Study on Impact Behavior of Composite Sandwich Structure with Different Interlayer Angles

Peng Yuyang · Chen Xiuhua

Abstract The paper investigates the influence of different interlayer angles on dynamic behavior of composite sandwich structure subjected to low-velocity impact. The composite sandwich structure is composed of CFRP/epoxy laminates and Nomex honeycomb core. 7 finite element models with 7 different interlayer angles, from [0°/0°/0°/Honeycomb/0°/0°/0°] to [0°/90°/0°/Honeycomb/0°/90°/0°], of composite sandwich are implemented by ABAQUS/Explicit. The damage mechanism for composite laminate is applied with 3D Hashin damage by VUMAT while the honeycomb is based on traction separation laws. The modelling results show that, as interlayer angle increases, the indent area is decreasing but the rate of decrease becomes slower. Meanwhile, the energy absorption is increasing with the higher interlayer angle. From mentioned above, it can be concluded that the interlayer angle has an effect on the impact behavior of composite, and the bigger interlayer angle will result in a better impact resistance.

Keywords Composite sandwich sturcture, impact, Interlayer Angle, Abaqus

1 Introduction

Advanced composite structures offer many advantages compared to conventional materials, especially where high strength and stiffness to weight ratio is concerned. Thus, composites have been used widely in many applications such as aerospace, sport equipment, pressure vessels and automotive parts. For composite sandwich structures, they have good resistance of fatigue, corrosion, and vibration, and the core, the panel can be chosen different to combine. However, composite sandwich structures perform not well in interlaminar properties and low velocity impact resistance, when subjected to low velocity impact of foreign objects during manufacturing, transportation, utilization and maintenance, such as tools dropping and hail impact, different types of damage such as matrix cracking, fiber breakage, and interface debonding between the panel and the core will occur. It should be emphasized that the damage caused by low velocity impact is considered very detrimental, this damage will leads to internal defects,resulting in weakening of structural bearing capacity during service, especially in the compress and shear bearing capacity, which seriously restrict the development and utilization of composite sandwich structure. [1] Meanwhile,In most cases, these defects are not visually identified so the detection techniques are needed. Non-destructive techniques is widely used because it can detect the damage without destructing the stucture. Ultrasonic C scanning, X-radiography and shearography also are applied for detecting the damage.[2] However, all these techniques are inadequate for in-service inspection of large components. As a new light structural material which widely used in aeronautic and astronautic, researches that related to impact damage of composite material are not complete and mature, no matter the dynamic mechanical

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properties of material or the theoretical analysis and numerical modeling of impact damage, which can't satisfy the needs for military technical development. [3]Therefore, go in deep with the research of impact damage of composite material has important theoretical value and practical significance.

Many parameters will influence the impact response of the composite sandwich structure. Wang Jie[4] did the research about the influence of impactor size,plate thickness and core thickness on the impact response.A. M. Amaro[5] studied the influence of the boundary conditions on the impact of composite, Johann Körbelin[6] investigated how the temperature and impact energy would affect impact process, and the effects of stacking sequence on impact was studied by A. Riccio and G. Di Felice[7]. In this paper, the influence of different interlayer angles was investigated by using ABAQUS simulation to create an 3D damage model of composite sandwich structures under low velocity impact. The model comprehensively considered main damage modes such as matrix cracking, fiber breakage, matrix compression and delamination, using VUMAT to realize the definition of material constitutive relationship, and predicted the impact response of composite sandwich structures.

2 Failure criterion

2.1 Composite

About the failure criterion of composite, many scholars have done plenty of researches, such as Max stress criterion, Tsai-Wu criterion, and Chang-Chang criterion. In this paper, 3D Hashin failure criterion was applied by combining user subroutine VUMAT.

The failure modes included in Hashin's criteria are as follows.

