Authors post-print (i.e. final draft post-refereeing): The actual journal version of the paper can be downloaded from Shah, S. Z., Choudhry, R. S., and Khan, L. A., "Challenges in Compression Testing of 3D Angle-Interlocked Woven-Glass Fabric-Reinforced Polymeric Composites," *Journal of Testing and Evaluation*, https://doi.org/10.1520/JTE20160191. ISSN 0090-3973

Challenges in compression testing of 3D angle interlocked woven glass fabric reinforced polymeric composites

S. Z. H Shah[1], R. S. Choudhry[2, 3], Laraib Alam Khan[4]

[1] National University of Science & Technology, Islamabad, Department of Mechanical Engineering, College of EME Campus NUST, 46000, Pakistan.
[2] HITEC University, Department of Mechanical Engineering, Taxila, 47080, Pakistan, E-mail address: rizwan.choudhry@gmail.com
[3] National Composites Certification and Evaluation Facility, University of Manchester, Manchester, UK
[4] Centre of Excellence in Applied Sciences and Technology (CESAT), 44000, Islamabad, Pakistan.

Abstract

This paper describes the challenges in using testing standards such as D6641/D6641M-14, for determination of compressive strength of 3D angle interlocked glass fabric reinforced polymeric composites (3D-FRPC). It makes use of both experimental investigation and finite element analysis. The experimental investigation involved testing both 2D and 3D-FRPC using ASTM D6641/D6641M-14 and subsequent scanning electron microscopic imaging of failed specimens to reveal the stress state at failure. This was further evaluated using laminate level finite element (FE) analysis. The FE analysis required input of effective orthotropic elastic material properties of 3D-FRPC, which were determined by customizing a recently developed micro-mechanical model. The paper sheds new light on compressive failure of 3D angle interlocked glass fabric composites, as only scarce data is available in literature about this class of materials. It showed that although the tests produce acceptable strength values the internal failure mechanisms change significantly and the standard deviation (SD) and coefficient of variance (COV) of 3D-FRPC comes out to be much higher than that of 2D-FRPC. Moreover, while reporting and using the test data some additional information about the 3D-fabric architecture, such as the direction of angle interlocking fabric needs to be specified. This was because, for 3D angle interlocking of fabric along warp direction, the strength values obtained in the warp and weft direction were significantly different from each other. The study also highlights that due to complex weave architecture it is not possible to achieve comparable volume fractions with 2D and 3D fabric reinforced composites using similar manufacturing parameters for the vacuum assisted resin infusion process. Thus, the normalized compressive strength values (normalized with respect to volume fraction) are the highest for 3D-FRPC when measured along the warp direction, they are at an intermediate level for 2D-FRPC and the lowest for 3D-FRPC, when measured in the weft direction.

Keywords: 3D fabric reinforced composites, Compression testing, Finite element analysis, Micro-mechanical modelling

1. Introduction

Polymeric composite materials are widely used because they have high specific strength, high specific stiffness and corrosion resistance. The fibre reinforcement for these composites is generally in a two dimensional (2D) format such as fabric, mat or unidirectional tape layers. In case of 2D woven fabric reinforced polymeric composites (2D-FRPC), the yarn reinforces the composite along warp and weft directions (Fig. 1 (a)). In such cases, 3D structure is formed by stacking up the plies on top of each other. Application of 2D FRPC is problematic in cases requiring thicker sections and structures that are designed for transverse and compressive loading. Both these types of loading result in significant out of plane stresses, which the composite cannot bear because of absence of fiber reinforcement in this direction. Consequently, these composites have relatively lower through-thickness properties. This makes them prone to delamination under impact and results in lower out of plane moduli and inter laminar fracture toughness. Such composites are also expensive in thick laminate applications (higher layup cost) [1-3]. Given the advancements in weaving technologies and development of novel braiding and robotic tow placement methods it is now possible to weave or braid the reinforcements in complex 3D architectures that can be made in near net shapes. Such 3D composites have reinforcing yarn in the out of plane direction, which provides through thickness binding and for continuous 3D reinforcement along fabric length the through thickness binding yarn generally traverses along the warp direction (see Fig. 1 (b)). Such a through thickness reinforcing yarn is also referred to as ‘warp weaver’. The warp-weaver generally results in higher delamination and shear resistance of 3D FRPC [4, 5]. These composites also offer the potential for reducing the overall manufacturing cost and time by reducing layups times [5].

In recent years the 3D-FRPC have found use is high profile applications such as landing gear strut for Boeing 787, inlet duct of joint strike fighter aircraft and aero-engine fan blades [6]. Besides aerospace there is a potential demand for these composites from many other industries such as wind turbine blades, body and vehicular armor, high performance sports goods, nuclear centrifuges and automotive crash protection structures [7-9]. The use of these composites however has been limited despite the great potential they offer. One main reason for this is that, being relatively new materials the standards for testing these materials for properties such as modulus, strength and fracture toughness have not fully evolved. This particular point will be further elaborated in the following section.

2. Requirement of Developing Testing Standards for 3D-FRPC.

Structural design requires the knowledge about the effective properties of the materials for relating stresses with strains (i.e. for constitutive equations) and for consequent failure and damage prediction. These properties are usually determined by following standard test methods which are designed so as to develop the required stress state in a material. For isotropic materials such as metal alloys the knowledge about only two material constants (the modulus and Poisson ratio) is sufficient to define the elastic structural response. For anisotropic and heterogeneous materials like laminated composites however, a much larger data set of material properties is required. It is customary to consider the structure made from composite material to be a stacking of anisotropic (usually orthotropic due to material symmetries) but homogenous layers called laminas. Since each layer is very thin usually plane stress assumption is justified. In such cases five material constants are usually sufficient to define the constitutive relationship.

In situations where the out of plane stresses are important or for materials such as 3D-FRPC which have a significantly thicker lamina, the plane stress assumption is usually not justified and at least nine effective material constants must be determined even for orthotropic elastic structural response. Unlike the 2D laminated composites the situation for 3D-FRPC is more complicated by the fact that no standard test methods are available to determine these properties. Guidelines by international testing organizations like ASTM and research organizations like NASA in some cases suggest the use of testing standards for 2D-FRPC with some special considerations such as the ones described in Ref [6, 10].

In practice however, large scale use of 3D-FRPC has not become a reality; owing primarily to the unavailability of relevant testing standards. Such tests are necessary for obtaining data, which is crucial to design of components and structures from these materials. When developing a standard test method, the basic requirement is to achieve the desired pure mode stress state in the specimen. When the same specimen dimensions and loading/boundary conditions as used for 2D-FRPC are used for a 3D-FRPC, there is no guaranty at prior that the same stress state would be achieved in the specimen due to the fact that micro structural architecture or (unit cell) of 3D-FRPC is entirely different from a 2D FRPC. The solution to this is the development of new testing standards and modification of existing standards to make them applicable to 3D-FRPC.

In this context the specific focus of this study is applicability of compression testing standard D6641/D6641M-14 [11] for 3D FRPC. In the following section, it will be established through the literature review that there is essential requirement to study testing standards for 3D FRPC for various types of tests in general and for compression testing in particular.

