EXPERIMENTAL STUDY ON THE LOW VELOCITY IMPACT RESPONSE OF CARBON-ARAMID HYBRID BRAIDED COMPOSITES

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ABSTRACT

The following three different types of carbon-aramid/epoxy hybrid braided composites were produced and tested, (a) interply hybrid, (b) sandwich-like hybrid and (c) unsymmetric hybrid. Non-hybrid carbon laminates were also tested for comparison. The effects of the hybrid structure on the impact properties such as the peak load, internal damage ,the DI(ductility index) and energy absorption are discussed .The non-hybrid carbon laminate has the highest impact peak load, and the peak load of hybrid structure is slightly lower.The internal damage and failure mechanisms were analyzed from the B-scan imaging and C-scan imaging. The carbon laminates show the largest depth of damage. The damage depth of interply hybrid laminates is lower than that of carbon laminates, while the damage on the impacted side is much more than that of carbon laminates. There are the most delamination in sandwich-like hybrid laminates ,and delamination also occurs in unsymmetric hybrid laminates. It could be concluded that the damage tolerance performance of composites with interply hybrid structure is the best than those of other hybrid composites.

1 INTRODUCTION

NASA developed a series of related basic research during recent years, the Boeing 787 aircraft engine cases use 2D triaxial braided composites to achieve the excellent containment and weight reduction [1,2].The carbon fiber has high specific-strength and specific-modulus.The aramid fiber has good fracture toughness and the ability of energy absorption , which is widely used in the field of impact protection [3,4].The carbon-aramid hybrid braided composites not only take full advantage of the excellent impact resistance of the two fibers, but also have flexible design and higher efficiency of weight loss.

There are a large number of researches on the mechanical properties (crush testing,low velocity impact behavior, flexural property)of hybrid braided composites . Chiu[5] designed six different hybrid structures of the triaxial composite tubes using carbon fibers and Kevlar fibers ,they were named CCC,KKK, KKC, CCK, KCC and CKK types respectively.The author wanted to study their crush-failure modes and specific energy-absorption capabilities.The results are the following : theKCC type may be the best choice in the application of crash-worthy structures because it has high crush energy absorption close to the CCC type and shows much better post crush integrity than the CCC type. In 2005, Wan et al .[6] assessed hybrid effects for flexural property of the 3D braided composites.Composites of six different relative Kevlar fiber contents (0%, A20%, B40%, C60%,D 80%, and 100% by volume) were prepared and characterized.It is concluded that the the three 3D hybrid composites with 20% , 40% and 60%Kevlar fiber by volume show higher(3%,19% and 11.4% respectively) flexural modulus than the 100% carbon fiber composite. These results confirm the existence of the positive hybrid effect. Fabrizio Sarasini et al .[7] investigated the low velocity impact behavior of woven aramid and basalt hybrid laminates in 2013. Specimens prepared with different stacking sequences (BT-HS:sandwich-like sequence with seven basalt fibre layers (core) and three aramid fibre layers (skins) for each side of the laminate ; BT-HI:six layers of basalt fabrics and seven of aramid fabrics were alternatively stacked, keeping aramid fabrics as outer layers).Not hybridized basalt (B) and aramid (T) were also manufactured as reference configurations.Results show that BT-HI have better impact energy absorption capability and enhanced damage tolerance with respect to the all- aramid laminates, BT-HS present the most favourable flexural behaviour.In 2015 ,Wang et al .[8]conclued the influence of different braiding yarn and axial yarn(carbon and glass fibers) on the impact property for 2D traxial braided composite laminates.In 2015 ,Wang et al .conclued the influence of different braiding yarn and axial yarns (carbon and glass fibers) on the impact property for 2D traxial braided composite laminates. After the impact ,he hybrid structure laminate(braiding yarn:glass fiber, axial yarn:carbon fiber) contain less surface cracks,smaller damage range in the thickness direction than others. It achieves better impact resistance .

