

Experimental and FEA Analysis of Biaxial Behavior of Cruciform shaped Carbon fiber reinforced polymer Composites

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Abstract: Composites are widely used in aerospace applications and may undergo multi directional loadings. In this work, the biaxial behavior of carbon fiber reinforced polymer composite (CFRP) has been carried out experimentally and numerically. To predict the biaxial behavior cruciform shaped specimens are fabricated using hand layup and compression molding process. Further, the study has been carried out on biaxial strength estimation of CFRP specimen with and without nano particles. The same geometry shaped modelling and analysis has been performed using ABAQUS. It is observed that the damage of the CFRP panel under biaxial loading is found to be good coherence using FEA and Experimental contour plots.

Keywords: Carbon fiber reinforced polymer (CFRP), Biaxial loading, Finite element analysis (FEA), Digital image correlation (DIC)

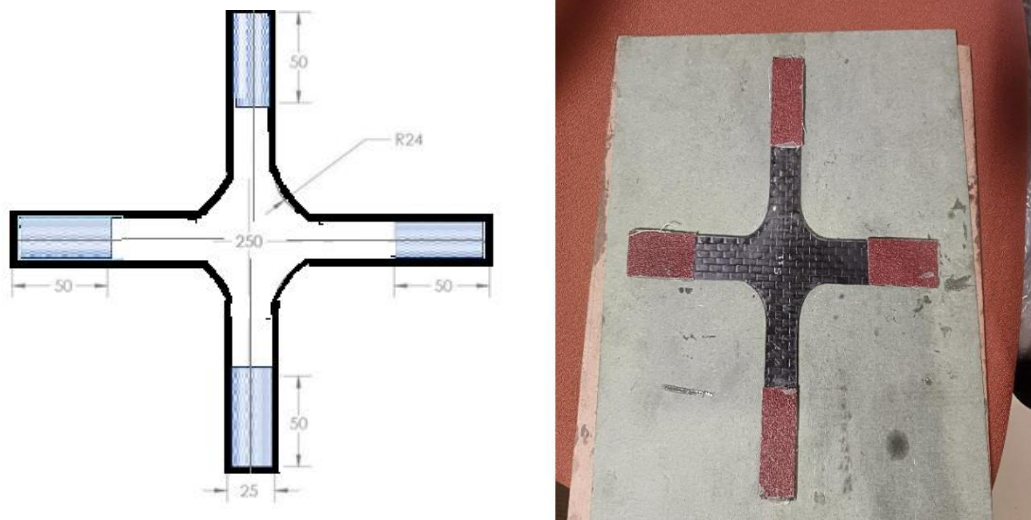
1. INTRODUCTION

The use of light weight high strength Fiber-reinforced Polymer (FRP) has been widely used in many different commercial and industrial applications such as aircraft, military, space, automotive, sporting goods, marine, infrastructure, power industries, medical industries, oil industries, many engineering fields and so on because of their exceptional stiffness- to-weight ratio, fatigue strength, noncorrosive, excellent load-bearing capability, exhibit high specific strength properties. Basically, FRP composites are made of a polymer matrix (like epoxy, vinyl ester, or polyester) and reinforced with various grades of carbon, glass etc [1]. Carbon fibre reinforced polymer (CFRP) composites have become one of the important type of materials for reinforcement because of their superior mechanical properties and wide industrial applications [2-3]. The aircraft components made of CFRP such as wings panels, pressure vessels and fuselage skins are subjected to multiaxial stresses. Hence there is a need exists to study the behavior of CFRP under biaxial loading. Priya and Vinayagam [4] have performed experimentation on estimation of biaxial strength of glass fiber reinforced polymer by varying geometries. Park et al. [5] have carried out the experimental and finite element analysis of biaxial compressive behavior of CFRP specimens. There are few more researchers focused on biaxial behavior of CFRP under compression [6,7]. However, these studies have not explained about tensile behavior of CFRP. Zhang et al.[8] have performed experimental analysis of CFRP under different biaxial load ratios. Further, few researchers have focused on the finite element analysis of CFRP under biaxial tensile loads [9-12]. In the fiber reinforced polymer, matrix is weak which prone to damage multi directional stresses. Therefore, the properties of FRPs need to be improved by adding as reinforcements inside the matrix to increase the safety and durability of their usage in the aerospace wing panels and several other applications. There are few research studied

