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Physical Behavior of Dog Bone Shape Specimen of Carbon Fiber Reinforced Composites during Longitudinal Tensile Test

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Abstract. Bonding characteristics, composition, and internal structure have a strong effect on the behavior of materials under mechanical loading. The paper explores the mechanical characteristics of dog-bone shape Carbon Fiber Reinforced Composite (CFRC) specimens with longitudinal tensile test. The first tests were done on an isotropic material i.e. Mild Steel, Brass, Aluminum, Acrylic and Poly Lactic Acid (PLA) under typical tensile testing conditions. These samples deformed in a homogeneous manner and broke in the gauge length without any supplement, and this was in line with the direction-independent mechanical properties of isotropic materials. Unlike this, CFRC specimens exhibited uncharacteristic failure, that is, they fractured at the gripping areas instead of the gauge section when put to the same test. This was due to the anisotropic nature of CFRC, which provided variations in mechanical properties with fiber orientation and loading direction, which were determined by detailed analysis as the cause of this anomaly. The low transverse constraint in gripping resulted in concentration of the stress and early failures in the holding portions. In order to integrate this problem, tensile testing fixture was adjusted to apply the right transverse clamping force, whereby the specimen remains stable with an even distribution of load. Further tests on the modified design brought about consistent failure in the gauge length and repeatability in tensile response. This research displays the need to deal adjustment in testing the approach to anisotropic composite materials and the practicality of testing on the correct mechanical identification of CFRC samples.

Keywords: Carbon Fiber Composites, Tensile Test, UTM, Transverse Force, Water Jet Machine

1 Introduction

The improvement of engineering professions is inextricably linked to the innovation and use of new materials. A broad variety of materials has been used in response to growing performance requirements both in structural and functional uses over the decades. Mechanical testing that is systematic to assess the material limits, i.e., tensile, compressive, hardness and impact testing are regularly carried out to ascertain material reliability and safety during service. Although such tests have long been used to identify mechanical properties, the behavior of materials as they are loaded is also interesting to know, especially when dealing with highly composite materials. The directional dependence of the properties of the materials broadly classifies materials as isotropic or the anisotropic materials. The physical behavior of isotropic materials, when they are placed under mechanical loading, is somewhat predictable since the inner structure of materials, as well as their property, is homogenous in every direction. As such, their deformation and failure capacity in tensile tests are usually repeatable and consistent. Conversely, the behavior of anisotropic materials depends on direction given the difference in the arrangement of their microstructure. This causes their response to applied loads to vary greatly with orientation of the loading therefore causing their physical behavior to be hard to predict during testing. Another notable category of anisotropic materials that are gaining significant penetration in the aerospace, automotive, energy, and structural markets due to their large strength-weight ratio and configurable performance features are known as CFRCs. In this research, the tensile tests of CFRC specimens are done in combination of longitudinal testing, the main aim of which is to research their physical behavior during and after loading [1]. It is not about the assessment of the inherent mechanical behavior of carbon fibers, epoxy matrix, and the composite system but about the concept of knowing the physical response observed when subjecting the specimen to a tensile load. The research also seeks to reason out the underlying causes of this action and the form of experimental adjustments that ought to be applied to yield credible and

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anticipated test results. Such knowledge is necessary due to the increased use of CFRCs to enable proper experimental characterization and better test approaches.

2 Design of the Specimen

The CFRC tensile specimen design was founded upon dog bone geometry, in order to provide proper uniformity in stress distribution and controlled failure in the gauge section when carrying out longitudinal tensile tests. The specimen size was chosen as per ASTM D3039 requirements, and the central gauge was smaller and consequently there was a higher end width so that they can be easily gripped, Figure 1. A gradual and gentle transition between the grip section and gauge length was put in to reduce stress concentration and to stop early failure at points of concentration of the gears. To make sure that the same load was transferred across the composite laminate, the thickness of the specimen was kept unchanged across the length. Unidirectional fiber orientation was sued in the same direction as loading direction to record anisotropic tensile behavior of CFRC [2]. The dog-bone shape has made it possible to observe precisely the elastic deformation, initiation of damage and ultimate fracture properties, which was critical in the situation to enable reliable assessment of the physical behavior of carbon fiber reinforced composites in longitudinal tensile deformation.

