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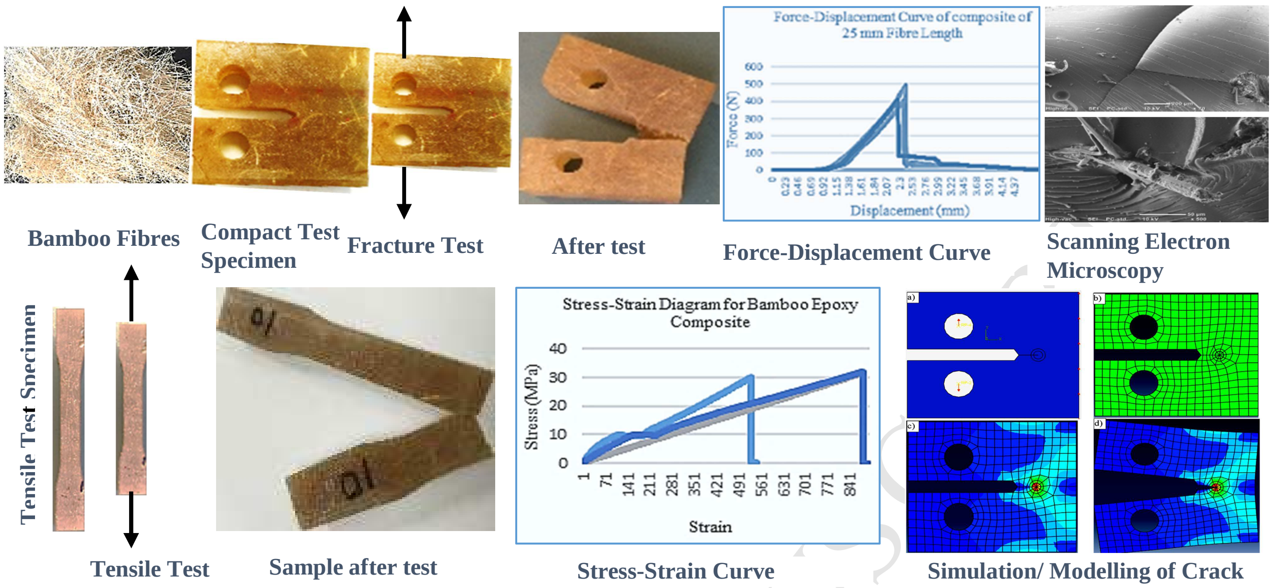
Bamboo Fibres
Compact Test Specimen
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Fracture Behaviour of Bamboo Fiber Reinforced Epoxy Composites

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Abstract

In this work, experimental and numerical study on fracture behaviour of bamboo fiber reinforced epoxy composites is presented. Optimum NaOH concentration for treatment of bamboo fibers was determined through single fiber tensile test and microscopic inspection of fiber surface through SEM (Scanning Electron Microscopy). The results demonstrated that 6% NaOH treated fibers showed maximum ultimate tensile strength of 234MPa. Single fiber fragmentation test results showed that interfacial adhesion is improved by treating fibers with 6% NaOH. Bamboo fiber reinforced epoxy composite was fabricated using 6% NaOH treated bamboo fibers of length 10 mm, 20 mm and 25 mm with random distribution in epoxy matrix. Mode-I plane strain fracture toughness (K_{IC}) of bamboo fiber reinforced epoxy composites was investigated based on Linear Elastic Fracture Mechanics (LEFM) approach as per ASTM D5045.Results showed that composites having 25 mm length of fibers had the largest KIC value of 2.67 MPa.m1/2, whereas composites with 10 mm fiber length showed lowest value of fracture toughness K_{IC} of 1.61 MPa.m1/2. SEM results revealed that fiber breakage, matrix cracking, fiber matrix debonding and fiber pull out are major causes of failure of composite. Simulation/modelling of crack propagation in compact tension specimen by using FEA software ABAQUS® showed similar results as experimental values.

Key Words: Mode-I Plane Strain Fracture Toughness (K_{IC}); Fracture Mechanics; Bamboo fibers; Epoxy Matrix.

1 INTRODUCTION

There has been tremendous interest in using natural fiber composites instead of synthetic fibers because of their low density, abundant availability, low cost and biodegradability. Natural fibers are getting high popularity as a replacement of synthetic fibers. This is evident through the amount of research being done on finding the best suitable material for reinforcement in place of synthetic fibers [1-10]. The increased applications of natural fiber composites have drawn attention of many researchers towards improving their mechanical properties as mentioned by many reported works, [11-17]. Abdul Khalil, Alwani [9] and [18] has shown the versatility of bamboo fibers application and also mentioned that bamboo has significant potential in composite making due to its high strength and environmentally friendly nature. As per Ratna Prasad and Mohana Rao [19], bamboo fiber has higher ultimate tensile strength than most of natural fibers such as jowar and sisal. Bamboo fiber also has higher tensile modulus than jowar, banana, sisal and coir fibers. According to [20, 21], bamboo fiber is a naturally existing composite material as it is unidirectional reinforced by fibers. Bamboo fiber has attracted attention of many researchers such as Abdul Khalil, Bhat [4], Correia, Santos [5], Hojo, Xu [7], Ren, Yu [22], Abdul Khalil, Alwani [9], Murali Mohan Rao, Mohana Rao [23], Zakikhani, Zahari [24], [25].The combination of Bamboo fiber with epoxy matrix has been used by various researchers. In a very recent work carried out by Biswas, Shahinur [26], it was concluded that bamboo fiber reinforced epoxy composite has high tensile strength than jute fiber reinforced epoxy composite. L. Osorio [27] concluded that bamboo fiber reinforced epoxy composites can be used in applications where carbon fiber and glass fiber based composites are being used. Anu Gupta [28] showed that there is increased tensile, flexural, hardness and impact strength of the composite as compared with epoxy. From review of above-mentioned work, it is concluded that bamboo fiber is one of the most widely used natural fibers and has great potential as reinforcement in polymer composites; hence, bamboo fibers have been chosen for the current work as a reinforcement fiber.

According to [29, 30], interface between fiber and matrix is critical in maintaining reliability of the composite. It is equally important to be able to predict the behaviour of material in presence of defects or built-in flaws. This behaviour is understood through study of fracture mechanics. In case of polymers, application of Linear Elastic Fracture Mechanics (LEFM) as per ASTM D5045, is still in the early stage as addressed by Silva, Spinelli [31] as polymers are heterogeneous. LEFM theory has been successfully used by many researchers, [11, 31-35], to find the fracture toughness of composites. In most of the structural applications, composites have brittle matrices and high elastic modulus fibers which results in overall brittle nature; hence application of LEFM theory is justified. Substantial work on the fracture behaviour of synthetic fiber composites has been done by the researchers as fracture toughness is one of the important characteristics of materials. Graciani, Varna [14] determined the fracture toughness at fiber-matrix interface by using single fiber pull out test using E-glass fiber in epoxy matrix using LEFM theory. In another work, Tsai, Huang [33] found out that the fracture toughness of glass/epoxy composite is increased by 82% by adding rubber Core Shell Rubber (CSR) and silica nanoparticles and 48% by adding Carboxyl Terminated Butadiene acrylonitrile (CTBN) rubber, silica nanoparticles. As per Melcher and Johnson [36], Mode-I inter-laminar fracture toughness of carbon fiber/epoxy composites was decreased at low temperature. Floros, Tserpes [32] determined Mode-I, Mode-II and mix Mode-I+ Mode-II fracture behaviour of adhesively bonded CFRP composites using DCB specimen and observed scattered behaviour of fracture toughness value.

Various techniques have been used by researchers to accurately simulate fracture modelling. Floros, Tserpes [32] performed modelling/simulation of fractured surfaces using Cohesive Zone Modelling (CZM) technique which has been developed for fracture behaviour of solids. According to Vigueras, Sket [37], development of more accurate and flexible numerical model to capture multiscale composite failure is still at an early stage.

In the current work, single fiber tensile test was carried out to establish effect of NaOH treatment on the strength of bamboo single fiber. Single fiber fragmentation test was carried out to determine the interfacial adhesion between fiber and matrix. Mode-I plain strain fracture toughness test was carried out to determine critical stress intensity factor K_{IC}, of bamboo fiber reinforced epoxy composite as per ASTM D-5045 [38]. Modelling of the test samples was carried out using FEA software ABAQUS. Crack initiation and propagation was also simulated accurately using ABAQUS.

2 Materials & Methods

2.1 Materials

Bamboo fibers were selected as reinforcement whereas epoxy resin R246TX Thixotropic was used as the matrix with H160 as hardener. In order to prepare fibers for making composites, they are washed with NaOH solution. It is important to determine the optimum level of NaOH concentration for treatment of fibers which is done by carrying out single fiber tensile test on fiber samples treated with different concentration of NaOH solution.

2.2 Single Fiber Tensile Test

2.2.1 Preparation of Fibers

In the current work, fibers were washed with water and treated with 2%, 6% and 10% NaOH solution for 24 hours in three different containers. Fibers were then thoroughly washed with clean water and left for another 24 hours for drying in air. Later on, they were placed in oven for 24 hours at temperature of 50° C for complete drying. In the following sections, detail procedure for conduction of single fiber tensile test, single fiber fragmentation test, fracture toughness test and tensile test has been explained.

Single Fiber Tensile Test was carried out on Hounsfield Testing Machine at a test speed of 0.5 mm/min. Fiber diameter was measured using Olympus XC10 microscope as shown in the Fig. 1. The test was conducted on three of each single bamboo fiber samples, treated with 2%, 6% and 10% of NaOH.

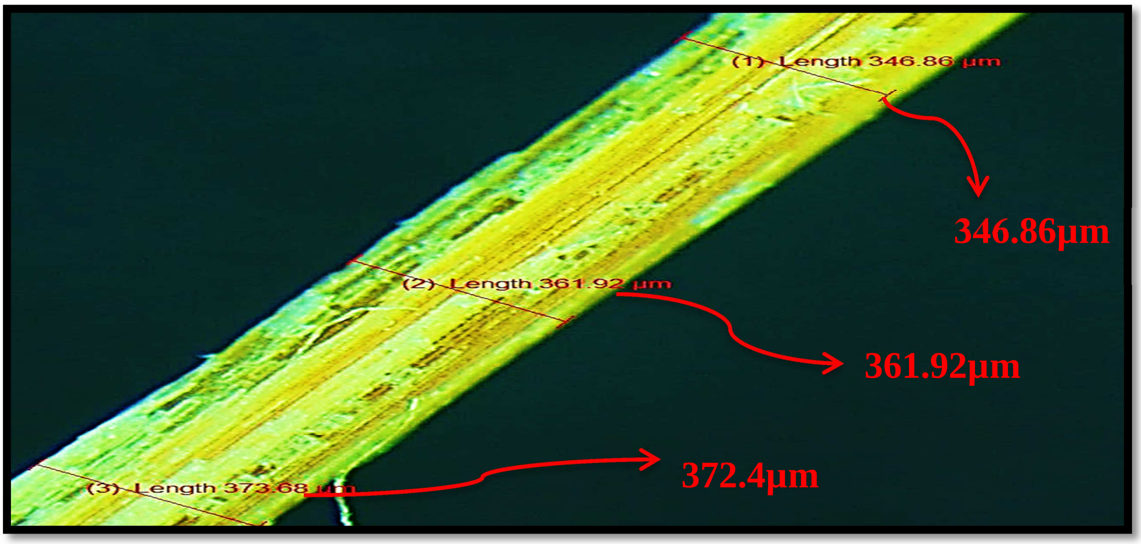


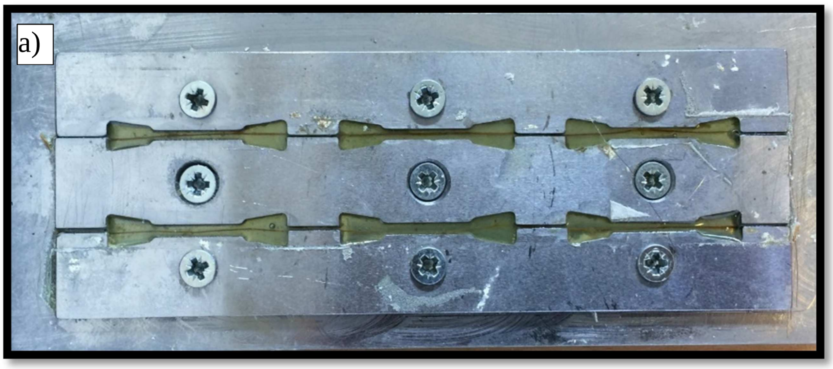
Figure 1 Optical Microscopy of bamboo fiber showing diameter of fiber