In order to pursue the development of testing standards for 3D FRPC one first needs to understand the issues that arise due to the use of testing standards for 2D-FRPC. The literature reviewed in this regard has shown that previously several researchers have tried to use the standards available for 2D laminated composites to determine the effective properties of 3D-FRPC. This has not been very successful because the micro-structural unit cell of 3D-FRPC is fundamentally different from 2D-FRPC due to the presence of out of plane reinforcement and thus the stress field is much more inhomogeneous and the stress state achieved in the 3D-FRPC during the desired standard test may not be same as the stress state achieved for the 2D laminated composites (see for example ref.[10, 12-15]). In addition, the failure modes achieved may not be the same as the desired one (e.g. see ref.[13, 16-18]) Consequently when standards for 2D-FRPC are applied to the 3D-FRPC the tests produce values which are not repeatable and it is also difficult to state with confidence if indeed one is measuring the intended property. In the following sub section problem faced by different researchers in testing of 3D FRPC under different test methods will be discussed in detail.

2.1. Tensile Testing.

Tensile tests are generally considered as the simplest test to perform. Despite this, when Quinn et al [12] used Electron Speckle Pattern Interferometer (ESPI) technique for the examination of failure and strain distribution under tensile loads (using Composites Research Advisory Group CRAG [19] test standard); he reported a marked increase in tensile strain (and consequently stress) in the area, where binder yarns enter the subsurface layer to bind the layers together. They also reported that when the same specimen is subjected to the loads repeatedly the strain maps based on ESPI do not remain the same. The fundamental requirement for tensile test to be valid is that the surface strains should be reasonably uniform (macroscopically homogenous) with the axial component being the largest. These results however, show that this fundamental assumption is not completely justified if the CRAG tests standard for 2D-FRPC is used for tensile test of 3D-FRPC.

Other authors such as Kuo et al [13] have also reported that the major challenge in the development of testing standard for 3D FRPC is obtaining the inhomogeneity of strain field. They also assert rightly that it would be difficult for a single standard to be used with all types of 3D-FRPC, due to the wide variety of dissimilar structures, possible with 3D fabrics. In his work, they have also highlighted that since 3D-FRPC are inherently thick and mostly formed in near net shape, the loads required to cause failure are difficult to achieve with the same testing rigs as used for 2D-FRPC. Thus even for simple tensile tests, due to the thickness the specimens must be machined in the dog bone type of shape usually employed for metals. He has also highlighted that during testing the architecture of interlacing surface loops is often as important as internal architecture because in practice most 3D fabrics are made in near net shapes. Thus, while testing it is important to keep the surface loops as they are in original state.

Fredrik Stig and Stefan Hallstrom [20] while working on new weaving technology for fully interlaced 3D-FRPC expressed their inability to measure the strength properties because they were not able to achieve the desired failure modes in the 3D-FRPC specimens by following the respective 2D-FRPC testing standard. They also attempted to calculate the different moduli in their work. For example they calculated the tensile modulus 'E_1' using ASTM D3039 / D3039M-14 [21] and reported that the standard deviation in the modulus calculation for 3D woven composite was ±6.1, while that for non-crimped fabric using the same testing standard was ±0.7. This clearly shows that besides the strength the standard test was even inadequate for measuring the modulus.

There is no testing standard for out of plane tension testing of composites and in a recent paper Gerlach [22] has proposed a new design of a cross shaped specimen for out of plane tension test. The specimen is loaded using U shaped steel clamps to produce the desired stress state. According to Gerlach [22], this modified shape of specimen introduces a pure out of plane tensile failure within the specimen. Although from this modified testing setup, desired failure stress state is achieved; however, the measured values show higher standard deviations. Thus, modifications are still needed to get the desired results.

2.2. Shear Test

Determination of shear related material properties of 3D-FRPC is challenging task. For 2D FRPC several test standards exist for the determination of shear properties (both in-plane and inter laminar properties). For in-plane properties (modulus and strength) a relatively exhaustive study was carried out in Russia and reported by Tarnopol'skii et al [16] to determine which 2D standard will be better for 3D-FRPC. Nine testing methods were experimentally evaluated for use with three different types of 3D-FRPC. The tests included Iosipescu shear test, asymmetric four-point bending (AFPB) test, torsion of rods with circular cut-outs, the double notch shear test, two rail shear test, shear of rectangular prisms, torsion of a straight rod, thin walled tube torsion and square plate twist test. The study reported that all of these test methods when applied for measuring shear strength of 3D-FRPC result in either a very large scatter of data or failure in unintended modes.

Tarnopol’skii et al [16] also suggested the modification in Iosipescu shear test method or ASTM D5379 / D5379M-12 [23] (i.e. shear properties of composite materials by the V-notched beam method) through addition of two extra notches across the specimen width to enable the specimen failure in pure shear mode through the notches. The region of pure shear achieved in these tests is relatively small and this requires the use of precise strain gages. Since 3D composites are highly heterogeneous one may argue whether the small region selected would actually represent the failure strength of the bulk material. This also means that by small deviations in performing the experiments as per standard will result in a high scatter in measured strength. Another important point to note about this study is that this study does not address the testing methods for out of plane or inter laminar shear strength and modulus properties. Besides the previously mentioned study the requirement of having a larger gage length than the one required for 2D-FRPC and consequent requirement of use of different sizes of gages and loading fixtures has also been highlighted by researchers for other tests. For example, Mahadik et al [24], Mouritz et al [25], Ping Tan et al [26, 27], Gerlach et al [22] have all highlighted this issue for various tests.

In order to determine transverse shear properties of 3D FRPC, Kuo et al [13] proposed modifications in method, previously developed by them. They reported that, it was difficult to get single mode failure as desired despite these modifications. This is because, yarns in different directions respond to the applied load differently as warp and weft yarns are under a shear force and binder yarn will be under tensile and compressive load for the proposed testing setup. Adding to this difficulty is the fact that in practice combined failure modes occur simultaneously, in addition.

Kuo et al [13] did not report stress-strain data required for modulus calculations, instead they presented the analysis in terms of loads and displacement. The reason for this as explained by them was that due to the highly non-uniform stress (stress concentration under loading point), it would be meaningless to define a stress measure on the basis of an averaged stress value. Thus, not only there is a real need to develop further the transverse shear standard for 3D-FRPC but also we may have to re-think whether traditional measures of defining strength of composites are appropriate for these materials or not.

Qin at el [14] used full field digital image correlation (DIC) technique (see [28-30] for details of DIC technique) with ASTM D5379 / D5379M-12 [23] to study the shear strain field and for measuring the shear modulus in orthogonally woven 3D C/C composites. They observed that the in-plane shear modulus could not be measured reliably due to the non-uniformity of strain field. This non-uniformity of strain field makes it difficult to choose the appropriate gage length and location for the strain gages. Even when using DIC several measures of modulus can be defined and guidelines are still needed to state with confidence that which of these measures define the effective in-plane shear modulus of the 3D FRPC. In terms of through thickness shear modulus Lijun believes that the standard can be applied since the strain non-uniformity is not too much in the through thickness direction. This however may change if different 3D weave architecture were studied.

