KAUNAS UNIVERSITY OF TECHNOLOGY

MECHANICAL ENGINEERING AND DESIGN FACULTY

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STRUCTURAL ANALYSIS OF GLASSFIBER SANDWICH STRUCTURE

Final project for Master degree

Supervisor
Assoc. Prof. Dr. Kazimieras Petkevičius.

KAUNAS, 2015

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SANTRAUKA

Šiandien aviacijos pramonė visame pasaulyje labai didelį dėmesį sutelkia į tradicinių medžiagų pakeitimą pažangiomis medžiagomis, kurios yra naudingos dėl lengvumo, gerų mechaninių savybių, ekonomiškumo ir labai tinkamos gaminti sudėtingas norimos konfigūracijos konstrukcijas. Trisluoksnė stiklo pluoštu armuoto polimerinio kompozito su lengvu užpildu konstrukcija tampa vienomis iš svarbiausių pažangiųjų medžiagų, naudojamų daugelyje sričių, pavyzdžiui, orlaivių, laivų, statybinių konstrukcijų, kuriose didelis konstrukcijos stiprumas ir mažas svoris yra būtini, todėl yra pageidaujamos lengvos, didelio stiprio ir standumo savybės ir ekonomiškos medžiagos. Šie veiksniai motyvuoja analizuoti trisluoksnio stiklo pluoštu armuoto polimerinio kompozito su užpildu konstrukcijos mechanines savybes.

Magistrinio darbo tikslas yra rasti mechanines savybes ir ribines būsenas trisluoksnio stiklo pluoštu armuoto polimerinio kompozito su užpildu. Tikslas yra pasiektas pirmiausia eksperimentiškai nustatant laminato medžiagos ir užpildo mechanines savybes ir atliekant kompozito 3 taškų lenkimo eksperimentą. Taip pat buvo atlikti analitiniai skaičiavimai ir skaitinis modeliavimas ABAQUS baigtinių elementų analizės sistema.

Eksperimentinėje bandymo, medžiagų savybės stiklo pluoštu armuoto polimero facesheet ir puta yra gaunamas atliekant tempimo bandymą dėl facesheet, suspaudimo bandymą ir šlyties bandymą ant putų pagrindas. Taigi įgyvendinant gautus savybių analizės apskaičiavimo ir baigtinių elementų modeliavimo ABAQUS testavimui 3 punkte. Tai baigtinių elementų modelis ir analizės skaičiavimas yra palyginti su eksperimentiniais kreivę ir gauti gerą sutartį. Bandinys naudojamas analizės ilgio = 60mm, plotis 25mm, storis = = 8mm. laminato storis yra 1.5mm ir branduolys yra 5mm. tarp paramos atstumas 3 taškų lenkimo yra 40mm.

ŽODŽIAI: GFRP, baigtinių elementų analizė, Sparno, žala, stresas, kamienas, deformacijos.

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FACULTY OF MECHANICAL ENGINEERING AND DESIGN

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MASTER STUDIES FINAL PROJECT TASK ASSIGNMENT
Study programme MECHANICAL ENGINERING

The final project of Master studies to gain the master qualification degree, is research or applied type project, for completion and defense of which 30 credits are assigned. The final project of the student must demonstrate the deepened and enlarged knowledge acquired in the main studies, also gained skills to formulate and solve an actual problem having limited and (or) contradictory information, independently conduct scientific or applied analysis and properly interpret data. By completing and defending the final project Master studies student must demonstrate the creativity, ability to apply fundamental knowledge, understanding of social and commercial environment, Legal Acts and financial possibilities, show the information search skills, ability to carry out the qualified analysis, use numerical methods, applied software, common information technologies and correct language, ability to formulate proper conclusions.

1. Title of the Project

STRUCTURAL ANALYSIS OF GLASSFIBER SANDWICH STRUCTURE

2. Aim of the project

1. To conduct 3-point bending (flexure) test on glass fiber reinforced polymer sandwich structure.
2. To obtain the material properties of the composite by experimental testing of laminate and core material.
3. To calculate deflection and stress analytically using mechanics of material formulas.
4. To do the simulation using Abaqus and to find the mechanical behavior and failure of the composite and compare the results.

3. Structure of the project

1. Material Testing of Glass Fiber Reinforced Polymer Composite.
2. Experimental Analysis and Analytical Calculation of Glass Fiber Reinforced Composite.
3. Finite Element Modelling and Analysis using Abaqus.
4. Result Comparison and Discussion
5. Conclusion

4. Requirements and conditions

Composite specimen, reliable equipment for testing, analysis software Abaqus, Matlab for calculation and graphs

5. This task assignment is an integral part of the final project

6. Project submission deadline:

Given to the student
PARAMESWARAN SUBRAMANIYAN PARAMESWARAN.
Task Assignment received ______________________
(*Name, Surname of the Student*) (*Signature, date*)

Supervisor Assoc. Prof. Kazimieras Petkevičius. ______________________
(*Position, Name, Surname*) (*Signature, date*)

PARAMESWARAN PS. “STRUCTURAL ANALYSIS OF GLASSFIBER SANDWICH STRUCTURE”, MASTERS IN MECHANICAL final project / supervisor Assoc. Prof. Dr. Kazimieras Petkevičius; Kaunas University of Technology, MECHANICAL ENGINEERING AND DESIGN faculty, MECHANICAL ENGINEERING department. **Kaunas, 2015. 58 p.**

SUMMARY

Nowadays aeronautical industries all over the world focus on the advanced materials to replace the traditional materials, which has many advantages like lightweight, good material properties, cost efficient and can manufacture to desire and complex structures. Glass fiber reinforced polymer composite (GFRP) with core sandwich structure is becoming one of the important advanced material used in many fields like aircraft, ships and in civil fields, where the need of high structural strength and low weight is required, so there is an increase in demand for lightweight, high strength, stiffness properties and cost economical materials. The composite content in the aircraft has been increased, the main composites used are Carbon fiber, glass fiber, and aramid fibers. These factors motivate to analyze the mechanical behavior of Glass fiber reinforced polymer composite with foam core sandwich structure by conducting 3-point bending test (Flexure test). The aim of the master thesis is finding the mechanical properties and failure of Glass fiber reinforced polymer composite structure. The goal was implemented initially by experimental material testing of facesheet material and foam core material and conducting point bending test of composite experiments, analytically and by simulation in Abaqus by creating the appropriate model.

In the experimental test, material properties of GFRP facesheet and the foam core are obtained by conducting the tensile test on facesheet, compression test and shear test on foam core. Thereby implementing the experimentally obtained material properties to analytical calculation and finite element simulation. These finite element simulations and analytical calculations are compared with the experimental result curve and obtain good agreement. The specimen used for analysis is of length=60mm, width =25mm, thickness=8mm. The thickness of the laminate is 1.5mm and core is 5mm. The distance between the supports for 3 point bending is 40mm.

KEYWORDS: GFRP, Finite element analysis, Wing, damage, stress, strain, deformation.

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Introduction

Glass Fiber-reinforced polymer (GFRP), also Glass Fiber reinforced plastic, is a composite material made of a polymer matrix reinforced with fibers. The polymer is usually an epoxy, vinyl ester or polyester thermosetting plastic, and phenol formaldehyde resins are still in use. FRP plays a major role in the aerospace, automotive, marine, and construction industries. The Commercial material has glass or fibers in matrices based on thermosetting polymers, such as epoxy or polyester resins. Sometimes, thermoplastic polymers may be preferred, since they are moldable after initial production. Composite materials are important to the Aviation Industry because they provide structural strength comparable to metallic alloys, but at a lighter weight. This leads to improved fuel efficiency and performance from an aircraft.

Because of the properties like higher strength, lighter weight, higher performance, longer lasting, rehabilitating existing structures and extending their life, low maintenance, low thermal conductivity, corrosion resistance and low cost. It motivates to test advanced material of GFRP composite use in the wing. Thereby experiments to be done to define material properties of GFRP and to implementing the obtained properties for analytical calculation and finite element simulation in Abaqus for 3-point testing. These finite element model and analytical calculation have to be compared with experimental data. So that mechanical behavior of the composite can be defined.

TASKS

1) Conducting experimental analysis on GFRP wing.
2) Obtaining material properties.
3) Obtaining 3-point bending result from experiment and calculation.
4) To model the composite in Abaqus and to do Finite element analysis.
5) Presenting the obtained results from all the methods.
6), Conclusion.

1. Introduction to Composites

A composite material is the combination of two or more materials that results in better material properties than those of the individual components used alone. Unlike metallic alloys, each material retains its separate chemical, physical, and mechanical properties. The two constituents of the composite are a reinforcement and a matrix. The advantage of composite materials over traditional materials are their high strength, stiffness and low density. This is the reason for a weight reduction in the finished part [1]. The idea of FRP is the combination of the long continuous fibers and a polymeric resin. More specifically, high strength fibers (glass, carbon, aramid or ultra-thin steel wires) provide strength and stiffness while the resin (polyester, vinyl ester or epoxy) protects the fibers and guarantees the stress transfer between them. As a result, enhanced final properties are obtained with respect to those exhibited by the individual constituents [2].

Figure 1. Structure of Composite [3]

The fibers used in modern composites have higher strength and stiffness than the traditional bulk materials. Higher strengths of the glass fibers are due to processing that avoids the internal or surface flaws which normally weaken the glass, and the strength and stiffness of the polymeric aramid fiber are a consequence of the nearly perfect alignment of the molecular chains with the fiber axis. [4]

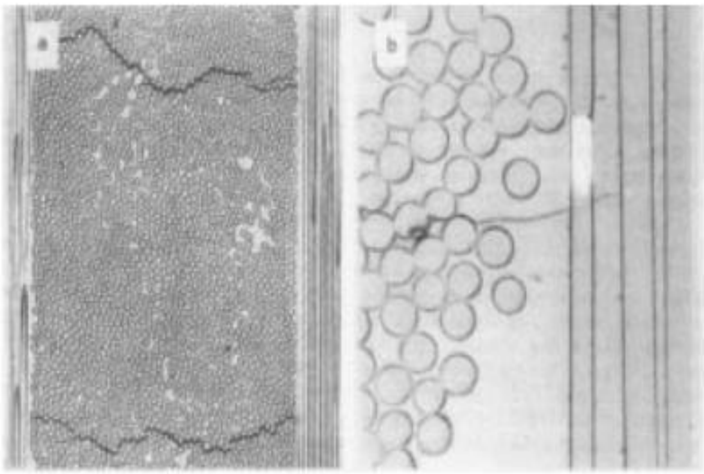

Figure.2 A cross-plied FRP laminate, showing non-uniform fiber packing [4]

The materials like glass, carbon and aramid are not used as fibers alone. They are impregnated by a matrix material that acts to transfer loads to the fibers, and also to protect the fibers from abrasion and environmental attack. The matrix decrease the properties to some extent, but to be so very high specific (weight-adjusted) properties are available from these materials. Metal and glass as matrix materials is readily available, but they are very expensive and restricted to R&D laboratories. Polymers are much more commonly used, the unsaturated styrene-hardened polyesters are used mostly on low to medium performance applications and the epoxy and sophisticated thermosets are used on higher performance application. Thermoplastic matrix composites are attractive materials, but it has many processing difficulties which is their principal limitation [4]. The composite wing used in this thesis is made up of glass fiber reinforced polymer (GFRP) laminate with polyurethane foam core structure.

1.1 Laminate

Laminate of Glass fiber reinforced polymer (GFRP) contains a glass fiber matrix with different fiber angles and orientations, which is bonded with resin of polyester, vinyl ester or epoxy. The tensile strength and bending strength of laminate depends on the fiber matrix and the shear strength of the laminate mainly depends on the type of resin used in the composite.

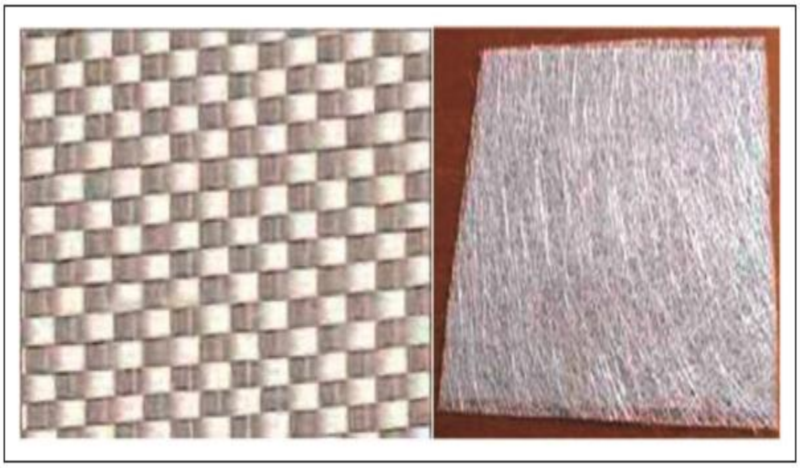

Figure.3. Woven and random glass fiber mat [5]

There are two types of Polymers used in the glass fiber reinforced polymer, which have their own unique properties,

1.1.1 Thermoplastic Polymers

Thermoplastics is the type of plastic polymer which soften when heated and become more fluid as heat is applied. The curing process is completely reversible as no chemical bonding takes place. This thermoplastics can to remolded and recycled without affecting the material's physical properties.

Commodity Thermoplastics

1. Polyethylene
2. Polypropylene
3. Polyester*

* Not same as thermosetting

Polyester

Engineering Thermoplastics

1. Polyamides [nylon]
2. Polysulphones
3. Polyphenylene sulphide
4. Polycarbonate

Aromatic Thermoplastics

1. Polyether sulphone

2. Polyether amide
3. Polyimide
4. Polyamide imide
5. Polyether ether ketone

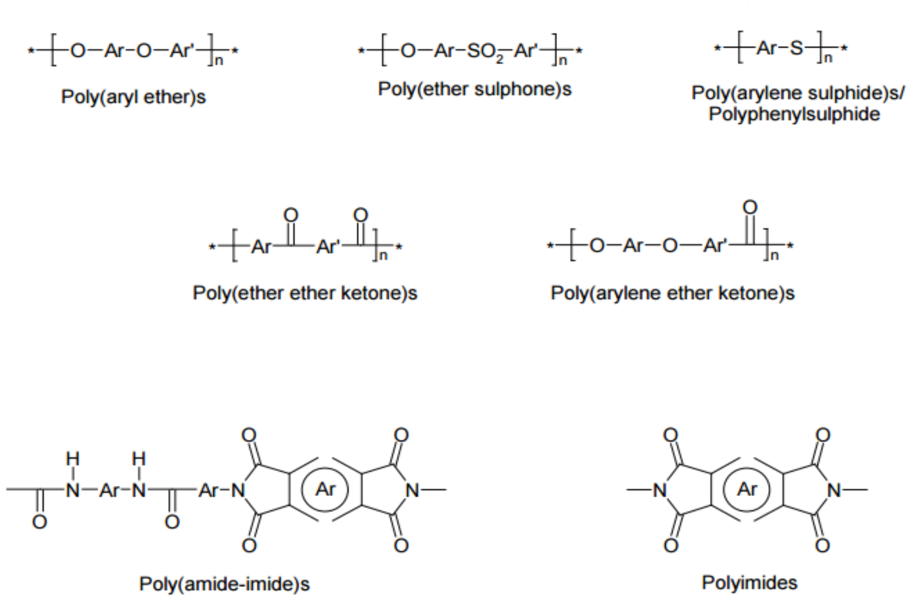

Figure.4 Thermoplastic Polymers [6]

1.1.2 Thermoset Polymer

Thermosetting polymers have the chain of cross links formed by covalent bonds. The materials are formed to the desired shape by molding. The polymer is heated or initiated by ultraviolet light to induce the chemical reactions to form the cross links between the chains. The three dimensional solid structures formed by molding are cannot be soften, melt or change by further heating. Thermoset plastics has significant mechanical properties as it enhances chemical resistance, heat resistance and structural integrity. Thermoset plastics are often used for sealed products due to their resistance to deformation.

Examples of thermosetting polymers are

1. Melamine resin - used in furniture.
2. Bakelite - used for saucepan handles and electric light fittings.

3. Epoxy resins - used in many glues.

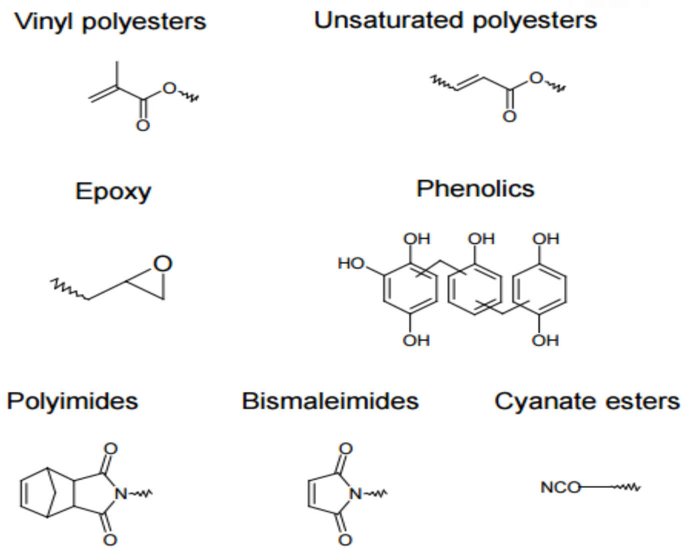

Figure.5 Thermoset Polymer [6]

1.2 Core

There are different types of core structure used in fiber reinforced polymer composites like Honeycomb and foam. The type of material used are mainly rely on the application and required property.

