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What is This?
Energy absorption of three-dimensional angle-interlock woven composite under ballistic penetration based on a multi-scale finite element model

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Abstract
This paper reports the ballistic energy absorption of three-dimensional angle-interlock composite (3DAWC) based on a ballistic experiment and a theoretical model with high strain rate constitutive equation of fiber tows. The 3DAWC panels were penetrated under a hemispherical–cylindrical steel projectile, while time testers recorded the initial velocities and residual velocities of projectile in this process. The damage modes of 3DAWC are observed and analyzed from the view of penetrated damage morphologies and experimental velocity data. In order to demonstrate the energy absorption mechanism with more accuracy, a multi-scale finite element model of 3DAWC under ballistic penetration is specially designed and established to calculate this ballistic event. The constitutive relationship of the Twaron® filament yarn in microstructural model is derived from the springs and dashpots model and compiled into user-defined material subroutine in commercial-available finite element software package LS-DYNA, which can introduce strain rate sensitivity of fiber bundles to ballistic energy absorption process. A comparison of theoretical and experimental results shows a good agreement indicating an accurate validity of the multi-scale finite element model of 3DAWC. Moreover, this model can deeply reveal the ballistic energy absorption mechanism of 3DAWC which will help to evaluate the structural tolerance of ballistic protection composite material.

Keywords
3D angle-interlock woven composite (3DAWC), multi-scale finite element model, energy absorption, damage mechanism, ballistic penetration
Introduction

Three-dimensional angle-interlock woven composite (3DAWC) consists of weft and warp systems, which construct a self-interlock structure. This angle-interlock structure integrates all filaments bundled together, providing excellent intermediate medium to transfer inner response stress when suffered from external dynamic loading. Along with inner stress transfer inside the composite material, there will be energy transfer and absorption among different components. It is important to reveal the ballistic damage mechanism of 3DAWC that analyzing energy absorption during ballistic penetration in the material structure point view. Based on the energy absorption analysis with numerical model, a comprehensive understanding about ballistic damage mechanism of 3DWAC will enlarge its application on high impact resistance components, ballistic protection field, and engineering structural design.

A series of studies about impact energy absorption of the structural composites have been carried out since the last 1980s (Boria and Belingardi, 2012; Farley, 1986b; Jacob et al., 2002; Naik et al., 2013; Quaresimin et al., 2013; Ramakrishna and Hull, 1993; Thornton and Edwards, 1982; Thornton, 1979). Damage modes and energy absorption of the composite material under external loading are highly dependent on its inner structure and material type (Cantwell and Morton, 1991). Farley (1983) studied on the energy absorption characteristics of different structural composites and found that the results of static compression and vertical impact varied significantly as a function of material type and ply orientation. Farley (1986a) also investigated the effects of fiber and matrix maximum strain on the energy absorption of graphite composite tubes and found that matrix of composite material having a higher failure strain will exhibit superior energy absorption capability. Thornton and Jeryan (1988) reviewed the energy absorption of fiber reinforced plastics (FRP) composite materials in structural automobile applications and concluded that the FRP composite materials have a greater energy absorption in simple tube structures for its structural fracture. Morton and Godwin (1989) compared the impact damage responses of crystalline thermal plastic and toughened carbon fiber composites with two different stacking sequences and found that the damage tolerance of the composite is closely related with resin category and stacking sequence. Beard and Chang (2002) conducted crushing tests on braided carbon fiber/epoxy-vinyl ester composite tubes with both circle and square cross sections. The results show that the overall energy absorption is significantly affected by the fiber architecture and cross-sectional shape of the composite tube. Therefore, both the material properties and reinforcement architecture of composite materials play key roles in the energy absorption of impact-resistance structural composite material.

