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Multiscale Mechanical Modelling of E-Glass Fiber Reinforced Polymer Matrix Composites with Experimental Validation for Micro Wind Turbine Blades

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Abstract: Composite materials are being used as structural elements for engineering applications in aerospace, automobile, and mechanical domains. To utilize composite materials in any application, the material being used needs to be fabricated in hundreds of numbers to test and characterize them for a statistical estimation of the elastic behaviour. Such an experimental process is time consuming, and the cost of experimentation also escalates. One of the solutions for these problems is to pre-design the composite materials using numerical models. A hierarchical multiscale numerical model has been implemented in this paper along with experimental validation with a view of applying these models for development of micro wind turbine blades. In this paper, E-Glass fibre reinforced polymer matrix composite (epoxy-resin: Ly556 and Hardener 951) is modelled using FEA method (Finite Elements used at micro and macroscale), implementing a hierarchical multiscale modelling scheme. A representative volume element (RVE) is used to model the E-Glass/Epoxy-resin composite at microscale consisting of the uniaxial fibres embedded in epoxy-resin polymer matrix. The material properties derived from the microscale finite element analysis is applied to the nodal points of the elements of the macroscale finite element model. The multiscale analysis provides both qualitative and quantitative results for experimental validation. An experimental test sample made of the E-Glass/Epoxy-resin composite is subjected to uniaxial tensile test. The experimental results validate the multiscale mechanical model built. The multiscale model predicts the maximum tensile strength with an error of 5 % and the breaking load with an error of 1 %. The location of breakage of sample predicted by the numerical model is confirmed by the experimental test specimen. With such validated numerical model, application in micro wind turbine blade would result in faster prototype development.

Keywords: Composite material, Micro wind turbine, E-Glass fiber, Tensile strength, FEA, Orthotropic Material, Numerical methods, Macrostructure, Microstructure.

1. INTRODUCTION

At present the composite materials are widely used worldwide because of their high strength to weight ratio, corrosion resistance and ease of fabrication. These advantages help composite materials to replace conventional materials in various advance applications. In addition to the properties of the fiber, mechanical properties of fiber-reinforced composites also depends on the degree at which load is transmitted, length of fibers their orientation and volume fraction. In recent years glass fiber composites have gained the attentions and interests among researchers due its environmental friendly reflections [1]. A detailed literature study [2- 13] illustrate that the glass fiber composites have a lot of potential in numerous advanced sectors such as automotive, structural, aerospace and marine applications. Among the thermosetting polymers, epoxy resins are the most widely used for high-performance applications, such as matrices for fiber reinforced composites, coatings, structural adhesives and other engineering applications. Epoxy resins are characterized by excellent mechanical and thermal properties, high chemical and corrosion resistance, low shrinkage on curing and the ability to be processed under a variety of conditions [14]. However, these composites have some disadvantages related to the matrix dominated properties which often limit their wide applications [15].

Turbine blade is an important part of the rotor of a wind turbine which provides an alternative way of generating energy from the power of wind. Sufficient energy can be produced by making use of wind turbines at places with high wind speed. The design of blade depends on the extraction of energy from wind and wind turbine blades are designed such that they generate lift from wind and thus rotate. Wind turbine blade design involves material selection, structural configuration and selection of the aerodynamic shape of the blade material. To achieve high strength and high modulus requirements, the properties of polymers are modified by using fibers.

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Unidirectional (UD) fabric of E-glass fiber is most common reinforcement used in composite structural applications which exhibits excellent strength, modulus, resistance to water degradation and corrosive environments, durability, good fatigue life and it is easily available and economical. E-glass is a low alkali glass with a typical nominal composition of SiO_2 54wt%, Al_2O_3 14wt%, CaO+MgO 22wt%, B_2O3 10wt% and Na_2OK_2O less then 2wt% other than this some other materials may also be present as impurity. Among the thermosetting polymers, epoxy resins are used for high-performance applications, such as matrices for fiber reinforced composites, coatings, structural adhesives and other engineering applications. Epoxy resins are characterized by excellent mechanical and thermal properties, high chemical and corrosion resistance and low shrinkage on curing. Epoxy resins (Epoxy resin namely Ly556 and Hardener 95) possess desirable properties for making them suitable as a matrix. The present work is related to the development of micro wind turbine blade. Blades are one of the most critical components of wind turbine, the E-Glass fiber / Epoxy resin composite is selected for the construction of the blade as it is more economical compared to other fibres.

