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Ballistic Perforation of Conically Cylindrical Steel Projectile into Three-Dimensional Braided Composites

Bohong Gu* and Yuling Li†
Donghua University, 200051 Shanghai, People's Republic of China

The high fracture toughness and interlayer shear strength of three-dimensional braided composites lead to high-energy absorption when the composites impinged by high-rate loading. An attempt is made to develop and validate a computational method for predicting the penetration resistance of three-dimensional braided composites. The ballistic perforation test results of four-step three-dimensional braided Twaron® epoxy composites, which were subjected to impact by conically cylindrical steel projectile, are presented. A simplified structural model was constructed to analyze the ballistic penetration of three-dimeniosnal braided composites target by conically cylindrical steel projectile. The finite element code of Ls-Dyna was employed to simulate the ballistic penetration between the projectile the and three-dimensional braided composite target. The calculated results of the finite element analysis are close to the penetration resistance of three-dimensional braided composites. From the acceleration-time history of projectile and damage morphology of three-dimensional braided composites in finite element analysis, it is indicated that the quasi-microstructure model can approximately simulate the real ballistic impact damage of three-dimensional braided composites. How to apply three-dimensional braided composites in ballistic protection is still a question and should be demonstrated further.

Nomenclature

a, b	=	the in-plane length of inclined lamina
C_1, C_2	=	velocity of stress wave propagation in the longitudinal and transverse directions
c	=	thickness of inclined lamina
E_f	=	Young's modulus of yarns
i, j	=	yarn array in four-step three-dimensional braiding
k	=	ratio of stress wave propagation velocities in the longitudinal and transverse directions
$L_{b,c}$	=	length of the composite along the y and z directions, respectively
$n_{b,c}$	=	number of repeated unit cells along y and z directions
P_a, P_b, P_c	=	size of unit cell of fiber inclination model
v_f, v_m	=	fiber volume fraction and matrix volume fraction in the lamina
Δt_e	=	critical time step size
θ	=	surface braiding angle of three-dimensional braided composites
ρ_c	=	volume density of the lamina
ρ_f	=	volume density of the yarns
σ, ε	=	stress and strain

I. Introduction

The distinct feature of three-dimensional braided composites under ballistic impact is that there is not interlaminar crack and delamination compared with that of laminated composites. It is of interest to study the ballistic properties of such an undelaminated composite. However, there are only a few works reported on this topic.

Flanagan et al.[1] observed the damage morphology of four-step three-dimensional braided ultra-high-molecular-weight polyethylene (UHMPE) composites after ballistic perforation. The damage region is circular, rather than the rhombic shape often observed in laminated or three-dimensional woven composites.[2] The ballistic limit of three-dimensional braided composites is approximately equal to that of laminates with the same area density. Xu and Gu[3] observed the damage morphology and macro- and microfractographs of the damage part of four-step three-dimensional Kevlar® epoxy composite impacted by a 56-type steel bullet (7.62 mm in diameter) at 300–700-m/s velocity and found that compression and shear failures in the incident side and tensile failures in the distal side were the principal damage modes. Jenq and Mao[4] and Jenq et al.[5] obtained the quasi-static penetration damage modes from the quasi-static perforation load-displacement curves of two-step and four-step three-dimensional braided glass/epoxy composites at different penetration displacements and from different regions of the composites. They applied them to ballistic penetration analysis of the composites (projectile velocity: 65–180 m/s). The three-dimensional braided composites were treated as an orthotropic material and meshed with different element densities at different zones that have different damage modes characterized by fiber breakage, matrix crack, etc. The residual velocity of the projectile after perforation and the ballistic limit of the composites were calculated by the finite element program Marc based on the homogeneous continuum assumption of three-dimensional braided composites. The feasibility of substituting the mechanical constants under high strain rate with those in quasi-static state to calculate the ballistic penetration of three-dimensional braided composites was also demonstrated. The calculations of ballistic penetration of three-dimensional braided composites carried out so far were all based on the homogeneous continuum assumption of three-dimensional braided composites whereas the microstructure of the composites was ignored, which led to low precision in the penetration resistance calculation and damage morphology simulation. If the ballistic penetration calculation is based on the actual microstructure of three-dimensional braided composites, the preprocessor in the finite element analysis will become complicated owing to the complexity of the microstructure of composites and the difficulty in characterizing the spatial configuration of the braiding yarn.[6,7] Additionally, such a scheme is difficult to extend to other kinds of three-dimensional textile preform reinforced composites. A simplified structural model of three-dimensional braided composites is constructed in this paper to calculate the ballistic penetration of the composites with the well-developed contact–impact interaction algorithms[8] and commercially available finite element software.

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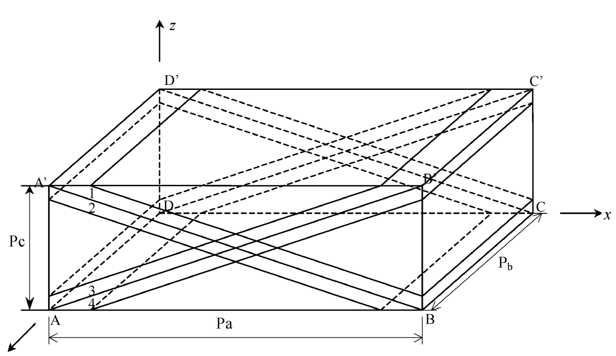
*Professor, Textile Materials Department, College of Textiles; also Scientist, Polymer Materials Department, Xi'an University of Engineering Science and Technology, 710048 Xi'an, People's Republic of China; gubh@dhu.edu.cn.

†Associate Professor, Textile Engineering Department, College of Textiles; lylu@dhu.edu.cn.

The objective of this paper is to develop and validate a computational method for predicting the penetration resistance of three-dimensional braided composites. However, we still do not know how these materials would be applied in a real-world situation, for example, ballistic protection (personnel, vehicles, components, etc.) against bullets, fragments, debris, etc. Only interest on this problem stimulates us to carry out the ballistic impact test and theoretical calculation of three-dimensional braided composites perforated by a conically cylindrical steel projectile.