Based on various effects and phenomena associated with the impact of structural composite materials, different models have been carried out to evaluate their impact performances, such as numerical models (Gu and Xu, 2004; Shim et al., 2001; Tan et al., 2003; Tang et al., 2011), analytical models (Cox and Flanagan, 1997; Naik et al., 2006), semi-empirical and empirical models (Cunniff, 1996; Wang and Chou, 1997), micromechanical models (Hallal et al., 2013; Marrey and Sankar, 1997), and so on (Dixit and Mali, 2013; Tabiei and Nilakantan, 2008). It is important to note that those models attend to fully find out the parameters that primarily affect the impact energy absorption of a composite material. Flesher et al. (2011) implemented a material model with viscoplastic constitutive behavior and other significant material phenomena to simulate the crash performance of braided composite tubes. And they concluded that the variation of tube structure, braid geometry, and matrix strength in the model will affect the specific energy absorption of braided composite tubes. Xiao (2010) carried out an improved continuum damage mechanics model to evaluate the energy absorption of composite tube and found that the stress–strain response in load reversal scenario in the model is the key factor which influence the energy absorption in crash event. Deka et al. (2008) used an explicit 3D finite element model to verify the high-velocity behaviors
of laminated composite of varying thicknesses. With the help of these models, the composite material structure and components material properties can be verified during the impact event. However, few literatures concerning about the impact behaviors of structural composite materials have reported a precise state of energy absorption and stress transformation in their different components. And less few can reveal morphologies of resin crack, yarn slippage, and yarn breakage during impact loading.

A multi-scale finite element model of 3DAWC under a hemispherical rigid projectile penetration has been established and developed by Luan et al. (2011, 2013) to evaluate its ballistic behaviors. This model consists of a microstructure model and a continuum model. The microstructure model was set in the area around ballistic area for simulation accuracy of the multi-scale finite element model. Also, the material constitutive equations of Twaron® filament yarn derived from viscoelastic model were compiled into user-defined subroutine UMAT (FORTRAN user-material subroutine) to increase the simulation accuracy. The continuum model was employed for the simulation efficiency. With those design purposes, the model can comprehensively evaluate the ballistic damage of the 3DAWC.

The objective of this investigation is to utilize the model to focus on analyzing ballistic energy absorption mechanism of the 3DAWC. Energy transformation during dynamic damage evolution and the energy absorption proportion in different components of this model can be obtained to illustrate the energy state of the 3DAWC during ballistic penetration. And ballistic damage morphologies after ballistic penetration will be compared with the experimental. From the damage morphologies, the energy absorption modes and mechanisms of the 3DAWC under ballistic penetration will be explored.

3D angle-interlock woven composite

3DAWC has an integrated structure with warps or wefts interlocking different yarn layers. This interlock structure increases the inter-layer shear strength and leads to the higher impact tolerance than laminated composite. It can be applied in the potential field of ballistic protection, high speed trains, and aircraft carrier.

As shown in Figure 1, the warps crisscross through thickness direction at an off-axis angle ($\theta$), and wefts are parallel straightly to each other. The warps and wefts form a plain-like structure in in-plane direction, which can provide tight surface and higher stiffness like plain fabric.

![Figure 1. Filament yarn distribution in 3DAWC.](image)
Meanwhile, the warp traverses from upper layer through the adjacent layer to interlock two layers together bundling all filaments in in-plane direction and through thickness direction. This integrated structure can improve the energy transformation and absorption abilities for the yarn undulation and interaction.

The reinforcement of 3DAWC is the 3D angle-interlock woven fabric (3DAWF) from Twaron® filament yarn, which is a kind of high-performance, continuous and long fiber. The 3DAWF were manufactured by an improved dobby machine with high weave efficiency. The specifications of 3DAWF are listed in former literature (Luan et al., 2013). 3DAWFs were consolidated by unsaturated polyester resin using VARTM (vacuum-assisted resin transfer molding) technique to form 3DAWC.

**Multi-scale finite element model of 3DAWC under ballistic penetration**

Beginning with material constitutive behavior and building up to reinforcement parameters, a comprehensive design analysis model conducted of multi-scale mechanic concepts of composite material before ballistic tests are necessary for energy absorption mechanism. The model is based on fundamental properties of the composite material and its constituents, and can precisely predict energy transmission and absorption in different components.

The multi-scale finite element model of 3DAWC consist two parts, microstructure model and continuum model. Microstructure model was established from fundamental parameters of 3DAWF and specifications of Twaron® filament yarn. The constitutive equations of Twaron® filament yarn under high strain rate was introduced into the microstructure model as a user-defined material subroutine. Continuum model was a simplified and equivalent model basing on a fiber inclination model, and the model design flowchart is shown in Figure 2.

**Geometrical model**

In 3DAWC, the warps travel through the adjacent weft layers with a crimp angle at the interactive point of yarns. The wefts are almost straight when bundled by warps. The warp and weft were
simplified as circular cross section, and designed as the actual yarn distribution in 3DAWC as shown in Figure 1.

