FEM SIMULATION OF BALLISTIC PERFORATION OF 3-D RECTANGULAR BRAIDED COMPOSITE

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Abstract

This paper presents a microstructure model for simulating ballistic impact damage of 4-step 3-D braided rectangular composite penetrated by a rigid steel projectile. The microstructure model is based on the same yarn spatial configuration with that of the braided composite and also on the assumptions of the braided yarns appear straight inside the braided preform, bending and then change to other directions only at the surface. The ballistic perforation of the braided composite by a cylindrical-conically steel projectile has been simulated with finite element method. The comparisons between FEA and experimental results show the validity of the microstructure model, especially for the penetration resistance and impact damage of the composite. The velocity history and acceleration history of projectile, and impact damage development of the composite in FEM simulation indicate the different damage and energy absorption mechanisms of the braided composite compared with those of laminated composite.

1 Introduction

Compared with the laminated composite with the same fiber volume fraction, 3-dimensional textile preform reinforced composites have higher interlaminar shear strength and fracture toughness because of the fibers running through the thickness direction. There is no delamination phenomenon for 3-dimensional textile preform reinforced composites under ballistic impact. Flanagan et al [1] observed the damage morphology of 4-step 3-dimensional braided UHMPE composites after ballistic perforation. Jenq et al [2, 3] obtained the quasi-static penetration damage modes from the quasi-static perforation load-displacement curves of two-step and four-step 3-dimensional braided glass/epoxy composites at different penetration displacements and from different regions of the composites, and applied them to ballistic penetration analysis of the composites (projectile velocity: 65-180m/s). Gu et al [4] established a quasi-microstructure model to calculate the residual velocity of projectile perforated from the 3-D braided composite target. Furthermore, Gu et al [5, 6] put forward a refined quasi-microstructure to calculate the ballistic impact damage of 3-D braided composite with FEM. The refined quasi-microstructure model can precisely predict the energy absorption of 3-D braided composites and velocity vs. time, acceleration vs. time history of projectile during ballistic perforation. However, the model can not simulate the ballistic impact damage pattern because of the model is only an equivalent model and not based on the actual microstructure of 3-D braided composites. The difficult in establishing the actual microstructure of 3-D braided composites is complex and lack of mathematical description of the microstructure. How to construct an actual geometrical microstructure model is the key to predict and simulate the damage pattern of 3-D braided composites under ballistic impact.

This paper resolves the problem of characterization of actual microstructure of 4-step 3-D braided rectangular Twaron®/epoxy composite in the pre-processor of FEM. The ballistic impact between the 3-D braided composite and steel cylindrical-conically projectile is calculated with the commercial available FEM code Ls-Dyna. The residual velocity of projectile, the energy absorption and especially the deformation and damage of 3-D braided composite under ballistic impact are simulated with FEM and compared with that in experiment. Some discussions on the velocity vs. time and acceleration vs. time history of projectile in ballistic penetration are also presented.

2 Microstructure descriptions of 4-step 3-D braided composite

According to the simulation results of Wang and Sun [7], the spatial configuration of all yarns in one yarn group is the same and the only difference is initial position in axial direction. When the spatial configuration of one yarn in a group is obtained, the configuration of other yarns in the same yarn group could also be obtained. Because the braiding yarns appear straight inside the braided preform, bending and then change to other directions only at the surface. We could get the coordinates of the transition point of the yarn on braided preform surface with image analysis method. Then the straight line between the two transition points could represent the yarn configuration in the interior of braided preform. In a machine cycle (i.e., all yarn carriers returning to their original positions) or in a pitch length of braided preform, the spatial configuration of trace yarn could be expressed by linking a series of straight lines.

