STRESS AND MODAL ANALYSIS OF FIBER REINFORCED EPOXY NANOCOMPOSITES

A
Dissertation
Submitted in partial fulfillment of the requirement for the award of degree
MASTER OF ENGINEERING
in
CAD/CAM ENGINEERING

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July, 2015

CERTIFICATE

I hereby declare that the disstertation entitled "Stress and modal analysis of fiber reinforced epoxy nanocomposites" is an authentic record of my work carried out in partial fulfillment of requirements for the award of Master of Engineering in CAD/CAM Engineering in Department of Mechanical Engineering of Thapar University, Patiala under the guidance of Mr. Bikramjit Sharma, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala during July, 2013 to July, 2015.

The matter embodied in this dissertation has not been submitted in part or full to any university or institute for the award of any degree.

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ACKNOWLEDGEMENT

I sincerely express to my deep sense of gratitude to my dissertation supervisor **Mr. Bikramjit Sharma,** Assistant Professor, Department of Mechanical Engineering, Thapar University, Patiala for his invaluable guidance and proper advice during my dissertation work.

I would also like to express my sincere regards to **Dr. S.K. Mohapatra,** Senior Professor and Head of the department, for proving me all necessary facilities to progress my work smoothly.

I am very thankful to other faculty members of Mechanical Department of Thapar University, for their constant support and inspirational thoughts which gave me a positive attitude for my dissertation work.

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Abstract

With the increase of competition in the field of materials, requirement of lighter and best material is in a huge demand in the market. Nanocomposites are a new class of materials which give better mechanical properties even at small amounts of nanofillers. So, the researchers are approaching from the direction of nanocomposites to meet the requirement of strength and mass. In this context, the finite element methods find application in studying the properties of new materials and evaluate their performance under different loading conditions. In the present work, the element meshes have been prepared in OOF2 after inputting the original morphology of fiber reinforced epoxy nanocomposites. The stresses and modal analysis have been carried out in Abaqus. The results of the analysis carried out under tensile loads are found to be close to experimental results under 22.5% deviation.

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Abbreviations

OOFEM	Object Oriented Finite Element Method
SEM	Scanning Electron Microscopy
FEM	Finite Element Method
OOF2	Object Oriented Finite Element Analysis Version 2
MRF	Modulus Reduction Factor
ROM	Rule of Mixtures
IROM	Inverse Rule of Mixtures
PNC	Polymer nanocomposites
MMT	Montmorillonite
OMMT	Organosilicates
NIST	National Institute of Standards Technology

Notations

E	Energy
E_{hom}	Homogenous energy
E_{shape}	Shape energy
α	Inverse aspect ratio
$M\ Pa$	Mega Pascal
$G\ Pa$	Giga Pascal
$Å$	Angstrom

Chapter 1 INTRODUCTION

1.1 Nanocomposites

The composites are a combination of two or more than two different components that are mixed in such a way that after combining they have the best properties of both. A nanocomposite is defined as multiphase solid material where one of the phases has one, two or three dimensions of less than 100nm, or structure having nanoscale repeat distance between the different phases that make up the material. The term nanocomposite is different from the traditional composites. The nanocomposites have a high surface-volume ratio of the reinforcement or its uncommon aspect ratio. The first publication on nanocomposites came in 1970. They were produced by Unitika Ltd. and Toyota laboratories that used nanocomposites parts for the manufacturing of their novel car models.

The rapidly growing field of nano–engineered materials is developing various perspectives for composites and plastics, which have a lot of applications for polymer nanocomposites in engineering industries. The level of control required for the process of fabrication, processing and performance is achievable up to the atomic level. Thus, nanocomposites can be distinguished from the conventional composites (nanocomposites have a high surface-volume ratio of the reinforcement phase or have a high aspect ratio). Nanocomposites have discontinuous phase (called as the reinforcing material) (one or more) dispersed in a continuous phase (called as the matrix phase). The discontinuous phase (reinforcing material) consists of minerals, fibers (carbon nanotubes), sheets (exfoliated stacks of clay). The interface area between the reinforcement phase and the matrix phase has a high magnitude, i.e. greater than traditional composite materials. If the reinforcement surface area is large, nanoscale reinforcement will become smaller and it will have observable scale properties of the composite.

Nanoparticulates may enhance the mechanical properties (strength, stiffness, wear resistance, physical properties, dielectric properties, heat resistance, optical properties etc.).

1.2 Constituents of Composites

Nanocomposites materials have following functional constituents

1.2.1 Matrix (primary phase):

The matrix (or primary phase) holds the fibers together freezing in the fiber orientation, if any. When and load is applied to the composite, then it is transferred into the fibers, which are the principal load-bearing component which withstand for the tensile, compression, shear forces as well as flexural loads. The matrix will act as separate entity only when it isolates the fibers from each other. The matrix protects the reinforcing filaments from environmental attacks and mechanical damage (e.g. Abrasion etc.). For example, for composites like ceramic matrix composites (CMCs) or metal matrix composites (MMCs) working at elevated temperature, the matrix needs to protect the fibers from oxidative attack. The desired properties necessary for a matrix phase have been discussed as follows:

(a) It should have Low shrinkage value.
(b) It should have low coefficient of thermal expansion.
(c) It should have a low moisture absorption rate.
(d) It should have good flow characteristics so that it thoroughly goes into the fiber bundles and removes the voids during the curing/ compacting process.
(e) It should have good strength at elevated temperature.
(f) It should be easily processable into the final composite shape.
(g) It should have reasonable strength, elongation and modulus. It must be elastic to transfer the loads to the fibers.
(h) It should have excellent chemical resistance (depending upon the applications).
(i) It should have dimensional stability.

1.2.2 Reinforcement (secondary phase):

The reinforcement (secondary phase or dispersed phase) is also the load bearing constituent of a composite. It can be in the size of nano, micro, or macro level. All the loads applied on the matrix are transferred to this reinforcement through an interface. Reinforcement is generally firmer or harder in nature in comparison to the matrix. Strong bonding at the matrix and reinforcement interface enhances the mechanical properties.

1.2.3 Interface:

The interface in fiber reinforced composites is defined as a surface made by a common boundary of matrix and reinforcing fiber that remains in contact with and keeps the bonds in between for transfer of the loads. It has some unique physical and mechanical properties that differ from fiber or the matrix. The interface is the geometrical surface of the classic fiber-matrix which remains in contact as well as the area of finite volume enlarging therefrom, wherein the physical, chemical and mechanical properties change either continuously or in a stepwise manner between those of the matrix material and bulk fiber. The interface is illustrated in Figure 1.1.

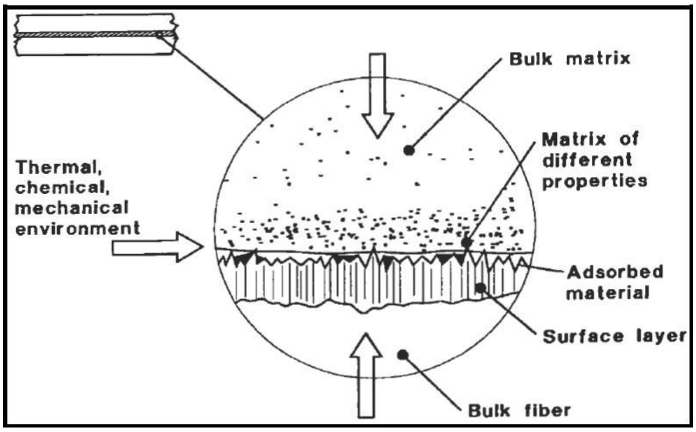


Figure 1.1: Schematic illustration of interface between fiber and matrix [1]

The manner in which the properties like in materials where the mechanical action depends on loads being shared between two or more different constituents or phases. When the toughness and strength of composites are studied, the strength of the interfacial bond between the matrix and the fibers becomes an important factor. Interface properties totally depend on the physical and chemical nature of the matrix and the fibers and the properties differs from those of either of the two major components. It is the interface's properties which decide the mode in which stresses are transferred from the matrix to fibers and, in aftereffect, finalize many of the physical, chemical and mechanical properties of the composite.

1.3 Polymer nanocomposites

Polymer nanocomposites (PNC) are a class of polymers like elastomers, thermosets, and thermoplastics with small amounts (>5 wt. %) nano-sized particles as the reinforcement.

Ultra-large interfacial area (per unit volume) between the host polymer and nanoparticles can be developed as a result of uniform dispersion (nanoparticles in polymer matrix). Thus, the huge internal interface area and the nanoscopic dimensions (among nanoparticals) primarily differentiate PNCs from traditional composites and filled plastics. Introduction of nanoparticles to polymer matrix ensure significant property improvements with very low loading levels. Traditional micro particle additives require much higher filler concentration to achieve similar results.

1.3.1 Epoxy nanocomposites

The nanocomposites have structural applications. The task is a very difficult one, a great care has to be taken to disperse nanoparticles in polymer matrix as nanoparticles have a tendency to aggregate together during manufacturing. The optoelectronic, thermal, and mechanical properties of the nanocomposites totally depend on the dispersion of nanoparticles in the polymer matrix.

1.3.2 Fiber reinforced epoxy nanocomposites

The fiber reinforced epoxy nanocomposites consists of following materials:

- **Epoxy:**

In 1946, the man-made epoxy resin approached the market. Since that day the demand of epoxy in applications of thermosetting polymers has increased day by day. Epoxy resin are systems mainly used in polymer industries as matrices in composite materials for a wide range of automotive parts, structure of the aircraft, for shipbuilding and in making of electronic devices. The term epoxy resin (representing prepolymer and cured resin/hardener system) is a three membered ring. It is generally known as epoxy, oxirane, epoxied, and glycidyl or ethoxyline group. Epoxy group can be represented as the following figure.

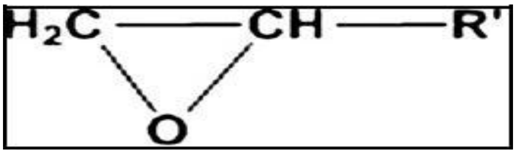


Figure 1.2: Epoxy or oxirane group [2]

This chemical structure of epoxy remains in strained position and it is highly reactive in nature. Epoxy resins are cross-linked through a polymerization reaction with hardening agent, at room temperatures (aliphatic amines) or at high temperatures (aromatic amines and acid anhydrides). Generally, system with resins cured at high temperature have good properties (strength, stiffness, and higher glass transition temperature), in comparison to those which cured at room temperatures. Epoxy resins have superior properties viz. heat resistance, chemical resistance, electric resistance, adhesive strength, impact resistance, hardness, strength, along with the absence of byproducts/volatiles during cuing reactions, low shrinkage during cure, curing over a wide range of the temperature, resistance to solvents, excellent adhesion for the wide variety of fillers, and other substrates. Cured epoxy resin shows good temperature performance because of high cross-linking density. But these cured resins have deficiency of required toughness and they are very brittle[3].

- **Clays:**

Clay is an inorganic component made of soil, which carries a negative charge. The chemical formula of clay is $[Al_4Si_4O_{10}(OH_8)]$. Sand is majorly composed of large size particles of silicon dioxide (SiO_2). Clay is composed of very small particles in diameter. In comparison, of the sizes of silt particles with sand particles, their sizes vary from 0.002 – 0.05 mm and 0.05 – 2.0 mm respectively. Clay is considered to have a fine texture, silts have a medium texture, and the sands have a coarse texture. According to Alexandre et al.[3], clay like montmoriillonite is used in making of polymer nanocomposite, which has unique mechanical, electrical and optical properties [4].

