Ballistic impact damages of 3-D angle-interlock woven composites based on high strain rate constitutive equation of fiber tows

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ABSTRACT

This paper reports the ballistic impact damage of three-dimensional angle-interlock woven composite (3DAWC) under a hemispherical rigid projectile penetration on the basis of high strain rate constitutive equations of fiber tows and multi-scale geometrical model of the 3DAWC. The constitutive equations of the Twaron® fiber tows (poly paraphenylene terephalamide, PPTA) under high strain rates have been established to characterize the mechanical behaviors under impact loading. The Twaron® fiber tows were assumed as transversely isotropic viscoelastic material to derive the constitutive equations. The maximum strain failure criterion was adopted for defining the failure of the PPTA fiber tows. A user-defined subroutine UMAT (FORTRAN user-material subroutine) was written for combining both the constitutive equations and the failure criterion in numerical calculation. Based on a micro-scale geometrical model of the 3DAWC, the UMAT for the PPTA fiber tows was combined with a commercial available finite element method (FEM) software package LS-DYNA to calculate the ballistic impact damage when the 3DAWC panel penetrated under a hemispherical–cylindrical steel projectile. It was found that the FEM simulation agrees well with the experimental results. The impact damage morphologies and damage propagations, the energy absorptions and the stress distributions in the 3DAWC panel were presented to elucidate the ballistic penetration damage mechanisms for optimizing the ballistic protection capacity of the 3-D woven composite material.

1. Introduction

Researchers had started the programs on a new lightweight strong fiber since early 1960s profiting from their knowledge of rayon, polyester and nylon processing [1]. Stephanie Kwolek, a female Polish-American chemist, synthesized and invented poly paraphenylene terephalamide (PPTA) in solution while she was working for Du Pont [2], and the original Kevlar patent was awarded to her in 1974 [3]. After that, researches on PPTA together with its applications have been flourishing in different fields, such as bullet-proof vest, aerospace crafts and armored vehicles [4,5]. In merit of high performance fiber bundles and textile structural reinforcement, 3-D textile composites have high impact damage tolerance and delamination resistance [6].

PPTA is a high modulus, high tenacity fiber from liquid crystalline solutions of synthetic para-aromatic polyamides [7]. Many investigations have been carried out to reveal the relationship between molecular structure and mechanical properties of PPTA [8–14]. Dobb et al. [10] studied supramolecular architecture of the aromatic polyamide fiber and analyzed a system of sheets regularly pleated along longitudinal direction. Rao et al. [11,12] found that structural modifications by shifting treatment conditions. Lacks et al. [13] presented molecular simulations to investigate the compressive failure of PPTA fibers for elastic buckling instability between hydrogen-bonded sheets. Grujicic et al. [14] studied the effect of four microstructural and topological defects on the strength, ductility, and stiffness of PPTA fibers/filaments, with taking stacks of sheets and an array of nearly parallel hydrogen-bonded molecules/chains into consideration. It is concluded that the mechanical behaviors of the PPTA fibers are mainly depend on a sheet-like structure including aromatic stacking interactions and the inter-chain bonds between the carbonyl groups and NH centers. Moreover, because of the inter-chain interaction of hydrogen bond in PPTA, the compressive strength is even greater than that of the poly p-phenylene benzobisoxazole (PBO) fiber which has higher initial tensile strength and modulus [15].

The mechanical behaviors of PPTA fibers under impact loading are different with that in the quasi-static loading. This is the rate dependent behaviors of the PPTA fibers. Wang et al. [16,17] tested the tensile behaviors of PPTA fiber tows under different strain rates.
They found that the Kevlar 49 fiber tows are sensitive to strain rate. Zhu et al. [18] found that the mechanical parameters of Kevlar 49, such as young’s modulus, tensile strength, maximum strain, and toughness, are also strain rate dependent. Languerand et al. [19] investigated the inelastic behaviors and fracture mechanism of PPTA fiber bundles under high strain rate loading using a Kolsky tension bar. Zhou et al. [20] carried out different strain rates tests for tensile behavior of Kevlar fiber reinforced aluminum laminates and found that the constitutive equations derived from the Weibull strength theory have good agreement with those in experimental. Tan et al. [21] conducted tensile tests for aramid yarns and employed a viscoelastic material model to present the mechanical behaviors under high strain rates. Shim et al. [22] established a three-element linear viscoelastic model to describe the mechanical behaviors of Twaron fibers under different strain rates. The results show that the combination of dashpots and springs can represent the constitutive relation of PPTA fiber tows under high strain loading.

