EXPERIMENTAL ASSESSMENT AND NUMERICAL ANALYSIS OF 3D WOVEN COMPOSITE T-JOINTS UNDER TENSILE LOADING

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Keywords: 3D woven composites, T-joints, Tensile properties, Meso-scale model, Finite element

ABSTRACT

This paper presents the experimental assessment and numerical analysis of the mechanical properties of 3D woven composite T-joints subjected to a pull-off loading scenario. Mechanical pull-off tests were performed on two types of 3D woven composite T-joint specimens with variation in weave pattern, as well as one type of 2D woven specimen for the purpose of comparison, all of which are made of carbon fibre/epoxy resin. Digital Image Correlation was used to monitor the full-field strains on the junction regions of all the specimens. Failure onset, stiffness and ultimate strength are discussed in the experimental results alongside failure mechanisms. The second type of 3D woven T-joint outperformed the other two in ultimate strength and damage tolerance, though the 2D woven T-joint was found to have higher stiffness and initial failure load due to its higher fibre volume fraction. The assessment demonstrates that using 3D woven reinforcements is an effective way to improve the damage tolerance of composite T-joints under tensile loading, and also this potential improvement could be optimised with regard to fibre architecture. As the reinforcement geometry plays an important role in determining the composite’s mechanical properties, geometric model is proposed to capture the realistic deformation in the 3D preform. Based on the realistic geometry, finite element analysis gives predictions in comparison with the experimental data on a selected 3D woven T-joint.

1 INTRODUCTION

3D woven composites have drawn great attention in recent decades for their advantages such as higher through-thickness properties that can overcome the weakness in delamination resistance encountered by 2D laminates. The exploration of 3D reinforced composites has been also extended to load-bearing profile components like T, I, Pi shaped joints. There are three basic ways to manufacture 3D reinforced composite joints with woven preforms. The first method is to use 2D woven fabric lay-ups, reinforcing the through-thickness direction with stitching or Z-pinning[1, 2]. The second way is to weave flat 3D preforms via a standard weaving machine with variation of through-thickness binder yarn path and then fold the preforms into the desired shape[3]. The third way is to fabricate the preform directly into a complex 3D shape through a specially developed 3D weaving loom[4, 5]. Although composites reinforced by the first method can offer better damage tolerance in terms of delamination than 2D laminated joints subjected to equivalent loads[1, 6], they might be less competitive in in-plane properties because of geometric defects or fibre damage caused by retrospectively inserting through-thickness reinforcements[7]. In addition, due to the high investment and innovation needed for developing a special 3D loom for the third kind of preform, 3D preforms woven by a conventional loom are commonly used for current composite T-joints.

Some studies have demonstrated that the using 3D woven reinforcement for composite T-joints offers some improvements in their mechanical properties under bending and in-plane tension[3, 6]. This paper experimentally evaluates the performance of two types of 3D woven composite T-joints made of carbon fibre/epoxy matrix under a tensile pull-out loading case in terms of failure initiation, stiffness and damage tolerance of the specimens, as well as one 2D woven T-joint for comparison. Investigation is furthered by focusing on the effect of weaving variation in the fibre architecture on the
failure modes and loads of the T-joints. To characterise the relationship between the fibre architecture and mechanical performance, geometric modelling of one selected 3D woven T-joint is proposed by analytical approximation of the observed geometric features. Finite element analysis gives predictions in comparison with the experimental data on the selected 3D woven T-joint based on the realistic geometry.

2 FABRICATION OF THE T-JOINT SPECIMENS

Vacuum-assisted RTM was used for moulding the composite T-joint. The 2D woven specimens are made of 6 layers of 2×2 twill weave IM7 carbon fibre fabrics with an areal density of 660g/m² and a filament count of 12K infused with Prime 20LV epoxy resin, corresponding to a fibre volume fraction(VF) of 56% with dimensions of 4mm thick in the web and 2mm thick in the flange. Two types of 3D woven composite T-joint specimens with the same VF of 45% were moulded in the same way as the 2D woven specimen, all of which are made of the same carbon fibre/epoxy. The preforms are based on 3D orthogonal weave with only variance in the junction, which are woven flat and folded into a T shape. The directions of warp, weft and binder yarns are marked in Figure 1. The preform consists of 8 layers of warp yarns and 9 layers of weft yarns in the web and 5 layers of warp yarn and 4 layers of weft yarns in the flange. Figure 1 from micro computed tomography(µCT) shows the weave pattern, Type 2, where half of the weft yarns are crossing over the other half at the T-junction, in comparison with Type 1.

