An evaluation of the loading direction sensitivity of 3D woven composite with novel web-shaped Z-binder architecture

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Abstract

3D orthogonal (ORT) through-thickness woven composites have excellent out-of-plane properties but exhibit inferior in-plane properties and are loading sensitive. This study proposes a novel web-shaped orientation of z-binder architecture in 3D orthogonal through-thickness model with in-plane uniform elastic moduli to address this drawback. On-axis tensile, Off-axis tensile and In-plane Shear tests were performed on the four macroscale models (ORT<sub>on</sub>, WEB<sub>on</sub>, ORT<sub>off</sub>, WEB<sub>off</sub>). The ORT model, validated by data from the literature, was used as a reference for the proposed WEB model. The overall fibre volume fraction of the WEB<sub>on</sub> and WEB<sub>off</sub> models were 7.07% and 8.67% lower than the ORT<sub>on</sub> and ORT<sub>off</sub> models. In the on-axis tensile test, the $E_x$ and $E_y$ were lower by 16.89% and 2.66% for WEB<sub>on</sub> model, but in the off-axis tensile test, they were higher by 13.75% and 13.77% for WEB<sub>off</sub> models. The $G_{xy}$ was 10.96% lower for WEB<sub>on</sub> model. The difference between the $E_x$ and $E_y$ under on-axis loading conditions was 14.81% for ORT model, whereas 0.22% for WEB model. Thus, the proposed WEB shaped z-binder architecture model outperforms the ORT model under the off-axis and is comparable in transverse loading conditions. It also possesses loading direction insensitivity, unlike the ORT model.

1. Introduction

Over the years, the development in material science, manufacturing, computers, and engineering made the adoption of composites accessible and affordable. This was due to the advanced studies on their development, which began with laminated composites, then 2D and now 3D composites. The application sectors of composites reach far and wide, including aerospace, automobile, civil, marine, sports and even leisure. The traditional laminated composites presented greater strength in the fibre direction and lacked in the transverse direction. This was addressed by stacking multiple plies at different orientations. Still, the disadvantages such as delamination failure, fibre pull-out failure, poor impact strength and labour-intensive manufacturing process made laminated composite less favourable (Clarke 1998, Stobbe and Mohamed 2003). The 2D composite (woven, braided and knitted) possesses good in-plane properties but is weak in the out-of-plane direction. These addressed the fibre pull-out and eased the manufacturing process to some extent, but when stacked to form a usable composite, they were still susceptible to delamination. The 3D woven composites are made of longitudinal yarns (warp or 0° yarn), transverse yarns (weft or fill or 90° yarn) and binder yarns. The interlacement angle of the binding yarn led to two classifications of the 3D woven composites, namely, Orthogonal (ORT) and Angle Interlock (AI), each subdivided into Layer-to-Layer (LTL) and Through-Thickness (TT) depending on the path taken by the binding yarn. The 3D woven composites exhibit outstanding delamination resistance (Stig 2012) and impact resistance (Ji et al 2007, Luo et al 2007, Hao et al 2008, Gerlach et al 2012, Seltzer et al 2013). They possess good out-of-plane properties due to binder yarn (z-binder), although it influences void content, failure mechanism, energy absorption, fibre rotation angle, directional fibre volume fraction and mechanical properties (Saleh et al 2016). Amongst these, 3D orthogonal through-thickness (ORT
Table 1. Fibre and matrix properties.

| Properties | T300J | Properties | RTM6 |
|------------|-------|------------|------|
| $E_t$      | 230 GPa | $E_{nc}$  | 3 GPa |
| $E_{is}$   | 15 GPa  | $E_{mat}$ | 3 GPa |
| $v_{ft}$   | 0.278   | $v_{mat}$ | 0.35 |
| $v_{fs}$   | 0.3     | $v_{mat}$ | 0.35 |
| $G_{ft}$   | 50 GPa  | $G_{m}$   | 1 GPa |
| $G_{is}$   | 5 GPa   |            |      |
| $\sigma_{ft}$ | 4210 MPa | $\sigma_{mC}$ | 90 MPa |
| $\sigma_{BC}$ | —       | $\sigma_{mat}$ | 300 MPa |
| $\sigma_{BT}$ | —       | $\sigma_{mt}$ | 90 MPa |
| $\sigma_{BC}$ | —       | $\sigma_{mC}$ | 300 MPa |
| $\tau_f$   | —       | $\tau_m$  | —    |
| $\rho$     | 1780 kg m$^{-3}$ | $\rho$ | 1140 kg m$^{-3}$ |

where $E$, $v$, $\sigma$, $\tau$, $f$, $T$, $C$, and $m$ indicate young’s modulus (modulus of elasticity), Poisson’s ratio, shear modulus (modulus of rigidity), normal stress, shear stress, density, fibre direction, transverse-to-fibre direction, tensile, compression and matrix, respectively.

