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A unit cell approach of finite element calculation of ballistic impact damage of 3-D orthogonal woven composite

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ABSTRACT

This paper presents ballistic impact damages of 3-D orthogonal woven composite in finite element analysis (FEA) and experimental. A unit-cell model of the 3-D woven composite was developed to define the material behavior and failure evolution. A user-defined subroutine VUAMT was compiled and connected with commercial available FEA code ABAQUS/Explicit to calculate the ballistic penetration. Ballistic impact tests were conducted to investigate impact damage of 3-D kevlar/glass hybrid woven composite. Residual velocities of conically-cylindrical steel projectiles (Type 56 in China Military Standard) and impact damage of the composite targets after ballistic perforation were compared both in theoretical and experimental. The reasonable agreements between FEA results and experimental results prove the validity of the unit-cell model in ballistic limit prediction of the 3-D woven composite. We believe such an effort could be extended to bulletproof armor design with the 3-D woven composite.

1. Introduction

Three-dimensional (3-D) orthogonal woven composites have been widely applied to structure engineering owing to the high stiffness and strength along in-plane directions and thickness directions. The non-crimp feature of yarns in 3-D orthogonal woven fabric leads the highest Young's modulus and stress wave propagation velocity compared with other textile preforms. Compared to laminated composites and other 3-D textile structural composites [1], 3-D orthogonal woven composite has been recognized as more competitive because of its higher stiffness and strength in three orthogonal directions [2]. The 3-D orthogonal woven composite allows the tailoring of properties for specific applications and shows better delamination resistance and damage tolerance [3], especially in thickness direction [4]. More recently, the impact behavior of 3-D orthogonal composites has been investigate by Shahkarami and Vaziri [5], Sun and Gu [6], Luo et al. [7], Ji and Kim [8], Ji et al. [9] and Hao et al. [10]. However, as for ballistic impact behavior of the 3-D orthogonal woven composites, only Gama et al. [11] reported numerical simulation of ballistic impact, damage and penetration of a single layer 3-D orthogonal weave fabric composite.

This paper will investigate the ballistic damage and energy absorption of 3-D kevlar/glass hybrid woven composite penetrated with conically-cylindrical steel projectile. A unit-cell model of the 3-D orthogonal woven composite was developed to characterize stiffness matrix and damage evolution of the 3-D woven composite. A commercial available FEM code of ABAQUS will be incorporated with a user-defined subroutine VUMAT to calculate ballistic penetration of the 3-D woven composite. The FEM results will be verified with ballistic impact results.

2. Description of composite target and projectile

2.1. Projectile

As shown in Fig. 1, conically-cylindrical steel projectile of 7.62 mm in diameter and 7.95 g in mass was used in ballistic test. This projectile was made in China and numbered as Type 56 in China Military Standard. The projectile is assumed to be rigid body in finite element analysis because no deformation of projectile after ballistic impact is found. The projectile was propelled along ballistic barrel by gunpowder. Strike velocities of projectiles were controlled by adjusting the weight of gunpowder. Striking and residual velocities were measured, respectively, with two laser-diode pairs.

2.2. Three-dimensional orthogonal woven fabric

The 3-D orthogonal woven fabric was made up of aramid and glass filament tows. Specification of the 3-D orthogonal woven fabric is in the Table 1. The schematic diagram of the fabric in cross-section is shown in Fig. 2(a). Fig. 2(b) is the structure of the 3-D

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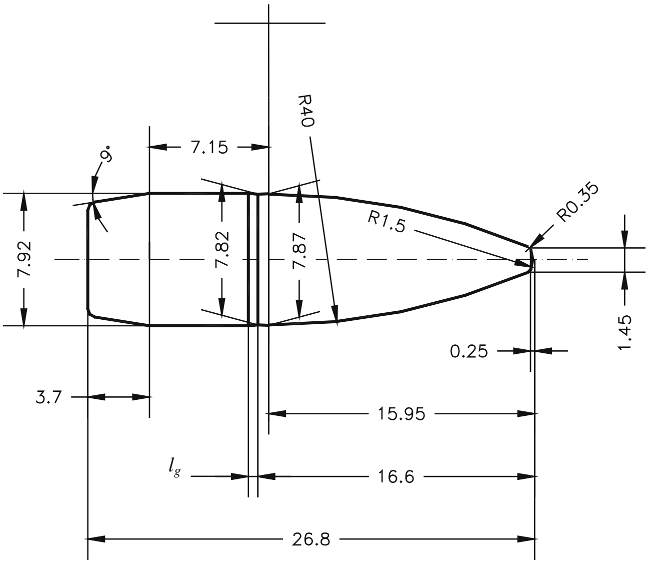

Fig. 1. The profile of projectile (mm).

Table 1
Specification of 3-D orthogonal woven fabric.

Yarns weaving density (ends/ 10 cm)	Materials	Layers	Linear density (tex)
Warp 50.1	E-glass	4	2400
Weft 40.2	E-glass	5	600
Z yarns	Aramid tows (Twaron)	–	110

orthogonal hybrid woven fabric. E-glass filament tows were employed as the warp and the weft yarns. The fineness of the E-glass filament tows is 2400 tex (Tex is a basic textile unit of linear density — the weight in grams of a fiber one kilometer in length. Units = g/km = (g/cm) $\times$ 10^{-5}). Twaron filament tows were as the binder yarns (type: Twaron® CT1000, 3360dtex/2000f, manufactured by Akzo Nobel). Twaron® is a kind of aramid fiber (poly paraphenylene terepthalamide, PPTA) similar to that of Kevlar® of Dupont De Nemours. The glass filament tows and aramid filament tows were interweaved with 90° each other. The unsaturated polyester resin was injected into the preform by VARTM (vacuum assisted resin transfer molding) technique and then consolidated in the condition of vacuum and room temperature for 12 h. The fiber volume fraction is about 60%. The size of rectangular composite target is 20 $\times$ 30 cm. The thickness of the 3-D woven composite is 1.5 cm. The photographs of the composite in surface and the cross-section are shown in Figs. 3(a) and (b).