![Figure 1 Images from µCT scan of the two types of 3D preform showing the weave variation in the junction region: (a) Type 1; (b) Type 2](image)

3 EXPERIMENT METHODOLOGY

All three types of the T-joint specimens were cut and tested under a tensile pull-off load. A displacement load at a constant rate of 1mm/min was applied on the web of the specimen through the 50kN Instron 5581 testing machine, of which the flange was clamped at the two ends by the fixture as demonstrated in Figure 2. A minimum of 4 specimens were tested for the 2D and 3D woven specimens respectively under the constant laboratory atmosphere. Specimens were painted on the front cross-sections before tests and Digital Image Correlation(DIC) was used to monitor the full-field strains on the junction regions of all the specimens.

![Figure 2 Test layout for the tests of composite T-joints](image)
4 TEST RESULTS AND DISCUSSION

4.1 Load-displacement responses of the T-joints

Load-displacement relationships for the three types of composite T-joints under tensile load are plotted in Figure 3(left). Both linear response in load-displacement curves and stiffness degradation can be observed in the tests. Each of the curves demonstrates the failure progress of one typical T-joint and can be divided into three stages in terms of the failure: 1) from the start of loading to the first load drop that presents the linear stiffness and failure onset of the T-joint; 2) from the first load drop to the peak load showing ultimate strength of the structure and its capacity in damage tolerance; 3) from peak load to final failure load showing the final extension on the T-joints needed to completely destroy the structure.

Figure 3 Left, load-displacement curves for the three types of composite T-joints; Right, linear response at the first failure stage for the T-joints

4.2 Failure initiation and stiffness of the T-joints

Figure 3(right) enlarges the initial linear section of the curves that presents the failure initiation load and stiffness of the structure. Initial and ultimate failure loads and their standard deviations from the tests are listed in Table 1. It shows that the 2D woven T-joint has the highest initial failure load at approximately 1128N from where a significant load drop can be observed on the curve, as well as a higher stiffness. This can be attributed to the high VF in the 2D woven T-joint but also shows that a 3D woven T-joint probably cannot offer obvious advantage on the above two properties. Limitations on the uniformity of VFs lead to the absence of direct comparisons between 2D woven and 3D woven T-joints. Although the two types of 3D woven joints present the same initial stiffness as they have the same VFs, the initial failure load of type 2 T-joint is 37.7% higher than that of the other type, which results from the weave variation in the junction regions. This finding that failure initiation of the 3D woven composite T-joints can be improved by varying fibre architecture is significant as the design of reusable aerospace structures is usually based on initial failure load.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Initial failure load/N (SD)</th>
<th>Ultimate failure load/N (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D woven</td>
<td>1128(±44)</td>
<td>1620(±88)</td>
</tr>
<tr>
<td>3D Woven Type1</td>
<td>710(±93)</td>
<td>2338(±152)</td>
</tr>
<tr>
<td>3D Woven Type2</td>
<td>978(±59)</td>
<td>4951(±234)</td>
</tr>
</tbody>
</table>

Table 1 Initial and ultimate failure loads of the three types of specimens

4.3 Ultimate failure loads and damage tolerance

3D woven composite T-joints show a significant improvement in the damage tolerance after initial failure over 2D woven T-joints in the tensile tests. It is observed that the peak failure load of the first type of 3D woven specimens is improved by 44.3% over the 2D woven specimens, and the peak
failure load of the second type of 3D woven specimens is 205.6% higher than that of the laminate as presented in Table 1. The non-linear behavior of the composite T-joints in load-displacement relationship is evident after the damage onset. The 2D woven T-joints show a greater degradation in stiffness after the initial failure as well as a lower failure extension than the 3D woven T-joints. This is partially explained by the absence of z-directional reinforcement that can prevent the propagation of damage. Moreover, specimens of the type 2 3D woven T-joints exhibit a higher stiffness post-failure compared with type 1 specimens, which is a desirable property in engineering applications. Strain distributions at a similar load after the failure onset of the types of 3D woven T-joints in Figure 4 reveal the possible reason for the high damage tolerance in type 2 weave. It is found that the weave variation in type 2 alleviates strain concentration in the junction region to a large extent therefore the resistance to damage is accordingly improved.

