Nonlinear viscoelastic multi-scale repetitive unit cell model of 3D woven composites with damage evolution

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\textbf{A R T I C L E   I N F O}

\textbf{Article info}

Received 18 July 2012
Received in revised form 15 May 2013
Available online 3 July 2013

\textbf{Keywords:}

3D orthogonal woven composites (3DOWCs)
Micro/meso-scale repeating unit cells (RUCs)
Viscoelasticity
User-defined material subroutine (UMAT)
Finite element analysis (FEA)

\textbf{A B S T R A C T}

Three-dimensional (3D) textile composites have great potential applications to aircrafts and high speed vehicles because of the high strength/weight ratios and the capabilities of manufacturing complex, net-shape preforms. This paper reports the nonlinear viscoelastic responses and damage mechanisms of one kind of 3D textile composites, named as 3D orthogonal woven composite (3DOWC) under quasi-static tensile loading based on a micro/meso-scale repetitive unit cells (RUCs) model. In the RUCs model, the resin is described with a nonlinear viscoelastic material and the fibers/tows with an elastic material. The damage initiation and propagation in resin are simulated by the post-damage constitutive models with maximum principal theory failure criteria. The fibers/tows impregnated with resin are defined by an elastic transverse-isotropic material model with ultimate strengths failure of 'expanded smeared crack' both along and perpendicular to fibers/tows axis direction. The engineering parameters and ultimate strengths of homogenized fibers/tows filled with matrix in meso-RUCs model are transferred from the numerical analysis of the micro-RUCs. The results are compared with experimental and theoretical values of RUC deformation and damage initiation and propagation under monotonic axial loading. The methodology of establishing the nonlinear visco-elastic multi-scale model of 3D textile composites without introducing the real fabric architecture in finite element analyses is explained. With the multi-scale RUCs model, the mechanical behaviors of other kinds of 3D textile composites can also be predicted.

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\section*{1. Introduction}

Three-dimensional (3D) textile composites have been developed to a commercial level because of the high ratio of strength/weight and inter-laminar shear strength. As one kind of 3D textile composites, 3D woven composites (3DWCs) are new types of advanced engineering materials that are currently used in only a few niche applications (Mohamed, 1990; Mohamed et al., 2001). 3D orthogonal woven composites (3DOWCs) are the special woven composites in which all yarns are interlaced in a straight way. There are not crimps both in the warp, weft yarns interlaced by Z-yarns in through-thickness direction (Bogdanovich and Mohamed, 2009). Compared with conventional laminated composites and other 3D textile structural composites, the 3DOWCs offer many structural advantages such as efficient delamination suppression, enhanced damage tolerance, and superior impact, ballistic and blast performance characteristics (Lomov et al., 2009). Now 3DOWCs gain fast growing scope and volume of industrial applications, including military markets, recreational marine, wind energy, civil engineering and aerospace.

A number of experimental studies have been conducted to understand the quasi-static behavior and damage mechanism of 3DOWCs. Under tensile loadings along yarns directions, the cracks form initially within the resin-rich channels between the fiber tows and around the through-thickness binder yarns, then propagates around the most heavily crimped in-plane tows and the failure occurs within a localized region by discrete tow rupture events (Callus et al., 1999). Averagely, the average failure strength in the weft yarn direction was slightly higher than that in the warp yarn direction. Fracture surface was always perpendicular to the loading direction and the crack caused the Z-yarn/resin interface to debond (Chen and Zanini, 1997; Ivanov et al., 2009; Lomov et al., 2009; Rudov-Clark and Mouritz, 2008; Tan et al., 2000). The compression-induced damage was in a kink-band pattern with a number of smaller modes of damage, such as microscopic fiber buckling, yarn deflection, yarn debonding, yarn split, and shear deformation in transverse yarns (Kuo et al., 2007, 2006). The compressive compaction of the fiber bundles and the through-thickness permeability depend on the flow-enhancing channels in the structure of the reinforcement, formed around the binder yarns (Endruweit and Long, 2010). The binder tow along the thickness direction leads to high interlaminar shear strength of 3D textile composites (Chen and Zanini, 1997).
Many analytical and numerical models for 3DOWCs have also been developed on elastic deformation and failure response. Based on a 3D mosaic unit cell model, the failure initiation and ultimate failure strains and loads including characteristic features of progressive failure processes were predicted (Bogdanovich, 2006, Bogdanovich, 2008, Bogdanovich, 2009). From micromechanical strength model, the stiffness and the strength with effects of stitch density were characterized (Karkkainen and Tzeng, 2009). And by applying mesh-free method on the micromechanical model, the elastic modules was evaluated (Li et al., 2011). The other modeling strategies for 3DOWCs were reviewed by Ansar et al. (2011), Ivanov et al. (2009), Jia et al. (2012), Lomov et al. (2009). The above-mentioned models have made different extents of simplifications on the fabric architecture and polyester resin, such as without effect of fiber packed patterns in resin. Therefore they may not be able to provide accurate details on local stress distributions at fiber or fiber yarn scale levels.

This paper will present a strategy to evaluate the effect of micro/meso-structural morphology on crack initiation and propagation leading to different global/local nonlinear responses, ultimate strengths and damage mechanisms. In the micro/meso-scale RUCs, the resin material behavior is modeled using nonlinear viscoelastic model with damage initiation on the concept of smear crack and damage evolution by post-damage constitutive model. The fiber in micro-RUC is considered to be isotropic one. The fiber tows in meso-RUC are defined by elastic transverse-isotropic material model with ultimate strengths failure by ‘expanded smeared crack’ independently in the fiber tows direction and transverse directions. The corresponding post-damage constitutive models are introduced simultaneously to represent the damage propagation of different initiated crack patterns. The above viscoelastic/elastic models are implemented with user-defined material subroutines (UMATs) and incorporated with a commercial finite element software ABAQUS/Standard. The simulated results display their mechanical nonlinearity, damage initiation and growth under monotonic axial loading, revealing the local and global response of the 3DOWC including the damage mechanism at multi-scale levels. The predicted results are also compared with experimental data and they show a good agreement.

2. Framework of micro/meso-scale unit cell model

2.1. Geometric RUCs and periodic boundary condition

For the whole body, the local representative volume element (RVE) as a small micro-region for the entire body keeps same averaged volume variables with global body by homogenization (Kanit et al., 2003; Kouznetsova et al., 2002). Conventionally, the studies have been conducted with the RVE represented by a repetitive unit cell (RUC) consisting of a single or multiphase heterogeneity in a uniform matrix (Magoariec et al., 2004). Furthermore, the periodic boundary conditions on RUC can satisfy the continuity of displacement between node pairs on corresponding opposite parallel surfaces and continuity of force automatically (Xia et al., 2006). For the multi-scale analyses, the micro-RUC reveals a uniform, periodically repetitive array of heterogeneities and macro-structure is a homogeneous body (Bogdanovich, 2006; Kruch and Chaboche, 2011).

