An Experimental Investigation on Transverse Tensile Response of Unidirectional Carbon Fiber Composites

Kunal Saurabh[1*], Baij Nath Singh[1], Vijaykumar S Jatti[2]

[1]Department of Mechanical Engineering Bennett University, Greater Noida, India

[2]Symbiosis Skills and Professional University, Pune, India

*e24soep0009@bennett.edu.in

ABSTRACT

The transverse behaviour of unidirectional carbon fiber reinforced polymer (CFRP) composites are vital advantage in design, analysis and reliability. To avoid overestimating the strength, the transverse behaviour based on fiber orientation alone is being thoroughly studied by tensile test analysis. This paper is based on the transverse tensile approach to analyse and predict the tensile stress and fracture behaviour of unidirectional carbon fabrics. This test is performed experimentally on test specimens with 90 degree fiber unidirectional orientations. The experimental results are validated with previous studies, both of which are affected by the orientation of composite fibers. This experiment demonstrates that CFRP composite material for tensile loading which is mainly affected by the orientation condition of fiber. In this research work experiment, test workpiece with 90 degree orientation of fiber is showing maximum error of +3.03% compared to validate with research of reference. The study also highlights the potential of predict CFRP tensile properties to emphasize the need to improve process control and extended feature representation in achieving reliable and physics-consistent predictions.

Keywords: *Transverse cracking, unidirectional CFRP, Tensile Strength, Maximum carrying load*

1. INTRODUCTION

Composites, as fiber reinforced polymer (FRP) are demand because of the important properties of low weight, high in specific strength, high stiffness, resistance to corrosive, and have environmental friendly. Because of these vital properties of FRP laminated composite materials, they are widely applying in aerospace, automotive, sports, coating, pipelines and electronics industries. Amongst all composites, carbon fiber-reinforced polymer (CFRP) composites are prominent due to superior mechanical performance and durability. However, the mechanical behaviour of CFRP composite is strongly affected by orientation of fiber, stacking sequence and interfacial bonding between the fiber and matrix. Consequently, accurate characterization behaviours of tensile stress-strain properties is vital to predict the structural integrity of composite components.

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Carbon fiber-reinforced polymer (CFRP) are becoming rapidly popular by combining composite fiber of the same or different phases which lead them for high-performance synthetic materials. These are advanced superior materials that possess higher strength and stiffness, can operate at high temperatures up to 2000°C, have a long fatigue life, low density, and a longer lifespan compared too many other common materials. With a single material, the two phases combination of composite can be achieved more yields essential mechanical properties. At temperatures of about 1300°C, 93 to 95% of the carbon is used in the manufacture of carbon fiber. On the other hand, Epoxy resin, along with its hardener, has been crucial for engineering applications for several decades.

To determine the mechanical behaviours of polymer composites, mechanical experimental such as tension, bending, torsion, and impact tests are often performed. Throughout the laminate as well as within the individual composite layers, knowledge of the stress and strain distribution is required by design of FRP structures. This data can also be obtained by modelling techniques or theoretically analysis of mechanical in laminates.

In the context of the above studies, fiber orientation has a strong influence on the tensile properties of unidirectional CF-reinforced polymer composites. However, there is need consensus for the most important approach. Therefore, there is a great opportunity for more research to boost the wider knowledge in these field of composite. The aim of the present work is to identify the effect of fiber orientation on the mechanical properties of CFRE when it is subjected to tensile load. Verified data from previous studies are compared with experimentally obtained data from simple stress tests.

2. LITERATURE REVIEW

Recent studies have shown rapid growth interest in carbon fiber-reinforced polymer (CFRP) composites due to their adaptability and high strength-to-weight ratio applications. A lots of research have to explore on the mechanical behaviours of glass, carbon, and hybrid fiber composites to emphasize better influence on orientation, volume fraction, and mechanical characteristics of fiber.

Yasser S. Mohamed and Ahmed Abdelbary [1] have worked on carbon fiber–reinforced polymer (CFRP) composites in which they have been examined the effect of fiber orientation on unidirectional configurations composite strength. The understanding application of orientation and tensile performance built in optimizing composite design for structural applications.