2.3 Single Fiber Fragmentation Test

2.3.1 Preparation of Single Bamboo Fiber Reinforced Epoxy Composite.

The samples were prepared with a single fiber encapsulated in epoxy resin in shape of a dog bone as shown in the Fig. 2(a,b) as per ASTM D638 [39]. In Fig. 2, specimen preparation for single fiber fragmentation test is shown. Metallic mould was machined as per shape of the specimen. Wax was applied on the mould to make it easier to remove the samples after curing. Epoxy resin was added to the mould with the help of a syringe. H160 hardener was added to epoxy resin. After the samples were left for curing for 24 hours at room temperature. Later on they were placed in an oven at 80 ° C for 4 hours. Cured samples have been shown in the Fig. 2 (b).

Single fiber fragmentation test (SFFT) was conducted as per Kelly and Tyson [40].Single fiber fragmentation test was carried out on Hounsfield Testing Machine at test speed of 2 mm /min. Three samples were tested for treated fibers and three for untreated fibers and results were recorded.



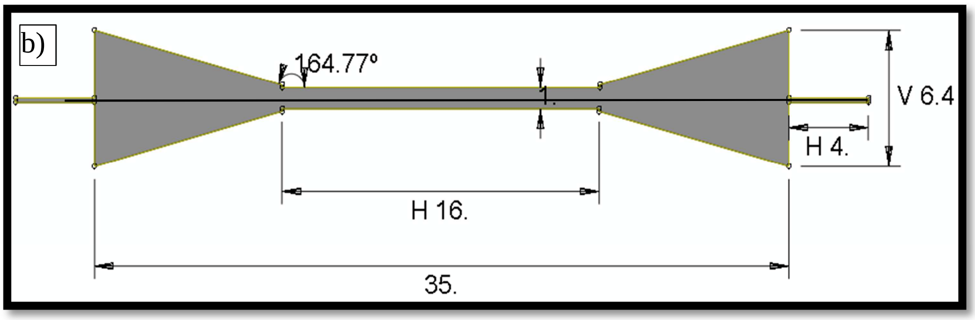


Figure 2 Arrangements for Single Fiber Fragmentation Test.

Interfacial shear strength was calculated using the formula 2.1 which is given below:

$$\tau = \frac{F}{L\pi D} \longrightarrow \quad (1)$$

τ = Interfacial shear stress, F=Applied force, L=Length of embedded fiber, D=Diameter of fiber.

2.4 Fracture Toughness Test

In the current work, fracture toughness of bamboo fiber reinforced epoxy composite has been determined by conducting fracture toughness test as per procedure defined in ASTM D-5045.

2.4.1 Preparation of Bamboo Fiber Reinforced Epoxy Composite.

Bamboo fibers (referred to as fibers hereafter) were treated with 6% NaOH solution for 24 hours prior to making composites. After treatment, fibers were washed with clean water and dried in air for approximately another 24 hours. Bamboo fiber reinforced epoxy (BFRE) composite was fabricated using hand layup method in form of 3 plates of thickness 10.5 mm. One of the plate had fibers of 10 mm length, the second plate had fibers with 20 mm length and the third plate had fibers of 25 mm length. Fibers were randomly distributed in the epoxy resin with volume fraction of 20% by weight of the composite. Composite plates were left for 24 hours for curing in air at room temperature. Later on curing was done in oven at temperature of 80 ° C for approximately 4 hours. Three samples of the shape shown in the Fig. 3 (b) were cut from each plate using water jet cutter. As per ASTM-D5045, the dimensions of the specimen should be such that 0.45<a/w<0.55 and W=2B. In order to insure that the plane strain condition has been met, the tentative values of fracture toughness "K_Q" is determined. The following condition should also be met for the result of the test to be a valid "K_{IC}" test i.e.

$$2.5(K_Q/\sigma_y)^2 < B, (w\text{-}a), a. \longrightarrow \quad (2)$$

Where

K_Q = Experimental value of Stress Intensity Factor, σ_y = Yield Stress obtained from tensile test

B = Thickness of the sample, W = Width of the sample, a = Initial crack length

The condition 2 holds true for all the specimens used for fracture toughness test.

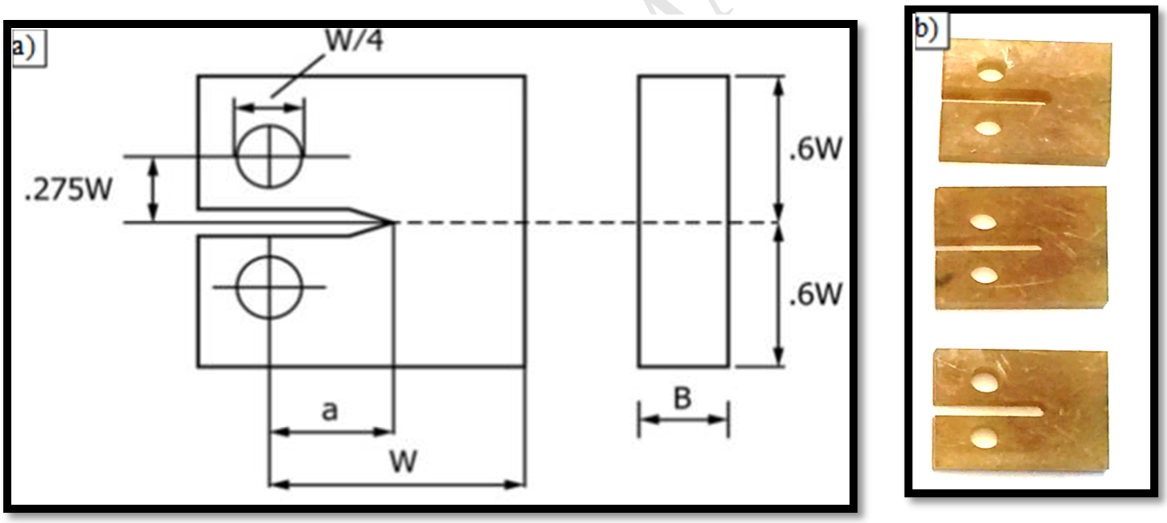


Figure 3 Compact Tension Specimen made from Bamboo Epoxy Composite.

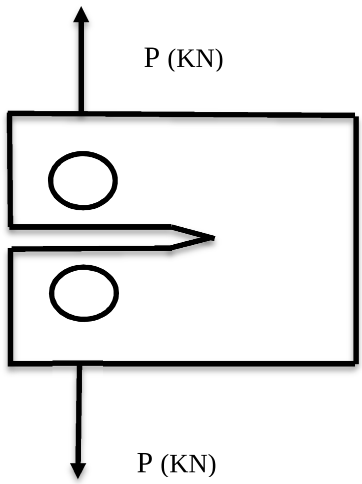


Figure 4 Schematic Arrangement of the Fracture Toughness Test

Schematic arrangements of the test have been shown in the Fig. 4. Fracture test was carried out on Hounsfield testing machine at a test speed of 5 mm/ min. The value of "K_{IC}" i.e. plain strain fracture toughness or critical stress intensity factor was calculated using the equation 3.

$$K_{IC} = \frac{P}{B\sqrt{W}} f(x) \longrightarrow \quad (3)$$

Where K_{IC} = Plain strain fracture toughness in MPa.$m^{1/2}$

P= Applied load in KN

B= Specimen Thickness in cm

W=Specimen Width in cm, a= crack length in cm, X= a/w

f(x) =Calibration Factor determined from ASTM D5045

$$f(x) = \frac{(2+x)(0.886 + 4.64x - 13.32x^2 + 14.72x^3 - 5.6x^4)}{(1-x)^{3/2}}$$

In total, 9 tests were performed i.e. 3 tests on samples with 10 mm fiber length, 3 tests on samples with 20 mm fiber length and 3 tests on samples with 25 mm fiber length for fracture toughness calculations. The percentage of error reported was 5% for composite of 10 mm and 20 mm fiber length whereas for 25 mm fiber length, percentage of error was 3%. Scanning Electron Microscopy (SEM) of fractured surfaces was performed on Neoscope JCL-6000 benchtop (JEOL Ltd USA) SEM Machine. Fractured surfaces were cut from each sample as per the size of sample holder in SEM machine. Each sample was gold coated in an enclosed chamber for 1-minute duration prior to conducting SEM. Coating is done to improve electrical conductivity and for ease in imaging. After coating, samples were placed on holder in SEM machine and examined at different magnification and focus to carryout failure analysis.

2.5 Tensile Test

Three test samples i.e. one each from same composite plates used for making fracture test samples having fiber length of 10 mm, 20 mm and 25 mm were cut as per dimensions shown in the Fig. 5. The tensile test was conducted on 100KN capacity MTS Insight machine at a test speed of 1 mm/min as per ASTM D-638, 2014[33]. Extensometers were also connected to the sample for getting the axial and transverse strain for finding out the poison's ratio. Three specimens were tested and their average values were noted.

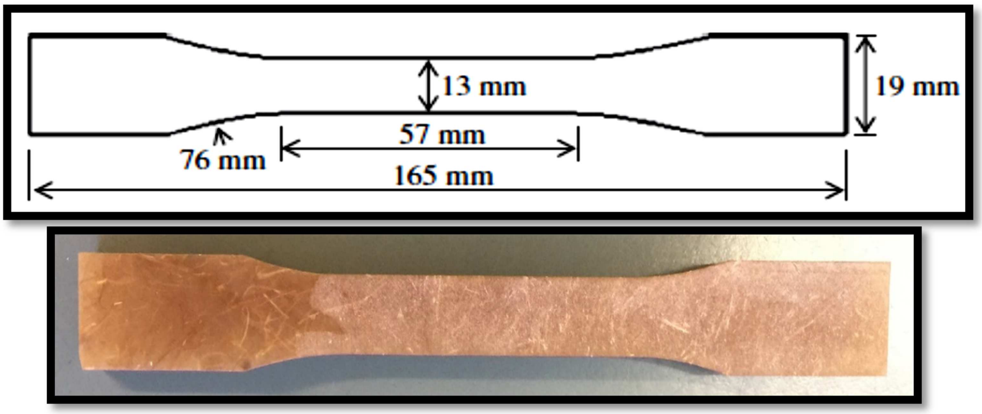


Figure 5 Tensile Test Specimen

3 Results & Discussion

3.1 SEM of Single Fiber Tensile Test Specimen

In Figs.6 to 8, SEM of bamboo fibers treated with NaOH solution of 2%, 6% and 10% concentration are shown. One can see that, there is an attached layer on the top of the surface which is lose and could not be removed (Fig. 6a), this is a tissue layer which has been found by many researchers in different natural fibers such as sugarcane [41], coir [42] etc. Based on this, it can be seen that the 2% NaOH treatment is not that sufficient to improve the surface of the fiber as was previously confirmed with the date palm fibers by Shalwan and Yousif [43] and coconut by Silva, Spinelli [31].