The woven fabrics of PPTA fiber also exhibit strain rate sensitivity [22–27]. It was found that the tensile strength and modulus of fabric increase with strain rate while the failure strain decreases, and also fail in a more brittle fashion as the strain rate increases. As for the 3-D woven fabrics, the authors also found that both the mechanical behaviors of 3-D orthogonal and 3-D angle-interlock woven fabric are sensitive to the strain rates [28,29].

Both for the PPTA fibers, fiber tows and fabrics, the strain rate sensitivity comes both from the fiber materials and the woven structures. It can be concluded that high strain rate responses and impact behaviors of PPTA fiber are significantly different from that of static loading tests. For the molecular structure of PPTA, inter-chain bonds form the rigid part of a PPTA fiber represented by elastic spring model, while aromatic stacking interactions lead to fluid-like behavior which can be expressed as dashpot model. Therefore the rate dependent behaviors of the PPTA fiber can be simplified by the combination of spring model and dashpot model.

The ballistic penetration damage of the 3DAWC has been investigated at the micro-structure level with the commercial finite element analysis (FEA) software of LS-DYNA by the authors of this paper [30]. The standard material model in LS-DYNA was used to characterize the constitutive equation of the PPTA fiber. However, this standard material model cannot reveal the molecular structure and deformation mechanisms of the PPTA fiber under impact loading. In this paper, a user-defined material model of PPTA fiber

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**Table 1**

<table>
<thead>
<tr>
<th>Mechanical parameters of Twaron° untwisted filament yarns.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass density, ρ (g/cm³)</td>
</tr>
<tr>
<td>--------------------------</td>
</tr>
<tr>
<td>1.44</td>
</tr>
</tbody>
</table>

**Table 2**

Specifications of the 3-D angle-interlock woven fabric.

<table>
<thead>
<tr>
<th>Fabric type</th>
<th>Count (dtex) warp/weft</th>
<th>Material type warp/weft</th>
<th>Densities (ends and picks/1 cm)</th>
<th>Fabric weight (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle-interlock</td>
<td>1680 × 2/1680 × 4</td>
<td>Kevlar/Kevlar</td>
<td>8 × 11/4 × 12</td>
<td>8600</td>
</tr>
</tbody>
</table>

**Table 3**

Mechanical parameters of unsaturated polyester resin.

<table>
<thead>
<tr>
<th>Tensile modulus, $E_m$ (GPa)</th>
<th>Shear modulus, $G_m$ (GPa)</th>
<th>Poisson’s ratio, $\gamma$</th>
<th>Tensile strength, $X_T$ (MPa)</th>
<th>Compressive strength, $X_C$ (MPa)</th>
<th>Shear strength, $S_S$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.8</td>
<td>2.46</td>
<td>0.38</td>
<td>338.4</td>
<td>366.8</td>
<td>153.6</td>
</tr>
</tbody>
</table>

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Fig. 1. Molecular structure of PPTA.

Fig. 2. Twaron° untwisted filament bundle.
tow with strain rate dependent behavior was established to introduce into a FEA model. The user-defined material model was also transformed to a user-defined material subroutine (UMAT) and connected with the LS-NYNA. The ballistic penetration damage of the 3DAWC was calculated based on the geometrical model developed by the authors of this paper [30]. The ballistic penetration damage mechanisms were also analyzed from the damage morphologies and stress wave propagations in the fiber tows and resins. We hope such an effort could be extended to the ballistic impact design of the structures made of 3D woven composite materials.

2. Twaron® untwisted filament yarn

As above-mentioned, Twaron® is a kind of high performance para-aramid fiber. It has high ratio of strength-to-weight, high Young’s modulus and tensile tenacity. The creep of Twaron® filament yarn is relatively lower than nylon fibers.

The molecular formula of PPTA is \([\text{CO} – \text{C}_6\text{H}_4 – \text{CO} – \text{NH} – \text{C}_6\text{H}_4 – \text{NH}]_n\). The simplest form of the AABB para-polyaramide is polymerized from \(\rho\)-phenylene diamine (PPD) and terephthaloyl dichloride (TDC). Fig. 1 shows different sectors of PPTA molecule. Sector A is monomer unit of PPTA as a rigid part of polymer molecule. Sector B is the inter-chain bonds between the carbonyl groups and NH centers. Those two sectors control the PPTA molecule strength and modulus. Sector C, hydrogen bond between molecular chains, provides hydrogen bonding force to aromatic stacking interaction of adjacent strands. This sector makes the molecule more flexible. In other words, PPTA molecule can be viewed as nylon with extra benzene rings in the polymer chain to increase stiffness. For those different sectors, PPTA conducts both good stiffness and higher toughness.

Additionally, the van der Waals forces also contribute to interactions and orientation of molecules. Though it is weaker than hydrogen bond or covalent bond, synergistic effect of van der Waals forces should be taken into consideration.