![Figure 4 DIC images showing maximum principal strain distributions of 3D woven T-joints type 1(a) and type 2(b) at a load of 1079N for (a) and 1089N for (b) respectively](image)

4.4 Characterisation of failure modes

Failures initiated in the junction regions of the three types of T-joint specimens and Figure 5 shows the failure propagation progress in those regions respectively, and all the tests ended by specimens rupturing at the edges of clamps in the flange due to stress concentrations. A thin crack in resin-yarn interface was experienced in the 2D woven specimen when the initial failure occurred and then the increasing load caused several obvious cracks in the junction until it reached the T-joint’s ultimate strength. After that the T-joint can no longer withstand further loading and delamination propagated widely to the web and flange of the T-joint until fracture happened. The main failure mode for 2D woven structures is delamination as detailed in previous studies and thus it is only briefly discussed in this paper.

Matrix-fabric debonding shown in Figure 5 Stage 2, was observed to be the dominant failure mode for the type 1 3D woven specimen and the 2D woven specimen. However in Stage 3, the binder yarns around the junction region limited the propagation of the delamination into the web and flange which led to a higher ultimate strength. This comparison with 2D woven specimen in terms of failure mechanism can obviously demonstrate the effect of the binder yarns in 3D woven composites on decreasing the extent of delamination. Post-mortem µCT scan was carried out to characterise the failure modes in the 3D woven T-joints. Additionally, transverse cracking in warp yarns, fibre fracture in binders and weft yarns, and matrix cracking were also experienced by the type 2 T-joint as shown in Figure 6. Moreover, section views at A-A and B-B in Figure 6 further show the benefit of binder yarns in reducing delamination. Unfortunately, accurate sequence of the damage events is not available due to the lack of in-situ µCT scan during the tests.
The type 2 3D woven T-joint has revealed a different failure mode in the test. Resin cracking was first observed at the fillets of the specimen as two resin-rich regions were formed there because of weave pattern as presented in Figure 7. After that the cracking kept growing until fractures happened in the flange near the clamps. Minor delamination, transverse and directional fibre ruptures were found in the µCT scan of failed specimen. Varying weave pattern is found to be an essential way to change failure modes of the T-joints which corresponds to a different load-displacement response. It is also concluded from the tests that delamination in composite T-joints can be considered as a catastrophic failure as the specimen without dramatic interfacial debonding absorbs more energy than those that failed because of delamination. In addition, the extent of non-linearity in the load-displacement response is found to be relevant to the delamination in the specimens, as the 3D woven type 2 specimen shows a more linear behavior than the other two.

This experimental assessment demonstrates that using 3D woven reinforcements is an effective way to improve the damage tolerance of composite T-joints under tensile loading, and also this potential improvement could be optimised with regard to reinforcement fibre architecture.

5 GEOMETRIC MODELLING FOR THE 3D T-JOINT TYPE 1

Models considering realistic geometry of the reinforcements of a 3D orthogonal woven composite were numerically analysed by Green et. al[8] and results showed that it can produce more accurate prediction in terms of stiffness and strength, when compared with idealistic models. Since the as-woven yarn lengths for the 3D preform are not identical with those when folded, it deforms when the flat woven preform is moulded into a 3D shape. Three types of fibre architecture features were characterized based on the µCT image analysis.
Figure 6 Failure behavior in 3D woven specimen type 1

