matrix.

5.10.2 Strain

The stain of type B, C and D was decreased by 8.77%. 3.86%, 18.69% and 9.04%, 4.07%, 19.11% in both elastic region and plastic region respectively whereas the strain of type A was increased by 20.87% and 21.13% in both elastic region and plastic region respectively over epoxy matrix.

5.10.3 Modulus

The modulus of type A, B, C and D composites was increased by 22.113%, 48.96%, 41.71%, 83.81% and 49.89%, 55.35%, 59.09%, 93.14% over epoxy matrix both in elastic region and in plastic region respectively.

5.10.4 Energy Absorption

The type A, B, C and D composites absorbed 114.15%, 85.69%, 76%, 35.23% and 153.05%, 93.37%, 91.84%, 39.11% higher energy than epoxy matrix both in elastic region and in plastic region respectively. The total energy absorption by type A, B, C and D composites was 150.96%. 92.96%, 90.99%, and 38.90% higher than epoxy matrix respectively.

5.11 FIBER VOLUME FRACTIONS

Tensile properties such as strength of a composite are typically in direct proportion with fiber content. In this project, the volume fraction of type A, B. C, D approximately 22.229%, 21.081%, 19.862%, and 19.975% were measured respectively. The areal density of CSM is higher than RM and it was measured experimentally in laboratory for each types of mat. Modification of the manufacturing technique increases the fiber volume. If the fiber content is increased, the tensile strength will increase significantly.

CHAPTER 6

CONCLUSIONS

In this thesis, mechanical properties of chopped fiber reinforced composite structures with 3D orientation of fiber mats. were determined and compared with other types of orientation of glass fiber mats. The orientation of fiber (3D CSM) studied in this thesis for elastic modulus. maximum stresses, and strain at maximum stress provide a significant improvement in compare with other orientations and epoxy matrix. It can be concluded from the results that the vertical orientation of CSM in longitudinal direction along with horizontal layers improves the mechanical properties such as tensile strength, of the GFR composites. In this research work, it was experimentally found that ultimate strength (referred as fracture strength) of type A (TLA) was 81.46% higher than epoxy matrix whereas type B (TLB), C (TLC) and D (TLD) had 43.73%, 52.53% and 56.2% higher ultimate strength over epoxy matrix respectively. It was, therefore, predicted that the tensile strength would be increased with the increasing of number of orientation of vertical layers of CSM. Though the ductility of the composite materials is most desirable. it is complicated to achieve. In this thesis, it was observed that the use of vertical layer of CSM in composites provided larger area under stress-strain curve than other types of orientation.

The manufacturing process and design of die to mold the composites are also the vital factors, which affect the mechanical properties of the molded composites. The air voids formation affects the structural quality and properties of the composite materials. The 3D architecture of CSM was complicated and some factors such as air voids formation, chemical bonding appear due to poor reinforcement of fiber mats. The formation of voids and poor wet out of fiber mats depend upon the types of the fiber mats. Though woven mat of continuous glass fiber provides higher mechanical properties than chopped strand mat, the woven roving mat in this research provided lower strength and toughness due to poor wet out of mats and easy entrapping of air. The quality of epoxy resin and glass fiber mat also largely affects the properties of the molded composites. In this research work, epoxy resin and glass fiber mats (CSM and Woven Roving Mat) used which were available in local markets.

To produce the data in this thesis, tensile test based on ASTM standards for plastics and composite testing were carried out. To manufacture the specimens. an open hand lay up (HLU) process was used along with compression process. The molded composite plates were compressed on a flat aligned table using a heavy load (Approximately 100 kgs). The HLU process was chosen because it is an affordable method for manufacturing composite structures.

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APPENDIX A

3D SAMPLE PREPARATION

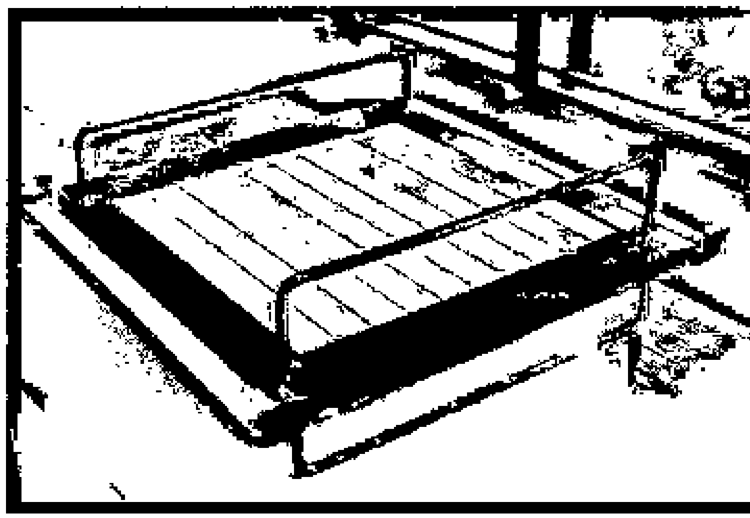

Figure A.1 Die design for 3D reinforcement (initial trial)