J.D. Vanegas-Jaramillo, J. Costa, A. Turon, L.J. Cruz, and J.A. Mayugo [2] have investigated the relationship between density effects and tensile properties in composite materials. They accurately predicted tensile strength of both reinforced of glass-fiber and carbon-fiber polymer composites as a linear function of density variations. For this prediction, they used GLS-based fragmentation modelling: GLS captures progressive damage and stress-strain behaviours up to moderate damage levels, while their break-density criterion defines the final failure (ultimate strength point).

S. Satish Kumar, P. Shyamala, and Prabhat Ranjan Pati [3] have predicted machine learning (ML) data sets in composite materials. They have used data-driven prediction to reduce the need for expensive tensile testing. They used a dataset from Kaggle containing 1168 samples for better performance optimization, which includes epoxy group content, density, elastic modulus, curing agent quantity, resin consumption, surface density, matrix-filler ratio, and tensile strength.

Akash Baral and Mostofa Aadeeb et al. [4] have reported on machine learning approach on fiber orientation by tensile and flexural loading. About 174 data-set in tensile loading and 108 in flexural loading are used to build machine learning model. Random Forest and XGBoost have achieved the best accuracy in predicting tensile strength and Young's modulus.

Paulina Spanu and Cristian-Vasile Doicin, et al [5] have tested about tensile strength of carbon fiber-reinforced epoxy composites using specimen standard of ASTM D638 and analysis these test specimen in digital image correlation for strain analysis. The test study also compared with experimental data by the rule-of-mixtures predictions, which significantly show both strength and stiffness.

Chao You, Yaoting Cai, Weilong Wu and Huajun Zhang, et al. [6] have explained about machine learning (ML) i.e. analysing composite structure and its application of design of composite structures in aerospace. The paper highlights ML helps in fasting and more accurate mechanical property prediction as failure analysis, fatigue modelling, and structural optimization. It also review shows machine learning can serve as a surrogate to finite element simulations which drastically reducing computation time.

Wei Liu, Shuguang Hu, and Qing Wan et al. [7] have reviewed a comprehensive study on multifunctional carbon composites for smart and sustainable civil infrastructure. The study explained about CFRP is superior in mechanical, electrical, and functional characteristic. Its applications is in self-heating, energy harvesting, self-sensing and electromagnetic interference (EMI) shielding. It discussed how CFRP enables its behaviours in piezo resistive which help in structural, health monitoring through strain detection, energy storage, and environmental sensing. The review also analysed the effects of temperature, humidity, and corrosion on CFRP performance. Despite these advances in large-scale production, challenges is remain qualities full in the field of durability, and signal reliability, pointing toward mineral-based CFRP (MCF) as a sustainable solution for future smart infrastructure.

N. Yu. Nikitin and Stepashkin [8] have applied data learning model as Random Forest, KNN, and CNN to find out tensile results of unidirectional carbon fiber-polysulfide composite. Their research on carbon-based materials highlight about high ML accuracy (93–99%) using neural networks, KNN, and Random Forest.

Donglin Gao, Zuguo Bao, Weijian Han and Xianpeng Wang, et al [9] have analysed the effective on strain rate tensile characteristics of carbon fiber laminates with different stacking sequences and ply orientations. They have worked on tensile strength which is increased with strain rate especially for off-axis (45° and 90°) specimens.

Alberto Parmiggiani & Mirko Prato & Marco Pizzorni [10] have explained about variability in strength due to differences in build parameters, fiber volume, and testing standards. The strain-rate effects to find about loading velocity and ply orientation that affect tensile performance. Also, additive manufacturing and hybrid systems were investigated who have demonstrated that continuous fiber orientation governs mechanical stiffness.

Seshaiah Turaka, Ravikiran Chintalapudi and Narayanan Kannaiyan Geetha, et al [11] have performed experimental and numerical analyses on glass-fiber-reinforced composites where mechanical properties strongly depend to the orientation of fiber orientation. Alignment with 0° consistent delivering the highest tensile, compressive, flexural, and shear strengths. SEM characterization has emphasized common failure mechanisms such as fiber pull-out, matrix cracking, delamination, and interfacial debonding. To show close agreement with experiment, numerical and finite-element analysis (FEA) methods have been used to predict tensile and shear characterization.