In order to determine the inter-laminar shear properties one of the easiest and most widely used test for 2D FRPC is the short beam test or ASTM D2344 / D2344M-13 [31]. This test when applied to 3D FRPC results in localized crushing failure occurring at the loading and supporting rollers due to higher contact stresses. This is because the load required to cause inter-laminar failure in 3D FRPC is much higher than that required for 2D FRPC. The other issue is that the failure mode is superimposed by both flexure and shear. Several researchers such as Ishikawa et al [18], Stig et al[20], Abali et al [32], Li et al [33], Walter et al [34] and Phar et al [35] have investigated the problems associated with using short beam test. They have all proposed different modifications to existing setup for improving the results. Literature indicates that in attempting short beam tests, researchers were not able to achieve the desired failure mode of inter-laminar shear. Researchers (for example[19, 31]) found that the specimens failed through local crushing under the loading point. This, on one hand indicates a much higher inter-laminar shear strength value for 3D-FRPC while at the same time it also indicates the inability of the standard to measure this property accurately.

The non-homogenous strain field and the effects of highly heterogeneous material architecture on strain field and strain rate dependence of modulus and strength were also investigated by Pankow et al [15] in a recent study where he used split Hopkinson pressure bar (SHPB) tests with DIC for obtaining the stress/strain response of orthogonally woven 3D-FRPC at varying strain rates.

2.3. Compression Test

Compression testing is fairly well developed for 2D laminated composites and a number of testing standards such as ASTM D695-96 [36] , ASTM D3410 / D3410M-03[37] and D6641/D6641M-14 [11] exist. The primary difference amongst these testing standards is in the method of load introduction i.e. through end loading (ASTM D695-96) see (Fig. 2 (a)), through shear loading (ASTM D3410 / D3410M-03) sees (Fig. 2 (b)) and by combined end and shear loading (D6641/D6641M-14) sees (Fig. 2(c)). Whether the use of these standards is appropriate for 3D FRPC cannot be assumed at prior because using these may not result in same stress state for 3D FRPC.

The compressive properties of 3D FRPC have been investigated by a number of researcher and some of these report lower strength values as compared to 2D-FRPC [38-40]. One possible reason for this reduction is the increase in fiber crimping caused by the warp weaver and complex weave architecture. The complex weave architecture results in the lower achieved volume fraction and higher void contents (for similar manufacturing process as used for 2D-FRPC). Thus this also results in an apparent reduction of compressive strength [8].

The damaged mechanisms and reduction in the strength of 3D FRPC was investigated extensively by Cox et al [41]. They explain that the mechanism of yarn kinking in 3D composites is different than that in 2D composites [41-43]. The kink band in case of compression testing of 3D composites is observed for the outer most lamina because in this zone the direction of warp weaver is altered as it moves from positive to negative thickness direction or vice-versa and this induces considerable crimping and pinching of warp yarns. Thus, there are two kink bands one at each outer surface. In case of 2D composites, the failure due to kink-band formation generally happens at the same time in the entire cross-section resulting in a much rapid brittle like progressive failure. On the contrary since 3D fabric composite have preferred sights for kink band formation the damage first initiates from these surface yarns and once they have failed the inner yarns can still resist substantial loads. This results in much slower progressive damage and apparent ductile like macroscopic stress -strain curve with higher strains to final failure Thus for example, Cox et al found that even at a strain of 15% 3D FRPC possess significant strength, which is significantly is uncharacteristic of the behavior observed for 2D composites [41].

Measurement of compressive modulus using ASTM D3410 / D3410M-03 [37] showed a standard deviation of ±5.5 for 3D composite as opposed to standard deviation of ±1.0 for NC-0 fabric. They provided the values for strength using this test however the failure mode observed could not be described completely by any of the specified nomenclature given in the standard. The observed failure was a combination of brooming see (ASTM D3410 / D3410M-03[37] for definition) and local failure of warp yarns at an angle with the lateral direction. Thus raising doubts about the acceptability of results.

According to our literature review, the applicability of D6641/D6641M-14 for use with 3D-FRPC, has not been established in published literature. Thus, in this study author has applied D6641/D6641M-14 for measurement of compressive properties of 3D-FRPC. In addition, SEM and microscopy have been used to observe the damaged and failure modes of 3D-FRPC. Furthermore, FE based simulation of the test have been used to investigate the resulting stress state in 3D-FRPC.

3. Research Methodology

3.1. Experimental Work

Experiments on both the 2D and 3D composites were carried out using ASTM D6641/D6641M-14. The procedure, setup, environment, loading and boundary conditions were kept same for testing both types of material. The standard ASTM D6641/D6641M-14 is used for to measurement of compressive modulus and strength, Poison's ratio and ultimate strain in compression. The test has been previously validated for a UD and multidirectional laminates, woven and non-crimp fabric as well as for short fiber composites. The load is applied to the specimen through a combination of end and shear loading.

The schematic of test fixture used in this study is shown in Fig. 3. The grips also act as anti-buckling guides, and ensure efficient transfer of load to the gage section. Axial compressive load is applied to the fixture, which is transferred along the specimen's surface (i.e. in shear) and at its ends through these grips. Tabbed specimens were used according to guidelines in reference [44, 45] to avoid damage caused by clamping force of grips to the specimen.

3.1.1 Materials Used and Specimen Preparation

The 3D composite specimens were manufactured using 3D angle-interlocked E-Glass woven fabric provided by National Composites Certification and Evaluation Facility (NCCEF), The University of Manchester, United Kingdom, while the 2D composites were manufactured using plain weave E-glass fabric. The same 2D fabric was used for the manufacturing of tabs in both cases. 3D fabric used in this study is composed of four layer of angle interlock with through the thickness warp binder yarn ($x = 4$, $y = 4$ and $n_{wft} = 4$) according to definition given by [46]. Where n_{wft} is number of weft layers, x is number of weft yarn between two points of warp binder yarn and y is a binding depth.

Specimens and tab panels for 2D and 3D FRPC are manufactured through vacuum infusion technique to achieve uniform resin distribution and less void content [47, 48]. Epoxy resin, 'Huntsman LA5052', having Araldite 5052 and Aradur 5052 mixed in 100:38 by weight, was used for the infusion process. After resin infusion, the panels are cured at 50ºC for 15 hours. Volume fraction of 2D and 3D FRPC panels was measured through burn off method [49]. Fiber volume fraction, matrix volume fraction and void contents for 2D and 3D FRPC are reported in Table 1.

Both 2D and 3D FRPC are manufactured under similar manufacturing conditions (i.e. similar temperature, vacuum pressure, resin viscosity) for vacuum infusion technique. Despite this, lower fiber volume fraction and higher void content is achieved for 3D fabric. This may be partially due to lesser aerial density of 3D fabric as compare to 2D counterpart and partially due to complicated weave architecture.

3.1.2. 2D and 3D FRPC Specimens Dimensions

Fig. 4 shows geometrical parameters for 2D and 3D FRPC specimens along with dimensions. Similar specimen dimensions were used for both types of specimens. When the panels are fully cured then they are cut in to specimens and tabs of required dimensions by using a suitable cutter. The specimens are slightly overcut to reduce damage to gauge section. Tabs are bounded with specimens through epoxy based resin 5052. These are then carefully grounded to the required dimensions as mentioned in D6641/D6641M-14 [11].

3D FRPC specimens are made in two different configurations. In the first configuration the warp yarns were aligned along the loading direction (i.e. along length of specimen). In second, the warp yarns were aligned transverse to the loading direction (i.e. along specimen width). This allowed us to compare the direction dependent effects of warp weaver in 3D FRPC.