Montmorillonite (MMT) is a very common name in the study of nanoclay and it is a layered aluminosilicate in the smectite family of clay. MMT can be dispersed into an individual layers of 1×(70 – 150) nm cross section.

Figure 1.3: Montmorillonite Clay [4]

a) Structure and properties of Nanoclay

The silicate is a composition of small crystalline particles composed of aluminosilicates where magnesium and iron are substituted by alkaline and alkalis earth elements. The tetrahedron is formed of silicon-oxygen unit, where four oxygen atoms enclose the central silicon. The tetrahedral is linked to make hexagonal rings. To form a sheet, this pattern is repeated in two dimensions. The octahedron is made with an aluminium oxygen combination, where the aluminium is at the center, and the octahedral link makes a closely packed two–dimensional sheet as shown in Figure. 1.4.

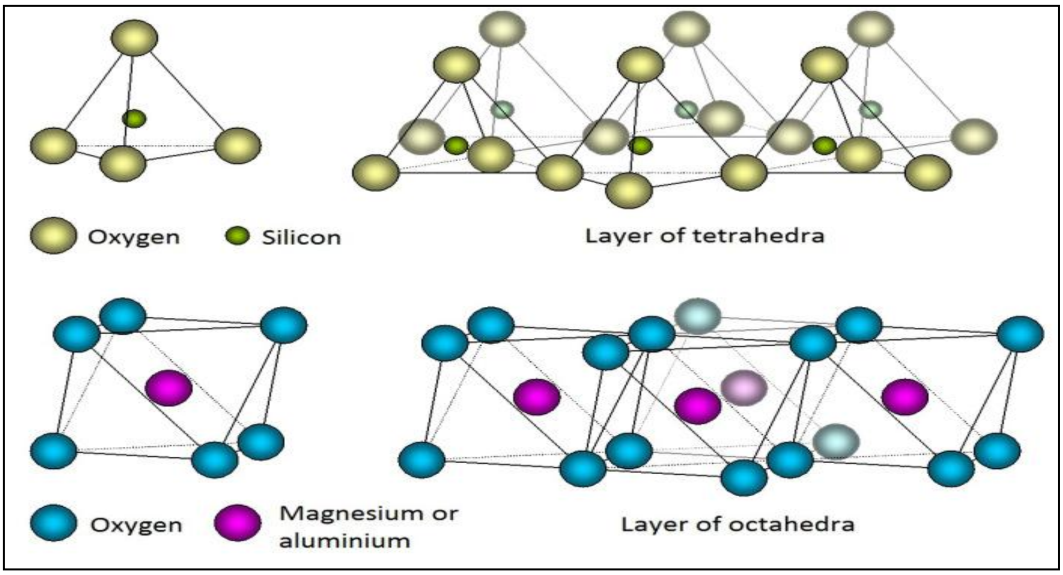


Figure 1.4: Structure of Tetrahedral and octahedral sheets [5]

Silicate structures have two basic types 1: 1 and 2: 1. Non-swelling dioctahedral silicate of 1:1 type is a Kaolinite and Montmorillonite is an example of 2:1 layered silicates in which two tetrahedral layers surround one octahedral layer, and the oxygen atoms are shared. Montmorillonite (MMT) is more popular layered silicates in polymer nanocomposites because of the weak bonding (Vander Waals) between layers. The chemical formula of MMT silicate is as follows:

$$Na_{0.33}(Al_{1.67}Mg_{0.33})Si_4O_{10}(OH)_2\mathrm{n}H_2\mathrm{O}$$

The crystal structure of montmorillonite is a composition of two silica tetrahedron combined with an edge shared octahedral sheet of either alumina or magnesia as shown in fig.1.5.

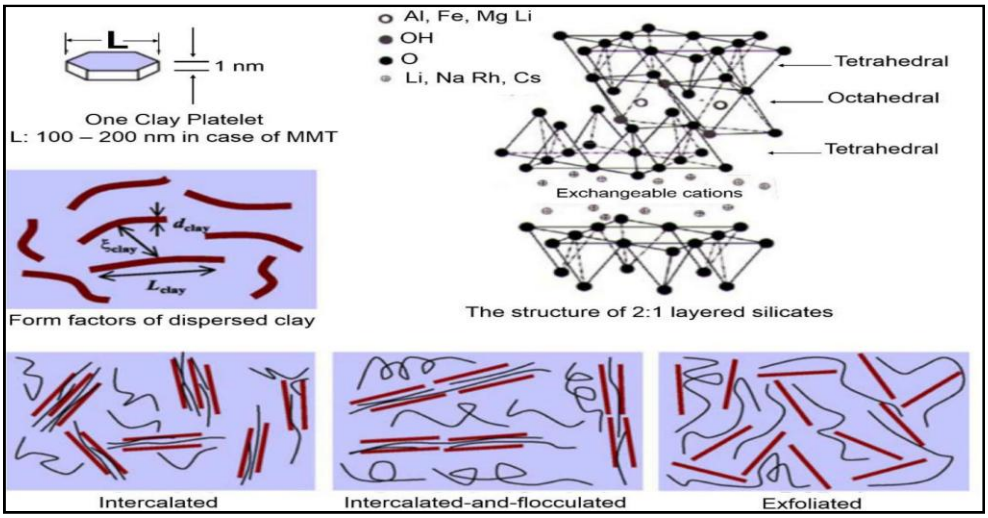


Figure 1.5: Schematic illustration of atomic arrangement in a typical MMT layer [5]

A number of these layers are piled together with weak Vander Waals forces to make a silicate particle. Silicate is required to be organophilic in order to disseminate then in monomer phase. So, organic modification of silicates is done by treatment with suitable modifiers.

b) Organically modified nanoclays

The most common type of layered silicates is montmorillonite which is used in polymer nanocomposites because of its swell able layered structure.

The lack of chemical attraction between hydrophilic silicate and hydrophobic polymer tends to the collecting of the mineral within the polymer matrix. Therefore, pre-treatment of the silicate is required. Pristine layered silicates (MMT) generally consist hydrated Na^+ or K^+ cations. The ion exchange reaction can substitute them with cationic surfactants, also including the amino acids, organic ammonium salts or tetra organic phosphoniums to render the normally hydrophilic silicate surfaces as organophilic. This reaction is exemplified schematically in the fig. 1.6. Alkylammonium ion is a common name of cationic surfactant due to its nature of easily exchanging with the ions placed between the silicate layers. Adoption of the alkylammonium ions various structures between the silicate layers totally depend upon the silicate layer charge density. After the modification silicate turns into organophilic which is known as organically modified montmorillonite (OMMT) and it is compatible with organic polymers. Pre-treatment is done only to gain the interlayer spacing as well as to give better compatibility with the polymer.

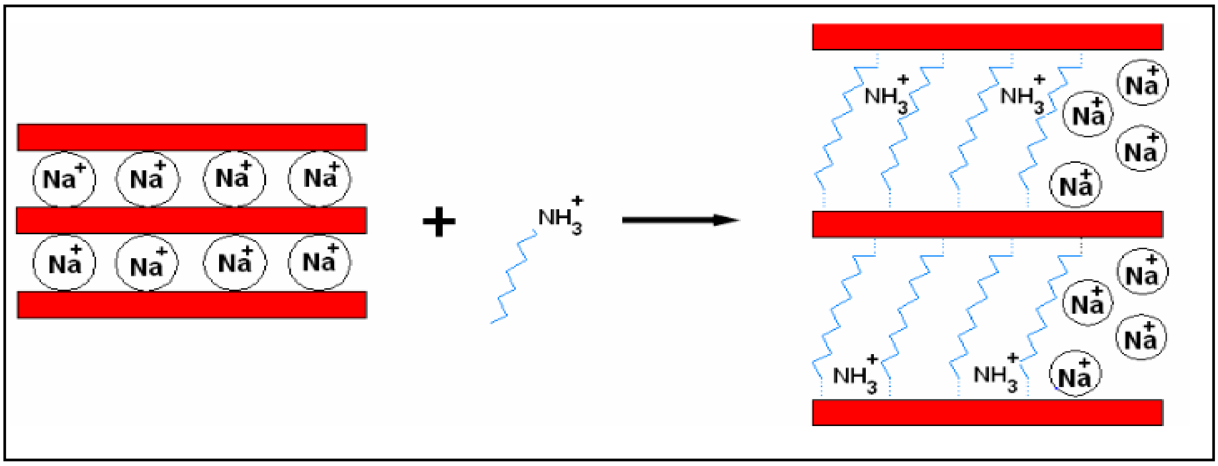


Figure 1.6: Modification of clay surfaces through ion exchange reaction by replacing the Na^+ cations with cationic surfactant [5]

The properties of Cloisite 15A® and Cloisite 30B®

Table 1.1: Properties of Cloisite 15A® and Cloisite 30B® [5]

Properties	**Cloisite 15A®**	**Cloisite 30B®**
Organic modifier	2M2HT	MT2EtOH
Modifier concentration	125 meq/100g clay	90 meq/100g clay
Density	1.66 g/cc	1.98 g/cc
Young Modulus	4.657GPa	4.657GPa
Poisson's ratio (2% weight)	0.34491e-3	0.34491e-3
d001 spacing	31.5Å	18.5 Å
% Weight loss on ignition	43%	30%

1.4 Morphology of nanocomposites

When layered silicates are organically modified and disseminated within a polymer, the spacing starts enlarging to allow for the intercalation of polymer between the unit layers. There are three different types of polymer nanocomposite morphology, which exist according to the nature of the layered clay and polymer matrix and the level of interactions between them. These are intercalated, phase separated and exfoliated.

- **Phase separated**

Layered silicates present the original combined state with no polymer matrix intercalation in the galleries (fig. 1.7a). The particles work as microscale fillers. Their properties are similar to traditional microcomposites.

- **Intercalated:** Intercalated state is the state when the spacing between the layers expands during the insertion of polymer resin into the gallery between the adjacent layers (fig. 1.7b). In the intercalated form, the molecules of matrix polymer are inserted between the ordered layers of silicate resulting enhanced the interlayer spacing with maintaining the order.
- **Exfoliated:** This is the state in which the thick silicate layers are parted and dispersed in a polymer matrix keeping average distances between layers dependent upon silicate concentration (fig. 1.7c). When the layers are fully separated, the silicate is known as exfoliated.

Exfoliated nanocomposites have better specific properties compared to that of intercalated nanocomposites (measured by the degree of dispersion and resultant interfacial area between polymer and silicate nanolayers).

In addition, partially exfoliated or intercalated composite morphology can also be obtained.

In this case, the intercalated clusters are arbitrarily distributed in the matrix. A wide range of variations in silicate composite can be achieved depending upon the degree of intercalation and exfoliation. X-ray diffraction measurements are utilized to characterize the exfoliation and intercalation structures. Reflections in the low angle region pointed intercalated composite, but if the peaks are extremely wide or disappear completely, this shows complete exfoliation.