Because of inner sheet-like molecular structure, Twaron® filament shown in Fig. 2 has a high degree of preferentially orientation along the fiber axis, which is the reason why Twaron® has unique characteristics apart from other synthetic fibers. Therefore, it is important to realize basic PPTA molecular structure for the constitutive relations of Twaron® filament bundle. Table 1 lists the mechanical parameters of Twaron® untwisted filament tow used in the 3DAWC.

3. Three-dimensional angle-interlock woven composite

The 3D angle-interlock woven fabric (3DAWF) structure is to interlock different layers of warp yarns with the weft yarns. Compared with 3-D woven structure formed by stitched fabric, there is no damage in warp and weft yarns caused by stitching. The woven architecture of the 3DAWF can be easily adjusted to manufacture the composite panels with different thicknesses. By increasing warp yarn layers, high thickness fabric can be woven. In general, the warp yarns in the 3DAWF structure are crimp while the weft yarns are straight.

The 3DAWF reported in this paper was woven by interlacing two adjacent layers of weft yarns with warp yarns. Such a structure will enable the fabric more flexible. The warp yarns and weft yarns are both the Twaron filament tows manufactured by Akzo Nobel. Twaron® is a kind of aramid fiber (poly paraphenylen ter-ephalamide, PPTA) similar to that of Kevlar® of Dupont De Nemours. The fineness of the warp and weft filament tows is 3360 dtex and 6720 dtex, respectively (tex is a basic textile unit of linear density – the weight in grams of a fiber in a length of 1 km.

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**Table 4**

Mechanical parameters of the simplified 3DAWC.

<table>
<thead>
<tr>
<th>Tensile modulus (GPa)</th>
<th>Shear modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Shear strength (GPa)</th>
<th>Tensile strength (GPa)</th>
<th>Compressive strength (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_1)</td>
<td>(E_2)</td>
<td>(E_3)</td>
<td>(G_{12})</td>
<td>(G_{13})</td>
<td>(G_{23})</td>
</tr>
<tr>
<td>55.3</td>
<td>16.0</td>
<td>16.0</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
</tr>
</tbody>
</table>
Units \(= \text{g/km} = (\text{g/cm}) \times 10^{-5}, 10 \text{dtex} = 1 \text{tex})\). The specifications of the 3DAWF are listed in Table 2. Table 3 lists the parameters of the 3DAWC panel for the ballistic impact tests.

Unsaturated polyester resin was injected into the preform adopting VARTM (vacuum assisted resin transfer molding) technique to form the 3DAWC. Table 3 lists the mechanical parameters of the resin.

Basing on weight of 3DAWF and the specifications of 3DAWC, the fiber volume fraction of 3DAWC is 44.6% calculated from:

\[
V_f = \frac{m_{3DAWF}}{\rho_{3DAWC}}
\]

where \(m_{3DAWF}\) is the weight of 3DAWF, \(\rho\) is the density of Twaron®, \(V_{3DAWC}\) is the volume of 3DAWC panel.

The cross section of the 3DAWC is shown in Fig. 3, where the configuration of interlock yarns in the thickness direction can be observed. After consolidation of the unsaturated polyester resin, the composite sample was cut according to the in-plane dimension of 192 \(\times\) 214 mm. The thickness of the composite panel is 10.8 mm.

In the continuum model, the mechanical parameters of the 3DAWC were derived from the material parameters of Twaron® filament and resin [as shown in Tables 1 and 3] by using the ‘Fiber inclination model’ [31]. This model combines the 3D textile geometrical structure and classical laminated plate theory to idealize the 3D textile structure as an assemblage of four unidirectional laminate. Table 4 shows the deduced material parameters of unidirectional laminate. From structure parameters of woven fabrics and the unidirectional laminate, the ballistic penetration of the 3DAWC panel could be calculated in a simple way [31].

4. High strain rate constitutive equations and viscoelastic model of PPTA fiber

4.1. Constitutive relations of strain rate dependent model in yarn axis direction

Benzene ring combines with inter-chain bonds together to form rigid strands aligning along fiber axis. Those rigid strands behave like Hookean springs standing for elastic behavior of polymer fiber. The van der Waals forces and hydrogen bonds control the relative movement of adjacent strands, which can be represented by viscous effects of Newtonian dashpot. According to the relationship between inner-structure and filament mechanics, untwisted...
filament yarn will be treated as linear viscoelastic material. Three elements springs and dashpot system which is called the standard linear solid model are shown in Fig. 4.