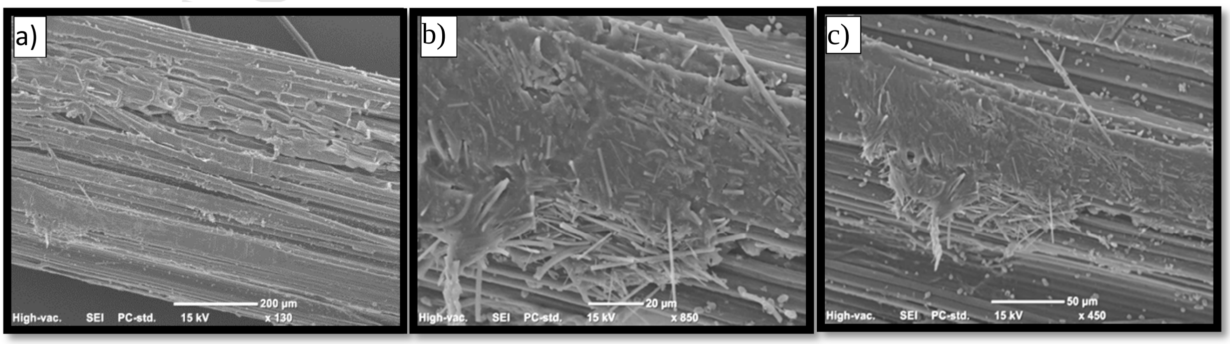


Figure 6 SEM of bamboo fibers treated with 2% NaOH

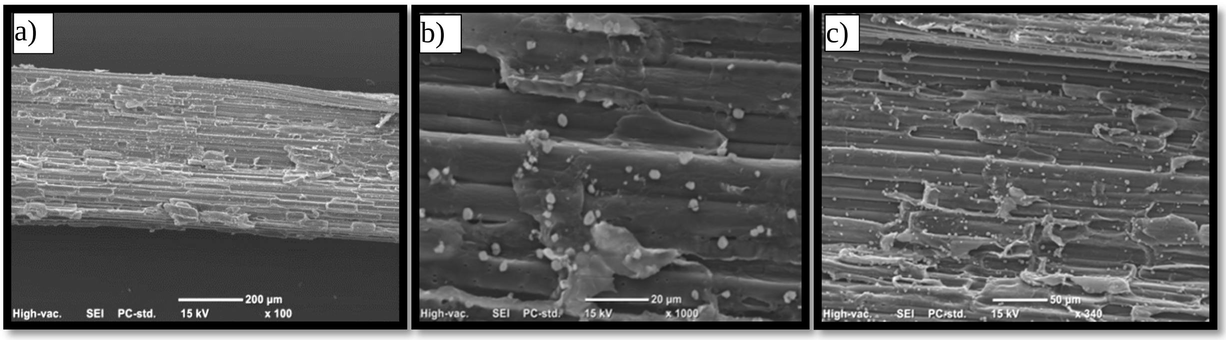


Figure 7 SEM of bamboo fibers treated with 6% NaOH

At medium concentration of NaOH (6%), the micrographs of the bamboo fibers shown in Fig. 7(a-c) indicate that there is a great washing up on the surface of the fibers This leads to the rougher surface of the bamboo fibers. In some reported works, it has been found that the outer layer stops the resin to penetrate inside the bundle of the fibers during the composite fabrication process [9]. In other words, the 6% NaOH improves the fiber-matrix adhesion. Hence it is recommended to treat fibers with 6% NaOH solution. With regards to the high concentration of the NaOH of 10%, Fig. 8(a-c) shows that there are many areas on the surface of the fiber which have been severely damaged due to the attack of the NaOH on the surface of the fiber. This is not recommended since this will further reduce the strength of the fibers.

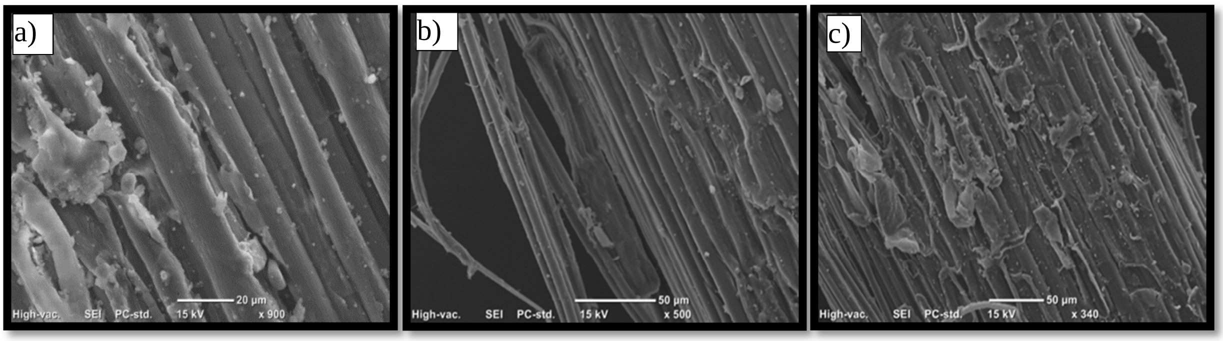
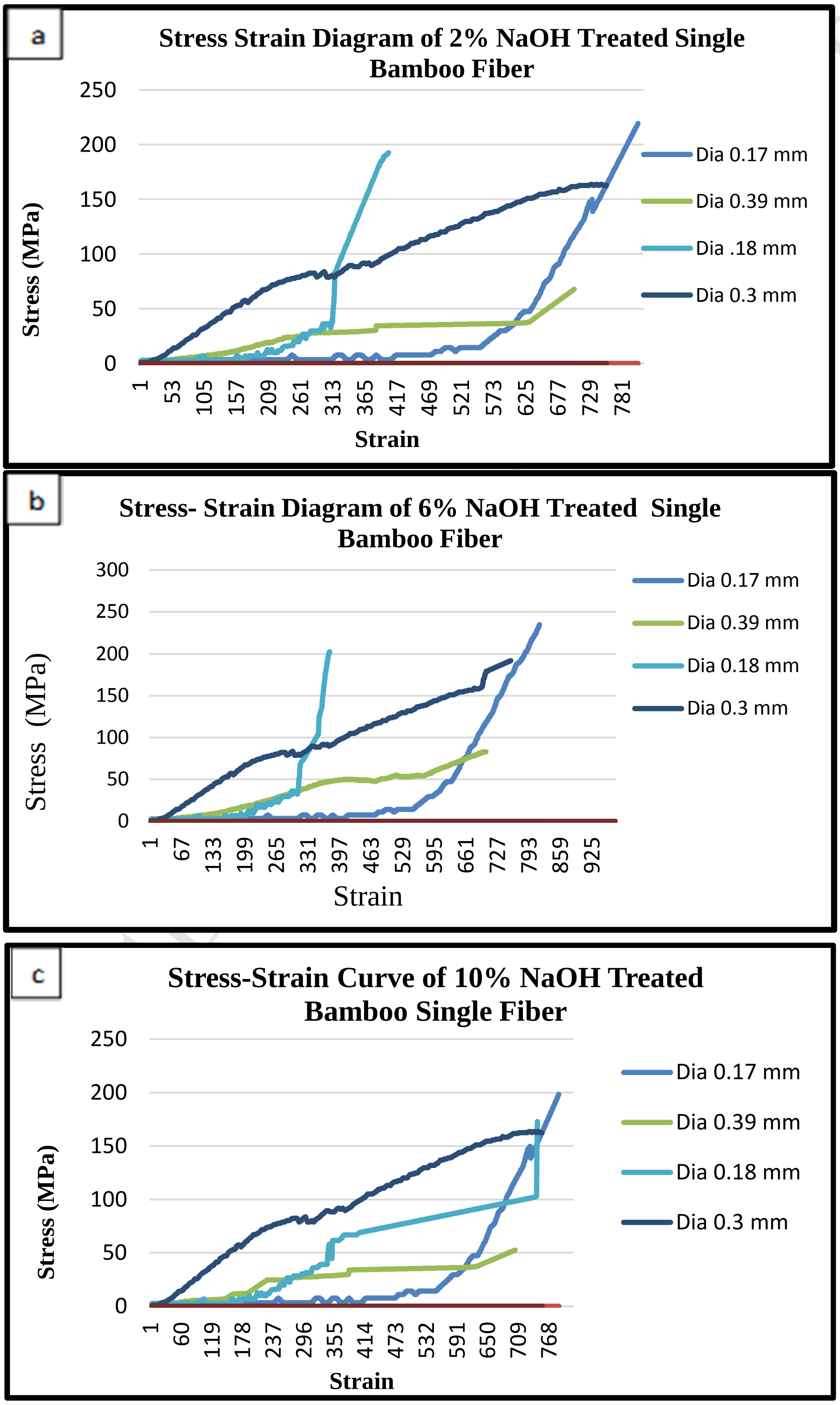


Figure 8 SEM of bamboo fiber treated with 10% NaOH solution

3.2 Stress-Strain Diagram of Single Fiber Tensile Test Specimens

Stress strain curves of Single fiber tensile test results have been shown in Fig. 9 (a, b, c). These results are also in line with the SEM results mentioned above. A comparison of ultimate tensile strength of single bamboo fiber treated with 2%, 6% and 10% NaOH and untreated has been presented in the Fig. 10 and Table-1. It is evident from the Fig. 9 (a, b, c, d), Fig. 10 and Table-1, that the fibers having smaller diameter show high tensile strength whereas fibers with larger diameters have lower tensile strength. This is true for all percentages of NaOH. It is due to the fact that at higher diameter of fibers, there are more surface defects and porosities than at lower diameters which makes the fibers weaker at larger diameters. The same phenomenon has been reported by [44], [45, 46]. The results indicate that Fibers treated with 6% NaOH show highest ultimate tensile strength which is also in line with the results of SEM described earlier. In a very recent work conducted by [47] on bamboo fiber reinforced polyester composites, it was concluded that 6% NaOH is the optimum level of NaOH concentration for treatment of bamboo fibers which is in line with the current findings.



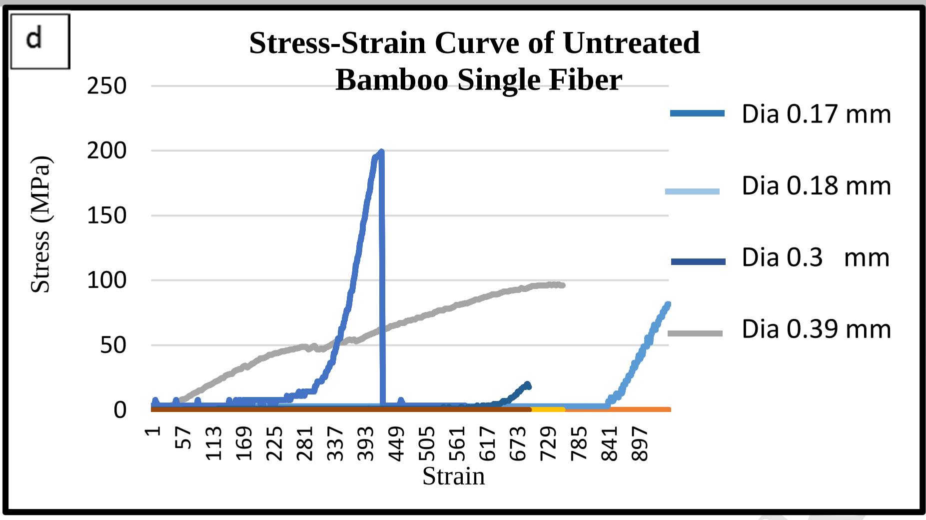


Figure 9 Stress Strain Curve of bamboo single fiber.

