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Flexural studies on asymmetric hybrid Kevlar fabric/epoxy composites

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For composites reinforced with Kevlar fabrics, the method of asymmetric hybridization is employed for the improvement of flexural properties such as maximum fibre yield stress and modulus of elasticity in bending. Calculations based on the elastic–plastic analysis are used to assess the shift in the neutral axis during bending, and the bimaterial beam model is invoked to estimate the arrangement and replacement of Kevlar fibres by carbon fibres in the compression face, for two relative fibre orientations. Flexural properties of the bimaterial are compared with those of unmodified Kevlar/epoxy composite for three different loading rates. Scanning electron microscopic examination of the fracture features is discussed.

1. Introduction

Composites reinforced with Kevlar-49 fibres show linear stress–strain curves when loaded in tension. However, the compressive and flexural behaviours are non-linear, and the stress–strain curve follows that of an elastic–perfectly plastic material [1]. The non-linearity arises from the compressive buckling, yielding and local shear failure of Kevlar fibres [2]. Due to the onset of compressive yielding during bending, the stress distribution shows a plastic behaviour in the compressive face and an elastic behaviour in the tensile face, with the result that the neutral axis of the beam is displaced towards the tensile face. Thus Kevlar fibre-reinforced composites show low flexural strength values compared with those reinforced with carbon or graphite fibres, due to the very low compressive strength of Kevlar. To improve the composite performance in flexure, the concept of asymmetric hybridization has been suggested, which employs the selective placement of a relatively small proportion of carbon fibres of high compressive strength in regions where the composite experiences a compressive stress. Marom and Chen [3] had previously studied the asymmetric hybridization of a unidirectional Kevlar fibre-reinforced J-polymer composite, with unidirectional carbon fibres.

In the present investigation, the concept of asymmetrical hybridization of woven Kevlar fabric with that of woven fabric of carbon has been used for two relative fibre orientations. The flexural properties of the bimaterial, such as the maximum fibre yield stress (MFYS) and the modulus of elasticity in bending, E_B, were studied for three different cross-head velocities and compared with those of a plain Kevlar/epoxy composite, to understand the effect of loading rates on their flexural behaviour. Fractographic investigations carried out are also reported. Previously, Amijima and Fuji [4] have reported the effect of shear strain rates on the mechanical properties of adhesives and adhesive joints. The effect of carbon coating on the flexural properties of Kevlar/epoxy composites, for three different loading rates is discussed elsewhere [5].

2. Theoretical considerations

Kevlar fibre composites possess high ultimate tensile strength, σ_{tu}, and low ultimate compressive strength, σ_{cu}. This implies that, once the compressive yield has occurred, the usual elastic-beam equations are not valid. Zweben [1] considered the compressive behaviour of Kevlar composites as an elastic perfectly plastic behaviour (a Bingham solid), and the tensile behaviour as an elastic brittle solid. His model predicted that the neutral axis at fracture is shifted towards the tensile face from the centroidal axis, governed by the ratio of σ_{tu} to σ_{cu}. The magnitude of neutral axis displacement, C', at failure is given by [1]

$$\frac{C'}{D} = \frac{1 - 2r + r^2}{2(1 + r)^2} \qquad (1)$$

where $r = \sigma_{tu}/\sigma_{cu}$ and D is the depth of the beam. Fischer and Marom [6] have also obtained a similar result.

For a 50 vol % unidirectionally reinforced Kevlar/epoxy system having $r \simeq 5.5$ [6], using Equation 1 it is found that $C'/D = 0.2396$. In the present system, where four-harness satin Kevlar prepregs are employed, values of $r_{0°/90°} \simeq 3.2$ and $r_{\pm 45°} \simeq 2.9$ were obtained experimentally, and the corresponding C'/D values were found to be 0.137 and 0.119, respectively. These values imply that the neutral axis shifts downward towards the tensile face by about one quarter of the beam depth in the unidirectional Kevlar composite, and by about half this value when present as a woven fabric composite. Thus the downward shift in the neutral axis in woven fabric composites is considerably less compared to the unidirectional ones.