The constitutive relations of fiber bundle in axis direction can be written as:

$$\sigma + \frac{\eta}{D_1 + D_2} \dot{\varepsilon} = \frac{D_1 D_2}{D_1 + D_2} \varepsilon + \frac{D_1}{D_1 + D_2} \dot{\varepsilon}$$  \hspace{1cm} (2)$$

where $\sigma$, $\varepsilon$, $\dot{\varepsilon}$ are the stress, strain and strain rate. $D_1$ and $D_2$ are spring stiffness, $\eta$ is viscosity constant. Suppose the filament is under a constant strain rate load,

$$\dot{\varepsilon} = C \quad \text{constant}$$  \hspace{1cm} (3)$$

and the initial conditions are as follows,

$$\varepsilon = 0, \quad \dot{\varepsilon} = 0, \quad \text{and} \quad \sigma = 0$$

From constitutive equation (Eq. (2)), an explicit expression of stress is

$$\sigma = \frac{D_1 D_2}{D_1 + D_2} \varepsilon - \frac{D_1^2 \eta}{D_1 + D_2} \dot{\varepsilon} \left( e^{-\frac{(D_1 + D_2)}{\eta} \dot{\varepsilon}} - 1 \right)$$  \hspace{1cm} (4)$$

then

$$\frac{d\sigma}{d\varepsilon} = \frac{D_1 D_2}{D_1 + D_2} + \frac{D_1^2}{D_1 + D_2} \dot{\varepsilon} \left( e^{\frac{(D_1 + D_2)}{\eta} \dot{\varepsilon}} \right)$$  \hspace{1cm} (5)$$

Eq. (5) includes strain rate variable $\dot{\varepsilon}$ which can represent rate sensitivity of material. $D_1$, $D_2$ and $\eta$ are regarded as input material parameters in LS-DYNA keywords. The material parameters and test data were referred as published literature [21,22].

4.2. Constitutive relation of Twaron® untwisted filament bundle

Fig. 5 is diagram of Twaron® untwisted filament bundle. From the diagram, we can tell that untwisted filament yarn has one axis of symmetry and fibers randomly distribute in cross section. It can be regarded as a transversely isotropic material.

The constitutive relation of transversely isotropic material is:

$$\{\sigma\} = [C]\{\varepsilon\}$$  \hspace{1cm} (6)$$

where $[C]$ is stiffness matrix of material. It is can be described by five constants. When axis of symmetry is the yarn axis direction, following relationship should be obeyed:

$$\frac{v_{ij}}{E_i} = \frac{v_{ji}}{E_j} \quad i,j = 1,2,3 \quad \text{and} \quad i \neq j$$  \hspace{1cm} (7)$$

The components of compliance matrix is written in terms of five engineering constants as follows,
The components of stiffness matrix given in term of engineering constants as

\[
[C_d] = [S_d]^{-1} = \begin{bmatrix}
\frac{1 - \nu_{23} \nu_{32}}{E_2 E_3 d} & \frac{\nu_{21} + \nu_{31} \nu_{23}}{E_2 E_3 d} & \frac{\nu_{31} + \nu_{13} \nu_{32}}{E_2 E_3 d} \\
\frac{1 - \nu_{13} \nu_{31}}{E_1 E_3 d} & \frac{\nu_{32} + \nu_{12} \nu_{31}}{E_1 E_3 d} & \frac{1 - \nu_{12} \nu_{21}}{E_1 E_2 d} \\
\end{bmatrix}
\]  

(12)

\[D(\nu) = \frac{1 - \nu_{12} \nu_{21} - \nu_{23} \nu_{32} - \nu_{31} \nu_{13} - 2 \nu_{21} \nu_{32} \nu_{13}}{E_1 E_2 E_3}\]  

(14)

where \(G_{12} = G_{13}\), \(E_2 = E_3\) and \(\nu_{12} = \nu_{13} = \nu_{21} \times E_1 / E_2 = \nu_{31} \times E_1 / E_3\) for transversely isotropic material.

The shear modulus \(G_{12}\) and \(G_{13}\) are defined as strain rate dependent. From Eqs. (5) and (7), the relationship of dependency:

\[
[C_s] = [S_s]^{-1} = \begin{bmatrix}
G_{23} & 0 & 0 \\
0 & G_{13} & 0 \\
0 & 0 & G_{12} \\
\end{bmatrix}
\]  

(13)

Fig. 10. (a) Micro-structure of 3DAWC and detailed magnification; (b) comparison between micro-structure model and actual structure of 3DAWC.
where \( \gamma \) is the shear strain, \( \dot{\gamma} \) is the shear strain rate. From Eqs. (6) and (12)–(15), the incremental form of stress-strain constitutive equations can be deduced for updating the stress vector.

