Flexural and impact performance of Kevlar/basalt fabric interlayer hybrid curved composites

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FANGTAO RUAN
HAO WANG
CHENGLONG XIA

QINGYONG YANG
LIHUA ZOU
ZHENZHEN XU

ABSTRACT – REZUMAT

Flexural and impact performance of Kevlar/basalt fabric interlayer hybrid curved composites

FRP composite has become one of the most preferred materials in lightweight applications. Design freedom is a key benefit which is reflected in the choice of fibres, stacking sequence and others. Hybridisation of hard inorganic fibre and organic ductile fibres can lead to synergetic effects. In this paper, an interlayer hybrid curved laminated composite reinforced with woven Kevlar and basalt fabrics and manufactured by a hand lay-up process with epoxy resin was prepared. Experimental investigation on the flexural and impact properties of composite laminates has been performed. The results of the investigation showed that the placement of Kevlar fibres on the impact side can increase the impact and flexural strengths, sample H3 (K3B2K3B2) has the highest impact strength and absorbed energy among seven hybrid laminates, valued at 92.89 KJ/m^2 and 2.48 KJ. Compared with H5(B4K6) improved 41.6% and 40.9%, respectively. However, H5 has the highest flexural strength, reaching 231.7 MPa. In addition, the use of basalt fabric on the impact reverse side or multi-layer hybrid structuring further improves the impact properties of the materials. A sandwich-structure composite with basalt layers in the middle and Kevlar layers on both sides shows further improvement in the flexural properties.

Keywords: *composites, woven fabrics, basalt fabrics, stacking sequence, stacking sequence, three-point flexural, impact*

Performanța la încovoiere și la impact a compozitelor hibride curbate interstrat din țesătură Kevlar/bazalt

Compozitul FRP a devenit unul dintre materialele preferate utilizate în aplicațiile cu greutate redusă. Libertatea de proiectare este un beneficiu cheie care s-a reflectat în alegerea fibrelor, secvența de stivuire și altele. Hibridizarea fibrelor anorganice dure și a fibrelor organice ductile poate duce la efecte sinergetice. În acest studiu, a fost pregătit un compozit laminat hibrid curbat interstrat, consolidat cu țesături Kevlar și bazalt și fabricat printr-un proces manual de întindere cu rășină epoxidică. Au fost efectuate investigații experimentale asupra proprietăților de încovoiere și de impact ale laminatelor compozite. Rezultatele investigației au arătat că plasarea fibrelor de Kevlar pe partea de impact poate crește rezistența la impact și la încovoiere, proba H3 (K3B2K3B2) având cea mai mare rezistență la impact și energie absorbită dintre cele șapte laminate hibride, cu valori de 92,89 KJ/m^2 și 2,48 KJ. Comparativ cu H5(B4K6), a existat o îmbunătățire cu 41,6% și, respectiv, cu 40,9%. Cu toate acestea, H5 are cea mai mare rezistență la încovoiere, ajungând la o valoare de 231,7 MPa. În plus, utilizarea țesăturii de bazalt pe partea inversă a impactului sau structurarea hibridă cu mai multe straturi îmbunătățește și mai mult proprietățile de impact ale materialelor. Un compozit cu structură tip sandwich cu straturi de bazalt în mijloc și straturi de Kevlar pe ambele părți arată o îmbunătățire suplimentară a proprietăților de încovoiere.

Cuvinte-cheie: *compozite, ţesături, țesături de bazalt, secvență de stivuire, încovoiere în trei puncte, impact*

INTRODUCTION

Fibre-reinforced polymer composite materials (FRP) consist of fibres of high strength and modulus embedded in a polymer matrix. In this form, both the fibres and the polymer matrix retain their physical and chemical identities, yet they act separately [1]. The earliest FRP materials used were glass fibres embedded in polymeric resins made available by the petrochemical industry [2]. The fibre arrangement structure in the composite typically follows that of two-dimensional fabrics, including unidirectional, plain, and twill weaves. The multilayer stacking method must be adapted to meet the requirements for the structure thickness of composite materials, owing to the decrease in fibre cost and improvements in the preparation technology. Recently, interest has grown in the use of FRP in structural applications because they have the characteristics of low weight, high strength, high chemical resistance, and design flexibility, making manufacturing of large integral structures feasible [3]. The application of high-performance fibres in civil fields has recently expanded. FRP is increasingly in demand for protective equipment applications in the sports and labour field, giving rise to new economic growth.