exists on the strength estimation of CFRP with nano fillers such as alumina, graphene nano pellets and carbon nano tubes(CNT) [13-18] under uniaxial tensile load. However, these studies not discussed about the biaxial behavior of CFRP with CNT. In this work, the study is focused on modelling and analysis and experimental validation of CFRP cruciform shaped specimens under biaxial loading. Further, the study has been carried out on the experimental biaxial behavior of CFRP with CNT. Numerically, the stresses on the CFRP specimen under biaxial loading are analyzed using ABAQUS and the whole field strain distribution of cruciform specimen under biaxial loading were obtained using digital image correlation technique.

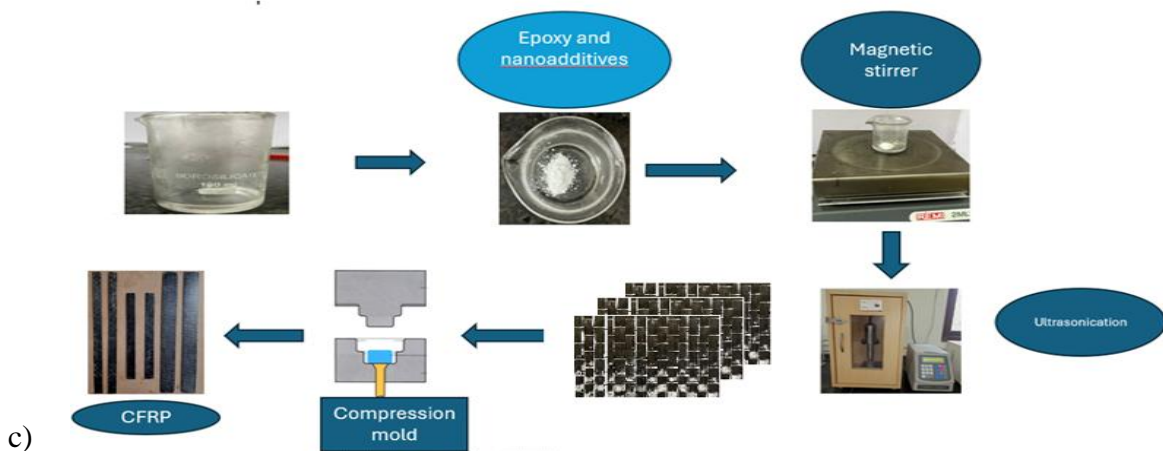
2. FABRICATION OF CFRP SPECIMENS FOR TESTING UNDER BIAXIAL LOADING

Cruciform specimen geometry which is shown in Fig.1(a) is chosen to achieve a uniform biaxial stress distribution in the gauge area during testing. The cruciform specimen consists of four arms extending along two perpendicular axes [19]. The central gauge region is designed with reduced thickness or narrower dimensions to ensure the stress concentration is focused at the center rather than at the gripping ends. All edges of the specimen are polished gently using fine abrasive paper to eliminate machining defects that could lead to premature failure. During preparation, care is taken to maintain consistent dimensions between specimens so that testing results remain comparable. Initially the wooden mold is prepared as per the specified dimensions. In this study the LY556/HY995 epoxy is used for making cruciform specimen. Initially, the fiber mat is cut as per the dimensions and weight is to be measured. The epoxy weight is taken same as weight of fiber mat. The ratio of epoxy and hardener are taken in the ratio of 10:1. Then the epoxy and hardener are thoroughly mixed with stirrer. The fiber mat is placed in the mold and epoxy is poured. The lay-up procedure involves placing the first ply on the mold surface and impregnating it with neat epoxy and the CFRP with nano fillers such as CNT was prepared as mentioned in series of steps shown in Fig.1(c). Care is taken to ensure complete wetting of the fibers, which is achieved by gentle rolling using a hand roller. Entrapped air is removed to prevent voids and resin-rich zones. The ply's are stacked and impregnated carefully. This stacking will be done until the number of plies is completed with proper alignment and without wrinkles. After stacking the entire mold is placed under compression. The laminate is allowed to cool at the room temperature. Then the cured laminate is demolded from the mold. The tabs are attached at the gripping region as shown in Fig.1(b). The cruciform specimen is mounted by clamping each arm firmly within the gripping jaws. Care is taken not to crush or damage the composite arms while ensuring proper load transfer. Instrumentation involves attaching biaxial strain gauges at the central gauge region or using a non-contact optical technique such as Digital Image Correlation (DIC). DIC provides full-field strain measurement, allowing visualization of strain distribution across the gauge length.