The geometrical model of 3DAWF as shown in Figure 3(a) is constructed from the duplication of a basic geometrical model which is a smallest repeating unit containing a weft and warp (Luan et al., 2011). Based on the geometrical model of 3DAWF, a rectangular solid is cut from it by Boolean operation to obtain a resin geometrical model, which is in accordance with the spatial distribution of reinforcement. Figure 3(b) shows the microstructural model of 3DAWC.

The microstructural model has complex inner structure, especially for the resin part. Using this structure to conduct full size microstructure model for simulating dynamic behaviors of 3DAWC will exceed the computing capacity of software and hardware. From observing the damage morphology of 3DAWC under ballistic penetration, the damage and deform area is around the ballistic hole within the range of 20 mm × 20 mm, which is the main energy absorption area that needs precise simulation. Moreover, as for the symmetrical structure of 3DAWC and vertical impact direction of bullet, one-quarter of geometrical model of 3DAWC panel was employed to be discretized into finite element model for evaluated ballistic event. Therefore, a 40 mm × 40 mm microstructural model was established for an accurate simulation, and the other part of composite panel was set as continuum model which can improve the calculation efficiency.

Material model

Fiber inclination model

The mechanical properties of 3DAWC can be derived and simplified from the ‘Fiber Inclination Model’ (Cui et al., 2011; Whitney and Chou, 1989; Yang et al., 1986). In this model, the smallest repeating unit-cell of 3DAWC can be regard as parallelepiped, and the filament yarn in the unit-cell is treated as four laminates along four body-diagonal directions.

Figure 4 is the fiber inclination model. Combining this model and basic fundamental specifications of 3DAWC, the relationship between unit-cell and one direction laminate are

\[ a = n_x \times \sqrt{P_x^2 + P_c^2} \]  

(1)
\[ b = n_y \times P_b \]  \hspace{1cm} (2)

\[ \theta = \tan^{-1}\left(\frac{P_c}{P_a}\right) \]  \hspace{1cm} (3)

\[ c = \frac{P_c \times n_z}{4} \times \cos \theta \]  \hspace{1cm} (4)

where \( P_a, P_b, \) and \( P_c \) are length, width, and thickness of the unit-cell, respectively, and \( n_x, n_y, \) and \( n_z \) are the unit-cell numbers in 3D direction.

Based on the classical laminate theory and material parameters of resin and Twaron® filament yarn, the mechanical parameters of 3DAWC can be deduced as follows

\[ E_1 = E_{f1}V_f + E_mV_m \]  \hspace{1cm} (5)

\[ E_2 = E_3 = \frac{E_m}{1 - \sqrt{V_f(1 - E_m/E_{f2})}} \]  \hspace{1cm} (6)

\[ G_{12} = G_{13} = \frac{G_m}{1 - \sqrt{V_f(1 - G_m/G_{f12})}} \]  \hspace{1cm} (7)

\[ G_{23} = \frac{G_m}{1 - \sqrt{V_f(1 - G_m/G_{f23})}} \]  \hspace{1cm} (8)

\[ v_{12} = v_{13} = v_{f12}V_f + v_mV_m \]  \hspace{1cm} (9)

\[ \frac{v_{12}}{E_2} = \frac{v_{21}}{E_1} \]  \hspace{1cm} (10)

\[ v_{23} = \frac{E_2}{2G_{23}} - 1 \]  \hspace{1cm} (11)

\[ \frac{v_{32}}{E_2} = \frac{v_{23}}{E_3} \]  \hspace{1cm} (12)

Figure 4. Fiber inclination model.
where subscript 1, 2, and 3 are the longitudinal direction, the width direction, and the height direction of laminate, respectively. $E_1$, $E_2$, and $E_3$ are the tension modulus in those three direction, and $\nu_{12}$, $\nu_{23}$, and $\nu_{31}$ are the Poisson’s ratio in 12, 23, and 31 directions.

The material parameters of resin and Twaron® filament yarn are shown in Tables 1 and 2. By putting these material parameters into equations (5) to (12), the material parameters of 3DAWC can be obtained. Those parameters are used in MAT_COMPOSITE_DAMAGE_MODEL (Hallquist, 1998) in LS-DYNA to calculate the ballistic response of continuum model.

