Investigation of compressive properties of 3D fiber reinforced polymeric (FRP) composites through combined end and shear loading

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The failure mechanisms and failure stress states of 2D and 3D FRP composite is investigated through experimental work, SEM, finite element analysis and failure theories. In this research work, feasibility of ASTM standard D6641 is investigated for testing of 3D FRP composite. A 3D finite element model is developed in ABAQUS with homogeneous orthotropic laminate to investigate the failure stress state in the gage section of the test specimens. Two failure theories are considered for failure investigation that is fully interactive three dimensional Tasi Wu failure criteria and limit criteria (maximum stress criteria). SEM is carried out to investigate the failure mechanisms and failure location in the specimens. Experimental results shows that the compressive strength of 3D FRP composite is less as compared to 2D FRP composite, also standard deviation (SD) and coefficient of variance (COV) of 3D FRP composite is high. This paper highlights the problems associated with the use of ASTM D6641 for 3D FRP composite, and internal failure mechanisms in 3D FRP composite using compression through combine end and shear loading.

Key words: 3D fiber reinforced polymeric (FRP) composites, 2D FRP composite, ASTM D6641, finite element analysis.

INTRODUCTION

Composite materials are one of the widely used materials because they are lighter, stronger and corrosion resistant. Composite materials have been designed to perform load bearing function by providing desirable combination of high specific strength and specific stiffness. These desirable properties can be achieved through different stacking sequences of lamina and through manufacturing techniques.

2D FRP composite have fibers in two directions, that is, warp and weft fibers (Figure 1a). Application of 2D FRP composites are restricted in many composites structures which are to be designed to support transverse load. In addition, 2D FRP composites have low through-thickness properties, high manufacturing cost, less delamination (that is, Separation of layers) and impact resistant, low strain-to-failure and inter laminar fracture toughness and they are expensive in thick laminate applications (Fredrik, 2009). To overcome this weakness of 2D FRP
Figure 1. Composites types based on fiber reinforcement (Rudov-Clark and Mouritz, 2008). a. 2D FRP composite, b. 3D FRP composite.

Composites, 3D FRP composites are developed. The basic concept of 3D FRP composite is that, it has reinforcement in the third direction also called warp weaver along with warp and weft fibers (warp weaver binds the warp and weft fibers together to increase though thickness properties (Figure 1b).

Motivation for 3D FRP composite is that it has high delamination resistance for applications where significant shear is expected. Furthermore, not all application of composites are necessarily thin shell type, so thicker laminates required laying up many layers which is expensive and defect prone, that is, cost/quality issue. 3D FRP composite have great potential in light weight aerospace structures and in industrial applications (Liyoung et al., 2002). But the major roadblock in using 3D FRP composite material is the lack of suitable testing method and standard to determine their mechanical properties.

The aim of this research work is to develop a reliable testing standard for compressive testing of 3D FRP composites. The specific aim of this research work is to check the feasibility of ASTM standard D6641 for testing of 3D FRP composites. This research work explores the differences in compression testing of 2D and 3D FRP composites through: a) Review of existing literature. b) Performing experimental testing for both 2D and 3D FRP composites based on ASTM standard D6641 (compression through combined end and shear loading) and investigating the resulting failure mechanism using SEM (Scanning Electron Micrograph). c) Simulating the ASTM D6441 test using Finite Element Analysis and analysing and comparing the failure stress state in the specimens for both 2D and 3D FRP composites. Drawing conclusion about the suitability of ASTM D6441 for its use with 3D fiber reinforced composites and making recommendations for further work in this area.

In this literature, it is found that the compressive properties of 3D FRP composite is lower than the 2D FRP composite (Brandt et al., 1996; Farley et al., 1992; Guess and Reedy, 1986), but 3D FRP composite posses high strain to failure ratio as compared to 2D FRP composite, which makes 3D FRP composite much more ductile material than 2D FRP composite (Figure 2a). This reduction in the compressive properties is mostly because of the fibers crimping due weft yarn and warp weaver.