The strength and modulus of elasticity of basalt fibre-reinforced composites (BFRP) are 30% higher than that of glass fibre-reinforced composites (GFRP), the thermal expansion coefficient is $6–8 \times 10^{-6}$/°C, the creep fracture stress is 0.54, and the price is close to GFRP. Compared with aramid fibre fibre-and carbon fibre-reinforced composites, BFRP has the highest performance-to-price ratio [4]. However, BFRP has low resistance under impact loading because of the lower elongation at the break of the basalt fibres [5]. For the optimal design of head protection equipment, it is important to improve the impact resistance of the composite material [6].

Hybrid fabric is an effective means of composite design, such fabric comprises two or more different types of fibres composited with a resin matrix to match the optimised performance requirements [7]. Fibres with different strengths, toughness, and elongations at break are mixed to obtain the advantages of all fibre types in terms of the different properties of the composites [8]. Kevlar fibres show excellent impact resistance owing to their high strength, ductility, and elongation at fracture, although they are considerably more expensive than basalt fibres. The primary limitation of Kevlar fibre-reinforced composites is their weakness in flexural and compression [9]. Notably, composite structures with curved shapes are common and easily experience delamination under loads owing to localised transverse stresses [10]. However, few investigations and little research have been conducted on this. Dong [11] discussed the flexural characteristics of hybrid composites fabricated using glass/carbon fibres and epoxy. Positive hybrid effects were observed when the glass laminae were placed on the compressive side. Similarly, Hung et al. [12] used glass/carbon to form a hybrid composite and found that the flexural strength was controlled by the strength of the bottom layers. Wu et al. [13] studied the flexural properties of a carbon/glass interlayer hybrid composite by theoretical analysis and experimental three-point flexural tests; their results agreed with the previous reports, and they found that the hybrid fibre content has no obvious influence. Subagia et al. [14] studied the effect of stacking order on the flexural properties of carbon/basalt inter-ply hybrid composites. The experimental results showed that the major failure mechanism was compressive failure. In addition, when carbon fibre plies were placed at the compressive side, higher flexural strengths and moduli could be obtained. Amuthakkannan et al. [15] found that sandwich-structured composites, in which the top and bottom layers contain the same fibres, have better impact strength than other interlayer structures for basalt/glass fibre-reinforced composites.

In addition to the use of hybrid fabrics of inorganic fibres, several studies have been conducted on hybrid composites utilising basalt and organic ductile fibres. Such hybrid composites combine the good mechanical properties of the brittle basalt fibre with the excellent impact resistance of the ductile organic fibre. Dehkordi et al. [16] studied the impact performance of basalt/nylon inter-ply hybrid composites. The results showed that the toughening mechanism of pure basalt fibre-reinforced composites under impact was fibre fracture, whereas those of the hybrid composites were debonding of nylon fibre and resin, basalt fibre fracture, and resin shear failure. The impact performance was dependent on the hybridisation and proportion of basalt/nylon fibres at high-impact energies. Sarasini et al. [17] analysed the low-velocity impact response of two different hybrid configurations and concluded that the Kevlar skin/basalt-core type exhibited better energy absorption capability than the lay-up type. Bozkurt et al. [18] investigated the effect of Kevlar/basalt inter-ply hybridisation and revealed that the introduction of basalt fibre on the compressive side provides greater improvement for the flexural resistance; in addition, the flexural properties of the composite are affected by the fibre stacking sequence.

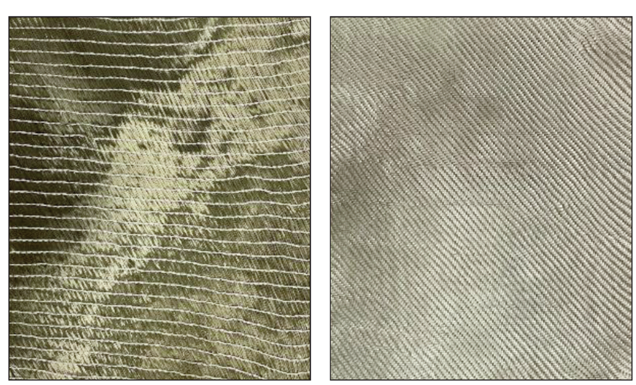
In this study, epoxy-based woven basalt/Kevlar fabrics hybrid composites with hemispherical shapes were prepared using a hand lay-up process.

Specimens with different configurations varying from 100% Kevlar to 100% basalt lamination and several types of inter-ply hybrid composites were designed. The impact and flexural properties of curved inter-ply hybrid composites with different hybrid structures were measured using cantilever impact and three-point flexural testers. The effects of different stacking sequences on the impact, flexural strength, and failure modes of the interlayer hybrid curved composites were discussed.