To analyze the effect of fiber packed pattern and yarns architecture in 3DOWC, a multi-scale RUC strategy is introduced separately for resin impregnated fiber bundles and 3DOWF in Figs. 1 and 2. The micro-RUC includes an elastic brittle fiber distributed hexagonally in the ductile resin. The meso-RUC consists of transversely isotropic fiber bundles (warp yarns, weft yarns and Z-yarns) in porous polyester resin (The details of their establishments and sizes are given in previous work (Jia et al., 2012)). The constitutive models and the material parameters for constituent materials in micro/meso-RUC are described in the subsequent sections.

The macroscopic strain increment is applied on RUC by decomposing the displacement increment on the boundary into macroscopic averaged and a part (Pellegrino et al., 1999; Segurado and Llorca, 2002), such as

\[ U_i = \tilde{e}_k X_k + U'_i \]  

where \( \tilde{e}_k = \tilde{e}_k \Delta t \) is the macroscopic strain increment. Due to periodic part of \( U'_i \) is equal on corresponding nodes of opposite parallel surface of RUC (e.g. \( n_1^i \) and \( n_2^i \)), the total displacement at this node pair are expressed with:

\[ (U_i)_{n_1^i} - (U_i)_{n_2^i} = \tilde{e}_k \Delta X_k \]

where \( \Delta X_k \) are the relative coordinates of node pair. Macrossopic strains are applied in conjunction with periodic constraint by master node to slave nodes technology provided in earlier research (Jia et al., 2012).

2.2. The constitutive models

This section briefly discusses the constitutive models before and after damage that are adopted to describe the global and local deformation and damage response of 3DOWC at multi-scale levels, with fiber, yarns and resin. Their mechanical responses are modeled by two different sets of constitutive equations and damage models, respectively. The interface/interphase between the resin and fiber is assumed to bond perfectly.

2.2.1. Resin model

The resin is assumed to undergo rate-dependent viscoelastic deformation and failure at maximum strain (Hu et al., 2003; Shen...
behave a damped exponential character in an exponential manner. 

The resin is assumed a uniaxial viscoelastic model represented by a finite series of ‘Kelvin–Voigt type’ elements and an elastic spring (Xia et al., 2003, 2005) and maximum principal strain failure on the concept of smeared crack (Zhang et al., 2005).

For a uni-axial loading, the nonlinear viscoelastic behavior can be represented by a list of nonlinear ‘Kelvin–Voigt type’ elements and a linear spring element to be connected as shown in Fig. 3. For the system of the serial elements, the global stress–strain relation is expressed by:

\[ \{ \dot{e}_i \} = \{ \dot{e}_i \} + \{ \dot{e}_a \} \]

(3)

\[ \{ \dot{\sigma} \} = E[A]^{-1} \{ \dot{e}_i \} \]

(4)

where \( \{ \dot{e}_i \}, \{ \dot{e}_a \}, \{ \dot{e}_c \}, \{ \dot{\sigma} \} \) are the total strain-rate, elastic strain-rate, creep strain-rate and stress-rate vectors (each includes six components, respectively). \( E \) is an elastic modulus which is assumed to be constant and \( [A] \) is a matrix only related to the value of Poisson’s ratio to be defined by

\[
[A] = \begin{bmatrix}
1 & -v & -v & 0 & 0 & 0 \\
-v & 1 & -v & 0 & 0 & 0 \\
-v & -v & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 + v & 0 & 0 \\
0 & 0 & 0 & 0 & 1 + v & 0 \\
0 & 0 & 0 & 0 & 0 & 1 + v \\
\end{bmatrix}
\]

(5)

The creep strain rate \( \{ \dot{e}_c \} \) is the sum of the strain-rate of each element \( \{ \dot{e}_i \} \) in the serial connection of above-mentioned elements such as

\[
\{ \dot{e}_c \} = \sum_{i=1}^{n} \left( \frac{[A]}{E} \{ \dot{e}_i \} - \frac{1}{\tau_i} \{ \dot{e}_i \} \right)
\]

(6)

where \( \tau_i = \eta_i/E \left( i = 1, 2, \ldots, n \right) \) denotes the retardation time. \( E_i \) is the spring elastic modulus and \( \eta_i \) represents the viscosity coefficient of dashpot for \( i \)th Kelvin (Voigt) element respectively. The retardation time \( \tau_i \) behave a damped exponential character in an exponential-type function from the experimental test (Xia et al., 2003). Its value determines the time duration after which contribution from the individual Kelvin element becomes negligible. The number of the Kelvin elements applied in the constitutive equation depends on the required time range. A time factor \( \alpha \) is introduced and defined as

\[
\tau_i = (\alpha)^{n-1} \tau_1
\]

(7)

In this way all \( \tau_i \) are related by the scale factor \( \alpha \). The span of time is determined by the order of \( n \) with \( n \) Kelvin elements to be included and the value of \( \alpha \) to be 10.

The nonlinear viscoelastic response in the current model is realized with the \( E_i \) described by the functions of current equivalent stress, \( \sigma_{eq} \) as expressed by

\[
E_i = E_1(\sigma_{eq})
\]

(8)

In the above \( \sigma_{eq} \) is defined as

\[
\sigma_{eq} = \frac{(R - 1)I_1 + \sqrt{(R - 1)^2 I_1^2 + 12R J_2}}{2R}
\]

(9)

where \( I_1 = \sigma_1 + \sigma_2 + \sigma_3 \) is the first invariant of the stress tensor, and \( J_2 = S_{01}S_{02}/2 \) is the second invariant of the deviatoric stress and \( R \) is the ratio of tensile to compressive ‘yield stress’. Note that when \( R = 1 \), then Eq. (9) reduces to the von Mises equivalent stress, \( \sigma_{eq} = \sqrt{3J_2} \).

In contrast to a single crack to be predefined in the isotropic material, the complex patterns and discrepant density distributions of cracks in the 3DOWC make it difficult to deal with above-mentioned cracks based on the classical fracture and damage method. In current analyses, the crack to be initiated in resin-rich zone of micro/meso-RUCs is modeled with the so-called ‘smeared crack’ approach (Cervenka and Papinokolau, 2008; Petr-angeli and Ozbolt, 1996; Rafi and Nadjai, 2012). During process of finite element analysis, the principal strains at each node belonging to the element with property of matrix are calculated for each iteration and a local (crack) coordinate system (O-1-2-3) is established with the three axes along the three principal strains \( (\varepsilon_1 \geq \varepsilon_2 \geq \varepsilon_3) \) as shown in Fig. 4. The failure criterion for matrix based on maximum principal strain theory is defined by \( \varepsilon_f \) as follows:

\[
\varepsilon_f = \varepsilon_{cr}
\]

(10)

\( (\varepsilon_{cr} \) is the failure strain of matrix under uniaxial tensile loading). Once the condition is satisfied, a crack in the plane perpendicular to the direction of \( \varepsilon_f \) in the local coordinate system is assumed to have initiated.