II. Simplified Structural Modeling of Three-Dimensional Braided Composites

Because the spatial configuration of braided yarns in three-dimensional composites cannot be precisely characterized in a mathematical way[9,10] and there are deformations of braiding yarns brought about by their mutual crush during the composites forming,[11] it is difficult to predict the mechanical properties of three-dimensional braided composites from the actual microstructure. From the general structural features of three-dimensional textile preform reinforced composites, Yang et al.[12] proposed the fiber inclination model as a unit cell composed of crossed inclined laminas to calculate mechanical properties of three-dimensional textile structural composites by adopting classical laminate theory. With this model, one can calculate uniaxial stiffness of three-dimensional textile preform reinforced composites precisely and predict uniaxial tensile strength after revision.[13] In this model, the three-dimensional textile preform reinforced composites were simplified as combination of cuboids shown in Fig. 1. Each cuboid is composed of four laminas, and the fibers in the different laminas extend along diagonal directions as shown in Fig. 1; for example, the fiber direction of lamina 1 in Fig. 1 is parallel to A′C, D′B for lamina 2, B′D for lamina 3, and C′A for lamina 4. The crossovers among laminas were ignored in the model.



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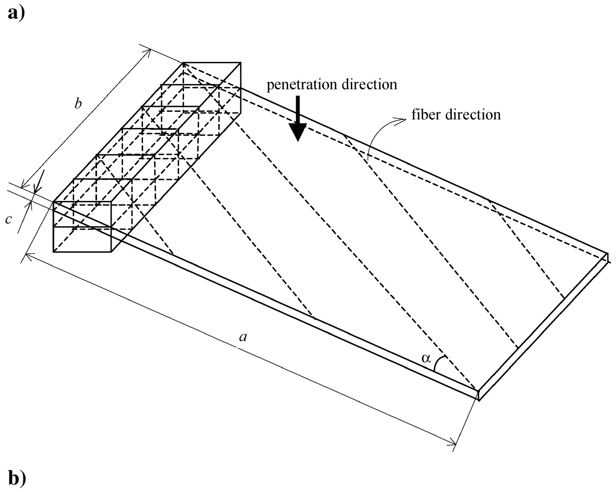
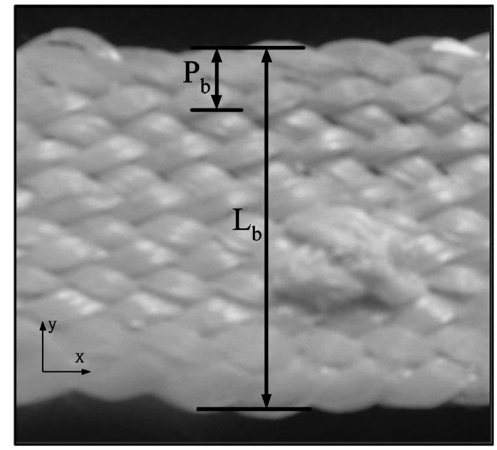


b)

Fig. 1 Quasi-microstructure unit cell of three-dimensional braided composites composed of four inclined laminas: a) fiber inclination model and b) quasi-microstructure unit cell of three-dimensional braided composites.



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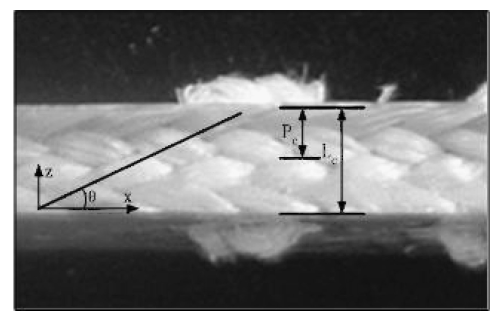


b)

Fig. 2 Morphology of three-dimensional braided composite after ballistic perforation: a) vertical view, *x–y* plane; and b) side view, *x–z* plane.

Figure 2 is the damage morphology of three-dimensional braided composites after normal perforation, that is, along the direction perpendicular to plane ABCD in Fig. 1. Because it was difficult to establish the geometrical model of three-dimensional braided composites at the actual microstructure level, the fiber inclination model is revised in this paper to construct the geometrical model of three-dimensional braided composites at the quasi-microstructure level and to analyze the ballistic penetration of the composites. Parameters in Fig. 1 are also shown in Fig. 2 and can be calculated as follows:

$$P_b = L_b/n_b, \qquad P_c = L_c/n_c, \qquad P_a = P_c/\cos\theta \tag{1}$$

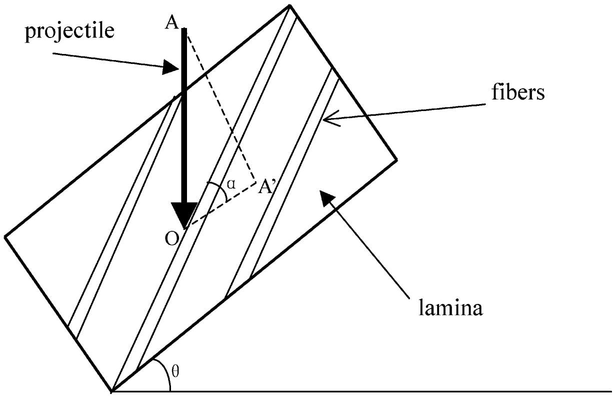
In Fig. 1, the fiber orientation angle in lamina is $\alpha = \tan^{-1}[P_b/\sqrt{(P_a^2 + P_c^2)}]$.