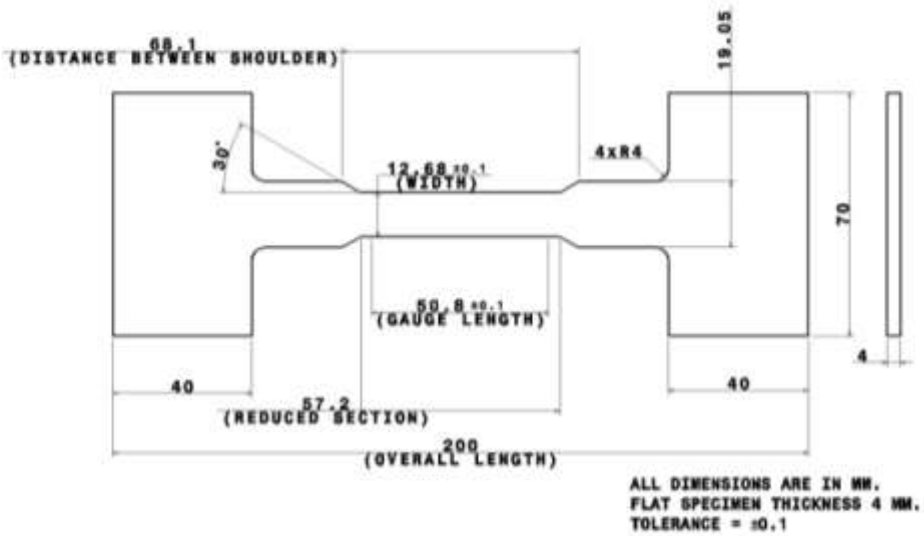

Fig. 1. Design of the Specimen

3 Preparation of the Specimen

The tensile test specimens were cut out CFRC laminates as per recommendation of ASTM D3039 and a dog-bone shape was taken to provide uniform distribution of stresses in the gauge length. The impregnation of unidirectional carbon fibres was done by hand lay-up method and vacuum bagging of the epoxy resin was done to reduce the content of void and to achieve good wapitance of the fibres. The laminate was allowed to cure at room temperature over 24 h after which post-curing of the laminate was performed in high temperature according to the laminate manufacturer instructions so that it attains consistent mechanical properties. On curing, the laminate specimens were cut with a diamond-coated abrasive cutter to prevent fiber pull-outs and delamination [3]. The edges were also polished carefully to eliminate defects of machining that might cause a stress center. Glass fiber reinforced polymer tabs at both ends were glued with a high strength adhesive as such that the tabs would not be damaged with gripping. Prior to testing, all specimens were tested by measurements of dimensional accuracy.

4 Reinforcement of the Specimen

To create longitudinal tensile loading to sustain the CFRC tensile specimen, the reinforcement of the long tensile strengthening was realized by the regulated positioning of carbon fibers in epoxy resin. The main alignment of unidirec-

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tional carbon fiber reinforcement was in the direction of the loading to ensure that the axial stiffness and load carrying capacity are optimized. The laminate fabrication was done with the fiber volume fraction being kept parsimoniously to achieve repeatability and consistency in the stress transfer between the fibers and matrix. In order to enhance interlaminar bonding and decrease the probability of premature delamination, the plies were bonded on top of each other by vacuum-assisted curing. There were more reinforcements in the grip parts of the dog-bone specimen through bonding the tabs made of glass fiber composite that served to promote transfer of loads and reduce the concentration of stress at grips [4]. The progressive change of width between the grip section and the gauge length was necessary in order to ensure that failure started in the central region and thus the observation of the physics during tensile loading could take place accurately. This reinforcement was used to characterize the evolution of anisotropic deformation behavior and damage reliably in CFRC specimens.

5 Matrix of the Specimen

The CFRC tensile material that was put in the CFRC tensile specimen was a thermosetting epoxy resin, which had the advantage of being highly adhesive, stiff and also compatible with carbon fibers. The epoxy matrix was important to hold the fibers together, to keep them straight, and to transfer the loads effectively when being subjected to longitudinal tensile loading [5]. In the fabrication of specimens, the resin was impregnated within the layers of fibers in a uniform manner, and the end result was to reduce the amount of voids and guarantee that all the parts of the gauge length react the same during mechanical response. When cured, the matrix gave the carbon fibers a dimensional stability and shielded them against the environment and mechanical damages. When tensile loading was applied, the matrix controlled the early linear elastic behavior and helped in transverse strain accommodation. With the increase in the applied load, micro-cracking in the epoxy matrix was observed before the fiber broke, indicating a gradual development of damage [6]. The matrix behavior had a heavy impact on the crack initiation and crack propagation patterns, thus, the general physical deformation and overall failure properties of the dog-bone shaped CFRC specimen in the tensile experiment.

6 Fabrication of the Specimen

The CFRC tensile samples were produced by control hand lay-up and vacuum bagging process to get a homogenous laminate. The plies of carbon fibers were unidirectional plies which were laid, in a sequential manner, on a flat surface of release agent coated mould under a longitudinal loading direction. Epoxy resin was measured and applied to each ply to allow the ply to be impregnated and the volume fraction of the fibers to be uniform. Once the number of layers needed was stacked, it was layered with a peel ply, breather material and a vacuum bag and pressed under vacuum pressure to force out the trapped air and excess resin. The laminate was allowed to cure at room temperature of 24 h and post cured at high temperature to further improve the cross-linking of the matrix and to make it mechanically stable [7]. After curing, dog-bone shaped specimens were machined using a diamond cutter accurately. The fabrication process provided a low level of defects, constant thickness, and the physical behavior when subjected to longitudinal tensile tests.