In this study, three different types of 2D carbon-aramid/epoxy hybrid braided composites were produced and tested, (a) interply hybrid, (b) sandwich-like hybrid and (c) unsymmetric hybrid. Non-hybrid carbon laminates were also tested for comparison. The effects of the hybrid structure on the impact properties such as impact load, impact energy absorption,the DI (ductility index) and impact damage morphology are discussed .The internal damage and failure mechanisms are analyzed from the B-scan imaging and C-scan imaging .

2 EXPERIMENTAL DETAILS

2.1 Raw materials

In this study, T700SC-12K carbon fiber (Toray) and HF200-6000D aramid fiber(Zhong Lan Chenguang Chemical Co, Ltd) were chosen as reinforcements and the TDE#86 epoxy resin (Tianjin Jingdong) was chosen as matrix.The physical and mechanical properties of fibers and resin are shown in table1 . The single-layers of 2D braided fabric used in composites was fabricated on the 2D braiding machine of Tianjin Polytechnic University,Ministry of Education and Tianjin Key Laboratory of Advanced Textile Composites ,as shown in Fig.1.

Engineering Constant		T700SC	HF200	TDE#86
Density (ρ)	[g/cm3]	1.80	1.44	1.26
Fiber fineness	[D]	5600	6000	—
Tensile strength (σ_b)	[MPa]	4900	2017	78.1
Tensile modules (E)	[GPa]	230	74	3.5
Elongation (ε)	[%]	2.10	3.12	4.0

Table 1 :Physical and mechanical properties of fibers and resin

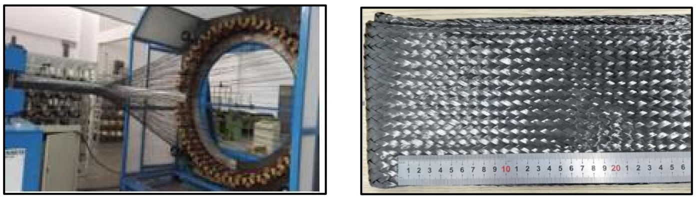


Figure 1: Diagram of braiding process

Structure parameters of 2D braided fabric are shown in table 2.

Raw materias	The number of yarns	Braiding angle	Width /mm	Surface density /kg/m^2	Thickness /mm
Carbon fiber	120	30°	125	0.785	0.88
Aramid fiber	120	30°	125	0.661	0.95

Table 2:Structure parameters of 2D braided fabric

The RTM process was chosen to manufacture laminates .The hybrid structure of 2D carbon-aramid hybrid braided composites are shown in Table 3. Table 4 is the structure parameters of 2D braided composites.

Specimen type	Hybrid structure	Ply structure	Sketch map
C	Single-carbon	[C7]	■■■■■■■
IE	Inter-hybrid	[C/A/C/A/C/A/C]	■□■□■□■
SA	Sandwich-like	[C2A3C2]	■■□□□■■
US	Unsymmetric	[C4/A3]	■■■■□□□

Table3 :The hybrid structure of carbon-aramid hybrid braided composites

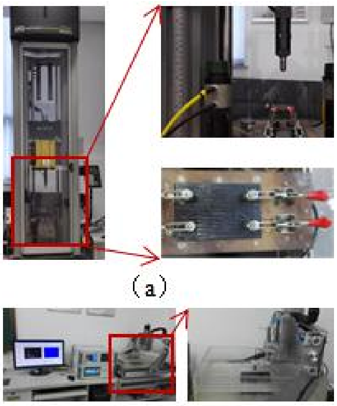
(Note:The specimen type of C represents carbon fiber laminate ; IE means that the carbon fiber is in the impact surface of the 7 layers of symmetry ; SA is a sandwich-like structure with 2 layers of carbon fiber and a core layer of 3 layers of aramid fiber; US represents 4 layers of carbon fiber as the impact surface, the 3 layers of aramid fiber in the back of the impact of usymmetric hybrid.)