For the four-step rectangular three-dimensional braided composites in which the braiding yarns are in $i \times j$ array,

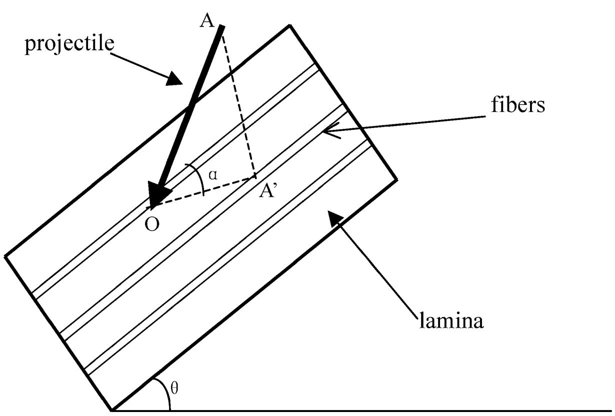
$$n_b = i/2, \qquad n_c = j/2 \tag{2}$$

When the unit cell is extended along the x, y, and z directions, respectively, in Fig. 2, the lamina in each unit cell would also be extended or enlarged and crossed with top and bottom surface of the three-dimensional braided composites. The size of the enlarged inclined lamina in unit cell was $(i/2)\sqrt{(P_a^2 + P_c^2)} \times L_b$, and the thickness was $(L_c/4)\cos\theta$. When the crossovers among the laminas were ignored, the number of reinforced yarns in each lamina could be calculated with the condition that the model had the same fiber volume fraction and yarn diameter as those in three-dimensional braided composites. The lamina was composed of matrix and yarns with the same diameter, and thus, the fiber inclination model of three-dimensional braided composites could be constructed considering the actual microstructure of the lamina.

As shown in Fig. 1, fibers in each lamina were laid at angle α. The projective line of the projectile axis in the inclined lamina plane when the projectile penetrated the composites at normal angle should be parallel to the lamina edge in the AA′B′B plane. The angle between the projective line and the diagonal line in the lamina, that is, fiber orientation in the lamina, is α, which is shown in Fig. 3a. The



a) Original position before transformation



b) New position after transformation

Fig. 3 Relative position between projectile and lamina.

local coordinate in the lamina was rotated, and the relative position between the projectile and the lamina remained unchanged, that is, the fiber orientation angle was adjusted until it paralleled the lamina edge (Fig. 3b). Then the incident angle of the projectile was adjusted while the angle between the projective line of the projectile and fiber in the lamina was still α. On the basis of the unchanged fiber volume fraction with the unrotated lamina, the same finite element calculation results could be obtained, and the preprocessor of finite element method calculation would be much easier than that in unrotated lamina.

III. Description of Projectile and Braided Composite Target

A. Projectile

As shown in Fig. 4, a conically cylindrical steel projectile 7.62 mm in diameter and 7.95 g in weight was used in ballistic test. This projectile was made in the People's Republic of China and numbered type 56 in the People's Republic of China Military Standard. The projectile is assumed to be a rigid body in the finite element analysis because no deformation of the projectile after ballistic impact is found. The projectile was propelled along the ballistic barrel by gunpowder. Strike velocities of projectiles were controlled by adjusting the weight of the gunpowder. Striking and residual velocities were measured with two laser–diode pairs.

B. Four-Step Three-Dimensional Braided Composite Target

The three-diemnsional braided preform was made with four-step 1×1 method. The array of the yarn carrier is 12×4. There are $i \times j + i + j = 64$ yarn carriers in total. The fiber is Twaron® aramid filaments (Type Twaron CT1000, 3360dtex/2000f, manufactured by Akzo Nobel). Twaron is a kind of polyaramid fiber [poly paraphenylene terepthalamide (PPTA)] similar to Kevlar of Dupont. The specifications of Twaron aramid filaments are as follows: 1.44-g/cm^3 volume density, 65-GPa Young's modulus, 2.8-GPa failure stress, and 3.4% failure strain. The braided composite was manufactured with epoxy matrix and resin transfer molding (RTM) technique. (This kind of three-dimensional braided composite is hereinafter referred to as 12×4 braided composite.) The fiber volume content of the composite is 27%. The size of the cross section of the composite is $(45 \pm 3) \times (12 \pm 2)$ mm. The length of target was 100 ± 10 mm, which was cut from 12×4 braided composite along the longitudinal direction.

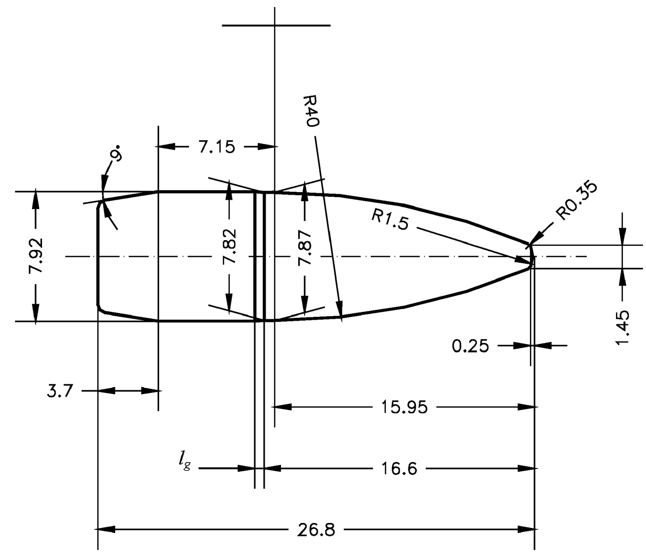
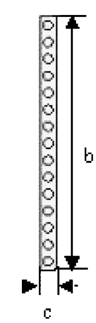
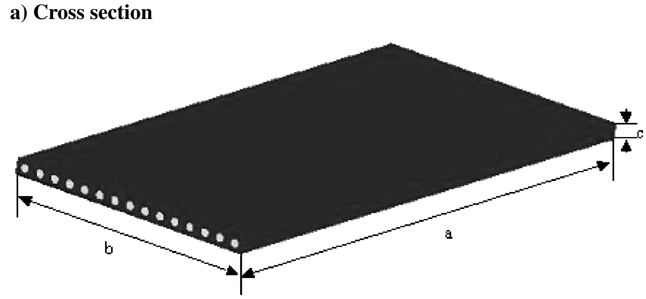


Fig. 4 Profile of projectile (millimeters).



a) Cross section



b) Panorama

Fig. 5 Microstructure of inclined lamina, 12 × 4 braided composite.