7 Water Jet Machining of the Specimen

The machining of the dog-bone shaped CFRC tensile specimens was done by using water jet machining with high level of dimensional accuracy and less machining damage. Abrasive water jet cutting had been chosen because it is a cold cutting method that avoided any thermal degradation of the epoxy matrix and allowed no burning of the fibers or softening of the matrix. The laminates were treated with CFRC and then clamped on the cutting bed, and using CAD data, the path to be followed during cutting was programmed. The parameters of the process were optimized to minimize the kerf taper and prevent delamination on the edges like water pressure, abrasive flow rate, and traverse speed Figure 2. Mechanical contact was kept to a minimum reducing fiber pull-out and residual stresses normally related to traditional machining processes [8]. The edges of the specimen were cut and the edges were examined and finished lightly to eliminate surface abnormalities. Water jet machining was applied to guarantee repeatable specimen geometry, enhanced edge geometry and consistency of physical behavior during longitudinal tensile testing.

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Fig. 2. Specimen of CFRC after Water Jet Machining

8 Fixture to test the Specimen

It was found that a special tensile testing apparatus was made and special built to secure the dog-bone-shaped CFRC specimen during longitudinal tensile testing. The design of the fixtures was to be in the form of self-aligning wedge-style grips composed of hardened alloy steel to provide a consistent load distribution along the specimen axis. The gripping surfaces were cut with small serrations so as to give the friction and to avoid slippage without causing premature damages to the composite, Figure 3. The CNC machining was used to make the fixtures of high dimensional accuracy and parallelism between the grips. Removable grip plates were added to suit differences in specimen thickness, and minimize wear [9]. The main objectives of the fitting were to ensure good alignment of the specimen, reduce tensile loads bending stress, and allow the uniform transfer of tensile load to the gauge section. This system of fixtures allowed acceptable failure in the gauge length and repeated and consistent testing of the physical behavior of CFRC specimens under longitudinal tensile loading.

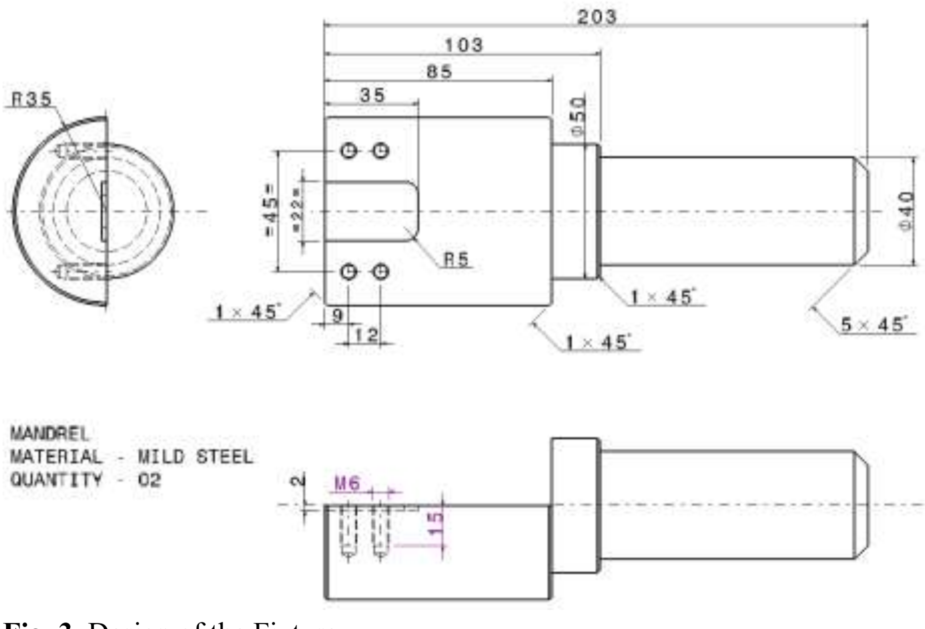

Fig. 3. Design of the Fixture

9 Arrangement of the Specimen on UTM for Longitudinal Tensile Testing

The dog-bone CFRC specimen was placed on the Universal Testing Machine (UTM) so that longitudinal tensile load could be applied properly. Before the mounting, physical examination of the specimen would be done to ensure that no edge defects and dimensional irregularities were present. The ends of the specimen were gently aligned in the upper and bottom grips of the UTM so that the longitudinal axis of the specimen aligned with the loading axis of the machine. Adequate alignment was checked to prevent eccentric loading stresses and bending stresses during testing, Figure 4. The grips were tightened at a slow and even rate to avoid crushing or slipping at the grip areas. To determine axial strain with a high level of precision a calibrated extensometer was connected to the gauge length [10]. UTM was used on the

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basis of displacement-controlled mode with constant-speed crosshead following the standard requirements. This design provided stable conditions of loading and effective evaluation of longitudinal tensile performance of CFRC specimens.