1.2.1 Honeycomb

Honeycomb is a series of cells, nested together to form panels similar in appearance to the cross-sectional slice of a beehive. Honeycomb is 90 to 99 percent open space. Honeycomb is fire retardant, flexible, lightweight, and has good impact resistance. It offers the best strength to weight ratio of the core materials. Honeycomb is used primarily for structural applications in the aerospace industry.[13]

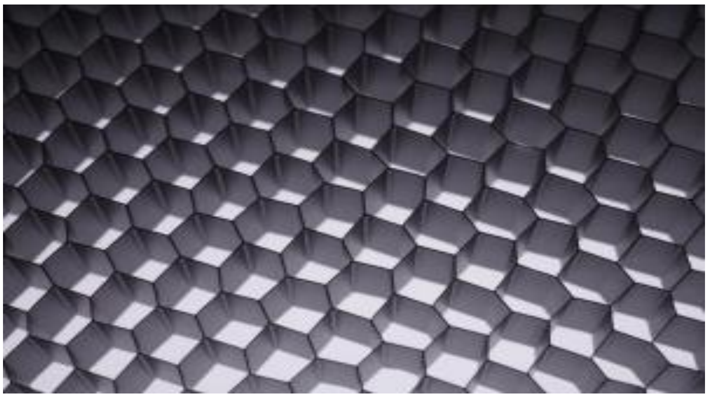

Figure.6 Honeycomb [12]

1.2.2 Vinyl Sheet Foam

Vinyl sheet foam is one of the most versatile core materials used engineering applications. It is a rigid, closed cell material that resists hydrocarbons, alkalis, dilute acids, methyl alcohol, sea water, gasoline, diesel oil, and it is self-extinguishing. It has been used extensively in aircraft and performance automotive structures, but it can be used anywhere when the high properties and easy handling are needed. Vinyl foam can be thermoformed in an oven or with a heat gun while applying pressure. The perforation roller is used to increase the surface area of the foam to increase 15-20% ultimate peel strength.[13]

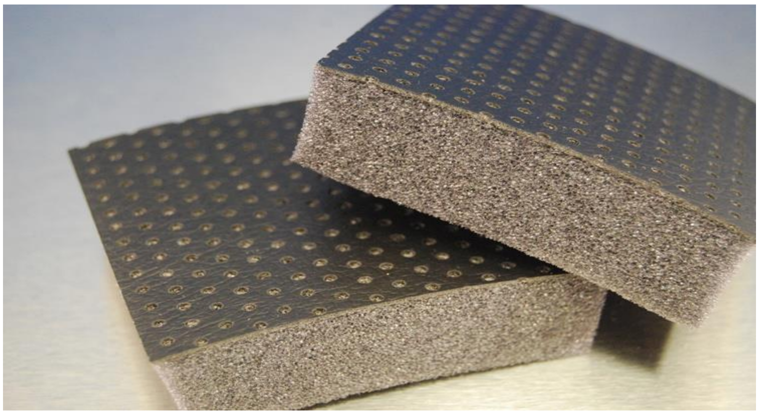

Figure.7 Vinyl Sheet Foam [7]

1.2.3 End-Grain Balsa

End Grain Balsa is the most widely used core material. It is high strength core and less expensive than vinyl or honeycomb. It has high compression strength because of honeycomb type of structure at microscopic level yet is quite dense. It is easy to cut and make to the desired shape. The individual small blocks of end grain balsa are bonded to a light scrim fabric which makes the sheet quite flexible.[13]

Figure.8 End-Grain Balsa [8]

1.2.4 Polyurethane Sheet Foam

This sheet foam is a rigid, closed cell material with excellent thermal insulation and flotation properties. This core has been widely used in the marine and aeronautical industry for decades and is inexpensive. It is used when the lower property cored laminate is needed. It is compatible with both polyester and epoxy resin systems.[13]

Figure.9 Polyurethane Sheet Foam [9]

1.2.5 Mix and Pour Polyurethane Foam

This foam is rigid, closed cell material with excellent thermal and floatation properties. It is generally suited to the sandwich core laminate, it can be poured into any closed cavity to stiffen the structure. The free rise density is 2 lbs. per cubic foot, but closed mold techniques can increase the density if required. Small amounts of this form may be added to the honeycomb to fill the cells. The filled honeycomb is then much easier to bevel and shape.[13]

Figure.10 Polyurethane Sheet Foam [10]

1.3 Preparation of GFRP matrix composites

The GFRP composites were prepared by adopting various manufacturing techniques as closed molding and open molding process. The manufacturing technique depends upon the required material property. Closed molding process is preferred when high strength, high volume, light weight, high strength is needed. Open molding process is preferred when low volume and moderate properties is required.

1.3.1 Closed Molding process

1.3.1.1 Compression Molding Process

Compression molding is used for high volume composite parts and often associated with SMC and BMC materials. This process produces high strength, complex parts in a wide variety of sizes. The metal dies are mounted in a hydraulic molding press. The material charge is manually or robotically placed in the mold, the heated mold valves are closed, and pressure up to 2,000psi is applied. Cycle time ranges from one to five minutes, depending on part size and thickness. Features such as ribs, bosses and inserts can be molded.

Compression molded fiberglass parts are characterized by net size and shape, two excellent finished surfaces, and outstanding part-to-part repeatability. Trimming and finishing costs are minimal. [14]

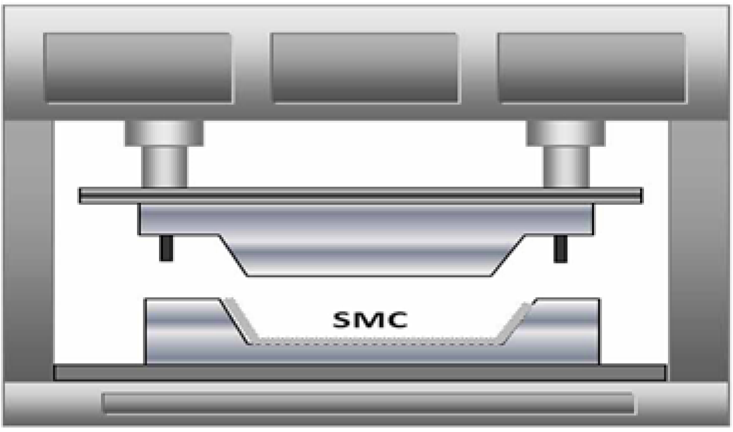

Fig.11 Compression Molding [14]

1.3.1.2 Liquid composite molding

The liquid composite molding (LCM) process for compression molding with pre-placed fiber reinforcement. The performance characteristics, cost and volume benefits are almost same as compression molding. It has a better structural efficiency that improves both mechanical and cosmetic properties of the molded part. This makes (LCM) popular for high volume automotive and truck parts that require greater structural integrity than SMC.

The pre-placed reinforcement's fibers are aligned precisely so it improves fiber efficiency and lower cost per weight. Use of robotics minimizes the variation in fiber, labor content, and further enhancing performance. Because of theses factor the design is improved and the energy cost is reduced by 50%

Figure.12 Liquid composite molding [14]

1.3.1.3 Reaction Injection Molding

Reaction Injection Molding requires closed tool, low PPM moisture and low PPM oxygen environment. The thermosetting polymers are used (dicyclopentadiene) in this mold which requires curing. The process is known as reinforced reaction injection molding (RRIM) if the reinforcement agent is added like glass fibers and mica. A subset of RIM is structural reaction injection molding (SRIM), which uses fiber meshes for the reinforcing agent. The fiber mesh is arranged in the mold and the polymer mixture is injection molded over it.

It can produce strong, flexible, lightweight parts that are easily painted. The bi-component mixture injected into the mold has a much lower viscosity than melted thermoplastic polymers, therefore large, light-weight and thin-walled items can be successfully produced with DCPD RIM.

Common items made with the DCPD RIM include automotive bumpers, air spoilers and fenders.

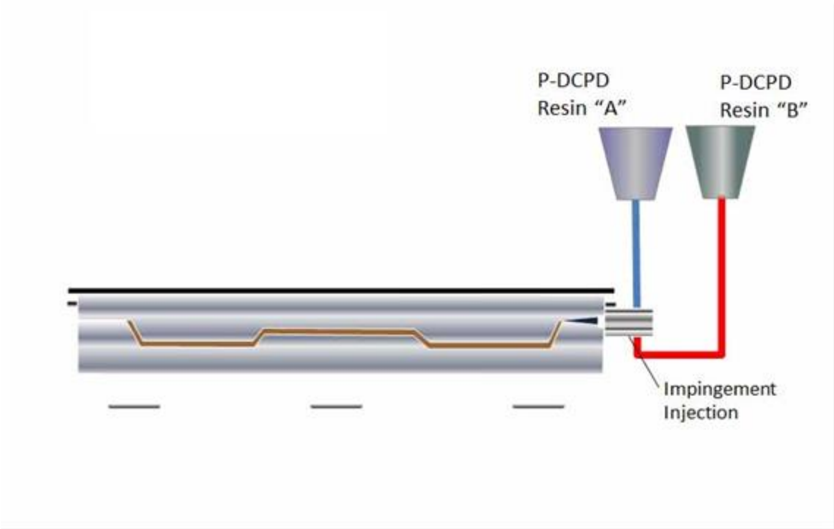

Figure.13 reaction injection molding [14]

1.3.1.4 Resin Transfer Molding (RTM) Process

RTM is a vacuum-assisted, resin transfer process with a flexible solid counter tool for the B-side surface compression. This process increase the yield strength of the laminate compression, a high glass-to-resin ratio, and outstanding strength to weight characteristics. RTM parts have two finished surfaces.

Reinforcement mat or woven roving is placed in the mold, which is then closed and clamped. Catalyzed, low-viscosity resin is pumped in under pressure, displacing the air and venting it at the edges, until the mold is filled. Molds for this low-pressure system are usually made from composite or nickel shell faced composite construction.

Suitable for medium volume production of larger components, resin transfer molding is usually considered an intermediate process between the relatively slow spray-up with lower tooling costs and the faster compression molding methods with higher tooling costs.

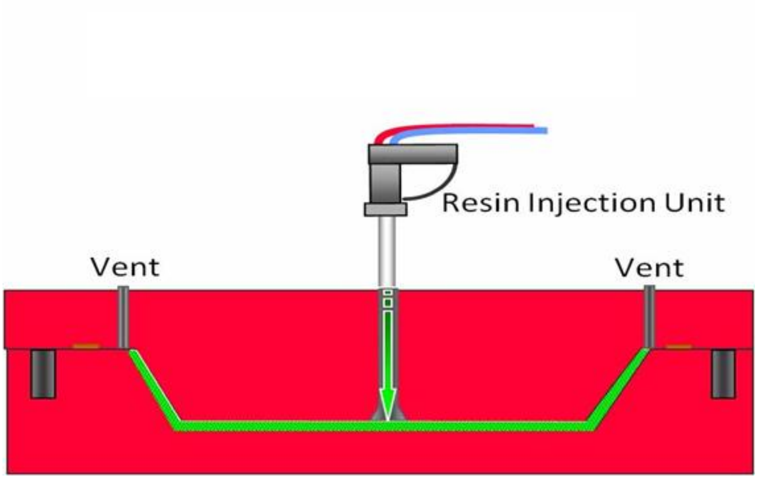

Figure.14 Resin transfer molding[14]

1.3.1.5 Vacuum Infusion Processing (VIP), RTM Light (LRTM, Resin Infusion, VARTM, SCRIMP)

RTM Light are vacuum-assisted, closed-mold resin processes. For compression on the B-side surface, VIP uses a flexible sheet or re-usable bag, and RTM Light employs a lightweight counter tool. This process yields increased laminate compression, a higher glass to resin ratio, and excellent strength-to-weight characteristics.

With these processes the reinforcements are placed in the mold dry, frequently combined with cores or other special inserts. Vacuum is then applied to compact the reinforcement and eliminate air. Resin is introduced and the vacuum draws it through the reinforcement.

Very large parts can be made by VIP method utilizing very low viscosity resin and an appropriate fill time with bleeder film and other venting. This resin infusion process results in very low void content and excellent mechanical properties due to the relatively high glass content. Fiber content is determined by fiber architecture and pressure.

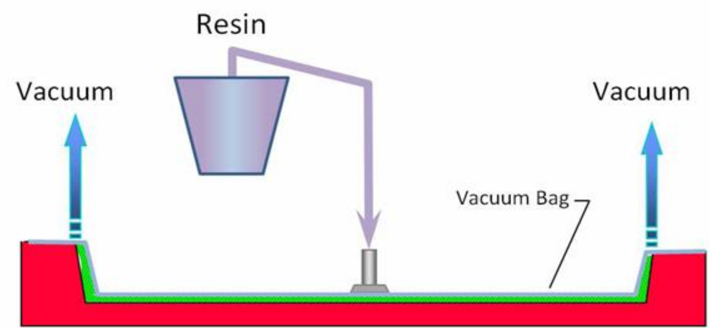

Figure.15 Vacuum infusion processing [14]

1.3.1.6 RTM Light process

In contrast, the RTM Light process resin is introduced via a pumping mechanism under 2psi. More flexibility in types of resins and fillers is possible, and an intermediate range of fiber contents. Benefits are better cosmetic finishes and variation in part thickness, and faster cycle times for lower cost. Tools can be aluminum, steel or composite.

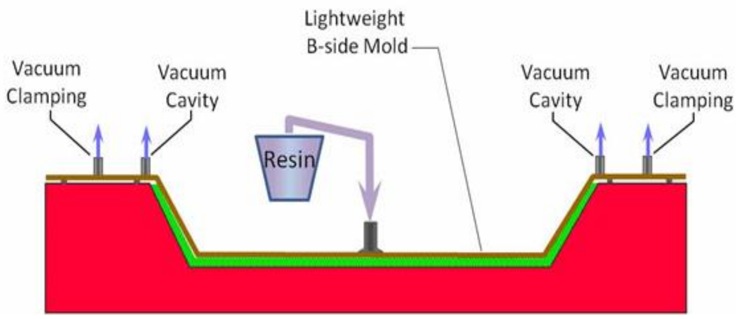

Figure.16 Direct Long Fiber Thermoplastic Molding (D-LFT) [14]

1.3.1.7 Long fiber thermoplastic molding

Long fiber thermoplastic molding is a newer technology where thermoplastic material is directly compounded with long glass fibers (ravings) and then molded in one operation. Glass fibers of 1/2”

(12 mm) up to 2" (50 mm) in length give much higher stiffness, strength and toughness than the 1/8“ (3 mm) fibers that are commonly used.

The advantage of D-LFT is the ability to control the length of the fiberglass being mixed into the thermoplastic pellets via an extruder. The process enables control of the compound properties, and therefore the part, with high consistency.

D-LFT process is generally a cross between injection and compression molding. Typically, the compound is mixed in the barrel of the injection machine where the material is heated (425˚F). The tool is run cold, to help cool or freeze the thermoplastic material placed in it. This is a cooling process "in the tool," rather than an exothermic reaction as with a true thermoset material like SMC. As a thermoplastic, the stiffness is good (typically 40% glass) but the material will soften and lose modulus with heat exposure.

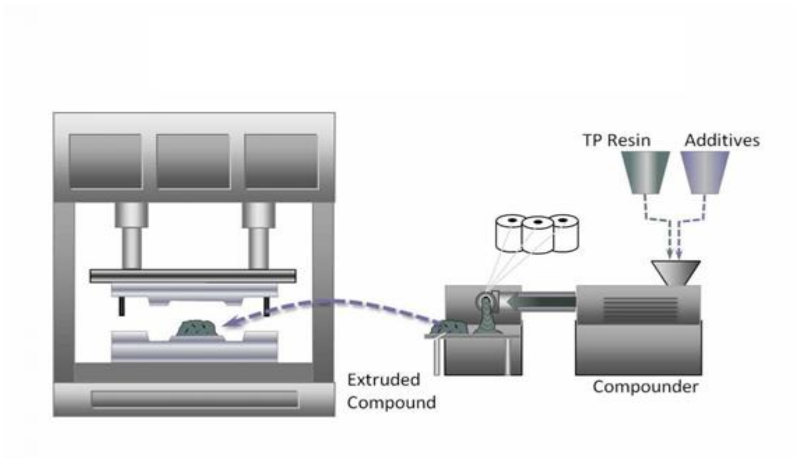

Figure.17 Long fiber thermoplastic molding [14]

1.3.2 Open Molding

1.3.2.1 Hand Lay-Up

The simplest of the fabrication processes, hand lay-up is used in low-volume production of large products, e.g., wind turbine components, concrete forms, and radomes. A pigmented gel coat is first sprayed onto the mold for a high-quality surface. When the gel coat has cured, glass reinforcing mat and/or woven roving is placed on the mold, and the catalyzed resin is poured, brushed or sprayed on. Manual rolling then removes entrapped air, compacts the composite, and thoroughly wets the reinforcement with the resin. Additional layers of mat or woven roving and resin are added for thickness. A catalyst or accelerator initiates curing in the resin system, which hardens the composite without external heat.