A bimaterial beam model, presented by Marom and Chen [3] for a Kevlar fibre/carbon fibre system, is

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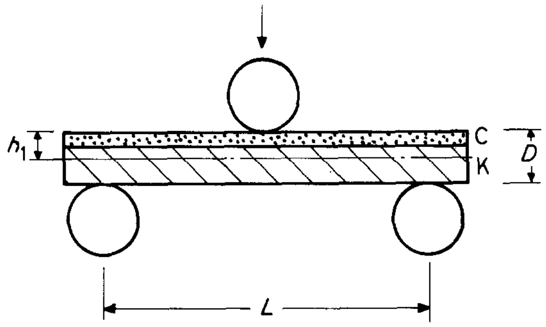

Figure 1 Schematic representation of flexural loading of carbon/Kevlar composite.

adopted here for a woven fabric composite system. Using the notation defined in Fig. 1, h_1 (the distance of the neutral axis from the compression face) is given by [3]

$$h_1 = \frac{E_C t_C^2/2E_K + t_K(t_C + t_K/2)}{E_C t_C/E_K + t_K} \qquad (2)$$

where E is the Young's modulus; t is the thickness of the beam; and subscripts C and K denote carbon and Kevlar. Also

$$h_1 = \frac{rt_C + t}{1 + r} \qquad (3)$$

where $r = \sigma_{tu}/\sigma_{cu}$.

In the present investigation, two sets of fibre orientations have been used for the bend test, as shown in Fig. 2. Using experimentally determined values of $E_C/E_K \simeq 0.7$ and $r \simeq 3.2$ for a weave orientation of $C \pm 45^\circ\ K_{0^\circ/90^\circ}$ (Fig. 2a), and $E_C/E_K \simeq 4.5$ and $r \simeq 2.9$ for a weave orientation of $C_{0^\circ/90^\circ} K \pm 45^\circ$ (Fig. 2b) in Equations 2 and 3, and denoting $P_C = t_C/t$, two separate quadratic equations were obtained for P_C.

$$P_C^2 - 8.78 P_C + 3.33 = 0 \qquad (4)$$
$$(\text{for } E_C/E_K \simeq 0.7 \text{ and } r \simeq 3.2)$$

and

$$P_C^2 + 1.92 P_C - 0.29 = 0 \qquad (5)$$
$$(\text{for } E_C/E_K \simeq 4.5 \text{ and } r \simeq 2.9)$$

The physically acceptable solutions are $P_C \simeq 0.40$ for Equation 4, and $P_C \simeq 0.14$ for Equation 5. These values mean that a replacement of 40% of 0°/90° Kevlar fibres by ± 45° carbon fibres, and 14% of ± 45° Kevlar fibres by 0°/90° carbon fibres, is required in the compression face to completely eliminate the compressive failure of Kevlar. However, such a large replacement poses difficulties in fabrication, as detailed in the following section.

3. Experimental procedure

Woven fabric prepregs of four-harness satin Kevlar with 50 vol % of fibres and five-harness satin carbon with 60 vol %. of fibres, impregnated with Fibredux 913 resin curing at 120 °C, were used to fabricate laminates of 5 mm thickness. The asymmetric bimaterial consisted of a 0°/90° layer of Kevlar fabric with a topmost layer of ± 45° carbon fabric which resulted in a P_C value of 0.06 in the laminate. This misorientation was done mainly to minimize the appearance of longitudinal and transverse cracks [3]. Further, a single layer of carbon ensured a minimum residual stress arising from the difference in the thermal expansion of Kevlar and carbon, due to curing. A double-dwell, standard autoclave cure recommended by the manufacturer was followed in the fabrication [7].

