Layup structure effect on the composite laminate impact resistance: experimental and finite element studies

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Abstract. Four kinds of sandwich laminates with different layup structures and same thickness are designed and fabricated by autoclave and heat pressing process respectively. The impact tests of four composite laminates were carried out to compare the impact resistance of composite laminates with different ply structures. The impact finite element model is established, and the impact process is simulated by the finite element method. To some extent, the impact failure mechanism of composite laminates and their impact failure results have been obtained.

1. Introduction

Composite materials have a number of advantages, such as high static and cyclic strength, substantial rigidity, light weight, vibration damping, high-temperature resistance, and high performance. These advantages imply their wide application in aviation, aerospace, energy, transportation, construction, and other industries [1-7].

In recent years, the high-speed impact resistance of composite laminates has been paid more and more attention, and the corresponding theoretical and experimental studies have been carried out [8-10]. Zhu [8] put forward the failure modes of Kevlar fiber-reinforced laminates, such as deformation, fiber delamination, and fiber failure, in the penetration of projectiles. From the observation of 3.3g cube projectile impact test of UHMWPE (Ultra-high molecular weight polyethylene) fiber laminated plates, Wang [9] also revealed the failure modes of UHMWPE in shear, impact delamination and tensile deformation, etc. By simulating the penetration behavior of fiber-reinforced composite laminates, Qin [10] found that the penetration mode of the flat projectile was a plugging mode, and the penetration of the ball projectile and cone projectile was a stabbing pattern. Besides, Naik [11] and Gu [12] have established an analytical model for the ballistic performance of composite laminates with orthotropic laminates. Several typical energy-absorbing forms of target plates were considered. Since the object of these models was orthotropic laminated composite laminates, the in-plane anisotropy was not apparent, and the results were acceptable. However, for the composite laminates with arbitrary layers, the analysis of high-velocity impact damage and numerous test results revealed that the anisotropy significantly influenced the damage shape and, thus, had to be considered in the further analysis [13-14].

To explore the impact resistance of the composite laminates with different layer structures, we designed and fabricated, in accordance with the UIC651 standard, four different layups with the same thickness and foam core, based on the driver's cabin of the last generation subway train. The experimental and simulation works have been carried on. In this paper, upon the impact tests, the
composite lamination layup and fiber arrangement angle were analyzed to assess the effect of layer structure on the impact resistance performance of composite laminates. The impact failure mechanism of composite laminates was simulated by the Hyperworks13.0 finite element analysis software.

2. Materials

The test materials were prepreg and foam. The prepreg was made of carbon fiber, glass fiber, and aramid fiber. The specifications of the material are shown in table 1. The prepreg was provided by SCN (Shanghai CEDAR &NISSEI Co., Ltd., China), while the foam material (model PMI, density of 52 kg/m³, thickness of 59 mm) was provided by Evonik Industries (Germany).

| Code | Material          | FAW(g/m²) | RC(%) | Thickness(mm) |
|------|-------------------|-----------|-------|----------------|
| 3kC  | 3K Twill(carbon)  | 200.0     | 37%   | 0.20 mm        |
| K    | Plain(Aramid)     | 235.0     | 40%   | 0.25 mm        |
| G    | Broken twill(glass)| 290.0 | 40%   | 0.24 mm        |
| C    | Unidirectional(carbon) | 150.0 | 40%   | 0.15 mm        |

3. Specimen preparation

The specimens are sandwich structures with inner and outer skins. They had different ply structures, as shown in table 2. The skin size was 1100*800 mm, fabricated with autoclave molding, at 130°C and pressure of 0.6 MPa; the curing time was no less than one hour. The cured sandwich composites were cut into 1000*700 mm specimens with CNC machine.

Step 1. Cut the clothes:
Cut and prepare the clothes according to the size of specimens.

Step 2. Cut the forms:
Cut and prepare the forms according to the size of specimens.

Step 3. Lay the skins:
Lay the skins according to the lay-up sequence of specimens. Mark the direction of the fiber at the same time. The tolerance of angle is ±2°.

Step 4. Form the skin:
Skins are formed in an autoclave; the curing program is shown below:
Air heating rate: 3 Ai;
Curing temperature: 80±3°C, maintain 30mins, 80±3°C, maintain 15mins, 130±3°C, maintain 60mins;
Pressurization time: when the temperature of 80±3°C is achieved, apply 0.3±0.01MPa, maintain 30mins, and then hoist the pressure to 0.6±0.01 MPa;
Pressure rate: 0.05MPa/min;
The specimens should be in the state vacuum of -0.9 atmosphere. Make sure that specimens were in the state vacuum until they are cured;
Air cooling rate: 3ºC/min;
Pressurization time: when the temperature of 60±3°C is attained, drop the pressure;
Pressure drop rate: 0.05MPa/min;
Step 5. Bond the skin and form:
The composite specimen is made by the hot pressing process. The structure of the specimen consists of outer skin, epoxy bond film, PMI foam, epoxy bond film, inner skin. The production process condition: pressure 0.2 MPa, temperature 130°C, 1.5h.