EXPERIMENTAL

Materials

Kevlar fibre (Kevlar1414, plain woven, 200 g/m^2) was purchased from China Tongxiang Xuanlei Composite Materials Co., Ltd. Basalt fibre (twill woven, 20013 g/m^2) was purchased from China Zhejiang Shijin Basalt Fiber Co., Ltd. Pictures of fabric used for curved laminates are shown in figure 1. Epoxy resin (JL-235) and Hardener (JH-242) were provided by Changshu Jiafa Chemical Co., Ltd, China. The mixture



a *b*

Fig. 1. Fabric used for curved laminates: *a* – Basalt twill fabric; *b* – Kevlar plain woven fabric

ratio of epoxy resin (1.12–1.16 g/cm^3 intensity, 0.54–0.57 eq/100 g in Epoxy value, 175–185 in Epoxy equivalent, 2500 MPa/s in viscosity) and curing agent (0.92–0.96 g/cm^3 in density, 450–510 mg KOH/g in amine value, 55–60 g/eq in active hydrogen equivalent, 40–80 MPa/s in viscosity) was 100:30 at ambient temperature (figure 1).

Preparation of hybrid composite samples and experimental design

The hybrid composite laminates were fabricated by using the hand lay-up and moulding process. The hand lay-up method was relatively simple to operate. There were several steps to accomplish all processes, which include: (a) resin and fabric preparation; (b) resin impregnation; (c) moulding by the self-made mould; and (d) curing of fabricated curved composites. The schematic diagram of the hand lay-up process is shown in figure 2. The hemispherical mould had a diameter of 8 cm and a depth of 5 cm, the radius of curvature was 50 mm. Basalt and Kevlar woven fabrics were cut to a size of 100×100mm, then arranged with different stacking orders in ten plies, among them, there were 4 plies of basalt fibre fabrics and 6 plies of Kevlar fabrics. Sketch maps of various stacking orders of Kevlar and basalt fabric and specimens are shown in figures 3 and 4. The relationships between laminate codes and the stacking sequence of the specimen are presented in table 1. The fibre weight portion of both Kevlar and basalt fibres was 50–55 wt.% in all of the hybrid composite laminate. The Kevlar and basalt fabric were immersed in the matrix with the epoxy resin with an amine curing agent. Then the immersed fabrics were put into the special mould and cured for 24 hours at room temperature.

Table 1

NUMBERED HYBRID LAMINATE WITH DIFFERENT STACKING SEQUENCE

Stacking sequence of specimen	Laminate codes
K10	KFRP
K3B4K3	H1
K6B4	H2
K3B2K3B2	H3
K2B2K2B2K2	H4
B4K6	H5
B2K3B2K3	H6
B2K6B2	H7
B10	BFRP

Experiments

Impact test

The impact tests were carried out using a digital display simple cantilever impact tester. The absorbed energy during fracture in the impact test is used as a