The parameters in Fig. 2 are as follows: $L_b = 45$ mm, $L_c = 12$ mm, $n_b = 6$, $n_c = 2$, $\theta = 20$ deg, $P_a = 16.5$ mm, $P_b = 7.5$ mm, and $P_c = 6.0$ mm. It could be calculated that there are 15 braiding yarns for 12×4 array braided composite in each inclined lamina when the fiber volume fraction of the three-dimensional braided composites was equal to that of the simplified structural model put forth in this paper.

Figure 5 shows the microstructure of inclined lamina for 12×4 braided composite.

C. Results of Ballistic Impact

Only normal impact tests were carried out to investigate the behavior of the braided composite target plate under ballistic penetration. To investigate the energy absorption capacity of composites target, the ballistic perforation tests, not the penetration, were considered. From the differences between striking velocities and residual velocities of the projectile, the decrease of kinetic energy of the projectile could be evaluated further. The residual velocities of the projectile perforating the 12×4 braided composite at different strike velocities are listed in Table 1. Because the striking velocity of the projectile could not be adjusted to the same value, no repetitions were performed for each impact velocity. Figure 2 shows the 12×4 braided composite after ballistic perforation. The damage zone was only around the perforation hole. Damages usually identified with laminated composites, such as delamination and matrix cracks in a large area, were not observed.

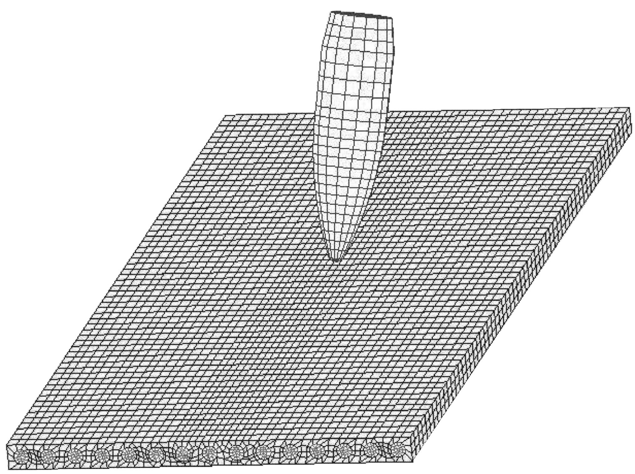
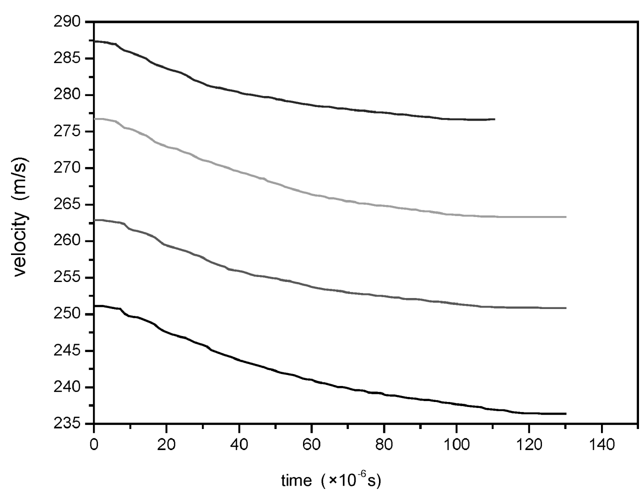


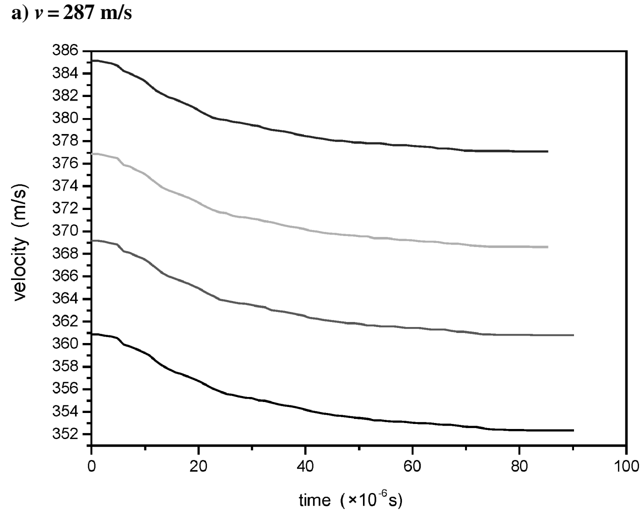
Fig. 6 Mesh scheme of inclined lamina and projectile.

Table 1 Residual velocity of projectile after perforating four-step three-dimensional braided composite targets

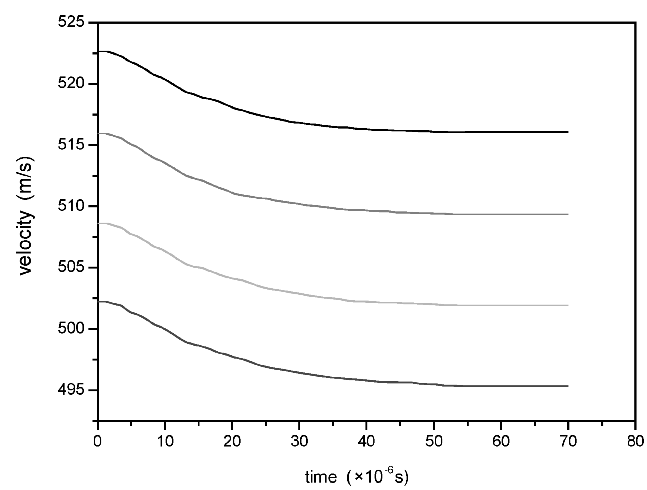
Experiment number	Strike velocity v_s, m/s	Residual velocity v_r, m/s	
		Experimental v_{re}	Theoretical v_{rt}
1	241	158	173
2	253	168	190
3	256	170	192
4	263	182	213
5	279	224	236
6	287	206	244
7	326	276	286
8	328	279	287
9	378	326	345
10	385	342	352
11	391	343	354
12	523	486	494
13	532	501	499
14	661	647	642
15	670	648	645