Figure 7 Failure behaviours in 3D woven specimen type 2
5.1 Warp yarn shift

The warp yarns within the same stack are aligned vertically with each other before folding the preform. Their relative positions are shifted afterwards. The warp yarn shift is inevitable due to the rigid body transformation in the noodle area. As illustrated in Figure 8, \( R_{1}^{w} , R_{2}^{w} \) and \( R_{3}^{w} \) are the radii of centrelines for weft yarns on layer 1, 2 and 3 respectively. As the radius of the inner surface of a T-piece is confined by the mould corner radius \( R_{m} \), we can obtain:

\[
\begin{align*}
R_{1}^{weft} & = R_{m} + \frac{H_{weft}}{2} \\
R_{2}^{weft} & = R_{1}^{weft} + D_{weft} \\
R_{3}^{weft} & = R_{2}^{weft} + D_{weft}
\end{align*}
\]

(1)

Where \( H_{weft} \) is the height of weft yarn; \( D_{weft} \) is the adjacent layer spacing of weft yarn.

Figure 8 Left, measurement of warp yarn shift in the µCT images; Middle and right, schematic view of warp yarn shift due to rigid body transformation

Assuming there is no yarn sliding, angle \( S_{\theta} \) (in radians) in can be expressed as:

\[
S_{\theta} = \frac{2(D_{warp} - d_{o})}{R_{1}^{weft} + R_{2}^{weft}} - \frac{2(D_{warp} - d_{o})}{R_{2}^{weft} + R_{3}^{weft}} = (D_{warp} - d_{o})(\frac{1}{R_{2}^{warp}} - \frac{1}{R_{3}^{warp}})
\]

(2)

Where \( D_{warp} \) is warp yarn spacing within the same layer, and \( d_{o} \) the offset distance from the centre of nearest unbent weft yarn describing the position where the weft yarns start to fold; therefore \( D_{warp} - d_{o} \) denotes the arc length in between bending onset position and bent yarn centre along the bend. \( R_{n}^{warp} = (R_{n}^{weft} + R_{n+1}^{weft})/2 \) is the radius of centreline for warp yarns on layer \( n \).

Also, the displacement shift in adjacent layers for the following stacks of weft yarns can be described as:

\[
S_{d} = \frac{\pi}{2} \left( \frac{R_{2}^{weft} + R_{3}^{weft}}{2} - \frac{R_{1}^{weft} + R_{2}^{weft}}{2} \right) = \frac{\pi}{2} D_{weft}
\]

(3)

Since the yarn shift is less significant for this preform, the shift angle measurements were only taken between yarns on layer 1 and yarns on other layers, whilst the displacement shift measurements were carried out between yarns on layer 2 and 3, as numbered in Figure 8(left). The results are shown in Table 2 in comparison with predicted values. It is noticed that the measured shift angle between layer 1 and 3 is negative, which means the warp yarn on layer 3 has slid to the flange while folding. Also it is the same with shift displacement for yarns on layer 1 and 4 in the next stack.
Warp yarn stack shift can be observed but the trend does not closely agree with the model since binder yarns influence the movement of warp yarns as well as yarn sliding induced by the weaving process.

<table>
<thead>
<tr>
<th>Measured value</th>
<th>Layer 1 and 2</th>
<th>Layer 1 and 3</th>
<th>Layer 1 and 4</th>
<th>Layer 2 and 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>-1.5</td>
<td>6.5</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>2.63</td>
<td>4.55</td>
<td>6.01</td>
<td>0.77</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Warp yarn shift measured and predicted results (10 measurements)

5.2 **Warp yarn bent cross-section**

Bent cross-sections of warp yarns were observed in the junction region as shown in the left of Figure 9. As the yarns comply with the fillet geometry of the mould surface, it is assumed that the major axis of the bent cross-sections of warp yarns follow circular paths with different radii. The cross-section of one warp yarn is presented in Figure 9 (right) prior to and after the deformation. According to the specified coordinate system, the original cross-section (the dashed line) can be defined by:

\[
C(t)_x = f(t) \quad 0 \leq t \leq 2\pi \\
C(t)_y = q(t) \quad 0 \leq t \leq 2\pi
\]

(4)