1. Tensile fiber failure for $\sigma 11 \geq 0$

$$\left(\frac{\sigma_{11}}{X_T}\right)^2+\frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2}=\begin{cases}\geq 1 & \text{failure}\\ <1 & \text{no failure}\end{cases}$$

2. Compressive fiber failure for $\sigma 11 < 0$

$$\left(\frac{\sigma_{11}}{X_C}\right)^2=\begin{cases}\geq 1 & \text{failure}\\ <1 & \text{no failure}\end{cases}$$

3. Tensile matrix failure for $\sigma 22 + \sigma 33 > 0$

$$\frac{\left(\sigma_{22}+\sigma_{33}\right)^2}{Y_T^2}+\frac{\sigma_{23}^2-\sigma_{22}\sigma_{33}}{S_{23}^2}+\frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2}=\begin{cases}\geq 1 & \text{failure}\\ <1 & \text{no failure}\end{cases}$$

4. Compressive matrix failure for $\sigma 22 + \sigma 33 < 0$

$$\left[\left(\frac{Y_C}{2S_{23}}\right)^2-1\right]\left(\frac{\sigma_{22}+\sigma_{33}}{Y_C}\right)+\frac{\left(\sigma_{22}+\sigma_{33}\right)^2}{4S_{23}^2}+\frac{\sigma_{23}^2-\sigma_{22}\sigma_{33}}{S_{23}^2}+\frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2}=\begin{cases}\geq 1 & \text{failure}\\ <1 & \text{no failure}\end{cases}$$

5. Interlaminar tensile failure for $\sigma 33 > 0$

$$\left(\frac{\sigma_{33}}{Z_T}\right)^2=\begin{cases}\geq 1 & \text{failure}\\ <1 & \text{no failure}\end{cases}$$

6. Interlaminar compression failure for $\sigma 33 < 0$

$$\left(\frac{\sigma_{33}}{Z_C}\right)^2=\begin{cases}\geq 1 & \text{failure}\\ <1 & \text{no failure}\end{cases}$$

where, σ_{ij} denote the stress components and the tensile and compressive allowable strengths for lamina are denoted by subscripts T and C, respectively. X_T, Y_T, Z_T denotes the allowable tensile strengths in three respective material directions. Similarly, X_C, Y_C, Z_C denotes the allowable compressive strengths in three respective material directions. Further, S_{12}, S_{13} and S_{23} denote allowable shear strengths in the respective principal material directions.[8][9]

2.2 Honeycomb

The damage mechanism for composite sandwich structure is quite complicated, so during the research following assumptions are often proposed: the plate is only subjected to interlaminar stress σ_x, σ_y, τ_{xy}, the honeycomb core is only subjected to transverse shear stress, evenly distributed through the thickness, the state of stress is : σ_x=σ_y=τ_{xy}=0, τ_{xz}≠0, τ_{yz}≠0; when the sandwich structure deforms, ε_z=0, and the effect of σ_z is omitted. Z-direction is vertical to the plate, x-direction and y-direction are the 2 directions on the plate. These assumptions can be considered that the interlaminar tensile, compression and shear are not taken into account, only the transverse shear failure and z-direction compression. [10]The failure criterion is presented as follows:

1. Z-direction compression failure: $\left\{\frac{\sigma_z}{Z}\right\}^2 = \begin{cases} \geq 1 \text{ failure} \\ < 1\ no\ failure \end{cases}$

2. Transverse(xz) shear failure: $\left\{\frac{\tau_{xz}}{S_{xz}}\right\}^2 = \begin{cases} \geq 1 \text{ failure} \\ < 1\ no\ failure \end{cases}$

3. Transverse(xz) shear failure: $\left\{\frac{\tau_{yz}}{S_{yz}}\right\}^2 = \begin{cases} \geq 1 \text{ failure} \\ < 1\ no\ failure \end{cases}$

where Z presents the z-direction compression strength, S_{xz} and S_{yz} are the transverse shear strength for the xz and yz direction, respectively.

2.3 Cohesive

To simulate the formation and evolution of the interlaminar damage of composite plate, cohesive behaviour was introduced in interaction between each ply of composite. The stress criterion used is given by Damage for traction separation laws-Maximum nominal stress criterion, which damage is assumed to initiate when the maximum nominal stress ratio (as defined in the expression below) reaches a value of one. Figure 1 shows a typical traction-separation response with a failure mechanism.[11]

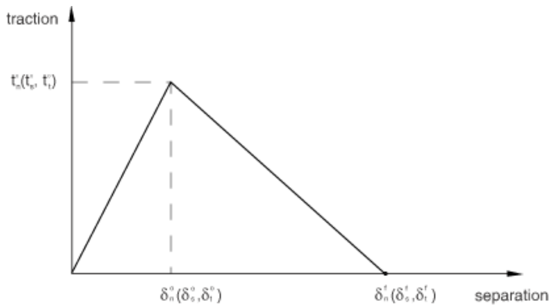

Figure 1. Typical traction-separation response.