Step 6. Machine the specimens:
The cured sandwich composites are cut into 1000*700 mm specimens with CNC machine.
Table 2. Ply structure of composite laminates.

| Specimen No. | Ply structure | Thickness (mm) |
|--------------|---------------|----------------|
| 1            | Outer         | 2.30           |
|              | Inner         | 1.80           |
| 2            | Outer         | 2.24           |
|              | Inner         | 1.86           |
| 3            | Outer         | 2.26           |
|              | Inner         | 1.81           |
| 4            | Outer         | 2.26           |
|              | Inner         | 1.81           |

4. Impact test

According to the UIC651 standard, the specimen size was 1000*700 mm, and the cylindrical projectile with a hemispherical tip was used to impact the specimen. The total weight of the projectile was 1 kg, and its structure is shown in Figure 1. The aluminum alloy cylindrical projectile hit four specimens at a speed of 300.67, 309.60, 300.57, and 304.93 km/h, respectively. During the testing, the temperature of the test board was kept at 15-35°C. The impact velocity of the projectile was assessed as follows:

\[ V_p = V_{max} + 160 \]  

where \( V_p \) is projectile velocity at impact (km/h) and \( V_{max} \) is the maximum speed for a towing device (km/h).

![Figure 1. Structure and size of the projectile for the impact test.](image)

Table 3. Results of impact tests.

| Specimen number | Thickness (mm) | FAW(Inner + outer skin) (g/m²) | Impact velocity (km/h) | Test result | Conclusion |
|-----------------|----------------|--------------------------------|------------------------|-------------|------------|
| 1               | 63.10          | 4100                           | 300.67                 | Penetrated  | Not pass   |
| 2               | 63.10          | 4600                           | 309.60                 | Penetrated  | Not pass   |
| 3               | 63.07          | 4425                           | 300.57                 | Penetrated  | Not pass   |
| 4               | 63.07          | 4425                           | 304.93                 | Not penetrated | Passed    |

In the actual test, the input impact angle was 90° to the composite lamination with the impact velocity of no less than 300 km/h. The test temperature was 20°C, and the test results are shown in table 3.
5. Experimental data and analysis

The impact test results are shown in table 3: specimen No.4 passed the impact test, while specimens 1-3 failed. Figure 2(a)-(d) show the front and back of the specimen after impact. In figure 2(d), the projectile did not penetrate the test specimen, while the rest of specimens were penetrated.

It was found that the inner skin of one side of the specimen was severely damaged, and the main forms of damage were matrix cracking and delamination.

Part of the projectile penetrated the out skin of the test specimen 4, and was embedded between the fiber layer and PMI foam. A portion of the inner skin was bent and delaminated from the PMI foam core. Although some fibers were broken, the inner skin was not penetrated.

(a) Specimen 1

(b) Specimen 2

(c) Specimen 3
The layer structure of specimen 4 is orthotropic, and the mechanical properties in the normal direction to the fiber length are quite high. Besides, the anti-impact performance of aramid layer was observed: so it had excellent impact resistance.

As compared to specimen 3, the number of aramid fibers was increased, the impact resistance was strengthened, and the impact resistance of test specimen 4 was improved.

The skin of specimen 1 was a pure carbon fiber structure, and specimen 2 was a hybrid structure, which consisted of carbon and glass fibers. As compared to specimen 4, it lacked aramid fibers, so it had poor impact resistance.

6. Impact simulation

6.1. The finite element analysis model

The finite element method was used to analyze the impact strength of specimens under study. The finite element mesh was prepared by the pre-treatment Hyper-Mesh, and RADIOSS was applied to calculate the specimen strength of the specimen. Loads and constraints were set according to the standard UIC651 “Layout of driver's cabs in locomotives, railcars, multiple unit trains and driving trailers”.

The simulation model of high-speed impact on composite sandwich panels adopts the form of skin + core material + skin, and the skin layer is subdivided into "laminate- interface-laminate" form. The single layer thickness of the material was shown in table 1. Each layer is simulated with interface properties in the thickness of zero. The dimension requirements of the impact head are shown in figure 1, and the weight is 1 kg. The boundary condition of the model is that the sandwich plate is fixed around it, the initial velocity of 300 km/h is applied to the warhead, and the contact type is integrated interface contact.

In the calculation, the carbon fiber layer was separated by finite element method with 2D shell element SHELL4N. The 3D solid element HEXA8N was used in the finite element dispersion of foam. The finite element model is shown in figure 3. The whole simulation model was constituted by 16352 shell elements, 56000 solid elements, and 57269 nodes.