The 3-D woven composites were perforated by the projectile along the normal line of the composites target plate. Four sides of the rectangular composite target plate were fixed in ballistic tests. The impact location was the center of the rectangular plate. The strike velocity v_s and the residual velocity v_r of the projectile were measured and the kinetic energy of projectile absorbed by composite targets was calculated.

3. Unit-cell modeling and FEM formulation

The principle of 3-D orthogonal woven fabric is to bind straight warp yarns and weft yarns together by using *Z* yarns which run through the whole thickness of the fabric. The warp and weft yarns provide high in-plane stiffness and strength, and the binder yarns run through the thickness direction to stabilize the woven structure. In ideal case, the warp and weft yarns, together with *Z*-yarns are perpendicular to each other. The unit-cell of 3-D woven composite could be set up as shown in Fig. 4.

As shown in Fig. 4, an ideal unit-cell for the 3-D orthogonal woven composite is composed of constituent tows (or yarns) (i.e., warp, weft, and *Z* tow) and matrix. In this unit cell, a global Cartesian coordinate, x–y–z, is defined as along longitudinal (warp yarns), transverse (weft yarns) and thickness (z yarn) direction. Each yarn has its own local Cartesian coordinate, 1–2–3, which along the yarn's axis (1-direction), perpendicular to the axis (2-direction) and 3-direction which perpendicular to 1–2 plane. The local coordinate can be shown in Figs. 5 and 6.

3.1. Elastic stiffness and compliances matrices of the unit cell

In a unit-cell of the 3-D orthogonal woven composite, fiber tows can be regarded as transverse-isotropic materials. Assume $[S]_1$ and $[S]_2$ are the compliance matrixes of Twaron® tows and E-glass tows in the local coordinate.

Then:

$$[S]_1 = \begin{bmatrix} S_{11}^{(1)} & S_{12}^{(1)} & S_{12}^{(1)} & 0 & 0 & 0 \\ S_{12}^{(1)} & S_{22}^{(1)} & S_{23}^{(1)} & 0 & 0 & 0 \\ S_{12}^{(1)} & S_{23}^{(1)} & S_{22}^{(1)} & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(S_{22}^{(1)} - S_{23}^{(1)}) & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55}^{(1)} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{55}^{(1)} \end{bmatrix} \quad (1)$$

$$[S]_2 = \begin{bmatrix} S_{11}^{(2)} & S_{12}^{(2)} & S_{12}^{(2)} & 0 & 0 & 0 \\ S_{12}^{(2)} & S_{22}^{(2)} & S_{23}^{(2)} & 0 & 0 & 0 \\ S_{12}^{(2)} & S_{23}^{(2)} & S_{22}^{(2)} & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(S_{22}^{(2)} - S_{23}^{(2)}) & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55}^{(2)} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{55}^{(2)} \end{bmatrix} \quad (2)$$

The matrix is isotropic material, the compliances matrix is:

$$[S]_m = \begin{bmatrix} 1/E_m & -v_m/E_m & -v_m/E_m & 0 & 0 & 0 \\ -v_m/E_m & 1/E_m & -v_m/E_m & 0 & 0 & 0 \\ -v_m/E_m & -v_m/E_m & 1/E_m & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_m & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_m & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_m \end{bmatrix} \quad (3)$$

For the warp yarns (tows) in the unit-cell (shown in Fig. 6), the local coordinate and the global coordinate is identical. Then: $[\bar{S}]_1 = [S]_1$. Generally, for the off-axis compliance matrix transformation, we have: $[\bar{S}] = [T]_\varepsilon^{-1}[S][T]_\varepsilon$

where

$$[T]_\varepsilon = \begin{bmatrix} l_1^2 & m_1^2 & n_1^2 & 2m_1n_1 & 2l_1n_1 & 2l_1m_1 \\ l_2^2 & m_2^2 & n_2^2 & 2m_2n_2 & 2l_2n_2 & 2l_2m_2 \\ l_3^2 & m_3^2 & n_3^2 & 2m_3n_3 & 2l_3n_3 & 2l_3m_3 \\ 2l_2l_3 & 2m_2m_3 & 2n_2n_3 & 2(m_2n_3+m_3n_2) & 2(l_2n_3+l_3n_2) & 2(l_2m_3+l_3m_2) \\ 2l_1l_3 & 2m_1m_3 & 2n_1n_3 & 2(m_1n_3+m_3n_1) & 2(l_1n_3+l_3n_1) & 2(l_1m_3+l_3m_1) \\ 2l_1l_2 & 2m_1m_2 & 2n_1n_2 & 2(m_1n_2+m_2n_1) & 2(l_1n_2+l_2n_1) & 2(l_1m_2+l_2m_1) \end{bmatrix}$$

From Fig. 6, the compliance matrix for the weft yarns is: $[\bar{S}]_2 = [T_2]^{-1}[S]_2[T_2]$, where T_2 is strain transformation matrix, and the elements of T_2 are