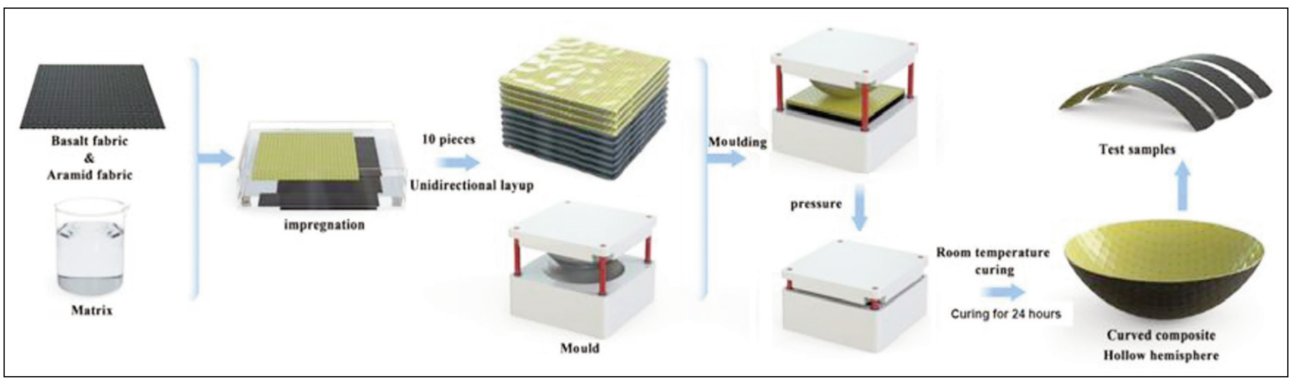


Fig. 2. Schematic diagram of a process for curve composite preparation

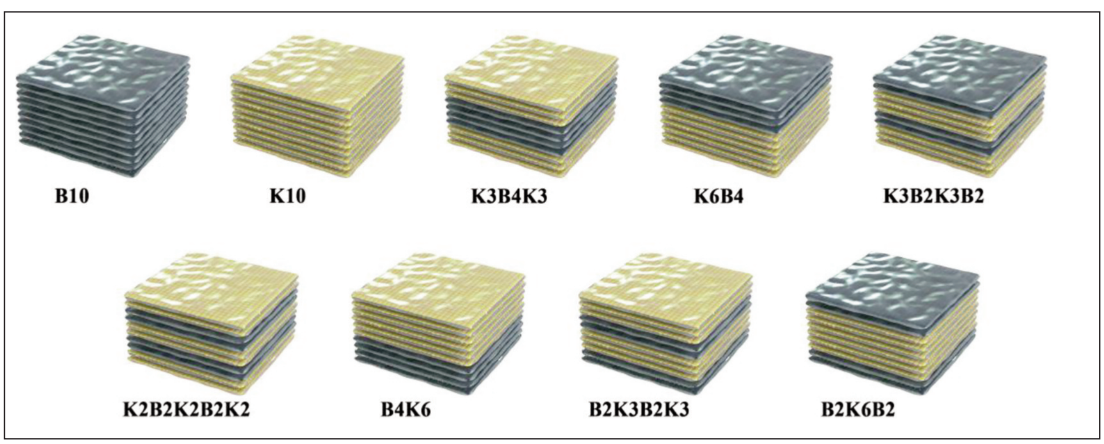


Fig. 3. Stacking sequence of Kevlar (K) and basalt (B) fibre woven

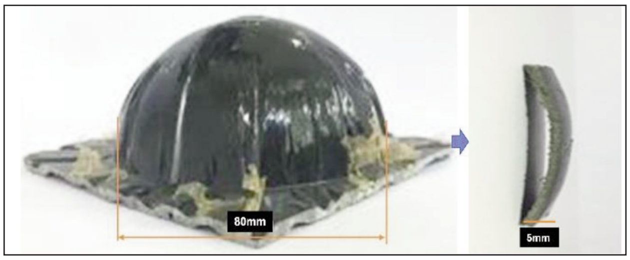


Fig. 4. Pictures of curve shape composite and specimen

measure of impact strength by GB/T1043-1993 [19]. Impact energy in an impactor was transmitted into a structure deformed or damaged, this geometry change for all specimens would absorb part of the energy. The distance between the support lines was 40 mm and the impact speed was 3.8 m/s. The dimensions of impact test specimens were about 5010 mm (length and width). The convex was the impact surface for all specimens, at least five specimens for each laminate. The impact strengths of the specimen were calculated by the formula which references formula 1:

$$a = \frac{P_{max}}{w \cdot h} \times 10^3 \qquad (1)$$

where P_{max} is impact strength, which available directly from the digital display. *w* and *h* are the width of the specimen, the thickness of the specimen, and the absorbed energy of the specimen, respectively.

Flexural test

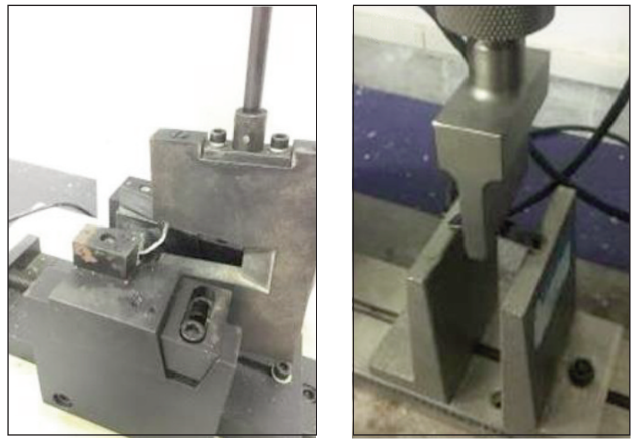
A flexural performance test was carried out using a universal mechanical testing instrument (WDW-20) by GB/T3356-2014 [20]. The span-to-depth ratio was 16, the test was performed at a constant crossed speed of 5 mm/min. The length of the specimen was about 60 mm, and the width was 10 mm. The convex was the compressive surface for all specimens. The cross-section at the point where the load is applied is consistent with the original stress situation because there is no axial force. Other cross-sections where the damage has changed must be the location where the strength limit occurs. Since the modulus and hardness of this material are high, not much plastic deformation occurs, and the damage to the midpoint of the upper section is completely dominated by bending, we believe that the flexural strength of the specimen can be obtained by formula 2:

$$\sigma_f = \frac{3 P_{max} L}{2 w h^2} \qquad (2)$$

where P_{max}, *L, w* and *h* represent the maximum load on the specimen, the span, thickness, and width of the specimen. The pictures of the mechanical properties test in this study are shown in figure 5.