a)

b)



c)

Figure 1 : Cruciform specimens for biaxial testing a) Geometry b) Fabricated specimen c) Steps involved in making CFRP/nano CNT

3. RESULTS AND DISCUSSIONS

3.1 Bi-directional tensile behaviour of CFRP Specimen

The specimens are tested under biaxial load in hydraulic operated biaxial Testing machine available at IITBombay. The load is applied in X and Y-direction. The strain distribution across the specimens have been captured using digital image correlation technique (DIC). DIC is a pattern matching technique, it measures the displacements by comparing the deformed and undeformed images. It is non-contact optical strain measurement technique. Figure 2 shows the load vs displacement curves obtained from the testing. The fig.2 (a)and (b) shows force–displacement curves obtained during a biaxial tensile test of a CFRP cruciform specimen, where forces are applied and measured independently along the X and Y directions (X1, X2, Y1, and Y2 arms). The load–displacement behaviour of CFRP laminates under biaxial loading with and without carbon nanotube (CNT) reinforcement is shown in Fig.2(a) and (b). The bar chart as shown in

Fig.2(c) indicates that CFRP with CNT carries higher load in both X and Y directions compared to neat CFRP, suggesting improved stiffness and strength due to CNT addition. From this testing it is observed that CNT incorporation enhances load-bearing capacity, stiffness, and resistance to crack propagation, resulting in improved mechanical performance of CFRP under biaxial loading.