Assume that the coordinates of center points of the yarn in two neighboring cross-section is (x_i, y_i, z_i) and $(x_{i+1}, y_{i+1}, z_{i+1})$ respectively, then the equation of straight line between the two points is (i.e., the equation of the ith section of the yarn):

$$\begin{cases} x_i = M_{i1}(t-b_i)+M_{i2} \\ y_i = N_{i1}(t-b_i)+N_{i2} \quad b_i \le t \le b_{i+1} \\ z_i = t \end{cases} \quad (1)$$

where:

$$M_{i1} = \frac{x_{i+1}-x_i}{z_{i+1}-z_i} \qquad M_{i2} = x_i$$

$$N_{i1} = \frac{y_{i+1}-y_i}{z_{i+1}-z_i} \qquad N_{i2} = y_i \quad (2)$$

$$b_i = z_i$$

Because other yarns in one yarn group have identical spatial configuration at a fixed space coordinate, the only difference among them is the initial position along the longitudinal direction of braided preform. Then these yarns could be expressed with the equations of the same form and coefficient as equation (1) and (2).

Assume:

(1)There are M yarns in one yarn group.

(2)Yarns are numbered with j ($j = 0,1,....,M_r - 1$).

(3)The 0th yarn is datum yarn.

Then the initial position of jth yarn relative to 0th yarn is:

$$s_j = j \cdot h / M_r \quad (3)$$

The ith segment in jth yarn in one yarn group could be expressed as follows:

$$\begin{cases} x_{ji} = M_{i1}(t+s_j-b_i)+M_{i2} \\ y_{ji} = N_{i1}(t+s_j-b_i)+N_{i2} \quad b_i \le t \le b_{i+1} \\ z_{ji} = t \end{cases} \quad (4)$$

where the parameters in equation (4) are the same with that in equation (2). This is the equation to describe the spatial configuration of every yarn in one yarn group.

The spatial configuration of the braiding yarn could be reconstructed in visualization way with the above-mentioned equations or directly from the coordinates of central points of cross-section in the braiding yarn, shown in Fig.1. The rest part in a rectangular parallelepiped cuboid 3-D braided composite except the braided preform is matrix, shown in Fig.2.Then the images are imported into the preprocessor of FEM code.

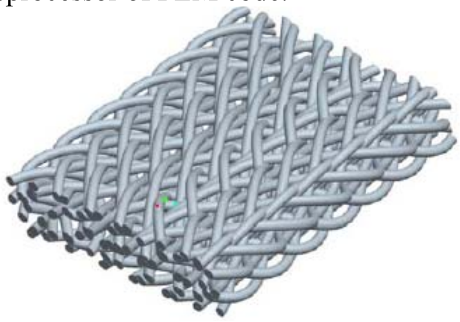


Fig.1 Microstructure geometrical model of 12×4 braided preform

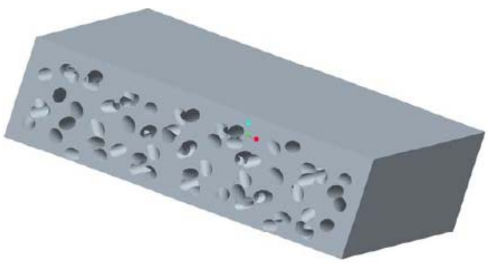
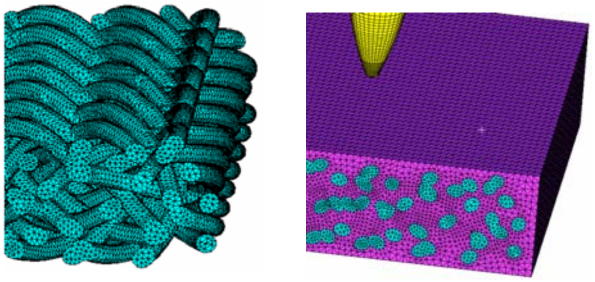


Fig.2 Microstructure of 12×4 type 3D braided composites (Yarns are in transparent)

3 Finite element analysis of ballistic penetration of 3-dimensional braided composite

3.1 Mesh scheme

The projectile was meshed by 8-node hexahedron solid elements. The microstructure geometrical model for 3-D braided composite was meshed by 4-node tetrahedron solid element. The mesh scheme for the 3-D composite is shown in Fig.3(a) and for 3-D braided preform is shown in Fig.3(b). There are about 2,500,000 tetrahedron solid elements in the microstructure geometrical model. On the assumption of the perfect bonding between yarn and matrix, the elements of yarns and matrix share the same nodes and surface in meshing.