P. M. Bhagwat, M. Ramachandranb, Pramod and RaichurkaraBhagwat [12] have observed mechanical enhancements through carbon–glass hybridization composite. In hybrid fiber-reinforced composites which get to combine glass and carbon fibers to achieve better mechanical performance at lower cost. Glass fibers provide good strength and corrosion resistance but its limited is stiffness, while carbon fibers offer high tensile strength and modulus, making the hybridization of composite with an effective strategy for balance performance and affordability.

The current research establishes a strong foundation for understanding tensile behaviours in CFRP However, significant gaps remain, including (i) for various fiber orientation and composition of resin which affects tensile strength and stiffness of unidirectional CFRE composites, (ii) absence of better study on unidirectional carbon fiber, glass fiber specially in single direction of fiber as 0^0, 90^0 etc. or hybridization of both, and (iii) features—fiber orientation, volume fraction distribution, porosity, moisture absorption—are not included in ML-reducing model. This motivates the present work to analysis transverse tensile strength of CRFP of unidirectional (90^0).

3. MATERIALS AND METHODS

3.1. Test specimen preparation.

For the preparation of composite materials, unidirectional woven carbon fiber 200GSM were used as sample workpiece. The epoxy resin (Epoxy LY556 + Hardener HY951) were prepared in the ratio of 10:1 which chemical formula has been shown in Figure 1.

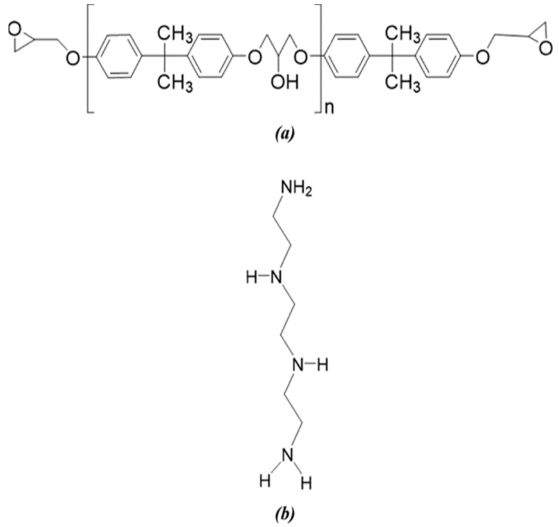

Figure 1 Chemical structure of
(a) Epoxy resin (LY 556) and (b) Hardener (HY951)

All dimension were refer with reference [1]. A rectangular shape of dimensions 240 mm x 18 mm x 0.8 mm with 90^0 was prepared which shown in Figure 2. To minimize stress concentration near the grips, carbon composites end-tabs of thickness was glued with the ends of workpiece specimens into the tensile testing machine. The gauge length of final unidirectional 90^0 specimens was 240 mm that was kept constant.

For the composite fabrication, the hand-lay-up method was used in making of the composite fiber. Using a thick mould, unidirectional laminates was fabricated by stacking layers of carbon fiber one on top of the other as per the desired orientation, the carbon fiber layers is applied by an epoxy matrix between them. Pressure and hand tools were used to remove trapped air and achieve a uniform distribution of the resin. In this current experiment, composite plates with a total thickness of 0.8 mm were created using 4 layers of carbon fiber with 90^0 degree orientation. In Table 1, epoxy resin and carbon fiber has showing the mechanical properties.

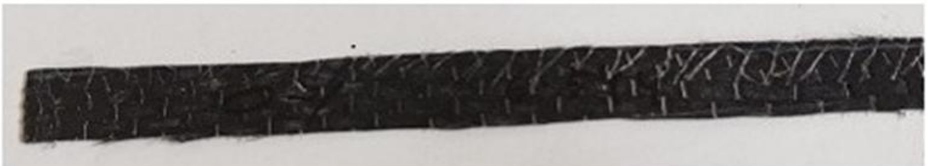

Figure. 2 A rectangular shape specimen having 90^0 orientation

Table 1. Mechanical Properties of epoxy matrix and carbon fiber

	Epoxy Matrix	Carbon Fiber
Density, g/cm3	1.15	1.81
Tensile modulus, GPa	35	250
Tensile strength, MPa	83	4887
Elongation at break, %	6	1.87

3.2 Experimental Procedure

Under INSTRON Universal Testing Machine UTM 100 kN, all transverse tensile tests were performed using with an electronic control unit which shown in Figure 3 and 4.