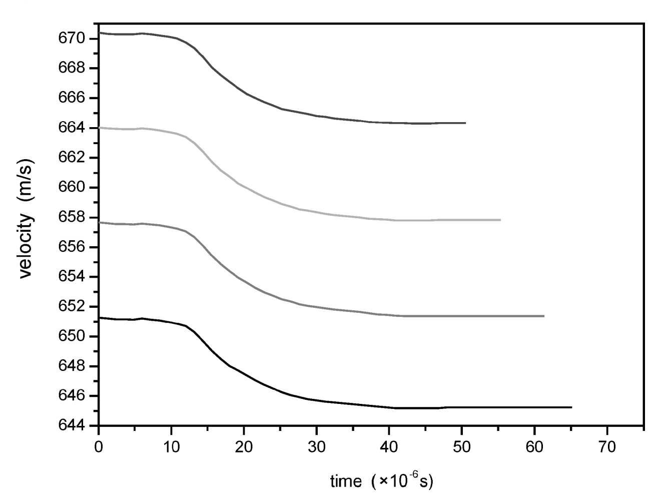
a) $v = 287$ m/s



b) $v = 385$ m/s



c) $v = 523$ m/s



d) $v = 670$ m/s

Fig. 7 Calculated velocity-time curve of projectile in ballistic penetration.

IV. Finite Element Analysis of Ballistic Penetration of Three-Dimensional Braided Composites

ANSYS was used as the preprocessor and Ls-Dyna as the solver and postprocessor. The projectile and the geometrical model of three-dimensional braided composites were meshed by eight-node hexahedron solid elements (SOLID 164 in ANSYS), as shown in Fig. 6. The calculation time required to finish the simulation depends on the mesh density. For an eight-node solid element, the critical time step size, Δt_e, is[14]

$$\Delta t_e = L_e \Big/ \left[Q + (Q^2 + C^2)^{\frac{1}{2}} \right] \tag{3}$$

where Q is a function of bulk viscosity coefficients C_0 and C_1,

$$Q = \begin{cases} C_1 c + C_0 L_e |\dot{\varepsilon}_{kk}| & \text{for} \quad \dot{\varepsilon}_{kk} < 0 \\ 0 & \text{for} \quad \dot{\varepsilon}_{kk} \geq 0 \end{cases} \tag{4}$$

$L_e = v_e / A_{e\,\max}$ is the characteristic length, v_e is the element volume, $A_{e\,\max}$ is the area of the largest side, and c is the adiabatic sound speed of the element material.

For a material with m elements, the time step Δt at the next calculation step is

$$\Delta t^{n+1} = \alpha \cdot \min(\Delta t_{e1}, \Delta t_{e2}, \ldots, \Delta t_{em}) \tag{5}$$

and the scale factor α in Eq. (5) is 0.9 or a small value for stability.

In the definition of materials contact, the surface of projectile is master surface, and the surface of composite target is slave surface. The CONTACT-ERODING_SURFACE_SURFACE was chosen.

The projectile was treated as a RIGID body (because no deformation of the projectile after it had perforated the composite target was found). The density of projectile is 7.81 g/cm^3, Young's modulus is defined as 200 GPa, and Poisson ratio is 0.292.

The epoxy matrix was treated as a PLASTIC-KINEMATIC material (1.17-g/cm^3 density, 5.0-GPa Young's modulus, 0.35 Poisson ratio, 0.35-GPa yield stress, and 4.5% failure strain.[15]

From the tensile curve of the Twaron fiber at strain rate of 1000 s^{-1} (Ref. 16), the constitutive equation could be deduced from the Weibull distribution of the yarn strength and was input as USER-DEFINED MATERIALS in finite element analysis software. The constitutive equation of Twaron fiber at the strain rate of 1000 s^{-1} is as follows[17]:

$$\sigma = 72\varepsilon \cdot \exp\left[-\left(\frac{72\varepsilon}{12.103} \right)^{1.139} - \left(\frac{72\varepsilon}{5.560} \right)^{6.098} \right], \qquad \dot{\varepsilon} = 1000\,\text{s}^{-1} \tag{6}$$

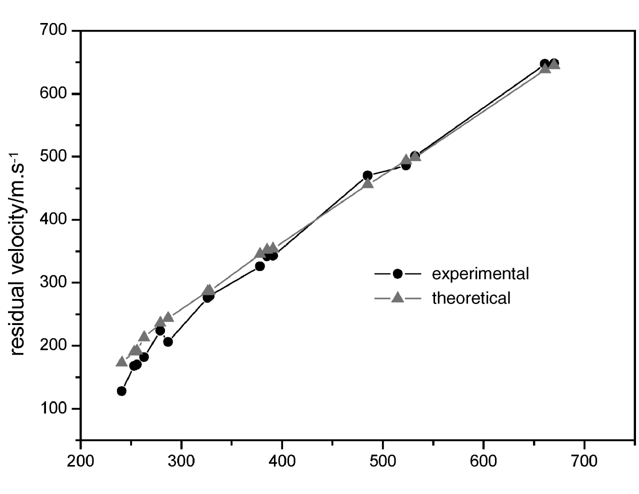


Fig. 8 Comparison of residual-striking velocity curve: theoretical and experimental.

V. Calculated Results and Comparisons

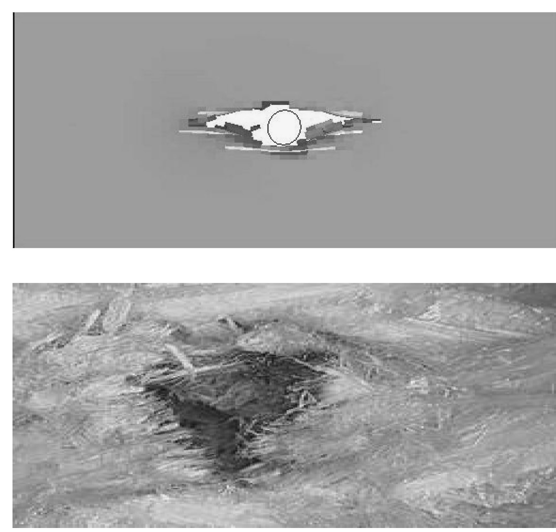
A. Comparison Between Finite Element Method Results and Experimental Results

In ballistic perforation test, only the striking velocity and residual velocity of projectile could be measured. In the finite element method (FEM) calculation, the striking velocity of the projectile is input and the residual velocity after perforating the refined quasi-microstructure model of three-dimensional braided composites could be calculated. Then the comparison between the two kinds of velocities could be conducted.