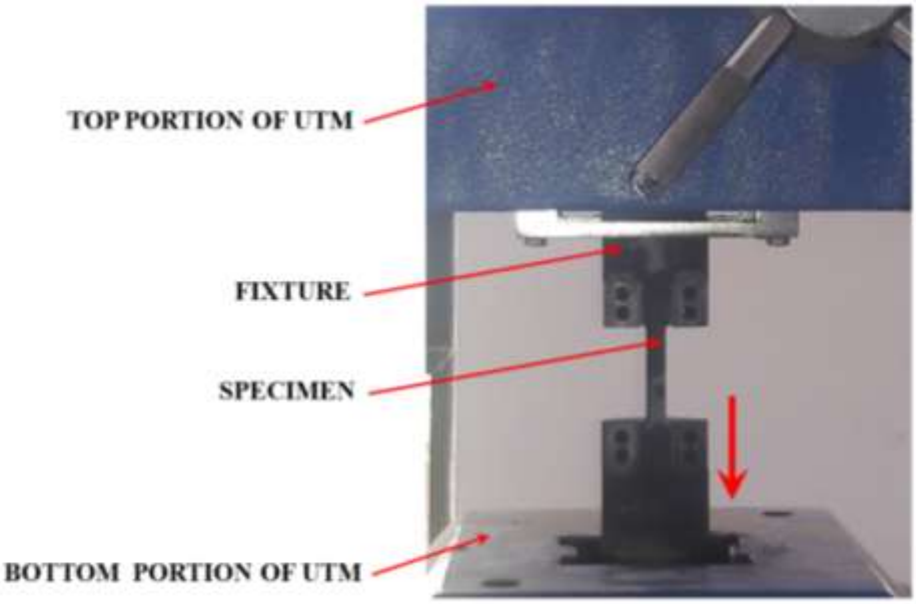

Fig. 4. Arrangement of the Specimen on UTM for Longitudinal Tensile Testing

10 Failure of the Specimen

Longitudinal tensile testing was done critically to study the physical response under the axial loading to analyze failure behavior of the dog-bone shaped specimens. Five steel specimens of the same size and geometry have been firstly tested under the same conditions of the same combination of the same type of fixtures, with the same alignment and loading. As anticipated, the specimen deformation and fracture were uniform across all steel specimens across the gauge length, a normal specimen design, fixtures alignment, and testing methodology. This positive result confirmed and standardized the whole experiment set-up.

This was followed by the same standardized procedure on CFRC specimens. In opposition to the expectations, the CFRC specimen failed at the gauge length. CFRC Specimen-1 showed early wear in the upper grip area rather than in the gauge middle [11]. Abnormal stress concentration was observed to have severe distortion and local damage in the proximity of the upper gripping area as presented, Figure 5. CFRC Specimen-2 was tested under the same conditions in order to check repeatability. In the same manner as in the former case, the failure took place again at the upper part instead of the gauge length, Figure 5.

These sudden failures indicate the anisotropy of CFRC and its sensitivity to gripping pressure, transfer of loads and stress concentration. The findings underscore the fact that the test procedures that have been validated in the case of isotropic materials such as steel might not be directly applicable to composite materials without specimen design or gripping strategy changes.