### 4.3. Failure criteria

In the continuum damage mechanics, the independence of damages avoids the seeking for a damage dissipation function often utilized. The damage of filament bundle is assumed to be independent ultimate strain failure mode in axis direction and transverse direction. During penetration progress, the compression failure occurs at the beginning part of composite panel, little damage is caused by compression and we eliminated the compression failure of filament bundle. Damage evolution in fiber axis and shear deformation of resin lead to ultimate failure of the 3DAWC. When the strain reach maximum strain of fiber or resin,

\[
\varepsilon_1 > X_1, \quad \varepsilon_t > Y_\epsilon, \quad \varepsilon_m > Z_m
\]

the element of FEM will be deleted, where \( \varepsilon_1, \varepsilon_t, X_1, Y_\epsilon, \varepsilon_m, Z_m \) are strains, maximum strains in fiber axis and transverse direction, respectively. \( \varepsilon_m \) and \( Z_m \) is strain, maximum strain of resin.

### 5. User-defined material in LS-DYNA

The explicit finite element code LS-DYNA was utilized to simulate the ballistic penetration of 3DAWC. In flow chart of the simulation procedure as shown in Fig. 6, the UMAT of Twaron® untwisted filament bundle was compiled and connected with the LS-DYNA. Strain increments, history variables, current time step, and current accumulated time supplied by main program were passed to the constitutive equations in UMAT. Calculated results of stress and history variable were given back to main program for next time step. Maximum strain failure criterion was applied to determine the failure of the elements. Elements will be deleted after it reaches to a maximum strain.

### 6. Multi-scale finite element model of ballistic penetration

#### 6.1. Geometrical model of 3DAWF

Based on basic parameters of materials in Table 2 and the definition of the “dtex”, a basic textile unit of linear density = the weight in grams of a fiber in a length of 1 km, units = g/km = (g/cm) \( \times \) 10\(^{-5}\) / 10 dtex = 1 tex:

\[
dtex = \frac{G}{L \times 10,000}
\]

(17)

\[
G_{\text{warp}} = 2G_{\text{weft}}
\]

(18)

where \( L \) is yarn length (m) and \( G \) is yarn mass (g).

Assuming filament bundle’s cross sectional area is idealized circle and its density is consistent, from relationship of yarn mass:

\[
D_{\text{weft}} = \sqrt{2}D_{\text{warp}}
\]

(19)

The total thickness of the composite panel is expressed as:

\[
T = N_{\text{warp}}D_{\text{warp}} + N_{\text{weft}}D_{\text{weft}}
\]

(20)

where \( D_{\text{warp}} \) and \( D_{\text{weft}} \) are diameter of warp and weft, \( N_{\text{warp}} \) and \( N_{\text{weft}} \) are the number of warp and weft in through thickness direction respectively.

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**Fig. 11.** Strike velocity vs. residual velocity curves in two FEM schemes and experimental.

**Fig. 12.** Velocity vs. time history and acceleration vs. time history of the projectile at the different strike velocities.
From Eqs. (19) and (20), the diameters of warp and weft as shown in Fig. 7 are obtained. Otherwise, based on the yarns spatial geometrical relations, we can set up the geometrical model of weft and warp, which is also shown in Fig. 7.

Duplicating and rotating the geometrical model in Fig. 7 in turns along both weft and warp directions, geometrical model of 3DAWF in Fig. 8 was established.

6.2. Geometrical model of 3DAWC under ballistic penetration

A geometrical model of the 3DAWC was established by the authors of this paper [30] in design software (Pro/Engineering® 5.0). For improving simulation efficiency, only one-quarter of the 3DAWC panel was modeled in the FEA. In Fig. 9, the model consists two parts. One is micro-structure of 3DAWC around impact point and another is continuum model. The sizes of the panel in the geometrical model are 100 mm × 100 mm × 10.8 mm, and in the micro-structure model are 40 mm × 40 mm × 10.8 mm. The micro-structure part was modeled in accordance with basic parameters of 3DAWC shown in Fig. 1, such as the fiber tows’ diameter, fiber tows configuration and fiber volume fraction. The undulate morphology of warp yarn in micro-structure was obtained and then Boolean operation was carried out for cutting the 3DWAF’s geometrical model from cubic solid to form space structure of resin.

6.3. Finite element model of ballistic penetration

The geometrical model of the 3DAWC is extended from a continuum model of Cui et al. [31]. The continuum model was meshed with hexahedron elements, while the micro-structure model was...
meshed with four-node tetrahedron elements. For the surrounding parts in the 3DAWC composite panel, there are no damage and little deformation occurring in this area during ballistic penetration. Hence this part can be homogenized as a continuum model without yarn structure and the part around penetration point was modeled as a micro-structure model.