Fracture surface observation

Fracture surface analysis was performed to observe the microstructure of the specimen after testing using an electronic magnifying camera (Gaoping, GP-300C) and to understand the failure mechanism.



a *b*

Fig. 5. Photo of: *a* – impact test; *b* – three-point flexural test

RESULTS AND DISCUSSION

Impact properties

The impact strength and absorbed energy of hybrid composites are shown in table 1. It was obvious that the KFRP showed the highest strength and absorbed energy because of the high strength of Kevlar fibre. This appears to be contrary to the Bozkurt [18] findings who reported that BFRP has higher impact strength and energy absorption than KFRP. It may be attributed to the fabric structure and curved structure for impact specimens. On the contrary, the BFRP shows the lowest impact strength and absorbed energy due to the basalt fibre being brittle. The KFRP showed impact strength which was 169% greater than that of BFRP. Figure 6 shows the morphology of the impacted and back surfaces for BFRP and KFRP composite. It can be seen from figures 6, *a* and *b*, that many cracks and fibre fractures for BFRP, show a typical failure of crack propagation attributed to the brittle failure of basalt fibres. it can be observed that the damage on the impacted side was relatively large and uncircular, compared with the back side.

While Kevlar fibres were not broken figure 6, *c* and *d*, impact failure was the loss of adhesion between fibre and resin, low-speed impact only causes some impact marks on the surface of the material, and some folds can be observed on the impact surface. It signifies that the material has a stronger impact toughness for KFRP. The deformation of Kevlar fibres is believed to be the key factor that improves the impact resistance of the composite [21]. In addition, it is found that almost no delamination phenomenon for neat basalt and Kevlar reinforced composite may be related to the curved structure.

From table 1, the hybrid composites of basalt and Kevlar fabrics (H1–H7, with different stacking sequences) showed average values between the values of KFRP and BFRP. The impact strength was proportional to the absorbed energy for all hybrid composite specimens. From the impact test results, it was found that the impact strength was higher when the Kevlar fabric was put on the surface. For

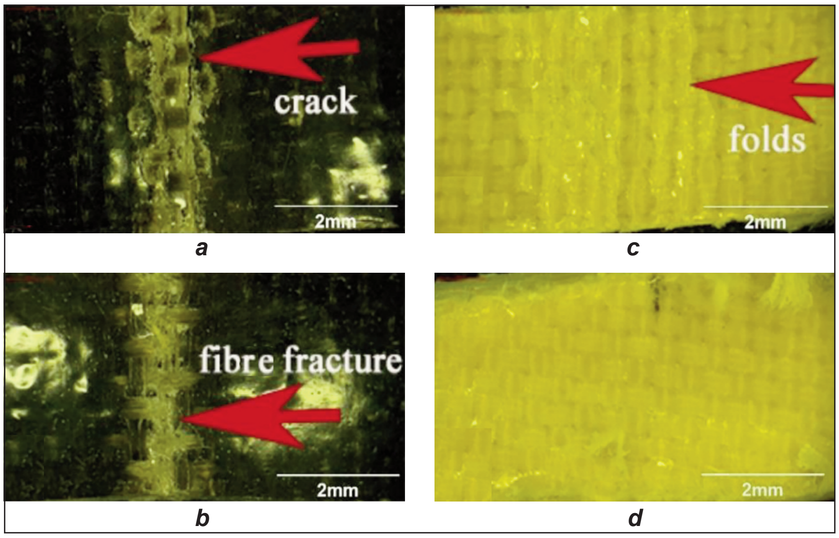


Fig. 6. Failure surfaces of samples after impact test: *a* and *b* – BFRP; *c* and *d* – KFRP; *a* and *c* – at the impacted side; *b* and *d* – at the back side, respectively

instance, the impact strength of H2 hybrid composite laminate was 92.43 kJ/m^2, compared with H5 increased by 41%. The impact strength of sample H3 increased by 14.4% compared with H6. The impact surface of the samples H2 and H4 were both Kevlar fabrics, due to the impact surface bearing more impact load, the placement of Kevlar fibres on the impact side should be the cause of increased impact strength. Bozkurt et al. got similar research results, changing the impact side showed differences in the impact absorbed energy of composite, aramid layer at the impacted side will improve impact absorbed energy.