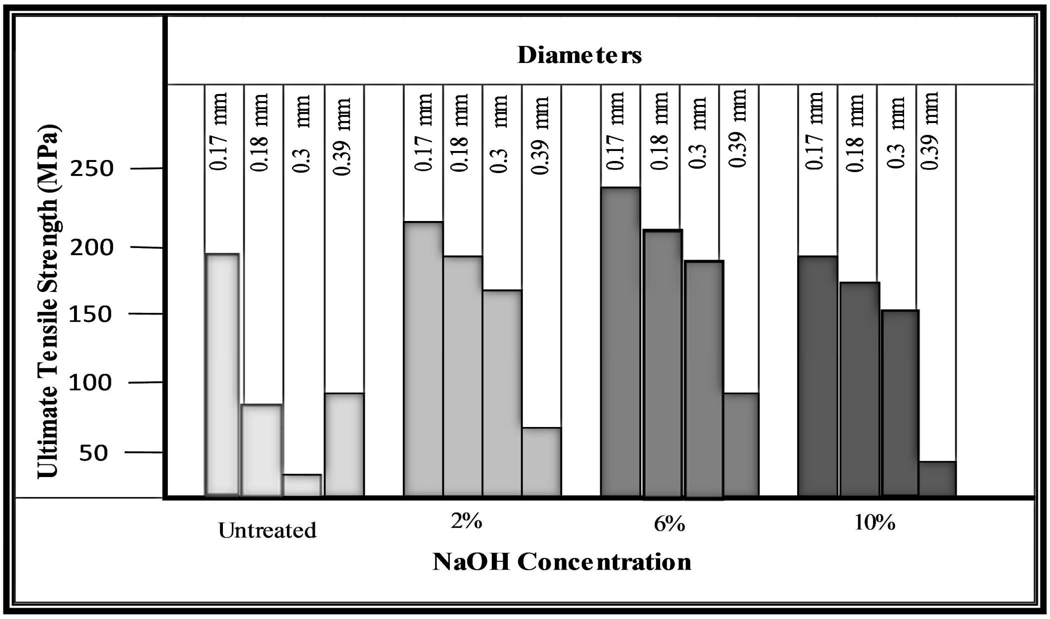


Figure 10 Comparison of Ultimate Tensile Strength between treated and untreated bamboo single fiber

Table 1 Comparison of Ultimate Tensile Strength of Treated and Untreated Bamboo Single Fiber.

Diameter (mm)	**Ultimate Tensile Strength (MPa)**			
	2% NaOH Treated	**6% NaOH Treated**	**10% NaOH Treated**	**Untreated**
0.17	219.18	234.6	198.25	199.25
0.18	192.55	202.45	172.9	81.54
0.3	162.65	191.82	162.65	17.68
0.39	67.42	83.12	52.63	96.27

3.3 SEM of Single Fiber Fragmentation Test Specimen

Fig.11 shows Scanning Electron Microscope (SEM) of untreated fiber composite specimen surfaces from Single Fiber Fragmentation Test. Fiber matrix debonding is visible in Fig.11 (a, b) where a small gap is present between fiber and the matrix marked with red. This is believed to be due to the waxy layer on fiber surface as it is an untreated fiber. The same has been observed by [44]. Fig.11(c) shows that the fiber has been pulled out of the matrix. This again shows that epoxy resin has not been able to penetrate on surface of fiber resulting in pulling out of the fiber from matrix.

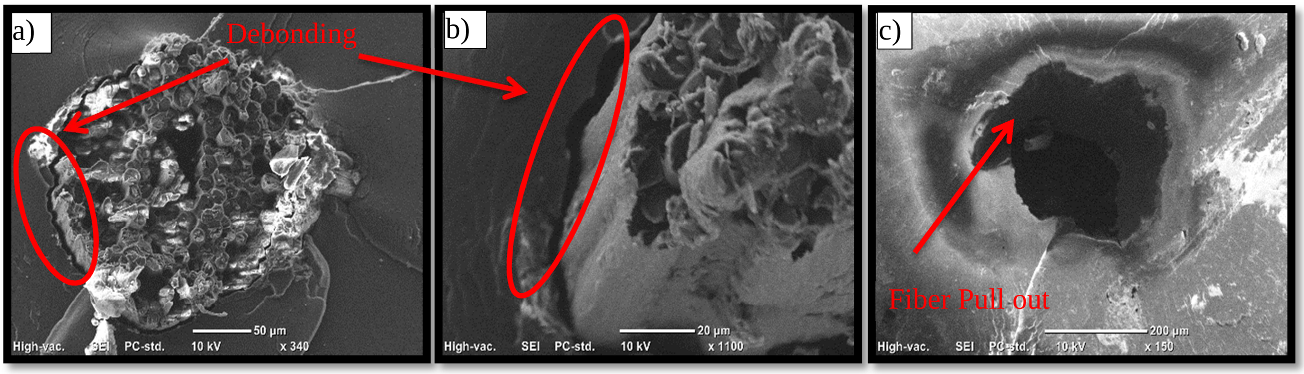


Figure 11 SEM of Untreated SFFT samples.

Fig.12 shows SEM of 6% NaOH treated samples from SFFT. It can be seen in Fig.10(a) that epoxy resin has fully penetrated on to the surface of the fiber hence there is a strong bond between fiber and the matrix. Fig.12 (b) shows some cracks on the matrix surface. The crack on the surface also indicates that there is a strong adhesion between fiber and the matrix. During the tensile test, the force has been transmitted from matrix to fiber, which causes crack on the surface of matrix.

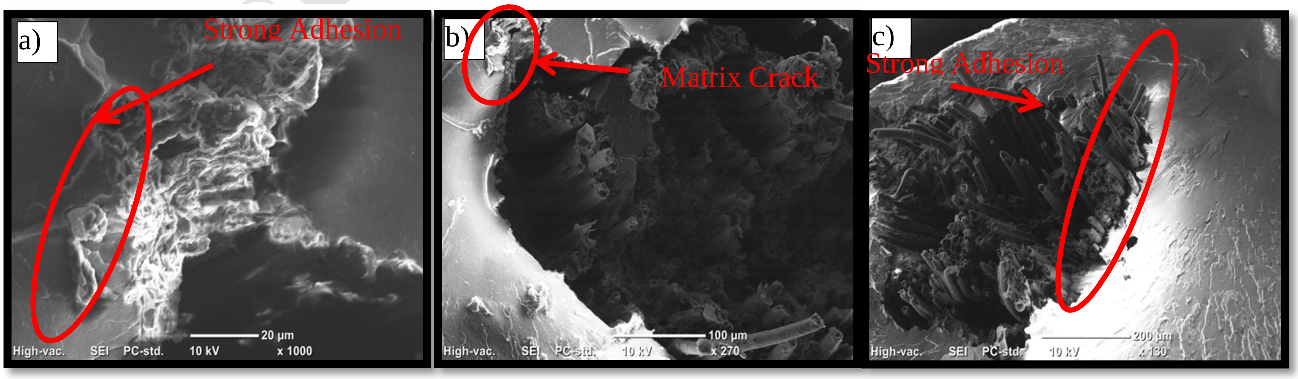


Figure 12 SEM of Treated SFFT Sample

Fig.12(c) also shows the same results where fiber breakage is seen at the interface of fiber and matrix. The waxy layer from the fiber has been removed due to NaOH treatment causing epoxy resin to penetrate on to the surface of the fiber resulting in a strong interfacial adhesion between fiber and the matrix.

3.4 Comparison of Interfacial Shear Strength of Single Bamboo Fiber Reinforced Epoxy Composites having Different Diameters.

Fig.13 shows comparison of interfacial shear strength of the single bamboo fiber reinforced epoxy composite at different fiber diameters between treated and untreated fibers. It is clear from the chart that interfacial shear strength is more for 6%NaOH treated bamboo single fiber than for the untreated bamboo single fiber. Same has been reported by [44] for date palm epoxy composite, [48] for Jute fiber, [49] for flax fibers. Detailed comparison of the results has been presented in the Table 2.

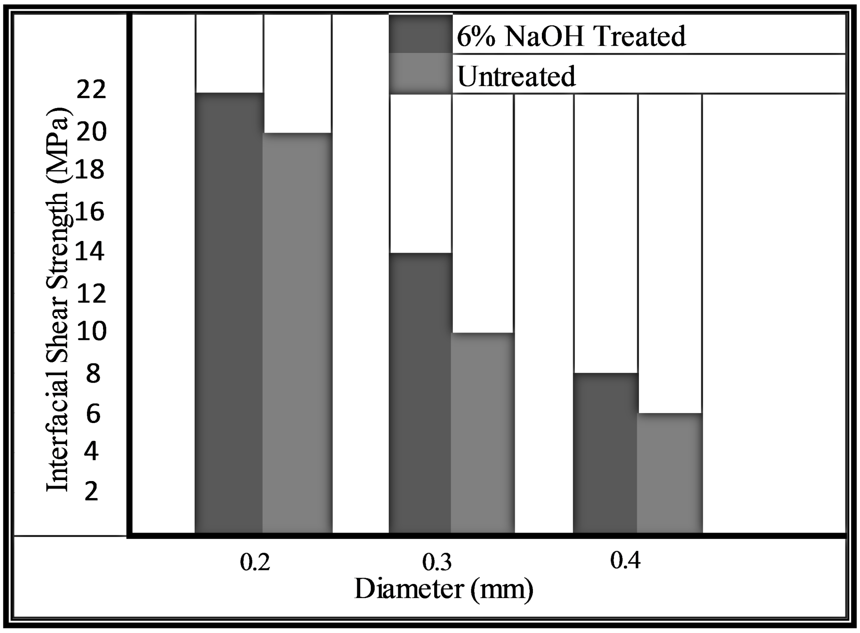


Figure 13 Interfacial Shear Strength of Single Fiber reinforced Epoxy Composite.

Table 2 Comparison of Interfacial Shear Strength of Treated and Untreated Bamboo Single Fiber Reinforced Epoxy Composite.

Diameter (mm)	Length (mm)	6% NaOH Treated		Untreated	
		Max. Force (N)	(τ) Interfacial Shear Strength (MPa)	Max. Force (N)	(τ) Interfacial Shear Strength (MPa)
0.2	16	222.6	22.142	207.56	20.64
0.3	16	209.75	13.91	152	10.07
0.4	16	174.8	8.69	156.6	7.78

3.5 Mechanical Properties of Bamboo Epoxy Composite

Tensile test results have been presented in the Table 3. Composite having fiber length of 25 mm shows maximum Ultimate Tensile Strength of 32.05 MPa and Poisson's ratio of 0.35. Whereas the composite with fiber length of 10 mm shows Ultimate Tensile Strength of 30.11 MPa and a Poisson's ratio of 0.38. During FEA modelling, average values of UTS, Poisson's ratio and Young's Modulus have been used. Fig.14 shows tensile test specimen which broke in two pieces during test.