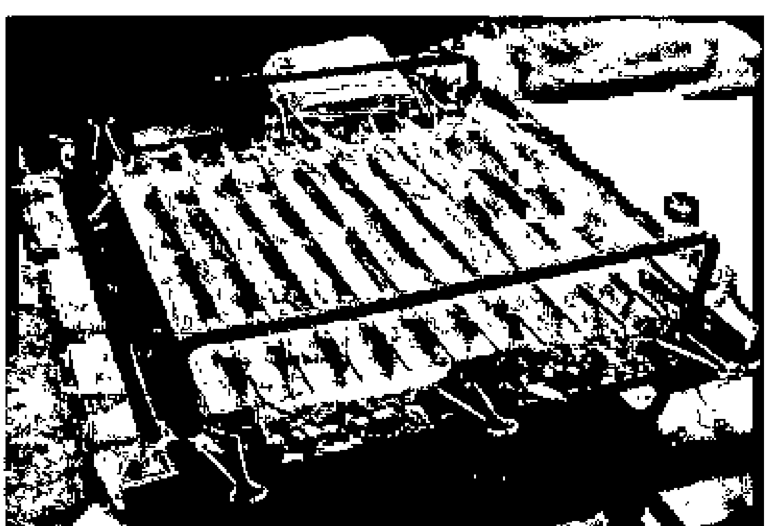

Figure A.2 3D reinforcement of CSM mat (vertical layers)(Initial trial)

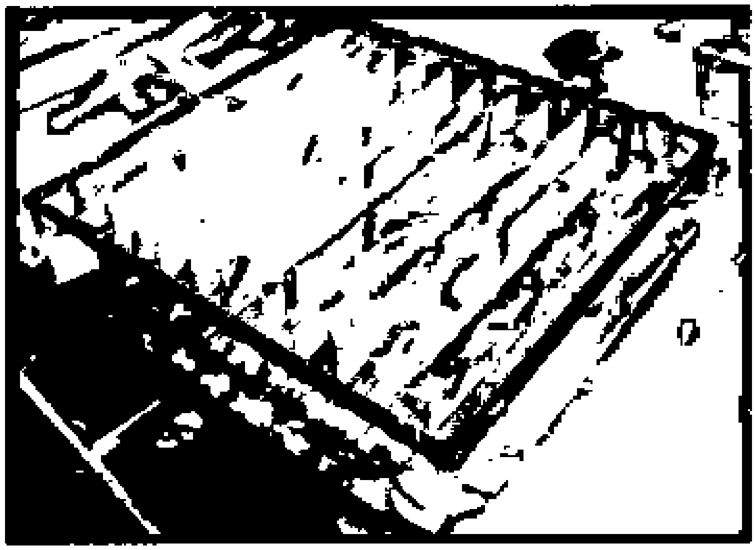

Figure A.3 3D reinforcement of CSM mat (vertical layers)(Second trial)

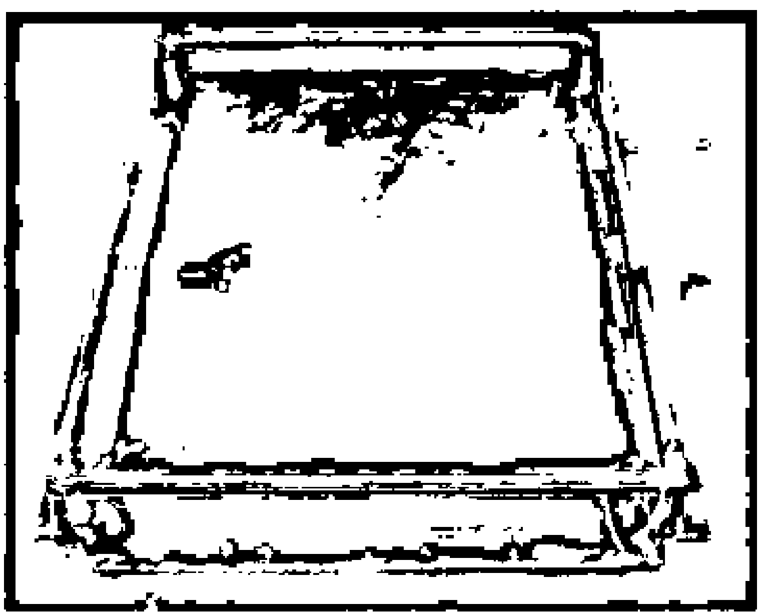

Figure A.4 Die design for 3D reinforcement (Final trial)