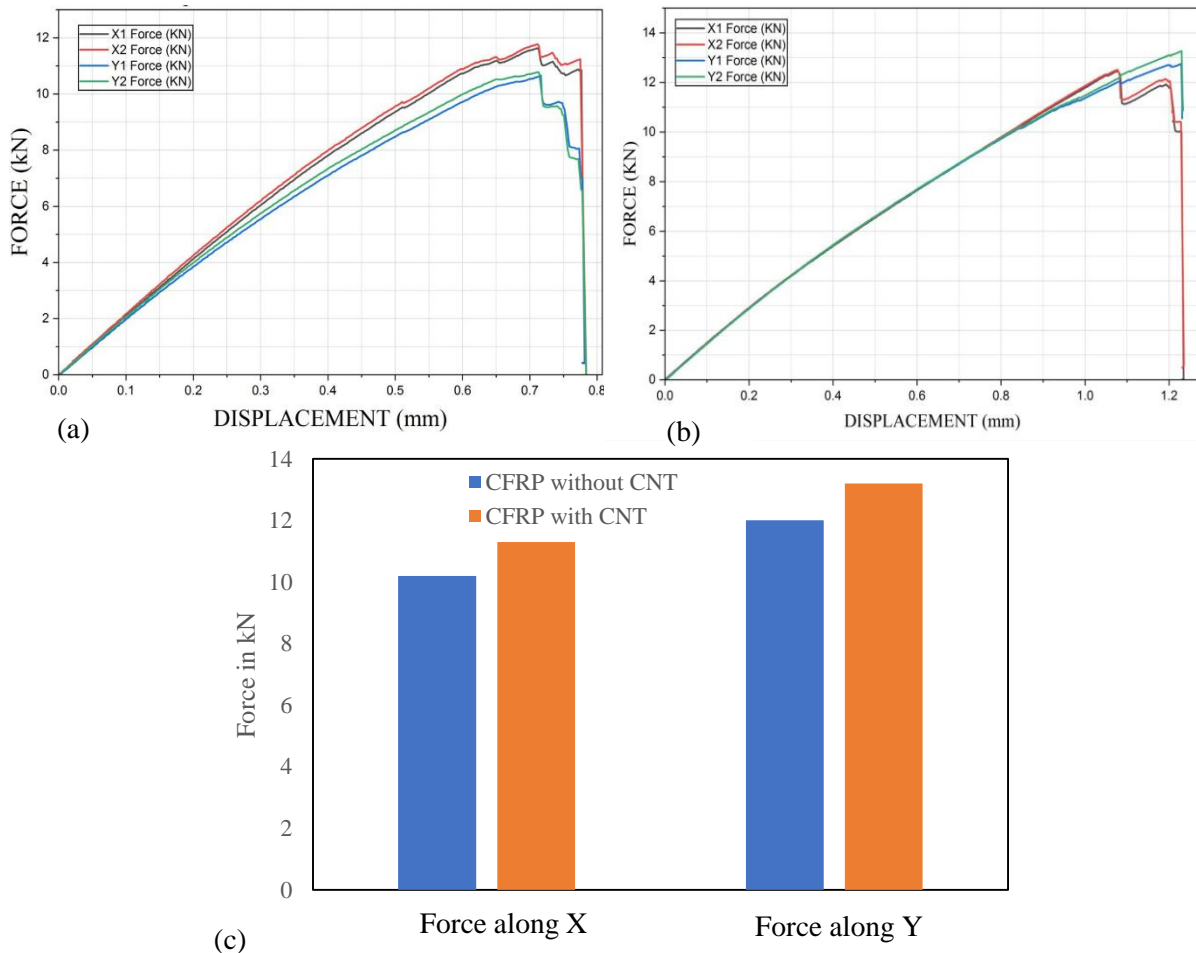


Figure 2 : Load vs displacement curve under Bi directional tensile load a) CFRP Without CNT b)With CFRP/CNT c)Comparison of Maximum load carrying capacity

3.2 Damage behaviour of CFRP with and Without CNT

The Von Mises strain plot of CFRP with CNT reinforcement and without CNT under biaxial loading obtained using DIC is shown in Fig.3(a) and (b) respectively. Comparison of the Von Mises strain plots shows that the CNT-reinforced CFRP exhibits a more uniform strain distribution with fewer intense localized high-strain regions, indicating improved load transfer and better stress redistribution due to the presence of carbon nanotubes. In contrast, the CFRP without CNT under biaxial loading displays more pronounced strain concentrations, especially near geometric discontinuities and interface regions, which suggests higher susceptibility to localized deformation and potential damage initiation. Overall, CNT reinforcement enhances the mechanical response of

CFRP by reducing strain concentration, improving structural stability, and increasing resistance to failure under complex loading conditions.