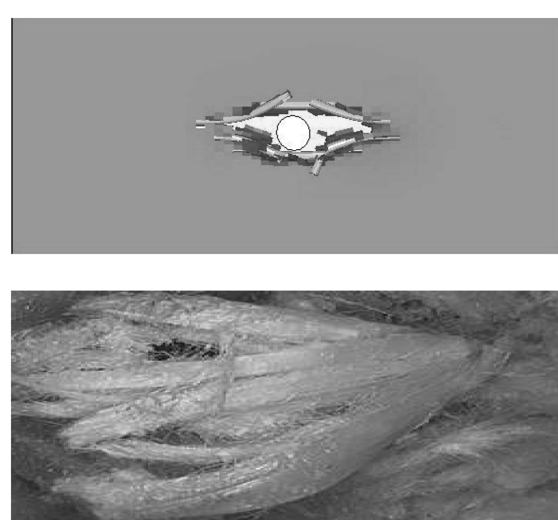
Take the incident velocity $v_s = 287$, 385, 523, and 670 m/s of the projectile as an example. The velocity-time curve of the projectile perforating the four laminas in Fig. 1 in succession are shown in Fig. 7. Table 1 and Fig. 8 show the comparison of residual velocities of the projectile between the experiment results and finite element analysis. It could be shown that there is good agreement of FEM and experimental residual velocities.

B. Damage Morphology

Figure 9 shows the comparison of damage morphology between the FEM simulation and experimental test. The damage modes of fiber breakage, fiber pullout, and matrix crack could be observed both in simulated and observed results.



a) Striking side



b) Distal side

Fig. 9 Comparison between simulated and observed damage morphology of inclined lamina of braided composites.

C. Comparison Between Two Structural Models

Figure 10 shows the comparison between the acceleration-time curves of the projectile in ballistic perforation from the simplified model of this paper and the homogeneous continuum model[18] of three-dimensional braided composites. In the calculation of the homogeneous continuum model, the matrix crack and fiber breakage in the ballistic penetration were not considered. At the initial stage of penetration, the penetration resistance that acted on the projectile gradually increased as the penetration went on and reached the maximum value when the projectile cross section with maximum diameter contacted the composite target. Afterward the penetration resistance decreased as the contact area between the composite target and projectile decreased, and meanwhile the acceleration of the projectile also decreased gradually to zero. This means that no penetration resistance acted on the projectile at the final stage of penetration. However, in the penetration process of actual composites

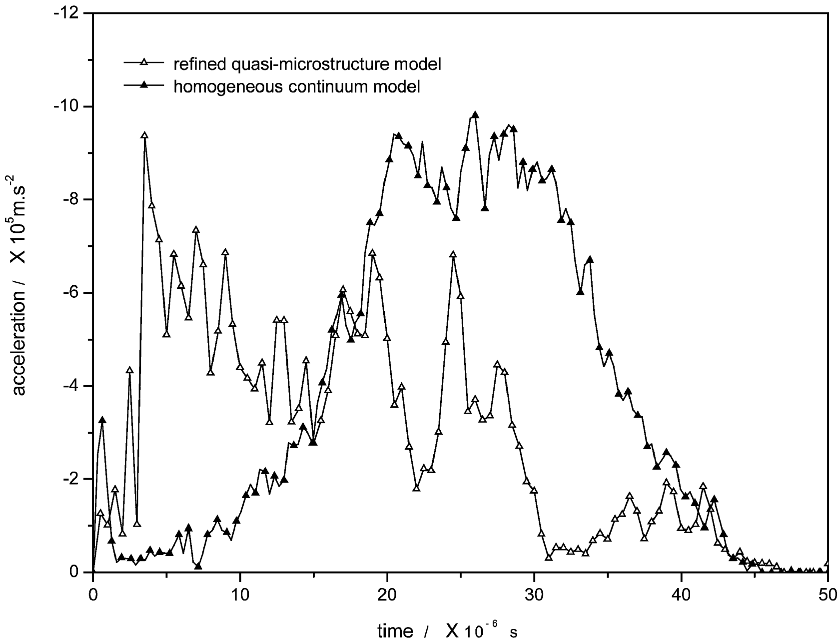


Fig. 10 Comparison of acceleration-time curves of the projectile from different models.