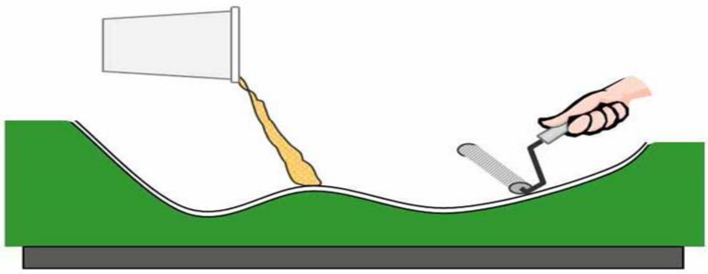

Figure.18 Hand layup manual process [14]

1.3.2.2 Spray-Up

Similar to hand lay-up in simplicity, spray-up offers greater shape complexity and faster production. Spray-up utilizes a low-cost open mold, room temperature curing resin, and is ideal for producing large parts such as tub/shower units and vent hoods in low to moderate quantities. Chopped fiber reinforcement and catalyzed resin are deposited in the mold from a chopper/spray gun.

As with lay-up, manual rolling removes entrapped air and wets the fiber reinforcement. Woven roving is often added in specific areas for thickness or greater strength. Pigmented gel coats can be used to produce a smooth, colorful surface.

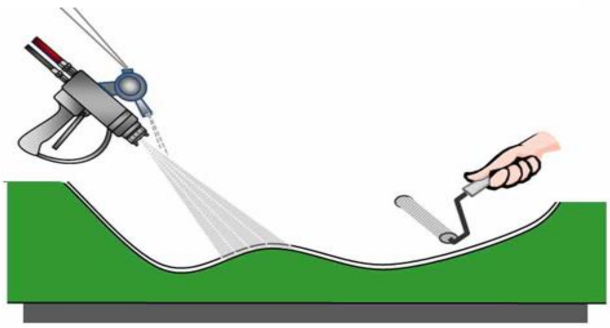

Figure.19 Spray up chopping process[14]

1.4 Testing Of Composites

The testing of composites include mechanical, physical, electrical, optical, thermal, flammability, exposure, emissions, barrier, surface, and chemical to identify the characteristics of your raw materials (such as resins, films, adhesives, fillers, prepreg) or laminates such as thermoset composites and thermoplastic composites. In this work the mechanical property of the composite is measured by conducting Tensile, Compression and Shear test of the GFRP composite.

1.4.1 Tensile Test

Tensile testing is a destructive test process that provides information about the tensile strength, yield strength and ductility of a material. A tensile test, also known as tension test, is probably the most fundamental type of mechanical test you can perform on material. Tensile tests are simple, relatively inexpensive, and fully standardized. By pulling on something, you will very quickly determine how the material will react to forces being applied in tension. As the material is being pulled, you will find its strength along with how much it will elongate.

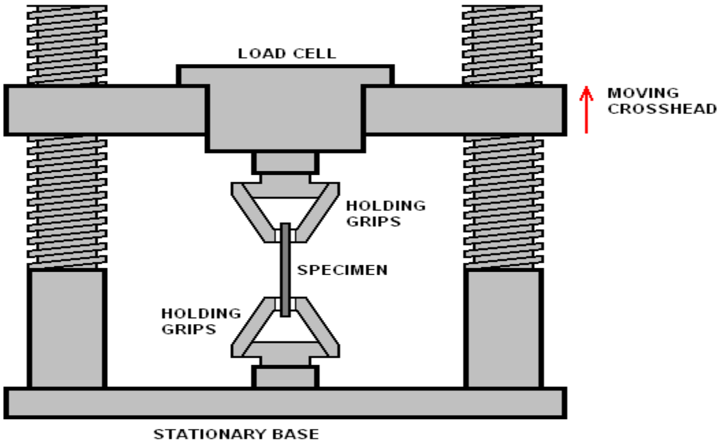

Figure.20 Tensile Test [15]

Stress Calculation

$$\sigma = \frac{F_n}{A}$$

Strain Calculation

$$\varepsilon = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0}$$

Where,

ΔL= change in length

L_0= Initial length

L=Length

σ= Stress

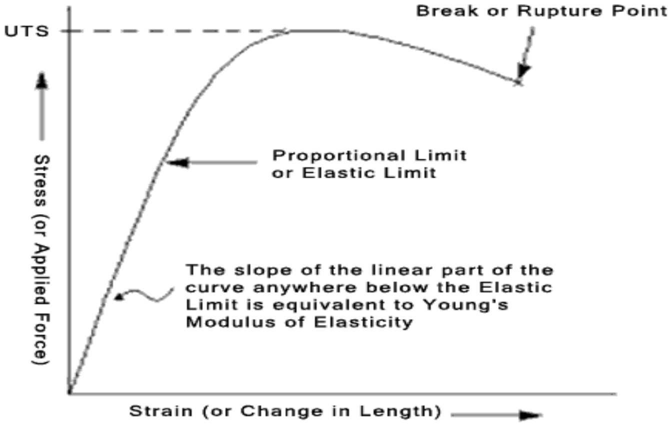

Figure.21 Tensile (Stress vs Strain) Graph[18]

1.4.2 Compression Test

A compression test determines behavior of materials under crushing loads. The specimen is compressed and deformation at various loads is recorded. Compressive stress and strain are calculated and plotted as a stress-strain diagram which is used to determine elastic limit, proportional limit, yield point, yield strength and, for some materials, compressive strength.

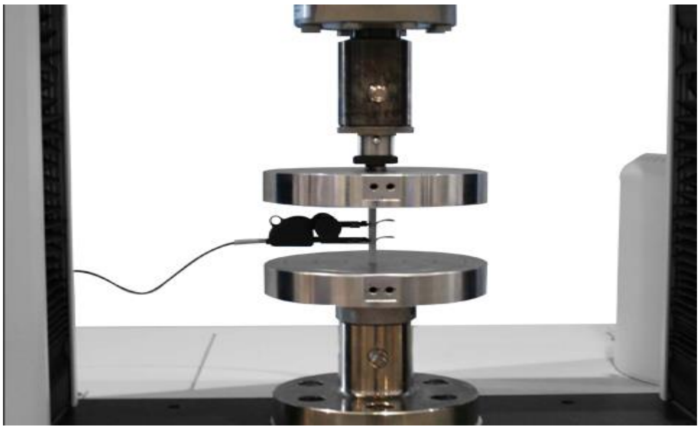

Figure.22 Compression Test[18]

Stress Calculation

$$\sigma = \frac{F}{A}$$

Engineering Stress Calculation

$$\sigma_e = \frac{F}{A_0}$$

Strain calculation

$$\epsilon_e = \frac{l - l_0}{l_0}$$

Where,

ΔL= change in length

L_0= Initial length

L=Length

σ= Stress

σ_e=Engineering Stress

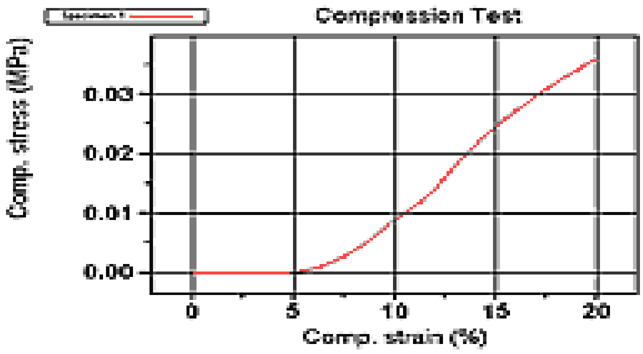

Figure.23 Compression (Stress vs Strain) Graph[18]

1.4.3 Shear Test

Shear testing is performed to determine the shear strength of a material. It measures the maximum shear stress that may be sustained before a material will rupture. Shear is typically reported as MPa (psi) based on the area of the sheared edge. Shear testing is commonly used with adhesives and can be used in either a tensile or comprehensive method.

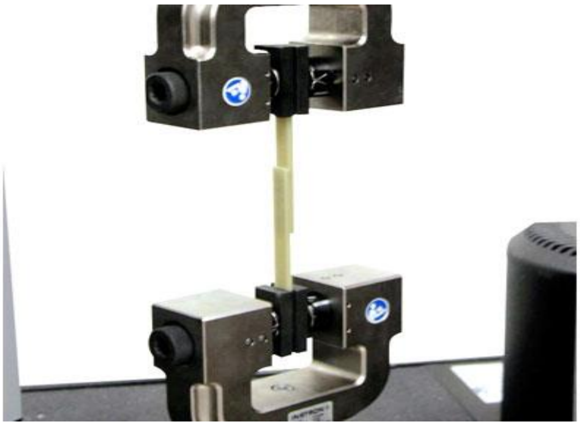

Figure.24 Shear Test [18]

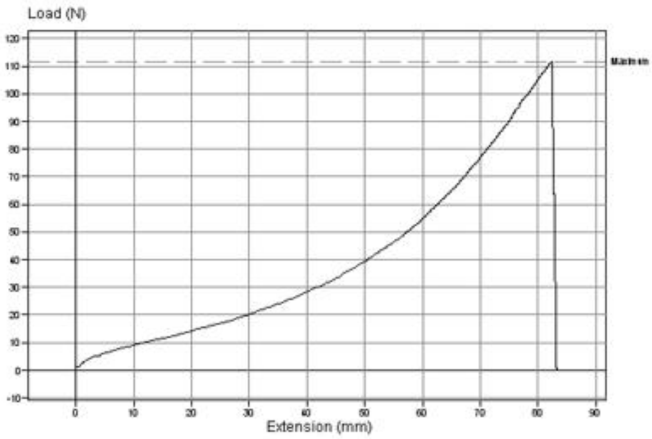

Figure.25 Shear (Load vs Extension) Graph [19]

Calculation

Shear Stress

$$\tau = \frac{F}{A},$$

Pure Shear Strain

$$\tau = \gamma G$$

Shear Modulus

$$G = \frac{E}{2(1+\nu)}.$$

Beam Shear

$$\tau = \frac{VQ}{It},$$

Where,

V = total shear force at the location in question

Q = static moment of area

t = thickness in the material perpendicular to the shear

I = Moment of Inertia of the entire cross sectional area

τ = shear stress;

F = the force applied;

A = the cross-sectional area of material with area parallel to the applied force vector

1.4.4 Flexure Test

The flexure test method measures behavior of materials subjected to simple beam loading. It is also called a transverse beam test with some materials. Maximum fiber stress and maximum strain are calculated for increments of load. Results are plotted in a stress-strain diagram. Flexural strength is defined as the maximum stress in the outermost fiber. This is calculated at the surface of the specimen on the convex or tension side. Flexural modulus is calculated from the slope of the stress vs. deflection curve. If the curve has no linear region, a secant line is fitted to the curve to determine slope.

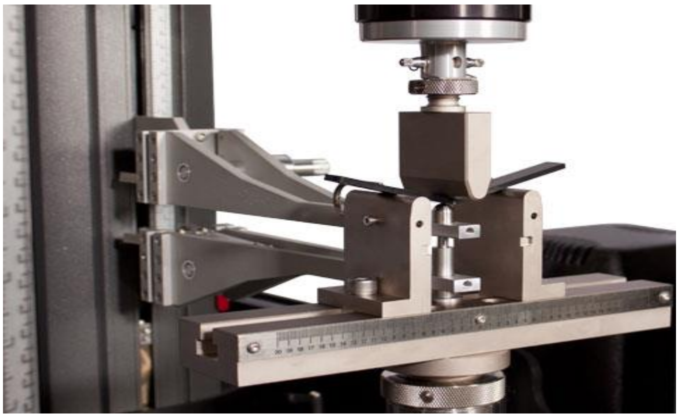

Figure.26 Flexure Test[18]

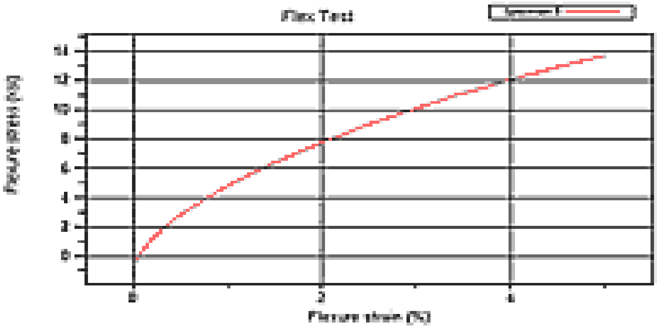

Figure.27 Flexure (Stress vs Strain) Graph[18]

Calculation

Flexure Stress

$$\sigma_f = \frac{3FL}{2bd^2}$$, for a rectangular cross section

$$\sigma_f = \frac{FL}{\pi R^3}$$, for a circular cross section

Flexure Strain

$$\epsilon_f = \frac{6Dd}{L^2}$$

Flexure Modulus

$$E_f = \frac{L^3 m}{4bd^3}$$

Fracture Toughness

$$K_{\mathrm{I}} = \frac{4P}{B}\sqrt{\frac{\pi}{W}}\left[1.6\left(\frac{a}{W}\right)^{1/2} - 2.6\left(\frac{a}{W}\right)^{3/2} + 12.3\left(\frac{a}{W}\right)^{5/2} - 21.2\left(\frac{a}{W}\right)^{7/2} + 21.8\left(\frac{a}{W}\right)^{9/2}\right]$$

Where,

σ_f = Stress in outer fibers at midpoint

ϵ_f = Strain in the outer surface

E_f = flexural Modulus of elasticity

F = load at a given point on the load deflection curve

L = Support span

B = Width of test beam

D = Depth of tested beam

D = maximum deflection of the center of the beam

M = The gradient (i.e., slope) of the initial straight-line portion of the load deflection Curve, (P/D)

R = The radius of the beam

1.5 Composite material used in aircrafts

The materials used in airplane design have been constantly evolving. The original Wright Flyer was comprised primarily of spruce and ash wood with muslin covering the wings, while today's airliners are made mostly of aluminum with some structure made from steel. In the mid 1960's, scientists and engineers began working on a new breed of aerospace materials called composites. A composite is an engineered material made from two or more ingredients with significantly differing properties, either physical or chemical. While no longer used today, an early example of a composite material was a mix of mud and straw that was used to make bricks. Composites have two significant advantages over some of the more traditional materials: greater strength and lighter weight. One of the most common forms of composite in use today is carbon fiber, glass fiber and aramid fiber reinforced composites. It is made by heating lengths of rayon, pitch or other types of fiber to extremely high temperatures (~2000ºC) in an oxygen-deprived oven. This heat, combined with the lack of oxygen, means that instead of combusting or burning completely, the rayon strands turn into strands of pure carbon atoms approximately 6μm (six micrometers) in diameter. These strands are spun into a thread, then woven into sheets and mixed with hardening resins to form the various components needed.[11] The figure below shows the types of composites used in the different parts of the Aircraft.