2. MATERIAL AND METHODS

The objective of this study is to compare the behaviour of E-Glass/Epoxy composite material specimens under a tensile test with the finite element analysis result. This study will help to determine the material properties of E-Glass fiber which is used in a wide range of engineering applications. The understanding from this study will help in the further development of the micro wind turbine blade.

2.1 Composite specimen fabrication

Fabrication of the composites is done at room temperature by hand lay-up techniques. The required ingredients of epoxy resin LY556 and hardener 951 are mixed thoroughly in a basin and the mixture is subsequently stirred constantly. E-Glass fibers are positioned manually in the open mould. Mixture so made is brushed uniformly, over the glass plies. Then the vacuum bag is mounted on the mould, vacuum bag molding helps eliminate excess resin that builds up when structures are made using (open-molding) hand lay-up techniques. Atmospheric pressure exerts a force on the bag. The pressure on the laminate removes entrapped air, excess resin, and compacts the laminate, resulting in a higher percentage of fiber reinforcement. Vacuum Bagging process is shown in Figure 1b.

The E-Glass fibers reinforced epoxy composite specimens were developed using Vacuum bagging process and then specimens of suitable dimensions were prepared from the composite Laminate for different mechanical tests according to ASTM standards. The test specimens were sized by using water jet cutting machine as shown in Figure 1c. Tensile test specimens were prepared according to ASTM D638. Test specimen having dimension of length 250 mm, width of 32 mm and thickness of 3 mm. Two identical test specimens were prepared for carrying out tensile test. Figure.2 shows the sample test specimens. The specimen used for the tensile test is having 6 layer of E-Glass fiber reinforced composite lamina having 0^o orientations. The dimensions of the tensile test specimen for composite materials are prepared as per the ASTM standards.

Figure 1a. E-Glass fiber Lamina

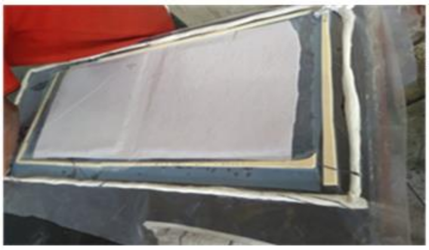

Figure 1b. Vacuum Bagging

Figure 1c. AJM Machining

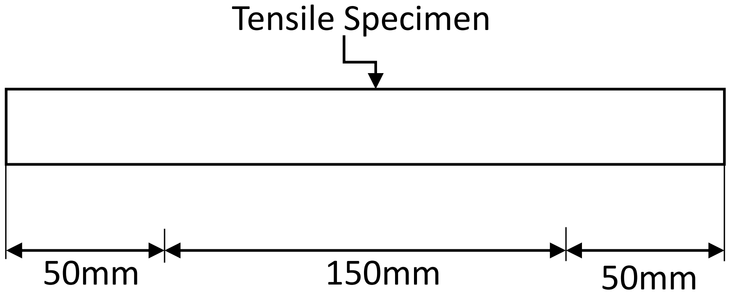

Figure 2. Specimens for Tensile test

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2.2 Multiscale mechanical modelling

The dimension of the CAD model used for tensile test simulation using FEA is same as that used for tensile test (as per ASTM). Figure 3 shows the macroscale scale model and the finite element model of the CAD model. Commercial FEA tool Ansys is used for the tensile test simulation. A two-dimensional model is used for the simulation. Fibre orientation and the layup are modelled in FEA as in test specimen. The orthotropic material property (with linear elasticity assumption) used for the macro structural analysis is obtained from micro structural study (with application of periodic boundary condition for constant material evaluation) as shown in table 2. Total element count is 2000 and total node count is 2142. The linear element is used for this analysis to reduce the computational time (explicit analysis requires more computation time). Since the geometry is rectangular plate, linear element is sufficient to capture the geometry appropriately. Ply thickness and orientation of the ply modelled in FEA are same as used in test specimen preparation. The CAD model of the specimen is constrained in all direction as shown in the Figure 5a as the bottom of the specimen is fixed as in test setup. The enforced displacement is applied as shown in the Figure 5b as in case of the testing the specimen is pulled gradually until it breaks. Tensile test is simulated using the explicit dynamic approach as the experimental tests are quasi-static in nature.