3.1.3. Testing Procedure and Setup.

Fig. 5 shows the schematic diagram of testing procedure and test setup, used in the experimental work. First of all, lower portion of the test fixture (i.e., lower grips and alignment rods) is placed on a flat surface table and then screws are loosened to accommodate the specimen. End of the specimen is aligned with the surface table and lower grips in order to transfer end load in to the specimen and all the four screws of the lower grips are tightened. Fig. 5 (a) shows installation of specimen in the lower grips of D6641/D6641M-14 test fixture. The upper grips are placed upside down; while insert the alignment rods and the lower grip assembly in to the two upside down grips as shown in (Fig. 5 (b)). Afterwards the end of the specimen is aligned with the surface table and the other four screws are tightened to complete the assembly as shown in the (Fig. 5 (c)) the torque of 2.5 - 3 N-m is applied on all eight screws. Then the whole assembly is placed between the flat plates of universal testing machine as shown in the (Fig. 5 (d)). The test is performed according to procedure described in D6641/D6641M-14. Six samples of each of the three configurations are tested. These are 2D FRPC, 3D FRPC with warp yarns and warp weaver along the loading direction and 3D FRPC with warp yarns and warp weaver transverse to the loading direction (in other words weft yarn is along loading direction in this case). During testing universal testing machine (Instron test frame model

5989) with 300kN load cell is used. Compressive load is applied at a load rate of 0.5mm/min at ambient temperature (18ºC).

3.1.4. SEM (Scanning Electron Micrograph) Investigation

The failure mechanisms were observed and identified using SEM imaging. Scanning electron micrograph is used for composite analysis at micro level due to large magnification range, which is required during analysis of failure regions. In SEM magnified Image of specimen is produce by scanning it through focused beam of electron. In this work SEM is carried out on selected specimens after performing compression test, to investigate failure mode of each specimen. Desired location (failure region) of cross section is polished and coated with carbon layer to make it conductive for higher magnification. To fix the specimen in specimen chamber, specimens are resized to 40mm x 10mm high.

3.2. Material model for FE analysis and micromechanical determination of elastic properties

The finite element analysis described in the following section assumes effective orthotropic elastic behavior for both 2D and 3D composites. The constitutive material model for such materials is given by the following well known equation (1) [50].

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{xz} \\ \gamma_{yz} \end{bmatrix} = \begin{bmatrix} \frac{1}{Ex} & -\frac{Vyx}{Ey} & -\frac{Vzx}{Ez} & 0 & 0 & 0 \\ -\frac{Vxy}{Ex} & \frac{1}{Ey} & -\frac{Vzy}{Ez} & 0 & 0 & 0 \\ -\frac{V13}{Ex} & -\frac{Vyz}{Ey} & \frac{1}{Ez} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{Gxy} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{Gxz} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{Gyz} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{xz} \\ \tau_{yz} \end{bmatrix} \tag{1}$$

This equation allows for modelling the constitutive behavior of both 2D and 3D composites depending on the choice of values for the effective material constants. These nine constants are the three elastic moduli (E_x, E_y, *and* E_z), *three shear moduli* (G_{xy}, G_{yz}, *and* G_{xz}) *and Poisson ratio* (v_{xy}, v_{yz}, *and* v_{xz}) along the material warp, weft and through thickness directions. In case of 2D woven composite these constants were, $E_x = E_y = 19.95$GPa, $E_z = 12.84$GPa, $v_{xy} = 0.165$, $v_{yz} = v_{xz} = 0.33$, $G_{xy} = 4.51$GPa, $G_{xz} = G_{yz} = 4.36$GPa. [51]

Elastic constants of 3D angle interlocked glass woven composite were determine through analytical model based on volume averaging method [52-54] . The method described in these studies [52-54] for orthogonal angle interlocked composites was customized and implemented via code written in MATLAB by the author, to determine elastic constants of the 3D angle interlock woven composites used in this study. The results of the code were validated by comparing with the experimentally determined values of E_1 and G_{12} provided by National Composites Certification and Evaluation Facility (NCCEF), UK [55] . The representative volume element (RVE) along with definition of the key terms used in analytical model is given in see (Fig. 6).

Overview of volume averaging method is shown in Fig. 7. In this methodology, engineering elastic constants of yarns and matrix are calculated from elastic properties of fibers and matrix, which are then used to calculate the local stiffness matrix of each constituents of RVE i.e. Warp, weft, z-binder yarn and matrix. These local stiffness matrix are transformed with respect to global coordinates to get transformed stiffness matrix of each constituent of RVE. After evaluating transformed stiffness matrix and volume proportions of each constituents, volume averaging method is applied to calculate the global stiffness matrix of RVE according to equation (2). Engineering elastic constants of RVE are calculated from compliance matrix by taking inverse of global stiffness matrix according to equation (3). Elastic constants of 3D angle interlocked woven composites are then calculated through equation (4) [56] . Table. 2 shows material and geometric properties of fibers and matrix used to calculate elastic constants and volume propositions of each constituents in RVE.

$$[Q_{RVE}] = \sum V_{pi}\ [\bar{Q}_i]\ (i = w, f, z, m) \tag{2}$$

$$[S_{RVE}] = [Q_{RVE}]^{-1} \tag{3}$$

$$\begin{array}{lll} E_x = \dfrac{1}{S_{11}} & E_y = \dfrac{1}{S_{22}} & E_z = \dfrac{1}{S_{33}} \\ \gamma_{xy} = -\dfrac{S_{21}}{S_{11}} & \gamma_{xz} = -\dfrac{S_{31}}{S_{11}} & \gamma_{yz} = -\dfrac{S_{32}}{S_{22}} \\ G_{yz} = \dfrac{1}{S_{44}} & G_{zx} = \dfrac{1}{S_{55}} & G_{xy} = \dfrac{1}{S_{66}} \end{array} \tag{4}$$

The effective material properties of the 3D angle interlocked woven composite calculated as described above along with the comparison with the experimental values provided by NCCEF, for model validation are shown in Table 3. The actual code used for calculating these values is provided in *Appendix-A*, and the reader is referred to [52-54] for details of methodology and explanation of equations used in the code. The above methodology is used for orthogonal interlocked woven composites, in this study it is used for 3D angle interlocked woven composites by modifying geometric parameters for calculating the z-binder geometry. Z-binder is divided in to three steps to calculate its stiffness matrix.

3.3. Finite Element Analysis

Finite element (FE) analysis is performed using ABAQUS/Standard (implicit). This analysis is used to explain the differences in the stress/strain state of 2D and 3D-FRPC specimens under testing conditions. This is done by comparing the stress and strain distribution along length, width and through thickness in the gauge section. Details of simulation are as under.

3.3.1. Load cases and Boundary Conditions

Two load cases are considered for each specimen one load case in each case corresponds with the failure load determined from the actual experiments. The other case considers same load for each specimen and was chosen equal to the lowest observed failure load. Thus the six load cases given in Table 4 were considered.

The computational requirements are reduced by noting and applying the symmetry boundary conditions. Thus, x and z-symmetry boundary conditions, as shown in Fig. 8, are imposed on the specimen and associated tab portion. With this symmetry conditions one quarter model is analyzed, which reduces the computational time. Symmetry boundary condition for solid elements involves restriction of translational degrees of freedoms. The applied symmetry boundary condition is described in Fig. 8.