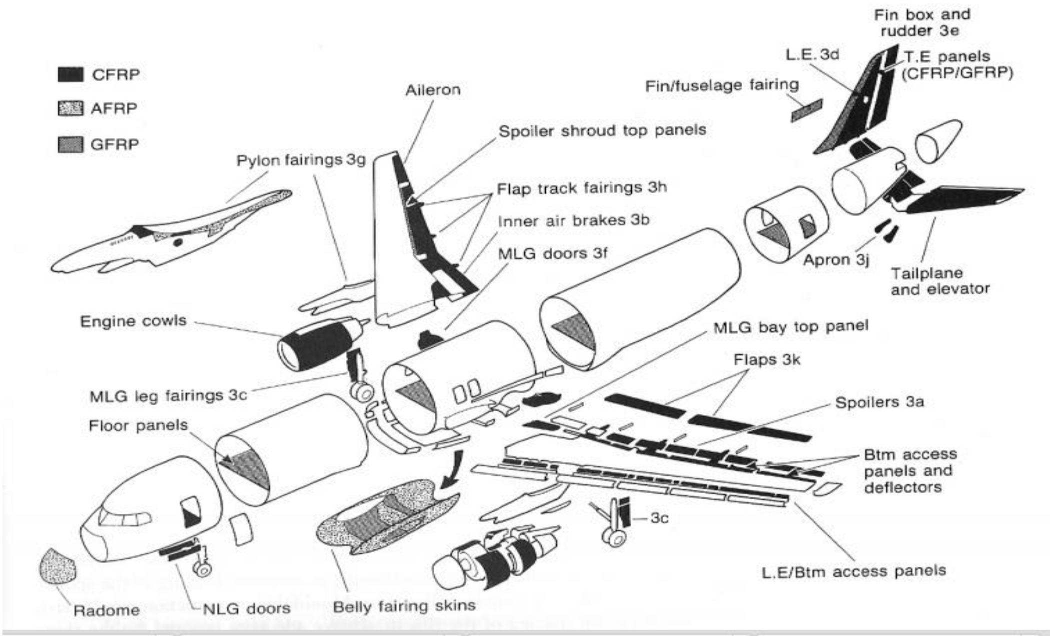

Figure.28 Composite material used in aircrafts [6]

1.6 Abaqus

The Abaqus/CAE software is used which can quickly and efficiently create, edit, monitor, diagnose, and visualize advanced Abaqus analyses. The intuitive interface integrates modeling, analysis, job management, and results visualization in a consistent, easy-to-use environment that is simple to learn for new users, yet highly productive for experienced users. Abaqus/CAE supports familiar interactive computer-aided engineering concepts such as feature-based, parametric modeling, interactive and scripted operation, and GUI customization.[20]

Users can create geometry, import CAD models for meshing, or integrate geometry-based meshes that do not have associated CAD geometry. Associative Interfaces for CATIA V5, SolidWorks, and Pro/ENGINEER enable synchronization of CAD and CAE assemblies and enable rapid model updates with no loss of user-defined analysis features.[20]

The open customization toolset of Abaqus/CAE provides a powerful process automation solution, enabling specialists to deploy proven workflows across the engineering enterprise. Abaqus/CAE also offers comprehensive visualization options, which enable users to interpret and communicate the results of any Abaqus analysis.[20]

1.6.1 Abaqus standard explicit

Abaqus/Standard employs solution technology ideal for static and low-speed dynamic events where highly accurate stress solutions are critically important. Examples include sealing pressure in a gasket joint, steady-state rolling of a tire, or crack propagation in a composite airplane fuselage. Within a single simulation, it is possible to analyze a model both in the time and frequency domain. For example, one may start by performing a nonlinear engine cover mounting analysis including sophisticated gasket mechanics. Following the mounting analysis, the pre-stressed natural frequencies of the cover can be extracted, or the frequency domain mechanical and acoustic response of the pre-stressed cover to engine induced vibrations can be examined. Abaqus/Standard is supported within the Abaqus/CAE modeling environment for all common pre- and post-processing needs.[20]

The results at any point within an Abaqus/Standard run can be used as the starting conditions for continuation in Abaqus/Explicit. Similarly, an analysis that starts in Abaqus/Explicit can be continued in Abaqus/Standard. The flexibility provided by this integration allows Abaqus/Standard to be applied to those portions of the analysis that are well-suited to an implicit solution technique, such as static, low-speed dynamic, or steady-state transport analyses; while Abaqus/Explicit may be applied to those portions of the analysis where high-speed, nonlinear, transient response dominates the solution.[20]

2.1 Material Testing of Glass Fiber Reinforced Polymer Composite

The glass fiber reinforced polymer composite (GFRP) with foam sandwich structure consist of glass fiber polymer laminate bonded with polyester resin, foam core is made of polyurethane. It is necessary to obtain the material properties of the laminate and core by conducting tensile, compression and shear testing. By obtaining the material properties of the GFRP composite, the analytical calculation and simulation in Abaqus is carried out with obtained material properties.

2.1.1 Tensile Testing

The glass fiber reinforced plastic laminate is used for experimental investigation. The FRP laminate is made of glass fiber matrix reinforced with polyester resin. In order to obtain material property of the laminate, experimental test were conducted according to the standard.

Instruments required

1, Force transducer.

2, Displacement transducer.

2, strain transducer.

Table 1. Specimen description

No.of specimens	Specimen	Length mm	Breath mm	Thickness mm
4	Laminate	115	15	1.5

Table 2. Testing condition

Rate	2.00000 mm/min
Humidity	50.00 %
temperature	18.00 C

This table represents the experimental result of GFRP laminate. The stress, strain and deformation of the laminate to given load is measured. The breaking point of the GFRP laminate is determined. The material properties of the laminate can be calculated by the obtained results.

Table.3 Tensile Test Result

specimens	Maximum Load [N]	Tensile stress at Maximum Load [MPa]	Tensile strain (Extension) at Maximum Load [%]	Load at Break (Standard) [N]	Tensile stress at Break (Standard) [MPa]	Tensile strain (Extension) at Break (Standard) [%]
1	1726.42	105.40	1.90	1726.42	105.40	1.90
2	1416.60	93.69	1.80	1411.56	93.36	1.84
3	1587.11	105.95	1.99	1587.11	105.95	1.9944
4	1617.13	99.58	1.75	1614.85	99.44	1.76

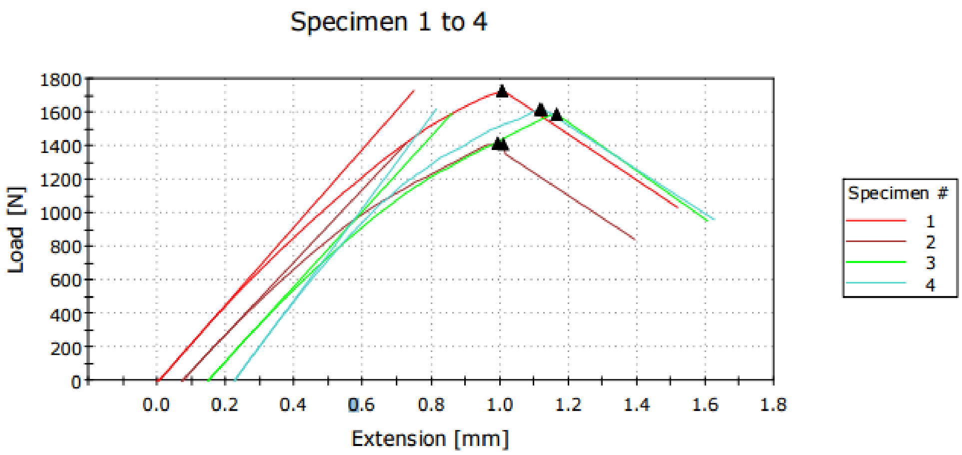

Figure.29 Load vs Deflection graph

2.1.2 Compression Testing

The polyurethane foam is used for experimental investigation. The Compression test is conducted to polyurethane foam core according to the standards, in order to obtain the material property of the foam.

Instruments required

1, Force transducer.

2, Displacement transducer.

2, strain transducer.

Table.4 Specimen description

No.of specimens	Specimen	Length	Breath	Thickness
5	foam	5mm	25mm	25 mm

Table.5 Testing condition

Rate	-5.00000 mm/min
Humidity	50.00 %
temperature	23.00 C

This table represents the experimental result of polyurethane foam. The stress, strain and deformation of the foam core to given load is measured. The failure point of the polyurethane is determined. The material properties of the foam core can be calculated by the obtained results

Table.6 Compression Test result

specimen label	Pre-Load [N]	Load at Break (Standard) [N]	Stress at Break (Standard) [MPa	Strain (Extension) at Break (Standard) [mm/mm]
1	-1.06	-2204.65	-2.40	-0.55
2	-1.05	-1868.68	-2.05	-0.51
3	-0.95	-404.09	-0.47	-0.29
4	-1.01	-903.31	-1.01	-0.30
5	-0.82	-121.19	-0.14	-0.26

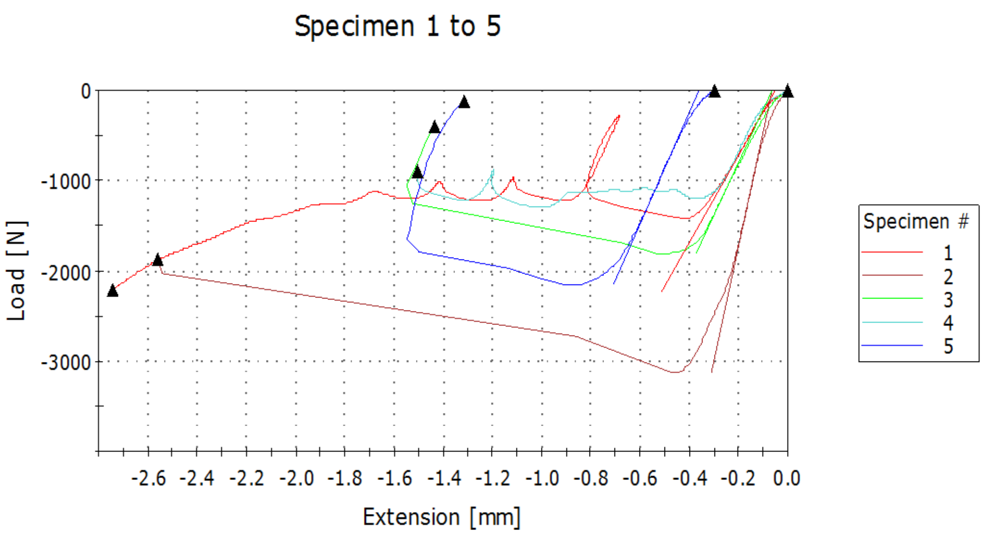

Figure.30 Load vs Deflection graph

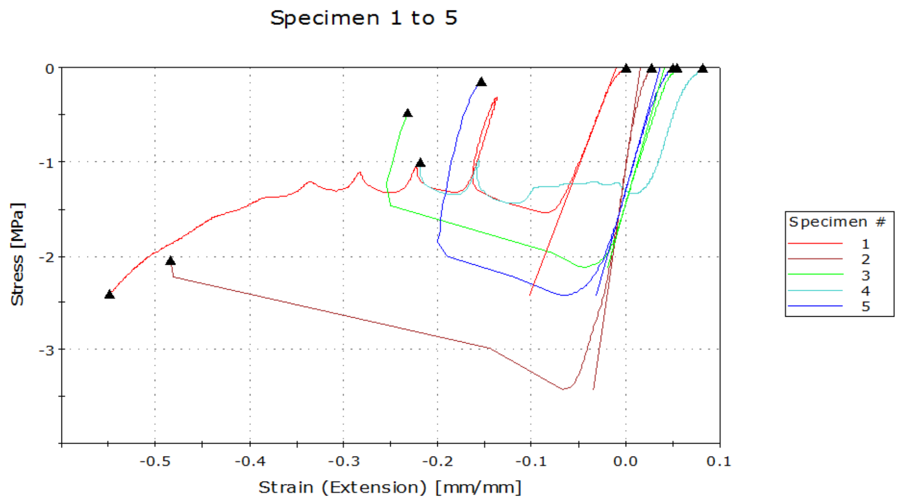

Figure.31 Stress vs Strain graph

2.1.3 Shear Testing

The polyurethane foam is used for experimental investigation. The shear test is conducted according to the standard to obtain the shear modulus of the polyurethane foam core.

Instruments requires:

1, Force transducer.

2, Displacement transducer.

2, strain transducer.

Table.7 Specimen Description

No.of specimens	Specimen	Length	Breath	Thickness
3	foam	5mm	25mm	25 mm

Table.8 Testing Condition

Rate	-5.00000 mm/min
Humidity	50.00 %
temperature	23.00 C

This table represents the experimental result of polyurethane foam. The stress, strain and deformation of the foam core to given load is measured. The failure point of the polyurethane is determined. The material properties of the foam core can be calculated by the obtained results

Table.9 Shear Test Result

Specimen label	Pre-Load [N]	Pre-Load [N]	Stress at Break (Standard) [MPa]	Strain (Extension) at Break (Standard) [mm/mm]
1	-0.32	-54.78	-0.09	-0.92
2	-1.11	-178.07	-0.28	-0.51
3	-1.00	-188.83	-0.30	-0.62

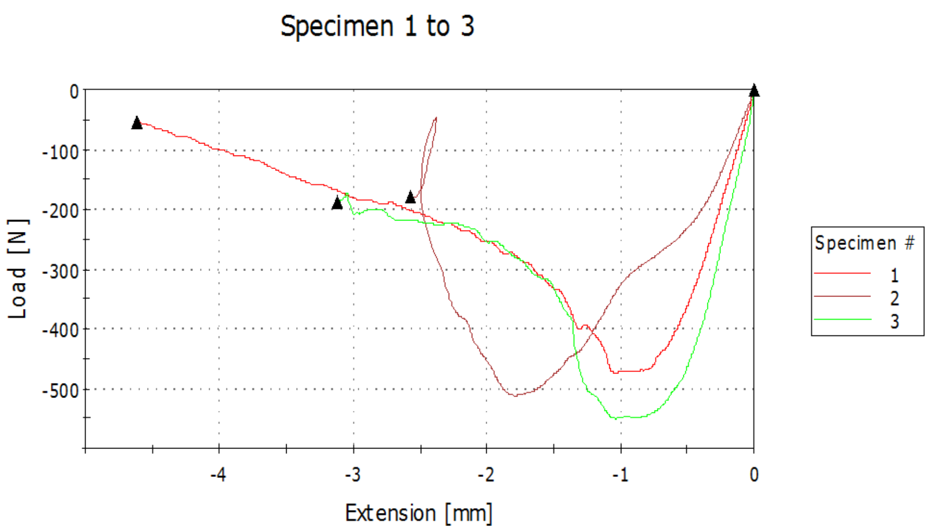

Figure.32 Load vs Deflection Graph

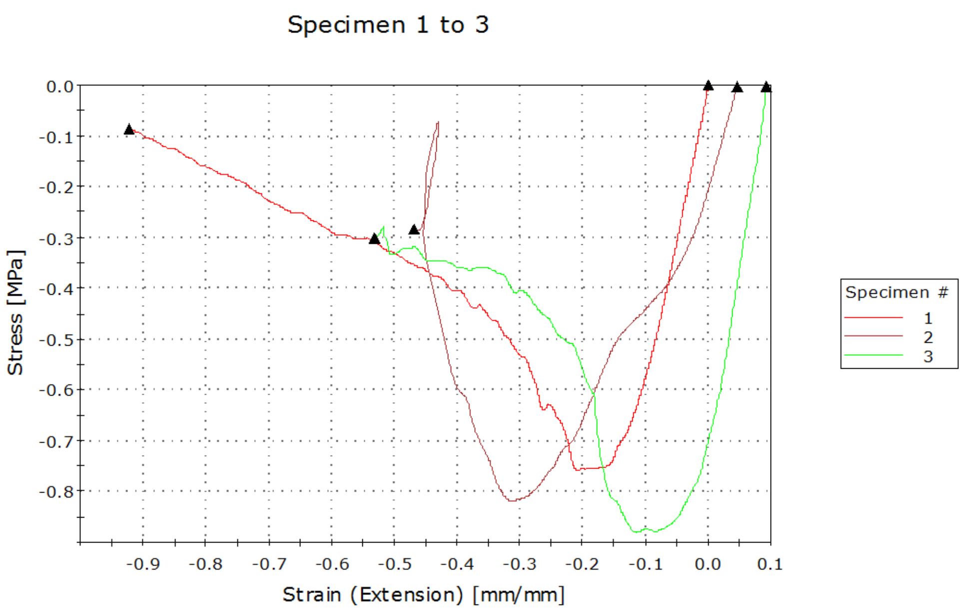

Figure.32 Stress vs Strain Graph

3. Material Properties Obtained by the Experimental Results

3.1 Laminate

The elastic property and ductility of Glass Fiber Reinforced Laminate with polyester resin is obtained from the tensile testing.

Table.10 Engineering Constant for Laminate

E1 (MPa)	E2 (MPa)	E3 (MPa)	Nu12	Nu13	Nu23	G12 (MPa)	G13 (MPa)	G23 (MPa)
10785	10785	34	0.3	0.3	0.3	94	8	8

Where,

E1= Young's modulus at X component

E2= Young's modulus at Y component

E3= Young's modulus at Z component

Nu12= Poisson's ratio at XY component

Nu13= Poisson's ratio at XZ component

Nu23= Poisson's ratio at YZ component

G12= Shear modulus at XY component

Nu13= Shear modulus at XZ component

Nu23= Shear modulus at YZ component

Assumptions made from Obtained Material Properties

The Young's modulus of laminate is 10785 MPa. It is assumed that Young's modulus is same at X and Y component. Young's modulus at Z component is 34Mpa which is the Young's modulus of foam core. The Poisson's ratio at XY, XZ and XY are 0.3. The Shear modulus at XY component is 94 MPa, which is the Shear modulus of polyester resin used in the GFRP laminate. The Shear modulus at XZ and YZ components is 8 MPa, which is the Shear modulus of the foam core.

Table.11 Plastic strain

No	Yield Stress (MPa)	Plastic Strain (mm/mm)
1	50	0
2	70	0.005
3	100	0.02
4	100	0.021

Table .12 Ductile damage and damage evolution for laminate

No	Fracture Strain	Stress Triaxiality	Strain rate
1	0.02	-10	1
2	0.02	0	1
3	0.02	10	1

The Plastic Strain and Yield Stress after yield point is given from the experimentally obtained data. Since the laminate is ductile material, the ductile damage property is given to the laminate. It is assumed that Fracture Strain and Strain Rate is constant from Stress Triaxiality -10 to 10.

3.2 Core

Table. 13 Engineering constant

E1	E2	E3	Nu12	Nu13	Nu23	G12	G13	G23
34	34	34	0.3	0.3	0.3	8	8	8

Where,

E1= Young's modulus at X component

E2= Young's modulus at Y component

E3= Young's modulus at Z component

Nu12= Poisson's ratio at XY component

Nu13= Poisson's ratio at XZ component

Nu23= Poisson's ratio at YZ component

G12= Shear modulus at XY component

Nu13= Shear modulus at XZ component

Nu23= Shear modulus at YZ component

The Young's modulus of core is 34 MPa. It is assumed that Young's modulus is same at X, Y and Z component. The Poisson's ratio at XY, XZ and XY are 0.3. The Shear modulus at XY, XZ and YZ component is 8Mpa.