Besides, the type of fabric on the impact reverse side also influenced the impact strength and absorbed energy, compare H1 with H3, the impact side was both Kevlar fibres, yet the impact reverse side of H3 was basalt fibres, its impact strength and absorbed energy were increased by 25.54% and 28.5%, respectively. In addition, the impact performance of H3 was also better than that of H4. In brief, the impact strength and absorbed energy are higher when the impact reverse side is basalt fabrics.

By further analysis, the multi-layer hybrid structure will improve the impact properties, the structures of H5 and H6 were similar, the impact side and reverse side were basalt fibre and Kevlar fibre respectively, and the two types of reinforced fabrics in H6 were arranged alternately, this resulted in a 23.83% increase in impact strength. While the impact side was Kevlar fibre and the reverse side was basalt fibre for both H2 and H3, the difference was that the core of the sandwich structure. There are no significant differences in impact strength and absorbed energy of H2 and H3. This further proves that the placement of Kevlar fibres on the impact side is the main reason for improving impact performance.

It can be seen from figure 6 that the main impact failure forms for hybrid composites were basalt fibre fractures, Kevlar fibre debonding and buckling as well as delamination. In general, the fracture of basalt fibre and the debonding of Kevlar fibre play a great role in absorbing impact energy.

Table 2

IMPACT PROPERTIES OF BFRP, KFRP AND HYBRID COMPOSITE LAMINATES			
Stacking sequence of specimen	**Laminate codes**	**Impact strength (KJ/m^2)**	**Absorbed energy (KJ)**
K10	KFRP	115.62	3.09
K3B4K3	H1	73.99	1.93
K6B4	H2	92.43	2.47
K3B2K3B2	H3	92.89	2.48
K3B2K2B2K2	H4	82.45	2.21
B4K6	H5	65.57	1.76
B2K3B2K3	H6	81.20	2.20
B2K6B2	H7	78.45	2.10
B10	BFRP	42.98	1.14

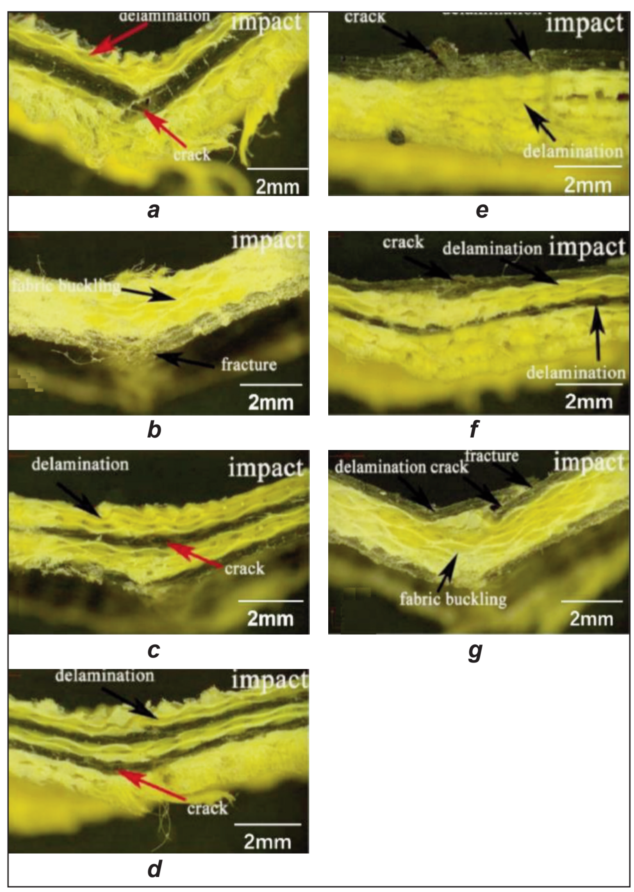


Fig. 7. Side images of failed samples after impact testing: *a* – H1; *b* – H2; *c* – H3; *d* – H4; *e* – H5; *f* – H6; *g* – H7

From the picture of failed sample H5–H7, the degree of deformation showed a reduction with an increase in the layers of basalt fibre at the impacted surface [22]. H1 is a sandwich structure, the basalt fibre in the middle has an obvious penetrating fracture after impact. Since basalt fibres are on the tensile side, the impact deformation of H3 decreases and the crack of basalt fibre becomes more inapparent. Both of them have obvious delamination of Kevlar fibre. H4 is more prone to delamination than H3. From the impact data in table 1, it seems that the fracture of basalt fibre plays a major role in improving the impact performance of the sandwich structure. For non-sandwich structures H2 and H5, the basalt on the impact surface can reduce its deformation but cause more cracks and delamination.