Figure 3. INSTRON UTM 100kN

Figure 4. INSTRON Universal Testing Machine UTM 100kN with transverse unidirectional carbon fiber specimen.

The test specimen of composite was placed in between the grippers and aligned. During the test, controlled stress was applied to the specimen at a fixed 2 mm/min strain rate until it broke. The load at point of the specimen broke apart is recorded as the breaking load. At the point of rupture, the testing machine was programmed to check out for safety reasons. To determine the tensile behaviour of composite, stress-strain curve was obtained under the elongation of the specimen by movement of cross-head during the testing machine. To understand patterns of failure in the composite specimen, inverted metallurgical microscope was taken images that was captured by using an HD digital camera.

4. RESULTS AND DISCUSSION

In the present experiment, the maximum load carrying capacity of 850 N is obtained for unidirectional transverse 90^0 orientation, as shown in Figure 5. This result is verified with the previous result, keeping the same parameters of the carbon fiber, its dimensions and preparation. The previous results for carbon fiber under similar conditions showed a maximum load carrying capacity of 825 N [1]. An error rate of 3.03% was obtained, indicating better loading efficiency.

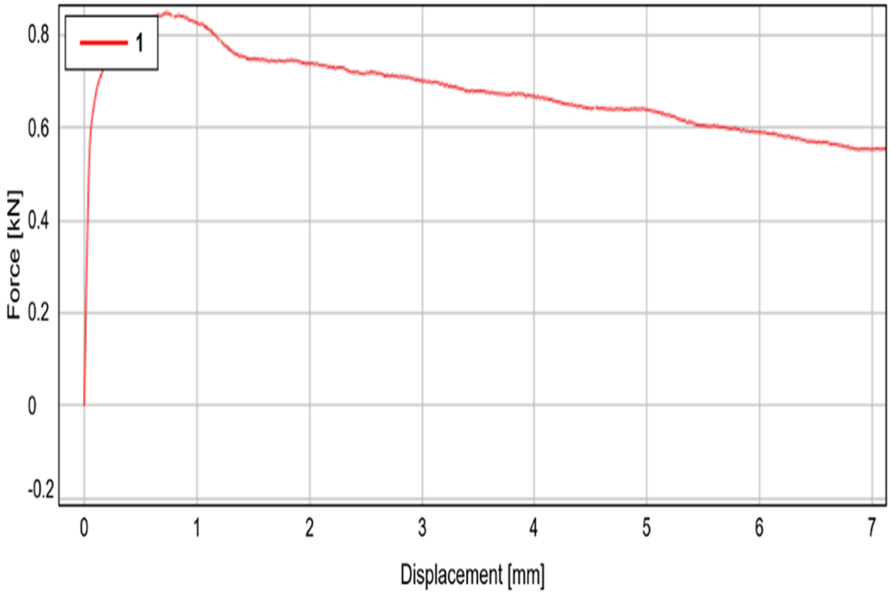

Figure 5. Force and Displacement Graph (maximum load carrying capacity)

The mode of failure of the transverse composites was because of the orientation in fiber of the transverse glandular cracks and a typical pattern of failure was observed under unidirectional transverse tensile load. In Figure 6, for composite specimens with 90^0 orientation, the cause of failure was referable to transverse matrix cracking. The samples split surfaces is appeared to be smooth, free and flat of any polymer adhering to fiber.