Under compression load bearing yarn starts kinking, this is observed by (Cox et al., 1994 and 1992; Kuo and Ko, 2000). Kink band formation in 3D FRP composite is different from 2D FRP composite, in 3D FRP composite, the kink band forms at the outer most surface yarn, where crimping is excessive due to warp weaver. It is observed that two kink bands forms due to pinching of surface yarn (Figure 2b), when surface yarn breaks, its stiffness reduced but it prevents other yarn from buckling. So, 3D FRP composite failed at different locations as compare to 2D FRP composite where kink band forms in plane causing failure (Figure 2c). As 3D FRP composite failed at different location by increasing load, so it possesses high strain to failure.

Up till now, a number of testing standards have been developed for the compression testing of 2D FRP composite, these standards have been used by various researchers and showed good repeatability and agreements with the theoretical predictions. Different ASTM standards used for compression testing of 2D FRP composite along with loading schemes are shown in Figure 3. These standards however, cannot be used for 3D FRP composite because the same test may result in a different internal stress state for 3D FRP composite as opposed to achieved stress state in 2D FRP composite.

Different researchers have used available 2D FRP composite standards for 3D FRP composite, but the results obtained through these test showed higher standard deviations coefficient of variance. On the basis of literature surveys major findings in the development of
FIGURE 2. Failure in 2D and 3D FRP composite under compression (Liyoung et al., 2002). a. Compressive stress Vs stain% b. Fiber kinking in 3D FRP composite c. Kink band formation in 2D FRP composite.

FIGURE 3. Schematic diagram of loading scheme in different ASTM standards for compression testing of 2D FRP composite (D6641, D3410), (a) End Loading ASTM D695 (b) Shear Loading ASTM D3410 (c) Combined End and Shear Loading ASTM D6641.

3D FRP composite testing standards are:

i. In-homogeneity of local displacement field (Kuo et al., 2003);
ii. Different failure modes occurring simultaneously in 3D FRP composite (Callus et al., 1999);
iii. Standard deviation (SD) and Coefficient of Variance (COV) variation in result data (Mahadik et al., 2011; Gerlach et al., 2012);
iv. Existing specimen size, loading configurations and test methods being used do not provide required failure stress state within the specimen (Harper et al., 1993; Seng, 1992);
v. Non availability of validated test methods for properties predictions.

EXPERIMENTAL WORK

The Standard whose feasibility for the testing of 3D FRP composite is considered as ASTM D6641 (ASTM D6641), in this test method compressive stress is introduced into specimen through combined end and shear loading. It is a well developed standard for testing of 2D FRP composites (Unidirectional and Bidirectional composites); it is used to measure compressive modulus, poisons ratio, ultimate compressive strength, and ultimate compressive strain. In this study, ASTM D6641 is used for testing of 3D FRP composite, in the same way it is used for 2D FRP composite, that is, testing procedure, test setup, loading conditions, testing environment, room temperature and load rate is same. Figure 4 shows ASTM D6641 test fixture, it consists of four grips and two alignment rods. These grips also act as antibuckling guides, these guides prevents the specimen from buckling and efficiently transfer entire load in the gage section.

In this test, compressive stress is introduced into the specimen through axial loading, which is then transferred into the specimen in a form of shear load (along the specimen’s surface) and end load (at specimen’s ends) through grips. Grips hold the specimen and apply shear load through friction between grips and specimen. In order to apply uniform shear force on specimens surface, the grips must be perfect smooth, because of low coefficient of friction of grips extra clamping force is required which may damage the specimen between grips. So tabbed specimen along with rough surface grips are used which required less clamping force and avoids damage of specimens between grips. Tabbed specimens
are used to avoid specimen crushing between guides and stress concentration (Nisitan et al., 2003; Anthoine et al., 1998). The acceptable and unacceptable compressive failure modes according to the ASTM D6641 standards are shown in Figure 5.

Materials used

Both specimens and tabs material for 2D FRP composite is bi-directional E-Glass plane weave. For 3D FRP composite specimens are made with 3D fiber reinforced angle-interlocked E-Glass woven composites and tabs are made with bi-directional E-Glass plane weave. The matrix used is 5052 (Araldite 5052 and Aradur 5052), which is an epoxy based system mixing ratio of Araldite/Aradur used is 100/38 parts by weight.