In order to further reduce computational cost and simplify the analysis, the test fixture is not modelled geometrically, instead loads are applied on the specimen and tabs (see Fig. 9) to replicate the test conditions of D6641/D6641M-14 [11]. The loads are applied in a manner similar to that described in ref [57-59]. Thus 2/3 of the total load applied through the load cell (as given in Table. 4) is transferred as shear surface traction on the un-tapered tab surface and 1/3 is transferred directly as axial compressive load on the end of the specimen.

3.3.2. Element Type and Material Properties

The specimen and tabs geometry is meshed using 3D solid elements C3D8R. This is an eight node reduced integration linear brick element. In this study an equivalent orthotropic material definition is assumed to model both 2D and 3D-FRPC specimens. The reason for choosing an orthotropic material definition and 3D solid continuum representation instead of shell element based representation was that, the shell element would not allow the detailed through thickness investigation of 3D stress state as required for comparison of two types of specimens. Moreover, in 3D-FRPC one layer comprised of an equivalent of 4 layers of 2D-FRPC held together with 3D fiber (Warp weaver), thus a shell representation would not be comparable for both specimens. Fig. 10 shows mesh convergence study, which clearly indicates that convergence of results are achieved at 110,000 elements.

4. Results and Discussion

4.1. Experimental Results

This section presents the comparison of failure mechanisms for all test configurations described earlier in detail. Fig. 11 shows tested specimens along with the failure modes. The tests were deemed acceptable according to ASTM D6641/D6641M 14 guidelines, as all specimens failed in the gage section Maximum compressive strength of 2D and 3D FRPC tested specimens and failure load are shown in Fig. 12.

A summary of experimental failure loads and strengths along with associated standard deviations and coefficient of variance are presented in Table 5. This shows that 2D FRP composite failed at average compressive stress (warp) around 266MPa. In contrast, in case of 3D-FRPC compressive strength of specimens in warp direction is 205MPa and that along weft direction is 176MPa. These results highlight that significant differences in strength exist not only between 2D and 3D composites but also for the two different test configurations of 3D composites. We attribute the increase in the compressive strength in warp direction to the component of warp weaver along warp yarn, which reduces the out of plane buckling and arrests and diverts delamination initiating between the layers due to compressive buckling. This is discussed in more detail later using SEM images of failed specimens. Table 5 also highlights that the compressive strengths of 3D FRPC are less than 2D FRPC. We attribute this mainly to high fiber volume fraction for 2D FRPC which is around 56.5% as compared to 40% for 3D FRPC. This low fiber volume fraction of 3D FRPC is mainly due to complex weave architecture. Moreover, void content of 3D FRPC is high around 5.4% as compared to 3.5% of 2D FRPC which caused reduction in the compressive strength of 3D FRPC, this high void content is again attributed to the complex weave architecture that may require lower resin viscosity and higher consolidation pressure for a better fabric wet-out.

An interesting comparison can be seen in Table 5, where the normalized strength values have been shown for the three cases. The normalization has been carried out by dividing the strength obtained with volume fraction in each case. Immediately it becomes apparent that the compressive strength per unit fiber volume fraction is highest for the 3D-FRPC loaded along the warp direction. It is at intermediate level for 2D-FRPC and interestingly it is lowest for 3D-FRPC in the weft direction. This clearly demonstrated two things firstly it shows that if by improving the manufacturing process, one can achieve volume fractions comparable to 2D counterparts, then the strength will be higher for 3D-FRPC along warp direction. Secondly it shows that in the weft direction despite the normalization with fiber volume fraction the strength remains lower than 2D counterpart. We can explain this as a consequence of higher void content for 3D-FRPC. This makes it easier for the layers to delaminate and buckle (kink) under compression in weft direction as will be shown by micrographs in the next section. The above discussion brings home two important point with regards to manufacturing of 3D-FRPC that it may be prudent to have the 3D interlocking fabric going through both the warp and weft directions for more balanced properties. Similarly, it also highlights that in order to ensure lower void content resins with lower viscosity may be preferable for use with 3D fabrics.

4.2 SEM Results.

SEM investigations (figures 13 and 14 point out that fiber micro-buckling, fiber breaking and kink band formation are the main failure mechanisms observed for 2D FRPC. The failure mechanisms of fiber breaking and kinking dominate for 3D-FRPC. The location and extent of this is different for 2D and 3D composites. These observations are explained below in more detail.

4.2.1. 2D Fiber Reinforced Polymeric Composites (FRPC)

Fig. 13 shows failure in 2D FRPC. Delamination failure along the two outer most lamina (top and bottom) are shown in Fig. 13 (a). Fiber kinking at different locations through the specimen thickness is shown in Fig. 13 (b). Fig. 13 (c) and Fig. 13 (d) shows magnified image of the two outer most lamina shown in Fig 13 (a). This shows fiber micro buckling at the tip of delamination cracks.

4.2.2. 3D Fiber Reinforced Polymeric Composites

SEM images of the failed specimens for the two configurations of 3D FRPC are shown in Fig. 14.

(i) Case -1: Warp Yarn along loading direction

Fig. 14 (a) and (b) shows failure mechanisms for the case where warp weaver and warp yarn, both, are along the loading direction. There is no evidence of fiber-micro buckling or extensive delamination along the two outer most lamina (see (Fig. 14 (b)). It can be seen in Fig. 14 (a) that the micro matrix cracking which can lead to delamination is arrested by warp weaver and thus, prevents further damage at that location see Due to this these specimens exhibit a higher compressive strength then ones loaded along the weft direction..

(ii) Case 2: Weft Yarn along loading direction

The location and mechanism of failure for this case is shown in Fig. 14 (c) and (d). In this case, the 3D yarn (warp-weaver) does not interfere with damage development in the same way as it does for the case when load is along the warp direction. Thus, the compressive strength in this case is less. It can be seen that in this case fiber kinking takes place at various location inside the specimen and rupture or breakage of yarn is also observed at the two outer most lamina. Unlike the case of failure of 2D FRPC no delamination is observed along the two outer most lamina. This shows that the presence of warp weaver keeps the layers together. As evidenced in Fig. 14 (d) however, the kink band formation at different locations reduces the axial strength of the yarn and thus overall strength of composite is lowest in this case.

4.3. Finite Element Analysis Results

Figures 15, 16 and 17 show the results of FE analysis and present a comparison of stress state for the 2D and 3D specimens under simulated testing conditions. The finite element analysis shows that the stress field developed in both types of material systems at failure loads observed in the experiments is primarily compressive (i.e. dominated by S_{11} with other stress components being significantly lower). Such a distribution is desirable because this test is expected to cause pure compressive failure. The compressive stress S_{11} is further investigated at different locations in the gage section, using Fig. 15 and Fig. 16 for 2D and 3D (loading direction along the direction of warp-weaver) specimens. Overall, both the figures show nearly uniform stress distribution in the gauge section with high stress gradient at tapper end of tabs. Fig. 15 (a) shows that within the gauge section the maximum compressive stress due to applied experimental load for 2D composites at failure is around 256 MPa, which is fairly close to the experimentally determined average failure strength of 266 MPa. Near the tapered tab end however, the stress abruptly rises to a value of around 350 MPa. This is also consistent with the experimental observation shown in Fig. 11 (b) and Fig. 13 (a), which shows that the crack initiated at a very short distance from the tapered end progressed towards the middle of the gauge section. Fig. 15 (b) shows different views of the stress distribution in the gauge section. This distribution indicates that stress concentration effect is only present on the surface element and near the tab. Fig. 15 (c) shows the distribution of stress within gauge section along both, the length and the width (i.e. warp and weft). These plots more clearly establish the fact that the stress distribution becomes reasonably uniform after around 1mm distance from the tabs.