Test specimens of two different orientations of carbon and Kevlar, with a P_C of 0.06 and a total fibre volume fraction of 0.55, were prepared from the same laminate with fibre orientations as follows:

Type A — carbon ± 45° Kevlar 0°/90°
Type B — carbon 0°/90° Kevlar ± 45°

All the specimens were of 100 × 10 × 5 mm [8]. The specimens were tested as per ASTM D 790 M standard test specifications at an L/D ratio of 16/1 in an Instron 8032 machine, with the carbon fibres in the compression face. Three different cross-head loading velocities, namely 0.0035, 0.035 [8] and 0.35 mm s^{-1} were chosen to study the effect of loading rate on the strength and modulus of the composite.

The failed specimens were sputter coated with gold and examined in a scanning electron microscope (SEM).

4. Results and discussion

Fig. 3 shows the load deflection plots for the bimaterial and the plain composite tested in two orientations, as described above. The figure shows the region of carbon-layer failure clearly. This failure is characterized by acoustic emission and a sudden dip

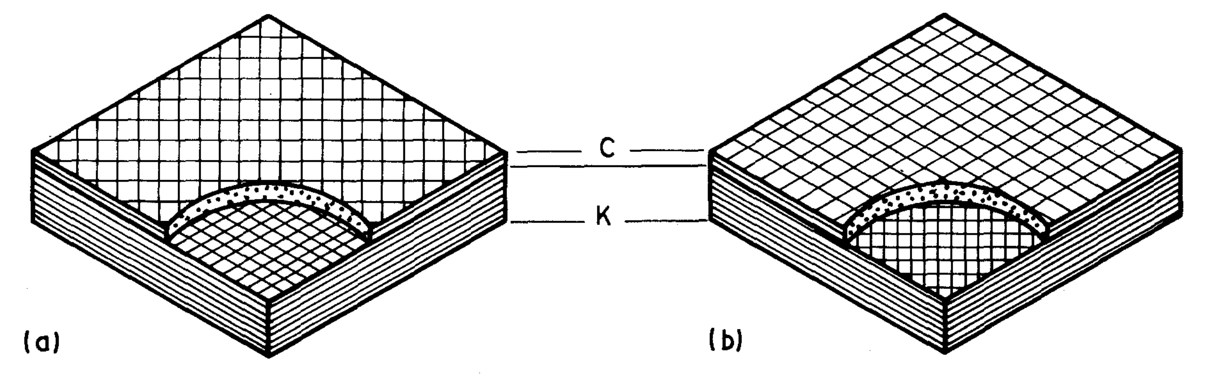

Figure 2 Two relative orientations of specimens used: (a) C ± 45°K 0°/90° (type A) and (b) C 0°/90°K ± 45° (type B).

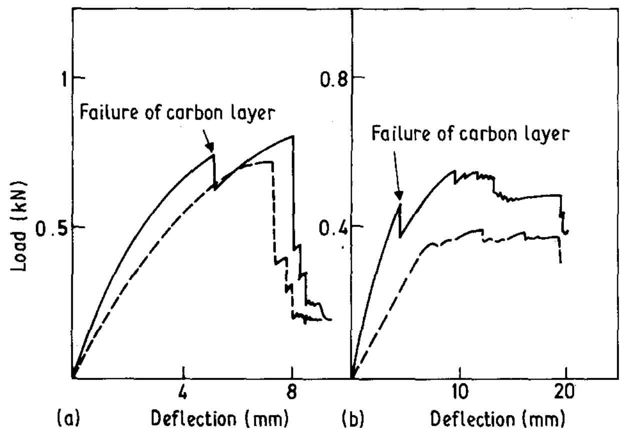

Figure 3 The load-deflection plots for (a) plain (K 0°/90°) and asymmetric type A (K 0°/90°C ± 45°); and (b) plain (K ± 45°) and asymmetric type B (K ± 45°C 0°/90°) composites (cross-head velocity = 0.035 mm s^{-1} (- - -) Plain; (———) Asymmetric.