Symbol	Hybrid structure	Thickness /mm	Density /g/m^3	Fiber volume fraction /%
C	Single-carbon	5.08	1.63	60.62
IE	Inter-hybrid	5.02	1.50	62.31
SA	Sandwich-like	5.00	1.55	62.31
US	Unsymmetric	5.04	1.52	62.67

Table 4 :The structure parameters of 2D braided composites

2.1 Specimen tests

The specimen of impact test were cut into size of 150 mm×100 mm and the impact energy was set to 33.5J, following the ASTM D7078-12 standard [9]. The experiments were conducted by Instron Dynatup 9250HV (Fig.2 (a)) machine setup . The diameter of hemispherical head is 12.7 mm and the weight 6.5 kg. Each group has 5 samples in order to investigate the internal impact damage of specimen.The results of B- scan imaging and C -scan imaging were exported using SN-C3409 ultrasonic immersion scanning system (Fig.2 (b)) .



(a)

(b)

Figure 2: (a) Instron Dynatup 9250HV (b)SN-C3409 ultrasonic immersion scanning system

3 RESULTS AND DISCUSSION

The commonly used parameters of assessing the low-velocity impact damage process are: the impact energy (E), the initial damage load (P_i), the initial damage energy (E_i) , the peak load (P_m), the energy at peak load (E_m), the total energy-absorption (E_t) and the energy-propagation (E_p=E_t-Em). Taking the typical load-time curve and energy-time curve of carbon fiber laminate as an example, the location of each characteric point after impact are shown in Fig.3 . The impact energy (E) is the maximum energy reached before the hammer touch with the specimen . The initial damage load (P_i) is the first oscillation point , here it begins to appear the apparent matrix cracks and fiber damage, and at the same time its corresponding energy is the initial damage energy (E_i).The peak load (P_m) is the maximum load (correspondence energy Em) ,at this time the hammer falls to the lowest place and begins to rebound .The total energy-absorption (E_t)(including energy dissipation of friction and damage mechanism) is the energy of material consumption and unrecoverable , representing the end of the hammer rebound . The energy of damage propagation (E_p) is the energy absorption after the peak load .At this stage , the hammer rebounds and the energy is absorbed by crack propagation [10,11].

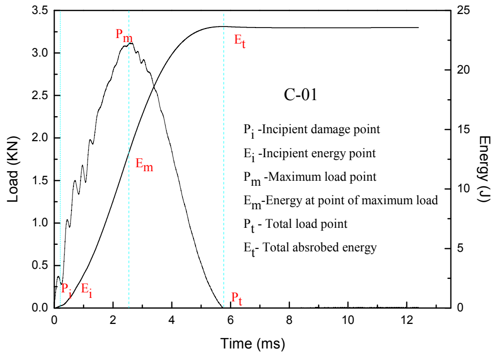


Figure 3: Typical load and energy versus time curve and characteristic points for post impact analysis

3.1 Impact load-time

The impact load-time curves for four kinds of typical laminates are shown in Fig.4 and they are very similar . At the initial stage of loading, the first oscillation point (P_i) appears in all the specimen and the load decreases obviously. The reason is that the stress focuses on the circular area where the head of hammer contacts with specimen when both just touch with .The specimen begins to produce the deformation of compression, resulting in the load slightly drop. The point of P_i is the initial damage point, which is the turning point of the specimen from the undamaged state to the damage state. The main forms of damages are delamination and matrix cracks.With the hammer continuing to fall , the stress redistributes and the load-time curve keeps rising smoothly with small fluctuations.The rising trend of load - time curve of different laminates is also different.