Flexural properties

Typical load-displacement curves of specimens (H5 as a representative of inter-layer hybrid composites) are shown in figure 8. BFRP has a typical "hard and weak" material, these curves implied that BFRP had higher flexural modulus but lower flexural strength. On the contrary, the flexural strength of KFRP was relatively high, and the slope of the curve was relatively low, which means that the flexural modulus was low. Like impact properties, the interlayer hybrid composites (H5) had average values between values of KFRP and BFRP. Due to the delamination phenomenon during the flexural test for interlayer hybrid composites, there were 2–3 peaks on each curve until it failed. The highest peak value was taken as the basis for the calculation of flexural strength. The calculation results are shown in table 3.

The three-point flexural experimental results show that flexural strength and modulus are related to the fabric type of compressive side and the tensile side (reverse side for specimens). It is known that the maximum values of the compressive and tensile stresses occur on the external layers. When Kevlar fabric was placed on the tensile side, the flexural strength was higher than that of basalt fabric on the tensile side. Moreover, basalt fibre on the compression side will help to improve flexural strength. In the case of H5, which has the highest flexural strength in interlayer hybrid composite specimens since there are 4 pieces of basalt fabric on the compressive side. Due to 2 pieces of basalt on their compressive side, specimens H6 and H7 also have relatively high flexural strength. Besides, it observed that the flexural strength also depended on what material was placed at the tension side. When the tensile side is Kevlar fabric, its flexural strength increases, and the value of H6 is 15.93% higher than that of H7.

Table 3

FLEXURAL PROPERTIES OF BFRP, KFRP AND HYBRID COMPOSITE LAMINATES

Stacking sequence of specimen	Laminate codes	Flexural strength (Mpa)	Flexural modulus (GPa)
K10	KFRP	133.6	0.167
K3B4K3	H1	217.1	0.135
K6B4	H2	137.1	0.161
K3B2K3B2	H3	153.6	0.133
K3B2K2B2K2	H4	180.6	0.116
B4K6	H5	231.7	0.109
B2K3B2K3	H6	198.0	0.132
B2K6B2	H7	170.8	0.095
B10	BFRP	301.4	0.083

For specimens H2, H3 and H4, the compressive sides of these specimens are all Kevlar fabric. However, the tensile side of H4 is Kevlar fabric, while the tensile side of H2 and H3 were basalt fabric. The flexural strength of H4 is 31.73% and 27% higher than that of H2 and H3, respectively, This suggests that Kevlar fibre on the tensile side can make the hybrid composites have higher flexural strength. It seems that the selection of tensile side material has a greater impact on the improvement of flexural strength. Sample H1 has a sandwich structure, both tensile and compressive sides are Kevlar fabric, and the interlayer is basalt, this kind of laminated structure also has better flexural strength. Due to the high modulus of Kevlar fabric reinforced composites, the more layers of Kevlar fabric in the compression surface, the higher the flexural modulus for inter-ply hybrid composite.

Figure 9 illustrates photographs of the fractured region for FRP after a three-point flexural test, which is along the sample's thickness. The damage is divided into three parts. Interlayer delamination, fibre fracture by compression and tensile debonding by tension. The cracks formed between

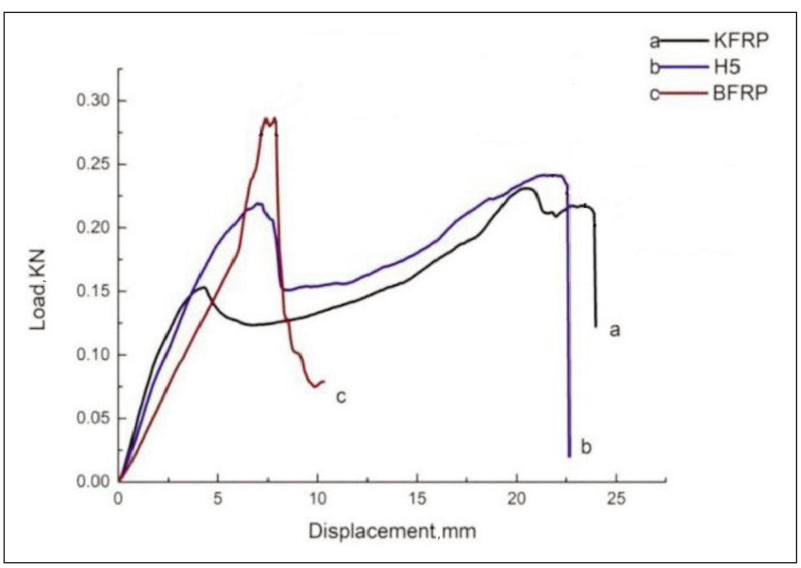


Fig. 8. Load-displacement curves for typical specimens

different components begin to start to cause fibre/matrix interface debonding.