This criterion can be represented as

$$max\left\{\frac{\langle t_n\rangle}{t_n^0},\frac{t_s}{t_s^0},\frac{t_t}{t_t^0}\right\} = 1$$

where t_n^0, t_s^0, t_t^0 represent the peak values of the contact stress when the separation is either purely normal to the interface or purely in the first or the second shear direction, respectively. t_n, t_s, and t_t denotes the traction stress vector in the normal and shear directions. The symbol $\langle\ \rangle$ represents the Macaulay bracket with the usual interpretation. The Macaulay brackets are used to signify that a purely compressive displacement (i.e., a contact penetration) or a purely compressive stress state does not initiate damage.

3 FEM Model

As shown in Fig.2 and Fig.3, the finite element model is built in ABAQUS/Explicit.

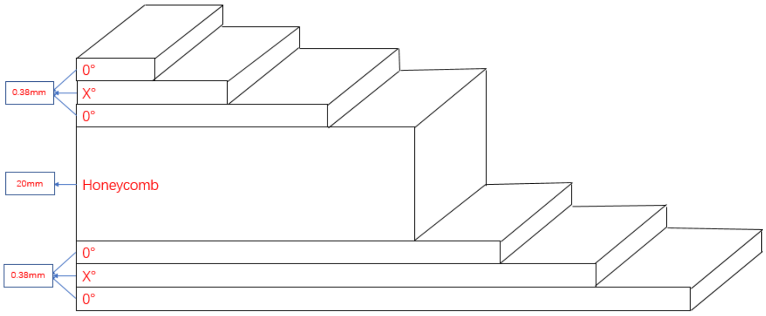

Fig.2 Composite sandwich structure

The composite sandwich structure was composed by 7 layers: [0°/x°/0°/Honeycomb/0°/x°/0°], including composite plate and honeycomb core. Each layer of composite plate was 0.38mm, and each upper plate was modeled with 5000 three-dimensional eight-node solid finite elements (C3D8R element type), the mesh was implemented by double-bias seeds with ratio 5, each side 50 elements while the lower plate was modeled with 256 C3D8R elements. The honeycomb was 20 mm thick, modeled with 20000 C3D8R elements. To better observe the impact response, on the thickness direction, 8 seeds with single-bias ratio 4 were implemented on the honeycomb core. The diameter of the impactor was 16mm, and the mass was 1.38kg. The impactor was assumed to be rigid with a velocity of 2.4m/s, and meshed as 2702 four-node linear tetrahedron solid finite elements(C3D4 element type). Between the impactor and the composite sandwich, a friction coefficient of 0.3 has been used to simulate the interaction. Layer-to-layer contact and layer-to-core contact has been modeled with cohesive behavior interaction included in the Abaqus element database. The boundary conditions were set as follows: impactor: U1=U2=UR1=UR2=UR3=0, support: U1=U2=U3=UR1=UR2=UR3=0. The whole step time period was 0.0005s, which made the indent about 1.2mm deep. Hence, our focus is on the upper composite plate, for reducing the calculating period, the mesh of lower plate is much coarser than the upper. Meanwhile, the support was not the emphazisement, meshed with 494 C3D8R elements.