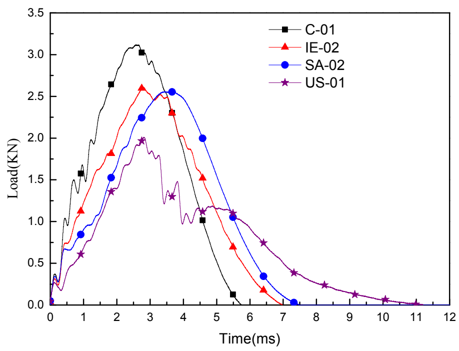


Figure 4: The impact load-time curves for four kinds of laminates

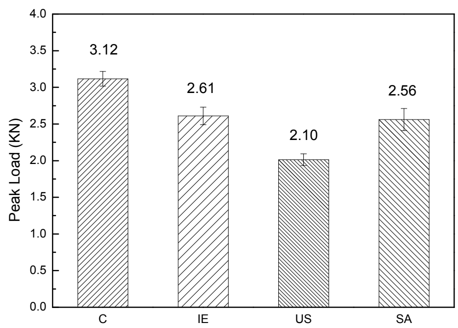


Figure 5: Maximum impact forces

The load -time curve of carbon fiber laminate (C) has the most oscillation points, the reason is that the carbon fiber exists with high strength, high modulus, low elongation and low bending strength . In the process of the impact damage, some carbon fibers would be suddenly broken, stripped and internal delamination. It results in the load decreases slightly, the specimen produces a small crack and stiffness reduction . Similar results are also presented in previous studies[12].In the hybrid laminates , the aramid fiber has good toughness and high elongation , and the damage is relatively slow in the impact damage growth .So the load-time curve rised relatively smoothly. As the hammer continued to fall, the curve rised and the specimen produced nonconnected small crack , which was considered as the stage of elastic strain . Until the point of P_m, the load reached the maximum, the hammer fell to the lowest and began to rebound. After the point of P_m, the curve entered the second stage : the load decreased rapidly, which was due to the serious structural damage of the specimen , including: matrix cracking, internal delamination, fiber pull-out fracture and pits and etc.

For the load-time curve of the unsymmetrical hybrid laminate, the load falls seriously and the curve enters the the violent fluctuating area after the point of P_m . The reason is that , after the structure damaged severely , the residual load is redistributed and it leads to a large load fluctuation.

The falling part of the load-time curve of IE and SA are relatively smooth , and there is no serious load failure , which indicates that both of then have relatively good impact resistance.

The peak load is an important index to evaluate the capacity of carrying load of composites ,which represents the maximum force that can be sustained by the composites before being seriously damaged. It is noted that the peak load is related to the initial stiffness of the material [13] . The peak load contrast of four different laminates are shown in Fig.5 , for the same impact energy, carbon fiber laminate has the highest peak load (3.12KN) .The reason is that the tensile modulus (230GPa) of carbon fiber is nearly 3 times that of aramid fiber (74.24GPa), which has good in-plane stiffness. Due to the addition of aramid fiber layer, the in-plane stiffness decreases slightly . However, among three kinds of hybrid structure, IE has the highest peak load(2.61KN) , US (2.10KN) is the lowest, SA (2.56KN) is between the two. Therefore, the interply hybrid could effectively resist the impact of the hammer.

3.2 Impact energy-time

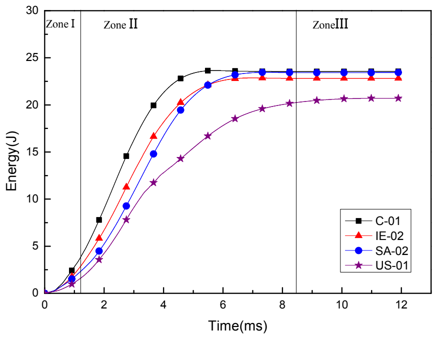


Figure 6 : The impact energy-time curves for four kinds of typical laminates

Fig.6 shows the comparison of the energy absorption-time curves for four kinds of the typical specimens , and the curves are divided into three regions[14,15] . In the first region (Zone I), the energy-absorption is relatively low. The reason is that under the instantaneous impact load, the hammer just only touch the specimen and the types of the energy-absorption is mainly the appearance of pits and the deformation of the thickness. In the second region (Zone II) ,the energy-absorption increases rapidly ,and then slowly till the maximum .The reason is the area where the specimen touching the hammer raises rapidly ,which leads to the energy-absorption increases rapidly . The third area (Zone III), the curve keeps straight and the falling of curve is not obvious .At this stage, the hammer ends the rebound and seperates with specimens.