### Constitutive relationship of Twaron® filament yarn

As for microstructural model, the real Twaron® filament yarn distribution was modeled. A user-defined material subroutine (UMAT) was compiled to implement the dynamic behavior of Twaron® filament yarn. In the molecular structure of Twaron® filament yarn, the molecular chains have a high degree of preferentially orientation along the fiber axis by inter-chain bonding, which are also stacked as sheet-like structure by hydrogen bonding and van der Waals’ forces. The mechanical behaviors of this structure can be simplified as standard three element model.

From the standard three element model, the constitutive relationship is

$$\sigma + \frac{\eta}{D_1 + D_2} \dot{\varepsilon} = \frac{D_1 D_2}{D_1 + D_2} \varepsilon + \frac{D_1 \eta}{D_1 + D_2} \dot{\varepsilon}$$  \hspace{1cm} (13)

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

\[ \dot{\varepsilon} = C \text{ (constant)} \]  \hspace{1cm} (14)

then initial conditions are

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

An explicit expression of stress is

\[ \frac{d\sigma}{d\varepsilon} = \frac{D_1D_2}{D_1 + D_2} + \frac{D_1^2}{D_1 + D_2} \dot{\varepsilon} \left( e^{\frac{D_1 + D_2}{\eta} \dot{\varepsilon}/\dot{\varepsilon}} \right) \]  \hspace{1cm} (15)

where \( \dot{\varepsilon} \) is strain rate variable, and \( D_1, D_2, \) and \( \eta \) are material parameters of Twaron® filament yarn.

This constitutive relationship was invoked into shear modulus along 12 and 13 directions in transversely isotropic material (Luan et al., 2013)

\[ G_{12} = G_{13} = \frac{D_1D_2}{D_1 + D_2} + \frac{D_1^2}{D_1 + D_2} \gamma \left( e^{\frac{D_1 + D_2}{\eta} \gamma/\dot{\gamma}} \right) \]  \hspace{1cm} (16)

where \( \gamma \) is the shear strain \( \dot{\gamma} \) and is the shear strain rate. And the material parameters in Table 3 were the inputs to calculate the dynamic behavior of this transversely isotropic material.

\[ \textbf{Table 3. Ballistic experiment results.} \]

<table>
<thead>
<tr>
<th>Panel number</th>
<th>Initial velocity, ( V_i ) (m/s)</th>
<th>Residual velocity, ( V_r ) (m/s)</th>
<th>Kinetic energy loss, ( \Delta E ) (J)</th>
<th>Penetration status</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>550</td>
<td>500</td>
<td>146.7375</td>
<td>Penetrated</td>
</tr>
<tr>
<td>L2</td>
<td>395</td>
<td>304</td>
<td>177.8716</td>
<td>Penetrated</td>
</tr>
<tr>
<td>L3</td>
<td>313</td>
<td>228</td>
<td>128.5281</td>
<td>Penetrated</td>
</tr>
<tr>
<td>L4</td>
<td>276</td>
<td>167</td>
<td>134.9622</td>
<td>Penetrated</td>
</tr>
<tr>
<td>L5</td>
<td>238</td>
<td>111</td>
<td>123.8828</td>
<td>Penetrated</td>
</tr>
<tr>
<td>L6</td>
<td>222</td>
<td>57</td>
<td>128.6678</td>
<td>Penetrated</td>
</tr>
<tr>
<td>L7</td>
<td>210</td>
<td>0</td>
<td>123.2595</td>
<td>Projectile seized</td>
</tr>
</tbody>
</table>

Multi-scale finite element model

The multi-scale finite element model was created from geometrical model with different mesh scheme in different parts. In microstructural model, a fine element density was sized and more than 10 million elements exist in this part. In continuum model, there are only 1.5 million elements with a gradient from internal part where contacts the microstructure model to external part. The detailed multi-scale finite element model is shown in Figure 5.

During penetration progress, the compression failure only 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 leads to ultimate failure of the 3DAWC.
When the strain reach maximum strain of fiber or resin,

\[
\begin{align*}
\varepsilon_1 & > X_{\varepsilon_1} \\
\varepsilon_t & > Y_{\varepsilon_t} \\
\varepsilon_m & > Z_m
\end{align*}
\]  

(17)

the element of finite element model will be deleted, where \(\varepsilon_1\), \(\varepsilon_t\), \(X_{\varepsilon_1}\), \(Y_{\varepsilon_t}\) are strains, maximum strains in fiber axis and transverse direction, respectively. \(\varepsilon_m\) and \(Z_m\) is strain, maximum strain of resin.