Table.14 Plastic strain

no	Yield stress	Plastic strain
1	1.54295	0
2	1.54232	0.00451
3	1.51745	0.01041

Table. 15 Ductile damage and damage evolution for core

No	Fracture strain	Stress Triaxiality	Strain rate
1	0.5	-100	1
2	0.05	100	1

Table. 16 Shear damage and damage evolution for core

No	Fracture strain	Shear stress ratio	Strain rate
1	0.01	-10	1
2	0.01	0	1
3	0.01	10	1

The Plastic Strain and Yield Stress after yield point is given from the experimentally obtained data. Since the core tends to ductile damage and Shear damage, both the damage criteria is given. The strain rate varies from 0.5 to 0.05 from triaxiality -100 to 100 and Strain rate is constant in the ductile damage. The fracture Strain and Strain Rate is constant from Stress Triaxiality -10 to 10 in the Shear damage.

4. Experimental Analysis and Analytical Calculation of Glass Fiber Reinforced (GFRP) Composite

4.1. Flexure test

The Glass fiber reinforced polymer composite is used for experimental investigation. The GFRP composite with foam core sandwich structure is flexure test to obtain the load deformation and stress strain graph to determine the material behavior and failure.

Table.17 Specimen description

No.of specimens	Specimen	Length	Breath	Thickness
6	Glass fiber reinforced polymer composite with foam core sandwich.	30mm	25mm	8 mm

Table.18 Testing condition

Rate	2.00000 mm/min
Humidity	50.00 %
Temperature	23.00 C

Instruments requires

1, Force transducer.

2, Displacement transducer.

2, strain transducer.

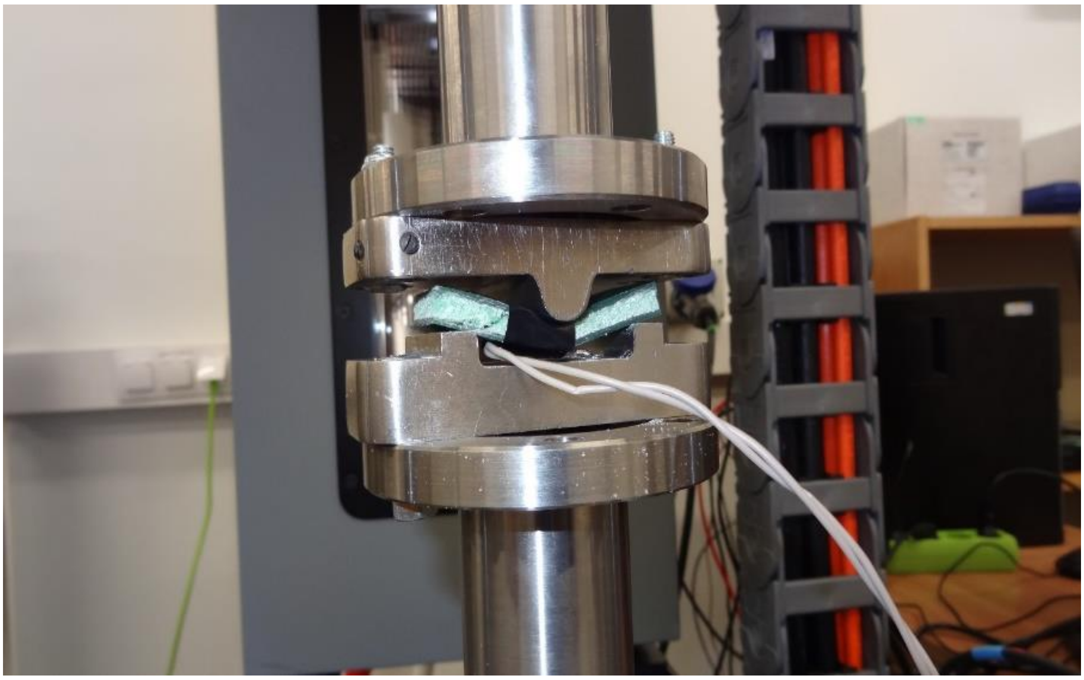

Figure.33 Flexure Test

The experimental flexure test is conducted on the Glass fiber reinforced polymer composite. The GFRP composite with foam core sandwich structure is flexure test to obtain the load deformation and stress strain graph to determine the material behavior and failure.

4.2 Result of Experimental Analysis

The 3-point bending (Flexure) test is conducted, the bending load is given to the GFRP composite till fracture. The given load is obtained by Force transducer, Deflection are obtained from Displacement transducer. The Strain transducer and Stress transducer gives the Strain and Stress acting on the GFRP composite. From the obtained Result of Force, Displacement, Stress and stress. The Stress vs Strain graph and Load vs Deflection Graphs are plotted. By the Plotted graph, the mechanical behavior of the GFRP composite at given load is Determined and the Load, Deflection, Stress and Strain at fracture is obtained.