TT) woven composite demonstrated the highest failure strength, highest failure strain, best interlocking mechanism and best energy absorbing capacity (Saleh et al. 2016). These composites are loading sensitive, i.e. their performance is different in warp and weft directions and is further complex in off-axis loading conditions. Also, they exhibit lower in-plane mechanical properties due to crimp arising from the weave architecture and tension force in the yarns during weaving. The weave architecture influences the void and resin-rich regions (Dai et al. 2015), making the damage mechanism complex and challenging to study.

Different numerical models such as the mosaic model (Ishikawa and Chou 1982b), undulation model (Ishikawa and Chou 1982b), bridging model (Ishikawa and Chou 1982a), series-parallel (SP) scheme, and parallel-series scheme (Shembekar and Naik 1992, Naik and Shembekar 1992a, 1992b, Naik and Ganesh 1992, 1996, Ganesh and Naik 1996a, 1996b), selective averaging model (Sankar and Marrey 1997), fibre-inclination model (Yang et al. 1986), orientation averaging model (Tarnopol’ski et al. 1973, Kregers and Melbards 1978), modified orientation averaging model (Cox and Dadkhah 1995), ZXY and ZYX model (Tan et al. 1999, Tan et al. 2000a, 2000b) and three-stage homogenisation model (Nehme et al. 2011, Hallal et al. 2011, Hallal 2013), have been developed to study the elastic and failure behaviour of woven composites. One of the assumptions in numerical analysis have been to consider the material as orthotropic. This study proposes a novel web-shaped orientation of z-binder architecture in 3D orthogonal through-thickness woven composite (named WEB hereafter), analysed by existing finite element analysis in ABAQUS, under both on-axis and off-axis tensile loading and in-plane shear loading conditions. The study was aimed to address the loading direction sensitivity of 3D woven composites by re-orienting the z-binder. As mentioned earlier, the 3D ORT TT (named ORT hereafter) woven composite has the highest failure strength, highest failure strain, best interlocking mechanism and best energy absorbing capacity; it was used as a reference to validate and assess the proposed WEB model.

Two macroscale representative volume elements (RVE) of 3D orthogonal through-thickness woven composite, ORT and WEB, were created based on the microscopic measurement of carbon fibre tow obtained via SEM (Nehme et al. 2011) and optical microscope (Dhiman et al. 2015). The periodic boundary conditions are applied to the RVEs to predict the structure’s mechanical properties using ABAQUS. The models were subjected to on-axis and off-axis displacement tensile loading, each in longitudinal (warp or 0° yarn) and transverse (weft or 90° yarn) direction and to an in-plane shear test. The modelling approach was validated by comparing results obtained from the ORT model with the data from other researchers (Dhiman et al. 2015, Saleh et al. 2016) working on a 3D orthogonal through-thickness woven composite. After that, comparisons were drawn between ORT and the proposed WEB model.

2. Materials and software

The properties of carbon fibre T300J (TORAYCA) and epoxy RTM 6 (HEXCEL), as shown in table 1, were used in this study. The cad models of the 3D composites were created in SolidWorks. Static-General Analyses, i.e., in-plane shear test, on-axis and off-axis tensile loading, were conducted in ABAQUS.
3. Finite element modelling

3.1. Macroscale model

Two macroscale RVE models, namely, the ORT model and WEB model, which represent the 3D orthogonal through-thickness woven composite, and the novel 3D woven composite with web-shaped z-binder architecture, respectively, were created in SolidWorks, as shown in Figure 1. The yarns are considered crimp-free with a constant elliptical cross-section along its path. Perfect bonding is assumed between the tows and pure matrix elements (Gerlach et al. 2009). The ORT model was developed to assess the potential and prospect of the WEB model.