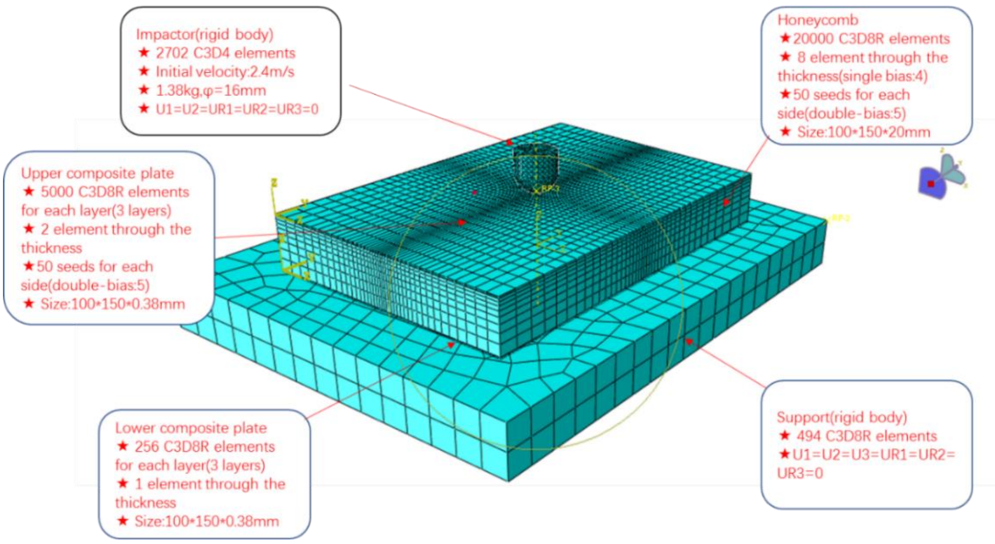

Fig.3 Abaqus FEM model

Parameters

1.Composite plate: Cycom 381 IM7 UD Nominal	
Engineering constants	E_1=156.5 GPa, E_2=E_3=8.83 GPa ν_{12}=ν_{13}=ν_{23}= 0.3 G_{12}=G_{13}=4.3GPa, G_{23}=3.39615GPa
Density Ultimate stress	1583 kg/m³ Xt =2468 MPa, Xc =1482MPa Yt=38 MPa, Yc=176.6 MPa Zt=38 MPa, Zc=176.6 MPa S12=S13=128 MPa.S23=50.9423MPa

2.Honeycomb core: ECA 3.2-48-(51)	
Engineering constants	E1=E2=E3=1e-009 GPa ν12=ν13=ν23= 0.42 G12=1e-009GPa, G13 =0.048GPa G23=0.03GPa
Density Ultimate stress	48 kg/m³ Z-direction compression: 2.1MPa Transverse direction(13):1.32MPa, Transverse direction(23):0.72MPa

3.Cohesive	
Traction-separation behavior	Knn=1500MPa, Kss=Ktt=1000MPa
Damage	Normal: 45MPa, Shear-1,Shear-2:30MPa Normal-only mode: 2.1MPa 1-direction:1.32MPa, 2-direction:0.72MPa

4 Results

The numerical results were obtained from the FEM model.

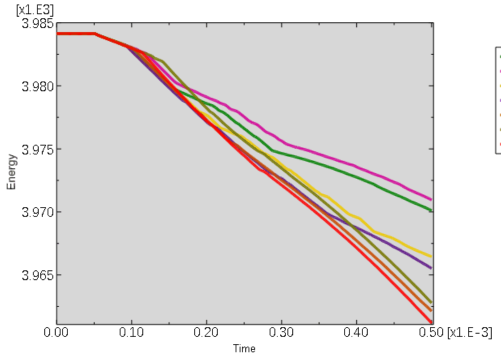

Fig.4(a) Energy-time curve

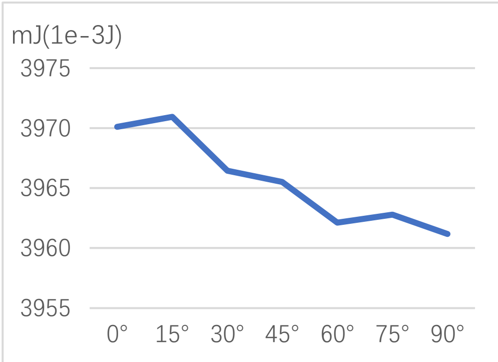

Fig.4(b) Residual energy-angle curve

From Fig.4(a) and 4(b),it's observed that energy absorbtion rate increases with the interlayer angle rising. E0, E15 and E90 means energy-time curve with different interlayer angles. For 15° and 75° interlayer angles, the results have some deviation, but the overall trend is certain.