Specimens’ dimensions

Specimens and tab panels for 2D and 3D FRP composite are manufactured through vacuum infusion technique to achieve uniformity and less void contents. After resin completely infused through the panels, it is left for curing for 15 h at 50°C. Specimen and tab dimensions for both 2D and 3D FRP composite are shown in Table 1 and Figure 6.
Table 1. Specimen Dimension Along with Tab.

<table>
<thead>
<tr>
<th>Description</th>
<th>Dimension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen thickness (St)</td>
<td>1.8</td>
</tr>
<tr>
<td>Specimen length (L)</td>
<td>140</td>
</tr>
<tr>
<td>Tab thickness (Tt)</td>
<td>2</td>
</tr>
<tr>
<td>Specimen and tab width (W)</td>
<td>13</td>
</tr>
<tr>
<td>Tab tapper angle (T_A)</td>
<td>20° - 30°</td>
</tr>
<tr>
<td>Gauge length (G_L)</td>
<td>12.7</td>
</tr>
</tbody>
</table>

Figure 6. Specimen geometry with tabs. Specimen thickness (St), Specimen length (L), Tab thickness (Tt), Specimen & tab width (W), Tab tapper angle (TA), Gauge length (GL).

Figure 7. Failure Modes in 2D and 3D FRP composite, LAB = Lateral At Tab Bottom, LGM = Lateral Gage Middle, LGT = Lateral Gage Top, LAT = Lateral At Tab Top. a) 3D FRP composite compression test specimen b) 2D FRP composite compression test specimen.

Experimental results

For comparison of compressive properties and internal failure mechanisms, both the 2D and 3D FRP composite specimens are made with same dimension and tested according to the ASTM D6641. Load rate used in testing is 0.5 mm/min and test is carried out at 18°C. Figure 7 shows tested specimens along with the failure modes, all
Figure 8. Load deflection curves of 2D and 3D FRP Composite. S1=Specimen 1, S2 = Specimen 2, S3 = Specimen 3, S4 = Specimen 4, S5 = Specimen 5, S6 = Specimen 6. (a) 3D FRP composite (warp yarn along length) (b) 3D FRP composite (weft yarn along length) (c) 2D FRP composite.

specimens failed in the gage section which is an acceptable failure. Load deflection curve of 2D and 3D FRP composite tested specimens are shown in Figure 8. Table 2 shows experimental results of 2D and 3D FRP composite, In 3D FRP composite warp and weft direction of yarns are very important, because in weft direction only weft yarns are along the length whereas in warp direction both warp yarn and warp weaver are along the length. The compressive properties and internal failure is different in both directions, so 3D FRP composite specimens are made in both directions. Table 2 shows that 2D FRP composite failed at average failure load of 6004 N, and average compressive strength in the loading direction (S22) is about 266 MPa. The results show that the compressive properties of 3D FRP composite are less as compared to 2D FRP composite, this is due to fiber crimping caused by the warp weaver and complex weave architecture. Table 2 shows that the compressive strength of specimens with warp yarns along the length is 205 MPa which is more as compared to weft yarn along the length having 176 MPa. This is because in warp direction both the warp weaver and warp yarn takes the load, so the additional warp weaver in warp direction increases the compressive strength.

SCANNING ELECTRON MICROGRAPH (SEM) INVESTIGATION

In order to investigate internal failure mechanisms in 2D and 3D FRP composite, SEM is carried out to enhance visual observation and to identify the internal failure mechanisms. For SEM images, specimens’ desired location is coated with carbon layer to get clear image.
Table 2. Summary of experimental results.

<table>
<thead>
<tr>
<th>Fabric type</th>
<th>Average failure load (N)</th>
<th>Average comp strength (MPa)</th>
<th>Standard deviation (SD)</th>
<th>Coefficient of variance (COV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D FRP composite (Average of five samples)</td>
<td>6004</td>
<td>266</td>
<td>8.1</td>
<td>3.04</td>
</tr>
<tr>
<td>3D FRP composite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warp yarn along length</td>
<td>4356</td>
<td>205</td>
<td>19.2</td>
<td>9.36</td>
</tr>
<tr>
<td>(Average of five samples each)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weft yarn along length</td>
<td>4137</td>
<td>176</td>
<td>16.2</td>
<td>9.2</td>
</tr>
</tbody>
</table>

Figure 9. Failure in 2D FRP composites (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.