The dimensions of the carbon fibre-tow were estimated from the practices followed by other researchers who developed the CAD model based on the SEM and optical microscopic data of the manufactured 3D orthogonal through-thickness woven composites (Nehme et al. 2011, Dhiman et al. 2015). Thus, the dimensions of the carbon fibre tow model for the ORT and WEB model are shown in Table 2 and represented in Figure 1(c).

The material fibre orientation for the ORT and WEB models were \( [0^\circ/90^\circ/0^\circ/90^\circ/0^\circ] \) and \( [-45^\circ/90^\circ/0^\circ/90^\circ/0^\circ] \), respectively. The fibre volume fraction of both models were kept similar, i.e., approximately 40%. This was done to prevent bias in the result due to fibre volume fraction. To perform an off-axis tensile test, both ORT and WEB model were rotated clockwise to re-align the local coordinate system with the global coordinate system such that the application of the load was still at \( 0^\circ \) and \( 90^\circ \) instead of \( 45^\circ \) and \( 135^\circ \), resulting in ORT_{off} and WEB_{off} models. Thus, four models, ORT_{on}, WEB_{on}, ORT_{off}, and WEB_{off} (as shown in Figure 2), were created where the former two were subjected to an on-axis tensile test and the latter two to an off-axis tensile test. The dimensions and volume fraction of the models for both on-axis and off-axis loading conditions are shown in Table 3.

3.2. Meshing

A coarse mesh will provide unreliable results, whereas a fine mesh will significantly increase the computational time. Thus, the mesh density influences the accuracy and reliability of the solution. Similar behaviour can be observed regarding the type and order of the mesh elements for the constituent materials. Hence, a mesh convergence study requires discrete attention.
A periodic mesh was generated in ABAQUS for all the models. For the mesh convergence study, the effect of mesh density, maximum deviation factor within the mesh and element type on the computational time was observed for the ORT_on model. The global mesh size was varied from 2.0 to 0.5, the maximum deviation factor was varied from 0.1 to 0.05 and the mesh element on the matrix was changed from quadratic to linear. Maximum Von-mises stress developed within the model for 0.25 mm on-axis displacement load was used as the parameter to evaluate the mesh convergence study.

Table 4 shows the data from the mesh convergence study. It can be observed that as the global mesh size reduces from 2 to 0.5, i.e., the mesh becomes finer, for both mesh element type and maximum deviation factor, there is an increment in the maximum von-mises stress from 1.119 GPa to 1.195 GPa and in the computational time from 05 min 23 s to 1805 min.
Figure 3 shows the effect of global mesh size, maximum deviation factor, and the mesh element type on the von-mises stress. It can be observed that for a global mesh size of 0.5 or less, there is a minor variation in the maximum von-mises stress. Similar behaviour is indicated between the linear and quadratic mesh element type and maximum mesh element deviation factor. Hence, from figure 3 and table 4, it can be concluded that the

Table 3. Dimensions and Volume fractions of RVEs.

| Model | ORT_on | WEB_on | ORT_off | WEB_off |
|-------|--------|--------|---------|---------|
| Length (mm) | 28 | 31.44 | 18 | 20 |
| Width (mm) | 30.4 | 31.44 | 18 | 20 |
| Thickness (mm) | 4.2 | 3.4 | 4.2 | 3.4 |
| $V_f$ (mm$^3$) | 1497.72 | 1308.23 | 575.90 | 525.60 |
| $V_m$ (mm$^3$) | 2077.32 | 2052.58 | 784.90 | 834.40 |
| $V_c$ (mm$^3$) | 3575.04 | 3360.81 | 1360.80 | 1360.00 |
| $V_f$ (%) | 41.89 | 38.93 | 42.32 | 38.65 |
| $V_m$ (%) | 58.11 | 61.07 | 57.68 | 61.35 |

where $V_f$, $V_m$, $V_c$, $V_f$, and $V_m$ indicate fibre volume, matrix volume, composite volume, fibre volume fraction and matrix volume fraction, respectively.