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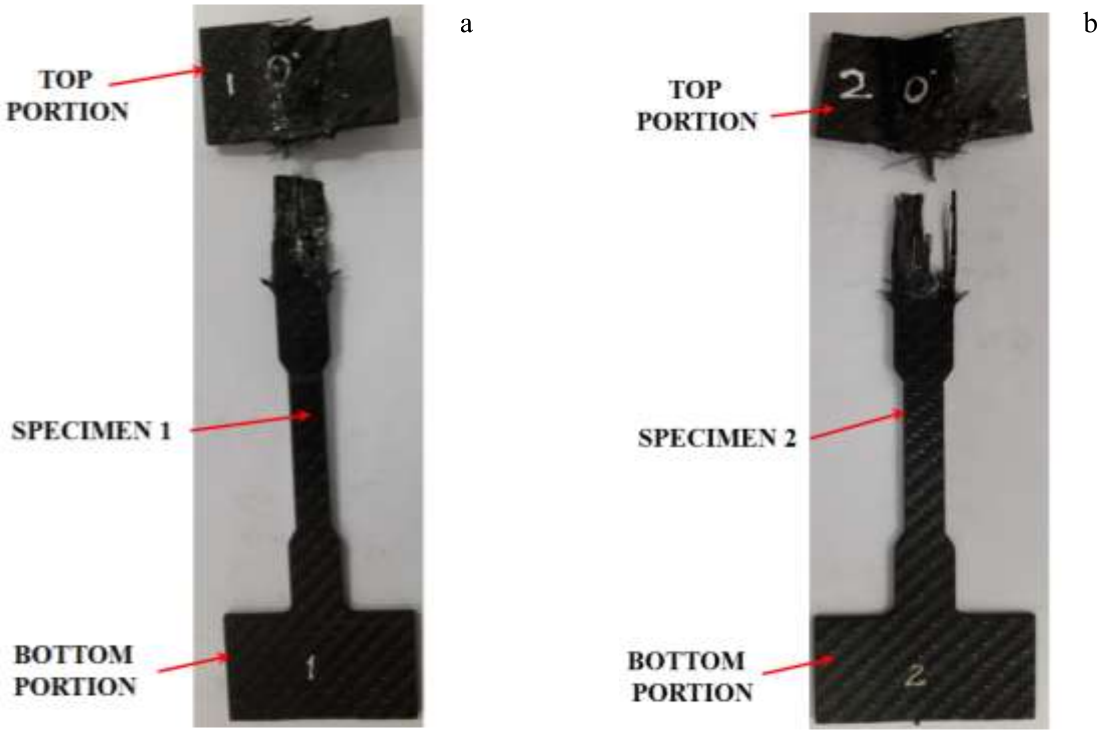

Fig. 5. Arrangement of the Specimen on UTM for Longitudinal Tensile Testing

The experiment of the CFRC specimens failure behavior showed atypical deformation in longitudinal tensile testing. Figure 6 demonstrates the area of focus of the CFRC Specimen 1. Ideally the upper part of the dog-bone specimen must be horizontal and axially lined parallel to the test. Overall, when loading, the upper part of CFRC Specimen 1 was seen to be moved by around 13 mm to a different position. This sudden displacement is a sign of other transverse or bending forces on the specimen which cause the stress distribution to be uneven and result in untimely failure beyond the gauge length. The same tendency was followed in CFRC Specimen 2, the area of which focus was also presented, Figure 6. Here the upper part had a greater displacement of approximately 17 mm before failure. These observations indicate that gripping-induced constraints and anisotropic rigidity of CFRC returned a significant impact on weight transfer leading to the development of misalignment and local deformation [12]. The specimens, therefore, did not follow the target gauge region indicating the necessity of better gripping and alignment techniques in testing composite tensile permeability.

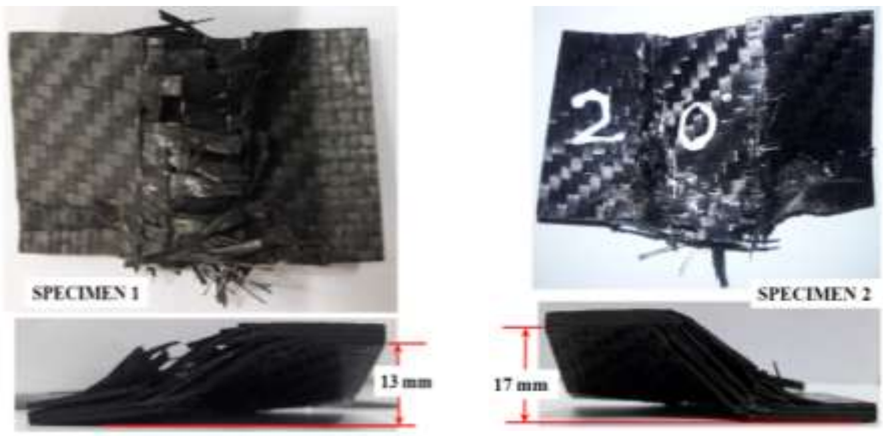

Fig. 6. Focused Area of Failure of CFRC Specimen 1 and Specimen 2

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11 Problem Identification of the failure of the Specimen

The steel specimens under longitudinal tensile testing failed within the gauge length as anticipated which validated the suitability of the specimen geometry, fixtures design, and loading regime. Nonetheless, after the identical testing procedure, the CFRC specimens failed abnormally, which means that there were material- and boundary-related problems that needed to be identified through systematic problem discovery. The tensile testing is controlled by the conditions of the boundaries and loading placed on the specimen by the UTM, which is why it became necessary to determine the process of interaction between the CFRC specimen and the grips.

Among the key reasons of the observed behavior is the variation in the material characteristics. Steel is an isotropic material and it has the same mechanical properties at all directions and therefore the material predicts the deformation and failure at the time of axial loading [13]. On the contrary, CFRC is very anisotropic and the mechanical behavior of this material is highly dependent on the orientation of the fibres, interlaminar behavior and the matrix behavior. Anisotropy of CFRC causes the material to be sensitive to grip pressure, misalignment and atypical distribution of loads.