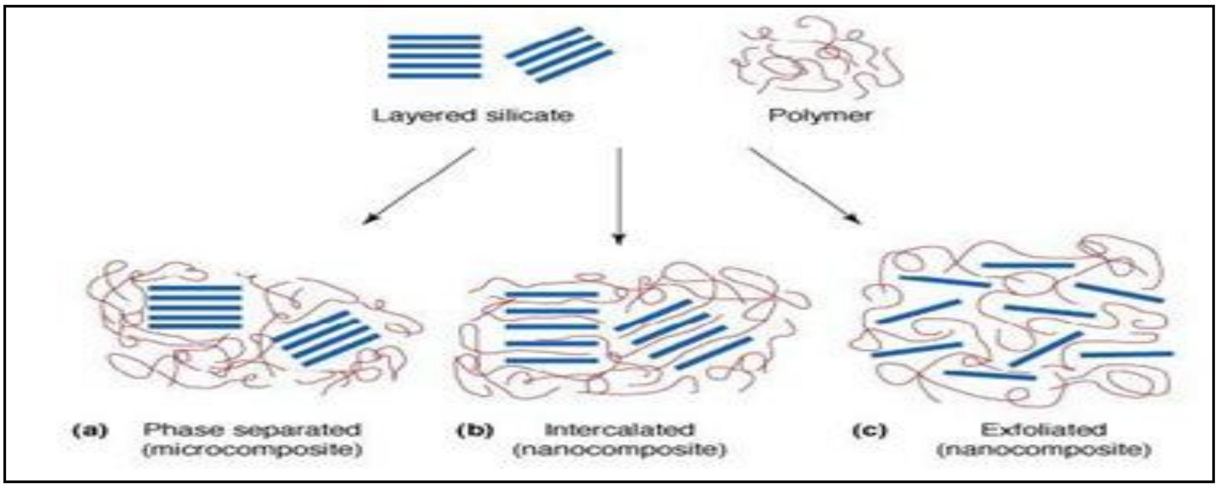


Figure1.7: Different morphology of layered polymer nanocomposites[5]

1.5 Glass fiber

Glass fiber is a material which consists innumerable extremely fine fibers of glass. E-glass is also known as electrical grade glass and it was developed to work as an insulator for electrical wires. But because of its excellent fiber forming capabilities, it was started using as reinforcing the face in composites. Glass fibers are manufactured by combining quarry products such as limestone, sand, kaolin etc. It has properties of resilience, light weight and high strength.

Fibers have been manufactured from glass since the 1930s. Glass fibers are manufactured by melt spinning method. In this method the composition of the desired glass is melted into a platinum crown. Small holes are provided in the platinum crown, so that the molten glass can flow out. Glass fibers coming out of the small holes are wound onto spindles. Due to the continuous spinning of crown molten glass is forced out through the holes by the application of (centrifugal force) to make short fibers. By the application of air jets the fibers of desired length are cut.

The properties of fibers and its dimension are controlled by controlling the process variables viz. Drawing/spinning rate, melting temperature, and viscosity. To decrease the effects of fiber–fiber abrasion which can considerably reduce the strength of individual fibers can be normally treated with mixing agents and sizing during the production of glass fibers. The matrix material to the fibers can be attached using several treatments which can also be used to promote wetting.

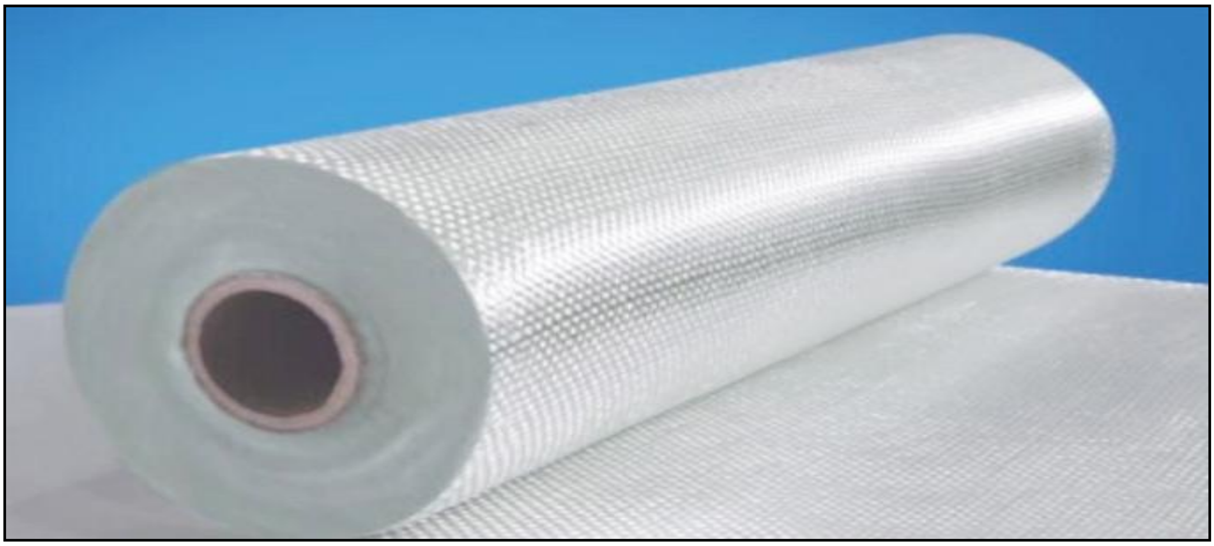


Figure 1.8: Woven fabric of glass fiber [6]

1.5.1 Types of glass fiber

Hartman et al 1996 studied glass fibers and classified it on the basis of its raw material used. He classified the glass fibers into following types

A-glass

It contains 72% silica and 25% soda and lime. It is close to window glass regarding to its composition. It is mainly used in the manufacturing of process equipment.

E-glass (electrical)

It is an alumina-calcium-borosilicate. It is mainly used as reinforcing fiber in polymer matrix composites. It has low alkali content.

C-glass (chemical)

It has high boron oxide content and applications to form a surface tissue in the outer-layer of laminates. It has the resistive nature of chemical attack.

R-glass

It is classified according to manufacturer’s trade names. R-glass is a calcium aluminosilicate which has higher strength than the S-glass.

S-glass

These are magnesium aluminosilicate and it is used in aerospace applications.

T-glass

It has higher tensile strength and better wet strength.

AE-glass

These are Alkali resistant glass.

Glass fibers generally consist of quartz sand, soda, potash, sodium sulphate, feldspar and a number of refining and dyeing additives.

1.5.2 Properties of glass fiber

Dimensional Stability

These are not elongated or shrink when expose to low or high temperature.

Moisture Resistance

They do not change chemically or physically in the water. They do not absorb the moisture.

Chemical Resistance

Generally, glass fibers are not affected by chemicals, but hydrofluoric, strong alkaline substances and hot phosphoric acids have some effect on glass fibers.

High Strength

They have high strength to weight ratio.

Fire Resistance

They are organic material and, therefore, they do not burn when exposed into the fire.

Thermal Conductivity

They have high thermal conductivity and low coefficient of thermal expansion. Therefore, they quickly dissipate heat during heating.

Electrical Properties

They work as an insulator for thermally conductive material.

There are some typical properties of glass fibers which are depicted in the following table

Table 1.2: Typical properties comparison of some common glass fibers [7]

Materials	Density (g/cm^3)	Tensile Strength (MPa)	Young's Modulus (GPa)
A-glass	2.44	3300	72
C-glass	2.52	3300	69
E-glass	2.58	3400	72
R-glass	2.54	4400	86
S-glass	2.46	4600	89
Kevlar 29	1.44	2860	64
Kevlar 49	1.44	3750	136

CHAPTER 2 LITERATURE REVIEW

This chapter shows some reviews on fiber-reinforced epoxy based polymer nanocomposites. This literature review covers briefly finite elements methods for solution to boundary value problems in composites, various elements, formulation method, modeling and analysis of composites in OOFf2 software.

2.1 Reviews of fiber-reinforced epoxy nanocomposites

Dong *et al.* [8] examined the numerical approach and object-oriented finite element (OOF) technique to assimilate the SEM into 2-D finite element modeling. He used SEM and TEM images to give the geometric micro and/or nano structure. Numerical results which are anticipated in the tensile behavior of polypropylene (PP)/organoclay nanocomposites were compared with the obtained experimental data and theoretically followed composite models. The found results proved that 2-D microstructure based numerical model can accurately anticipate the various properties of nanocomposites.

Jasra, 2014 [9] analyzed the thermal and mechanical properties of epoxy-clay nanocomposites using finite element analysis and compared thermal and mechanical properties figured from different analytical models and OOF2 technique and found that OOF2 was an effective tool for assessing material behavior under mechanical and/or thermal conditions, because he took the actual microstructure of the material (including distribution, size and shape of particles) in the form of SEM image. Prediction by using OOF2 for 9 vol. % clay-reinforced composites was lying between the upper and lower bond of Hashin-Shtrikman values. Predicted Young's modulus by OOF2 disagreed from that of rule-of-mixture's predictions and within the range of 5%, where OOF2 predicted 4.4% lower value than that calculated using ROM methods. OOF2 results were more effective and reliable than that of rule of mixture which simply predicated on the basis of respective volume fractions and individual properties of the elements.

Subramaniyan *et al.* [10] examined and found that the fracture toughness of polymers could be enhanced notably by using a relatively small quantity of nanoclay SEN-3PB specimens with sharp crack tips. They also studied and found that the compressive strength of unidirectional nanoclay reinforced GFRP was more in comparison to the GFRP containing no nanoclay.

Hackman *et al.* [11] examined clay nanocomposite materials and studied their applications in structures of civil engineering. It was found that the material's ability of enhanced service life, when subjected to aggressive environmental conditions could be employed to enhance the durability of carbon and glass fiber composites.

The study showed that surface modified clays were biddable to make polymer/clay nanocomposites due to weak bonding between montmorillonite layers 100. For this work, a low viscous epoxy resin Epikote 807 was used for better depletion. The diffusion coefficient was reduced to 1/10 during nano-clay loading at 4 vol. % (about 6 wt.%), and the theoretical predictions on the basis of 0.001 aspect ratio value were confirmed with the experimentally obtained results.

Isik *et al.* [12] synthesized DGEBA-polyether polyolorganically treated MMT clay ternary nanocomposites. They investigated the effects of polyether polyol (impact modifier) adding on morphology, mechanical and thermal properties of nanocomposites using SEM, X-ray diffraction, DSC, tensile and impact testing. The results pointed that organoclay got intercalated by epoxy because the interlayer spacing was enlarged from 1.83 to 3.82 nm upon nanocomposite fabrication. They found that the basal spacing was not affected upon adding polyether polyol. SEM analysis indicated that polyether polyol formed an unmixable phase in an epoxy matrix. For polyol modified nanocomposites, tensile and impact strengths showed a decreasing trend upon raising the amount of nanoclay and maximum value of tensile and impact strengths were observed with respect to the polyol content at constant MMT loading.

Berkits *et al.* [13] examined the properties of an E-glass/epoxy composite before mechanical loading and moisture conditioning and after mechanical loading and moisture conditioning. They found that initial results were indicating that the tensile modulus, strain, along with strength of E-glass/epoxy composite elaborated upon the application of moisture as well as mechanical loading in comparison with control specimens.

A very small increase in strength and a very small decrease in modulus were observed in shorter periods of conditioning at room temperature and at a very long duration of 3000 h, a significant strain-to-failure and reduction in strength were observed. Specimens conditioned in water under stress, at 650 ℃ for the period of 1000 hr showed a higher decrement in modulus. It was found that a constant stress applied may have a positive influence for a short duration of time, and that long exposure to moisture at room conditions lead to brittle fracture while exposure at large temperatures may be followed by ductile failure of fiber-reinforced epoxy composites.