After the initiation of a crack, the normal and shear stresses are assumed not to be transferred between the surfaces of the crack. In the local (crack) coordinate system, the \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) approach zero correspondingly. The subscript 1 denotes the Cartesian axis perpendicular to the crack plane while 2 and 3 are in the crack plane. The rest of stresses are transferred normally without the

![Fig. 3. A uniaxial viscoelastic model represented by a finite series of ‘Kelvin–Voigt type’ elements coupled with an elastic spring.](image)

![Fig. 4. A local coordinate system for crack.](image)
effect of the crack formation. The stress and strain vectors in local (crack) coordinate system are defined by $[\sigma]^c$ and $[\varepsilon]^c$ respectively. The post-damage constitutive model for matrix in the local (crack) coordinate system can be expressed by

$$[\Delta\sigma]^c = E_i[D]([\Delta\varepsilon]^c - \chi[B][\sigma]^c]$$  \hspace{1cm} (10)

or written in its full form with

$$
\begin{bmatrix}
\Delta\sigma_1 \\
\Delta\sigma_2 \\
\Delta\sigma_3 \\
\Delta\sigma_{12} \\
\Delta\sigma_{13} \\
\Delta\sigma_{23}
\end{bmatrix}^c = E_i
\begin{bmatrix}
0 & Z_1 & Z_2 & 0 & 0 & 0 \\
0 & Z_2 & Z_1 & 0 & 0 & 0 \\
0 & 0 & 0 & \beta Z_3 & 0 & 0 \\
0 & 0 & 0 & 0 & Z_3 & 0 \\
0 & 0 & 0 & 0 & 0 & Z_3 \\
\end{bmatrix}
\begin{bmatrix}
\Delta\varepsilon_1 \\
\Delta\varepsilon_2 \\
\Delta\varepsilon_3 \\
\Delta\varepsilon_{12} \\
\Delta\varepsilon_{13} \\
\Delta\varepsilon_{23}
\end{bmatrix}^c
- \chi
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\sigma_{12} \\
\sigma_{13} \\
\sigma_{23}
\end{bmatrix}$

where

$$Z_1 = \frac{1 - \nu}{(1 +\nu)(1-2\nu)}, \quad Z_2 = \frac{\nu}{(1+\nu)(1-2\nu)}, \quad Z_3 = \frac{1}{2(1+\nu)}$$  \hspace{1cm} (11)

$E_i$ is the tensile modulus of the matrix at the instant of damage initiation. $\beta = 0.01\Delta t$ is a small number to describe the stiffness degradation in these three particular stress directions and the constant $\chi = 0.2\Delta t$ allows the three stress components to decrease to a near zero value in a sufficiently short time duration ($\Delta t$ is time increment for each iteration).

Note that the above Eqs. (3), (4), and (10) are expressed in the local coordinate system. If the local coordinate system is different from the global coordinate system where FEM analyses carry out, the Eq. (6) must be transformed to the global coordinate system as,

$$([\Delta\sigma])^g = [D]^T([\Delta\sigma])^c - \chi[B]^T([\sigma])^c$$  \hspace{1cm} (12)

with

$$[D'] = [T]^T[D][T]$$

and

$$[B'] = [T]^T[B][T]$$

$$[T] = 
\begin{bmatrix}
\tilde{\iota}_1 & m_1 & n_1 & l_1 & m_{n_1} & n_{l_1} \\
\tilde{\iota}_2 & m_2 & n_2 & l_2 & m_{n_2} & n_{l_2} \\
\tilde{\iota}_3 & m_3 & n_3 & l_3 & m_{n_3} & n_{l_3} \\
2l_1 l_2 & 2m_1 m_2 & 2n_1 n_2 & l_1 m_2 + l_2 m_1 & m_1 n_2 + m_2 n_1 & n_1 l_2 + n_2 l_1 \\
2l_1 l_3 & 2m_1 m_3 & 2n_1 n_3 & l_1 m_3 + l_3 m_1 & m_1 n_3 + m_3 n_1 & n_1 l_3 + n_3 l_1 \\
2l_2 l_3 & 2m_2 m_3 & 2n_2 n_3 & l_2 m_3 + l_3 m_2 & m_2 n_3 + m_3 n_2 & n_2 l_3 + n_3 l_2
\end{bmatrix}$$

(13)

where $l_i, m_i, n_i$ are directional cosines of the local coordinate axes in the global coordinate system.

2.2.2. Fiber/yarns phase models

The mechanical behavior of E-glass fiber is characterized by high stiffness and strength. The failure process is short and the stress drops very suddenly at the inception of brittle fracture. The brittle fiber is assumed to be isotropic, elastic model in smeared crack pattern with maximum principal stress failure (Jia et al., 2012).

At meso-scale level, a post-damage constitutive model for weft, warp yarns and Z-binders with transversely isotropic property is proposed. As shown in Fig. 5, three kinds of cracks are initiated appropriately along fiber yarns direction (Crack 1, Fig. 5(a)) and transversely (Crack 2, Fig. 5(b) and Crack 3, Fig. 5(c)). A crack once created and then its normal stress component perpendicular to surface of crack and shear stress components in in-plane surface of crack are not transferred. For example in Fig. 5(a), the post-damage constitutive model can be expressed with

$$
\begin{bmatrix}
\Delta\sigma_1 \\
\Delta\sigma_2 \\
\Delta\sigma_3 \\
\Delta\sigma_{12} \\
\Delta\sigma_{13} \\
\Delta\sigma_{23}
\end{bmatrix}^c = \begin{bmatrix}
\beta C_1 & 0 & 0 & 0 & 0 & 0 \\
0 & C_2 & C_3 & 0 & 0 & 0 \\
0 & 0 & C_3 & C_2 & 0 & 0 \\
0 & 0 & 0 & 0 & \beta C_4 & 0 \\
0 & 0 & 0 & 0 & 0 & C_6 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\Delta\varepsilon_1 \\
\Delta\varepsilon_2 \\
\Delta\varepsilon_3 \\
\Delta\varepsilon_{12} \\
\Delta\varepsilon_{13} \\
\Delta\varepsilon_{23}
\end{bmatrix}^c
- \chi
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\sigma_{12} \\
\sigma_{13} \\
\sigma_{23}
\end{bmatrix}$

(14)

where

$$C_i = \frac{E_1(1 - v_z^2)}{1 - v_z^2 - 2(1 + v_z)\frac{E_1}{E_2}v_z^2},$$

$$C_2 = \frac{E_2(1 - \frac{v_z}{v_2})}{1 - v_2^2 - 2(1 + v_2)\frac{E_2}{E_1}v_2^2},$$

$$C_3 = \frac{E_3(v_2 + \frac{v_z}{v_2})^2}{1 - v_2^2 - 2(1 + v_2)\frac{E_1}{E_2}v_2^2},$$

$C_4 = G_{12}$ and $C_6 = C_{23}$ (15)

$E_i$ is the modulus of matrix impregnated fiber bundles along fiber direction while $E_2$ is transverse directions with $E_2 = E_3$.