Figure A.5 Malate paper

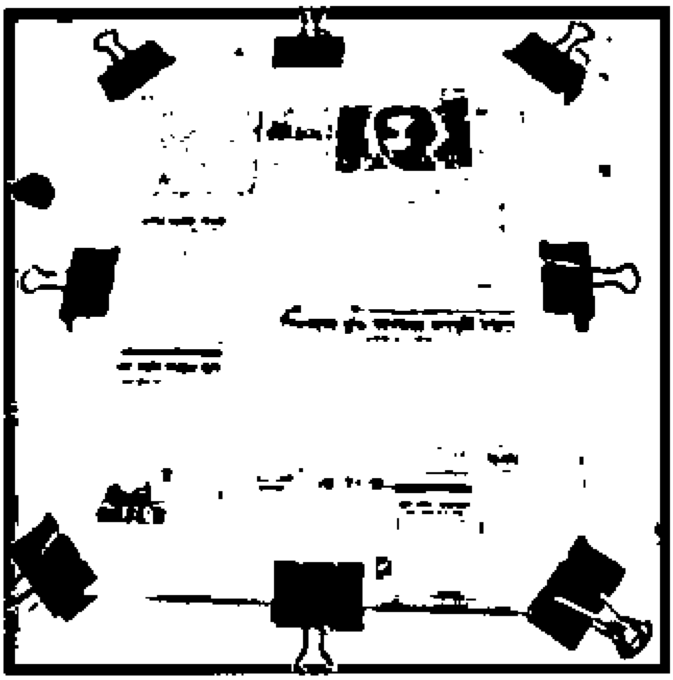

Figure A.6 Die decoration for 3D reinforcement (Final trial)

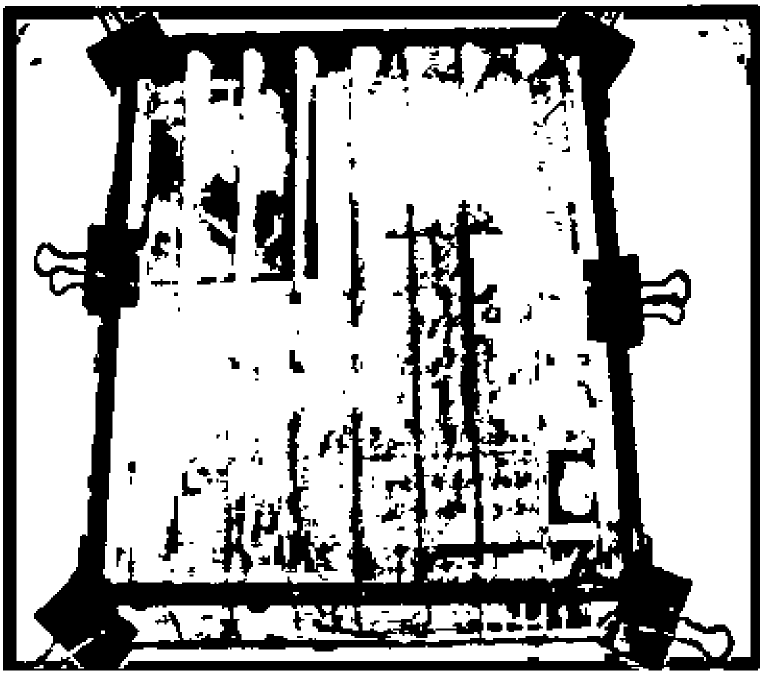

Figure A.7 3D reinforcement of CSM mat (vertical layers)(Final trial)