TABLE 1 a. Material Property E-Glass

Material Property E-Glass		
Density	2600	kg/m^3
Young's Modulus	85000	MPa
Poisson's Ratio	0.23	MPa

TABLE 1.b Material Property Epoxy

Material Property Epoxy		
Density	1160	kg/m^3
Young's Modulus	3780	MPa
Poisson's Ratio	0.35	MPa

TABLE 2. Material Property for Analysis

Material Property from microstructure Study		
Density	1664	kg/m^3
Orthotropic Elasticity		
Young's Modulus X Direction	32322	MPa
Young's Modulus Y Direction	9867.6	MPa
Young's Modulus Z Direction	9867.6	MPa
Poisson's Ratio XY	0.26392	
Poisson's Ratio YZ	0.60332	
Poisson's Ratio XZ	0.26392	

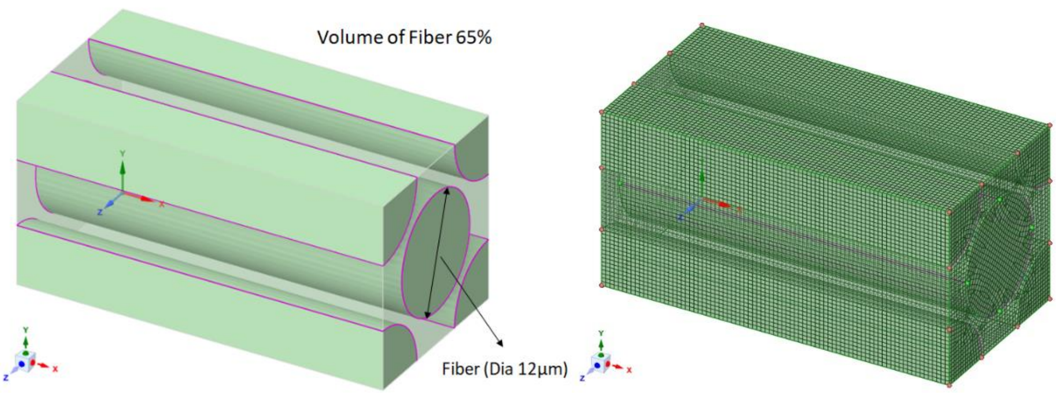

Figure 3. Representative Volume Element implemented at the microscale with E-Glass fiber and epoxy-resin

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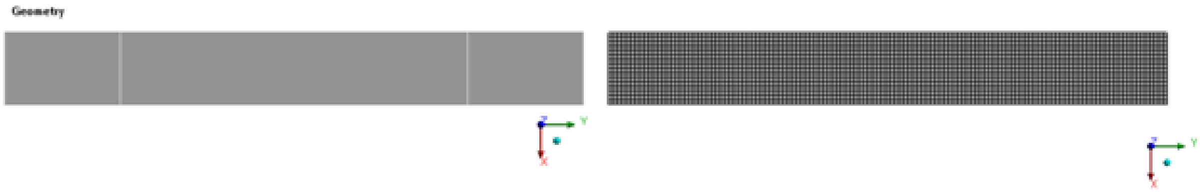

Figure 4 (a) Macroscale CAD model. (b) FE meshing for the CAD model

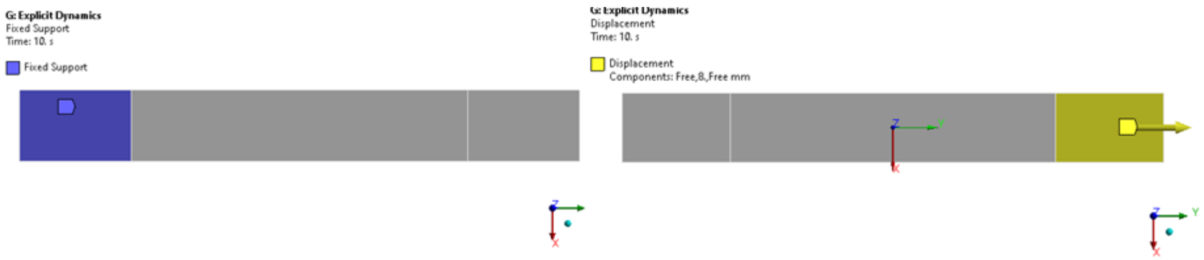

Figure 5 (a) Fixed Boundary Condition (b). Enforced displacement

2.3 Experimental method for validation

A universal testing machine (UTM) is used to test the tensile strength. A movable cross head is controlled to move up and down at a constant speed either using servo-hydraulic system or electromechanical system. A UTM with electromechanical system is used for tensile test. Machines have a computer interface for analysis and printing of output.