The above three kinds of cracks are damaged independently. The yarn is only damaged partly when one or two of three cracks (crack 1, crack 2 and crack 3) occur. Subsequently, the damage increases and elastic modulus decreases in particular orientations as shown in Fig. 5. For completed damage when all three kinds of cracks occur at same node in finite element analyses, the stress reduces to zero indicating loss of load carrying capacity.

2.3. Numerical implementation of the constitutive models in UMATs

The nonlinear viscoelastic model with crack initiation and propagation is implemented for finite element analysis using the user defined material subroutine (UMAT) in a commercial code ABAQUS/Standard. The essential steps in the UMAT update algorithm for $t^{(n)}$ and $t^{(n+1)}$ are shown in Fig. 6.

(1) Initialize the threshold value of maximum principal strain for damage at the beginning of the first increment and input mechanical parameters.

(2) Obtained $\varepsilon_{\text{crit}}^{(n)}$, evaluate the maximum principal strain, $\tilde{\iota}^i$.

(3) If $\tilde{\iota}^i < \varepsilon_{\text{crit}}$, there is no damage to be initiated. In this case, calculate increment of creep strain, $\Delta\varepsilon^c$, $\Delta\varepsilon^c = \sum_{n=1}^{N-1} (\varepsilon^c - \frac{1}{2} \Delta\varepsilon^c)$ and elastic strain one, $\Delta\varepsilon^e = \Delta\varepsilon^c - \Delta\varepsilon^c$. And calculate the stress increment by Jacobian matrix from elastic stiffness ($\Delta\sigma^e = [C]\Delta\varepsilon^e$).

(4) If $\tilde{\iota}^i \geq \varepsilon_{\text{crit}}$, the damage occurs as shown in Fig. 4. In this case for matrix/fiber:

In local coordinate system, the stresses increment between the surface of initiated cracks are with
Fig. 5. Crack patterns in matrix impregnated fiber bundles.

Fig. 6. Flow chart of UMAT in ABAQUS/Standard.
Table 1

<table>
<thead>
<tr>
<th>Yarns</th>
<th>Linear density (tex)</th>
<th>Layers</th>
<th>Weaving density (end/10 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weft</td>
<td>800</td>
<td>17</td>
<td>47</td>
</tr>
<tr>
<td>Warp</td>
<td>800</td>
<td>16</td>
<td>47</td>
</tr>
<tr>
<td>Z-yarns</td>
<td>56</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

\[
\Delta \sigma_{11}^{r} = \beta E_{1} \Delta \varepsilon_{11}^{r} - \chi \sigma_{11}^{0}, \Delta \sigma_{12}^{r} = \beta E_{1} \Delta \varepsilon_{12}^{r} - \chi \tau_{12}^{0} \quad \text{and} \quad \Delta \sigma_{13}^{r} = \beta E_{1} \Delta \varepsilon_{13}^{r} - \chi \tau_{13}^{0}.
\]

If \( \sigma_{i}^{0} \geq \sigma_{i}^{u} \) (i = 1, 2, 3), the crack occurs in Fig. 5. In this case for yarns:

(a) If \( i = 1 \), the crack is created with its surface vertical to fiber yarns direction (in Fig. 5(a)). The disturbed stresses are with \( \Delta \sigma_{11}^{t} = \beta E_{1} \Delta \varepsilon_{11}^{t} - \chi \sigma_{11}^{0}, \Delta \sigma_{12}^{t} = \beta E_{1} \Delta \varepsilon_{12}^{t} - \chi \tau_{12}^{0} \quad \text{and} \quad \Delta \sigma_{13}^{t} = \beta E_{1} \Delta \varepsilon_{13}^{t} - \chi \tau_{13}^{0} \).

(b) If \( i = 2 \) the crack is created with its surface vertical to transverse directions (in Fig. 5(b)). The components of stress are not transferred such as:

\[
\Delta \sigma_{22}^{t} = \beta D_{1} \Delta \varepsilon_{22}^{t} - \chi \sigma_{22}^{0}, \Delta \sigma_{12}^{t} = \beta D_{1} \Delta \varepsilon_{12}^{t} - \chi \tau_{12}^{0} \quad \text{and} \quad \Delta \sigma_{13}^{t} = \beta D_{1} \Delta \varepsilon_{13}^{t} - \chi \tau_{13}^{0}.
\]

where \( D_{1} = C_{2}, D_{2} = C_{4} \) and \( D_{3} = C_{6} \).

(c) If \( i = 3 \) the crack is created with its surface vertical to transverse directions (in Fig. 5(c)). The components of stress are not transferred such as:

\[
\Delta \sigma_{33}^{t} = \beta D_{2} \Delta \varepsilon_{33}^{t} - \chi \sigma_{33}^{0}, \Delta \sigma_{13}^{t} = \beta D_{2} \Delta \varepsilon_{13}^{t} - \chi \tau_{13}^{0} \quad \text{and} \quad \Delta \sigma_{23}^{t} = \beta D_{2} \Delta \varepsilon_{23}^{t} - \chi \tau_{23}^{0}.
\]

where \( F_{1} = C_{2}, F_{2} = C_{4} \) and \( F_{3} = C_{6} \).

(6) Update the creep strains and stresses for the undamaged or damaged constitutive models for fiber/matrix and yarns respectively, \( \varepsilon_{i}^{u} = \varepsilon_{i}^{t} + \Delta \varepsilon_{i}^{t} \) and \( \sigma_{i}^{u} = \sigma_{i}^{t} + \Delta \sigma_{i}^{t} \).

3. Experimental verifications

3.1. Polymer resin

The thermosetting polyester resin of AROPO™ INF80501 (pre-accelerated, orthophthalic based resin) was supplied by Ashland Composite Polymers (Ashland Inc., United States). Initially, the thin plates (with 3.3 mm in thickness) were made using vacuum infusion/RTM technology. And then they were manufactured in dog-bone shaped sample using water cutter machine as shown in Fig. 7, being 12 mm in width, effective length of 60 mm in middle fields with total length of 170 mm, and the end size of 25 mm, which implies the uniform loading distribution in the middle fields of samples, even up to ultimate failure.