Also, grips might have imperfect boundary conditions which could have caused transverse forces and bending moments which are not ideal uniaxial loading assumptions. The principle of Saint Venant suggests that local stress disturbances around the grips may play an important role in the action of composite specimens because they are unable to redistribute stresses to a large extent, Figure 7. All these effects combined to cause premature failure beyond the gauge region thus necessitating refined testing strategies of CFRC specimens.

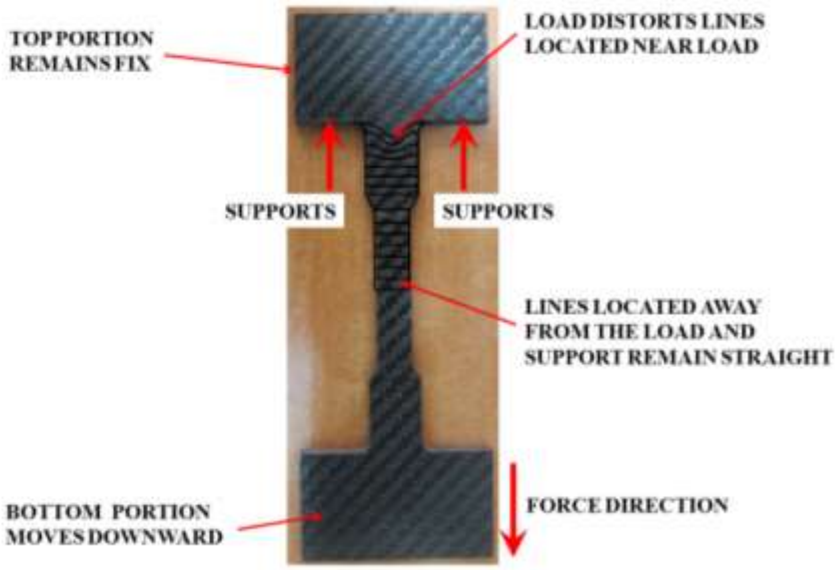

Fig. 7. Boundary and Loading Conditions of the CFRC Specimens

12 Characteristics of Anisotropic Material

Anisotropic materials are by definition hard to comprehend and are hard to determine due to the directionality of mechanical and physical characteristics. CFRC would be classified as an anisotropic material as compared to an isotropic material in which the properties are the same in every direction. Stiffness along with strength and deformation behavior of CFRC varies greatly along the x, y and z directions and this is mainly based on the orientation of the fiber. The longitudinal direction which is parallel to the fibers is very strong and stiff and transverse and through-thickness direction is controlled by mostly the matrix and interlaminar properties. Boundary conditions and loading conditions that are introduced during testing are a strong determinant of the overall behavior of CFRC. Moreover, the level of anisotropy is determined by the type of composite used (unidirectional or bidirectional), i.e. woven or cross-ply [14]. Unidirectional composite exhibits a strong directional sensitivity and the bidirectional laminates display rather balanced characteristics.

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Because of this directional dependence CFRC specimens do not have the same tensile loading response as that of isotropic materials and predicting the actual physical behavior and failure pattern becomes more complicated.

13 Saint Venant's Principle

According to the principle of Saint Venant's, the difference between the actions of two equivalent loads at rest will be negligible at a sufficiently far distance of the action region. In perfect tensile tests, this means that there should be a uniform distribution of stresses in the gauge section without being dependent on the specific way the load is applied at the grips. The assumption worked on the steel specimens that had anticipated failure within the gauge length. But with the CFRC specimens the stress around the shoulder and the upper parts were not decaying as expected. Localized stress disturbances formed at the grip regions propagated through the specimen rather than being redistributed quickly because of the anisotropic character of CFRC. Consequently, this made the stress field at the top part non-uniform, which caused new components of force [15]. A transverse force that was applied to the upper part of the specimen was considered to be one of these forces, Figure 8. This transverse force was a contributor to misalignment, abnormal deformation, and pre-mature failure beyond the gauge length hence breaking ideal uniaxial tensile loading assumptions.

Fig. 8. Concept of Saint Venant's Principle

14 Implementation of Transverse Force on the specimen through Modified Fixture

It was evident that experimental outcomes showed that an inappropriate distribution of stress in the area of the grip started triggering a transversal force that worked perpendicular to the upper part of the CFRC specimen, which caused abnormal deformation and untimely failure. To reduce this effect, tensile testing fixture was also adjusted to cancel out the transverse force in order to restore the near ideal uniaxial loading conditions. This change was made by drilling three accurately oriented holes in the body of the fixation and then internally threaded to fit high-strength bolts. A solid metal strip was used and clamped with the aid of these bolts to stop the longitudinal movement of the specimen around the grip area. This design offered a restraint to transverse impetus and liberation of axial expansion throughout tensile loading [16]. The adjusted design was an efficient way of reducing errors in alignment and preventing undesirable transverse forces induced by anisotropic material behavior and by stress concentrations caused by the grip, Figure 9. Consequently, better load transfer and stabilized stress distribution was obtained that could allow more valid determination of the physical behavior of CFRC specimens in longitudinal tensile testing.