Table 4. Mesh convergence data.

| $M_S$ | $D_f$ | $\sigma_{VM}$ (GPa) | $t$ (m:s) | Nodes | Elements | Linear | Linear |
|-------|-------|---------------------|----------|-------|----------|--------|--------|
|       |       |                     |          | C3D8R | C3D4     |        | C3D10  |
| 0.5   | 0.10  | 1.188               | 56:05    | 207,594 | 455,361 | 102,640 | 352,721 |
| 1     | 0.10  | 1.135               | 13:07    | 72,894  | 156,677 | 37,392  | 119,285 |
| 1.5   | 0.10  | 1.131               | 06:48    | 40,671  | 92,992  | 20,808  | 72,184  |
| 2     | 0.10  | 1.121               | 05:23    | 30,713  | 70,868  | 15,408  | 55,460  |
| 0.5   | 0.05  | 1.191               | 130:26   | 295,664 | 650,644 | 145,584 | 503,060 |
| 1     | 0.05  | 1.161               | 74:11    | 153,697 | 307,656 | 82,444  | 225,212 |
| 1.5   | 0.07  | 1.130               | 07:20    | 40,901  | 93,394  | 20,808  | 72,586  |
| 2     | 0.05  | 1.119               | 07:43    | 46,961  | 100,328 | 24,288  | 76,040  |

| $M_S$ | $D_f$ | $\sigma_{VM}$ (GPa) | $t$ (m:s) | Nodes | Elements | Linear | Linear |
|-------|-------|---------------------|----------|-------|----------|--------|--------|
|       |       |                     |          | C3D8R | C3D4     |        | C3D10  |
| 0.5   | 0.10  | 1.187               | 335:21   | 721,413 | 455,361 | 102,640 | 352,721 |
| 1     | 0.10  | 1.161               | 41:11    | 251,277 | 156,677 | 37,392  | 119,285 |
| 1.5   | 0.10  | 1.144               | 17:58    | 147,043 | 92,992  | 20,808  | 72,184  |
| 2     | 0.10  | 1.13                  | 12:58    | 112,277 | 70,868  | 15,408  | 55,460  |
| 0.5   | 0.05  | 1.195               | 1805     | 1,020,349 | 650,644 | 145,584 | 503,060 |
| 1     | 0.05  | 1.169               | 320:12   | 485,882 | 307,656 | 82,444  | 225,212 |
| 1.5   | 0.07  | 1.145               | 19:40    | 148,154 | 93,394  | 20,808  | 72,586  |
| 2     | 0.05  | 1.137               | 18:20    | 159,086 | 100,328 | 24,288  | 76,040  |

where $M_S$, $D_f$, $\sigma_{VM}$, $t$, m, and s indicate global mesh size, maximum deviation factor, maximum von-mises stress, time, minutes, and seconds, respectively.

Figure 3 shows the effect of global mesh size, maximum deviation factor, and the mesh element type on the von-mises stress. It can be observed that for a global mesh size of 0.5 or less, there is a minor variation in the maximum von-mises stress. Similar behaviour is indicated between the linear and quadratic mesh element type and maximum mesh element deviation factor. Hence, from figure 3 and table 4, it can be concluded that the
linear mesh element with a maximum deviation factor of 0.1 at a global mesh size of 0.5 provides the result with an acceptable computational time of 56 min.

Thus, considering the slight difference in the maximum von-mises stress value and the significant increase in computational time, for smaller global mesh size and lower maximum deviation factor, first-order, 8-node linear brick element with reduced integration (C3D8R) and 4-node linear tetragonal element (C3D4) were assigned to the fibre tow and matrix, respectively with the global mesh size of 0.3 and deviation in curvature control of 0.1. The coincidence of the nodes of both the elements was ensured, as shown in figure 4. The resulting mesh is given in table 5.

### 3.3. Periodic boundary conditions

When periodically arranged, the RVE is an element that will represent the whole composite. The periodic boundary conditions (PBCs) couple the translational degrees of freedom of the nodes on the opposing faces of the RVE. Displacement and traction boundary conditions must be satisfied at the opposite boundaries to ensure no overlapping or separation of adjacent RVEs, i.e., the structure remains continuous after deformation. It was shown by (Xia et al. 2006) that the traction continuity condition is satisfied for a displacement-based FEA. Thus, traction continuity equations need not be implemented in the model. Hence the following PBCs are implemented for the model in Abaqus (Dassault 2014).