3.2. DOWC

3D orthogonal woven composite (3DOWC) was made with 3D orthogonal woven E-glass fabric (3DOWF) and unsaturated polyester of AROPOL™ INF 80,501. In the system of 3DOWF as shown in

Fig. 9. Specimen of 3D orthogonal woven composite (3DOWC) in length along warp yarns direction.
3.3. Quasi-static tensile test

Mechanical tests were performed by means of universal MTS-810 machine equipped with an electro-mechanical sensor to record the longitudinal strains in the middle fields of samples. The engineering stress $\sigma$ was determined as the ratio of axial force to cross-sectional area of specimens in the stress-free state. Two series of quasi-static tensile tests were conducted at room temperature. Each one was carried out on a new sample and repeating at least twice to assess reproducibility of measurements.

For the polyester resin, the first series of experiments included two monotonic tensile tests at loading rate of $\dot{\varepsilon} = 6.34 \times 10^{-5}$ as shown in Fig. 10. Due to the molecular structure for thermosetting polyester, nonlinear mechanical responses are observed. The failure strain is near $\varepsilon_{\text{ult}} = 4.3\%$ and corresponding failure strength of $\sigma_{\text{ult}} = 71\text{ MPa}$. It displays the time-dependent property for the AROPOL™ INF 80501 polyester resin.

The tensile response for 3DOWC in length along warp yarns direction is shown in Fig. 11 and its instantaneous stiffness response is in Fig. 12 (the instantaneous stiffness is the ratio of differential stress to differential strain, e.g. $E_k = \left. \frac{d \sigma}{d \varepsilon} \right|_{\varepsilon = \dot{\varepsilon}} = \left( \sigma_{k-1} - \sigma_k \right) / \left( \varepsilon_{k-1} - \varepsilon_k \right)$. Totally, three kinds of damaged stages can be noticed. At initial stage ($\varepsilon < 0.5\%$), the curve keeps nearly linear response with micro-scale crack initiated by obvious vibration of instantaneous stiffness response. After the kink point of strain ($\varepsilon = 0.5\%$), the tensile modulus decreases gradually with increase of axial loadings. The amplitude of instantaneous stiffness vibrates in stable and decreasing trend, with new cracks created continuously. Then the tensile modulus continues to be constant with increase of loading (from $\varepsilon = 1.3\%$ to $\varepsilon = 2.7\%$). Upon the further loading, the cracks on the surface of 3DOWC were observed and the Z-binders fractured on surface fields of 3DOWC. The specimen of 3DOWC started to expand in thickness direction corresponding to the small sliding movement in stress against strain curve at $\dot{\varepsilon} = 2.73\%$. Furthermore, the warp yarns fractured one after another up to final failure of the sample. This similar mechanical response was also founded from previous work based on acoustic emission test (AE) (Lomov et al., 2009). The principal damage threshold of 3DOWC occurred nearby $\dot{\varepsilon} = 0.5\%$ and three stages can be divided with early stage, intermediate stage and prior-to-final stage as above mentioned. Compared with the stress against strain curves of two specimens, the mechanical behaviors are in good agreement with ultimate strain and strength ($\dot{\varepsilon}_1 = 3.30\%$; $\sigma_1 = 450.20\text{ MPa}$ and $\dot{\varepsilon}_2 = 3.18\%$; $\sigma_2 = 438.67\text{ MPa}$), keeping consistent with those in experimental (Lomov et al., 2009). As shown in Fig. 13, the matrix cracking occurred in the zone of rich resin and matrix impregnated fiber bundles failed in modes of yarns splitting, yarns peeling and yarns pull out. The tested specimen also displayed the delaminating failure mode with layer-to-layer debonding after the fracture of Z-binders in thickness direction.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Mechanical properties of AROPOL™ INF 80501 polyester and E-glass fiber.</th>
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<tr>
<td>E/GPa</td>
<td>Poisson's ratio $\nu$</td>
</tr>
<tr>
<td>Polyester</td>
<td>2.4</td>
</tr>
<tr>
<td>Fiber</td>
<td>72.5</td>
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Fig. 11. Tested stress–strain curve for 3DOWC under tensile loading along warp yarns direction.

Fig. 12. Instantaneous stiffness responses of 3DOWC under warp yarns directional tensile loading.

Fig. 13. Damaged morphology for 3DOWC under tensile loading along warp yarns direction.
4. Numerical calculation results and discussions

The above-mentioned viscoelastic/elastic models with damage initiation and propagation is realized by above-mentioned user-defined material subroutines (UMATs) and then incorporated into commercial finite element software ABAQUS/Standard. The mechanical response, damage initiation and evolution of micro/meso-RUCs are simulated respectively.

4.1. Nonlinear responses of polyester

Fig. 10 shows the predicted time-dependant response of AROPOL™ INF80501 polyester based on the tested data in Table 2 (Based on the creep tests at different stress levels following a routine procedure as described by (Xia et al., 2003), the values of constants \(E_0, m_0, a_0, s_1, R\) and the functional form of \(E_i = E_i(\sigma_{eq})\) were obtained from experimental tests and tested results. According to above experimental procedure, the geometric finite element model was established initially and incorporated into commercial finite element software ABAQUS/Standard together with UMATs. Compared with tested results, the current viscoelastic model can predict its mechanical behavior well under same loading rate. For initial loading \((\varepsilon \leq 1.5\%)\), the specimen keep linear response. Then the nonlinear behavior is noticed obviously in range of \(1.5\% < \varepsilon < 4.3\%\) with the tangent modulus degradation progressively, due to essential molecular characteristics of polyester.

![Fig. 14. Predicted stress–strain curve for micro-RUC under transverse tensile loadings at \(\varepsilon = 4.0\times 10^{-5}\).](image)

![Fig. 15. Stress distribution and damage evolution of micro-RUC under tensile loading at 2-direction.](image)

![Fig. 16. Stress distribution and damage evolution of micro-RUC under tensile loading at 3-direction.](image)
4.2. Responses of micro-RUC and damage evolution

Mechanical response with damage behavior of micro-RUC is predicted using the parameters of polyester resin and E-glass fiber as listed in Table 2. Under fiber longitudinal loading, the averaged stress against strain curve keep linear response with tensile elastic modulus of \( E_{11} = 53.96 \) GPa and ultimate strength of \( \sigma_{11} = 1.637 \) GPa. Since structural symmetry of micro-RUC, no stress concentration zone is found in the fields of interphase/interface between the fiber and resin. The damage of cracks initiations and propagations are mainly focused on the intra-constituents of micro-RUC. For the transverse loadings respectively (\( E_{22} \) and \( E_{33} \)), the global mechanical responses of micro-RUC are shown respectively in Fig. 14. Initially, micro-RUC behaves transverse isotropic responses with tensile modulus of \( E_{22} = E_{33} = 14.05 \) GPa. Upon further loading, the behavior of matrix is revealed by nonlinear responses of \( S_{22} \) and \( S_{33} \). Since different damage locations to be initiated, different ultimate strengths in transverse directions are observed with \( \sigma_{22} = 85.92 \) MPa and \( \sigma_{33} = 71.56 \) MPa. For conservative estimate in meso-RUC of 3DOWC, lower failure strength is adopted in transverse directions, \( \sigma = 71.56 \) MPa. The damage details of micro-RUC transverse loadings respectively are revealed in Figs. 15–18.