Fig. 10a shows the detailed information of the micro-structure of the 3DAWC composite material and the projectile. There are 10,044,800 elements and 2,277,571 nodes in the micro-structure model and 1,575,840 elements and 1,622,247 nodes in the continuum model. Projectile was meshed with 521,760 hexahedron elements and 527,098 nodes. In this mesh scheme, 10 million fine elements exist in the micro-structure model. With uniform meshes, the amount of computational time is too large to enable us to obtain useful numerical approximations. This is another reason to adopt a continuum model in this FEM of ballistic penetration. Otherwise, both the computational grid number and size have effect on calculation precision and time, which will be discussed in Section 6.4. Two parts were merged by sharing nodes to ensure smooth transferring of energy distribution and stress wave.

Fig. 10b displays the comparison between micro-structure model and actual structure of 3DAWC. The micro-structure model is in accordance with the actual 3D yarn distribution, providing an accurate model to calculate the ballistic performance of 3DAWC.

One-quarter of FEM was modeled, thus two symmetry planes were defined in the thickness direction. The other two planes in the thickness direction were defined with 0 degree of freedom, because all of four sides of composite target being clamped by securing device. As for bullet, only 1 degree of freedom in penetration direction is allowed to move. Those boundary conditions were employed and suitable for vertical ballistic penetration problem.

For material models, the FEM was improved by invoking UMAT of Twaron® untwisted filament bundle as mentioned above, which will also help to increase simulation accuracy. Material model of resin is standard model in LS-DYNA.

### 6.4. Contact definition and calculation time

Contact algorithm of sliding and impact along interfaces is an important approach in LS-DYNA. Interfaces including slave surface and master surface are listed in arbitrary order all triangular and quadrilateral segments. In addition to symmetric penalty method, the nodes lying on slave surface are constrained to the master surface after impact, and the constrain will stay until a tensile force works between slave node and master surface. The contact interface between the 3DAWC composite panel and projectile was defined as “ERODING_SURFACE_TO_SURFACE”. The impact dynamics and concerned finite element algorithms can be found in [32].

In the multi-scale model, the continuum model and the micro-structure model were discretized into hexahedron elements and tetrahedron elements, respectively. Calculating time in LS-DYNA is determined by the length of the shortest side, i.e., by the shortest side of hexahedron or tetrahedron element. In the model, the tetrahedron element is much smaller hexahedron element. The smallest tetrahedron element determines the calculating time of the FEM. Meanwhile, the time step size $\Delta t$ should be less than the stress wave transmission time $\Delta t_e$ in the smallest element.

$$\Delta t < \Delta t_e$$

Hence, a scale factor $\alpha (0 < \alpha < 1)$ is set to satisfy time step $\Delta t$ is less than the stress wave transmission time $\Delta t_e$. Therefore the time step $\Delta t$ of $m$ elements at next calculating step is

$$\Delta t^{n+1} = \alpha \cdot \min(\Delta t_1, \Delta t_2, \ldots, \Delta t_m)$$

and $\alpha$ is time step scale factor and its value is 0.9 or some smaller value for stability.

### 7. Results and discussions

#### 7.1. Impact velocity vs. residual velocity curves in experimental and FEM

Fig. 11 shows the comparison of impact velocity vs. residual velocity curves between experimental and two FEM simulation schemes. The fitting curve of FEM with UMAT (theoretical 2 fitting curve in Fig. 11) with considering the strain rate effect has the higher precision with the experimental (experimental fit curve) than the theoretical 1 fit curve from the FEM without involving the UMAT [28]. The accuracy of FEM is improved when the strain rate effect and the UMAT were employed in the FEA calculation. It indicates that the strain rate effect is an important factor to design the impact behaviors of the 3DAWC, especially at the high impact velocities.

Fig. 12 shows velocity vs. time history and acceleration vs. time history of the projectile at the different strike velocities. As shown in Fig. 12a, the lower the impact velocity is, the more penetration time the projectile will have. This means that the bullet at lower impact velocity will spend more time to perforate the composite
target. The differences of velocity vs. time history curve increase as much as the perforate time. Taking 210 m/s for example, it is a velocity around the ballistic limit and decrease to 0 at the end of penetration, and the projectile was arrested by the composite panel. During the penetration, the velocity decreases significantly which lead to the biggest absolute difference of seven velocities. After this stage, the projectile flies at a relatively low velocity, closes to zero and is caught by the panel in the end. These two stages lead to a longer penetration time for this velocity. Also, the shape of curve indicates a typical decline trend of the ballistic limit velocity for 3DAWC.