1. **Specimen 1**

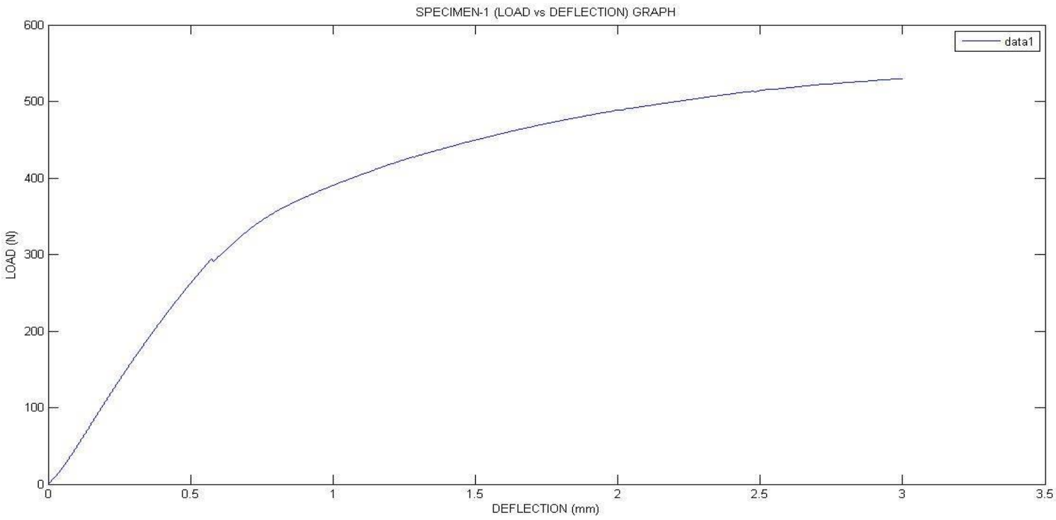

Figure.34 Load vs Deflection Graph

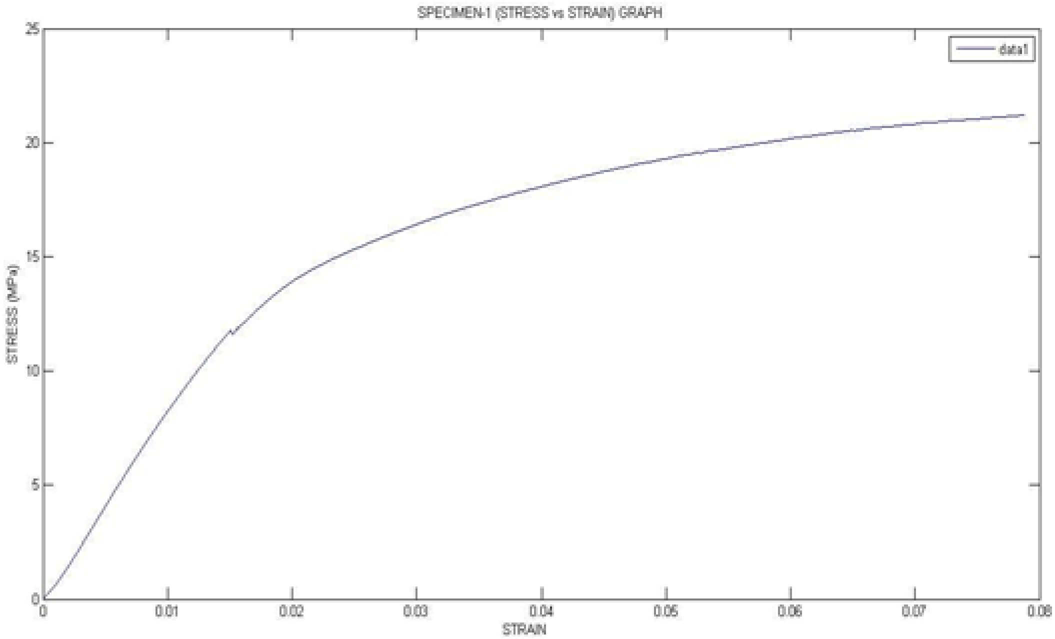

Figure.35 Stress vs Strain Graph

2. Specimen 2

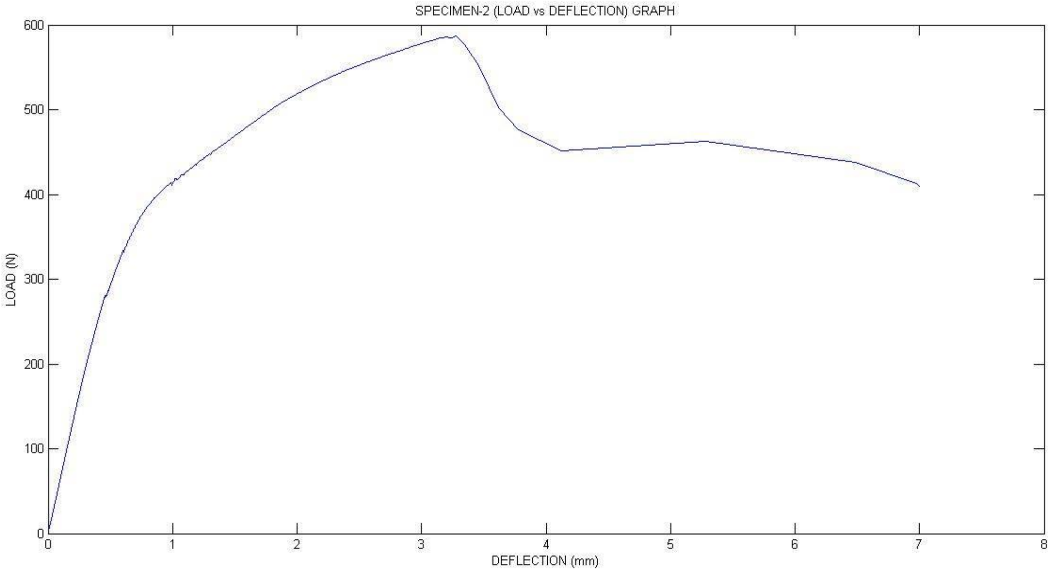

Figure.36 Load vs Deflection Graph

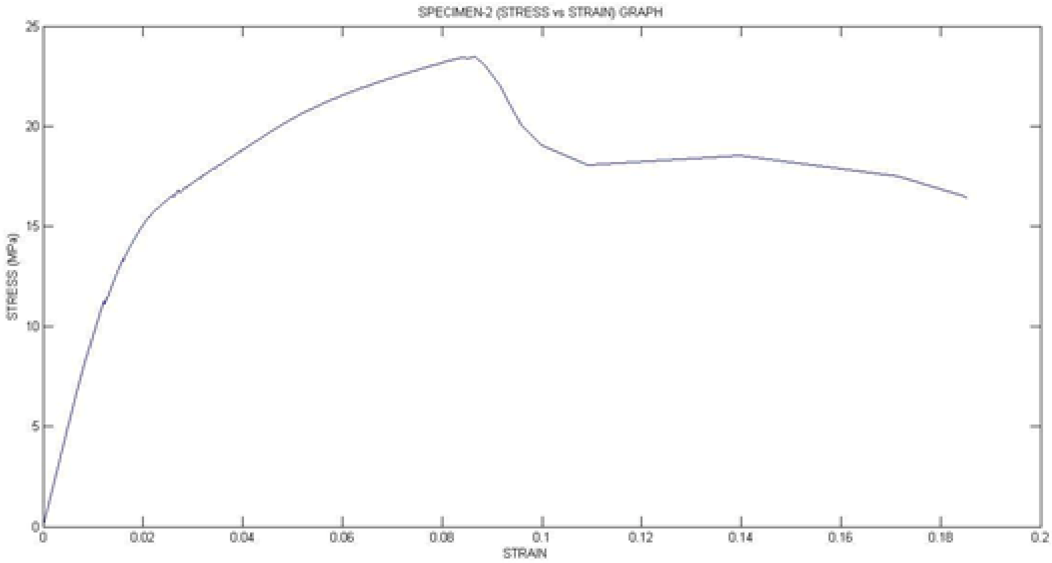

Figure.37 Stress vs Strain Graph

3. Specimen 3

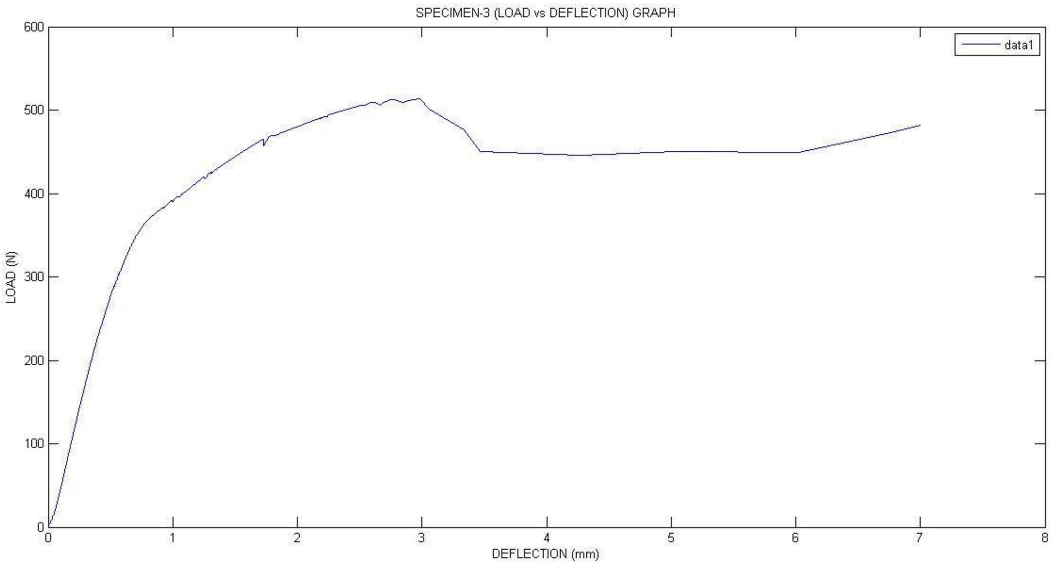

Figure.38 Load vs Deflection Graph

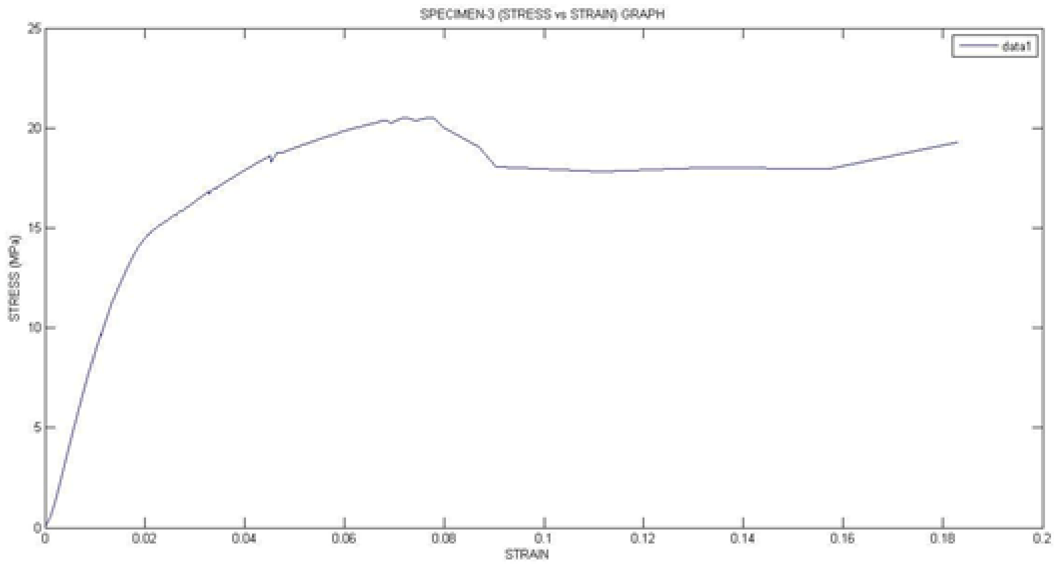

Figure.39 Stress vs Strain Graph

4. Specimen 4

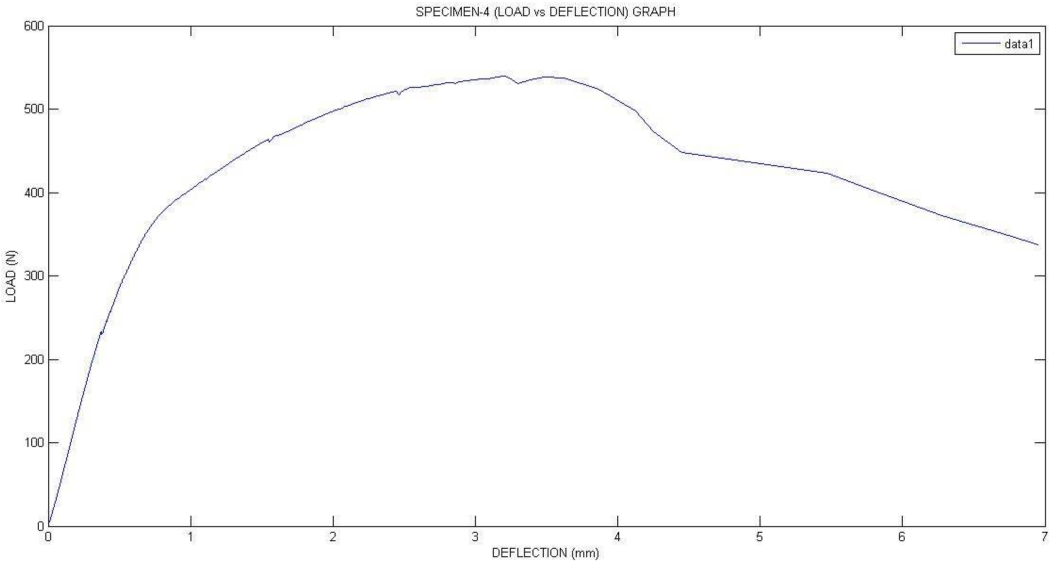

Figure.40 Load vs Deflection Graph

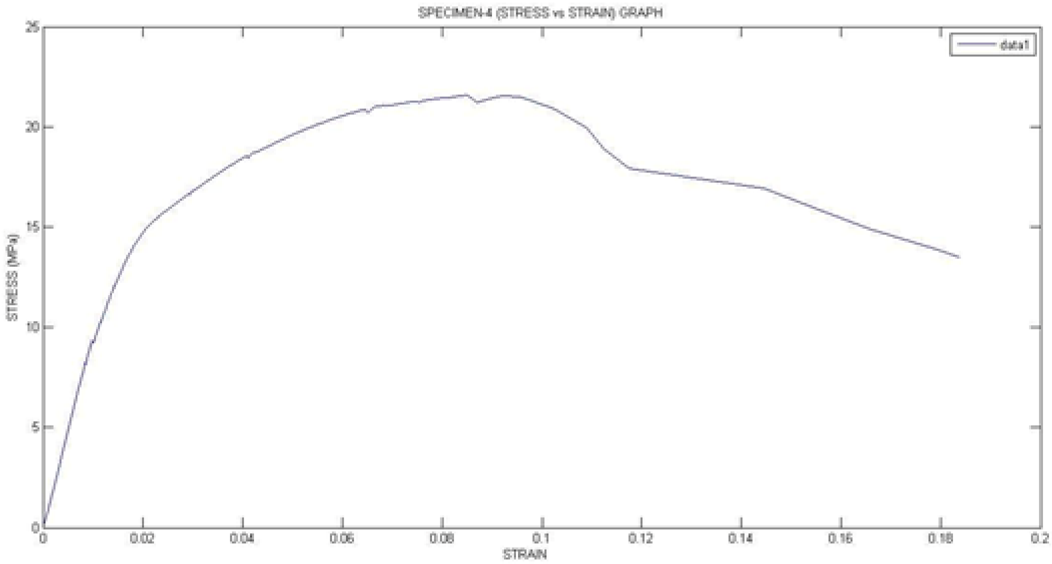

Figure.41 Stress vs Strain Graph

5. Specimen 5

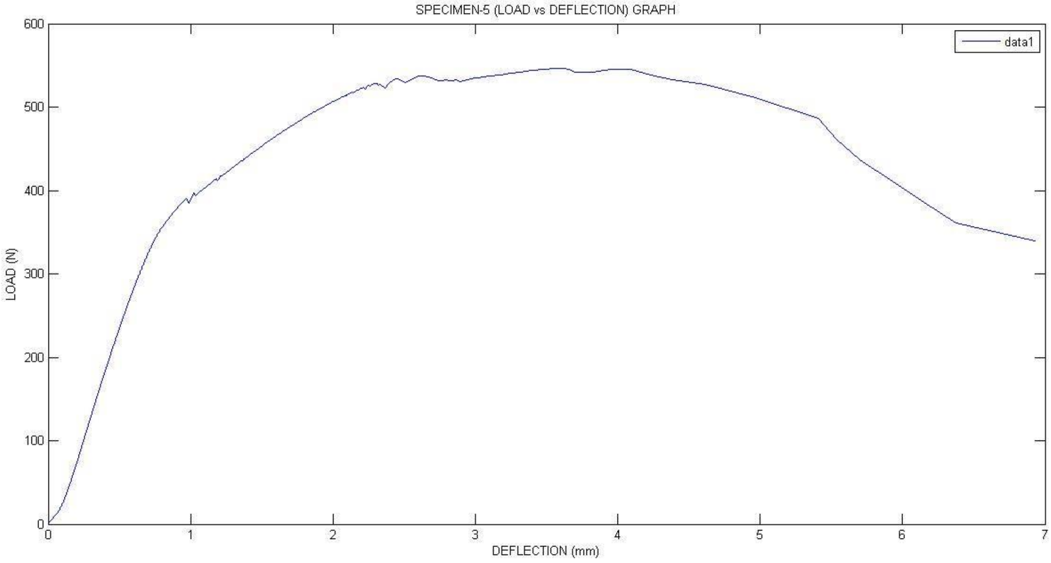

Figure.42 Load vs Deflection Graph

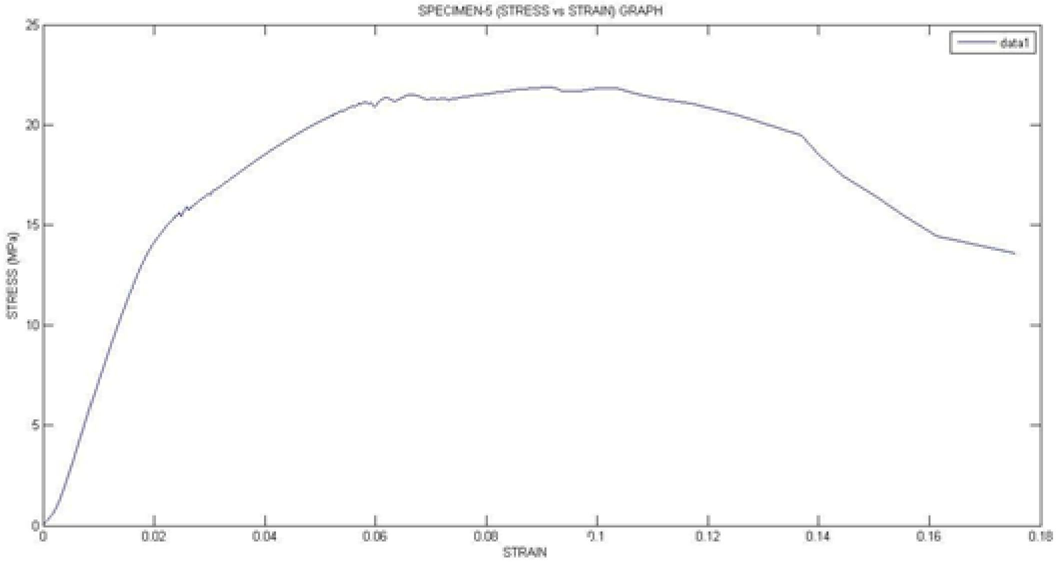

Figure.43 Stress vs Strain Graph

Table.19 Flexure Test Result

Specimen label	Flexure stress at Tensile strength [MPa]	Flexure strain (Extension) at Tensile strength [mm/mm]	Load at Tensile strength [N]	Position at Tensile strength [mm]
1	20.89028	0.07876	529.93378	11.18483
2	22.53654	0.08666	587.16907	10.93768
3	20.22257	0.07799	513.01459	11.15232
4	21.00095	0.08476	539.34662	11.01528
5	12.33217	0.01546	303.80539	13.63816
6	23.17123	0.09032	546.40997	10.71494

Table.20 Flexure Test Result

S. NO	Specimen	Load at fracture (N)	Deformation at fracture(mm)	Stress at fracture(MPa)	Strain at fracture(mm/mm)
1	Specimen1	294.3798	0.57365	11.77519	0.01506
2	Specimen2	280.7434	0.45752	11.22974	0.0121
3	Specimen3	391.0749	0.99028	15.643	0.02587
4	Specimen4	233.134	0.37179	9.325359	0.00982
5	Specimen5	397.2476	1.02497	15.8899	0.02594

From the Obtained Stress vs Strain and Load vs Deflection graphs, it can be seen that the Stress, Strain and deflection are similar to the various specimen. But the fracture occurs in different load points. So the Average of all the Result obtained from the various specimen are taken for comparison.

4.3 Analytical Calculation

The analytical calculation of the GFRP composite is done using the mechanics of materials formulas. The stress, deflection at the given load point can be calculated.

A reduction element width/ width of reduced layers

B_1 =B

$$B_2 = B_1 * \left(\frac{E2}{E1}\right)$$

$$B_3 = B_1 * \left(\frac{E3}{E1}\right)$$

Center of area

$$Y_C = \frac{\left(\frac{B_1 * H_1 * H_1}{2} + B_2 * H_2 * \left(\frac{H_1 + H_2}{2}\right) + B_3 * H_3 \left(\frac{H_1 + H_2 + H_3}{2}\right)\right)}{(B_1 * H_1 + B_2 * H_2 + B_3 * H_3)}$$

Moment of Inertia

$$I_{XC} = \left\{\left(\frac{B_1 * H_1^3}{12}\right) + \left(\frac{Y_C - H_1}{2}\right)^2 * B_1 * H_1 + \left(\frac{B_2 * H_2^3}{12}\right) + \left(Y_C - \left(\frac{H_1 + H_2}{2}\right)\right)^2 * B_2 * H_2 + \left(\frac{B_3 * H_3^3}{12}\right) + \left(Y_C - \left(\frac{H_1 + H_2 + H_3}{2}\right)\right)^2 * B_3 * H_3\right\}$$

Maximum stress

Stress max at center area= $\left(\frac{M_X}{I_{XC}}\right) * (H_1 - Y_C)$

Stress max at other area= $\left(\frac{M_X}{I_{XC}}\right) * (H_1 + H_2 + H_3 - Y_C) * \left(\frac{E_2}{E_1}\right)$

Stress on layer joint

Stress at layer joint 1= $\left(\frac{M_X}{I_{XC}}\right) * (H_1 - Y_C)$

Stress at layer joint 2=$\left(\frac{M_X}{I_{XC}}\right) * (H_1 - Y_C) * \left(\frac{E_2}{E_1}\right)$

Stress at layer joint 3=$\left(\frac{M_X}{I_{XC}}\right) * (H_1 + H_2 - Y_C) * \left(\frac{E_2}{E_1}\right)$

Stress at layer joint 4=$\left(\frac{M_X}{I_{XC}}\right) * (H_1 + H_2 - Y_C) * \left(\frac{E_3}{E_1}\right)$

Where,

L= Length in m

B= Breath in m

H= Height in m

Mx= Moment in Nm

E1= young's modulus of laminate in Pa

E2= Young's modulus of core in Pa

F= Force in N

I= Moment of inertia m^4

V= Deflection in m.

4.4 Result of Analytical Calculation

Data used for Analytical calculation in Matlab

B=25e-3; Breadth in m

H1,H2,H3=1.5e-3; Height in m

Mx=300*60e-3/4;   Moment in N/m

E1,E2,E3=10.78e9; Young's modulus in Pa

F=300; Force in N

L=60e-3; Length in m

G=8e6; Shear modulus in Pa

Table.21 Analytical Result

S.NO	Load at fracture (N)	Deformation at fracture(mm)	Stress at fracture(MPa)	Strain at fracture(mm/mm)
1	300	0.511	13.9	0.01295

5. Finite element modelling and analysis using Abaqus

5.1 Modelling

The glass fiber reinforced polymer (GFRP) composite with foam sandwich structure is modelled using Abaqus. The 3D deformable solid body is created with the dimension of Length=30, Width=12.5, Thickness=8 which is one fourth of the experimental model.

Then the composite layer up is created using solid composite in material section. The material properties obtained from the experimental testing are

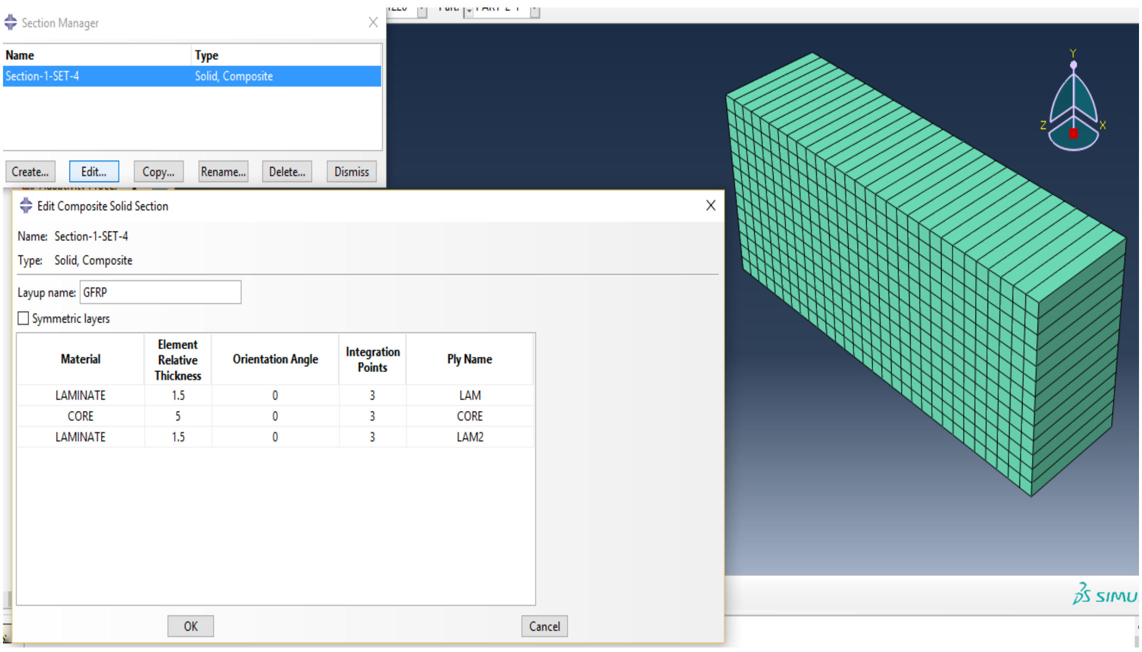

Figure.44 Assigning Material Properties

The material properties which are obtained from the Experimental analysis of laminate and foam is given to the finite element model. Where, elastic properties is given as engineering constant to laminate and core material and yield stress and plastic strain is given as plastic property.

5.1.1 Meshing

Finite element mesh is done on the the composite using sweep option, in order to obtain stress and deformation at different layers

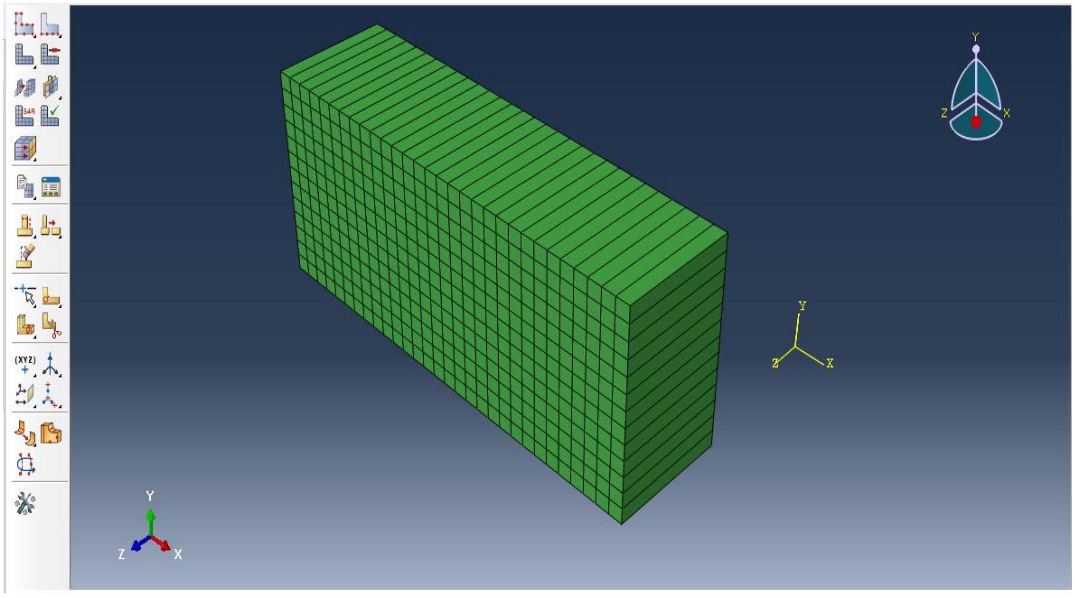

Figure.45 Meshed Model

5.1.2 Boundary conditions

The displacement and rotation of the model is constrained as per the conditions and the load of surface traction is applied in the composite.