(a) (b)

Fig.3 Mesh scheme for the 12×4 type 3-D composite

3.2 Materials' definition

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 7.81g/cm^3, Young's modulus is defined as 200GPa and Poisson's ratio is 0.292.

The epoxy matrix was treated as a PLASTIC-KINEMATIC material (density: 1.17 g/cm^3, Young's modulus: 5.0GPa, Poisson's ratio: 0.35, yield stress: 0.35 GPa, failure strain: 4.5%) [8].

The braiding yarn was Twaron® fiber (type 1000, density: 1.44 g/cm^3). Because the composite are under high strain rate state penetrated by projectile, the mechanical parameters of Twaron® fiber under high strain rate should be adopted in finite element calculation. The tensile curve of Twaron® fiber at various strain rates was tested by split Hopkinson tension bar (SHTB). The mechanical parameters in Ref. [5] are used in FEM calculation.

4 Calculated results and comparisons

4.1 Comparisons of residual velocity of projectile between FEM and experimental

Given different strike velocities of projectiles which are same with those in ballistic impact test into the microstructure geometrical model, the residual velocities could be calculated and compared with the residual velocities in experimental. In ballistic perforation test, only the striking velocity and residual velocity of projectile could be measured[5]. However in FEM calculation, the velocity vs. time history and the acceleration vs. time history of projectile could all be obtained.

Comparison between the calculated residual velocities and experimental residual velocities of projectile is shown in Fig.4. Taking the strike velocities of v_s=263m/s as examples, the velocity vs. time history and acceleration vs. time history of projectile in ballistic penetration is shown in Fig.5.

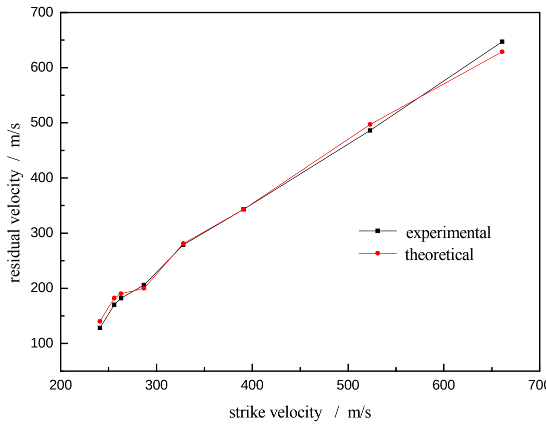
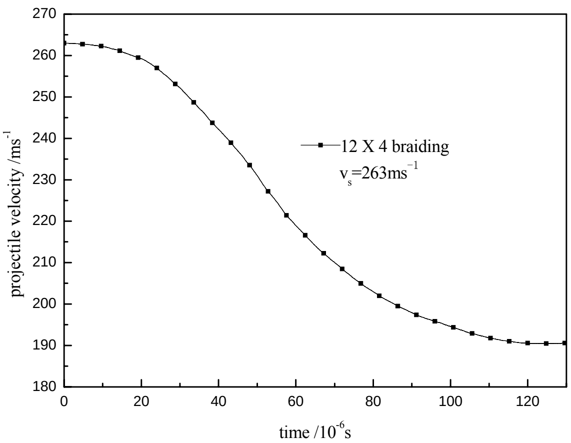