For \( E_{22} \) loading case, the obvious stress concentration is initially located in ‘A’ area of resin-rich zone among fibers (in Fig. 15(a)). With loading increase, the cracks are initiated in ‘A’ area and propagated in resin-rich zone in interior fields of micro-RUC (in Fig. 15(b)). Upon further loading, the damaged zone is extended towards ‘B’ area (as shown in Fig. 16(a)) and new cracks are initiated in matrix zone around the edge fields of fiber.

In the contrary, a different damaged procedure under \( E_{33} \) loading case is observed (in Fig. 16). For matrix, a little higher stress is located initially in ‘B’ area of micro-RUC (in Fig. 16(a)). Then it is damaged in the higher stress concentrated ‘B’ zone, the higher stress concentrated locations move to the resin-rich ‘A’ zone in the interior fields of micro-RUC (in Fig. 16(b)). Finally, the matrix around fiber is fully damaged. For the transverse loading of \( E_{22} \) and \( E_{33} \), the distinctive mechanical behaviors are found with corresponding different damage procedures.

Furthermore, the local responses for initiation and propagation of cracked zone are analyzed as shown in Figs. 17 and 18. Two nodes are selected in ‘A’ area and ‘B’ area respectively by node 8519 and node 474 as shown in Figs. 17 and 18(a). Fig. 17 shows different responses for node 8517 and node 474 that imply the cracks are firstly initiated at averaged strain loading of \( \bar{e}_{22} = 1.03\% \) in ‘A’ area by efficient decrease of stress value in short time. With propagation of damaged zone in ‘A’ area, new cracks are created around the interphase/interface between resin and fiber. The stress in ‘B’ area is deduced with effect of damage in ‘A’ area. Correspondingly, Fig. 18 reveals another damage procedure by local responses of node 8517 and node 474. The cracks are initiated at both location ‘A’ and ‘B’. Upon the loading increase, the crack is firstly created in ‘B’ area at averaged strain loading of \( \bar{e}_{33} = 0.51\% \) with following damage propagation around the location ‘B’. The stress in location ‘A’ is transferred normally without effect of damage in ‘B’ zone. Then another damaged region is created at averaged strain loading of \( \bar{e}_{33} = 1.24\% \) in ‘A’ area.

The above-mentioned micro-RUC provides detailed global and local damage characteristics and stress/strain responses under fiber longitudinal and transverse loadings, respectively. For the fiber directional loading of \( E_{11} \), the fiber is the reinforcement and determines the mechanical properties mostly, such as tensile modulus and ultimate strengths. In the contrary, it is local stress concentration to determine the damage initiation and propagation for off-fiber axis loadings. For example, under the transverse loading of \( E_{22} \), the maximum value of von-Mises stress occurs in the fiber near the fiber/matrix interface and along the fiber direction. Thus, upon further loading, there will be two symmetric ‘narrow bands’ of matrix cracking along the fiber direction and deduction of stress with increase of axial loading. The similar failure mechanism occurs when micro-RUC is under the loading of \( E_{33} \), which means that the matrix determines mainly the transverse mechanical properties of micro-RUC. These numerical findings are consistent with the experimental results (Callus et al., 1999).

4.3. Responses of meso-RUC and damage evolution

The meso-RUC (in Fig. 2(a)) consists of matrix impregnated fiber bundles system (in Fig. 2(b), warp yarns, weft yarns and Z-yarns) and pure matrix (in Fig. 2(c)). The above-mentioned mechanical parameters of micro-RUC including ultimate failure strengths in fiber longitudinal and transverse directions (in Table 3) are now applied in analysis on meso-RUC. Based on expanded smeared crack, the ultimate strengths failure criterion is used for the matrix impregnated fiber yarns as shown in Fig. 5 (Assuming 1-direction as fiber longitudinal direction and 2,3-direction as transverse directions respectively in local coordinate system), i.e. if either of the longitudinal or transverse stress values of the matrix impregnated fiber yarn reaches the corresponding ultimate strength value, a crack with its surface perpendicular to the axial direction is assumed to have initiated. The global and local stress/strain responses including damage initiation and

<table>
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<td>Elastic parameters being predicted for micro-RUC.</td>
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</table>

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<thead>
<tr>
<th></th>
<th>E11</th>
<th>E22</th>
<th>E33</th>
<th>G12</th>
<th>G13</th>
<th>G23</th>
<th>ν12</th>
<th>ν13</th>
<th>ν23</th>
<th>σ11</th>
<th>σ22</th>
<th>σ33</th>
</tr>
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<tbody>
<tr>
<td>Gpa</td>
<td>53.90</td>
<td>14.05</td>
<td>14.05</td>
<td>5.04</td>
<td>5.04</td>
<td>5.20</td>
<td>0.2479</td>
<td>0.2479</td>
<td>0.3510</td>
<td>1637</td>
<td>71.56</td>
<td>71.56</td>
</tr>
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Note: 1-fiber direction, 2,3-transverse directions
propagation of meso-RUC at strain-controlled uniaxial loadings ($\varepsilon_{11}$ and $\varepsilon_{22}$) are analyzed respectively.

4.3.1. Global responses and damage evolution

Fig. 19 shows mechanical behaviors of full thickness RUC under in-plane principal loadings ($\varepsilon_{11}$ and $\varepsilon_{22}$, respectively). Compared with the tested results in length along warp direction as shown in Fig. 11, the predicted results are in good agreement with experimental data. For the load of $\varepsilon_{11}$, the tested result shows initial stiffness of $E_{11} = 20.94$ GPa (nearby $\varepsilon_{11} = 0.2\%$) and ultimate strength of $\sigma_{11} = 437.38$ MPa (at $\varepsilon_{11} = 3.25\%$). And the predicted results are with initial stiffness of $20.30$ GPa (at $\varepsilon_{11} = 0.2\%$) and failure strength of $475.50$ MPa. The predictions are a little higher than the tested ones because there no consideration of the defects (e.g. micro-cracks, voids etc.) in specimen. For another in-plane principal loading response, $\varepsilon_{22}$, the meso-RUC has initial stiffness of $21.86$ GPa and failure strength of $546.31$ MPa, which are higher than that of meso-RUC in warp yarns direction. The predicted variety for meso-RUC at principal directions reveals essential structural difference for warp yarns layers and weft yarns layers system as shown in Fig. 2(b). The above predicted results are also similar with previous experimental in Table 1 (Lomov et al., 2009).