In Fig. 12b, the first five acceleration curves have a similar trend during ballistic penetration. At the beginning of perforation, the composite panel is hit by the head of projectile, and the acceleration increases sharply. The acceleration fluctuates up and down in different time step for the element deletion and the non-simultaneous breakage between yarn and matrix. The relationship between peak acceleration and the impact velocity is notable. For the higher impact velocity, the peak acceleration is greater. According to Newton’s law, this also represents the impact force on the composite panel. For instance, the peak acceleration of 550 m/s is the greatest among those velocities and the composite target suffers the maximum impact force. Otherwise, the acceleration curves of two velocities around ballistic limit velocity show a different acceleration states after reaching the peak value. In this stage, the average value of acceleration is obviously higher than that of the other five velocities. The projectile with lower velocity around ballistic limit velocity will be subjected to resistance of the composite for a longer time, and perforate the composite target in a low residual velocity or even decrease to zero. Hence, the acceleration curves of 220 m/s and 222 m/s have plateau with a continued fluctuate and fall sharply in the end of penetration.

![Fig. 16. Ballistic penetration damage evolution of the composite panel under the impact velocity of 550 m/s (45° view and front view).](image)
7.2. Damage morphologies

The theoretical damage morphology shows a good agreement with experimental as shown in Fig. 13. In Fig. 13a, it is the final damage stage when the projectile flies away from the rear surface of composite target. In order to illustrate clearly, the damage morphologies of the reinforced fabric and resin were given separately. Local fractures, pull-out, extrusion, debris of filament tow occur in the penetration area, which result from a complex damage evolution. And, the resin damage morphology is similar comparing with reinforced fabric. That is because that it is cracked as the progress of the yarn deform and breakage, and attached to the fractured filament yarns. The cross section of damage area is illustrated in Fig. 13b. It is easy to be found that the 3DAWC is damaged without delamination. The thickness direction of 3DAWF is reinforced by the integrated interlock structure so that no delamination appears in different layers, and in the meantime the resin consolidation also contributes to the structural stability for this phenomenon of ballistic impact of 3DAWC.

7.3. Impact deformation

As shown in Fig. 14, there are seven selected nodes to illustrate the impact deform of 3DWAC. Node 2381486 is the node on the filament yarn which will be pulled out after penetration. Node 2382785 and node 2384782 is located around the ballistic hole. The other nodes are far from the ballistic hole distributing at different distances or layers. Fig. 15 shows the deflection vs. time history of
selected nodes before 60 μs under the strike velocity of 395 m/s. As the node on the pull-out yarn, node 2381486 has a larger deflection with nonlinear increase among those 7 nodes before the projectile rushes out of the rear surface. For node 2382785 around the ballistic hole, it is in the middle of composite target and deformed by the shear force, whose deflection is similar but smaller than node 2381486. But for node 2384782, the beginning part of deflection is negative, showing that there is a bulging around ballistic hole when the projectile begins to penetrate the top surface of the target. Only a little deformation occurs in the middle distance from the ballistic hole as node 2428857 shown in Fig. 15. As for the three nodes at different layers far away from the penetration line, almost no deformation occurs.

7.4. Ballistic damage evolution

Fig. 16 reveals the ballistic damage evolution of the composite target under the impact velocity of 395 m/s at different time steps. In Fig. 16a and b, caused by the initial contact between the hemisphere head of projectile and the 3DAWC panel, the compression and shear stress waves travel along the thickness direction. In this stage, the compression stress dominates the initial damage. Under the stress transformed from the kinetic energy of the projectile, the area around penetration hole is compressed, resin is cracked and filament yarns are distorted. As the vertical surface of projectile plugging into composite displayed in Fig. 16c, the contact surface between them is becoming larger. This will give rise to the shear stress and the stress will spread to neighbor area of penetration hole in the stage. Some filament yarns on the top surface are cut off by the shear stress as shown in Fig. 13b. At the meantime, there will be a bulge formation in the rear surface under the compression stress. From Fig. 16d—f, the stage expresses the escaping progress of projectile and the composite target is finally perforated. The projectile brings some debris of yarns and resin, and pulls out filament yarns. And in the end the stress wave spread to the whole composite panel which absorbed the most of kinetic energy of projectile.

7.5. Energy absorption

In the FEM, no external forces were applied in the projectile—target penetration system. Only initial impact velocity was introduced to the projectile. Hence, the external energy is zero, while the total energy is constant during the penetration progress. The change of kinematic energy $\Delta E_{\text{Kinematic}}$ is

$$\Delta E_{\text{Kinematic}} = \Delta E_{\text{Internal}} + \Delta E_{\text{Sliding}}$$

(23)

where $\Delta E_{\text{Internal}}$ and $\Delta E_{\text{Sliding}}$ are the changes of internal energy and sliding energy, respectively. In other words, the whole change of kinematic energy corresponding from the velocity decrease of projectile is transformed and divided into the internal energy and sliding energy.