Avila *et al*. [15] studied the contribution of the presence of nanoclay in the plate impact strength by using a set of fiberglass laminate-nanoclay reinforced-epoxy composites. They manufactured S2-glass/epoxy-nanoclay composites for this purpose. The S2-glass/nanoclay was reinforced epoxy composite with 16 glass layers having 65% fiber volume fraction. They manufactured using VARIM. 1%, 2%, 5%, 10% wt. % nanoclay was added into epoxy resin, respectively. For comparison of the results, a set of S2-glass/epoxy laminated composites also manufactured. Composite's impact strength was increased in addition of nano-sized clays and the damaged area was reduced by approximately 20% of small nanoclay contents. The increase in impact strength was near to 50% when the concentration reached around 10%. Nano-clay composites showed good performance over the conventional composites under the rebound/spring effect. When the four edges clamped condition was enforced, the overall composite vibration damping was raised by the increasing nanoclay content. The favorable nanoclay concentration suggested by them was close to be 5%. This may be because of vibration mode superposition related to a stiffness enhancement.

Chow *et al.* [15] manufactured the epoxy/glass fiber/ organo- montmorillonite (OMMT) nano composites by hand lay-up technique. They characterized the epoxy nano composites by using differential scanning calorimetry (DSC), X-ray diffraction (XRD) and water absorption tests. Epoxy/glass fiber/OMMT hybrid nanocomposites manufactured by hand-lay-up method indicated exfoliation characteristics and insignificant enhancement in glass transition temperature. They improved water resistance of epoxy by an addition of both OMMT and glass fiber, which was attributed to raising of the torturous path of water penetration.

Manjunatha *et al*. [16] tested tensile fatigue behavior of the silica nanoparticle reinforced-glass fiber/epoxy nanocomposite. The epoxy resin used was DGEBA. They made GFRP composite by performing resin infusion under flexible tooling method and then he modified an anhydride-cured epoxy polymer by integrating 10 wt.% silica nanoparticles. They also found that the fatigue life of 10 wt.% silica nanoparticle modified epoxy was about 3–4 times more than of pure epoxy whereas the fatigue life of GFRP nanocomposite with 10 wt.% silica nanoparticle-epoxy matrix was also about 3–4 times more as compared to GFRP with pure epoxy matrix. The inhibited cracks in matrix and decreased crack growth rate because of particle bonding along with plastic void growth mechanisms contributed to the enhancement of the fatigue life in the nanoparticle-modified GFRP.

Zainuddin *et al*. [17] examined and found that E-Glass FRP composite was more sensitive to environment controlled parameters, especially hot-wet conditions in comparison to simple epoxy nanocomposite. They found that weight gained was more for all wet conditioned samples which was introduced to high temperatures. The weight gain was decreased on nanoclay loading by 1–2 wt.% and flexural properties put down as time increased. 2 wt.% nanoclay GFRP composites indicated inflation in properties under all conditions as compared to neat composites. There were few samples which were tested in hot dry condition at 600 ℃ and presented gain in properties of the samples which were higher than the room temperature condition. SEM showed clearly proves of the consequences of clay, moisture absorption and elevated temperatures. He observed interfacial bonding in 2wt. % composite samples, both in hot-wet condition and at room temperature.

Bondioli *et al.* [18] analyzed SEM images of silica-epoxy nanocomposites. They modeled mechanical properties by using OOF2 technique and constructed a numerical model using SEM images of the material. They prepared a reliable model by looking the presence of an interface layer surrounding the particles, having intermediate elastic properties behavior common between the inclusions and epoxy.

Sharma *et al.* [19] examined the thermal and mechanical trends of phase composites (IPCs) of Ni-Al2O3 by using object-oriented finite element method (OOFEM). They combined the images in OOFEM with the fundamental material properties in order to understand the behavior of the materials. They examined thermal expansion coefficient, thermal conductivity and modulus of elasticity of the composites using OOFEM and after then they compared these properties with other analytical methods which showed good agreement with the numerical modeling.

Siddiqui *et al.* [20] examined the mechanical properties of nanoclay reinforced-GFRP, and proved that inter laminar plain strain fracture toughness of nano-clay disseminated GFRP is more than the conventional GFRP.

Bhangu [21] examined the mechanical properties of GFRP composites such as microhardness, tensile modulus, flexural strength and examined these properties in addition of nanoclays after manufacturing the composites of vacuum assisted resin infusion molding technique. He found that 2 wt.% of Cloisite 30B nanoclay reinforced specimens had the best combination of properties. He analyzed that negligible improvement in tensile strength of glass fiber reinforced nanocomposite over glass fiber reinforced composite and he also found that glass fiber reinforced nanocomposite could be imputed to clustering of nanoclay or to the occasional development of micro size voids in microstructure, especially at the interface of matrix and nanoclay.

Langer *et al.* [22] studied the material’s macroscopic properties by using 2 public-domain programs which were jointly anticipated the behavior. They used OOF2 to look into the microstructure program which begin from an SEM image of the microstructure and end up with the results of finite-element calculations. They determined the mechanical properties by using OOF2 modeling technique and they compared those results with the analytical models.

Duarte *et al.* [23] analyzed mechanical properties of a laminated composite using modal analysis technique. They took the FEM model of composite plate and performed modal analysis test on that and compared these results with experimental results. They got different properties like Poisson’s ratio, tensile modulus and shear modulus of that composite plate by Modal analysis test. For this test they used the plate of 16 layers made from S-glass and epoxy. They also used nanoclay particles in weight % of 1, 2 and 3 percentage in epoxy. They observed that Tensile modulus was increasing in increasing weight of nanoclay in the composite.

CHAPTER 3 PROBLEM DEFINITION AND FINITE ELEMENTS MODELING

3.1 Modeling of fiber-reinforced epoxy nanocomposite

There are various types of material modeling techniques for determining the microstructural characteristics of material as given in figure 3.1. Using Finite Elements Method an effort is built to examine the mechanical characteristics of the Fiber-reinforced epoxy nano-composite. This technique is utilized for several composites/heterogeneous materials using the software OOF2. OOFEM is an open source software which is grown by NIST and available at NIST, USA website. Because of its some special features, it is a very efficient software for image based material analysis [24, 25].

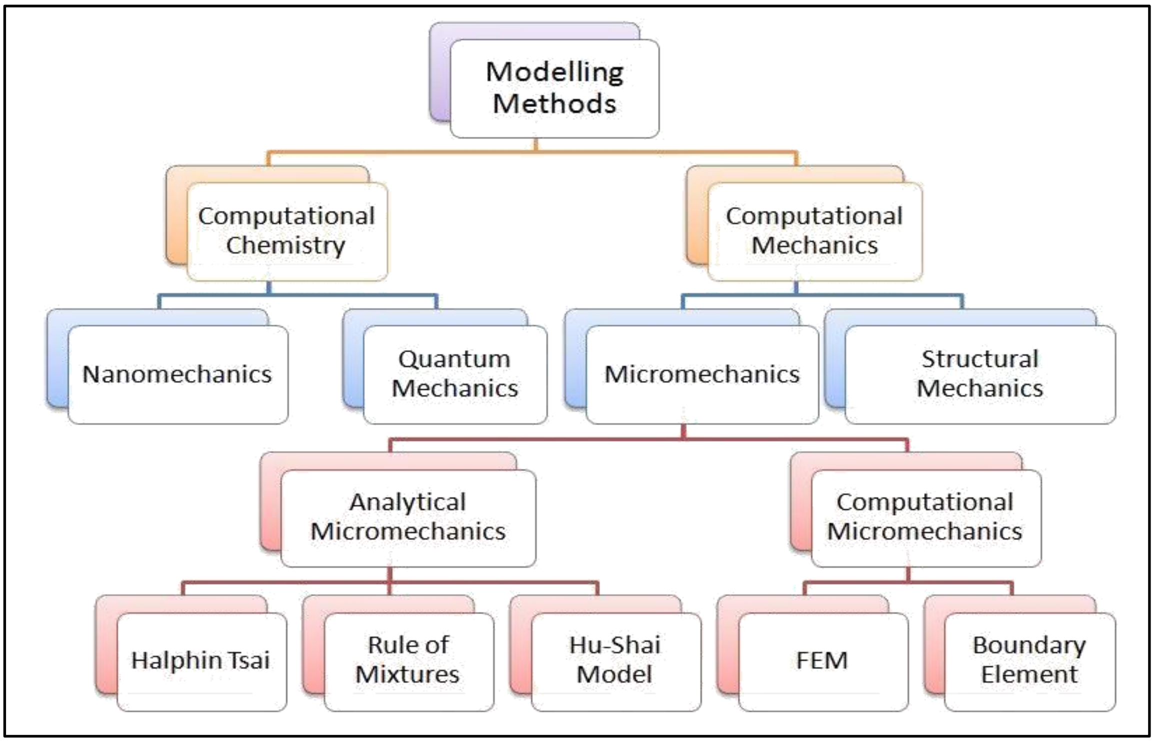


Figure 3.1: Material modeling techniques [26]

There are several steps to model a microstructure. After taking SEM micrograph as an input and specifying finite element model by performing pixel selections, skeleton formation, mesh generation, equation formulation and boundary conditions as shown in fig. 3.2.

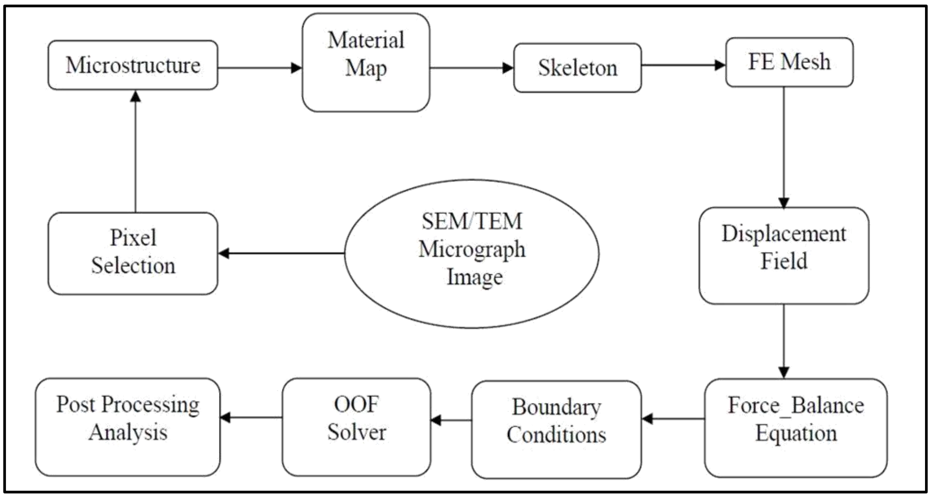


Figure 3.2: Steps for OOF modeling [8]

3.1.1 Inputs required for OOf2 modeling

The OOF2 software is grounded on the SEM micrographs, which accumulate all the micro structural characteristics of the nanocomposite. There are a lot of tools to improve an image like recognition of edges, boundary filters, etc. There is no rigid method which speculates that which tool should be employed on a certain stage, it only looks the nature of the image to be worked.

3.1.2 Image processing

The input micrograph in OOF2 software is only a microstructure and it does not subsist any useful data. For making the micrograph meaningful, segmentation is done. By selecting the pixels from the micrograph and allotting a pixel group in the micrograph, different constituents of the heterogeneous material are discovered. The meaning of micrograph segmentation is to distinguish different materials from the microstructure. To select a pixel, there are various options like point, pixel selection by a circle, burn and color. We take effective part of the SEM to model the microstructure. The part of SEM micrograph which contains all necessary features of the microstructure is named as an effective part of SEM micrograph. The picture which is captured clearly indicates the various components of heterogeneous material.