For the predicted mechanical behavior under fiber longitudinal loadings, there are two damaged kink corner with $\varepsilon_{11} = 0.68\%$ and $\varepsilon_{11} = 3.0\%$. Thus in the tested loading process, three damage stages are noticed with initial damage nearby $\varepsilon_{11} = 0.7\%$, further damage at $\varepsilon_{11} = 2.0\%$ and final fracture with ultimate strain of $\varepsilon_{11} = 3.25\%$. As a whole, the mechanical responses of meso-RUC and 3DOWC under in-plane principal loadings behave similar trend from initial damage to final failure, respectively.

4.3.2. Local response and damage evolution

The detailed damage mechanism of 3DOWC under warp yarns directional loading are analyzed by local response of matrix impregnated fiber bundles and pure matrix.

![Fig. 19. The predicted stress–strain curve of meso-RUC under in-plane principal tensile loadings.](image1)

![Fig. 20. Initial damaged evolution of meso-RUC under warp yarns directional loading.](image2)

(a) $\overline{\varepsilon_{11}} = 0.6\%$

(b) $\overline{\varepsilon_{11}} = 0.7\%$

![Fig. 21. Locations of damaged zone in meso-RUC under warp yarns directional loading at $\varepsilon_{11} = 0.75\%$.](image3)
With increase of applied strain-controlled loading $\varepsilon_{11}$, the preliminary cracked stage is initiated near $\varepsilon_{11} = 0.68\%$ as shown by $S_{11}$ in Fig. 19. Before the damage initiation such as the loading of $\varepsilon_{11} = 0.6\%$ in Fig. 20(a), as the reinforced structure system of 3DOWF, the warp yarns and Z-yarns undertake loadings directly. The higher stress concentrated zone is located in warp yarns and Z-yarns and highest one is in warp yarns around Z-yarns channels. For pure matrix in meso-RUC, the obvious stress concentration and maximum equivalent von-Mises stress occur in the intersected zone between warp yarns and weft yarns nearby the channels around the Z-bundles. Upon further loading of $\varepsilon_{11} = 0.7\%$ in Fig. 20(b), the 3DOWF still hold the higher loadings and obvious stress concentration occurs in yarns system (warp yarns, weft yarns and Z-yarns) nearby the channel of Z-binders. A little lower stress zone exists in ‘L’ corner area of Z-binders. For the matrix, the higher stress zone propagates from the out-plane zone around the Z-binders to in-plane intersected zone between warp yarns...
layers to weft yarns layers. The response of $S_{11}$ against averaged strain $e_{11}$ as shown in Fig. 19, the stiffness of meso-RUC decreases a little after further loading ($e_{11} > 0.68\%$), but much higher load are still undertaken in 3DOWF system as shown in Fig. 20(b). In pure matrix of meso-RUC, the higher stress zone has moved to intersected zone between in-plane the warp yarns layers and weft yarns layers in thickness direction. After a few iterations, the damaged zone is noticed obviously in weft yarns along transverse directions as shown in Fig. 21. The node 35,766 and node 51,275 are selected respectively in weft yarns and matrix, whose stress against strain responses are shown in Fig. 22. For node 35,766 on weft yarns in Fig. 22(a), the $S_{22}$ increases linearly firstly and then is reduced quickly in short time while the rest of stress components ($S_{ij}$) are transferred normally, which implies a crack is initiated with crack surfaces perpendicular to 2-direction in the local coordinate system (applied strain-controlled loading direction) as illustrated by 3DOWC composite where the damage starts with transverse cracks appearing in fill yarns (Ivanov et al., 2009). The weft yarns mainly hold compressive stress in fiber yarns direction and 3-direction with no obvious shear loadings. For the matrix on node 51,275 as displayed in Fig. 22(b), stress increases linearly initially before damage ($e_{11} < 0.68\%$). Then the nonlinear stress–strain behavior is observed with effect of initiated smear cracks in weft yarns and structural characteristics of 3DOWF ($e_{11} > 0.68\%$). The initiated smear cracks in weft yarns hinder the stress transformation normally among matrix and fiber yarns in particular orientation. For current loading status, no smear crack is created in matrix just by responses of node 51,275 while weft yarns have been damaged in transverse directions.

The second obvious decrease of stresses occurs near $e_{11} = 1.7\%$ in details by comparison of Figs. 23 and 24. With the load of $e_{11} = 1.5\%$ as displayed in Fig. 23(a), the warp yarns hold most of loads by highest stress distribution. For Z-yarns, the stress concentration is located at the middle fields of Z-yarns nearby surface layers. ‘L’ corner area of Z-yarns is with lower stress due to damage of the connected matrix. And the matrix is filled with higher stress distributed zone from area around Z-yarns channels to layers...
between warp yarns and weft yarns system. And further load of $\varepsilon_{11} = 1.75\%$ as shown in Fig. 23(b), the stress in Z-yarns is decreased with the initiation of cracks in matrix surrounding 'L' corner beam. The details for Z-yarns can be revealed with stress against strain responses of node 69,616 in Fig. 24. The six stress components value of Z-Z-yarns in fiber direction are less than the pre-defined failure criterion, with tensile loading of $S_{11}$ as leading load along fiber yarns direction. It means that the reduction of stress in Z-yarns is due to matrix damage, rather than the cracks to be initiated in Z-yarns. Furthermore, compared with maximum stress of $S_{11}$ at $\varepsilon_{11} = 1.7\%$, it is can be determined that the 'L' corner area in matrix is damaged and then the cracked zone propagates to zone between warp yarn layers and weft yarn layers as shown in Fig. 23(b). This result is that in such cross-over region, densely packed with mutually orthogonal Z and weft yarns becomes a natural local site of stress concentrations. This was confirmed by above predicted results and the experimental results (Ivanov et al., 2009).