2D FRP composite

Figure 9 shows failure in 2D FRP composite. Figure 9a shows failure and delamination (separation of layers) at top and bottom face of the specimen. Figure 9c and d show magnified image of top and bottom face which identifies fiber micro buckling after matrix cracking. Figure 9b shows fiber kinking a different location.

3D FRP composite

Both 3D FRP composite specimens are investigated, that is, warp yarn along the length and weft yarn along the length.

3D FRP composite (warp yarn along length)

Figure 10 shows failure in 3D FRP composite specimens with warp yarn along the length. In this case, both warp weaver and warp yarn are along the length. As compared to 2D FRP composite, there is no fiber micro buckling found at the top and bottom face due to influence of warp weaver (Figure 10b). In 2D FRP composite delamination is found under compression but in 3D FRP composite
when failure starts, it is arrested by warp weaver and prevents further damage at that location (Figure 10a). As in these specimens, both warp weaver and warp yarn are along the length so they have higher compressive strength as compared to specimens which have only weft warp yarn along specimen length.

3D FRP composite (weft yarn along length)

Figure 11 shows failure locations of specimens with weft yarns along the length. In this case, only weft yarns are along the length, so compressive strength in this case is less. Figure 11a shows fibers kinking at various location inside the specimen and fiber breaking at top and bottom surface due to the influence of warp weaver. No Delamination is found in this case because; warp weaver binds the layers together. Figure 11b shows kink band formation at different locations. The dominant failure mode of 3D FRP composite in this arrangement is due to kinking at different location at different loads.

Finite element analysis

ASTM D6441 test is simulated by using finite element analysis in ABAQUS to analyze and compare the failure stress state of 2D and 3D FRP composite specimens. To
achieve this, implicit finite element analysis is carried out in ABAQUS based on homogeneous orthotropic laminate. Homogeneous orthotropic laminate is considered because 2D FRP composite can be modeled as laminate (ply’s stacking together to form laminate) whereas 3D FRP composite cannot be modeled with ply’s due to influence of warp weaver, as it required approximation in order to model it in a form of layer. After approximation properties of each layer can be calculated through unit cell model, which is then used to calculate laminate properties, this is a very extensive exercise and requires complete study. Failure stress state is investigated in the gage section of the specimen that is along length, width and through thickness at macroscopic scale. Load applied in the analysis is taken from experimental work (failure load) and effective material properties are used.

**Boundary conditions**

Symmetry boundary conditions are applied in ABAQUS. Specimen along with tabs is modeled with geometric symmetry in two planes, that is, Y-symmetry and Z-symmetry as shown in Figure 12. With this symmetry conditions quarter model is analyzed, which reduced the computational time. Each Y and Z symmetry condition has six degree of freedom three translational (U1, U2, U3) and three rotational (UR1, UR2, UR3) along X, Y and Z axis (Table 3).

**Table 3. Symmetry BC’s applied in ABAQUS.**

<table>
<thead>
<tr>
<th>Symmetry</th>
<th>U1</th>
<th>U2</th>
<th>U3</th>
<th>UR1</th>
<th>UR2</th>
<th>UR3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-symmetry</td>
<td>Free</td>
<td>Constrained</td>
<td>Free</td>
<td>Constrained</td>
<td>Free</td>
<td>Constrained</td>
</tr>
<tr>
<td>z-symmetry</td>
<td>Free</td>
<td>Free</td>
<td>Constrained</td>
<td>Constrained</td>
<td>Constrained</td>
<td>Free</td>
</tr>
</tbody>
</table>

**Applied load**

Compressive load is applied on the specimen according to the ASTM D6641 (ASTM D6641). Load is applied on the un-tapered tab surface and at the end of specimen simultaneously (Figure 13). To simulate compressive load applied by the fixture grips on the specimen, a shear surface traction is applied on untapered tab surface and end load is applied on the specimens end parallel to the fixture grips. In finite element analysis in ABAQUS 2/3 of the load is transferred on the un-tapered tab surface through shear surface traction and 1/3 of the load is transferred through the end of the specimen (Seng, 1992; U.S. Department of Federal Aviation Administration, 2002). This end load and shear surface traction is shown in Figure 12.