\[
\begin{align*}
    u_{x+dx} - u_x &= l\varepsilon_x \\
    v_{x+dx} - v_x &= 0 \\
    w_{x+dx} - w_x &= 0 \\
    u_{y+dy} - u_y &= 0 \\
    v_{y+dy} - v_y &= b\varepsilon_y \\
    w_{y+dy} - w_y &= 0 \\
    u_{z+dz} - u_z &= 0 \\
    v_{z+dz} - v_z &= 0 \\
    w_{z+dz} - w_z &= t\varepsilon_z \\
\end{align*}
\]

where \(u\), \(v\), and \(z\) indicate displacement of nodes at six faces, \(\varepsilon\) is strain and \(l\), \(b\), and \(t\) are length, breadth, and thickness of the composite in x, y, and z direction, respectively.
4. Simulation test

4.1. On-axis and off-axis tensile test

The nodes on all six surfaces of the 3D models were created as named sets, such as XFront, XBack, YTop, YBottom, ZFront, and ZBack. The displacement constraint equations were applied along the x-axis on the XFront nodes, the y-axis on the YBottom nodes, and the z-axis on the ZBack nodes. A reference point was created in the XY plane at a distance from the XFront face.

For longitudinal loading, i.e., displacement load along the x-axis, the XFront nodes were constrained with the reference point, and the displacement load was then applied to this reference point. Similarly, for transverse loading, i.e., displacement load along the y-axis, the YTop nodes were constrained with the reference point, and the displacement load in the y-direction was then applied to the reference point.

On-axis tensile test was conducted at 0° (longitudinal loading) and 90° (transverse loading) to the global coordinate system on ORT_on and WEB_on models. To perform an off-axis tensile test (load applied at 45°), both ORT and WEB model were rotated clockwise to re-align the local coordinate system with the global coordinate system such that the application of the load was still at 0° and 90° instead of 45° and 135°, resulting in ORT_off and WEB_off models.

4.2. In-plane shear test

This was performed on the ORT_on and WEB_on models. The above created named sets were applicable for the current loading conditions. The equations to constraint all degrees of freedom were applied on the XBack nodes, whereas the displacement constraints in the x and z directions were applied on the XFront nodes.

For in-plane shear loading, i.e., along the y-axis in the XY plane, the XFront nodes were constrained with the reference point, and the displacement load in the y-direction was then applied to this reference point.

5. Results and discussion

This study aimed to deal with the loading direction sensitivity of 3D woven composites by re-orienting the z-binder yarn and thereby developing a novel web-shaped orientation of z-binder architecture in a 3D orthogonal through-thickness composite model with the same in-plane elastic moduli. The successful development of such composite independent of in-plane perpendicular loading direction would lead to freedom from aligning the preforms.

As mentioned in the sections above, the dimensions of the carbon fibre-tow were referenced from the practices followed by other researchers who developed the CAD model based on the SEM and optical microscopic data of the manufactured 3D woven composites. The modelling approach of the proposed WEB model was validated by comparing results obtained upon analysing the ORT model, which was created similar to the conventional 3D orthogonal woven composite, with the data from other researchers working on similar woven architecture (Dhiman et al 2015; Saleh et al 2016).

Table 6 shows the result from the on-axis tensile test of the ORT_on model in comparison to the data from other studies for 3D orthogonal woven composites. The young’s modulus in longitudinal, i.e., warp direction, is lower with respect to data from the first reference, whereas it is comparable to the data from the second reference. The young’s modulus in the transverse direction is lower than the data in the first reference because, in that study, the wet fibre volume fraction is more than its warp fibre volume fraction. The total fibre volume fraction is higher in the former data than in our ORT_on model, and in the case of data from the latter, the slight difference in the total fibre volume fraction and the material difference can be held accountable for slight yet comparable young’s modulus in the longitudinal direction.

The result from the off-axis tensile test shown in table 7 depicts the comparable off-axis behaviour of the ORT_off model compared to the data from the first reference, even with a lower overall fibre volume fraction. From tables 6 and 7, it can be concluded that the modelling approach of the 3D woven composites is reliable and just.