Fig.4 Strike velocity vs. residual velocity curve for 12×4 braided composites



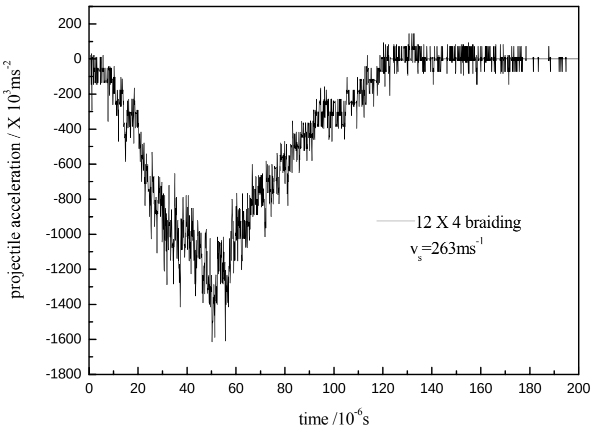


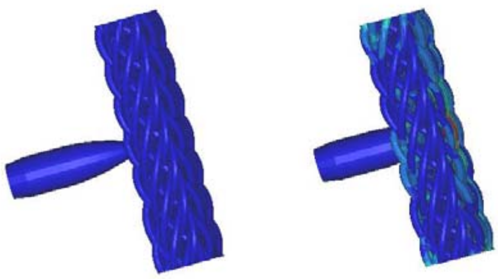
Fig.5 Velocity vs. time and acceleration vs. time history of projectile

From Fig.4, it could be shown that there are good agreement of residual velocities in FEM and experimental. The residual velocities of projectile of FEM are almost all less than those in experimental, i.e., the FEM results are conservative to estimate the penetration resistance of 3-D braided composite. The microstructure geometrical model can precisely calculate the energy absorption of 3-D braided composite under ballistic impact.

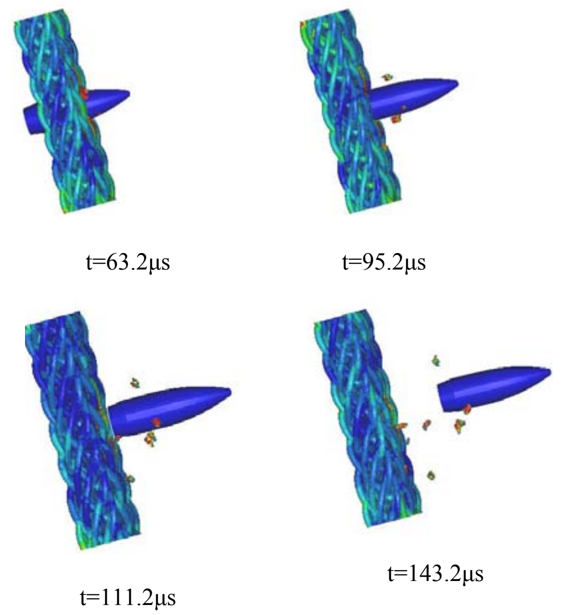
4.2 3-D braided composite deformation under ballistic impact

The FEM calculation can predict this damage and deformation phenomenon.

On account of 3-D braided perform absorbed majority of energy of projectile impact, Fig.6 is the ballistic perforation process of 12 × 4 type 3-D braided preform at the strike velocity of 391m/s. From the FEM simulated results, the damage modes of fiber breakage, fiber pullout and matrix crack could be observed and compared with those in Fig.7. The damage pattern in Fig.7 is the local magnification near perforating hole.

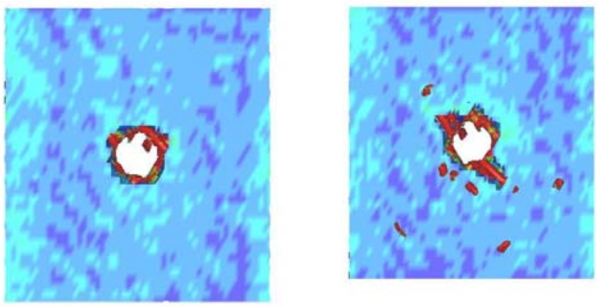


t=0μs   t=31.2μs



color mark (stress: 4.405×10^{-3}~5×10^{-1}Gpa)

Fig.6 Ballistic perforation process of 12×4 3-D braided reinforcing preform at the strike velocity of 391m/s