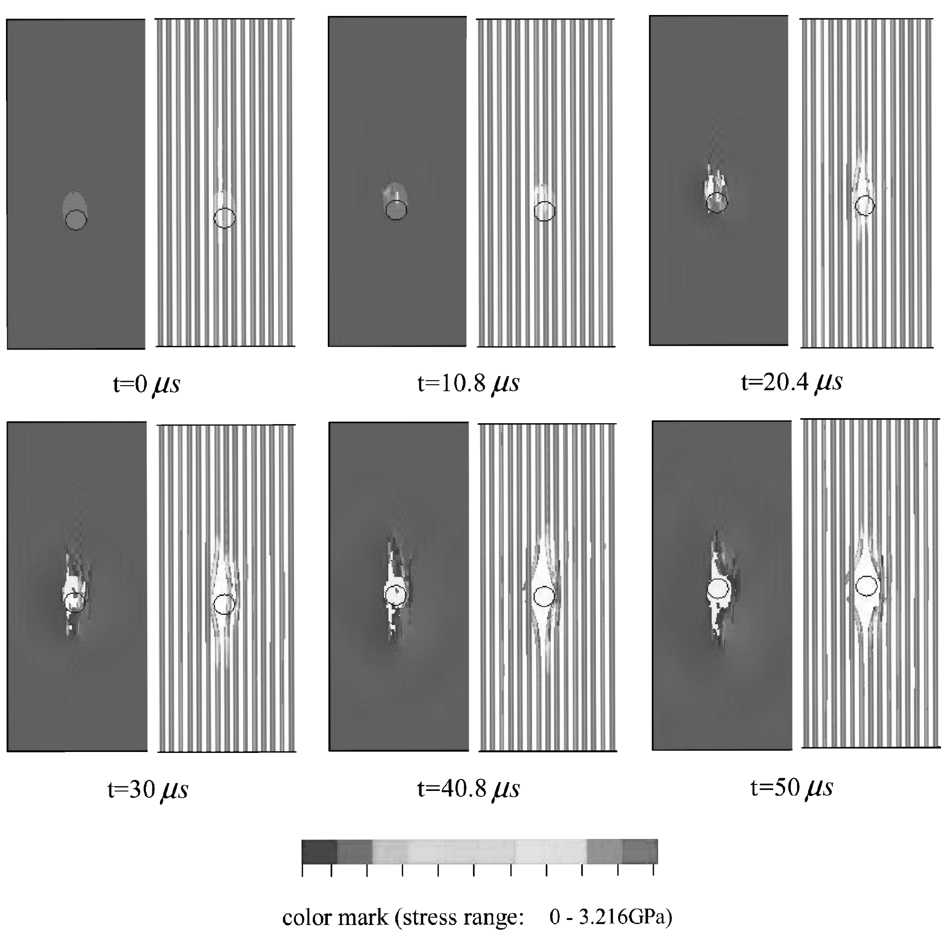


Fig. 11 Von Mises stress in the inclined lamina and its reinforcing yarns at different time.

by a projectile, the penetration resistance acting on a projectile is fluctuant at high amplitude because of the combined effects of the whole composite target bending, asynchronous fiber breakage, and matrix crack.

VI. Discussion

A. Comparison of Theoretical and Experimental Residual Velocities

In Table 1, the residual velocities of the projectile in experiment are greater than those calculated through finite element analysis by a mean value of 6.5%, which demonstrates that the kinetic energy absorption capacity of three-dimensiona braided composites in the experiment is greater than that in quasi-microstructure finite element calculation and that the penetration resistance estimation is conservative.

B. Propagation of von Mises Stress

Figure 11 is the Von Mises stress distribution in reinforcing yarns of the inclined lamina in the process of ballistic perforation. The velocity of stress wave propagation in the longitudinal direction of the yarns is greater than that in the transverse direction of the composites. The velocity of stress wave propagation in the longitudinal direction of the yarns is $C_1 = \sqrt{(E_f/\rho_f)}$. The elastic modulus in the transverse direction of the lamina perpendicular to the longitudinal direction of the yarns is $E_2 = E_f E_m/(E_f v_m + E_m v_f)$. The stress wave velocity in the transverse direction is $C_2 = \sqrt{(E_2/\rho_c)}$, and the volume density of the lamina $\rho_c = \rho_m v_m + \rho_f v_f$.

The ratio of stress wave propagation velocities in the longitudinal and the transverse directions in Fig. 11 is

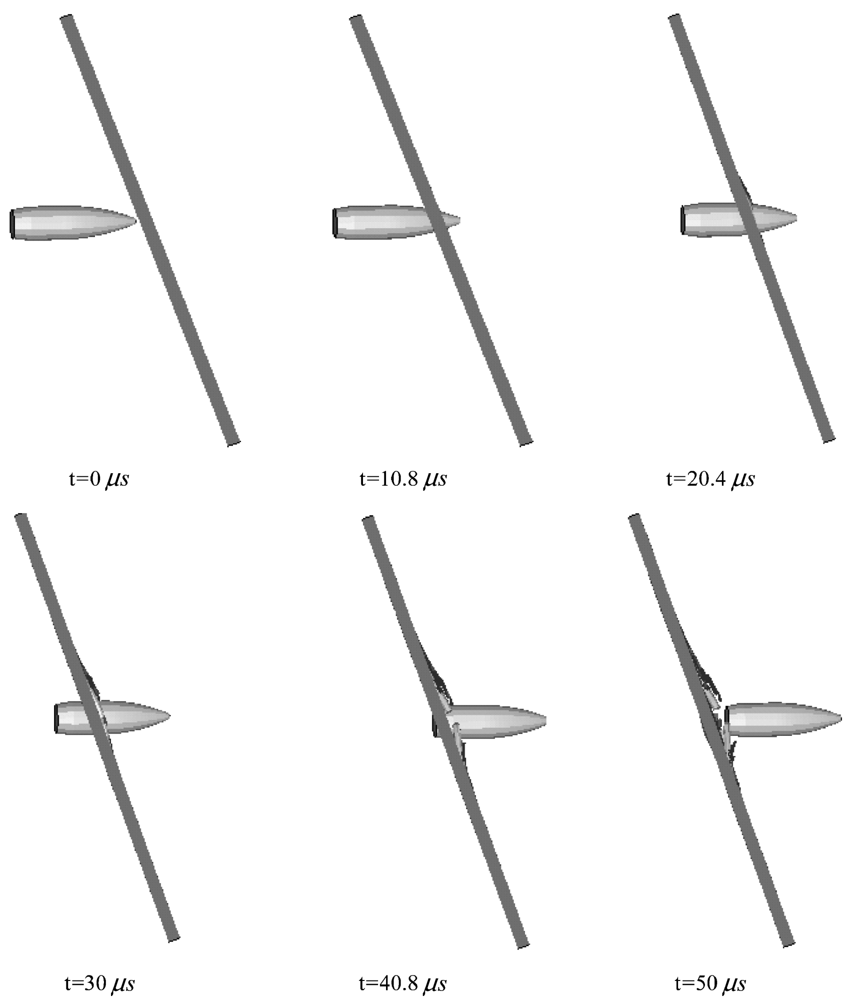
$$k = C_1/C_2 = \sqrt{\rho_c E_f/\rho_f E_2} \tag{7}$$

The calculation result for Eq. (7) approximates 4, which agrees with the results shown in Fig. 11.