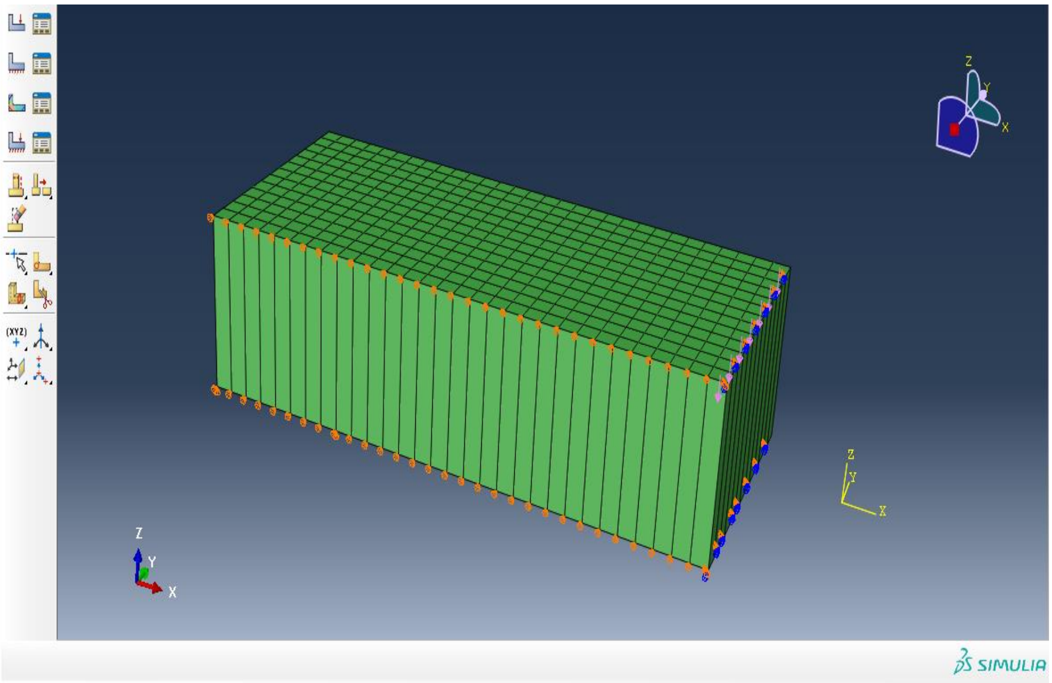

Figure.46 Boundary Condition

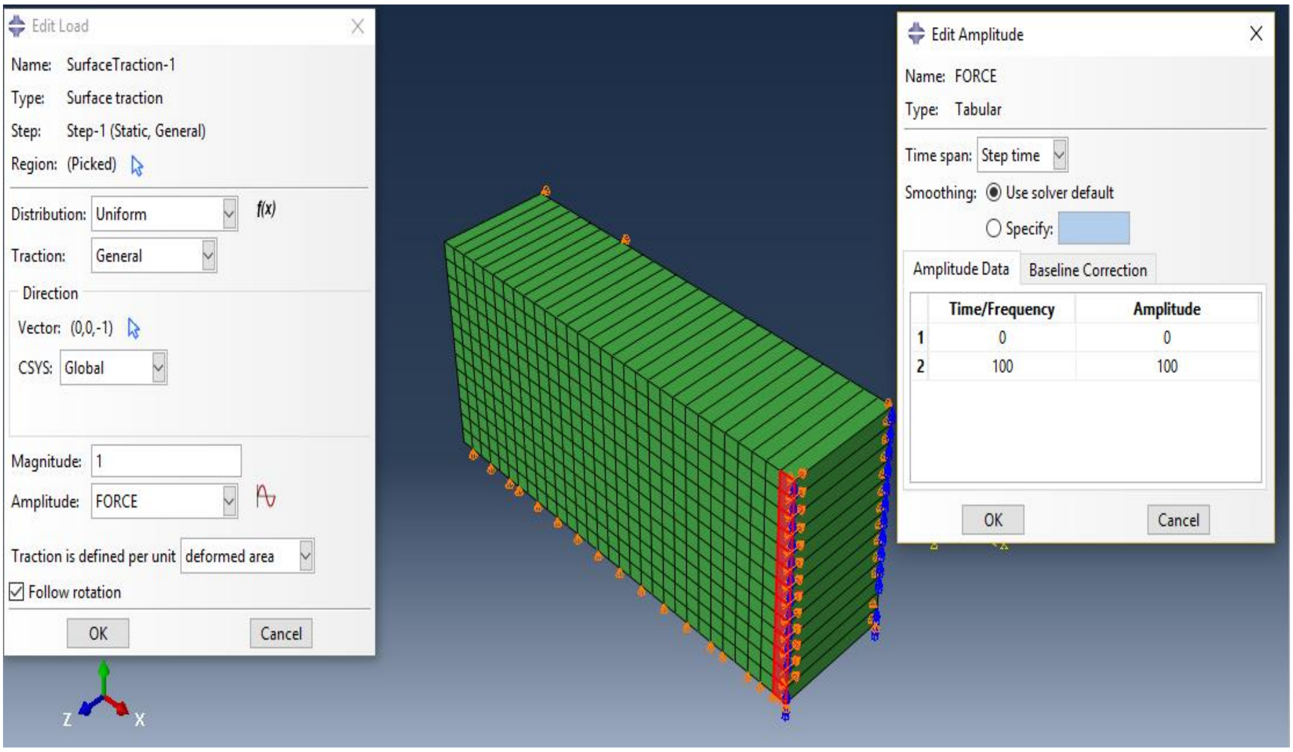

Figure.47 Load Condition

5.2 Simulation Result in Abaqus

The 3-point bending simulation is done in the Abaqus software. The Static, general type of analysis is conducted. The desired field outputs and history outputs are given in the step. The results obtained are

5.2.1Stress Plot

The Maximum Principle Stress plot shows the distribution of Stress in the Finite Element Model to the given load. It can be seen that the Stress is concentrated on the elements, where the load is applied.

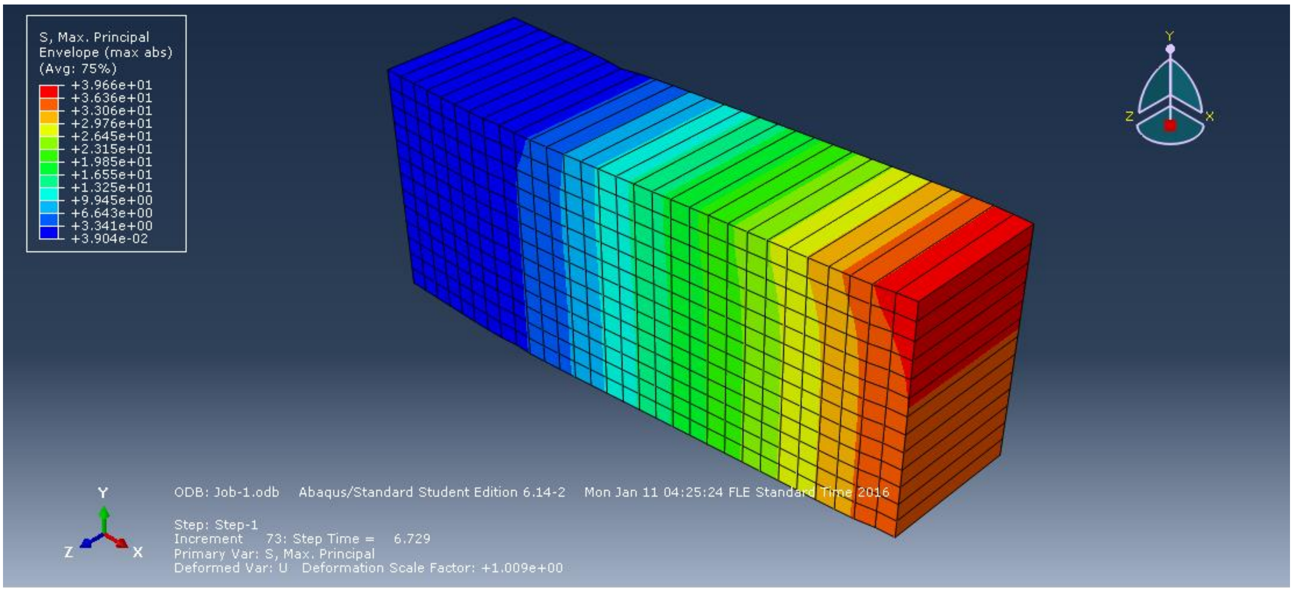

Figure.48 Stress plot of the model

5.2.2 Strain Plot

The maximum principle Strain plot shows the distribution of the strain in the Finite element model to the given Load. It can be seen that the Strain concentration is high on the fixed end U3. Since the load is applied on the U3 direction.

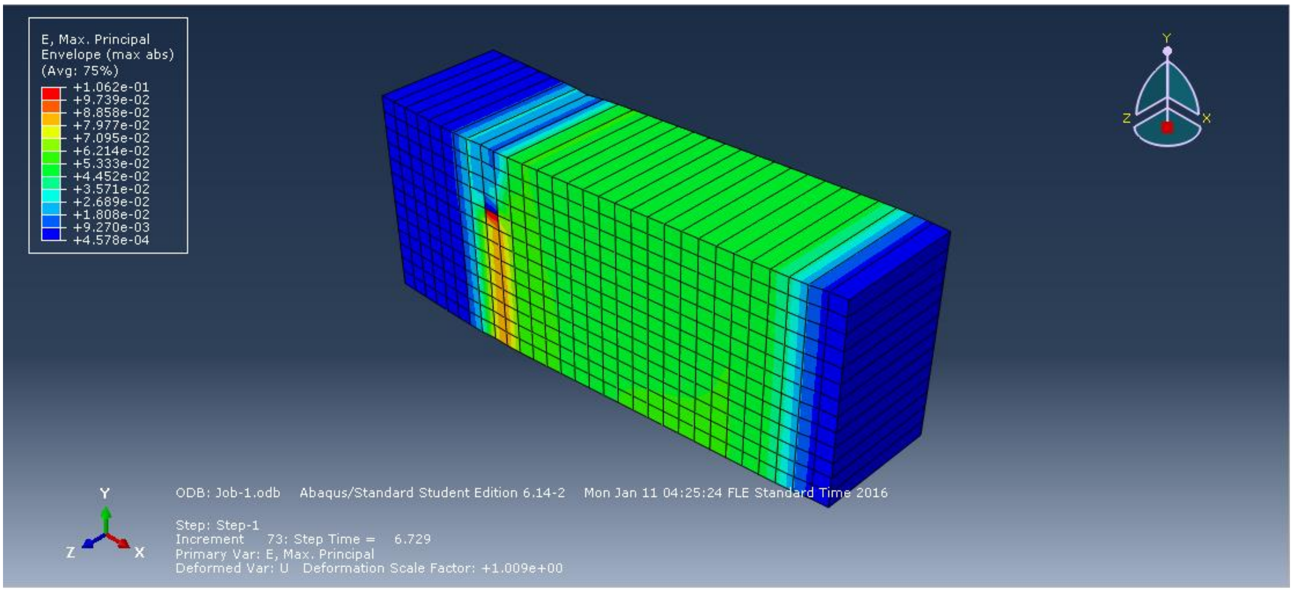

Figure.49 Strain plot of the model

5.2.3 Deformation

The Deformation plot shows the deformation of the model to the applied traction load. It is seen that the element at which the load is applied, shows maximum deformation.

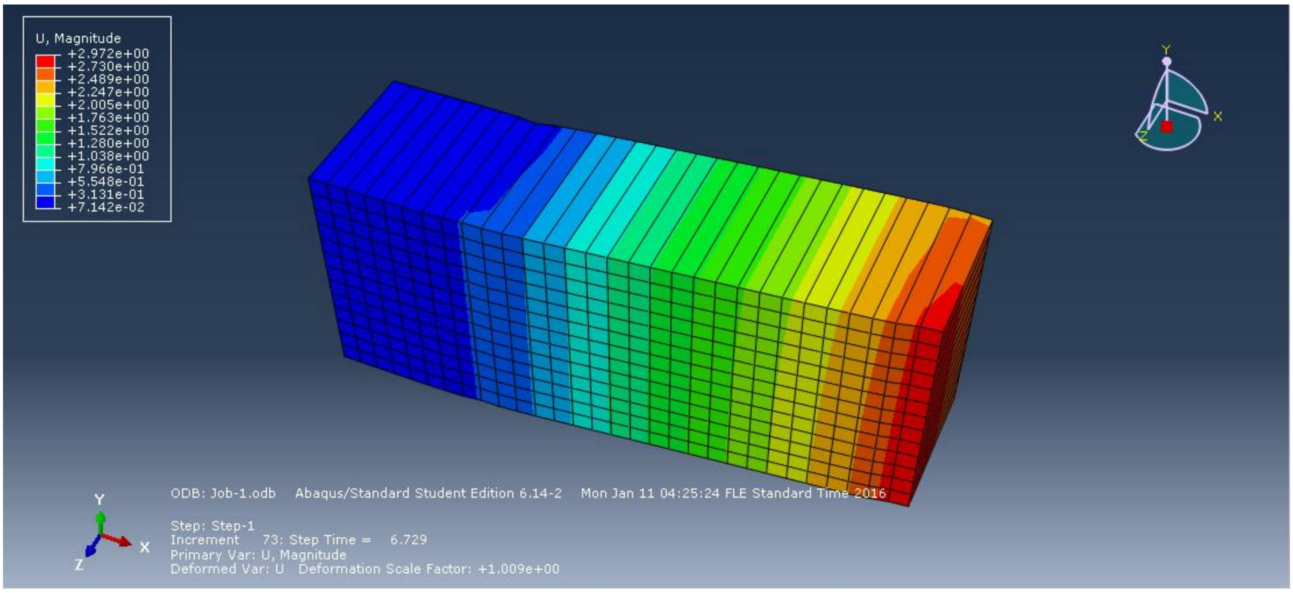

Figure.50 Displacement plot of the model

5.2.4 Stress Triaxiality

Stress Triaxiality plot shows the state of stress in the plastic deformation part. It can be seen that Stress Triaxiality is concentrated on the fixed end U3, where the strain concentration is more according to the strain plot (Figure.49 Strain plot of the model).

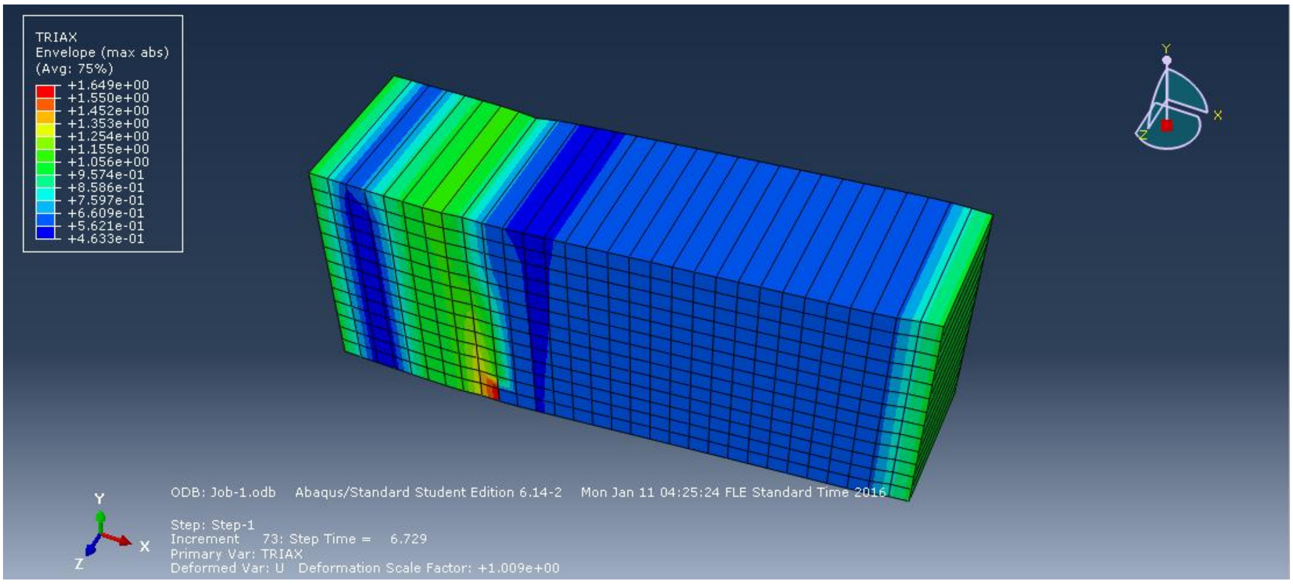

Figure.51 Stress Triaxiality in the model

5.5 Reaction Force Plot

Reaction force plot shows the force acting opposite to the given load. It can be seen that reaction force is concentrated on the load element.