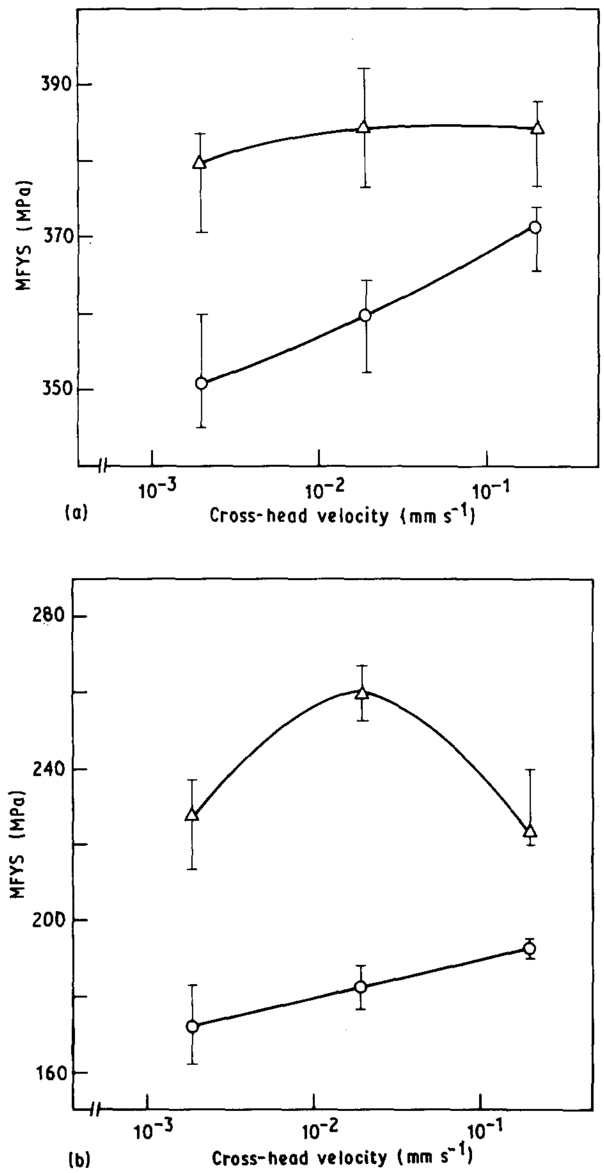

Figure 4 Changes in MFYS values for three loading rates for plain, (a) type A and (b) type B composites. △, Asymmetric; ○, Plain.

in load values due to the brittle nature of the carbon fibres. Further, the carbon fabric layer increases the flexural strength of the composite, as evident from the plots. Hence it is clear that this bimaterial ar-