C. Comparison of Theoretical and Experimental Impact Damage Morphology

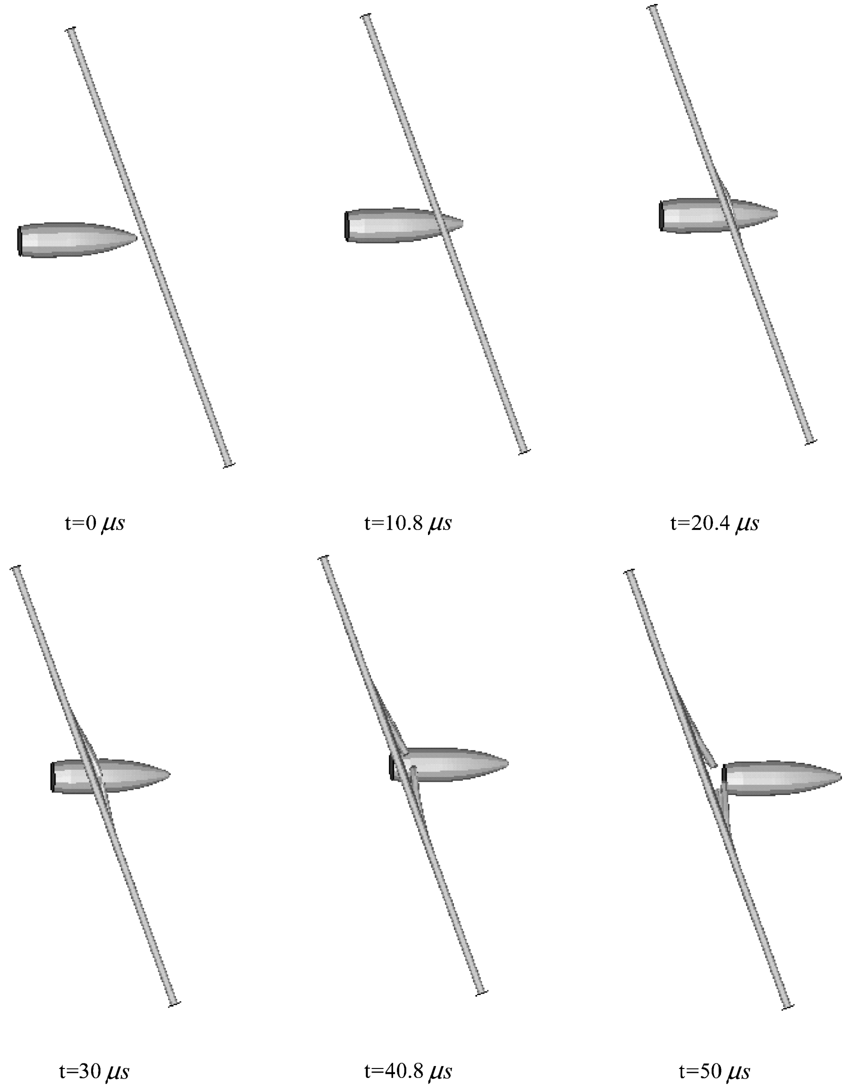
The ballistic penetration damage of inclined lamina and reinforced fibers at different times is shown in Fig. 12. In beginning stage of ballistic penetration, the projectile contacts with the matrix of composites. The elements in the matrix are failed and deleted gradually, which corresponds to the matrix crack. Then the projectile contacts the reinforced fibers in the inclined lamina. The reinforced fibers will be in deformation and breakage, and the fiber element will be deleted gradually in the FEM calculation. Also, the penetration hole will be formed and the deformation of lamina will be developed gradually. The fluctuation in the acceleration-time curve corresponds to the change of contact-eroding force between projectile and composite target, that is, corresponding to the interaction between the projectile and matrix fibers at different times in Fig. 12.

The fiber inclination model was employed to decompose the three-dimensional braided composites, whose unit cell was simplified by four inclined laminas ignoring their crossovers to represent the microstructure of three-dimensional braided composites, on the basis that the microstructure of the inclined lamina has the same fiber volume fraction and yarn diameter as those in three-dimensional braided composites. Because the fiber inclination model can be applied to all kinds of three-dimensional textile preform reinforced composites, such as three-dimensional woven reinforced composites, the simplified structural model in this paper can also be extended to calculate the ballistic penetration of other kinds of three-dimensional textile preform reinforced composites



a) Damage morphology of inclined lamina

Fig. 12 Simulated damage of inclined lamina of three-dimensional braided composite at different stages.



b) Damage morphology of reinforced fibers in inclined lamina

Fig. 12 Simulated damage of inclined lamina of three-dimensional braided composite at different stages (continued).

through the FEM. Compared with the homogeneous continuum model of three-dimensional composites,[18] this model can be used to simulate fiber breakage and matrix crack of the composite under ballistic penetration. Additionally, this model is simpler than the geometrical model of three-dimensional braided composites at actual microstructure level and more accurate in calculation.

VII. Conclusions

How can three-dimensional braided composites be applied in actual ballistic protection? There is currently no answer. This paper put forward a simplified structural model of three-dimensional braided composites in cooperation with FEM to evaluate the ballistic perforation of the composites impinged by conically cylindrical steel projectile. The simplified structural model of three-dimensional braided composites was constructed from the revised fiber inclination model of three-dimensional textile preform reinforced composites, that is, the three-dimensional braided composite was decomposed into four inclined laminas by ignoring the crossovers among these laminas and the inclined lamina was constructed at actual microstructure level based on the same fiber volume fraction and yarn diameter as those in three-dimensional braided composite. From finite element calculation results, it is revealed that this model can be employed to calculate accurately the kinetic energy of the projectile absorbed by three-dimensional braided composites target and the acceleration-time curve of the projectile, which agrees well with the actual impact damage process of the composites. The deficiency of the model lies in the simulation of damage morphology of the composite under ballistic impact. The ultimate goal of this model is to calculate the ballistic property of three-dimensional braided composites and then extend it to other three-dimensional textile preform reinforced composites at their actual microstructure levels. Then the penetration resistance prediction and damage morphology simulation of various three-dimensional composites can be obtained.

In summary, how to extend the three-dimensional braided composites in ballistic protection application is the most important. Whether three-dimensional composites could be applied in ballistic protection and how they compare with two-dimensional laminated composites should be demonstrated further.

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A. Palazotto
Associate Editor