It is assumed that the bent shape is a result of a simple conformation of the major axis from the axis X to the arc in radius \( R_n^{\text{warp}} \). Thus, for each point on the upper half of the edge of a bent cross-section, the transformation can be achieved by adding \((\Delta x, \Delta y)\) to the coordinates of corresponding points on the original cross-section, where \((\Delta x, \Delta y)\) can be defined by:

\[
\Delta x = (R_n^{\text{warp}} - H_{\text{warp}} / 2) \sin\left(\frac{C(t)_x}{R_n^{\text{warp}} - H_{\text{warp}} / 2}\right) - C(t)_x \\
\Delta y = (R_n^{\text{warp}} - H_{\text{warp}} / 2)(1 - \cos\left(\frac{C(t)_x}{R_n^{\text{warp}} - H_{\text{warp}} / 2}\right))
\]

(5)

Where \( H_{\text{warp}} \) is the height of the warp yarn. Similarly, for the point on the lower half of the edge of a bent cross-section, \((\Delta x, \Delta y)\) are given by:

\[
\Delta x = (R_n^{\text{warp}} + H_{\text{warp}} / 2) \sin\left(\frac{C(t)_x}{R_n^{\text{warp}} + H_{\text{warp}} / 2}\right) - C(t)_x \\
\Delta y = (R_n^{\text{warp}} + H_{\text{warp}} / 2)(1 - \cos\left(\frac{C(t)_x}{R_n^{\text{warp}} + H_{\text{warp}} / 2}\right))
\]

(6)

Figure 9 Left, bent warp yarn in the µCT images; Right, schematic view of yarn bending
Usually the value of $H_{warp}/2$ is quite small comparing with $R_n^{warp}$, thus the above equations can be simplified and merged into one transformation for all the points on the cross-section:

$$\Delta x = R_n^{warp} \sin\left(\frac{C(t)}{R_n^{warp}}\right) - C(t)$$

$$\Delta y = R_n^{warp}(1 - \cos\left(\frac{C(t)}{R_n^{warp}}\right))$$

(7)

It is observed that a real cross-section shape can be better approximated with a super-ellipse than an ellipse, thus validation of warp yarn bending is based on the cross-section function for super-ellipse (n=0.4), where Eq. (4) can be expressed as:

$$C(t)_x = \begin{cases} \frac{\text{Yarnwidth}}{2} \cos(t) & 0 \leq t \leq 2\pi \\ \frac{\text{Yarnheight}}{2} \sin^n(t) & 0 \leq t \leq \pi \\ -\frac{\text{Yarnheight}}{2} \left(-\sin(t)\right)^n & \pi \leq t \leq 2\pi \end{cases}$$

(8)

Then the bent cross-sections for different radii can be plotted and compared with real yarns as shown in Figure 9(left). The modelled cross-section gives good agreement with realistic bent cross-section shapes.

5.3 Weft yarn flattening

In Figure 10, sectional view A-A shows the cross-sections of weft yarns at the noodle area, while B-B denotes cross-sections of weft yarns in the flat region. There was significant flattening in the weft yarns, which is caused by fibre repacking/migration due to bending of high stiffness carbon fibre around a small radius. Due to the limit in pages, the modelling of this feature is not discussed in this paper.

![Image of μCT images showing yarn flattening](Image)

Figure 10 μCT images showing yarn flattening

5.4 Geometric model

The reinforcement geometry of the 3D woven T-joint type 1 is modelled using TexGen open source software[9], based on the geometric parameters of yarns extracted from μCT analysis. Benefiting from the periodic feature of reinforcement, in this model only a unit width of the yarns was modeled along its X-axis direction, as illustrated in Figure 11. The model is comprised of three sub-geometries: the junction region representing the weave variation, the flange and the web which are tessellated by two unit cells of orthogonal weaves. This modeling strategy could be extended to the other types of 3D woven T-joints by only varying the geometry of the junction region.
6 FE MODELLING

6.1 Multiscale modelling framework

The mechanical tests have demonstrated that failure of the two types of 3D woven T-joints is observed in the vicinity of the junction, including delamination, fibre breakage and resin cracking. Consequently, a multiscale modelling method is feasible given the dimension of the specimen, in which the mesoscale model considering yarn and matrix architecture is used in the junction region for predicting the failure events and a homogenised macroscale model is utilized in the web far away from the junction as it is a region without observed damage in the test.