![Figure 3. Finite element analysis model of the high-speed impact of the composite.](image)
Carbon fiber/epoxy resin, glass fiber broken twill fabric/epoxy resin, aramid fiber plain fabric/epoxy resin with the volume fraction of 60%, its performance parameters are shown in tables 4~6, respectively.

The interlayer interface uses the material properties of the matrix, and its performance parameters are shown in table 7.

### Table 4. Carbon fiber/epoxy composite property parameters.

| E1 (GPa) | E2=E3 (GPa) | n12 | n23 | G12=G13 (GPa) | G23 (GPa) |
|----------|------------|-----|-----|---------------|-----------|
| 135      | 8.5        | 0.29| 0.3 | 4             | 3.5       |
| XT (MPa) | XC (MPa)   | YT (MPa) | YC (MPa) | S12=S13 (MPa) | S23 (MPa) |
| 2750     | 911        | 35  | 130 | 63            | 32        |

Note: Subscript 1 corresponds to the fiber main direction, Subscript 2 to normal to the main direction, Subscript 3 to thickness direction, XT is tensile strength in the main direction, XC is main direction compression strength, YT is tensile strength 90º-direction, YC is compression strength in 90º-direction, S is shear strength.

### Table 5. Aramid fiber plain fabric/epoxy composite property parameters.

| E1 (GPa) | E2 (GPa) | n12 | n23 | G12=G13 (GPa) | G23 (GPa) |
|----------|----------|-----|-----|---------------|-----------|
| 37.3     | 15.9     | /   | 0.3 | 4             | 3.5       |
| XT (MPa) | XC (MPa) | YT (MPa) | YC (MPa) | S12=S13 (MPa) | S23 (MPa) |
| 517      | 200      | 67.9| 130 | 77.2          | 80        |

### Table 6. Glass fiber broken twill fabric/epoxy composite property parameters.

| E1 (GPa) | E2 (GPa) | n12 | n23 | G12=G13 (GPa) | G23 (GPa) |
|----------|----------|-----|-----|---------------|-----------|
| 28.1     | 24.6     | /   | 0.3 | 4             | 3.5       |
| XT (MPa) | XC (MPa) | YT (MPa) | YC (MPa) | S12=S13 (MPa) | S23 (MPa) |
| 346      | 140      | 252 | 130 | 20            | 18.5      |

### Table 7. Performance parameters of matrix materials.

| E(GPa) | G(GPa) | T(MPa) | S(MPa) |
|--------|--------|--------|--------|
| 8.3    | 4.5    | 55     | 60     |

6.2. Failure criteria

1) Damage of single layer composite
The composite unit strength is defined with the Tsai-Wu criterion. Before the limit of the Tsai-Wu criterion is reached, it is assumed that the material is an orthotropic linear elastic material.

\[ F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_{11}^2 + F_{22}\sigma_{22}^2 + F_{12}\sigma_{12}^2 + 2F_{12}\sigma_1\sigma_2 \leq F(W_p,\dot{\varepsilon}) \]  

where \( \sigma_1, \sigma_2, \sigma_{12} \) are stresses in the material coordinate system.

Beyond the limit of the Tsai-Wu criterion, the material is transformed into nonlinear one, and the maximum strain rate and the maximum strain energy failure theory of brittle materials are adopted. The material hardening is simulated by the plastic strain energy and strain rate to set the limit of the Tsai-Wu criterion. The delamination failure is reduced to delamination induced by the shear strain.

The coefficients in the Tsai-Wu criterion are determined by ultimate stresses.

\[ F_1 = \frac{1}{\sigma_{11}} + \frac{1}{\sigma_{12}} F_{22} = \frac{1}{\sigma_{11}} \sigma_{11}^2 \]  

\[ F_2 = \frac{1}{\sigma_{22}} + \frac{1}{\sigma_{12}} F_{44} = \frac{1}{\sigma_{22}} \sigma_{22}^2 \]  

\[ F_{11} = \frac{1}{\sigma_{11}^2} F_{12} = \frac{1}{\sigma_{12}} \sigma_{12} \]  

Here superscripts c and t represent compression and tension, respectively.

In the above formula, \( F \) is a variable Tsai-Wu criterion limit function defined by the strain energy \( (W_p) \) and true strain rate \( (\dot{\varepsilon}) \).

\[ F(W_p,\dot{\varepsilon}) = \left(1 + b \left(\frac{w_p}{w_p^{ref}}\right)^{n} \right) \left(1 + c \ln \left(\frac{\varepsilon_p}{\varepsilon_p^{ref}}\right)\right) \]  

where \( w_p^{ref} \) is the reference strain energy, \( B \) is the strain-hardening coefficient, \( n \) is the strain-hardening index, \( \dot{\varepsilon}_0 \) is the true strain rate, and \( C \) is the strain rate factor.