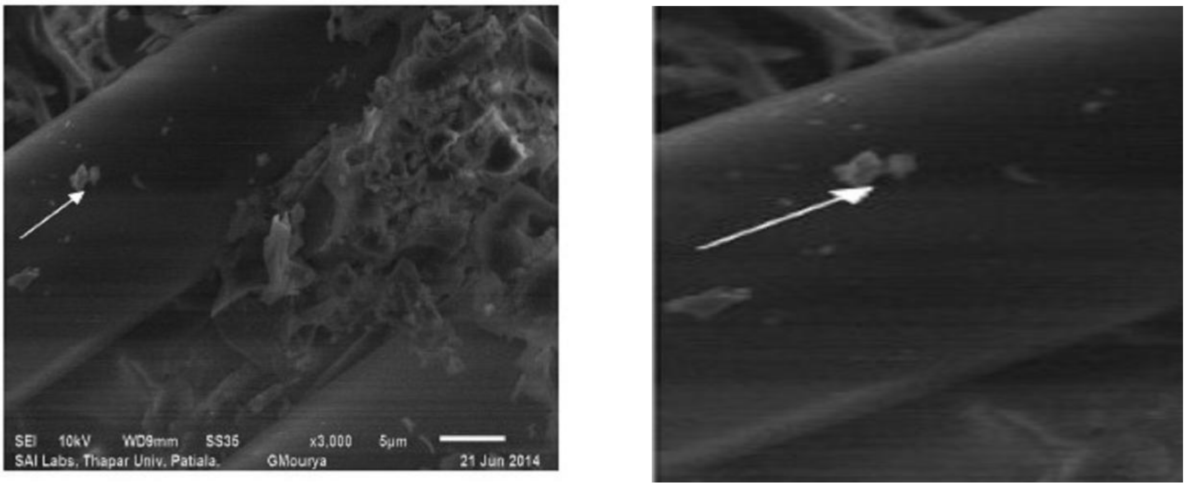


Figure 3.3: SEM image portion (a) Captured image portion (b) Cropped SEM image to be modeled

3.1.3 Image segmentation

Meaning of image segmentation is picking up various pixels of the same material from SEM. The process of image segmentation is carried out by various options in the pixel selection tool box. Figure 3.4 shows the process of pixel selection.

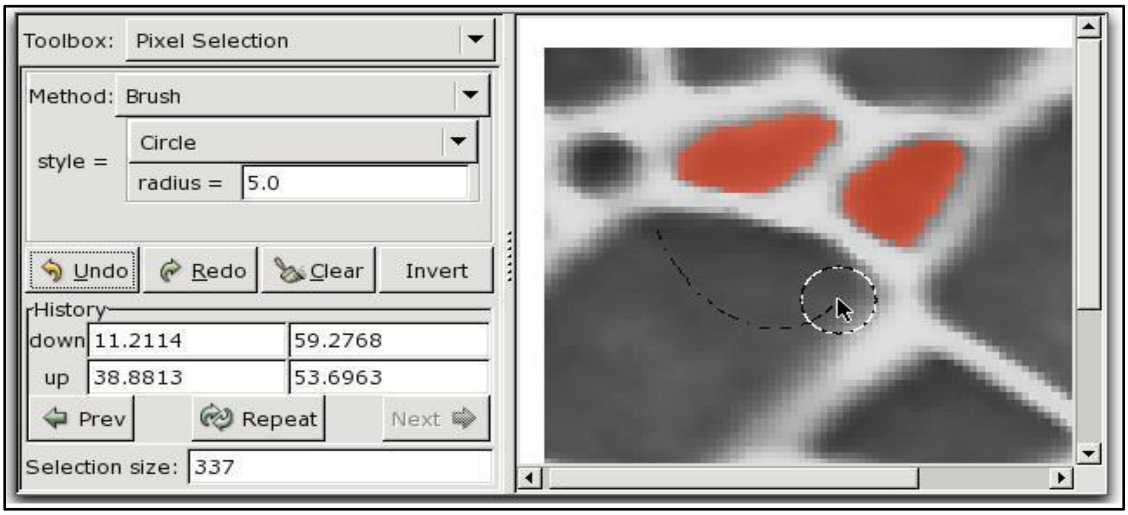

Toolbox: Pixel Selection
Method: Brush
style = Circle
radius = 5.0
History
down 11.2114 59.2768
up 38.8813 53.6963
Selection size: 337

Figure 3.4: Image segmentation using pixel selection [27]

The picked out pixels of various constituents makes the pixel group. The material properties are allotted to these pixel groups. In doing this mapping of material, constituents makes the FEM model more accurate.

3.1.4 Assigning material properties

The materials in OOF2 exist independently of microstructures. Figure 3.5 shows the window of material properties in OFF2. In this window we can assign the properties of materials. The OOF2 Software differentiates materials in SEM micrograph with the help of color variation and assigns pixel group to them.

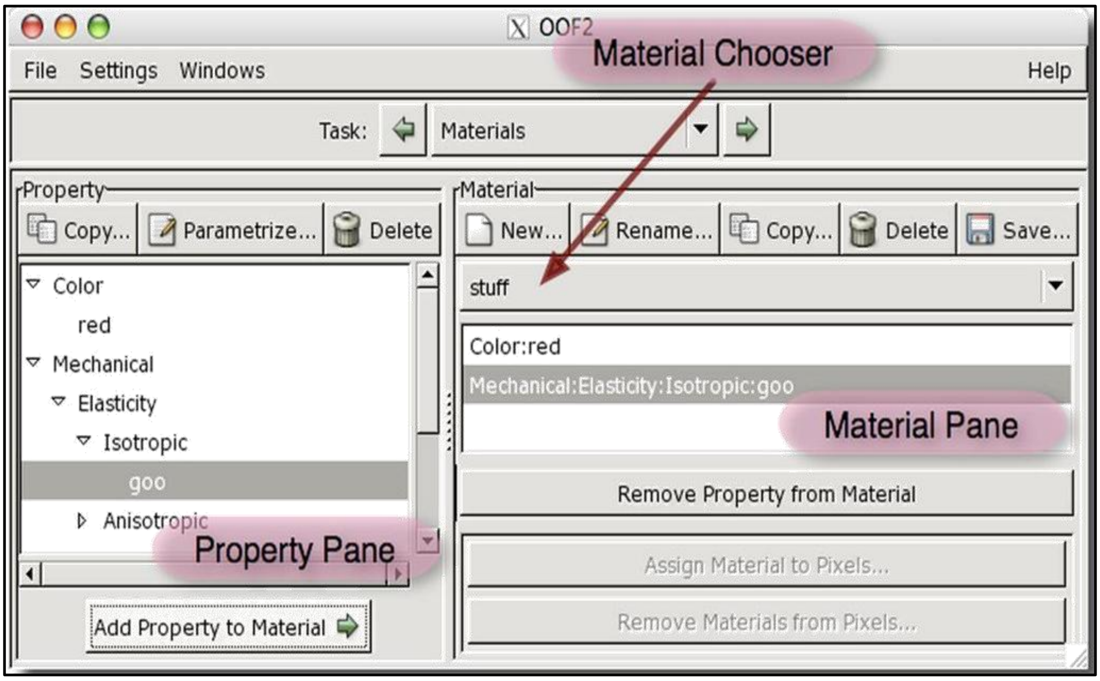


Figure 3.5: Material page [27]

Properties window contains a hierarchical list of material properties. Table 3.1 shows the mechanical properties assigned to the Fiber-reinforced epoxy nanocomposite.

Table 3.1: Material Properties of Fiber-reinforced epoxy nanocomposite [9, 28, 29]

Properties	**E-glass**	**Clay (Cloisite 30B$^{\circledR}$)**	**Epoxy Resin MGS RIM 135 and Hardner MGS RIM H134**
Density (g/cc)	2.55	0.2283	1.18
Young's modulus (GPa)	72	4.657	0.0027
Poisson's ratio	0.40	0.26	0.23

The properties shown in the above table 3.1 are allotted to the groups identified as epoxy, nanoclay and glass fiber. The properties of interface are not considered in the OOF2. The properties of interface are different from the matrix and reinforcement.

3.1.5 Skeletons

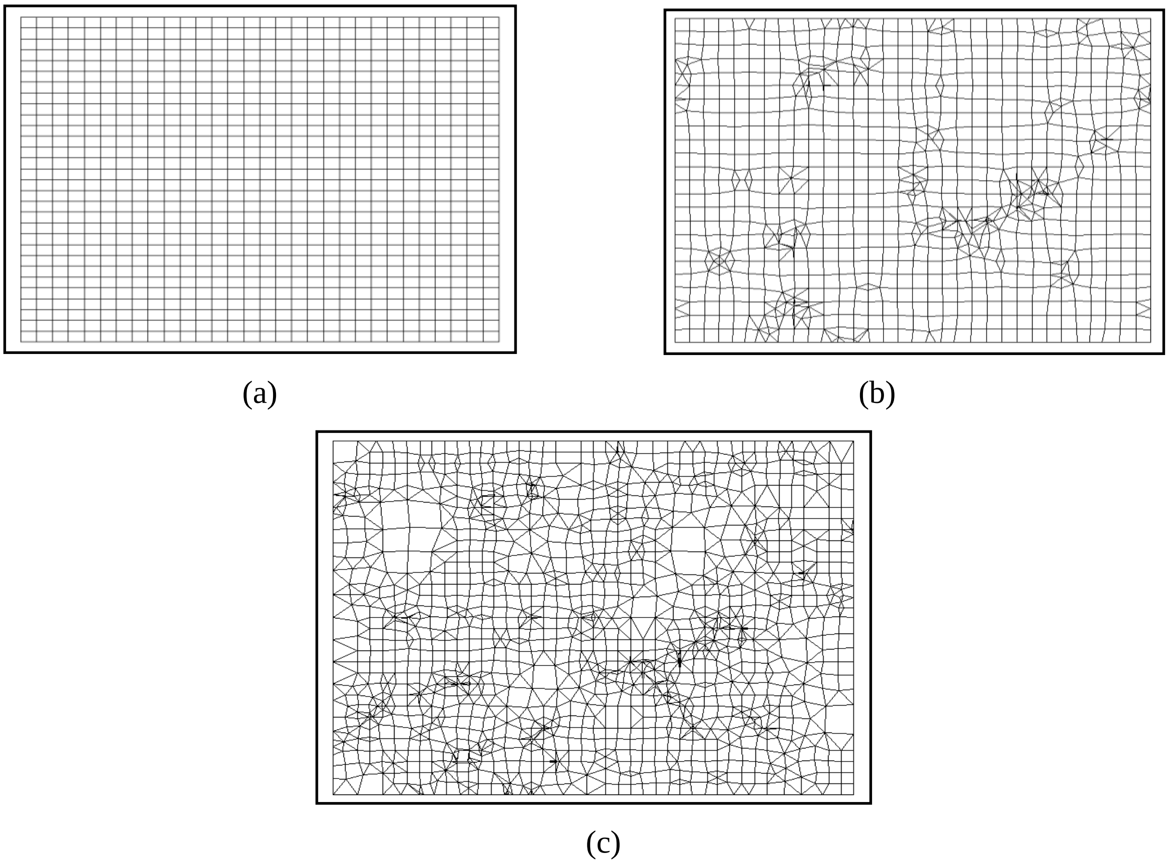
First step to model an SEM micrograph is created of Skelton in SEM micrograph. The skeleton fixes the geometry of the mesh. In doing skeleton, we don't require data about fields, peers, or shape functions of finite element. All of these data are used in the generation of meshes, which is the next step after the skeleton. The skeleton is an intercede step between finite element solution and the panelized microstructure. Finite element discretisation of the microstructure is indicated by skeletons. Representing different discretizations, a microstructure may have various skeletons,

In a single geometry, one skeleton may generate many meshes, allowing different solution methods and physics. There are some tools in a skeleton window for modification and generation of skeletons. Skeleton window has various tools to analyze different points of a skeleton in the window named as a graphics window. Skeleton elements inhibit their material properties from the pixels underneath them in the microstructure. If the geometry of the skeleton is to be a good estimation of the microstructure geometry, then pixels groups lying in underneath an element will contain the similar allotted materials. Skeleton element homogeneity measures that how well the element reaches this goal. Homogeneity can be calculated by estimation of the area of the element which overlays each class of the pixels. Pixels which contain various allotted materials or relate to various meshable pixel groups are categorized differently. A Category which claims bigger area of the element is called supreme category. Homogeneity can be defined as the ratio of the dominant area category for the total element area [29]. A completely homogeneous element will have the value 1.0 homogeneity.