Figure 14 Tensile Test Specimen after test

Table 3 Tensile Test Results

Specimen #	Peak Load (N)	Ultimate Tensile Strength (MPa)	Modulus of Elasticity (MPa)	Poisson' Ratio (mm/mm)
1	4284	32.05	3344	0.3582412
2	4110	30.11	3346	0.3821791
3	4248	31.64	3345	0.3782401
Average	4214	31.26	3345	0.372881

Stress-strain diagram of Bamboo epoxy composite has been shown in the Fig.15. Three curves obtained during the test show linear elastic behaviour before failure. No yielding has been observed which shows the brittle failure of the composite.

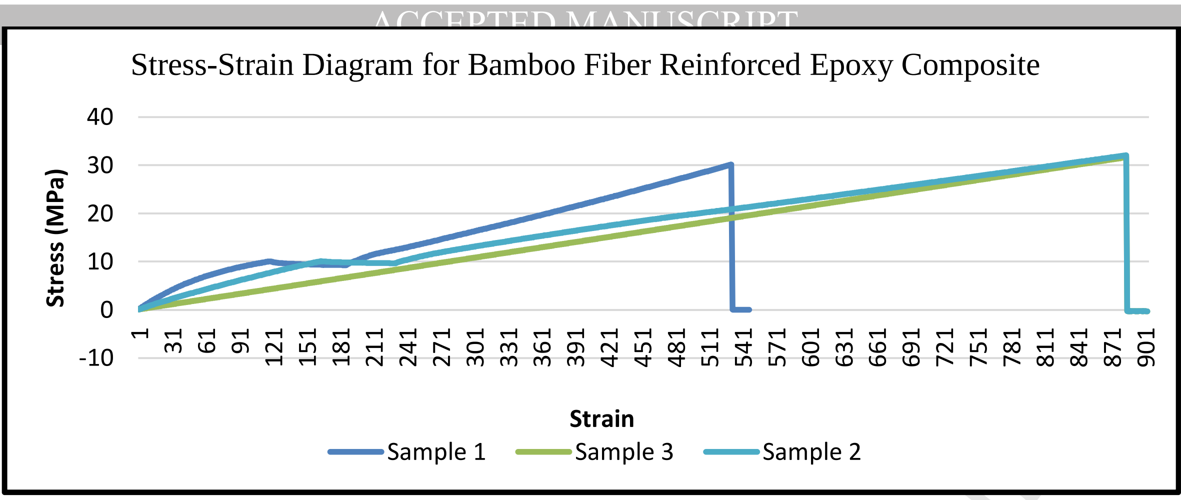


Figure 15 Stress Strain Curve for Bamboo epoxy composite

3.6 Fractrographic Examination of Fracture Toughness Test Samples

SEM images of fractured surfaces have been presented in Figs. 16 to 18. In Fig. 16, the fracture surface of the epoxy matrix shows a typical brittle fracture with river lines on the fracture surface which are marked with a red arrow. These lines have been observed by other researchers such as

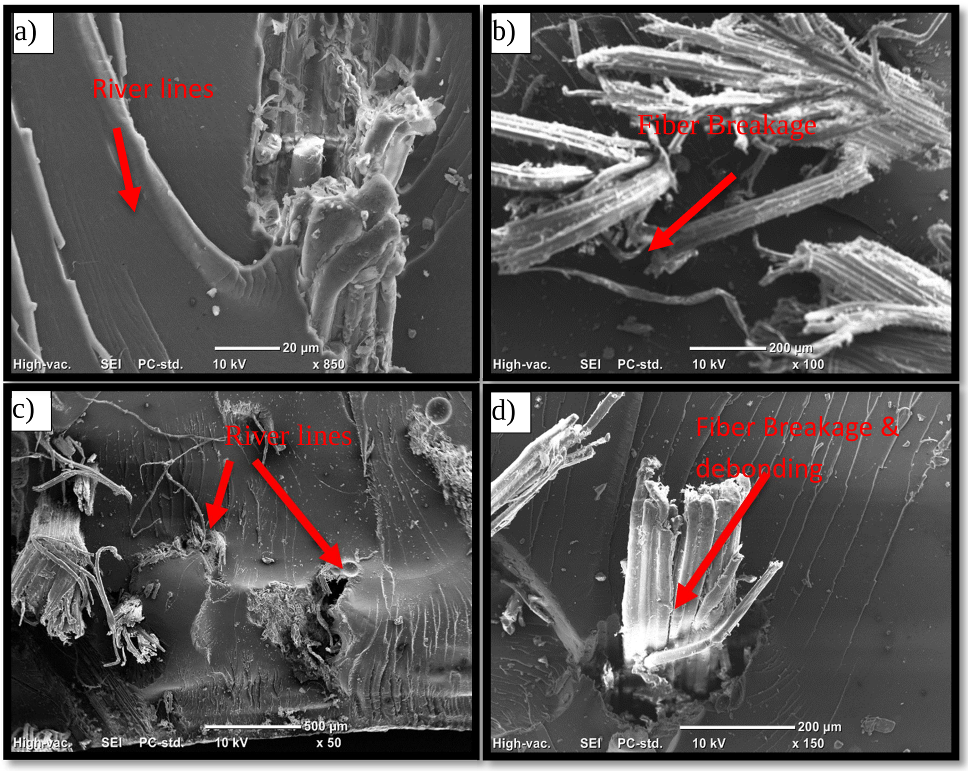


Figure 16 SEM of Composite with Fiber Length of 10 mm

[50], [51]. Fiber breakage and slight debonding between fiber and matrix is also visible and marked in the Figures. As the composite was fabricated using randomly distributed fibers, hence

this phenomenon of fiber breakage is due to the fact that fiber is deeply embedded in the matrix. As the stress is transferred from epoxy matrix to the fibers, the fiber breakage takes place instead of debonding or pull out. Fibers which have not been embedded deeply in the matrix show debonding as shown in the Fig. 16(d).The same has been explained by [52] during their work on effect of filler particles on the fracture of composite. Another type of fracture which has been observed is the fiber pull out from the matrix as shown in the Fig.17(b, c, d) marked with a red circle. Greater length of extended fiber out of matrix has been observed in case of 20 mm fiber length in the composite Fig. 17(c). Debonding between fiber and matrix has also been observed as shown in the Fig. 17(c). Matrix cracking is another type of failure that has been observed as shown in the Fig. 17 (a, d). Matrix cracking is usually observed when there is a strong bond