In case of 3D-composite specimens loaded along the warp direction, we see certain similarities as well as differences in the stress distribution. These have been explained with the help of Fig. 16 and Fig. 17. We note that the value of maximum stress in the gauge section corresponding to the average experimental load at failure are around 190 MPa, while the stress rises to a value of 250 MPa in the gauge section near the tapered end of tabs due to stress concentration see (Fig. 16 (a)). While the numerical values appear very different from the previous case, due to the fact that the experimental failure load in this case was much less (4356 N compared to 6004 N for 2D case);The stress concentration factor is the same. Thus, in both the cases the increase in stress near the tabs from the maximum stress in gauge section is around 24% which corresponds to a stress concentration factor of around 1.3 in both cases. In general, unlike isotropic materials, the stress concentration factor for orthotropic materials is not a purely geometric property and depends on degree of orthotropy of material as well. In this case, however, it appears that the influence of z-binder yarn is not sufficient to alter this stress concentration factor drastically. These points are further elaborated using Fig. 17, which shows a comparison of all stress components developed in each specimen for the same value of applied load. The applied load in this case was 4137 N (i.e. the average failure load of 3D composites loaded along weft direction), this was the minimum average load observed in experiments. By keeping the load level same, it becomes easier to see the influence of material properties on variation in stress state distribution. From these graphs it is observed, that for all specimens the most significant stress component is the longitudinal compressive component (S_{11}). The next most significant component is the transverse tensile stress, however this is of the order 10^5 while the longitudinal compression is of the order 10^8, thus it is only expected to slightly influence failure. It is noted that for the transverse stress the most significant contribution is for the case of 2D woven specimens. The rest of graphs show that the overall stress distribution pattern is similar with localized differences in each case, these are however considered less important for influencing failure as their values are much smaller than the other two components.

5. Conclusion

3D and 2D woven glass fabric reinforced composite specimens were compared in terms of compressive strength, internal failure modes and stress state using experimental as well as simulated (FEA) testing according to ASTM D6641/D6641M-14. The comparison highlighted that for 3D angle interlocking of fabric along warp direction, the strength values obtained in the warp and weft direction were significantly different from each other. The volume fraction achieved with 3D fabric was lower than that achieved with 2D fabric and consequently the strength of 3D fabric reinforced composite was lower in absolute sense, this is in agreement with the previous study for orthogonal 3D composites [3]. When this strength was expressed as normalized parameter however (normalized with respect to volume fraction), the highest values were observed for 3D-FRPC loaded along the warp direction, they were at an intermediate level for 2D-FRPC and the lowest for 3D-FRPC loaded in the weft direction. The significant difference in the warp and weft direction for 3D FRPC arises because the z-binding yarn was woven along the warp axis. This highlights that for balanced property enhancement the z-binder should be woven in both warp and weft directions. In case where the z-binder is only along the warp direction as in this study, it is important to state both the warp and weft compressive strengths.

The comparison of stress state using FEA and the failure state using SEM establishes that although at a macroscopic level pure compressive stresses dominate and stress-field is uniform for a significant portion of gauge length for all specimens, local differences lead to very different failure mechanisms. Thus, the compression failure in 3D-FRPC in warp direction takes place due to compressive fiber failure in warp direction whereas for 2D-FRPC and 3D-FRPC loaded in weft direction, this is caused by kink band formation. Due to complex and relatively more non-uniform internal structure, the standard deviation (SD) and coefficient of variance (COV) is higher in case of 3D composites than that for specimens without the out of pane reinforcement. The SD and COV was particularly high in warp direction 3D-FRPC due to variability in the effectiveness of failure arresting mechanism by the warp-weaver at various locations and due to a higher and non-uniform void content. Since D6641/D6641M-14 does not specify an upper bound on COV and since the achieved values are within the range given in example test cases described in the standard [11], we have considered the tests to be valid despite the high value of COV.

We successfully used an analytical micromechanical model to predict effective elastic properties that were then used for FEA, which explored the macro level stresses. Predictive failure modelling for 3D composites would however, require a multiscale analysis of failure based on a feedback loop from the FEA to the analytical micromechanical model for evaluating constituent level stresses and subsequent degradation of effective properties. Further work is required to validate such an approach.

Acknowledgement

The authors are thankful to British Council and Department of International Development (DFID, UK) for partially funding this research work through the DelPHE-780 Project grant. We would also like to thank Professor Paul J Hogg (Royal Holloway, University of London), Dr. Prasad Potluri and Dr. Payyam Jamshidi (National Composites Certification and Evaluation Facility (NCCEF), The University of Manchester) for providing 3D fabric for performing experimental work described in this study.

Authors post-print (i.e. final draft post-refereeing): The actual journal version of the paper can be downloaded from Shah, S. Z., Choudhry, R. S., and Khan, L. A., "Challenges in Compression Testing of 3D Angle-Interlocked Woven-Glass Fabric-Reinforced Polymeric Composites," *Journal of Testing and Evaluation*, https://doi.org/10.1520/JTE20160191. ISSN 0090-3973

References

1. Fredrik Stig, *"An introduction to the mechanics of 3D-woven fibre reinforced composites"*. 2009.
2. R. S. Choudhry, K.A.K., Sohaib Zia Khan, Muhammad Ali Khan, Abid Hassan,, *"Micromechanical Modeling of 8-Harness Satin Weave Glass Fiber Reinforced Composites".* Journal of Composite Materials,Sage Publishers. DOI: 10.1177/0021998316649782, 2016.
3. R.S. Choudhry, H.S., Li S, Day R, *"Damage in single lap joints of woven fabric reinforced polymeric composites subjected to transverse impact loading".* International Journal of Impact Engineering, 2015. 80: p. 76-93.
4. Kamiya R., B.A.C., P. Popper, and T.W. Chou, *"Some recent advances in the fabrication and design of three-dimensional textile preforms: a review".* Composites science and technology, 2000. 60(1): p. 33-47.
5. Potluri, P., P.J. Hogg, T. Sharif, D. Jetavat, R.S. Choudhry, and A. Aktas. *"Bench-marking of 3D preforming strategies"*. in *ICCM 17, 17th International Conference on Composite Materials*. 2009.
6. Masters, J.E. and M.A. Portanova, *"Standard test methods for textile composites"*. 1996: National Aeronautics and Space Administration.
7. Tong, L., A.P. Mouritz, and M. Bannister, *"3D fibre reinforced polymer composites"*. 2002: Elsevier.
8. Mohamed, M.H. and K.K. Wetzel, *"3D woven carbon/glass hybrid spar cap for wind turbine rotor blade".* Journal of Solar Energy Engineering, 2006. 128(4): p. 562-573.
9. Clemente, R., et al., *"3D Composite Sandwich Structures Applied to Car Manufacturing"*. 1998, SAE Technical Paper.
10. *ASTM D6856-03, "Standard Guide for Testing Fabric-Reinforced Textile Composite Materials", ASTM International, West Conshohocken, PA, 2003, www.astm.org*.
11. *ASTM D6641 / D6641M-14, "Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture", ASTM International, West Conshohocken, PA, 2014, www.astm.org*.
12. Quinn, J., A. McIlhagger, and R. McIlhagger, *"Examination of the failure of 3D woven composites".* Composites Part A: Applied Science and Manufacturing, 2008. 39(2): p. 273-283.
13. Kuo, W.-S., J. Fang, and H.-W. Lin, *"Failure behavior of 3D woven composites under transverse shear".* Composites Part A: Applied Science and Manufacturing, 2003. 34(7): p. 561-575.
14. Qin, L., et al., *"Full-field analysis of shear test on 3D orthogonal woven C/C composites".* Composites Part A: Applied Science and Manufacturing, 2012. 43(2): p. 310-316.
15. Pankow, M., et al., *"Split Hopkinson pressure bar testing of 3D woven composites".* Composites Science and Technology, 2011. 71(9): p. 1196-1208.
16. Tarnopol'skii, Y.M., V. Kulakov, and A. Aranautov, *"Measurements of shear characteristics of textile composites".* Computers & Structures, 2000. 76(1): p. 115-123.
17. DF, A. and W. DE, *"Further development of the losipescu shear test method".* Experimental Mechanics, 1987. 27(2): p. 113-119.
18. Ishikawa, T.a.Y.H., *"Standardization of Tests for Advanced Composites".* NAL Res Prog (Natl Aerosp Lab Jpn), 2003: p. 50-53.
19. Curtis, P., *"CRAG (Composite Research Advisory Group) Test Methods for the Measurement of the Engineering Properties of Fibre Reinforced Plastics"*. 1988, DTIC Document.
20. Stig, F. and S. Hallström, *"Assessment of the mechanical properties of a new 3D woven fibre composite material".* Composites Science and Technology, 2009. 69(11): p. 1686-1692.