The element containing equally N components contains 1/N homogeneity. The material allotted to an element is known as material of its pixel prevailing category. The first step in skeleton generation, we form the square or rectangular grid of elements, then it is modified by the different tools present in the skeleton task page. The development stages of the skeleton are shown in Fig 3.6

There are various tools which are used to change the skeleton like smooth and anneal function by cutting down an effectual functional energy, E, of mesh. Its function is assigned by a number which should be between 0 and 1 to each element. It has a role in the annealing the operation, therefore it is called as energy, and it has a great significance of the energy in a statistical simulated process of annealing mechanically. The energy function keeps two benefactions, one is homogeneity E_{hom} And another one is shape energy, E_{shape}.

Relative information about them can be managed by a parameter of α = 0


(a) (b)

(c)

Figure 3.6: Skeleton development stages (a) Quad skeleton initiation of fiber reinforced epoxy nanocomposite, (b) Skeleton moving stages, (c) Developing skeleton

$$E = \alpha E_{hom} + (1-\alpha)\, E_{shape}$$

When α = 1 then Skeleton modifications which use E is regarded as elements shape, and resulted in homogeneous, poorly shaped elements. When α = 0, changes are not looking at homogeneity, and effect in considerable shaped but may be inhomogeneous elements. When the value of α lies, $0< \alpha< 1$, there will be a settlement between shape and homogeneity as shown in the given Fig 3.6.

3.1.6 Meshing

Mesh object of OOF2 shows a real finite element mesh. The values of displacements are stored in meshing and it also consists data of the geometry of the skeleton with the information of its equation and conditions of boundary. By using skeleton meshes are derived. The shape and position of the mesh elements are same related to skeleton elements. The assigned material to every mesh element is the dominant pixel category of a skeleton element of the material. A single skeleton can be grown into more than one mesh [27].

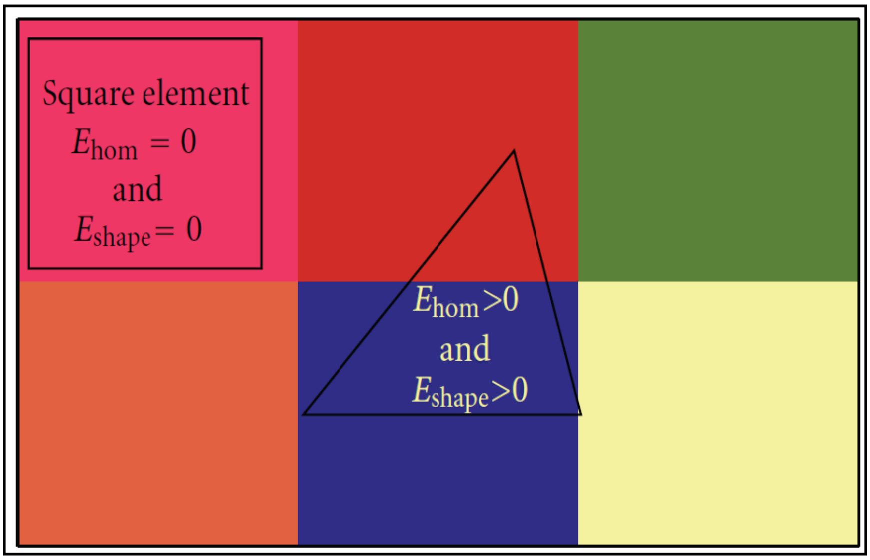
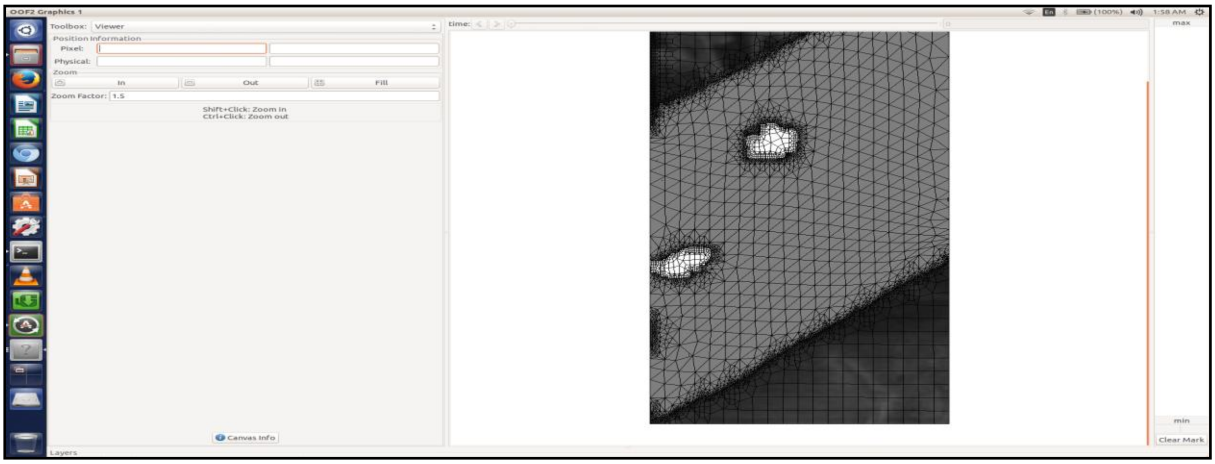


Figure 3.7: Energy factor [27]

Interpolation order within an element is obtained by polynomial order of element shape functions, and it has involvement in regulation of the accuracy of the solution for e.g. (Linear shape functions give the fields and it is desirable to keep constant gradients within elements) Present node has value of shape function 1 and others have 0. The node number on an edge decides of element decide the order of shape functions. An edge consisting nodes only at its end points should have shaped functions linearly, while an edge in its interior keeping nodes at its end points must have quadratic shape functions. The finalize meshes generated on an SEM micrograph is shown in Figure 3.8.



Toolbox: Viewer

Zoom Factor: 1.5

Shift+Click: Zoom in
Ctrl+Click: Zoom out

Figure 3.8: Mesh generated SEM image model in OOF2

There are three types of nodes are present: nodes, which are utilized to consist function nodes, which are utilized to find out element geometry known as mapping nodes, and nodes which are utilized to get both purposes. The geometry of an element is determined by the nodes by describing a function from a “master” element consisting a standard shape and real element position.

The mapping nodes of the principal element are represented to the nodes of the real element, and all other points are represented by utilizing the mapping node shape functions for interpolation. Curved edge elements are produced by non-linear mapping. The elements which have the same number of mapping and function are known as isoparametric. The elements which have field values greater than element geometry are known as subparametric, and the elements which have element geometry greater than field values are known as superparametric.

Chapter 4 RESULTS AND DISCUSSIONS

4.1 Finite Element Analysis

The finite element analysis was performed on nanocomposite material under different loading conditions, *i.e*, static structure and dynamic conditions using the Abaqus simulation software. The material properties and meshing, model for the purpose of analysis was imported from OOF2 software in Abaqus. The different type of analysis is discussed below:

4.1.1 Tensile stresses analysis

The boundary conditions for this analysis are shown in Figure 4.1. It can be seen that one end of the model is fixed and at other end displacement in Y-direction is applied gradually in the range from 0.5 mm to 6 mm.

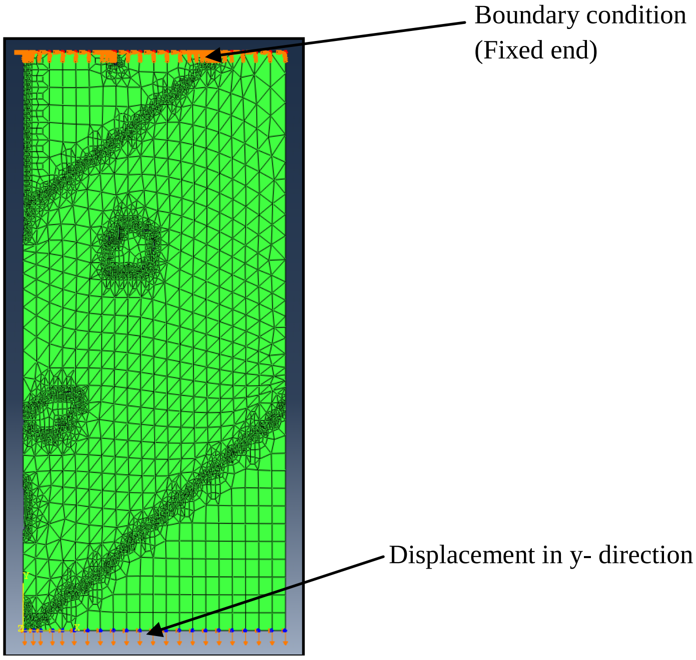


Figure 4.1: Boundary conditions of SEM model for tensile analysis

The tensile stresses obtained at different displacements are shown in Table 4.1

Table 4.1 Tensile stresses at different displacements

S. No.	Displacement (in mm)	Tensile stress (in MPa)
1	0.5	8.415
2	1	16.83
3	1.5	25.23
4	2	33.64
5	2.5	42.05
6	3	50.44
7	3.5	58.83
8	4	67.22
9	4.5	75.60
10	5	83.98
11	5.5	92.36
12	6	100.7

It can be seen from Table 4.1 that the maximum stress is produced at a displacement of 6 mm. Figure 4.2 shows the maximum value of tensile stress at 6 mm. The maximum stress of 100.7 MPa is obtained at clay and glass fiber bonding interface.