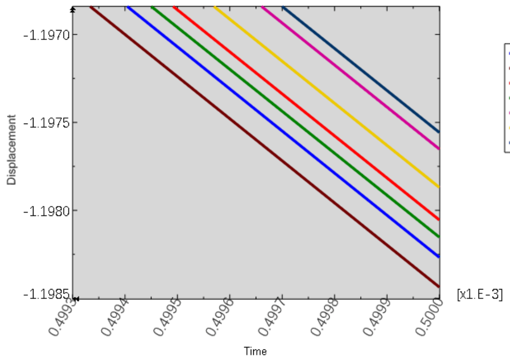

Fig.5(a) Displacement-time curve

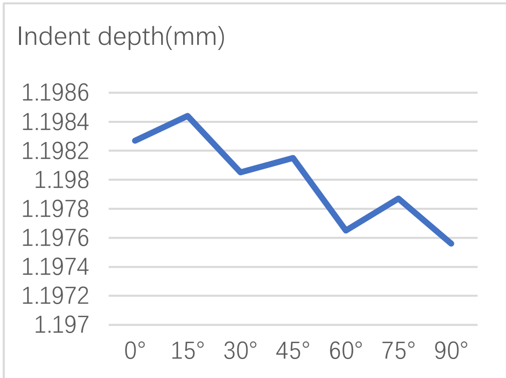

Fig.5(b) Indent depth-angle curve

Next, for indent depth, as is shown in Fig.5(a) and (b), it has the opposite tendency with energy absorbtion rate. As interlayer angle goes up, the indent depth presents an overall downward trend.

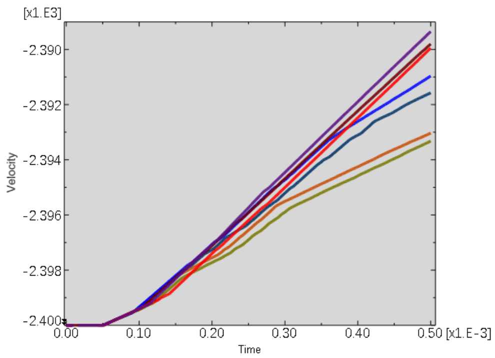

Fig.6(a) Velocity-time curve

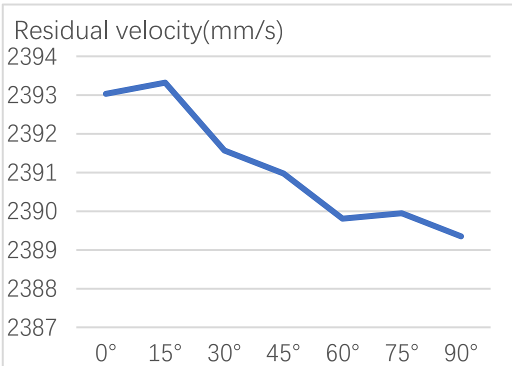

Fig.6(b) Residual velocity-angle curve

Meanwhile, it's consistently observed in Fig.6(a) and (b) that residual velocity corresponds well with the relationship between residual energy and interlayer angle.