Fig. 17 shows energy vs. time history of the projectile-target system under the strike velocity of 395 m/s.

$$E_{\text{Total}} = E_{\text{Kinematic}} + E_{\text{Internal}} + E_{\text{Sliding}}$$

(24)

where $E_{\text{Kinematic}}$, $E_{\text{Internal}}$, and $E_{\text{Sliding}}$ are the residual kinematic energy, internal energy and sliding energy, respectively. Fig. 18 displays the energy proportion of two FEM strategies after 60 μs when striking velocity is 395 m/s.
As being illustrated, the proportion of residual kinematic energy

\[ E_{\text{Kinematic}} = \frac{1}{2}mV_{\text{residual}}^2 \]  

(25)

is the majority of the total energy, followed by the internal energy and the sliding energy. According to the comparison between the two FEM strategies, the proportion of internal energy and sliding energy is larger for the FEM with UMAT. The two FEM schemes have the same initial velocity and shape of projectile, and therefore the change of material property leads to this difference. As the effect of strain rate in UMAT, filament yarns in FEM behave more sensitive to high velocity impact. Especially for the internal energy \( E_{\text{Internal}} \), it contains different kinds of sub-energy concerning about UMAT, \( E_{\text{Internal}} = E_{\text{Deform}} + E_{\text{Debris}} + E_{\text{Fracture}} \) 

(26)

where \( E_{\text{Deform}} \) is the deform energy, \( E_{\text{Debris}} \) is debris residual kinematic energy of the target and \( E_{\text{Fracture}} \) is the fracture energy of filament yarns and resin, which are updated in main program basing on the stress and the strain rate dependent history variant (the shear modulus) calculated from the subroutine. Along with the factor of the strain rate, the internal energy was increased during calculation. Thus, the proportion of energy corresponding with strain rate will take up larger percentage of total energy.

The internal energy taking up 20.13% of total energy in Fig. 18(b) is also absorbed by different parts of FEM. Fig. 19 illustrates the internal energy proportion absorbed by different parts of the FEM with UMAT. As shown in Fig. 19, the 3DAWF absorb 53.6%, and continuum part absorbs 3.33%, while the resin absorbs 43.06% of the total internal energy. For the continuum part, the main energy absorption is the deform energy for there being no ballistic damage on it. Yet the internal energy absorbed by 3DAWF in micro-scale model takes up more than half of the total internal energy, which reveals that fiber assemblies in 3DAWC dominate the energy absorption during ballistic penetration. This is mainly caused by the different mechanical properties under high strain rate between Twaron® untwisted filament tows and unsaturated polyester resin. For example, from Table 2, the modulus of Twaron® untwisted filament tows is higher than that of unsaturated polyester resin, and the associated stress in filament yarns are higher than in the resin when the composite target is penetrated by bullet. Thus, according to the law of energy conversion and conservation, the energy stored in the fiber assemblies is higher than in the resin within the same displacement.

Furthermore, as can be seen from Fig. 19, the weft yarns in 3DAWF absorb 56.23% of the total internal energy, while the warp yarns absorb 43.77%. The internal energy absorbed by wefts is higher than warps. That is because there are 11 warps and 12 wefts through the thickness direction, and meanwhile the weft diameter is larger than warp. When the projectile strikes the composite target, resulting from the fundamental structure parameters of 3DAWF, more filaments in the weft system contributes to ballistic performance.

8. Summary and conclusions

A transversely isotropic nonlinear viscoelastic model was introduced to evaluate the mechanical behaviors of PPTA fiber tow. The model approximates the constitutive relation of macromolecular chain with the three-elements model. The shear modulus \( G_{12} \) and \( G_{13} \) are defined as strain rate dependent. This model was converted into a user-defined materials (UMAT) subroutine and connected with the commercial FEA software LS-DYNA. The ballistic penetration damage of the 3DAWC was calculated with the UMAT subroutine and the LS-DYNA.

The model was validated with the comparisons of ballistic penetration damages between experimental and FEA simulations. It is found that the strain rate factor considered in FEM with UMAT lead to more accurate results than that of FEM without UMAT subroutine. The damage morphologies and evolutions were presented to demonstrate the ballistic penetration damage features of the 3DAWC panel, which reveal that the stress propagation in 3D textile structural composite can be divided into three stages:

1. Initial impact by the projectile.
2. Perforation after the shear wave reaching to rear surface of the target.
3. Complete damage of the composite material panel.

Moreover, from the comparisons of energy proportion between two FEM schemes, it is found that the internal energy is obviously...
influenced by the strain rate dependent mechanical behaviors of yarns. The internal energy absorbed by wefts and warps of FEM were compared and it is found that the woven structure parameters of 3DAWF play an important role in energy absorption of ballistic penetration.

This FEM strategy presented herein, combined with the user-defined material model of the PPTA fiber tow and the micro-structural model of the 3DAWC panel, is found to make accurate predictions for the simulation of ballistic properties of 3DAWC. We hope such an effort could be extended to the design and optimization of the ballistic penetration behaviors of other 3D textile composite materials.

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