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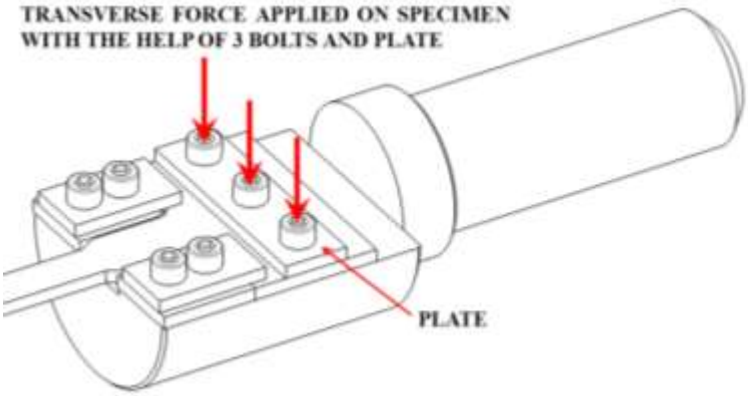

Fig. 9. Implementation of Transverse Force on the specimen through Modified Fixture

15 Modified CFRC Specimen to accommodate the Transverse Force

CFRC specimens were appropriately altered to allow the transverse force to be managed and controlled when conducting longitudinal tensile testing. Three holes were created on the top and bottom grip of the CFRC specimen at well-defined points based on the analysis of failure and the interaction between the fittings. These holes were also meant to connect to the altered arrangement of the fixtures and thus, control the lateral movement. The hole positions were picked beyond the gauge length to make sure that no stress state was influenced on the central region. Low-speed machining was done to perform precision drilling which prevented delamination, fiber pull-out, and matrix cracking along the drilled hole [17]. This change allowed interacting the specimen and the fixture effectively with the help of bolts and a metal strip, which suppresses transverse displacement, Figure 10. The new specimen structure enhanced greater alignment, less stress concentration in the grips, and enhanced more consistent transfer of loads, which increased the reliability of the physical behavior method in assessing the longitudinal tensile loading of CFRC specimens.

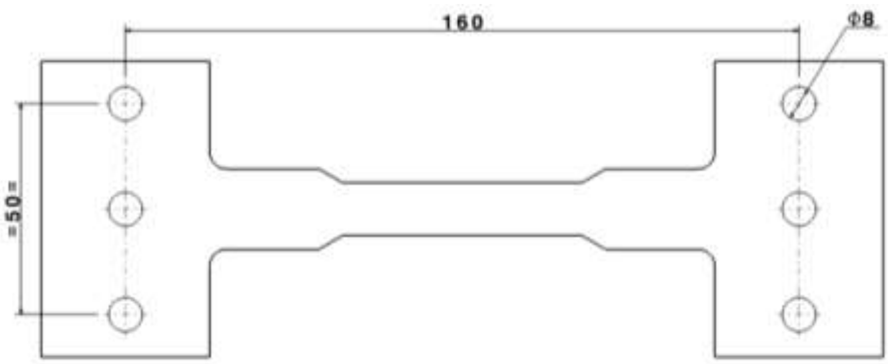

Fig. 10. Modified CFRC Specimen with holes at both ends

16 Modified Assembly of CFRC Specimen and Fixture

The CFRC specimen and tensile testing fixed was modified to achieve the alignment of the load and transverse displacement inhibition. The CFRC specimen was fastened with the new fit using three holes that are provided in the top and bottom grip parts. These holes were passed with bolts and fastened with internal threads in the fixture and by a strip of rigid metal the clamping was uniform and the lateral restraint maintained [18]. This was a set up that restricted undesired transverse motion and allowed free axial elongation of the specimen, Figure 11. The altered assembly created stable boundary conditions, reduced stress concentration at the grips and allowed the distribution of the stress within the gauge length to be more uniform during longitudinal tensile testing.