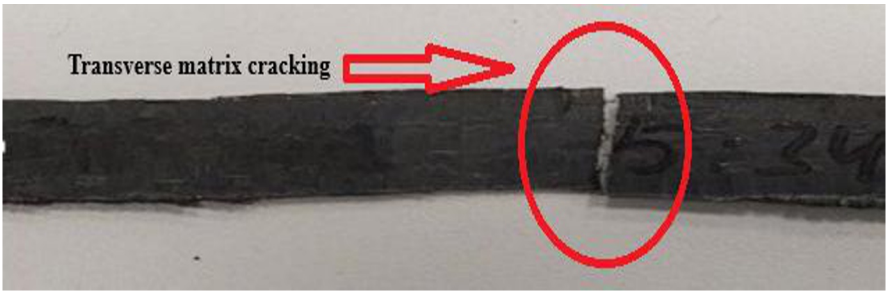

Figure 6. Transverse cracking in 90^0 orientation

To identify patterns of failure in the composite samples, optical microscope was under taken for using optical images and image was captured using HD digital camera. Optical images of the transverse matrix cracking samples after tensile testing is shown in Figure 7. This image is taken from an optical microscope of inverted metallurgical microscope manufactured by Chennai Metco. In the fiber-matrix interaction region, optical microscope images of composite samples damaged during tensile testing were studied and analysed to realize the failure behaviour. In composites, the mode of failure was observed during the fibre orientation found under transverse tensile load. Generally, it was observed that fiber fragmentation and flat failure of the matrix occurred more often than breakage of fiber. In this sample, the angle of cracks in the matrix of polymer is same as the angle of the carbon fiber, i.e., 90 degrees.

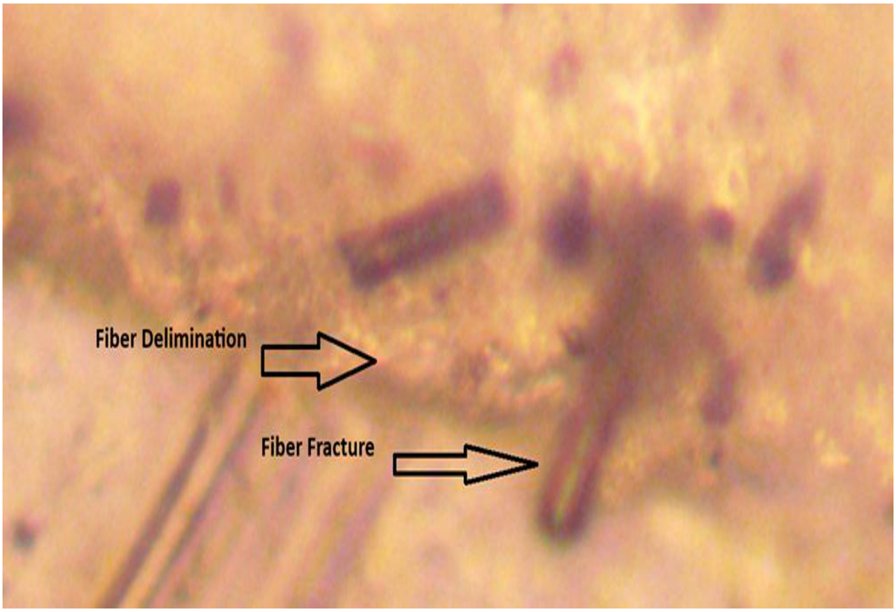

Figure 7. Image of fracture surface by using under optical microscope of tensile tests for transverse fiber unidirectional orientation

5. CONCLUSION

This experiment was developed to investigate the tensile response of composite materials which is effected by the orientation of carbon fiber reinforced polymer (CFRP). Specifically, tensile tests were performed on carbon composite samples at transverse unidirectional orientations. A reference study was validated with the experimental work in predicting of maximum tensile stress in the composites using transverse glandular crack. The positive error percentage showed that the loading capacity of carbon fiber was better modelled and results were obtained with effective loading conditions.

6. FUTURE SCOPE

Future research can explore hybrid machine learning frameworks integrating stacking sequences, multiple fiber orientations and material structures to enhance the robustness of prediction. Fiber volume fraction-aware machine learning architectures can be developed to predict the tendency of tensile and bending properties in hybrid composites. Combining rule of mixture models and finite element analysis with ML-based correction layers can further improve prediction accuracy while maintaining physical relevance. At the microscopic level, CNN-based models using microstructural images can be used to predict damage processes such as fragmentation and fiber breakage. Additionally, machine learning-driven optimization of glass-carbon hybrid ratios could aid in the design for lightweight, high-performance composite structures.

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