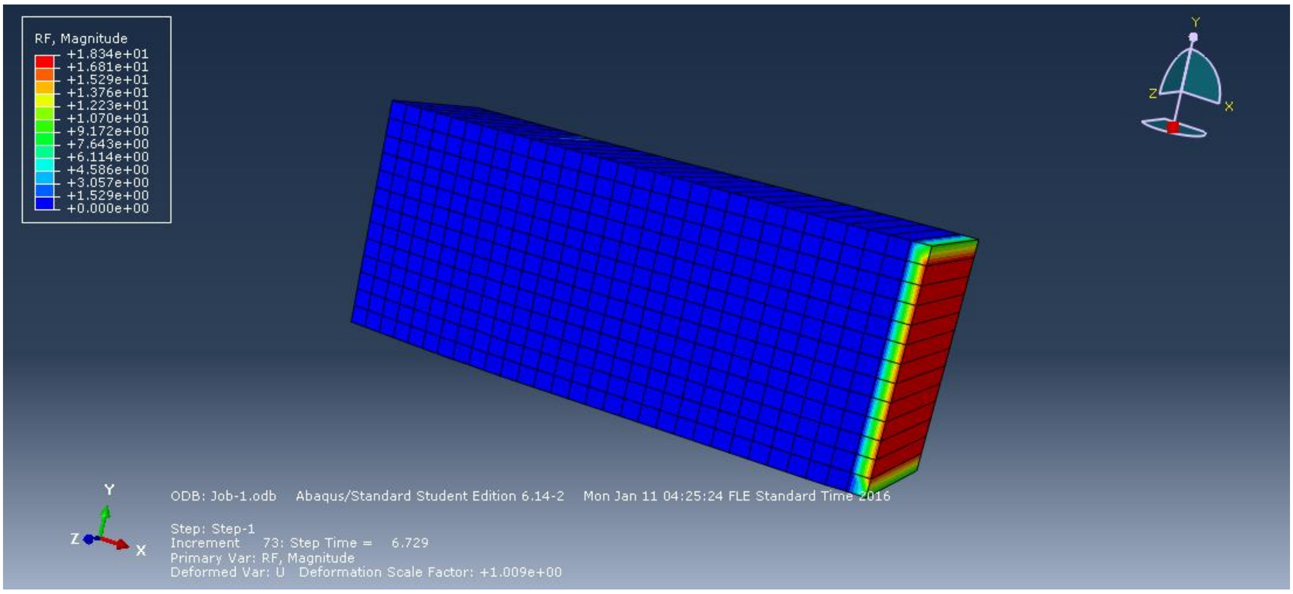

Figure.52 Reaction Force Plot

5.6 Ductile Damage of the Composite

Ductile Damage Plot shows the area of the ductile damage evolution. The ductile damage evolves from the fixed end at U3 and at load point of the model.

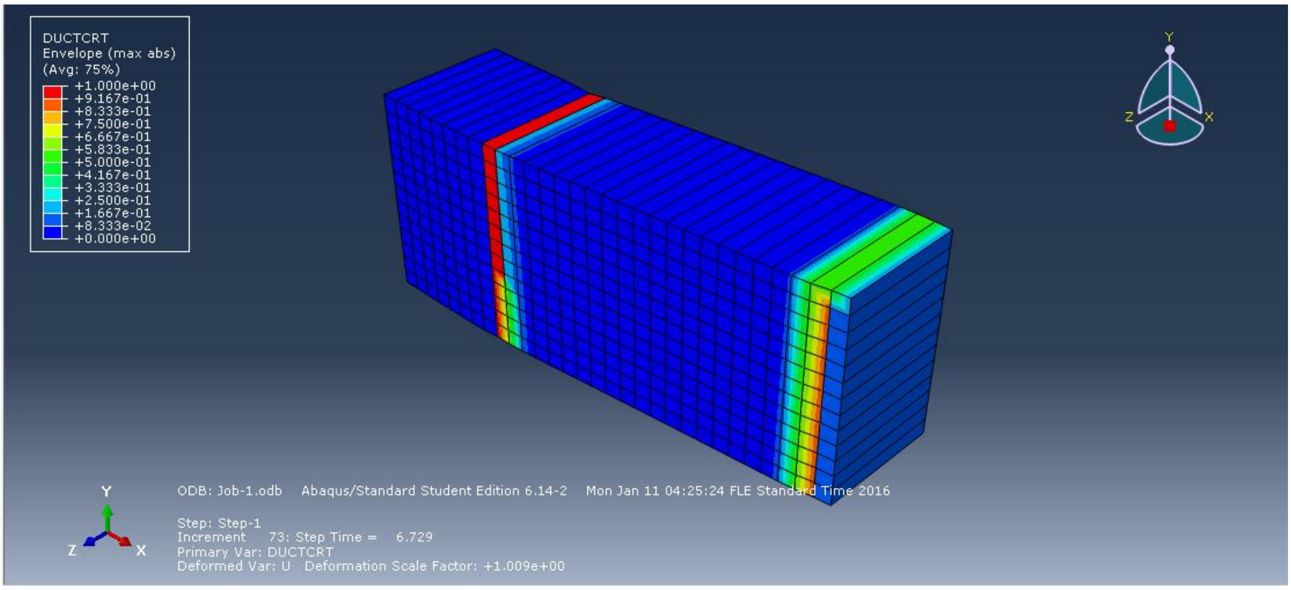

Figure.53 Ductile damage of the model

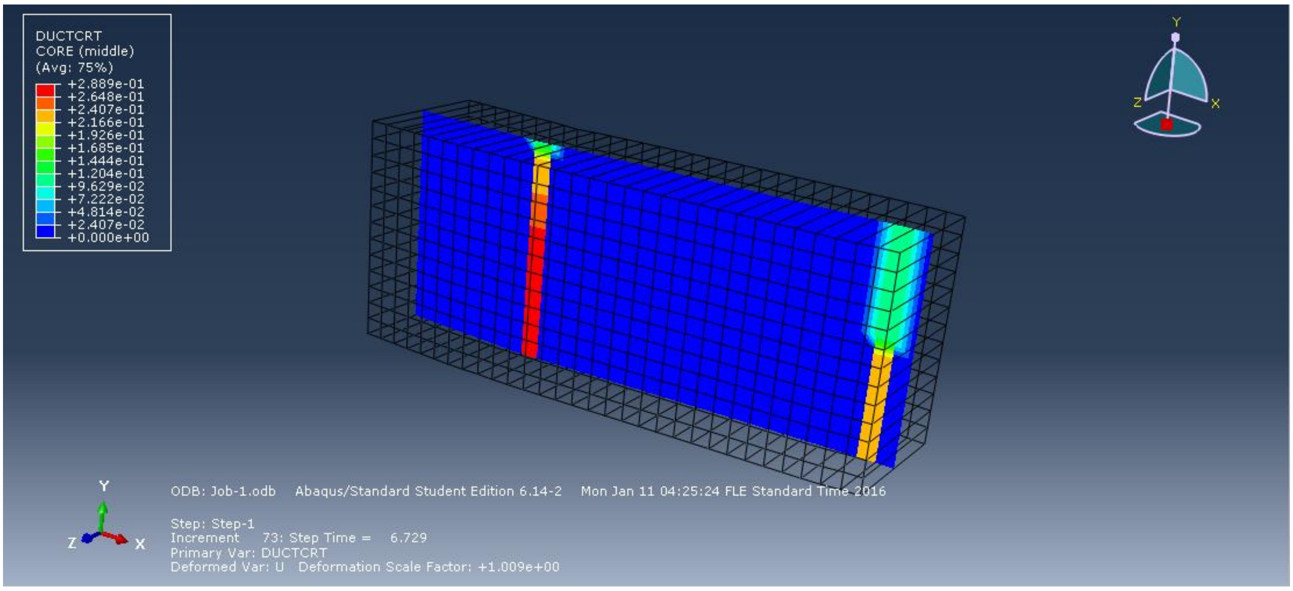

Figure.54 Ductile damage at Core

5.7 Shear Damage of the Model

Shear Damage plot shows the evolution of the Shear damage in the composite. Shear damage evolves from the core part of the composite model.

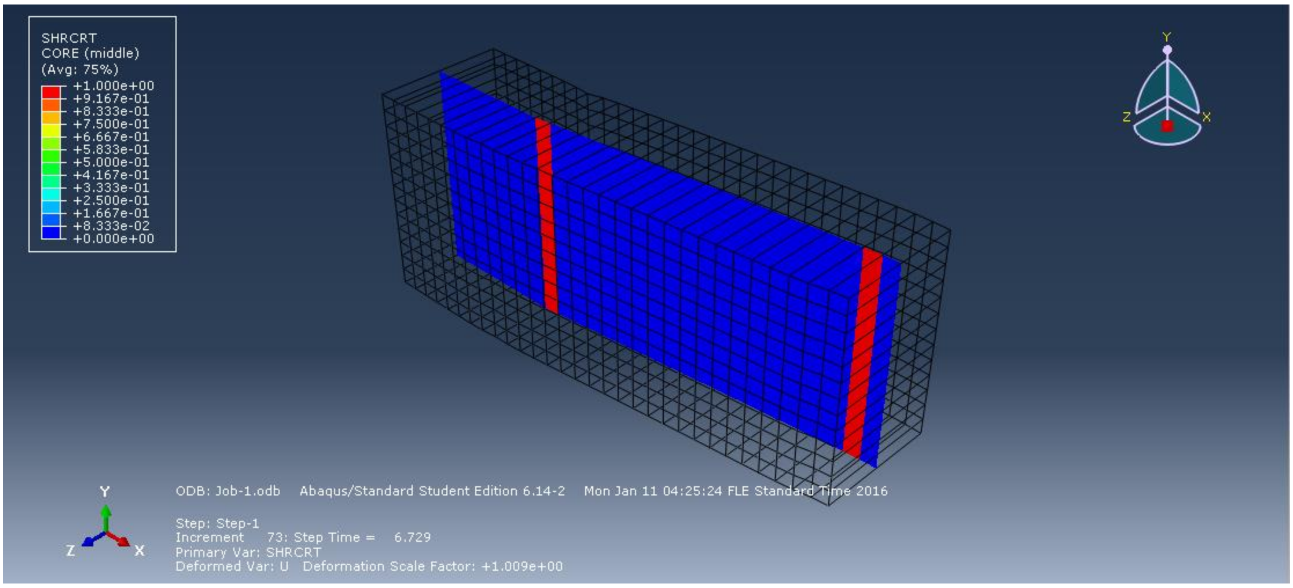

Figure.55 Shear damage at core

From the above Results from Abaqus, the mechanical behavior of the composite model to the given load can be seen through the various Stress, Strain and Deformation plots. The evolution of the ductile and shear damage is determined. Ductile damage evolves on both Laminate and Core material. The shear damage evolves from core Material. The results shown above are at the fracture point of the composite, which at load of 336.45 N.

6. Result Comparison and Discussion

The 3-point bending (Flexure) test is conducted, the Result are calculated from the Load vs Deformation Graph as shown in Figure. 34, 36,28,40,42 and Stress vs Strain Graph as shown in Figure. 35, 37,39,41,43. Simulation is done in Abaqus software with the obtained material properties from Experimental testing. The obtained material property are shown in Table.10, 11, 12, 13,14,15,16. The Stress, Strain, Deformation, Ductile damage and Shear damages are simulated as shown in Figure48,49,50,51,52,53,54,55. The analytical calculation is done using Matlab and the obtained result are shown in Table 21.

Table.22 Comparison of Results

S. NO	Analysis Method	Load at fracture (N)	Deformation at fracture(mm)	Stress at fracture(MPa)	Strain at fracture(mm/mm)
1	Experimental(Specimen1)	294.3798	0.57365	11.77519	0.01506
2	Experimental(Specimen2)	280.7434	0.45752	11.22974	0.0121
3	Experimental(Specimen3)	391.0749	0.99028	15.643	0.02587
4	Experimental(Specimen4)	233.134	0.37179	9.325359	0.00982
5	Experimental(Specimen5)	397.2476	1.02497	15.8899	0.02594
6	Experimental(Average)	319.31594	0.683642	12.7726	0.0177
7	Simulation	336.45	0.69578	14.544	0.01831
8	Analytical	300	0.511	13.9	0.01295

The obtained Result from Experimental, Analytical and simulation analysis are tabulated above. It can be seen that the Load at fracture differs for different specimen in Experimental analysis, so the Average value of the five specimen is taken. The experimental and analytical data shows good qualitative and quantitative agreement to the FE simulations data as shown in Table. 22. Thus the mechanical behavior of the Glass Fiber Reinforced (GFRP) composite is predicted.

Conclusion

1. The Glass fiber reinforced polymer (GFRP) composite is tested experimentally and the material properties are obtained.
2. The experimental analysis and analytical calculation of GFRP composite is done.
3. The Finite Element Model is created and the Stress, Strain, Deformation and Damages are simulated in Abaqus.
4. The experimental and analytical data shows good qualitative and quantitative agreement to the FE simulations data.

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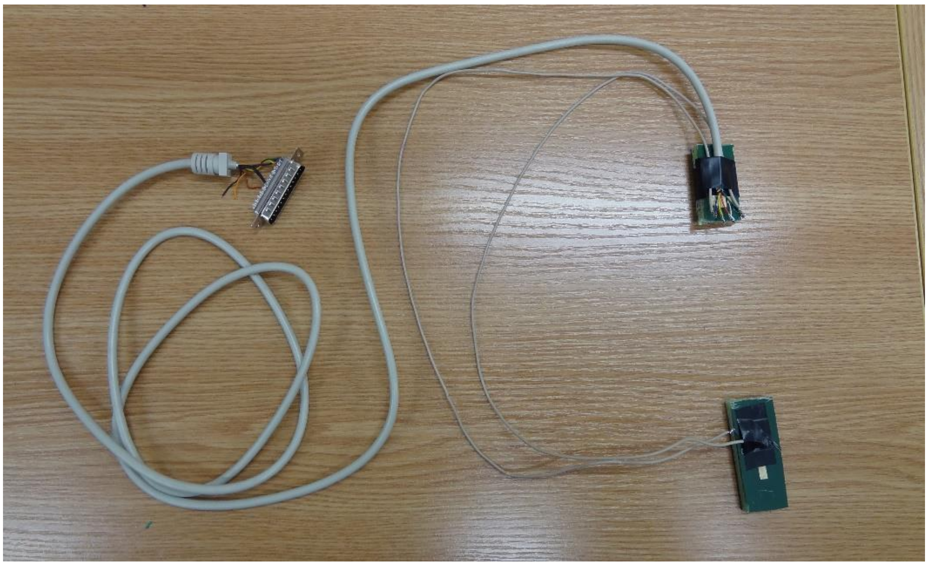
Appendices

1. Matlab Program for Analytical Calculation

```
%                B
%     ------------------------
%    |           E3           |  H3
%     ------------------------
%    |           E2 ->xc      |  H2
%     ------------------------
%    |           E1           |  H1    Mx
%     ------------------------------------>x
%                                              x

      B=25e-3; H1=1.5e-3; H2=5e-3; H3=1.5e-3; % m
      Mx=300*60e-3/4;                          % Nm
      E1=10.78e9; E2=3.4e7; E3=10.78e9;             % Pa

%  A reduction element width / widths of reducted layers
    B1=B; B2=B1 * E2/E1; B3=B1 * E3/E1;

%  Calculated reduced area of ??the coordinate of the center / Center of area
    yc=(B1*H1*H1/2 + B2*H2*(H1+H2/2)+ B3*H3*(H1+H2+H3/2))/...
           (B1*H1 +  B2*H2 +  B3*H3);

% Compute the reduced area, moment of inertia of the center
%  Inertia moment of reducted cross section
     Ixc=B1*H1^3/12 + (yc-H1/2)^2 * B1*H1 +...
            B2*H2^3/12 + (yc-(H1+H2/2))^2 * B2*H2+...
            B3*H3^3/12 + (yc-(H1+H2+H3/2))^2 * B3*H3;

%   maximum  stress
    s_z1max=Mx/Ixc*(-yc);
    s_z3max=Mx/Ixc*(H1+H2+H3-yc)*E3/E1;
    [s_z1max s_z3max]

%  stress on layer joins
    s_z12_1=Mx/Ixc*(H1-yc);
    s_z12_2=Mx/Ixc*(H1-yc)*E2/E1;
    s_z23_2=Mx/Ixc*(H1+H2-yc)*E2/E1;
    s_z23_3=Mx/Ixc*(H1+H2-yc)*E3/E1;
    [s_z12_1 s_z12_2 s_z23_2 s_z23_3]

%  stress plot
    figure; plot([0 s_z1max s_z12_1 s_z12_2 s_z23_2 s_z23_3  s_z3max     0],...
                 [0 0                H1          H1            H1+H2    H1+H2
H1+H2+H3 H1+H2+H3],...
                 [0 0],[0  H1+H2+H3],'r--');
              xlabel('STRESS, Pa'); ylabel('y, m');


%  deflection
F=338; L=60e-3; E=10.78e9; G=8e6; I=Ixc; A=(5e-3*25e-3+2*1.5*25*54/8);
v=F*L/4*L/2/2*2/3*L/4*2/E/I+F/2*L/2*2/G/A
sew33
```

2. Strain Transducer is made as per the Bridge circuit. It is used in Experimental analysis of

composite to find Strain.



3. These photos are taken during the initial works of calibrating the Force transducer.

4. This photo is taken during the initial work of testing the wing like structure of wooden beam.