6.2 Mesh and boundary conditions

A voxel mesh was generated in TexGen based on the reinforcement geometry in Figure 11 providing an element size of 0.1. Periodic boundary conditions[10] in the width direction(x-axis) were used whereas the height and length of the FE model are equivalent to those in the experiment as shown in Figure 2. Homogenised hexagon and wedge elements with effective material properties from a web unit cell of the T-joint were added to the voxel mesh satisfying displacement continuity in the interface. There is a gradual increase in the sizes of homogenised elements from the interface to the clamped edge in order to improve the computation efficiency as Figure 12 shows.
6.3 Constituent material properties

It is common to use an averaged intra-yarn VF by preserving the overall VF of the composite based on the yarn’s VF in the specific geometry model to calculate the yarn properties, though the intra-yarn VF may vary in different yarns or regions[11]. In this model, the properties of yarn that is considered as transversely isotropic are calculated based on the Chamis model[12], whereas the intra-yarn VF is 71.9% corresponding to an overall VF of 45% in the composite. Effective properties of the homogenised bulk material are extracted based on FEA of the TexGen unit cell model[10]. Table 3 lists the material properties for constituents, yarn and homogenised bulk material.

<table>
<thead>
<tr>
<th></th>
<th>E_{11}(GPa)</th>
<th>E_{22}(GPa)</th>
<th>E_{33}(GPa)</th>
<th>v_{12}</th>
<th>v_{13}</th>
<th>v_{23}</th>
<th>G_{12}(GPa)</th>
<th>G_{13}(GPa)</th>
<th>G_{23}(GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon fibre</td>
<td>276</td>
<td>15</td>
<td>15</td>
<td>0.279</td>
<td>0.279</td>
<td>0.5</td>
<td>12</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>Matrix</td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yarn</td>
<td>199.4</td>
<td>10</td>
<td>10</td>
<td>0.3</td>
<td>0.3</td>
<td>0.48</td>
<td>5.1</td>
<td>5.1</td>
<td>3.4</td>
</tr>
<tr>
<td>Homogenised</td>
<td>53.8</td>
<td>61.5</td>
<td>8.3</td>
<td>0.04</td>
<td>0.4</td>
<td>0.44</td>
<td>3.2</td>
<td>5.0</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Table 3 Material properties for constituents, yarn and homogenised bulk material

6.4 Results and discussion

Due to the lack of inclusion of a damage model at present, only the initial linear stiffness from the FEA is compared with the test results at a displacement below 0.2 mm. Displacement measured from the DIC was used for calculation of the stiffness in order to improve the accuracy. As presented in Table 4, the predicted initial linear stiffness of the 3D woven T-joint is about 31% higher than that of the test. The over-predicted stiffness can be attributed to two main reasons: 1) This model used an averaged intra-yarn VF for the calculation of yarn properties without preserving the VF in each direction of warp, weft and binder yarns. 2) Coarse voxel mesh could lose the accuracy of the fibre geometry especially in the through-thickness directions of the yarns, which was found to lead to an error in the proportion of VF in each direction by a mesh sensitivity study of a unit cell model.

<table>
<thead>
<tr>
<th></th>
<th>Experiment(SD)</th>
<th>FE prediction(SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Stiffness(N/mm)</td>
<td>1736.5(222.1)</td>
<td>2278.8(-)</td>
</tr>
</tbody>
</table>

Table 4 Initial linear stiffness from experiment and FE prediction

7 CONCLUSIONS

Using 3D woven reinforcement in engineering structures has drawn great interests. This study showed that the variation in the fibre architecture for the T-joint can considerably enhance the properties such as delamination resistance, damage tolerance and total energy absorption to failure through tensile pull-out tests on two types of 3D woven T-joints. Three geometric deformations for composite T-joint were observed by μCT analysis and geometrically modelled. A mesoscale model of the fibre architecture was implemented in TexGen. Preliminary FE result for initial linear stiffness was obtained and further investigation is to be carried out on failure prediction and design optimisation of the 3D woven composite T-joint.

REFERENCES