| Table 6. Comparison of on-axis tensile test data of ORT model with 3D ORT Woven Composites. |
|---------------------------------|-----------------|-----------------|--------------|---------|---------|---------|-------------------|
| On-Axis Tensile Test            | Vf (%)          | E_x (GPa)       | σ_x (Mpa)    | ε_x (%)  | E_y (Gpa) | σ_y (Mpa) | ε_y (%)          |
| HexTow IM7 + MTM 57             | 51.8            | 56.6            | 711          | 1.2     | 70       | 862      | 1.25             | (Saleh et al 2016) |
| T700 + Matrix                   | 45              | 42.50           | 580.00       | 1.25    | —        | —        | —                | (Dhiman et al 2015) |
| ORT_on model                    | 41.89           | 41.64           | 520.48       | 1.25    | 35.47    | 445.19   | 1.26             |
|                                 |                 |                 |              |         |          |          |                  |                      |
The data from the on-axis tensile test for the ORTon and WEBon model is shown in table 8 and presented in figure 5. For the same displacement load of 0.35 mm in respective on-axis tensile loading conditions, the longitudinal and transverse young’s modulus of the WEBon model was lower by 16.89% and 2.66%, respectively, compared to the ORTon model. This can be attributed to the lower overall fibre volume fraction of 7.07% for the WEBon model. The warp fibre volume fraction was not used for comparison, as the binder yarn in the WEBon model is at an angle of 45° compared to its usual 0° orientation in the ORTon model. The difference between the Ex and Ey in on-axis loading conditions was 14.81% for the ORTon model, whereas 0.22% for the WEBon model. Even though the ORTon model possesses a higher longitudinal young’s modulus than the WEBon model, it is susceptible to loading direction sensitivity due to different young’s modulus in warp and weft directions. As mentioned in the introduction section, this behaviour makes the failure study of the 3D woven composite complex. On the other hand, the WEBon model presents almost similar in-plane elastic. Hence, it can be stated that except for the longitudinal loading condition, the proposed WEB model performs similar to the ORTon model in transverse on-axis tensile loading conditions and is insusceptible to the loading direction sensitivity.

Table 7. Comparison of off-axis tensile test data of ORT model with 3D ORT Woven Composites.

| Off-Axis Tensile Test | Vf (%) | E (GPa) | Reference |
|-----------------------|--------|---------|-----------|
| HexTow IM7 + MTM 57   | 51.8   | 7.93    | (Saleh et al 2016) |
| ORToff model          | 42.32  | 7.98    | —         |

Table 8. On-axis tensile test results.

| On-Axis Tensile Test | Vf (%) | E (GPa) | σx (MPa) | εx (%) | E (GPa) | σy (MPa) | εy (%) |
|----------------------|--------|---------|----------|--------|---------|----------|--------|
| ORTon Model          | 41.89  | 41.64   | 520.48   | 1.25   | 35.47   | 445.19   | 1.26   |
| WEBon Model          | 38.93  | 34.61   | 386.20   | 1.12   | 34.52   | 385.29   | 1.12   |

The data from the on-axis tensile test for the ORTon and WEBon model is shown in table 8 and presented in figure 5. For the same displacement load of 0.35 mm in respective on-axis tensile loading conditions, the longitudinal and transverse young’s modulus of the WEBon model was lower by 16.89% and 2.66%, respectively, compared to the ORTon model. This can be attributed to the lower overall fibre volume fraction of 7.07% for the WEBon model. The warp fibre volume fraction was not used for comparison, as the binder yarn in the WEBon model is at an angle of 45° compared to its usual 0° orientation in the ORTon model. The difference between the Ex and Ey in on-axis loading conditions was 14.81% for the ORTon model, whereas 0.22% for the WEBon model. Even though the ORTon model possesses a higher longitudinal young’s modulus than the WEBon model, it is susceptible to loading direction sensitivity due to different young’s modulus in warp and weft directions. As mentioned in the introduction section, this behaviour makes the failure study of the 3D woven composite complex. On the other hand, the WEBon model presents almost similar in-plane elastic. Hence, it can be stated that except for the longitudinal loading condition, the proposed WEB model performs similar to the ORTon model in transverse on-axis tensile loading conditions and is insusceptible to the loading direction sensitivity.