**Ballistic experiment**

The ballistic experiment was carried out to evaluate and verify the efficiency and the accuracy of multi-scale finite element model of 3DAWC under hemispherical cylindrical steel projectile. This experiment consist three parts: launcher and projectile, time testers, clamps and composite panel as shown in Figure 6. According to laser-diode pairs, time tester can record the flying time of projectile within a constant distance for calculating its initial velocity and residual velocity. And with the further calculation, the initial kinematic energy and residual kinematic energy of projectile can be achieved.

The projectile used in the experiment is Type 56 in China Military Standard and its diameter is 7.62 mm as shown in Figure 7. The bullet weight is 5.59 g.
Results and discussion

Experimental results

Table 3 lists experiment results of projectile. The kinetic energy loss was calculated by

\[ \Delta E = \frac{1}{2} m_{\text{projectile}} (V_i^2 - V_r^2) \]  

(18)

where \( V_i \) and \( V_r \) are the projectile initial velocity and residual velocity. \( m_{\text{projectile}} \) is the projectile mass. From these results in Table 4, the ballistic limit \( V_{50} \) is around 220 m/s.

Table 4. Characterization results of energy absorption of 3DAWC under ballistic penetration.

<table>
<thead>
<tr>
<th>Panel number</th>
<th>( E_a ) (J)</th>
<th>( \text{BPI} ) (J/(kg m(^{-2})))</th>
<th>( E_h ) (J/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>146.7375</td>
<td>11.545</td>
<td>13,586</td>
</tr>
<tr>
<td>L2</td>
<td>177.8716</td>
<td>13.995</td>
<td>16,470</td>
</tr>
<tr>
<td>L3</td>
<td>128.5281</td>
<td>10.112</td>
<td>11,901</td>
</tr>
<tr>
<td>L4</td>
<td>134.9622</td>
<td>10.619</td>
<td>12,497</td>
</tr>
<tr>
<td>L5</td>
<td>123.8828</td>
<td>9.747</td>
<td>11,471</td>
</tr>
<tr>
<td>L6</td>
<td>128.6678</td>
<td>10.123</td>
<td>11,914</td>
</tr>
<tr>
<td>L7</td>
<td>123.2595</td>
<td>9.698</td>
<td>11,413</td>
</tr>
</tbody>
</table>

Figure 6. Principle of ballistic test.

Figure 7. Hemispherical cylindrical steel projectile and finite element model.
From the results in Table 3, the ballistic energy absorption of 3DAWC can be comprehensively evaluated by the total energy absorption ($E_a$), ballistic penetration indicator (BPI) and energy absorption per unit thickness ($E_h$) as shown in Table 4, which are calculated from

$$E_a = \Delta E$$

$$\text{BPI} = \frac{E_a}{\text{AD}}$$

$$E_h = \frac{E_a}{h}$$

where AD is the area density of 3DAWC panel (kg/m²) and $h$ is the 3DAWC panel thickness.

**Kinetic energy absorption**

The ballistic penetration is a sudden release of projectile motion energy. Based on the difference between initial kinetic energy and residual kinetic energy of projectile, the energy absorbed by composite panel can be abstained to analyze the energy absorption mechanism and evaluate the accuracy of the multi-scale finite element model.

Figure 8 shows theoretical and experimental kinetic initial energy versus residual kinetic energy curves of projectile.

![Figure 8. Theoretical and experimental kinetic initial energy vs. residual kinetic energy curves of projectile.](image)

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Figure 8 shows theoretical and experimental kinetic initial energy versus residual kinetic energy curves of projectile. A comparison of the two curves shows a good agreement between experimental and theoretical model. Furthermore, the theoretical curve displays a higher residual kinetic energy with low initial kinetic energy, which indicates that the 3DAWC absorbs less kinetic energy under low impact velocity. On contrary, 3DAWC absorbs more kinetic energy of projectile under higher impact velocity from comparing theoretical and experimental curves. This shows that there is a slight
instability energy absorption of the multi-scale finite element model in lower and higher initial kinetic energy range, yet the theoretical curve is in good agreement with experimental in the middle range of kinetic energy.