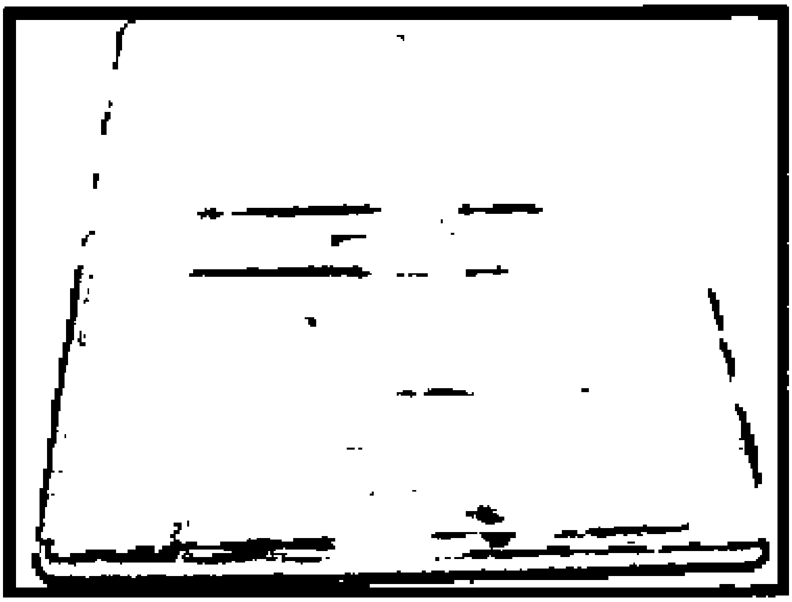

Figure A.8 Wooden board for load supporting (Final trial)

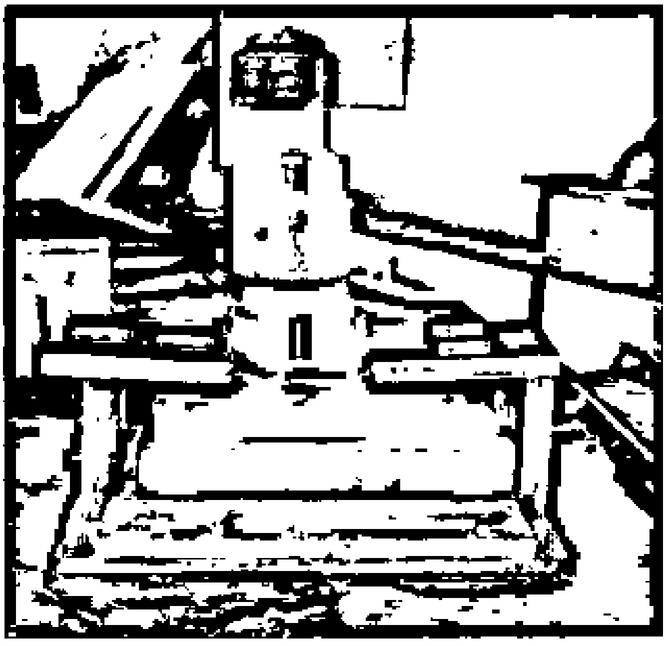

Figure A.9 Normal curing under pressure (Final trial)

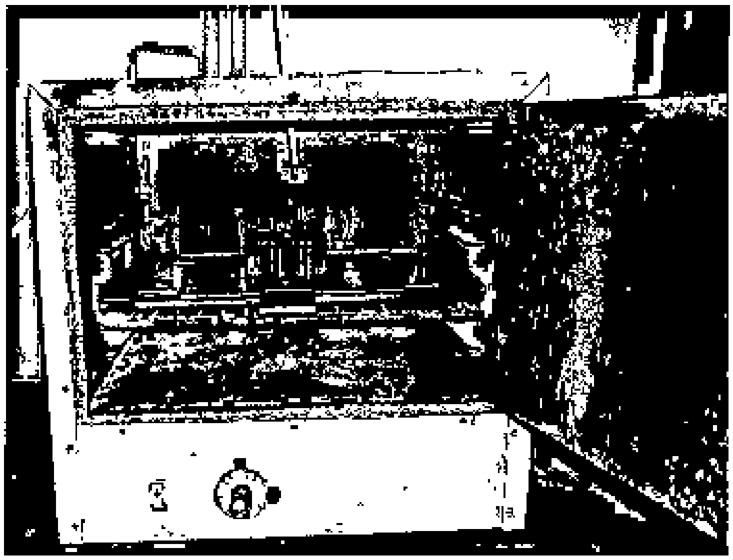

Figure A.10 Curing oven with thermometer.