Symbol	Hybrid structure	E_t/J	E_m/J	E_p/J	DI
C	Single-Carbon	23.65	13.95	9.70	0.70
IE	Inter-hybrid	22.87	11.68	11.19	0.96
SA	Sandwich-like	23.46	13.58	9.88	0.73
US	Unsymmetric	20.71	8.15	12.56	1.54

Table 4:Summary of average ductility index for four kinds of laminates

Table 4 shows the ductility index for four kinds of laminates. The E_t , E_m , E_p represents the total absorbed energy , the energy at point of maximum load and the damage propagation energy respecttively. The DI is the ratio between the E_p and E_m [16]. The larger the DI value is, the larger the EP is, and the peak load energy E_m is relatively small.

The DI of carbon fiber laminates is minimum (0.70) ,so the energy of damage propagation is smaller .Because the shear capacity of carbon fiber is poor, and at the same time, the elongation of it is low. The energy absorption of fiber fracture is less in the impact process .The DI of carbon-aramid hybrid laminates is larger than those of carbon fiber laminates .That is because the elongation of aramid fiber is larger ,and meanwhile the tensile and pull-out of aramid absorb more energy during impact.The peak load (2.61KN) and the DI (0.96) of IE are 1.95% and 31.5% higher than that of SA (2.56KN 0.73) .

3.3 Observation and analysis of impact damage morphology

The impact damage morphology is showed in Fig.7.There are circular dents on front side of four kinds of laminates and the dents are surrounded by resin crack and fiber fracture etc. This is due to the stress encounters the reverse braided yarns when it transmits along the fiber direction, which hinder the propagation of stress and result in fiber fracture.

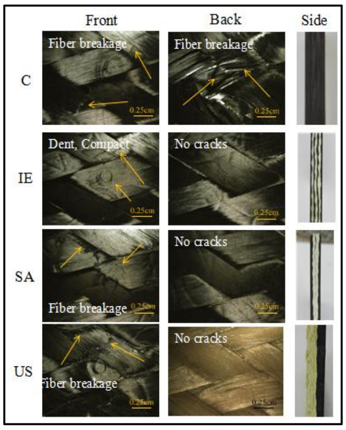


Figure 7: Impact damage morphology photos for four kinds of laminates

The back side of carbon fiber laminates emerges the pull-out and fracture of fibers .The reason is that the shear resistance of carbon fiber is weak and the elongation is low . There is no visible impact damage on the back side of carbon-aramid hybraid laminate, but a certain degree of arching deformation . This because aramid fiber has a high elongation and consumes energy within the process of plastic deformation. This delaies the occurrence of damage and increases the toughness of the specimen .

The front side damage degree of the four kinds laminates under the impact of low velocity is larger than that of the back .The impact damage of the front side extends from the center of the impact point along the fiber direction. In the interply hybrid structure， the interval arrangement of aramid fiber layer could effectively reduce the stress transfer .That is , the degree of impact damage is smaller than other structures .