For the further loading, the weft yarns are populated with transverse cracks, and there are also transverse cracks in the matrix pockets between them. The cracked initiated with and around Z yarn develop into local debonding cracks. Before $\varepsilon_{11} = 3.0\%$, there is still no larger scale damage involving warp yarn as whole (like mutual warp yarns splitting off) that may lead to the final macro-failure. Nearby $\varepsilon_{11} = 3.0\%$ (in Fig. 19), the final damage occurred. The averaged stress ($S_{11}$) for meso-RUC increases with peak value at $\varepsilon_{11} = 3.0\%$ due to fracture of warp yarns as shown in Fig. 25. The node 40,191 is selected in warp yarns and its mechanical responses are shown in Fig. 26. The $S_{11}$ increases linearly with ultimate stress of $\sigma_{11} = 1.608$ GPa at $\varepsilon_{11} = 3.0\%$. Then it reduces towards to small value in a short time, leaving a smear crack to be created in node 40,191 with its surfaces perpendicular to warp yarns direction.

For complete investigation of damage mechanism for 3DOWC under in-plane principal loadings, the damage procedure of meso-RUC under weft yarns directional loading is introduced by $S_{22}$ in Fig. 19. The stress against strain cure under weft yarns directional loading ($S_{22}$) has similar response with that along warp yarns directional loading ($S_{11}$).

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Fig. 28. locations of damaged zone in meso-RUC under weft yarns directional loading at $\varepsilon_{22} = 0.9\%$.

Fig. 29. Mechanical responses of local nodes in warp yarns, matrix and Z-yarns respectively.
Fig. 27 shows the local stress distribution and damage initiation of 3D orthogonal woven fabric (3DOWF) and matrix separately under initial loading in weft yarn direction ($\tilde{e}_{22} = 0.7\%$). For $\tilde{e}_{22} = 0.6\%$ the weft yarns carry the load mostly and directly. Compared by Fig. 20(a), the Z-bundles hold lower stress level for current applied load. For matrix, the higher stress zone is distributed in the intersected zone between the warp yarns layers and weft yarns layers as displayed in Fig. 27(a). With further loading of $\tilde{e}_{22} = 0.8\%$, it developed into the fields between weft yarns and warp yarns system as displayed in Fig. 27(b). The weft yarns still hold most of applied load and the warp yarns/Z-yarns undertake higher loading than before with effect of filled matrix around the resin impregnated fiber bundles. To analyze the local mechanical responses for warp yarns, matrix and Z-yarns, three nodes on warp yarns (N69423), matrix (N69342) and Z-Z-yarns (N69616) are selected as shown in Fig. 28, respectively. The corresponding mechanical behaviors are displayed separately in Fig. 29(a)–(c). For initial loading ($\tilde{e} \leq 0.7\%$), similar local responses under in-plane principal loadings ($\tilde{e}_{11}$ and $\tilde{e}_{22}$) are found by Figs. 22 and 29(a) and (b). It shows similar damaged mechanism for crack initiation and evolution. The $S_{22}$ in Fig. 22(a) and $S_{33}$ in Fig. 29(a) commonly reveal that the smear crack is easily created in resin impregnated fiber bundles transversely with their surfaces perpendicular to loading direction (Ivanov et al., 2009). With evolution of damaged zone, the stress in matrix show similar trends in Figs. 22 and 29(b). No obvious higher shear stress ($S_{12}$, $S_{13}$ and $S_{23}$) is observed. Furthermore, different mechanical responses of Z-yarns are noticed in Fig. 29(c), being compared with Fig. 24. The Z-yarns undertake compressive loading ($S_{11}$) in fiber yarns direction and are damaged transversely in form of smear crack (with $S_{33}$ perpendicular to the surface of crack).

Upon further loading ($\tilde{e}_{22} = 1.7\%$) as shown in Fig. 30(a), the weft yarns undertake most of applied load. And the warp yarns and Z-yarns are further damaged transversely along loading direction just shown by 3DOWC composite sample (Ivanov et al., 2009). With effect of fiber yarns (warp yarns, weft yarns and Z-yarns), the matrix has higher stress distribution located among the fiber yarns (3DOWF) compared with initial loading in Fig. 27(a). This higher stress concentrated zone is source of damage and cracked with increase of applied load ($\tilde{e}_{22} = 2.65\%$) in Fig. 30(b). The resin filled zone between weft yarns and warp yarns is damaged gradually.
With evolution of damaged zone in matrix, the load is hindered to be transferred to the warp yarns, Z-yarns from matrix and weft yarns. Only the weft yarns can undertake the higher load. At strain of $\varepsilon_{22} = 3.0\%$ as shown in Fig. 19, the maximum peak value of stress ($\sigma_{zz}$) is reached and its local response is obtained in Fig. 31 (One node is selected in weft yarns by N69240) and Fig. 32. The stress ($\sigma_{yz}$ in Fig. 32) shows the smear cracks have been created similarly with above-mentioned in Fig. 26. Its maximum failure strength keeps consistent with the failure criterion for fiber bundles in fiber yarn direction ($\sigma_{f11} = 1.637$ GPa) in Table 3.

Compared with mechanical responses and damage evolution of meso-RUC under in-plane principle loadings, separately, the detailed damage mechanisms of 3DOWC are revealed essentially. Along warp (weft) yarns directional loading, the weft (warp) yarns are damaged initially in transverse direction. Then matrix around the Z-yarns channels is damaged with increase of applied load. Finally the warp (weft) yarns fracture. The matrix transfers the load among warp yarn, weft yarns and Z-yarns. Finally warp (weft) yarns hold higher load up to fracture. For warp yarns directional loading, similar damaged procedure of damage initiation and propagation in 3DOWC is also observed on damaged morphology.

5. Concluding remarks

The nonlinear mechanical responses and damage mechanism of 3D orthogonal woven composite (3DOWC) are obtained combined multi-scale RUCs and nonlinear viscoelastic model with damage evolution. The predicted mechanical results display their mechanical nonlinearity, damage initiation and growth under monotonic axial loading, revealing the local and global response of the 3DOWC including the damage mechanism. In the micro-RUC, the damage is easily created initially in resin-rich zone and develops around fiber under transversely loadings. The fiber determines the axial elastic modulus and failure strength of micro-RUC and no obvious stress concentration is noticed due to structural symmetry of fiber packed pattern. For the meso-RUC under warp yarns directional tensile loading, the crack is initiated firstly in fields of resin pocket around L corner of Z-yarns. Then the cracked damage propagates along Z-yarns. Simultaneously another damaged zone is occurred in weft yarns in transversely parallel to loading direction. Upon further loading, the matrix between weft yarns and warp yarns layers starts to be damaged in thickness direction. And the loading warp yarn fractures ultimately leaving the 3DOWC without capability of load. The above damage procedure is observed for meso-RUC under weft yarn loading and verified by experimental results.

Acknowledgments

The authors acknowledge the financial supports from the National Science Foundation of China (Grant Number 11272087). The financial supports from Foundation for the Author of National Excellent Doctoral Dissertation of PR China (FANEDD, No. 201056), Shanghai Rising-Star Program (11QH1400100) and the Fundamental Research Funds for the Central Universities of China are also gratefully acknowledged.

References