The kinetic energy absorbed by 3DAWC retrieved from the calculated results of theoretical model and experimental is shown in Figure 9. Also, the kinetic energy of projectile absorbed by 3DAWC distributes a similar curve as that of kinetic initial energy versus residual kinetic energy curves of projectile. The kinetic energy points in lower and higher initial kinetic energy range distribute less evenly than in the middle range of kinetic energy. Additionally, the kinetic energy points scatter in the range between 100 J and 180 J, which shows that 3DAWC has a high energy absorption efficiency under different strike velocity.

**Energy absorption process**

Figure 10 shows total energy process curve and its components process curve of 3DAWC panel under 395 m/s. For the projectile-target system without external loading, the total energy and external energy remain constant during ballistic penetration. The kinetic energy change of the projectile-target system is dependent on the projectile velocity decrement as the energy absorbed by composite panel. And the kinetic energy of projectile decreases when the 3DAWC absorbs and transfers it into internal energy and sliding energy in ballistic penetration progress.

The system energy change is dependent on the penetration depth before the projectile leaves the 3DAWC as shown in Figure 10. At the beginning of kinetic energy curve (0–35 μs), the kinetic energy decreases along with the penetration depth increases, and the response stress begin to disperse into different components in the composite. The energy transformation velocities in yarn bundles and resin are different as shown with different legend colors (from blue to red). In resin component, it is easy to reach the maximum breakage stress that shows a higher stress value than that in yarn.
component. Moreover, the main energy absorption modes of 3DAWC are yarn deformation and resin crack under projectile’s compression and shear force.

After the projectile head coming out of 3DAWC panel (>35 μs), the energy states of projectile-target system begin to gain rebalance. Kinetic energy of projectile reaches to a certain value concerning projectile residual velocity. The stress absorbed by composite panel transfers along both in plane and through thickness directions. The main energy absorption volume is the part around the penetration hole in composite panel. Except for the yarn deformation and resin crack, resin deformation, yarn tension, and breakage are also absorption modes in this penetration stage.

During penetration progress, the kinetic energy transfer into internal energy and sliding energy. The transformation of sliding energy is resulting from friction interaction between components and projectile, resin, and fiber bundles. The internal energy meanwhile is caused by response stress inside 3DAWC when the projectile shock on the composite panel. These two energies are the main transformations as ideal model conditions without considering acoustic energy and air vibrational energy in ballistic event of 3DAWC.

Figure 10. Energy decomposition curves and the stress distribution of 3DAWC at different penetration times.

Energy absorption in fiber bundles and resin

For different components of microstructural model, the absorbed energy distributing in fiber bundles and resin can be achieved as shown in Figure 11. The most energy absorption area is around ballistic hole in 3DAWC shown an energy concentration in this area. The energy absorption modes around ballistic hole are filament bundle deformation, compression and fracture, resin deformation, and fracture. As shown in Figure 11(a), in wefts, the absorbed energy has a distinctly transfer into the remote off ballistic hole. Yet, there is an energy concentration in the winding side of warps. This is stand for that wefts absorbs more ballistic energy than warps and undertake more ballistic resistance. In Figure 11(b), the resin have an evenly energy absorption distribution transferring from reinforcement fabric, which results the 3DAWC ballistic resistance system more efficiently to afford impact loading.

To further verify the energy absorption mechanism of 3DAWC, the internal energy absorption percentages in different parts were obtained as shown in Figure 12. The microstructural part absorbs
96.66% internal energy, and continuum part far away from ballistic hole absorbs only 3.33% internal energy in the projectile-target system, which shows that the ballistic resistance area is around ballistic hole in the view of the amount of internal energy.

Furthermore, in microstructural part, the reinforced 3DAWF absorbs 53.6% internal energy, while the resin matrix absorbs 43.06% internal energy. The dominate energy absorption medium in 3DAWC is reinforced 3DAWF, which should have even larger percentage in practical situation because of the idealized parameters in the theoretical model, such as idealized circle yarn cross-section, idealized fiber fraction, and so on. The resin matrix assists 3DAWF to evenly transfer energy into the whole composite panel when suffering from projectile impact.
Besides, weft yarns in 3DAWF bear more internal energy than warp yarns resulting from the fabric structure and yarn count in this penetration area. In 3DAWC, the weft yarn count is 1680/4 ply comparing with warp yarn’s 1680×2ply, and meanwhile the weft is 12 layers through thickness direction of composite panel. These two structure factors make wefts absorb more impact energy.