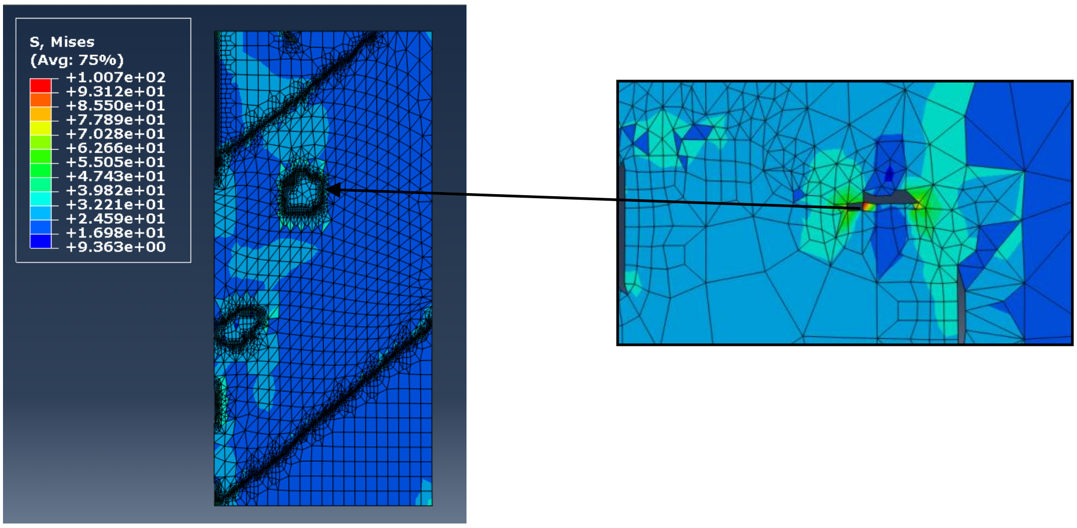


Figure 4.2: Tensile stress (MPa) obtained at a displacement of 6 mm

4.1.2 Compressive stresses analysis

After performing tensile structural analysis, compressive structural analysis was also performed to check the behavior of the nano-composite material under compressive loading conditions. The boundary conditions for compressive structural analysis was considered to be same as that of tensile structural analysis, except the displacement was applied in the opposite direction as compared to tensile condition.

The results of compressive stresses obtained at different displacements are shown in table 4.2

Table 4.2: Compressive stresses obtained at different displacements

S. No.	Displacement (in mm)	Tensile stress (in MPa)
1	0.5	8.41
2	1	16.84
3	1.5	25.27
4	2	33.70
5	2.5	42.13
6	3	50.57
7	3.5	59.01
8	4	67.45
9	4.5	75.90
10	5	84.35
11	5.5	92.81
12	6	101.3

The maximum stress obtained at displacement of 6 mm is shown in Figure 4.3. It can be seen from the Figure that the maximum stress of value 101.3 MPa is obtained at the bond interface of clay and glass fiber.

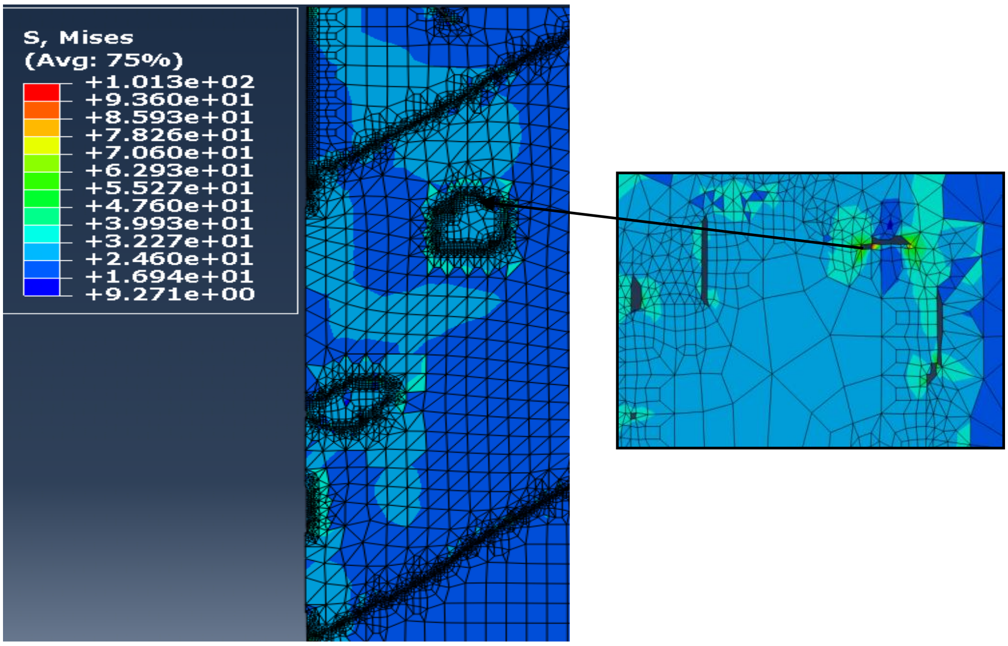


Figure 4.3: Compressive stress (MPa) obtained at a displacement of 6 mm

4.1.3 Shear stresses analysis

The shear structural analysis was performed to check the behavior of nanocomposites at shear loading conditions. For this, the displacement is given gradually in tangential direction as shown in Figure 4.4

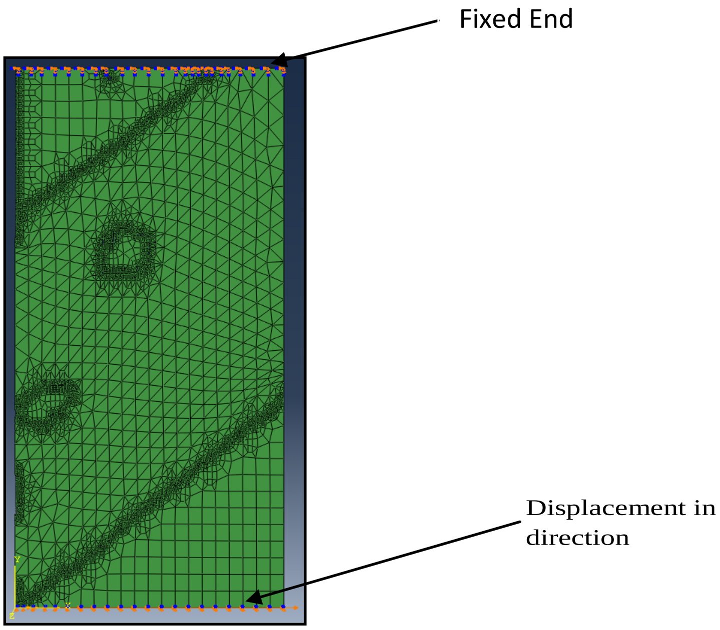


Figure 4.4: Boundary conditions of SEM model for shear analysis

The shear stresses obtained at different displacements are shown in Table 4.3. It can be seen that the maximum shear stress is obtained at displacement of 6 mm that is 53.58 MPa.

Table 4.3: Shear stresses obtained at different displacements

S. No.	Displacement (mm)	Tensile stress (MPa)
1	0.5	4.49
2	1	8.98
3	1.5	13.47
4	2	17.95
5	2.5	22.42
6	3	26.89
7	3.5	31.35
8	4	35.81
9	4.5	40.26
10	5	44.70
11	5.5	49.14
12	6	53.58

The shear stress obtained at a displacement of 6 mm is shown in Figure 4.5. It can be seen that the maximum stress is obtained at the bonding interface of clay and glass fiber.

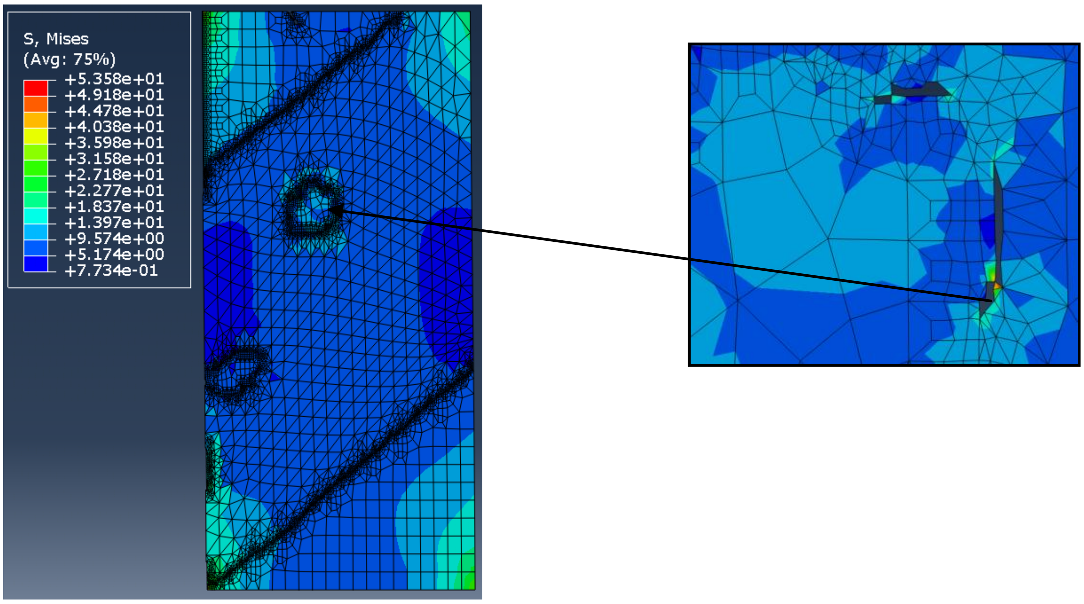


Figure 4.5: Shear stress (in MPa) obtained at a displacement of 6 mm

4.2 Dynamic analysis

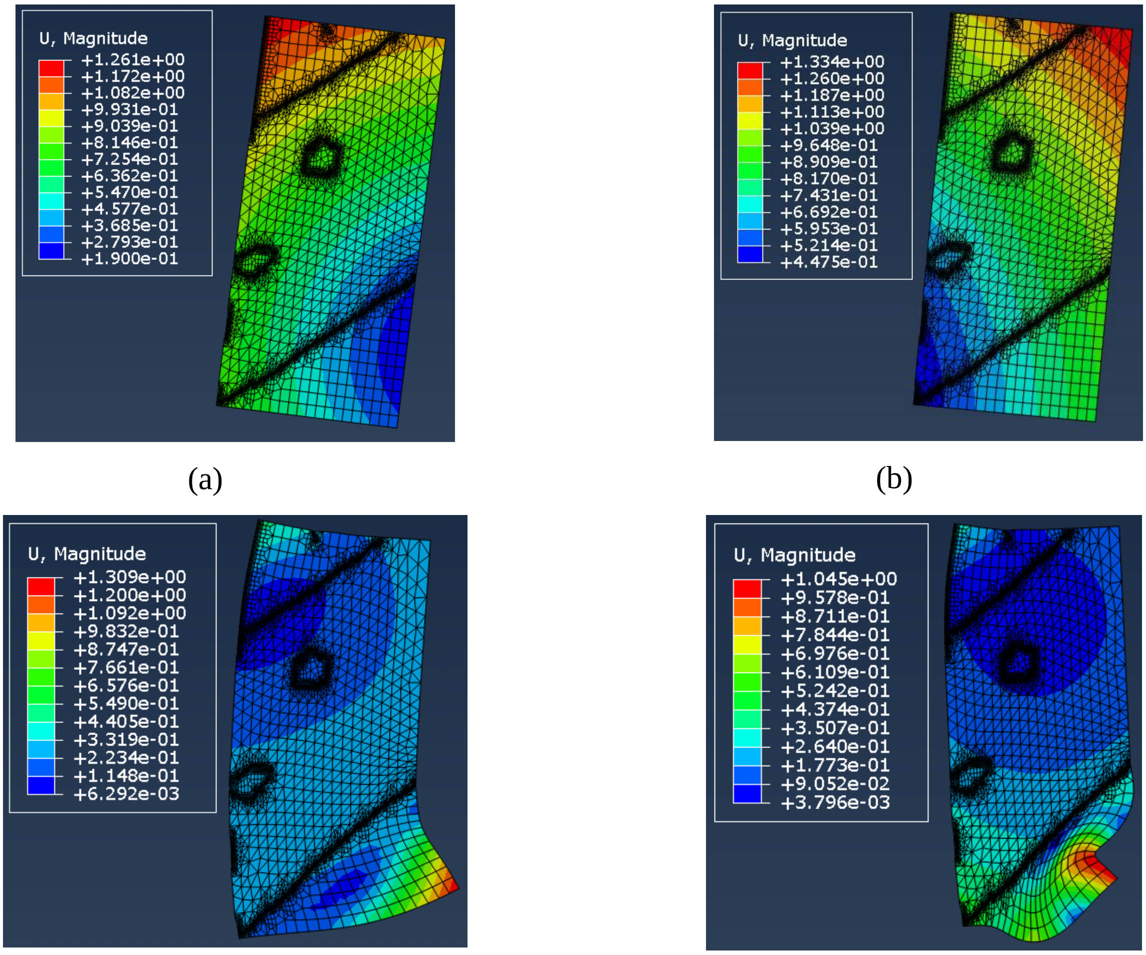
To see the behavior of nanocomposite material under dynamic conditions, the dynamic analysis was performed. The following type of analysis was performed under dynamic analysis:

4.2.1 Modal analysis

Modal analysis is performed to obtain the natural frequencies and their corresponding mode shapes of a sample of nanocomposite material. The modal analysis was performed under two conditions that are given below:

I. Free- free condition

Under this condition, the model is free to move in any direction, *i.e*, there is no constraint applied in this case. The different natural frequencies and their corresponding mode shapes are shown in Figure 4.6. The mode shapes are the different patterns of vibration obtained at its natural frequencies.