3.4 Ultrasonic evaluation of impact damage

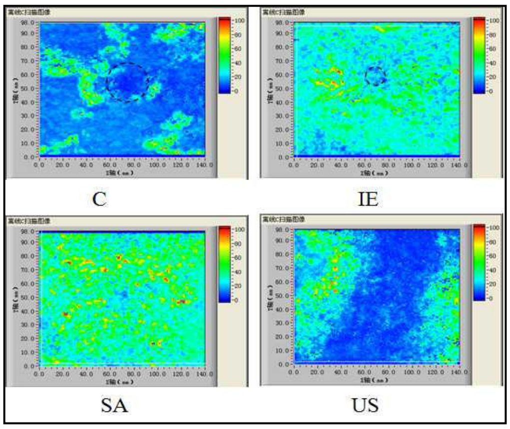


Figure 8: The C-scan results after impact of typical laminates

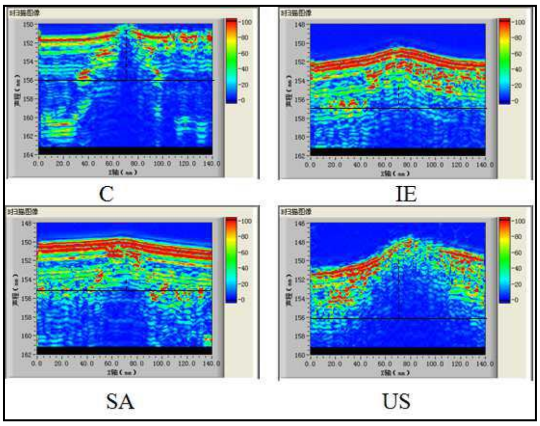


Figure 9: The B-scan results after impact of typical laminates

Fig.8 are the C scan results of the four kinds of typical laminates. The X axis represents the scanning length of the specimen, the Y axis the scanning width. Fig.9 are B scan results, the length of the specimen at the center of the impact represents the horizontal axis (X axis) and the distance of sound propagation in the sample (i.e. the thickness direction) is longitudinal axis (Y axis) . The surface of arched red area is the back side of the specimen .Due to the thickness of the sample is about 5mm , the black line is the front side below 5mm of the distance of sound .

As shown in Fig.8 and Fig.9 , the C scan images and B scanning images of the four typical laminates are different .The hybrid structure has a great influence on the internal damage characteristics of the specimen . Although the external damage morphology of the carbon fiber laminate is not serious (Fig. 7), the specimen has serious internal damage . As can be seen from Fig.8, the damage area concentrates at the impact point, the range of damage propagation is large and the boundary is blurry .Also , the area of circle center is deep blue . In Fig.9 , the damage length (X axis) in the front side of the specimen is smaller (about 50 mm) ,but the thickness (Y axis) direction is the largest (6.5 mm) . This indicates that the specimen occurs the deformation of bending. In the center of the back side , the reflected wave is weak and green .This is because the shear strength of carbon fiber is low . At the center of the back there are fiber pull-out and fracture ,and also the depth of damage is large .

The internal damage (blue area) of the interply hybrid laminate concentrates around the impact point (Fig. 8), other areas are green . The area of damage growth is small and the boundary is clear, which is much smaller than the damage area of the carbon fiber laminates. According to the B scanning images (Fig. 9) ,the damage length (X axis) in the front side of the specimen is 75 mm , which is 50% higher than that of the carbon fiber laminates. The thickness (Y axis) direction is 2 mm , 69% lower than that of the carbon fiber laminates .The intensity of the reflected wave signal on the back side is high and equivalent, and also the bending deformation of the specimen emerges. The height of the arch is 1.5mm, but the slope of the arch is smoother than that of the carbon fiber laminates.The results show that the aramid fiber layer maight has good toughness and the ability of plastic deformation ,which could effectively prevent the damage growth along the thickness direction of the laminates.

For the sandwich hybrid laminate, the C-scan imaging shows a wide range of bright yellow and red dots (Fig. 8). The B-scan imaging representing the intensity of the reflected wave signal is large(Fig. 9) .That is due to the side of specimen appears serious cracks (Fig. 7) .Also , the ultrasonic scanning is based on water as the propagation medium, so the gap is filled with water . It forms the mirror reflection and the intensity of reflected wave is large. Therefore ,it could be concluded that the sandwich hybrid structure may be due to the sudden delamination and breakage of the core layer, leading to structural instability. The internal damage area of the usymmetric hybrid laminate is the largest (Fig. 8) . Due to the serious internal delamination of the specimen, the degree of arch is serious after impact (Fig. 9) . The large interior delamination voids are formed . To sum ,the sandwich and the usymmetric hybrid structures can not optimize the impact properties of laminates.

4 CONCLUSIONS

(1) Under the same impact energy, carbon fiber laminates represent the highest peak load (3.12KN) . Due to the addition of aramid fiber , the peak load of the laminate decreases slightly. But among the three kinds of hybrid structure, the interply hybrid laminates gain the highest peak load (2.61KN), unsymmetric hybrid peak load (2.10KN) is the lowest, sandwich hybrid (2.56KN) between the two. Therefore, the interply hybrid laminate could effectively resist the impact of the hammer.

(2) The hybrid structure has great influence on the internal impact damage characteristics. However, there are serious delamination cracks in sandwich hybrid laminates and the internal delamination occures in the asymmetric hybrid laminates. The results show that the interply hybrid could effectively balance the unequal bending stress between layers.

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