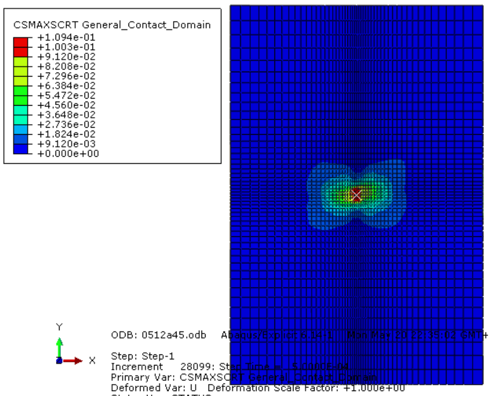

Fig.7(a) CSMAXSCRT between 1st and 2nd layer

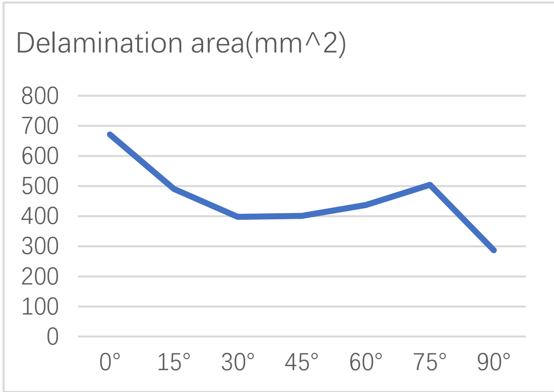

Fig.7(b) Delamination area-angle curve between 1st and 2nd layer

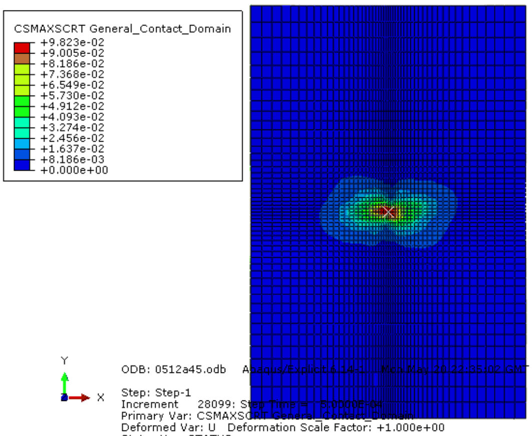

Fig.8(a) CSMAXSCRT between 2nd and 3rd layer

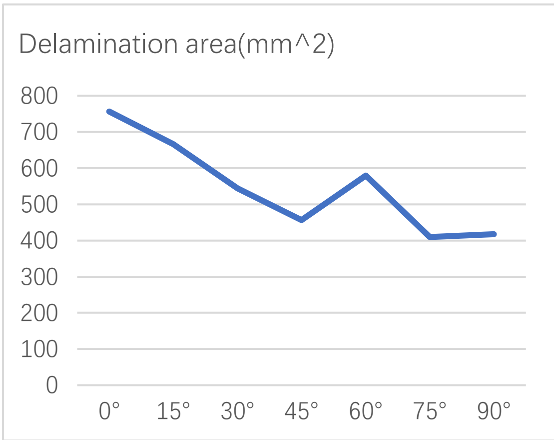

Fig.8(b) Delamination area-angle curve between 2nd and 3rd layer

Fig.7 and Fig.8 show that the influence of interlayer angle on the delamination area of the upper composite plate, interface delamination are presented by maximum contact stress damage initiation criterion(CSMAXSCRT). We can observe that the delamination area between 2nd and 3rd layer is much bigger than the one between 1st and 2nd layer. Because during the impact process, the plate was mainly subjected to bending deformation, for the 2nd layer, the upper surface was subjected to compress stress, while the lower surface was subjected to tensile stress, and the bending deformation of the lower surface was larger than the upper, so the stress on the lower surface was much higher, resulting in damage easilier. Meanwhile, for the delamination of both interfaces, as interlayer angle multiplies, the delamination area presents an overall decreasing trend. Except for 60° and 75°, the others are monotonically decreasing. This represents the composite sandwich with a larger interlayer angle has a better interlaminar performance.