21. *ASTM D3039 / D3039M-14, "Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, ASTM International", West Conshohocken, PA, 2014, www.astm.org*.
22. Gerlach, R., et al., *"In-plane and through-thickness properties, failure modes, damage and delamination in 3D woven carbon fibre composites subjected to impact loading".* Composites Science and Technology, 2012. 72(3): p. 397-411.
23. *ASTM D5379 / D5379M-12 "Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method", ASTM International, West Conshohocken, PA, 2012, www.astm.org*.
24. Mahadik, Y. and S. Hallett, *"Effect of fabric compaction and yarn waviness on 3D woven composite compressive properties".* Composites Part A: Applied Science and Manufacturing, 2011. 42(11): p. 1592-1600.
25. Mouritz AP, B.M., Falzon PJ, Leong KH., *Review of application for advanced three dimensional fiber textle composites.* composite Part A: Applied Science and Manufacturing, 1999. 30(12): p. 1445-61.
26. Tan, P., L. Tong, and G. Steven, *"Behavior of 3D orthogonal woven CFRP composites. Part II. FEA and analytical modeling approaches".* Composites Part A: Applied Science and Manufacturing, 2000. 31(3): p. 273-281.
27. Tan, P., et al., *"Behavior of 3D orthogonal woven CFRP composites. Part I. Experimental investigation".* Composites Part A: Applied Science and Manufacturing, 2000. 31(3): p. 259-271.
28. Yoneyama, S., Y. Morimoto, and M. Takashi, *"Automatic Evaluation of Mixed-mode Stress Intensity Factors Utilizing Digital Image Correlation".* Strain, 2006. 42(1): p. 21-29.
29. Vendroux, G. and W. Knauss, *"Submicron deformation field measurements: Part 2. Improved digital image correlation".* Experimental Mechanics, 1998. 38(2): p. 86-92.
30. Zhou, P. and K.E. Goodson, *"Subpixel displacement and deformation gradient measurement using digital image/speckle correlation (DISC)".* Optical Engineering, 2001. 40(8): p. 1613-1620.
31. *ASTM D2344 / D2344M-13, "Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates", ASTM International, West Conshohocken, PA, 2013, www.astm.org*.
32. Abali Felix, P.A., Shivakumar Kunigal, *"Modified short beam shear test for measurement of interlaminar shear strength of composites".* Journal of composite materials, 2003. 37(5): p. 453-464.
33. Li, M., R. Matsuyama, and M. Sakai, *"Interlaminar shear strength of C/C-composites: the dependence on test methods".* Carbon, 1999. 37(11): p. 1749-1757.
34. Walter, T., et al., *"Monotonic and cyclic short beam shear response of 3D woven composites".* Composites Science and Technology, 2010. 70(15): p. 2190-2197.
35. Pahr, D.H., et al., *"A study of short-beam-shear and double-lap-shear specimens of glass fabric/epoxy composites".* Composites Part B: Engineering, 2002. 33(2): p. 125-132.
36. *ASTM D695-96, "Standard Test Method for Compressive Properties of Rigid Plastics", ASTM International, West Conshohocken, PA, 2002, www.astm.org*.
37. *ASTM D3410 / D3410M-03(2008), "Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading, ASTM International", West Conshohocken, PA, 2008, www.astm.org*.
38. Brandt, J., K. Drechsler, and F.-J. Arendts, *"Mechanical performance of composites based on various three-dimensional woven-fibre preforms".* Composites Science and Technology, 1996. 56(3): p. 381-386.
39. Farley, G.L., B.T. Smith, and J. Maiden, *"Compression response of thick layer composite laminates with through-the-thickness reinforcement".* Journal of reinforced plastics and composites, 1992. 11(7): p. 787-810.

40. REEDY, E. and T. Guess, *"Additional comparisons of interlocked fabric and laminated fabric Kevlar 49/epoxy composites".* Journal of Composites Technology and Research, 1986. 8(4): p. 163-168.
41. Cox, B., et al., *"Mechanisms of compressive failure in 3D composites".* Acta Metallurgica et Materialia, 1992. 40(12): p. 3285-3298.
42. Cox, B., et al., *"Failure mechanisms of 3D woven composites in tension, compression, and bending".* Acta Metallurgica et Materialia, 1994. 42(12): p. 3967-3984.
43. Kuo, W.-S. and T.-H. Ko, *"Compressive damage in 3-axis orthogonal fabric composites".* Composites Part A: Applied Science and Manufacturing, 2000. 31(10): p. 1091-1105.
44. Nisitani, H., et al., *"Effects of gage length and stress concentration on the compressive strength of a unidirectional CFRP".* Engineering fracture mechanics, 1994. 49(6): p. 953-961.
45. Anthoine, O., J. Grandidier, and L. Daridon, *"Pure compression testing of advanced fibre composites".* Composites science and technology, 1998. 58(5): p. 735-740.
46. François Boussu , I.C., Saad Nauman, *"General definition of 3D warp interlock fabric architecture".* Composites Part B: , 2015. 81: p. 171-188.
47. Khan, L., et al., , *"Cost-effective composites manufacturing processes for automotive applications, in Lightweight Composite Structures in Transport".* Design, Manufacturing, Analysis and Performance. 2016, Woodhead Publisher: p. 93-119.
48. Khan, L., et al.,, *"Cost-effective manufacturing process for the development of automotive from energy efficient composite materials and sandwich structures".* Polymer Composites, 2014. 35(1): p. 97-114.
49. *ASTM-D3171-99, "Standard test method for constituent content of composite materials",American society for testing and materials, 1999.*
50. Datoo, M.H., *"Mechanics of fibrous composites"*. 2012: Springer Science & Business Media.
51. *Scida, D., Aboura, Z., Benzeggagh, M.L. and Bocherens, E. (1999) A Micromechanics Model for 3D Elasticity and Failure of Woven-Fibre Composite Materials. Composite Science and Technology, 59, 505-517. http://dx.doi.org/10.1016/S0266-3538(98)00096-7.*
52. Ansar Mahmood, X.w.a.C.Z., *"Elastic analysis of 3D woven orthogonal composites".* Emerald Group Publishing 2043-9377. 1(3): p. 228-239.
53. Ansar Mahmood, X.w.a.C.Z., *"Modeling strategies of 3D woven composites: A review".* Composites Structures, 2011. 93: p. 1947-1963.
54. Ansar Mahmood, X.w.a.C.Z., *"Generic stiffness model for 3D woven orthogonal hybrid composites".* Aerospace Science and Technology, 2013. 31: p. 42-52.
55. NCCEF test report, J.I.x.C.I.U.O.C.C. 2011: The University of Manchester NCCEF, .
56. Sadd, M.H., *"Elasticity Theory, Applications and Numerics",.* Elsevier, 2005.
57. Tan, S.C., *"Stress analysis and the testing of Celanese and IITRI compression specimens".* Composites science and technology, 1992. 44(1): p. 57-70.
58. Administration, U.S.D.o.F.A., *"Tabbing Guide for Composite Test Specimens".* 2002.
59. Coguill, S.L. and D.F. Adams, *"Use of the Wyoming Combined Loading Compression(CLC) fixture to test unidirectional composites".* Evolving and revolutionary technologies for the new millennium, 1999: p. 2322-2331.