**Element type**

In this analysis, 3D solid elements C3DR are used. C3DR is an eight node brick element having eight nodes in the corner. These elements perform linear interpolation in all three directions. For comparison of 2D FRP composite with 3D FRP composite solid elements are used. In shell element, the authors are ignoring through thickness properties by considering thickness is very small, but here authors want to study the through thickness properties and stress variation.

![Figure 12. Schematic diagram of BC’s applied in ABAQUS.](image)
Table 4. Material properties of 2D and 3D FRP composite (Ye hia and Mohammed, 2008; Tan et al., 2000).

<table>
<thead>
<tr>
<th>Material</th>
<th>E1 (GPa)</th>
<th>E2 (GPa)</th>
<th>E3 (GPa)</th>
<th>V12</th>
<th>V13</th>
<th>V23</th>
<th>G12 (GPa)</th>
<th>G13 (GPa)</th>
<th>G23 (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D FRP composite</td>
<td>18.7</td>
<td>18.7</td>
<td>10.8</td>
<td>0.104</td>
<td>0.155</td>
<td>0.155</td>
<td>6.4</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td>3D FRP composite</td>
<td>20</td>
<td>24</td>
<td>18.5</td>
<td>0.138</td>
<td>0.18</td>
<td>0.18</td>
<td>2.76</td>
<td>4.44</td>
<td>4.44</td>
</tr>
</tbody>
</table>

Table 5. Comparison of FE and experimental results.

<table>
<thead>
<tr>
<th>Material</th>
<th>Applied Load (N)</th>
<th>Experimental Results S22 (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D FRP composites</td>
<td>6004</td>
<td>266</td>
</tr>
<tr>
<td>3D FRP composites</td>
<td>4356</td>
<td>205</td>
</tr>
</tbody>
</table>

Material properties

Constitutive material model for orthotropic materials used to calculate stress in finite element analysis is given in Equations 1 and 2 (Mahmood, 2010)

\[ \{\varepsilon\} = [K] \{\sigma\} \]

\[ \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{12} \\ \gamma_{13} \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_1} & \frac{-v_{12}}{E_2} & \frac{-v_{13}}{E_3} \\ \frac{-v_{12}}{E_1} & \frac{1}{E_2} & \frac{-v_{23}}{E_3} \\ \frac{-v_{13}}{E_1} & \frac{-v_{23}}{E_2} & \frac{1}{E_3} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{12} \\ \tau_{13} \\ \tau_{12} \end{bmatrix} \]

Finite element results

Failure in 2D and 3D FRP composite is caused by the compressive stress $S_{22}$ which is desired. Investigation of stress variation at different locations in the gage section shows uniform stress distribution and maximum compressive stress is found in the gage section. Stress concentration effects are only present at tab taper end as expected, and it does not contribute in specimen failure. At some locations, mixed stress state (shear, tensile and compressive) is present due to $S_{11}$ (Stresses along x-direction) and $S_{22}$ (Stresses along Y-direction) which is not significant. The maximum compressive stress found in the gage section due to applied load is shown in Table 5. This analysis is an exploratory analysis not a predictive analysis, just to see the internal stress state due to applied load (Not predicting or validating the compressive strength).

Failure stress state in 2D FRP composite

The compressive stresses developed in the gage section due to applied load are around 256 MPa. The maximum compressive stress developed in the specimen is
488 MPa which is due to stress concentration, but it will not contribute in specimen failure (Figure 14a). Figure 14b shows stress variation along length and width of the gage section. Stress paths are plotted at different locations to see stress variation. Stress path plots at different locations shows uniform stress distribution.

Failure stress state in 3D FRP composite

Compressive stresses developed in the gage section due to applied load are around 190 MPa. The maximum compressive stress developed in the specimen is 344 MPa which is due to the stress concentration, but it will not contribute in specimen failure (Figure 15a). Figure 15b shows stress variation along length and width of the gage section.