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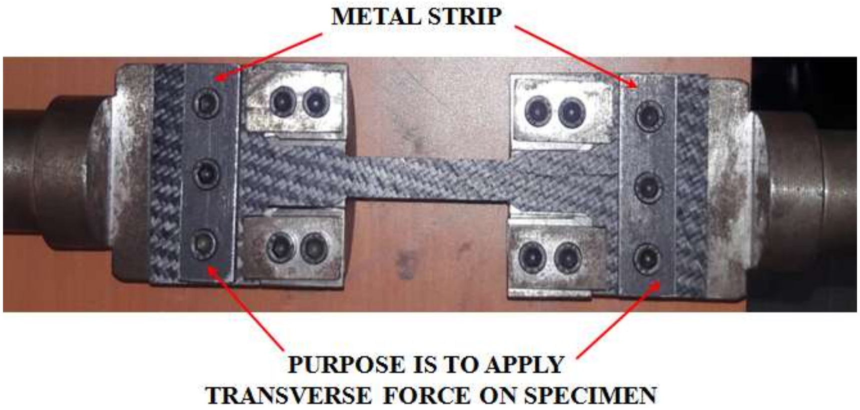

Fig. 11. Modified Assembly of Fixture and CFRC Specimen

17 Tensile Testing of CFRC Specimens using the Modified Fixture

CFRC specimens were experimented with the modified holding set without changing any other parameter of the universal testing machine. The loading rate, alignment process, and boundary conditions were preserved to keep the experiments consistent. The transverse motion at the grip area was effectively eliminated using the improved fit-specimen assembly and this gave steady and constant load transfer, Figure 12. Consequently, the CFRC samples showed a regulated deformation and fractured at constant gauge length [19]. This established the validity of the readjusted holding fixture in reducing transverse forces as well as allowed a consistent appraisal of the physical behavior of CFRC specimens during longitudinal tensile tests.

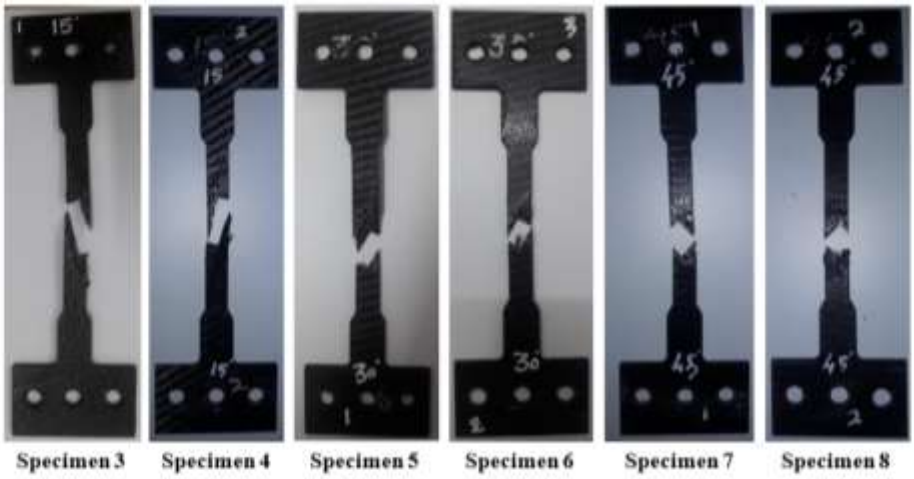

Fig. 12. Failure of CFRC Specimens from the Gauge Length

18 Results of Tensile Testing of CFRC Specimens using the Modified Fixture

The outcomes of the introduction of the adjusted arrangement of the fixing as well as the revised arrangement of the CFRC samples were in accordance with the anticipated response of dog-bone shaped composite samples when subjecting them to longitudinal tensile loads. The enhanced boundary conditions worked well to eradicate the transverse displacement and the stress concentrations in the grip. The rest of the CFRC specimens broke at the same point across the gauge length and it was therefore observed that the stress distribution was constant and the axial loads were transferred correctly [20]. The success of the modifications was proven by the repeatability of gauge-length failure and justified the use of the revised experimental approach. These findings show that proper design of fixtures and contact of the speci-

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men and the fixtures are essential in the proper tensile characterization of an anisotropic material like carbon fiber reinforced composites.

19 Conclusion of Tensile Testing of CFRC Specimens using the Modified Fixture

This experiment examined physical behaviour of dog-bone-shaped CFRC specimens in longitudinal tensile experiments. The findings indicate that CFRC responses to mechanical forces are hard to predict because of the interaction of constituent materials whose properties are not similar. The entire composite is anisotropic, carbon fibers are highly anisotropic and the cast epoxy matrix is an isotropic material. This non-uniform mixture produces complicated stress interactions especially when the conditions of constraint of boundaries and loading are involved. The experimental results indicated that the traditional tensile testing methods that can be used in the isotropic materials cannot be applied directly to the CFRC specimens. The transverse forces, misalignment, and premature failure were caused by low holding and boundary conditional outside the gauge length. It was possible to obtain steady axial loading and anticipated gauge-length fracture by changing the setup of the fixtures and specimens. According to the study, it is important to have appropriate holding and fitting design in order to have accurate characterization and stable functioning of the composite components. The significance of proper specimen holding in CFRC behavior assessment has been properly articulated by this investigation.

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