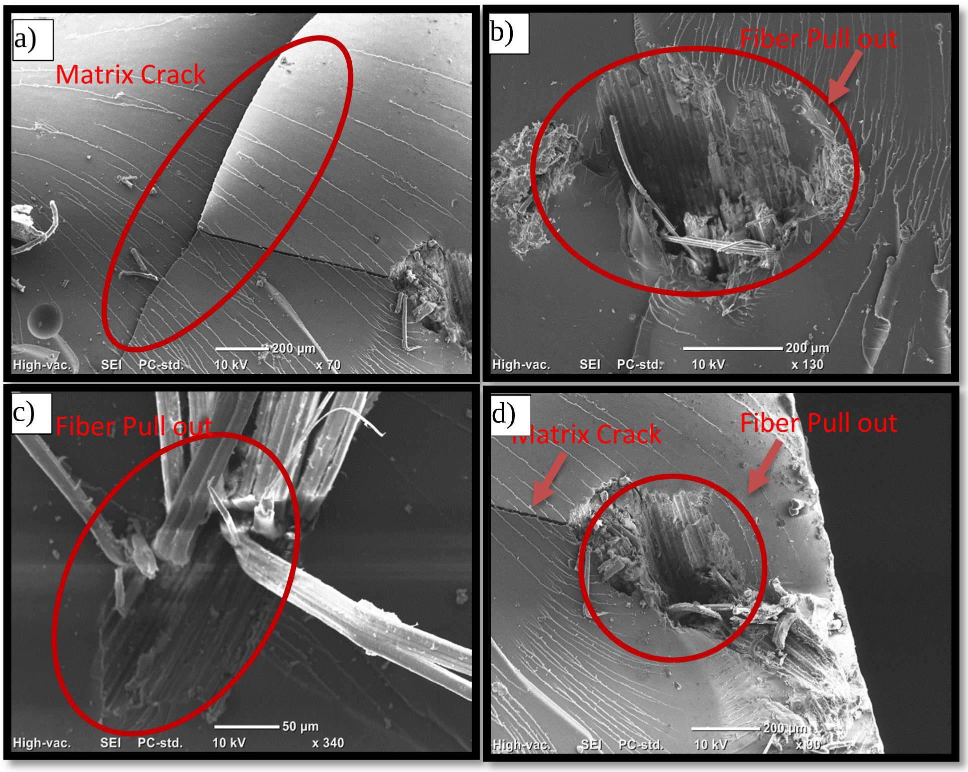


Figure 17 SEM of Composite with Fiber Length of 20mm

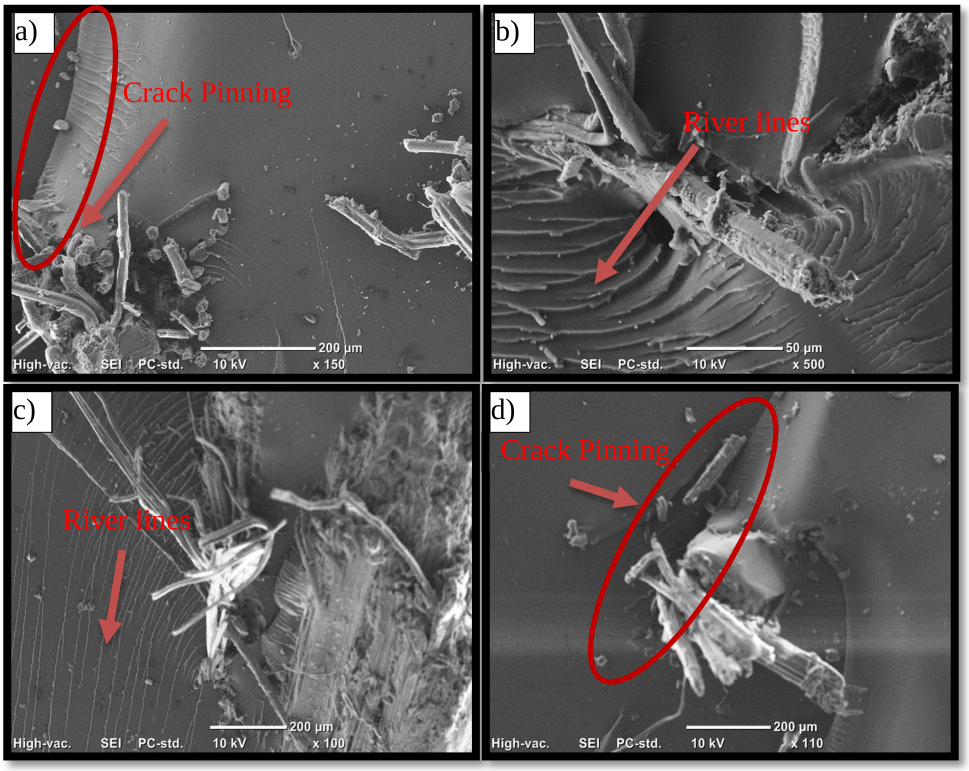
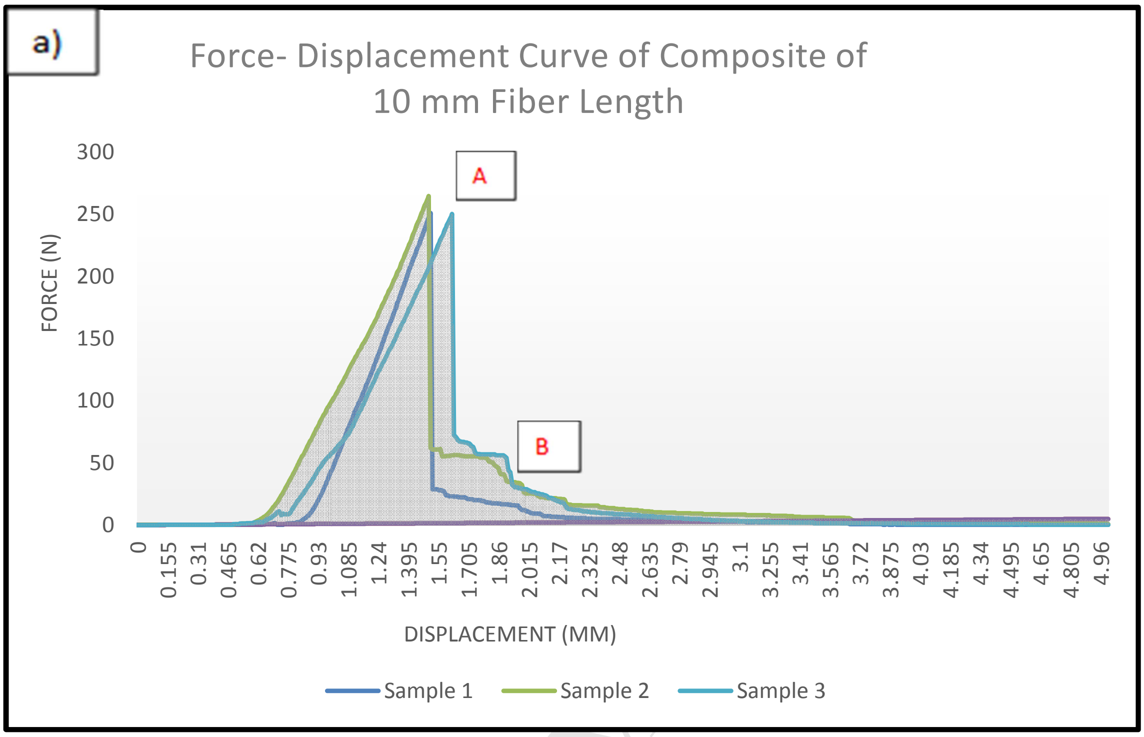


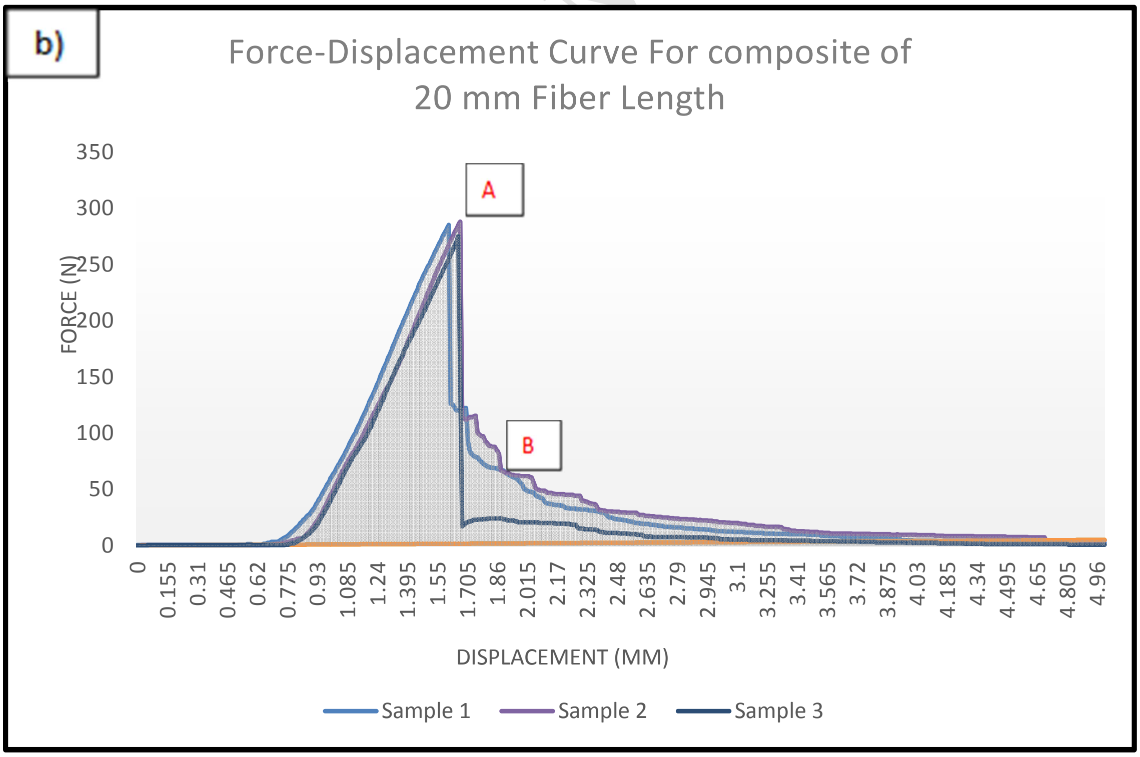
Figure 18 SEM of Composite with Fiber Length of 25mm

between the fiber and the matrix so when the fiber gets pulled due to the transfer of stress then the matrix surrounding the fiber gets cracked. Same phenomenon has been explained by [53] during their work on fiber matrix debonding phenomenon at the interface and by [54] during their work on role of the matrix crack and fiber/matrix debonding on the stress transfer between fiber and matrix in a single fiber fragmentation test. [54] attributes this matrix cracking to strong interface between fiber and the matrix which results in transverse crack on the matrix. Fig. 18 (a, b, c, d) shows SEM images of composite having fiber length of 25 mm. Crack pinning behaviour has been observed as shown in the Fig. 18 (a, d) where the crack path has been blocked or deflected by the presence of fiber. Crack pining or deflection of the crack path is the same phenomenon which has been explained by [55] during their work on flax fiber composite where they observed deflection or change in crack path with change in fiber orientation and fiber volume fraction. River line fracture is quite visible on the matrix surface as shown in the Fig. 18 (b, c). It is observed that presence of fiber in the brittle epoxy matrix has somewhat changed the overall nature of failure from totally brittle to somewhat ductile. Presence of fibers in the matrix help to form a barrier which disrupts the river lines on the brittle matrix surface. To summarize the failure mechanism, it can be stated that matrix cracking, fiber pull out, debonding and fiber breakage are the types of failures that have been observed during SEM of fractured surfaces in bamboo fiber reinforced epoxy composite.

3.7 Force-Displacement Curves of Fracture Toughness Test Samples

In Fig. 19 (a, b, c) force-displacement curves obtained during fracture toughness tests on composite





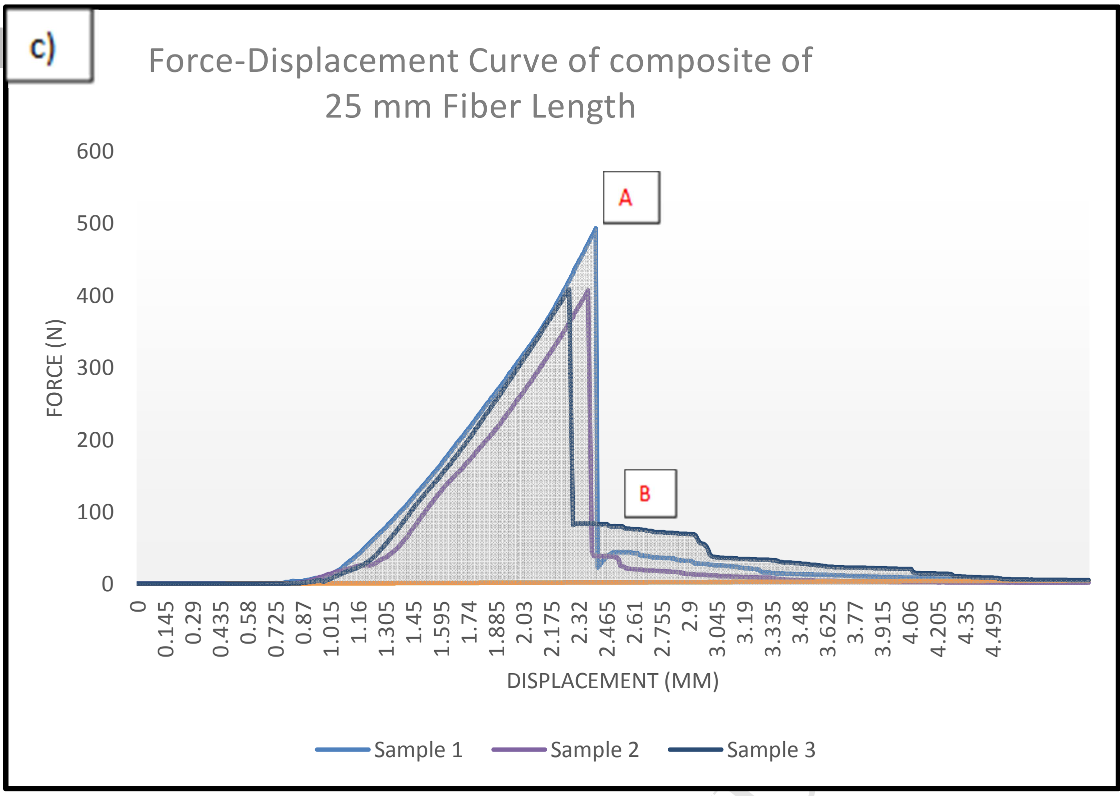


Figure 19 Force-Displacement Curves & Bamboo Fiber Reinforced Epoxy Composites

having fiber length of 10, 20 and 25 mm have been shown. The composite show linear elastic behaviour until point 'A' i.e. the point where the initial crack starts to extend in the matrix. After extension of crack, there is a sudden drop in the load till point 'B' followed by small extension at same load. The small extension of the curve is due to fiber bridging mechanism. It is also evident from the curves that composite having greater length of fiber, absorb more energy and are able to withstand larger loads than the composites with smaller fiber length. Values of the fracture toughness have been shown in the Table 4 below. Bamboo fiber reinforced epoxy composite having 25 mm length of fiber has maximum fracture toughness value. This is in line with the earlier findings by [56]. These are the average values obtained from tests conducted on 3 of each samples of composite having fiber length of 10 mm, 20 mm and 25 mm.