The three-point flexural test can be regarded as an impact test with ultra-low speed. There is sufficient time to transfer the force. With the change of flexural strain, the compression layer is destroyed first [23]. The fracture of basalt fibre on the compression side plays a major role in improving flexural performance. The Kevlar fibre on the tension side shows a delamination phenomenon that can be seen in pictures of failed samples after flexural testing.

CONCLUSIONS

The effects of the interlayer hybrid of Kevlar and basalt fabric on the impact, flexural, and damage appearance of interlayer hybrid curve composites have been experimentally investigated. The hybrid composite laminates were fabricated into a curved shape with the aid of a hemispherical mould. Seven different hybrid laminate configurations and two neat Kevlar and basalt-reinforced epoxy composites were prepared. Each type of interlayer hybrid composite laminate contained 4-layer Kevlar fabric and 6-layer basalt fabric. The main conclusions that can be drawn are the following:

- BFRP showed a relatively lower impact strength and flexural strength compared to KFRP, but this was enhanced by the interlayer hybrid with Kevlar layers. The KFRP showed impact strength which was 169% greater than that of BFRP.
- The type of fabric on the impact reverse side also influenced the impact strength and absorb energy, the placement of Kevlar fibres on the impact side should be the cause of increased impact strength. Besides, if the basalt fabric is on the impact reverse side or multi-layer hybrid structure, that will further improve the impact properties of the material. Sample H3 (K3B2K3B2) has the highest impact strength and absorbed energy among seven hybrid laminates, valued at 92.89 KJ/m^2 and 2.48 KJ. Compared with H5(B4K6) improved 41.6% and 40.9%, respectively.
- Sample H5 has the highest flexural strength, reaching 231.7 MPa. The placement of Kevlar fabric was placed on the compressive side, the flexural strength was higher than that of basalt fabric on the compressive side. If it is made into a sandwich structure with basalt layers in the middle and Kevlar layers on both sides, the flexural properties of the material will be further improved.

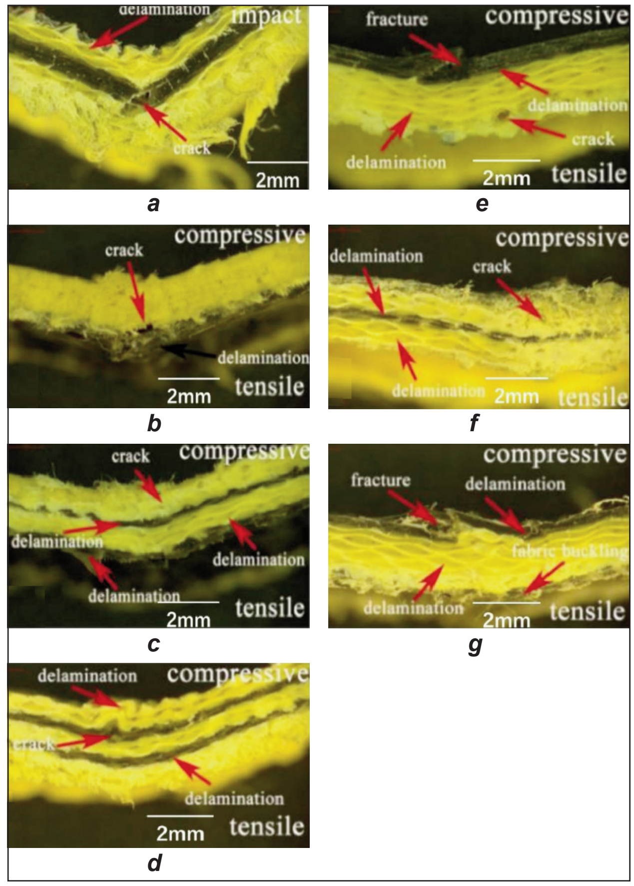


Fig. 9. Side images of failed samples after flexural testing: *a* – H1; *b* – H2; *c* – H3; *d* – H4; *e* – H5; *f* – H6; *g* – H7

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Authors:

FANGTAO RUAN[1], HAO WANG[2], CHENGLONG XIA[1], QINGYONG YANG[1], LIHUA ZOU[1], ZHENZHEN XU[1]

[1]Anhui Polytechnic University, School of Textile and Garment, 241000, Wuhu, China

[2]Shinshu University, Faculty of Textile Science and Technology, 386-8567, Ueda, Japan

Corresponding authors:

FANGTAO RUAN
e-mail: ruanfangtao@ahpu.edu.cn
ZHENZHEN XU
e-mail: xuzhenzhen@ahpu.edu.cn