(a) striking side   (b) distal side

(1) Simulated damage morphology of 12×4 braided composite

Damage morphology near penetration hole in striking side

Damage morphology near penetration hole in distal side

(2) Local magnification of damage pattern around the perforating hole

Fig.7 Observed damage morphology of 3-D braided composite

4.3 Contact force of projectile comparison between preform and resin of 3-D braided composite

Fig.8 is contact force of projectile vs. time curves comparison between perform and resin for 12×4 type 3-D braided composite at strike velocity of 391m/s. The contact force of projectile vs. time curve reflects the penetration resistance acts on projectile by composite target. The breakage of fibers in yarn, matrix crack, and deformation of 3-D braided composite can all influence the penetration force. All these can be shown from contact force of projectile vs. time curves. When projectile strike composite , it reach epoxy resin in the beginning. So contact force between projectile and epoxy resin take place. When projectile reach preform of 3-D braided composite, contact force between projectile and preform increased at once and get to maximum. With time increasing contact force has fall trend. This is due to stress wave effect. Owing to module and strength of Twaron® fiber much higher than that of epoxy resin, the contact force between projectile and fiber is much higher than that of epoxy resin. This can be explained that the preform of 3-D braided composite is main energy absorption part at the ballistics penetration.

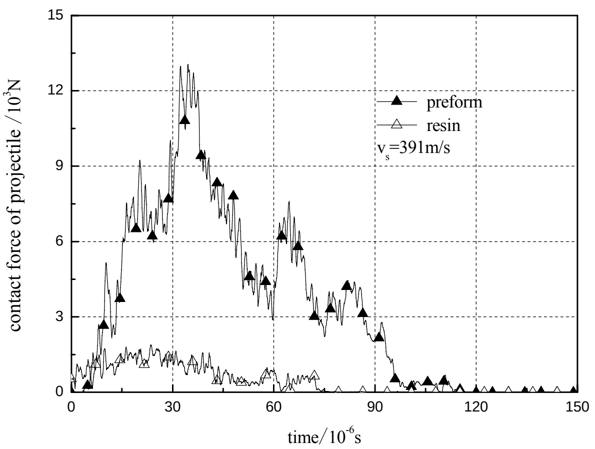


Fig.8 Contact force of projectile vs. time curves comparison between 3-D braided perform and resin at strike velocity of 391m/s

5 Conclusions

The ballistic penetration of 4-step 3-D 1×1 braided rectangular composite was simulated with FEM at microstructure level. The microstructure model is based on the same fiber volume fraction and braided yarn geometry with the braided composite. The ballistic penetration of the steel projectile into the composite has been simulated to illustrate the impact damage. The velocity and acceleration history of the projectile, the energy absorption and damage of the composite have been calculated and showed the agreement with those in experimental. From the comparison of results obtained from the microstructure model and other models based on continuum assumption, the microstructure model is more precise in calculation of energy absorption, damage propagation and deformation development. The further works will still be carried out for calculating the ballistic impact of other 3-D textile structural composite.

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References

[1] Flanagan M P, Zikry M A, Wall J W, et al. An experimental investigation of high velocity impact and penetration failure modes in textile composites. *Journal of composite materials*, 1999, 33(12): 1080-1103

[2] Jenq S T, Mao J J. Ballistic impact response for two-step braided three-dimensional textile composites, *AIAA Journal*, 1996, 34(2):375-384

[3] Jenq S T, Kuo J T, Sheu L T. Ballistic impact response of 3-D four-step braided glass/epoxy composites, *Key engineering materials*, 1998, 141-143: 349-366

[4] Gu B, Xu J. Finite element calculation of 4-step 3-dimensional braided composite under ballistic perforation. *Composites: Part B*, 2004, 35(4), 291-297

[5] Gu B, Ding X. A refined quasi-microstructure model for finite element analysis of 3-dimensional braided composites under ballistic penetration, *Journal of composite materials*, 2005(4); 39(8): 685-710

[6] Gu B, Li Y. Ballistic perforation of conically cylindrical steel projectile into 3-D braided composites, *AIAA Journal*, 2005, 43(2): 426-434

[7] Wang Y, Sun X. Digital-element simulation of textile processes, *Composites science and technology*, 2001, 61: 311-319

[8] Gu B. Prediction of the uniaxial tensile curve of 4-step 3-dimensional braided preform. *Composite structures*, 2004, 64: 235-241

[9] Gu B. Prediction of the uniaxial tensile curve of 4-step 3-dimensional braided preform. *Composite structures*, 2004, 64: 235-241