Table 4 Average Values of Fracture Toughness K_{IC}

Sample	Fiber Length (mm)	Fracture Toughness K_{IC} (Mpa.m$^{1/2}$)
1	10	1.61 ± 0.5
2	20	1.79 ± 0.5
3	25	2.67 ± 0.3

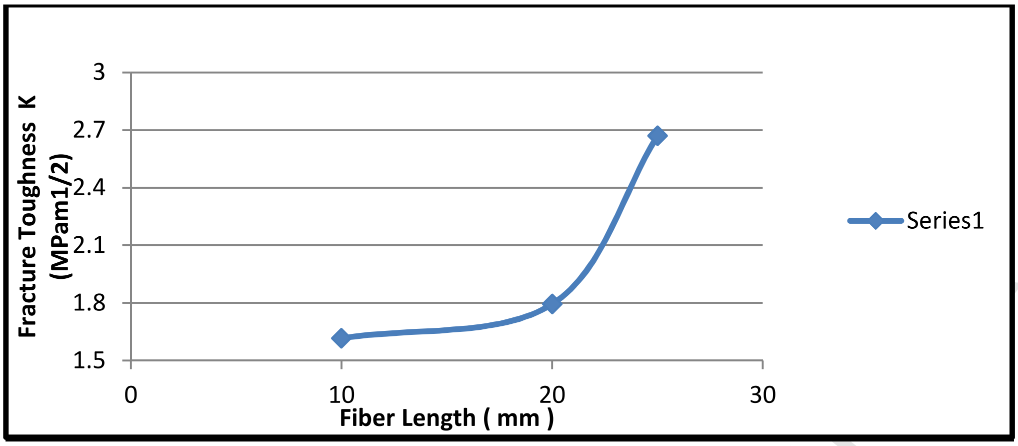


Figure 20 Fracture Toughness of Bamboo Epoxy Composite at different fiber lengths.

In the Fig. 20, the fracture toughness values have been drawn against the length of the fiber used in making the bamboo epoxy composite to show that the fracture toughness has increased by increasing the fiber length in the composite.

4 Numerical Analysis

Finite element analysis was carried out using ABAQUS version 6.13. Model was created by building 2D shell planar deformable part in the part module with dimensions as per original specimen. The complete 2D model is shown in the Fig. 21. Material properties were defined in the property module and were extracted from the tensile test carried out earlier. After creating assembly instance in Assembly module, two steps were defined for analysis purpose. In the step 1, history output 2 was created for inclusion of crack analysis in the results. In order to simulate crack growth, a seam is defined as shown in the Fig.19a with a black line. Two circles are drawn at the tip of the seam to represent crack tip region. The crack is simulated using contour integral method. The direction of crack growth is defined by q-vector. Two reference points, RP2 and RP4 are defined in the centre of two holes as shown in the Fig.21a. Two MPC-beam constraints are defined at these two points in

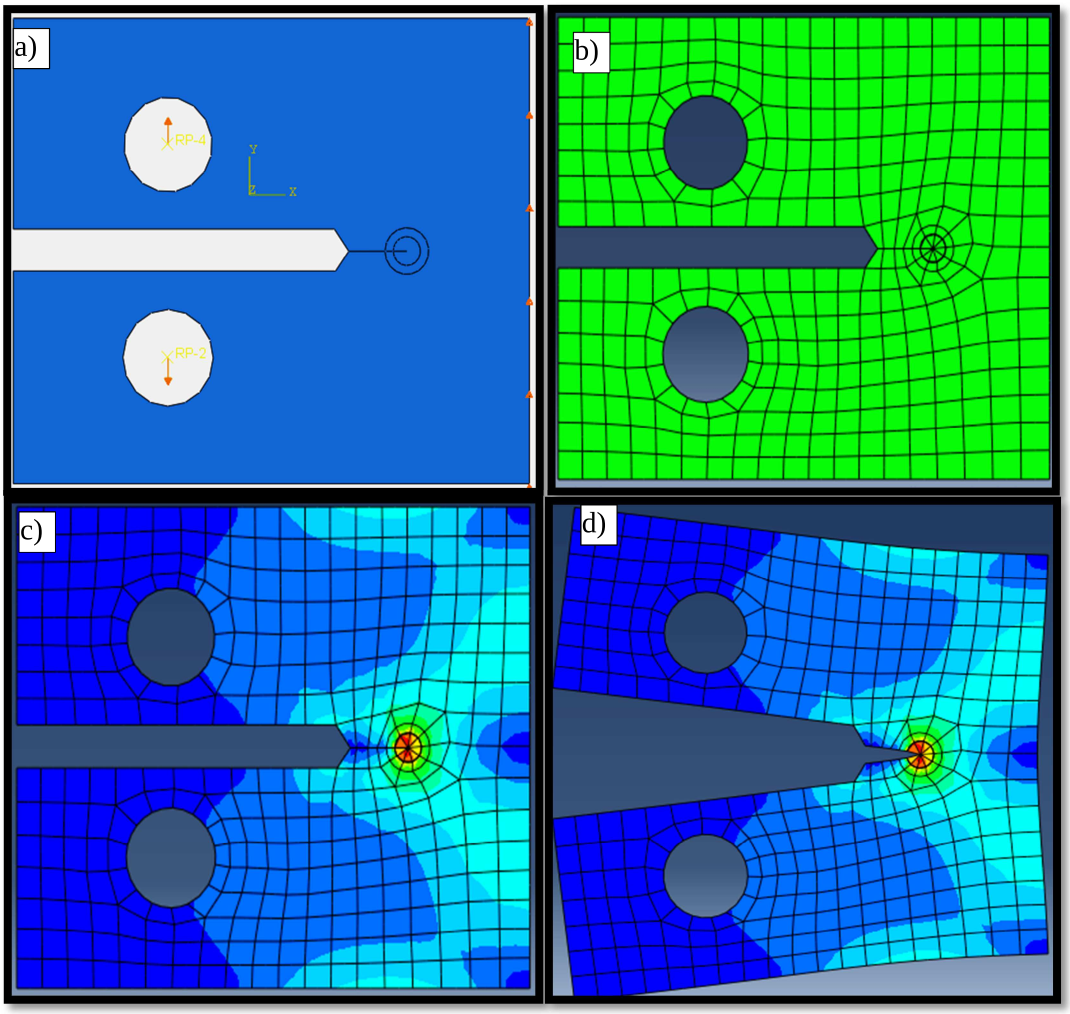


Figure 21 Simulation of Crack Propagation Using ABAQUS

order to accurately simulate the loading pins. For the case of 10 mm fiber length, two forces of 260 N are applied at two reference points in the load module. Displacement of 0.179 mm is defined on points RP2 & RP4 whereas on one edge, displacement is constrained in such a way that U1=0 as shown in the Fig.21a whereas for the case of 25 mm fiber length, two forces of 410 N are applied on RP2 & RP4 with a displacement value of 0.28 mm. The two circles drawn at the tip of the crack seam also help to define mesh controls. Crack tip region is meshed with 3 nodes linear triangle whereas rest of the part is meshed with 8 nodes biquadratic quadrilateral. The meshed model is shown in the Fig.21 (b). Fig.21(c, d) shows the model after analysis and also showing the model in deformed shape with propagation of crack. Results of the simulation modelling obtained were within 5% range of the values obtained during experiments. Fig. 22 shows force displacement curve obtained through ABAQUS. This is also a straight line graph showing elastic behaviour of the bamboo epoxy composite before failure. Table 5 shows comparison of experimental and numerical values for peak loads of 260 N (for 10 mm fiber length) and 410 N (for 25 mm fiber length). At peak load of 260 N, the value of stress intensity factor achieved during numerical analysis is 1.69 $MPa.m^{1/2}$ which is within 5% range of experimental value.

Similarly, at peak load of 410 N, the numerical value of stress intensity factor achieved is 2.64 MPa.m$^{1/2}$ which is also within 5% range of experimental value.

Table 5 Comparison of Experimental & Numerical values of Stress Intensity Factors

Stress Intensity Factor (K_{IC})	**Peak Load** (260N,10mm fiber length)	**Peak Load** (410N,25mm fiber length)
Experimental Values (MPa.m$^{1/2}$)	1.61 ± 0.5	2.67 ± 0.3
Numerical Values (MPa.m$^{1/2}$)	1.69 ± 0.05	2.64 ± 0.05

Two different peak loads i.e. 260 N and 410 N were used for simulation purpose because 260 N was the peak load observed during fracture test on composite having 10 mm fiber length and 410 N peak load was observed during fracture test on composite having 25 mm fiber length

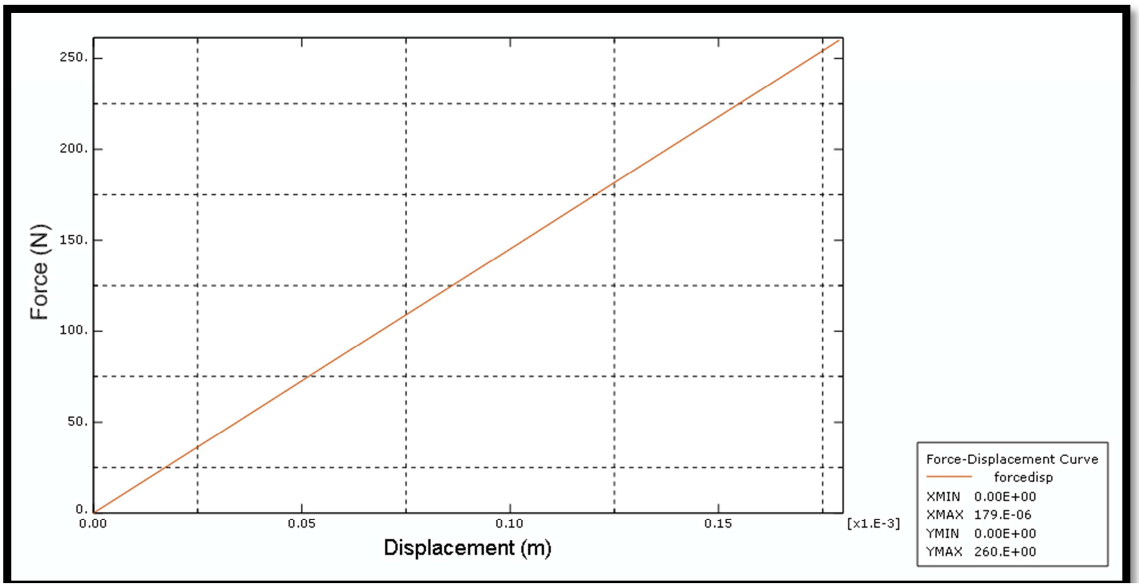


Figure 22 Force Displacement Curve Obtained through ABAQUS

5 Conclusions

In this work, experimental and numerical studies on fracture behaviour of bamboo fiber reinforced epoxy composite have been carried out. Effect of NaOH treatment on fiber surface has been investigated using single fiber tensile and single fiber fragmentation tests. Fracture toughness tests were conducted on compact tension specimens having fiber length of 10, 20 and 25 mm as per ASTM D-5045. FEA modelling was carried out using ABAQUS. Following conclusions have been made from this study:

1. Single fiber tensile test and Single Fiber Fragmentation test results followed by SEM of the test samples show that fibers treated with 6% NaOH show better ultimate tensile strength

and interfacial shear strength. Hence in order to achieve better interfacial adhesion and tensile strength, bamboo fibers should always be treated with 6% NaOH solution.

2. Bamboo fiber reinforced epoxy composite having 25 mm fiber length has more fracture toughness (K_{IC}) value than the composites having smaller fiber lengths.
3. Fractrographic results show that matrix cracking, fiber pull out, fiber breakage and fiber matrix debonding are the significant causes of failures observed in fracture toughness tests.
4. FEA modelling using ABAQUS shows similar results as experimental work for fracture toughness of bamboo epoxy composite.