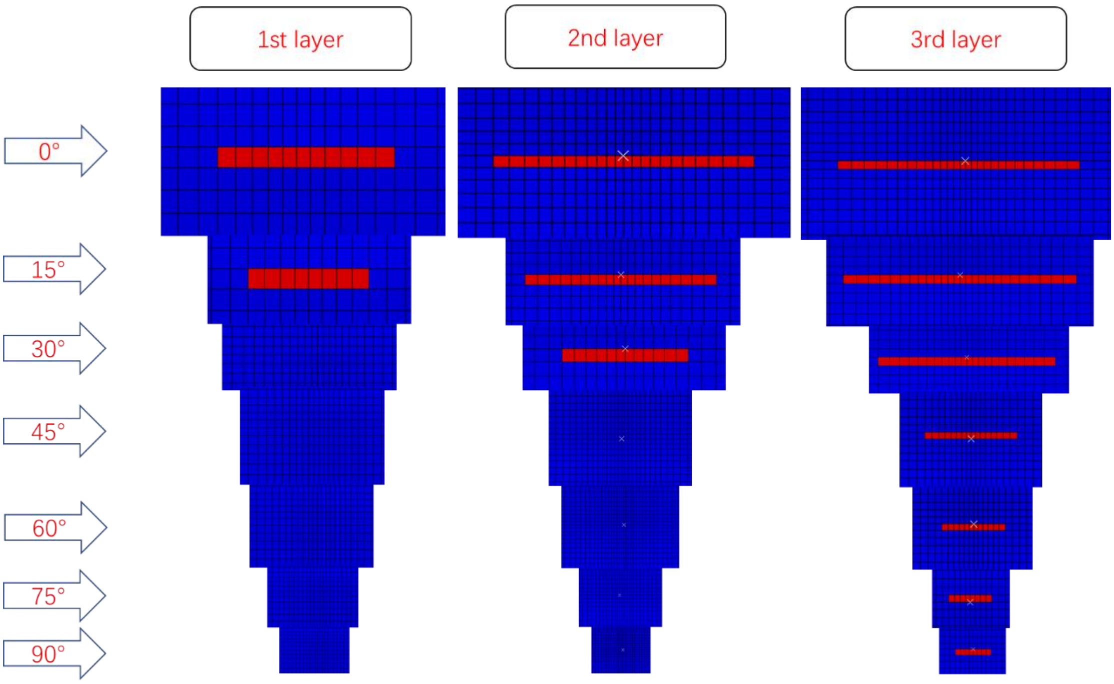

Fig.9 The matrix tensile damage of upper composite plate

The matrix tensile damage of each layer of the upper composite plate are represented by figures 9. It can be appreciated that how the matrix tensile damage is influenced by the interlayer angle, with the incresement of interlayer angle, matrix tensile damage area is decreasing for all 3 layers. In summary, we can conclude that for the layup of [0°/x°/0°/Honeycomb/0°/x°/0°], as the interlayer angle increases, the energy aborbtion rate also gose upward, the indent depth decreases, the residual velocity becomes lower, the matrix tensile damage area and delamination are reduce, which means the composite sandwich structure has the better impact resistance.

For the further research, the layup of [45°/x°/45°/Honeycomb/45°/x°/45°] with different interlayer angles were studied. 3 models with the interlayer angles of 0°, 45°, and 90° are created with Abaqus/Explicit. All parameters and settings are the same as the previous model except the layup. And the results are as follows.

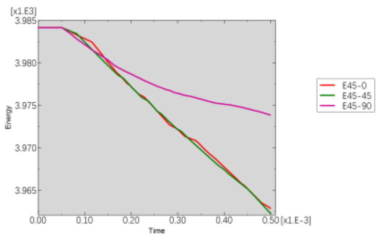

Fig.10(a) Energy-time curve

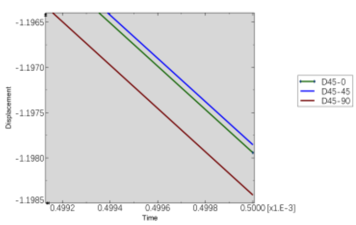

Fig.10(b) Displacement-time curve

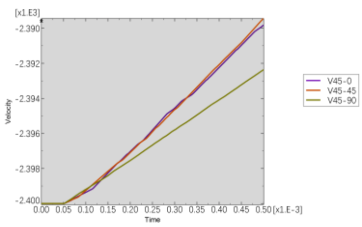

Fig.10(c) Velocity-time curve

From Fig.10(a), (b), and (c), the impact energy-time, displacement-time and velocity-time curves for the layup of [45°/x°/45°/Honeycomb/45°/x°/45°] with different interlayer angles are reported. As is shown in the figure, the interlayer angle of 90°, whose layup of [45°/-45°/45°/Honeycomb/45°/-45°/45°] has the worst impact resistance in terms of energy absorbtion, indent displacement and velocity. We presume that the stiffness gets weaker after the stiffness matrix transformation, however, this is beyond the scope of this study and ought to be researched in details in the future.

5 Conclusion

1. For the layup of [0°/x°/0°/Honeycomb/0°/x°/0°], with the increasement of interlayer angle, the energy aborbtion rate multiplies, the indent depth, the residual velocity, the matrix tensile damage area and delamination area decrease, which means the composite sandwich structure with a higher interlayer angle has a better impact resistance.
2. For the layup of [45°/x°/45°/Honeycomb/45°/x°/45°], the layup with the largest interlayer angle has the worst impact resistance, which needs to be studied more detailed in the future.

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