Comparison of FE and experimental result

Table 6 shows comparison of experimental and finite
Figure 15. Stress variation in 3D FRP composite, (a) Stress concentration in 3D FRP composites (b) Stress variation at different locations in 3D FRP composite.

element analysis results of 2D and 3D FRP composite. The difference between FE and experimental results is less which is expected because effective material properties are used and applied load is the failure load taken from experiments. The compressive strength of 3D RFP composite obtained from FE analysis is an effective compressive strength because material properties used are parallel to material axis but fabric used is angle interlocked where warp weaver is at an angle.

FAILURE ANALYSIS

In order to predict failure, two different failure theories are considered, that is, fully interactive three dimensional Tasi Wu failure criteria and limit criteria (maximum stress). Shear and normal stresses which are obtained from FE analysis are used to predict failure in specimens. Strength properties (Compressive strength $X_c$, $Y_c$, $Z_c$, tensile strength $X_t$, $Y_t$, $Z_t$ and in plane shear strength $S_{13}$, $S_{12}$, $S_{23}$) of materials used to predict failure region
Table 6. Comparison of FE and experimental results.

<table>
<thead>
<tr>
<th>Material</th>
<th>Compressive stress at failure load</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FE analysis (MPa)</td>
<td>Experimental results (MPa)</td>
</tr>
<tr>
<td>2D FRP composite</td>
<td>256</td>
<td>266</td>
</tr>
<tr>
<td>3D FRP composite</td>
<td>190</td>
<td>205</td>
</tr>
</tbody>
</table>

Table 7. Strength properties of 2D and 3D FRP composites.

<table>
<thead>
<tr>
<th>Material</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X_T</td>
</tr>
<tr>
<td>2D FRP composite</td>
<td>328</td>
</tr>
<tr>
<td>3D FRP composite</td>
<td>350</td>
</tr>
</tbody>
</table>

Three dimensional Tasi Wu criteria

According to this failure criteria specimen of orthotropic laminate failed when Equation 3 is satisfied (Isaac et al., 2008):

\[ F_1 S_{11} + F_2 S_{22} + F_3 S_{33} + F_{12} S_{11} S_{22} + F_{13} S_{11} S_{33} + F_{23} S_{22} S_{33} = 1 \]

Equation 3 consist of six stress components and twelve constants, which includes three normal stress components \((S_{11}, S_{22}, S_{33})\), three shear stress components \((S_{12}, S_{13}, S_{23})\) and twelve constants which are determined from unidirectional test, these constants are:

\[
\begin{align*}
F_1 &= \frac{1}{\gamma_{11}^2} - \frac{1}{\gamma_{12}^2} \\
F_{11} &= \frac{1}{\gamma_{11}^2} - \frac{1}{\gamma_{12}^2} \\
F_{12} &= -\frac{1}{2\gamma_{12}^2} \\
F_2 &= \frac{1}{\gamma_{22}^2} - \frac{1}{\gamma_{12}^2} \\
F_{22} &= \frac{1}{\gamma_{22}^2} - \frac{1}{\gamma_{12}^2} \\
F_{23} &= \frac{1}{\gamma_{23}^2} - \frac{1}{\gamma_{13}^2} \\
F_3 &= \frac{1}{\gamma_{33}^2} - \frac{1}{\gamma_{13}^2} \\
F_{33} &= \frac{1}{\gamma_{33}^2} - \frac{1}{\gamma_{13}^2} \\
F_{31} &= -\frac{1}{2\gamma_{13}^2} \\
F_{44} &= \frac{1}{\gamma_{44}^2} - \frac{1}{\gamma_{23}^2} \\
F_{55} &= \frac{1}{\gamma_{55}^2} - \frac{1}{\gamma_{33}^2} \\
F_{66} &= \frac{1}{\gamma_{66}^2} - \frac{1}{\gamma_{23}^2}
\end{align*}
\]

Max stress criteria

Maximum stress criteria is one of the oldest and easiest failure criteria, it is used for multi-dimensional woven laminates. According to this failure criterion if principle stress in compressive direction, that is, \(S_{22}\) is greater than compressive strength in that direction then failure occur. This failure criterion is a non-interactive failure criterion having no interaction between failure modes, which means that specimen under combine loading or uni-axial loading is same. This failure criteria accurately tells us weather failure is due to compression or tension (Mahmood, 2010):

\[ S_{22} \geq X_T \tag{5} \]