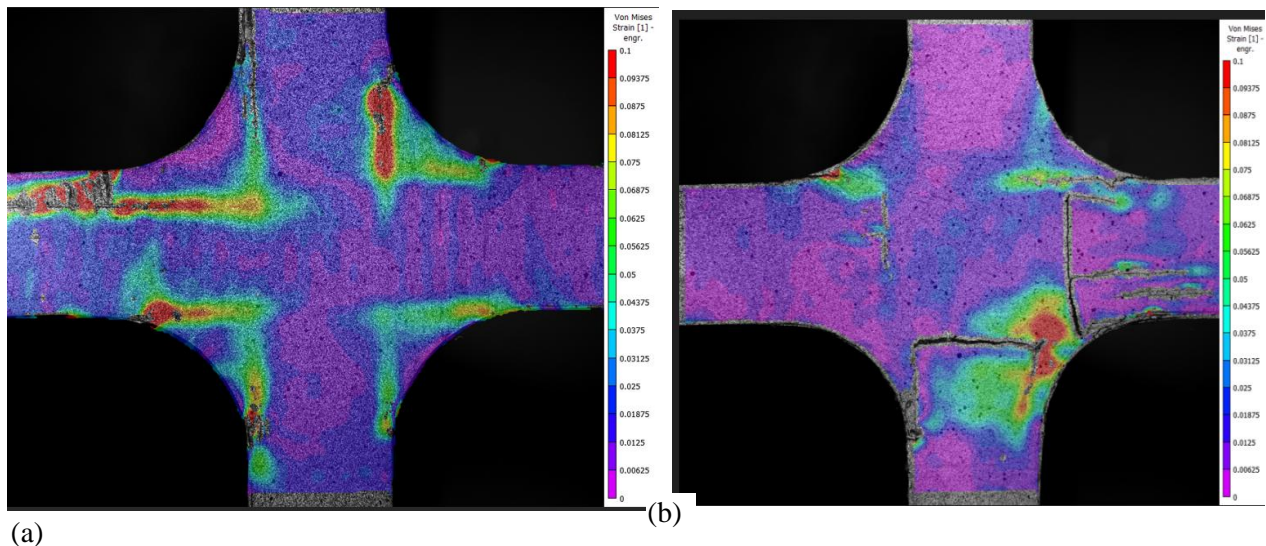


Figure 3: Von-Mises Strain plot obtained from DIC a)with CNT b)without CNT

3.3 Finite Element Modelling and Analysis of CFRP under Biaxial load

This section discusses about the modelling of CFRP specimen in ABAQUS software. Fig.4(a) meshed model of the cruciform specimen. The bi-directional load is applied on the specimen. Strain contours from FEA are compared with DIC strain maps to determine whether the simulation accurately captured deformation patterns. Failure indices based on Hashin or Tsai–Wu criteria are checked to identify failure initiation points. The predicted failure location is compared with the experimentally observed failure region which are shown in fig.3(a) and (b). Comparison of the experimental Von Mises strain plots with the FEA (as shown in Fig.4(b), shows particularly the higher concentration near geometric transitions and loading directions, indicating that the numerical simulation reasonably predicts the mechanical response of the CFRP specimen. However, the experimental plots display more localized variations and irregular strain patterns due to real material effects such as fiber–matrix interaction, defects, and measurement noise, whereas the FEA plot appears smoother and more symmetric because it is based on idealized material properties and boundary conditions. Overall, the agreement suggests that FEA provides a good approximation of the structural behavior and it is predicted the localised stress distribution.

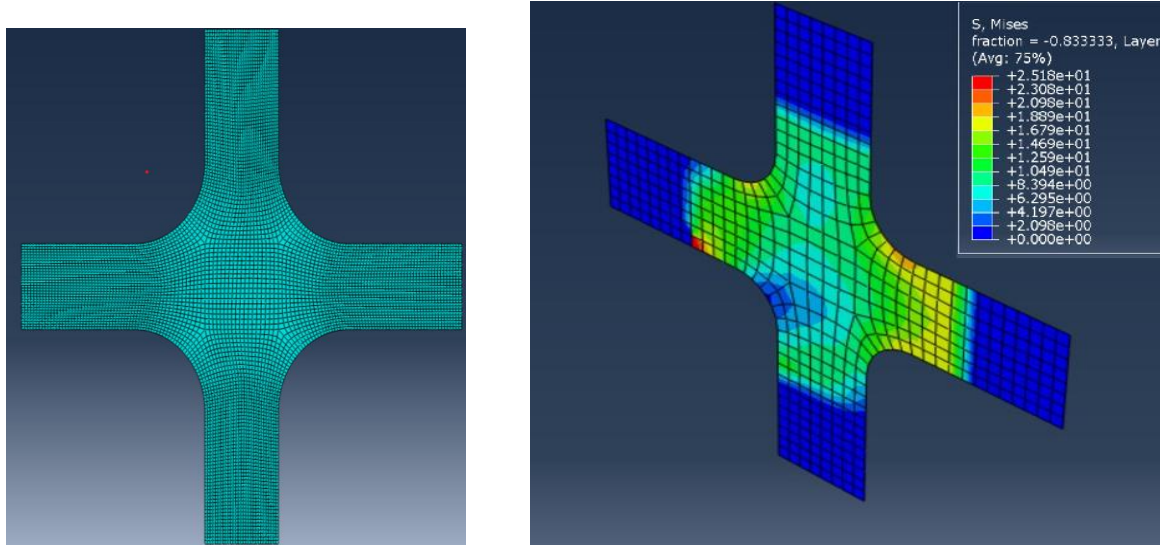


Fig. 4. a) Meshed view b) Von-Mises stress plot from FEA

4. CONCLUSION

In the present study, the mechanical behaviour of CFRP composites subjected to multidirectional loading was investigated through both experimental and numerical approaches. Cruciform-shaped CFRP specimens were fabricated. From the experimental study and FEA study the following conclusions were listed:

- The influence of nanoparticle enhances the biaxial strength of CFRP in terms of improvement in load-carrying capacity and damage resistance compared to the unmodified laminates. This enhancement is attributed to improved matrix–fibre interfacial bonding and effective stress transfer under biaxial loading conditions.
- Finite element modelling and analysis were carried out using ABAQUS with identical specimen geometry and loading conditions. The numerical predictions showed good agreement with experimental observations in terms of stress distribution, damage initiation, and failure contours.

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