Table 9 and figure 6 show the results from the off-axis tensile test of ORToff and WEBoff models. Contrary to the on-axis behaviour of WEBon model, the WEBoff model, with an 8.67% lower fibre volume fraction, shows 13.75% and 13.77% higher young’s modulus in longitudinal and transverse directions, respectively, compared to the ORToff model for the same displacement load of 0.35 mm. It is observed that alongside the WEBoff model, the ORToff model also presents almost similar in-plane elastic behaviour. It is due to the re-alignment of the warp and binder yarns from 0°, in ORTon model, to 45°, in ORToff model, which is getting subjected to loading at 0° and 90°. Also, for the same strain of 1.93%, the WEBoff model projects 13.2% higher tensile strength than
Thus, it can be stated that the proposed WEB model continues to be loading direction insensitive and exhibits higher strength under off-axis loading conditions. To affirm the loading direction insensitivity of the proposed WEB model and discern it from the ORT model, both were subjected to a displacement load of 0.45 mm at 5° intervals. Table 10 shows the tensile test results at a 1.25% strain value. It can be seen that the Ex and Ey values, though decreasing, remains almost similar at all 5° interval angles for the WEB model. In case of ORT model, the Ex and Ey values are distinctly different but tend to come closer as the off-axis loading shifts towards 45°. This behaviour of traditional 3D orthogonal through-thickness woven composites makes their failure study cumbersome. At 20° and 25° loading condition, the longitudinal stress generated is similar in both models, whereas transverse stress sustained by the WEB model is higher than in the ORT model. Hence it can be concluded that the proposed WEB model has superior mechanical properties in the off-axis direction compared to the ORT model.

Table 10. Tensile test results at every 5° loading interval for 1.25% strain.

| Off-Axis Tensile Test | Vf (%) | Ex (GPa) | σx (MPa) | εx (%) | Ey (GPa) | σy (MPa) | εy (%) |
|-----------------------|-------|--------|--------|-------|--------|--------|-------|
| ORT off Model         | 42.32 | 7.98   | 155.10 | 1.94  | 7.98   | 155.09 | 1.94  |
| WEB off Model         | 38.65 | 9.07   | 159.25 | 1.76  | 9.07   | 159.26 | 1.76  |

The ORT off model. Thus, it can be stated that the proposed WEB model continues to be loading direction insensitive and exhibits higher strength under off-axis loading conditions.

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Table 11 and figure 7 show the results from the in-plane shear test of ORT on and WEB on models. Similar to the on-axis behaviour, the difference of 10.96% in the shear modulus and 11.38% in the shear strength for a similar shear strain can be somewhat attributed to the 7.07% difference in the overall fibre volume fraction.
It is important to note that a reduction in the difference in the overall fibre volume fraction amongst the models will result in decrement in the differences in the on-axis tensile test values and in-plane shear test values and further increment in the off-axis tensile test values.

6. Conclusion

This study addressed the loading direction sensitivity of 3D woven composites by re-orienting the z-binder yarn and thereby developing a novel web-shaped orientation of z-binder architecture in a 3D orthogonal through-thickness composite model with the same in-plane elastic moduli. Four macroscale RVE models, namely, ORT\textsubscript{on}, WEB\textsubscript{on}, ORT\textsubscript{off} and WEB\textsubscript{off}, were created where the former two were subjected to an on-axis tensile test and the latter two to an off-axis tensile test. The data from the literature validated the ORT models. The overall fibre volume fraction of the WEB\textsubscript{on} and WEB\textsubscript{off} models were 7.07% and 8.67% lower than the ORT\textsubscript{on} and ORT\textsubscript{off} models. The longitudinal young’s modulus was 16.89% lower in the on-axis tensile test but 13.65% higher in the off-axis tensile test, whereas the transverse young’s modulus was 2.66% lower in the on-axis tensile test but 13.77% higher in the off-axis tensile test, for WEB models compared to ORT models. Similar to the on-axis behaviour, the shear modulus of WEB\textsubscript{on} model was lower by 10.96%. The difference between the $E_x$ and $E_y$ in on-axis loading conditions was 14.81% for the ORT model, whereas 0.22% for the WEB model.

The ORT models were susceptible to loading direction sensitivity due to differences in the longitudinal and transverse young’s modulus. This behaviour, reminiscent of the 3D orthogonal woven composites, makes the failure study of the damage mechanism arduous and complicated. The proposed WEB shaped z-binder architecture model has similar in-plane strength and elastic properties, thereby addressing the loading direction sensitivity of 3D woven composites. It shall outperform the ORT model, with equivalent fibre volume fraction, in transverse on-axis tensile loading and off-axis tensile loading conditions while reducing the gap in the longitudinal on-axis tensile loading and in-plane shear loading conditions.

Future work would include a study of the proposed model’s impact resistance behaviour leading to the development of a prototype and lab testing.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: Panwar, Arpit (2022), ‘ORT_WEB_Modelling_DATASET’ Mendeley Data, V2, doi: 10.17632/rcknck49xr.2.

Disclosure statement

The author reported no potential conflict of interest.

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