The damage between the initial and maximum fracture elongation rates \( \varepsilon_{m1} \) and \( \varepsilon_{m2} \), respectively, is controlled by the damage constant \( d \).

\[ d_i = \max \left(\frac{\varepsilon_m}{\varepsilon_m^{ref}}, d_{\max}\right) \text{, } i = 1, 2 \]  

According to the damage constant \( d \), stresses in the damaged layer in the laminates are reduced as follows:

\[ \sigma_{i}^\text{reduced} = \sigma_i (1 - d) \]  

The maximum value of damage constant \( d \) is \( d_{\max} \), strain energy per unit volume is \( w_p^{max} = \frac{w_p}{w_p^{ref}} \), while the maximum strain energy per unit volume is \( w_p^{max} = \frac{w_p^{max}}{w_p^{ref}} \).

In case of \( w_p^{max} > w_p^{max} \), the fiber fracture occurs; when the strain in direction 1 is higher than \( \varepsilon_{m1} \), the fiber fracture occurs; when the strain in direction 2 exceeds \( \varepsilon_{m2} \), the matrix fracture occurs; the stress in the unit drops to zero, and the unit is removed.

2) Delamination damage

The simplified delamination failure theory is based on out-of-plane shear strain \( (\gamma_{31}, \gamma_{23}) \). When the shear stress \( \gamma = \sqrt{(\gamma_{31})^2 + (\gamma_{23})^2} \) meets the condition \( \gamma_{max} > \gamma_{lat} \), stress \( \sigma_{31}, \sigma_{23} \) in the element decreases gradually. If the value of \( \frac{\gamma_{p}}{\gamma_{lat}} \) in a layer of the laminate is higher than \( d_{\max} \), the delamination occurs, and the unit is removed.

3) Foam damage

The material is linear elastic until the yield stress is reached. When the stress in the material is exceeds the yield stress, we get

\[ \sigma = (a + b \varepsilon_p^n) \left(1 + c \ln \left(\frac{\varepsilon_p}{\varepsilon_p^{ref}}\right)\right) \]  

where \( a \) is yield stress, \( b \) is strain-hardening coefficient, \( c \) is strain rate coefficient, \( \varepsilon_p^n \) is plastic strain, and \( \dot{\varepsilon} \) is strain rate.

When the plastic strain of the material is higher than the maximum allowable plastic strain, failure occurs, and the unit is removed.
6.3. Simulation results

Specimen 1 is the representative specimen, which has not passed the impact test (failed). Specimen 4 is the specimen, which passed the impact test. Simulations were performed separately. The impact simulation is shown in figures 4 and 5.

Figure 4. Simulation diagram of the shock process of specimen 1.

Figure 5. Simulation diagram of the shock process of specimen 4.
From the finite element analysis results depicted in figure 4, the composite core plate had a tapered projection in the thickness direction after being penetrated by the projectile. The damage area increased gradually from the point near the projectile to the direction away from the projectile. Matrix collapse damage occurs mainly in contact with projectiles. In cases of matrix cracking or matrix collapse damage, the distribution of any damage in the thickness direction had a funnel shape and was very similar to the form of delamination damage. This implies that the matrix damage is related to the delamination damage.

Through the finite element simulation calculation, the velocity change curve in the impact process can be obtained. As shown in figure 6, different specimens are impacted by the impact head and change in velocity during the impact. And figure 7 also shows that the final velocity and kinetic energy of specimen 4 are reduced to zero, while the remaining specimens 1–4 eventually had some residual velocities, indicating that the plate was eventually broken down.

![Figure 6. Velocity curves during impact.](image)

![Figure 7. Kinetic energy curves during impact.](image)

7. Conclusions
The test results show that some specimens of carbon/glass/aramid fiber structure with alternative layups passed the impact test, while other specimens failed.

The thickness of specimens 1–4 was the same, as well as thickness and density of the foam. The test specimens 1–3 with (i) anisotropic layer carbon fiber, (ii) carbon fiber/glass fiber, and (iii) non-anisotropic layer carbon/glass/aramid fiber hybrid composite layers, respectively, failed during the
impact test. In specimen 4, the aramid material (available in specimen 3) was replaced by the alternately anisotropic ply. As compared to specimens 1 and 2, aramid material with better impact resistance was added, which improved its impact resistance. As compared to specimen 3, specimen 4 is alternately anisotropic. As a result, specimen 4 had the most excellent impact resistance and passed the UIC651 test standard.

Through the finite element simulation, the impact process and penetration results of specimens with different ply structures can be effectively predicted. The finite element numerical model elaborated in this study is considered instrumental in the impact failure prediction of composite laminates.

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