Tables with captions.

Description	3D FRPC	2D FRPC
Volume Fraction of Fibers	39.8 %	56.5%
Volume Fraction of Matrix	54.8 %	40%
Void Content	5.4 %	3.5%

Table 1. Volume Fraction and void content for 2D and 3D FRPC

Material	Material / Geometric properties	
E-Glass	Modulus of Elasticity E (GPa)	73
	Modulus of Rigidity G (GPa)	30
	Poisson’s Ratio	0.22
	Volume Proportion of warp yarn	0.40
	Volume Proportion of weft yarn	0.20
	Volume Proportion of z-binder/warp weaver	0.04
Matrix	Modulus of Elasticity E (GPa)	3.50
	Modulus of Rigidity G (GPa)	1.30
	Poisson’s Ratio	0.35
	Volume Proportion of Matrix	0.36

Table. 2. Engineering Elastic constants and Volume Proportion of Fibers and Matrix

Engineering Elastic constant	Experimental values	Calculated Values	% Difference
Axial modulus , Ex (GPa)	20	19.9	0.5
Transverse modulus Ey, (GPa)	-----	12.6	-----
Transverse modulus Ez, (GPa)	-----	8.20	-----
Poisson’s ratio in xy-plane, Vxy	-----	0.19	-----
Poisson’s ratio in xz-plane, Vxz	-----	0.33	--------
Poisson’s ratio in yz-plane, Vyz	------	0.35	------
Shear modulus in yz-plane, Gyz (GPa)	-----	2.84	-----
Shear modulus in zx-plane, Gzx (GPa)	-----	2.82	-----
Shear modulus in xy-plane, Gxy (GPa)	2.76	2.84	2.8

Table. 3. Engineering elastic constants of 3D angle Interlocked woven composites determined using the volume averaging method and comparison with experimental values

Load Cases		
2D-FRPC	3D-FRPC (loaded along warp)	3D-FRPC (loaded along weft)
6004 N (equal to average failure load for 2D-FRPC from experiments)	4356 N (equal to average failure load for 3D-FRPC along warp from experiments)	4137 N (equal to average failure load for 3D-FRPC along weft from experiments)
4137 N (equal to average failure load for 3D-FRPC along weft from experiments)	4137 N (equal to average failure load for 3D-FRPC along weft from experiments)	4137 N (equal to average failure load for 3D-FRPC along weft from experiments)

Table. 4. Load cases used for simulation.

Fabric Type		Average Failure Load (N)	Average Comp Strength (MPa)	Normalized Comp Strength (w.r.t V_f *fiber volume fraction*) (MPa/V_f)	Standard Deviation (SD)	Coefficient of Variance (COV)
2D FRPC (Average of five samples)		6004	266	470.8	8.1	3.04
3D FRPC (Average of Five Samples Each)	Warp yarn along length	4356	205	515.1	19.2	9.36
	Weft yarn along length	4137	176	442.2	16.2	9.2

Table. 5. Summary of Experimental Results

List of captions of Figures.

Fig. 1 Composites types based on fiber reinforcement. (a) 2D FRP composite, (b) 3D FRP composite
Fig. 2 Schematic diagram of loading scheme in different ASTM standards for compression testing of 2D FRPC [11, 36, 37], (a) End Loading ASTM D695-96, (b) Shear Loading ASTM D3410 / D3410M-03, (c) Combined End & Shear Loading D6641/D6641M-14.
Fig. 3. D6641/D6641M-14 test fixture
Fig. 4. Specimen dimension along with tab
Fig. 5. Schematic Diagram of test procedure and setup (a) Specimen Placement and Alignment on Surface Table, (b) Specimen Placement and Upper/Lower Grips Assembly, (c) Final Assembly with Specimen, (d) Fixture placement in UTM and load application
Fig. 6. Represented volume element (RVE). W= width of RVE, H=Height of RVE, L=Length of RVE, ww=Width of warp yarn, wf=Width of weft yarn, wz=Width of z-binder, tw=Thickness of warp yarn, tf=Thickness of weft yarn, ʎ=No of weft yarn that a binder passes before reversing its direction
Fig. 7. Volume Averaging Methodology for calculating elastic constants of RVE
Fig. 8 Schematic diagram of Symmetry Boundary conditions applied for FEA
Fig. 9 Applied Load for FEA
Fig. 10. Mesh Convergence study
Fig. 11 Failure Modes in 2D and 3D FRPC, (a) 3D FRPC compression test specimen, (b) 2D FRPC compression test specimen. LAB=Lateral at Tab Bottom, LGM=Lateral Gage Middle, LGT=Lateral Gage Top, LAT=Lateral at Tab Top
Fig. 12. (a) Compressive strength of 2D & 3D FRP Composite (b) Failure Load of 2D & 3D FRPC
Fig. 13 Failure in 2D FRPC, (a) Failure location and delamination, (b) Fiber kinking, (c) Fiber micro buckling at the top of specimen, (d) Fiber micro buckling at the bottom of specimen
Fig. 14. (a) & (b) Failure in 3D FRPC with warp yarn along the Length, (a) wary weaver resist Delamination failure, (b) Warp weaver prevent fiver micro buckling. (c) & (d) Failure in 3D FRP composite (weft yarn along length), (c) Fiber breaking and kink band formation at various location, (d) Kink band formation
Fig. 15 Stress variation in 2D FRPC. (a) Stress Distribution in 2D FRPC, (b) Stress distribution in gauge section, (c) Stress variation at different locations in 2D FRPC
Fig. 16 Stress variation in 3D FRPC, (a) Stress Distribution in 3D FRPC, (b) Stress distribution in gauge section, (c) Stress variation in 3D FRPC,
Fig. 17 Stress Variation at same load in 2D & 3D FRPC at gauge section. (a) Shows warp stresses (S11), (b) Shows weft stresses (S22), (c-e) shows stress distribution S33, S12 and S23 respectively