3. RESULTS AND DISCUSSION

3.1 Multiscale modelling outcomes

The maximum principal stress and the reaction forces are extracted after the solution in FEA. The max principal stress is 390.3 MPa as shown in figure 6 and the reaction force is 33.83 kN as shown in Table 3. It is observed that the max principal stress and reaction force from FEA is very close to the test result. The error for stress is 5% and for the force is 1%.

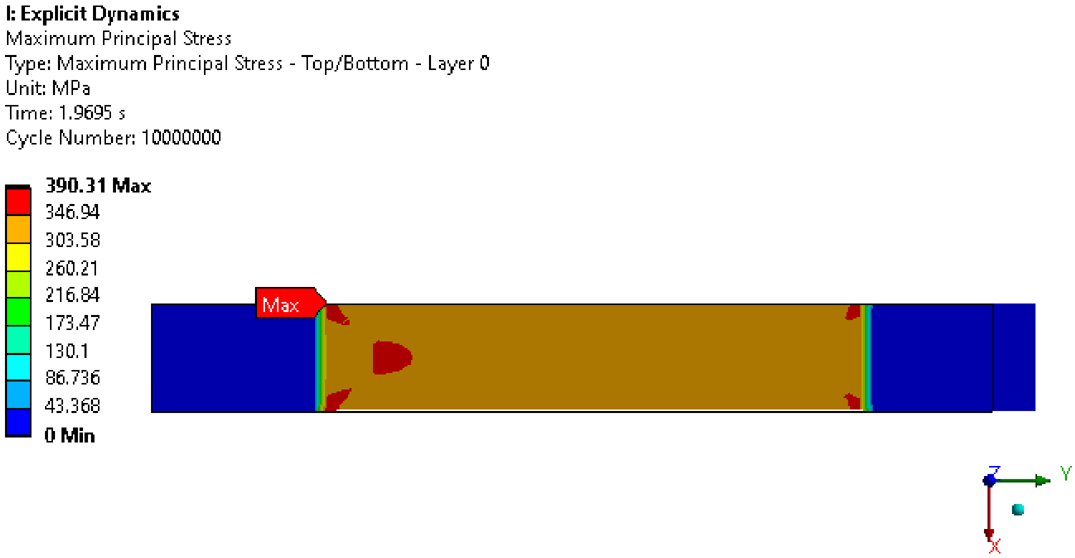

Figure 6. Maximum principal stress 390.3 MPa (N/mm^2)

TABLE 3. Reaction force at the fixed boundary condition location

	Time (s)	Force Reaction X (kN)	Force Reaction Y (kN)	Force Reaction Z (kN)	Force Reaction Total (kN)
1	0	0	0	0	0

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2	0.5	-4.12E-07	-8.7	0	8.7
3	1	2.26E-07	-17.3	0	17.3
4	1.5	-3.57E-07	-25.8	0	25.8
5	1.97	2.34E-07	-33.8	0	33.8

3.2 Experimental validation and comparison

Results obtained from the tensile test are presented in this section. The result from the test is shown in the Table 4, Figure 7. In Table 4 tensile strength and break load of the E-Glass fiber-reinforced epoxy are shown for the applied load. The average standard deviation for the maximum principal stress is 373 MPa and for break load it is 34.2 kN.

Figure 7. Test specimen after Tensile Testing

TABLE 4. Result from Tensile Testing

Specimen No.	Thickness (mm)	Width (mm)	Tensile Strength (N/mm2)	Break load (kN)
1	3.1	31.95	338.624	33.539
2	2.8	31.75	406.56	34.853

4. CONCLUSIONS

In the present investigation E-Glass/Epoxy reinforced composite specimen tensile test result are compared with the FEA result. The orthotropic material properties derived from the microscale finite element analysis is applied to the nodal points of the elements of the macroscale finite element model. A close correlation is observed between test result and the FEA result. The values obtained from test result and the FEA result has been analyzed and an excellent agreement between them is observed. Thus, FEA can be used for the development of micro wind turbine blade in future.

This investigation of mechanical behaviour of E-Glass fiber reinforced Epoxy matrix composite leads to the following conclusions:

- The average maximum tensile strength from tensile test is 373 N/mm^2 and from FEA Maximum principal stress 390.3 N/mm^2. Which is very close enough to the experimentally obtained results (5% error) and the stress deformities is found in the same location as that of the experimental model also there is a qualitative comparison between test and FEA result
- Also the average breaking load from the tensile test is 34.2 kN and from FEA Reaction force is 33.82 kN. In this case also the test result and the FEA result are close (1% error).

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- As the difference between test result and the FEA result is very less this material property can be used as a reference for the design of the micro wind turbine blade.

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