6 REFERENCES

1. Rao, K.M.M. and K.M. Rao, *Extraction and tensile properties of natural fibers: Vakka, date and bamboo.* Composite Structures, 2007. **77**(3): p. 288-295.
2. John, M.J. and S. Thomas, *Biofibers and biocomposites.* Carbohydrate Polymers, 2008. **71**(3): p. 343-364.
3. Akil, H.M., et al., *Kenaf fiber reinforced composites: A review.* Materials & Design, 2011. **32**(8–9): p. 4107-4121.
4. Abdul Khalil, H.P.S., et al., *Bamboo fiber reinforced biocomposites: A review.* Materials & Design, 2012. **42**(0): p. 353-368.
5. Correia, V.d.C., et al., *Potential of bamboo organosolv pulp as a reinforcing element in fiber–cement materials.* Construction and Building Materials, 2014. **72**(0): p. 65-71.
6. Dai, D. and M. Fan, *1 - Wood fibers as reinforcements in natural fiber composites: structure, properties, processing and applications*, in *Natural Fiber Composites*, A. Hodzic and R. Shanks, Editors. 2014, Woodhead Publishing. p. 3-65.
7. Hojo, T., et al., *Tensile Properties of Bamboo, Jute and Kenaf Mat-reinforced Composite.* Energy Procedia, 2014. **56**(0): p. 72-79.
8. Akil, H., M.H. Zamri, and M.R. Osman, *5 - The use of kenaf fibers as reinforcements in composites*, in *Biofiber Reinforcements in Composite Materials*, O. Faruk and M. Sain, Editors. 2015, Woodhead Publishing. p. 138-161.
9. Abdul Khalil, H.P.S., et al., *16 - The use of bamboo fibers as reinforcements in composites*, in *Biofiber Reinforcements in Composite Materials*, O. Faruk and M. Sain, Editors. 2015, Woodhead Publishing. p. 488-524.
10. Hebel, D.E., et al., *Process-controlled optimization of the tensile strength of bamboo fiber composites for structural applications.* Composites Part B: Engineering, 2014. **67**: p. 125-131.
11. Zhou, X., et al., *Fracture and impact properties of short discrete jute fiber-reinforced cementitious composites.* Materials & Design, 2013. **49**(0): p. 35-47.
12. Rokbi, M., et al., *Effect of Chemical treatment on Flexure Properties of Natural Fiber-reinforced Polyester Composite.* Procedia Engineering, 2011. **10**: p. 2092-2097.
13. Mulinari, D.R., et al., *Mechanical Properties of Coconut Fibers Reinforced Polyester Composites.* Procedia Engineering, 2011. **10**(0): p. 2074-2079.
14. Graciani, E., et al., *Evaluation of interfacial fracture toughness and friction coefficient in the single fiber fragmentation test.* Procedia Engineering, 2011. **10**(0): p. 2478-2483.
15. Mivehchi, H. and A. Varvani-Farahani, *The effect of temperature on fatigue strength and cumulative fatigue damage of FRP composites.* Procedia Engineering, 2010. **2**(1): p. 2011-2020.
16. Verma, C.S. and V.M. Chariar, *Development of layered laminate bamboo composite and their mechanical properties.* Composites Part B: Engineering, 2012. **43**(3): p. 1063-1069.

17. Li, H.-t., et al., *Mechanical performance of laminated bamboo column under axial compression.* Composites Part B: Engineering, 2015. **79**: p. 374-382.
18. Fu, Y. and H. Fang, *Study on the properties of the recombinant bamboo by finite element method.* Composites Part B: Engineering.
19. Ratna Prasad, A.V. and K. Mohana Rao, *Mechanical properties of natural fiber reinforced polyester composites: Jowar, sisal and bamboo*, in *Materials & Design*. 2011. p. 4658-4663.
20. Amada, S., et al., *Fiber texture and mechanical graded structure of bamboo.* Composites Part B: Engineering, 1997. **28**(1): p. 13-20.
21. Amada, S. and S. Untao, *Fracture properties of bamboo.* Composites Part B: Engineering, 2001. **32**(5): p. 451-459.
22. Ren, D., et al., *The effect of ages on the tensile mechanical properties of elementary fibers extracted from two sympodial bamboo species.* Industrial Crops and Products, 2014. **62**(0): p. 94-99.
23. Murali Mohan Rao, K., K. Mohana Rao, and A.V. Ratna Prasad, *Fabrication and testing of natural fiber composites: Vakka, sisal, bamboo and banana.* Materials & Design, 2010. **31**(1): p. 508-513.
24. Zakikhani, P., et al., *Extraction and preparation of bamboo fiber-reinforced composites.* Materials & Design, 2014. **63**: p. 820-828.
25. Kinoshita, H., et al., *Development of green composite consists of woodchips, bamboo fibers and biodegradable adhesive.* Composites Part B: Engineering, 2009. **40**(7): p. 607-612.
26. Biswas, S., et al., *Physical, Mechanical and Thermal Properties of Jute and Bamboo Fiber Reinforced Unidirectional Epoxy Composites.* Procedia Engineering, 2015. **105**: p. 933-939.
27. L. Osorio, E.T., A.W.V. Vuure, I. Verpoes, *Morphological aspects and mechanical properties of single bamboo fibers and flexural characterization of bamboo/epoxy composites.* J Reinf Plast Compos, 30 (2010), 2010: p. pp. 396–408.
28. Anu Gupta, A.K., 1 Amar Patnaik,2 and Sandhyarani Biswas3 *Effect of Different Parameters on Mechanical and Erosion Wear Behavior of Bamboo Fiber Reinforced Epoxy Composites.* International Journal of Polymer Science, 2011. **2011**.
29. Sethi, S. and B.C. Ray, *Environmental effects on fiber reinforced polymeric composites: Evolving reasons and remarks on interfacial strength and stability.* Advances in Colloid and Interface Science, 2015. **217**(0): p. 43-67.
30. Doan, T.-T.-L., H. Brodowsky, and E. Mäder, *Jute fiber/epoxy composites: Surface properties and interfacial adhesion.* Composites Science and Technology, 2012. **72**(10): p. 1160-1166.
31. Silva, R.V., et al., *Fracture toughness of natural fibers/castor oil polyurethane composites.* Composites Science and Technology, 2006. **66**(10): p. 1328-1335.
32. Floros, I.S., K.I. Tserpes, and T. Löbel, *Mode-I, mode-II and mixed-mode I+II fracture behavior of composite bonded joints: Experimental characterization and numerical simulation.* Composites Part B: Engineering, 2015. **78**(0): p. 459-468.
33. Tsai, J.L., B.H. Huang, and Y.L. Cheng, *Enhancing Fracture Toughness of Glass/Epoxy Composites for Wind Blades Using Silica Nanoparticles and Rubber Particles.* Procedia Engineering, 2011. **14**(0): p. 1982-1987.
34. Wong, K.J., et al., *Fracture characterisation of short bamboo fiber reinforced polyester composites.* Materials & Design, 2010. **31**(9): p. 4147-4154.
35. Liu, Q. and M. Hughes, *The fracture behaviour and toughness of woven flax fiber reinforced epoxy composites.* Composites Part A: Applied Science and Manufacturing, 2008. **39**(10): p. 1644-1652.
36. Melcher, R.J. and W.S. Johnson, *Mode I fracture toughness of an adhesively bonded composite–composite joint in a cryogenic environment.* Composites Science and Technology, 2007. **67**(3–4): p. 501-506.
37. Vigueras, G., et al., *An XFEM/CZM implementation for massively parallel simulations of composites fracture.* Composite Structures, 2015. **125**: p. 542-557.
38. D5045-14, A.S.T.M., *ASTM D5045-14, Standard Test Methods for Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials, ASTM International, West Conshohocken, PA, 2014, www.astm.org*.
39. D638-14, A., *Standard Test Method for*

Tensile Properties of Plastics1. 2014.
40. Kelly, A. and W.R. Tyson, *Tensile properties of fiber-reinforced metals: Copper/tungsten and copper/molybdenum.* Journal of the Mechanics and Physics of Solids, 1965. **13**(6): p. 329-350.
41. El-Tayeb, N.S.M., *Two-body abrasive behaviour of untreated SC and R-G fibers polyester composites.* Wear, 2009. **266**(1-2): p. 220-232.
42. Yousif, B.F. and H. Ku, *Suitability of using coir fiber/polymeric composite for the design of liquid storage tanks.* Materials & Design, 2012. **36**(0): p. 847-853.
43. Shalwan, A. and B.F. Yousif, *Investigation on interfacial adhesion of date palm/epoxy using fragmentation technique.* Materials & Design, 2014. **53**(0): p. 928-937.
44. Shalwan, A. and B.F. Yousif, *Investigation on interfacial adhesion of date palm/epoxy using fragmentation technique.* Materials & Design, 2014. **53**: p. 928-937.
45. Placet, V., et al., *Diameter dependence of the apparent tensile modulus of hemp fibers: A morphological, structural or ultrastructural effect?* Composites Part A: Applied Science and Manufacturing, 2012. **43**(2): p. 275-287.
46. Duval, A., et al., *Influence of the sampling area of the stem on the mechanical properties of hemp fibers.* Materials Letters, 2011. **65**(4): p. 797-800.
47. Manalo, A.C., et al., *Effects of alkali treatment and elevated temperature on the mechanical properties of bamboo fiber–polyester composites.* Composites Part B: Engineering, 2015. **80**: p. 73-83.
48. Virk, A.S., W. Hall, and J. Summerscales, *Failure strain as the key design criterion for fracture of natural fiber composites.* Composites Science and Technology, 2010. **70**(6): p. 995-999.
49. Andersons, J., E. Poriķe, and E. Spārniņš, *Modeling strength scatter of elementary flax fibers: The effect of mechanical damage and geometrical characteristics.* Composites Part A: Applied Science and Manufacturing, 2011. **42**(5): p. 543-549.
50. Cholake, S.T., et al., *Improved Mode I fracture resistance of CFRP composites by reinforcing epoxy matrix with recycled short milled carbon fiber.* Construction and Building Materials, 2016. **111**: p. 399-407.
51. Madsen, B., M. Aslan, and H. Lilholt, *Fractographic observations of the microstructural characteristics of flax fiber composites.* Composites Science and Technology, 2016. **123**: p. 151-162.
52. Yesgat, A.L. and R. Kitey, *Effect of filler geometry on fracture mechanisms in glass particle filled epoxy composites.* Engineering Fracture Mechanics, 2016. **160**: p. 22-41.
53. Brighenti, R., A. Carpinteri, and D. Scorza, *Fracture mechanics approach for a partially debonded cylindrical fiber.* Composites Part B: Engineering, 2013. **53**: p. 169-178.
54. Johnson, A.C., S.A. Hayes, and F.R. Jones, *The role of matrix cracks and fiber/matrix debonding on the stress transfer between fiber and matrix in a single fiber fragmentation test.* Composites Part A: Applied Science and Manufacturing, 2012. **43**(1): p. 65-72.
55. Keck, S. and M. Fulland, *Effect of fiber volume fraction and fiber direction on crack paths in flax fiber-reinforced composites.* Engineering Fracture Mechanics, 2016.
56. I. Scheider, Y.C., A. Hinz, N. Huber, J. Mosler, *Size effects in short fiber reinforced composites.* Engng Fract Mech,, 2013. **100**(2013): p. 17-27.

Highlights

- Optimum concentration of NaOH for treatment of bamboo fibres is 6%.
- Bamboo fibre reinforced epoxy composite having 25 mm fibre length has more fracture toughness (K_{IC}) value than the composites having smaller fibre lengths.
- Matrix cracking, fibre pull out, fibre breakage and fibre matrix debonding are the significant causes of failures of bamboo epoxy composites during fracture tests.
- FEA simulation using ABAQUS shows similar results as experimental work for fracture toughness of bamboo epoxy composite.