(a) (b)

(c) (d)

Figure 4.6: Total deformation (in mm) of nanocomposite at free-free condition: (a) Mode shape 1 at 12 Hz; (b) Mode shape 2 at 13.45 Hz; (c) Mode shape 3 at 20 Hz; (d) mode shape 4 at 24.75 Hz.

II. Constraint condition

Under this condition, the model is fixed at one end and the other end is free to move as shown in Figure 4.7.

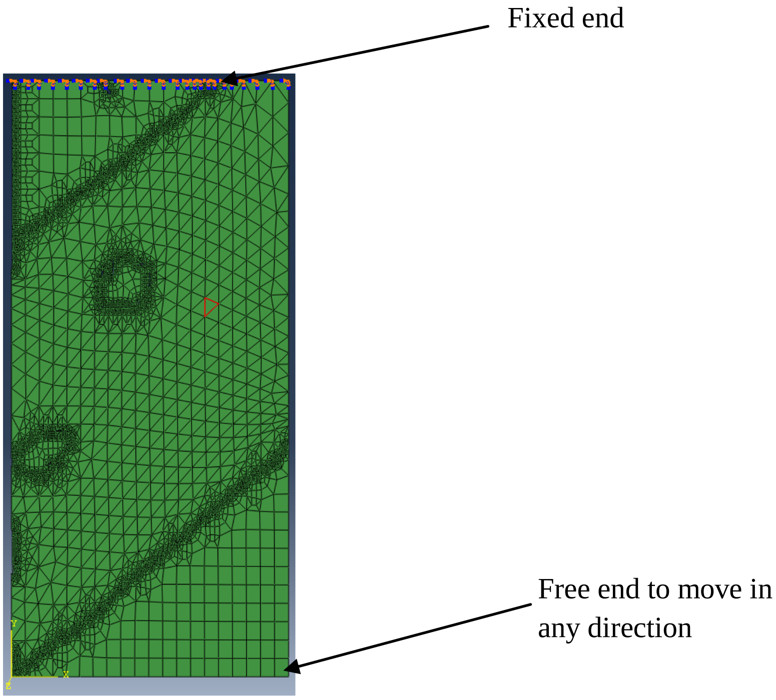
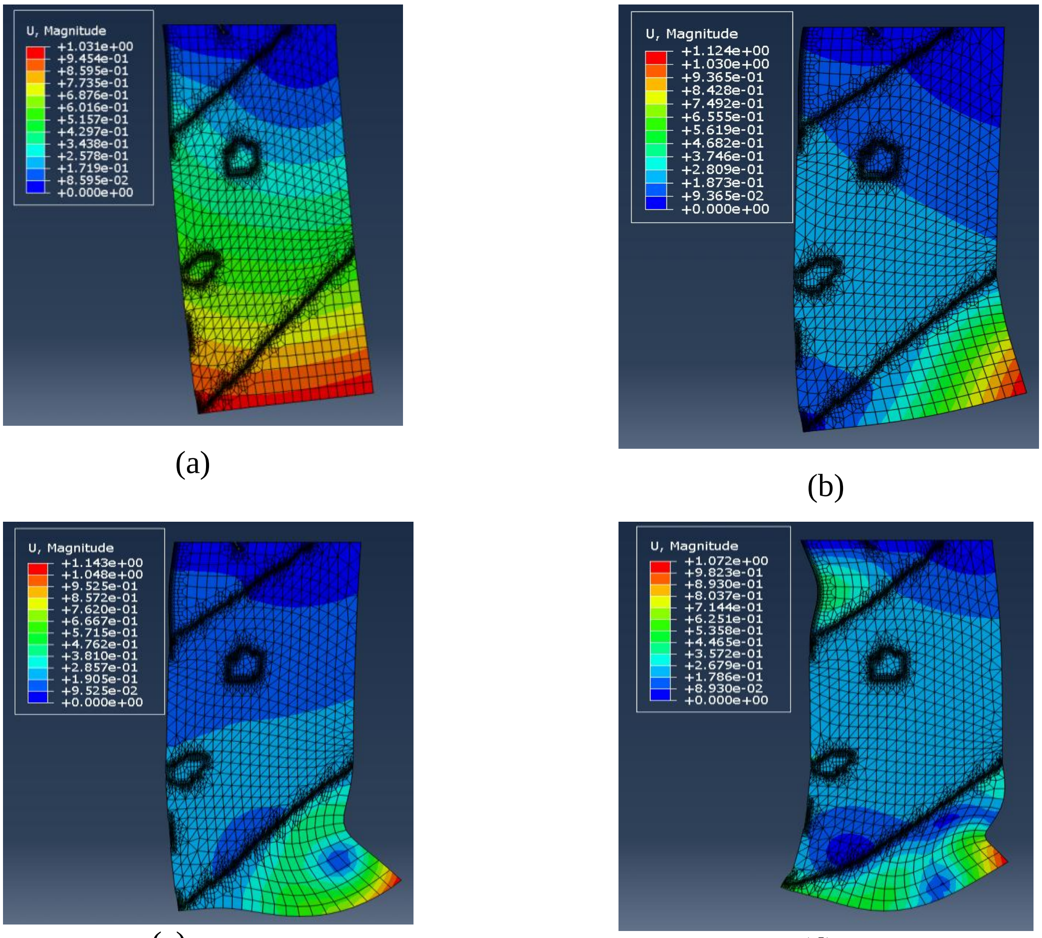


Figure 4.7: Boundary conditions of SEM model for modal analysis (constraint condition)

The natural frequencies and their corresponding mode shapes are shown in Figure 4.8



(a)

(b)

(c)

(d)

Figure 4.8: Total deformation (in mm) of nano-composite at constraint condition: (a) mode shape 1 at 15 Hz; (b) Mode shape 2 at 17.52 Hz; (c) Mode shape 3 at 23.25 Hz; (d) mode shape 4 at 26.35 Hz

It can be seen from Figure 4.6 and 4.8 that during free–free condition, the first value of natural frequency is 12 Hz and during constraint condition, the value of first frequency is 15 Hz. Under the constraint condition, the material becomes more stiffen than free-free condition. These natural frequencies should not be matched with the natural frequencies of other components because due to this, resonance may occur that results in more vibration with higher amplitude.

4.3 Experimental results

The experimental work was already performed in the previous work [21]. The results obtained by performing the tensile test are shown in Table 4.4.

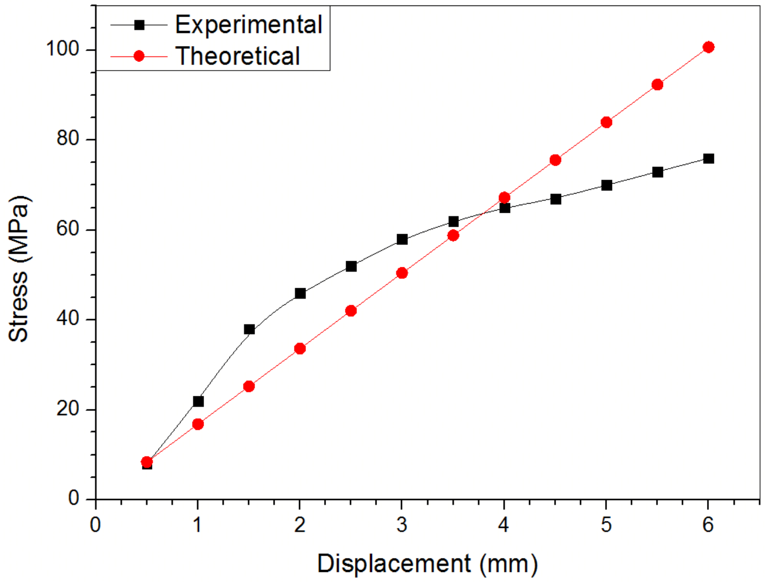
Table 4.4: Tensile stresses obtained at different displacements

S. No.	Displacement (mm)	Tensile stress (MPa)
1	0.5	8
2	1	22
3	1.5	38
4	2	46
5	2.5	52
6	3	58
7	3.5	62
8	4	65
9	4.5	67
10	5	70
11	5.5	73
12	6	78

It can be seen from the table that the maximum value of the tensile stress is 78 MPa at a displacement of 6 mm.

4.4 Comparison of results

The comparison of the tensile stresses in nanocomposites, obtained from approximate method at different displacements and stresses obtained from experimental work [21] is shown in Graph 4.1.



Graph 4.1: Comparison of experimental stresses with theoretical results (finite element approach) in nanocomposites at different displacements

4.5 Discussion

It can be seen that the results obtained from experimental approach and FEM approach are correlated with each other. The maximum tensile stress by experimental value was 74 MPa while the maximum value which is obtained through FEM analysis is 100.7 MPa. The maximum shear stress should be less than half of the yield strength of the material. So, in this case it is satisfied and accordingly, the value of shear stress obtained is accurate.

The maximum tensile, compressive and shear stresses is obtained at the bonding interface of clay and glass fiber. So, in future the composition of clay can be changed to meet the requirements of reduction of stresses at more displacements *i.e.*, greater than 6 mm. Under dynamic conditions, the natural frequency of the material is less, but it can also be improved in future work by changing the composition.

Chapter 5 CONCLUSION

5.1 Conclusion

The nanocomposite material was analyzed under static and dynamic conditions. Various analysis, *i.e.*, Tensile, compressive, shear structural and modal analysis was performed, the values of stresses were evaluated. There was a good correlation between the results obtained from finite element analysis and experimental values. There was a good correlation between the results obtained from both methods till 65 MPa at 4 mm displacement after that the results started diverging. The maximum stress was obtained at the bonding interface of clay and glass fiber.

5.2 Scope for future work

The present performed work can be extended in the future in the following ways:

a) The composition of the material can be changed to meet the factor of safety.
b) Harmonic response analysis can be performed to check the behavior of material under dynamic conditions.
c) Fatigue analysis can be performed to check the life of a material.
d) Results obtained from other analysis using simulation approach can also be compared with the experimental results.

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