Failure theories results

Figure 16 shows comparison of element failure predicted by Tasi wu failure criteria in 2D and 3D FRP composite. A Tasi Wu failure criterion is an interactive failure criterion (interaction of normal and shear stresses). Figure 16a shows elements failed in the gage section of 3D FRP composite due to influence of warp weaver. In 3D FRP composite mixed stress state developed in the gage section due to crimping caused by the warp weaver and complex weave architecture, so it has less compressive strength as compare to 2D FRP composite. In 2D FRP composite less elements failed in transverse direction because there is no reinforcement in the third direction (Figure 16b), hence there is less fiber crimping and 2D FRP composite has more compressive strength. Failure predicted in 2D and 3D FRP composite due to maximum stress failure criteria shows that failure occurs in the gage section near the tab.

RESULTS AND DISCUSSION

Experimental results show that all specimens failed in acceptable failure Modes, that is, in the gage section, which is according to ASTM D6641 standard, and average compressive strength of 3D FRP composite is less as compare to 2D FRP composite. 3D FRP composite are famous for high strain to failure under
Figure 16. Comparison of failure region predicted by Tasi Wu failure criteria (a) Element failure predicted by Tasi Wu criteria in 3D FRP composite (b) Element failure predicted by Tasi Wu criteria in 2D FRP composite.

compression loading, but load deflection curve do not show such behavior. Standard deviation and co-efficient of variance for 3D FRP composite is high; this is due to non uniform internal architecture and mixed failure modes. SEM investigation shows that in 2D FRP composite, the major cause of failure is due to fiber micro-buckling, fiber breaking and kink band formation, where as in 3D FRP composite the major cause of failure is due to fiber breaking and kinking at various locations. Compressive strength of 3D FRP composite is less as compare to 2D FRP composite; the main reason for this reduction is fiber crimping caused by the warp weaver and complex weave architecture. In 3D FRP composite compressive stresses in the warp direction is more because warp weaver and warp yarn both share the applied load, where as in weft direction only weft yarn takes the whole load. This identifies that in case of 3D FRP composite compressive strength must be measured in both warp and weft direction due to the influence of warp weaver. Failure theories show that failure occurs in the gage section of the specimen which is desirable. But it does not give any detail regarding internal failure mechanisms. Based on experimental work, SEM investigation and finite element analysis; it is clear that ASTM D6641 is not suitable for testing of 3D FRP composite because SD and COV is high. Further load deflection curves do not show high stain to failure as expected.

Future recommendations

Micro-mechanics model
In finite element model specimen is modeled with homogeneous orthotropic material which can identify maximum stress location and stress variation pattern but it does not give any detail regarding internal failure mechanisms. For this purpose micro mechanics model is required for detailed FE analysis, it will also helpful in determining material properties of 3D FRP composite.

Advance failure theories for 3D FRP composite
More advanced failure theories such as LARC04 (Langely Research Center) can be applied to predict failure in 3D FRP composites, because it includes fiber misalignment plane and kink band angle to determine kink band formation in composites. This failure criterion can be implemented in FE analysis which can effectively identify fiber and matrix failure along with failure modes.

Modification in specimen size
Specimen size given in ASTM D6641 standard is not suitable for compression testing for 3D FRP composite. Specimen size for 3D FRP composite requires modification as compared to 2D FRP composite, because when the warp weaver is along the width of specimens then at least one complete cycle of warp weaver must be present along the width of the specimen.

Properties determination for available material
There is a need to determine all material properties of available 3D FRP composite for detailed FE analysis.

Validation of compressive strength with other standard
In this present work, ASTM D6641 is considered for
determination of compressive strength of 3D FRP composite, for validation other compression testing standards such as D3410, D695 can be used.

Conflict of Interest

The authors have not declared any conflict of interests.

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ASTM D6641, Standard test method for determining the compressive properties of polymer matrix composites laminates using a combined loading compression (CLC) test fixture.