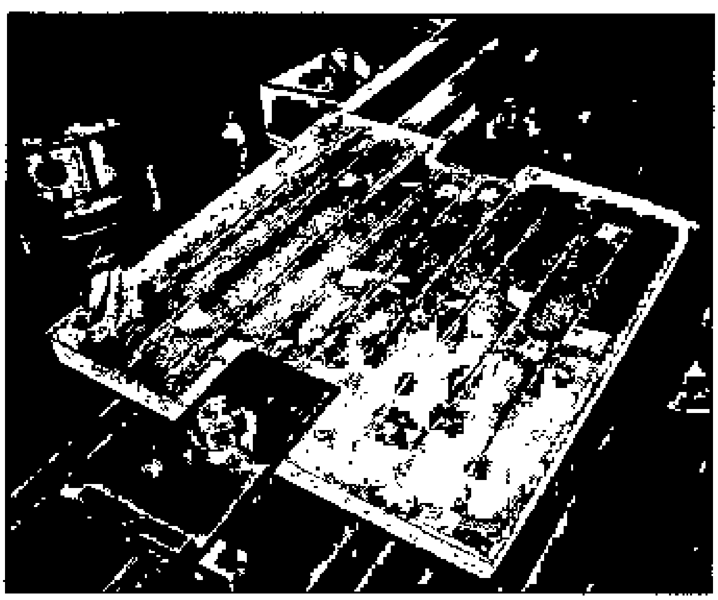

Figure A.11 Milling operation to remove extra vertical ribs of CSM

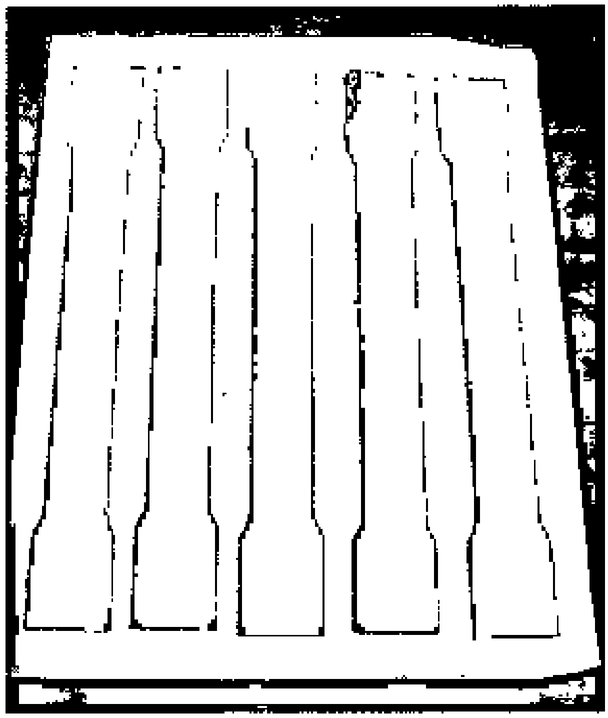

Figure A.12 Samples for tensile test

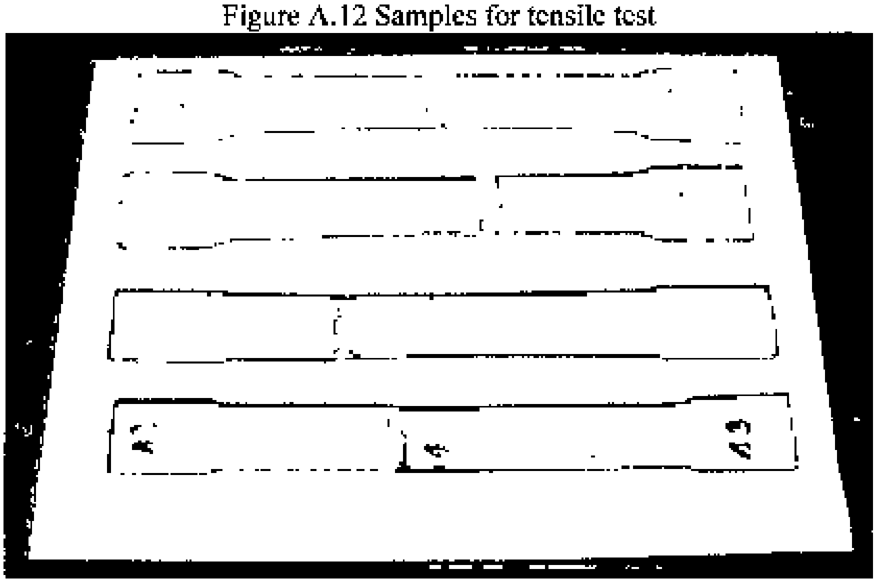

Figure A.13 Failure modes of samples under tension