**Damage morphology and energy absorption area**

As discussed above, the main energy absorption is around the ballistic hole in multi-scale finite element model. This area is about 24 mm × 24 mm, obtained to compare with practical ballistic damage morphology of 3DAWC as shown in Figure 13(a) and (b). The penetration hole diameter is 10.4 mm which is the perforation and damage area.

In incident surface of 24 mm × 24 mm area near the penetration hole, the main damage modes are compression breakage of fiber and filament bundle, resin cracking. However, in rear side of composite panel, except for fiber extrusion by projectile, shear, and compression damage of fiber bundle, there is also a volume swell which can be seen in a sectional view of Figure 13(a). These damage modes occur in the volume of 24 mm × 24 mm × 10.8 mm, which is the main energy transformation and absorption volume of projectile-target system. This also means that most of projectile kinetic energy transfer into internal energy and sliding energy in this volume.

From above analysis, the efficiency of multi-scale finite element model for ballistic behaviors can be verified, and the area of microstructural part in multi-scale finite element model is 80 mm × 80 mm × 10.8 mm which is larger enough to evaluate the energy mechanism of 3DAWC under ballistic penetration.

**Figure 13.** Comparison of damage morphologies between theoretical and experimental.
In Figure 13, there is no obviously delamination occurring between different layers of 3DAWC, no matter in experimental or theoretical. This is due to a net-like structure in through thickness direction formed by warp yarns interlocking the different weft layers. When under impact loading, this interlock structure can eliminate simultaneous yarn breakage, which makes its structure integrated and stable. Furthermore, it has energy concentration, as shown in Figures 11(a) and 13(c), for diffusing ballistic energy like an energy absorber in the projectile-target system. The shear damage between layers is reduced by this energy absorber. Hence, this kind of composite material can express a good damage tolerance and ballistic resistance.

Conclusions

A multi-scale finite element model based on geometrical model of 3DAWC and high strain rate constitutive equations was established and developed for evaluating its ballistic performances. For comparing the experimental and theoretical results, the main ballistic energy absorption medium is 3DAWF reinforcement when under ballistic penetration. Resin matrix can transfer partial impact energy uniformly to the whole composite panel. These comparisons showed good accordance between simulations and experimental curves.

With the ballistic test characterization parameters and theoretical results, the energy absorption mechanism of 3DAWC under ballistic penetration is well understood. The main ballistic damage modes are fiber bundle breakage, resin crack, fiber slippage, and volume swell deformation, which is due to different energy transformation inside composite panel. Internal energy diffuses around the whole ballistic panel, while the sliding energy is absorbed in surfaces between projectile and target. The integrated structure disperses these energies for reducing the layer-to-layer shear damage which makes 3DAWC less delamination damage. 3DAWC shows a good energy absorption capability under ballistic penetration resulting from its unique interlock structure and component materials’ properties.

According to the analyses of energy absorption mechanism of the 3DAWC, it shows a good structural integrity and stability of the 3DAWC during ballistic penetration. At the beginning of penetration, only resin crack and yarn compression occur in the front surface of composite panel with little deformation around ballistic hole. When the projectile gradually penetrates into inside of the composite panel, there will be shear and compression deformations and fractures of yarn and resin through the thickness direction. After the projectile head penetrating out of the composite panel, a swell deformation occurs in the rear surface of composite panel, and yarns were stretched to breakage by projectile. The main deformation and fracture occur inside the volume of the ballistic hole and rear surface of the composite panel, and only small panel deformation and little resin cracking exists away from ballistic hole. The damage modes in ballistic penetration of the 3DAWC are resin crack, yarn breakage, panel deformation, resin and yarn deformation, which are dominant factors in its energy absorption mechanism.

Also, the multi-scale model of 3DAWC under ballistic penetration, capturing the ballistic energy absorption process, as well as microstructure damage morphologies, offers new possibilities to study dynamic performances of structural composite materials. Particularly, high strain rate constitutive equations of filament yarn introduced in the model improve the calculating accuracy of nonlinear large deformation in ballistic event. For these reasons, this multi-scale model can be used for the fields of safety calculation and hazard assessment in ballistic event of the composite materials.
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References