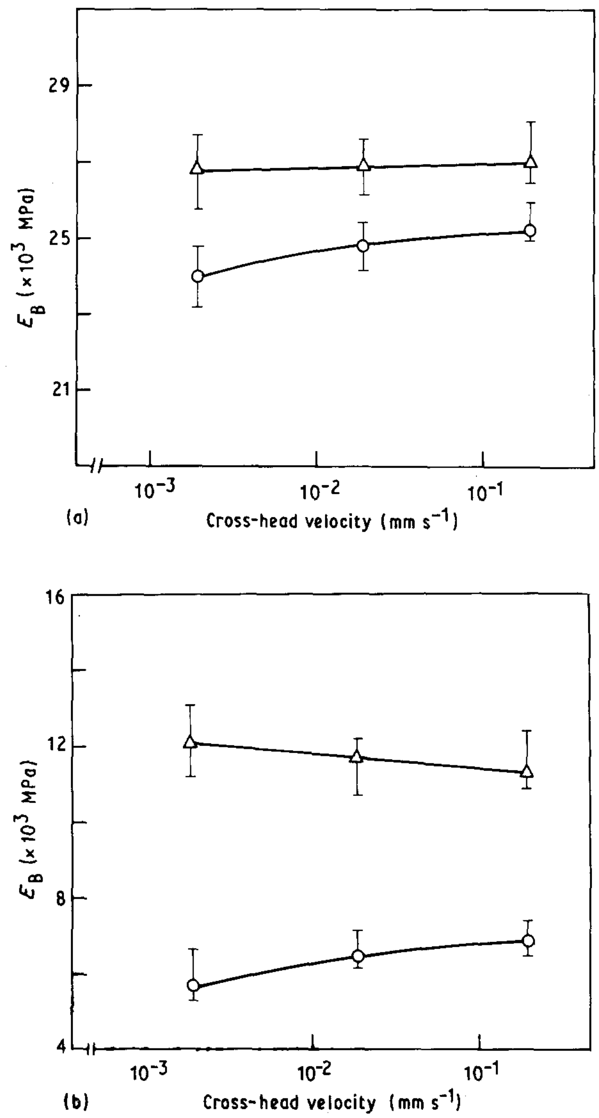

Figure 5 The E_B values at three different cross-head velocities for (a) type A and (b) type B composites, against their respective plain specimen values. △, Asymmetric; ○, Plain.

rangement enables development towards the true ultimate tensile strength of Kevlar, σ_{tu}, at the tensile face of the sample. It is also seen that the samples with Kevlar in the ± 45° orientation show large deflection (~ 20 mm) before ultimate tensile failure. The failure is of a characteristic delamination mode [9] in Fig. 3a, for both asymmetric and plain samples.

The MFYS values of the plain and asymmetric specimens (Fig. 4a and b) and their E_B values (Fig. 5a and b) are shown for three different cross-head velocities. The plain specimens show increasing MFYS and E_B values at varying magnitudes for increasing loading velocities. However, for both the fibre orientations, the asymmetric specimens exhibited no such steady trends, even though their MFYS and E_B values were higher than those of plain specimens. For a Type A specimen, it was noticed that the MFYS and the E_B values improved appreciably (8 and 11%, respectively) for the lowest loading rate, and marginally (3 and 6%, respectively) for the highest loading rate. Similarly, for a type B specimen a significant improvement in MFYS values (31 and 18%) was noticed at the lowest and highest loading rates, respectively. The corresponding E_B values showed a phenomenal 100 and

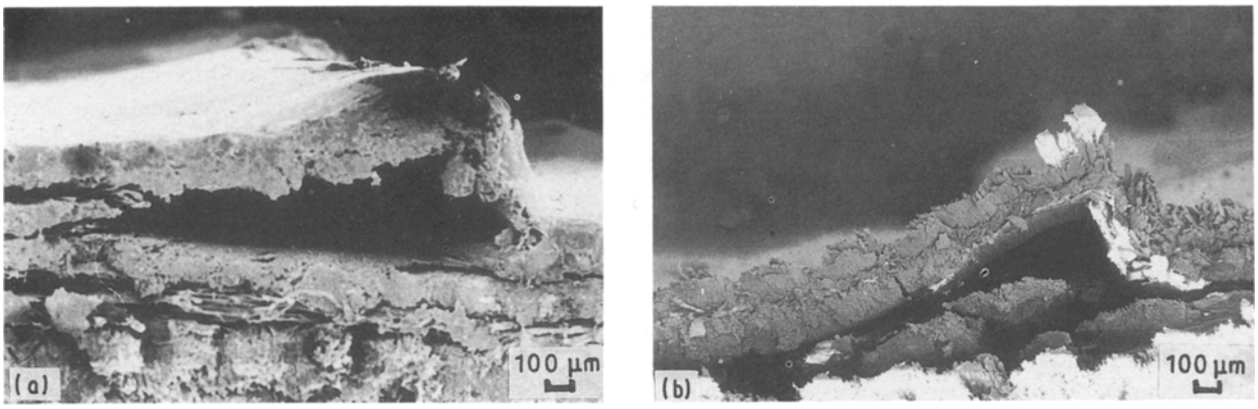

Figure 6 SEM fractographs of buckling delaminations of carbon layer in (a) type A and (b) type B composites.

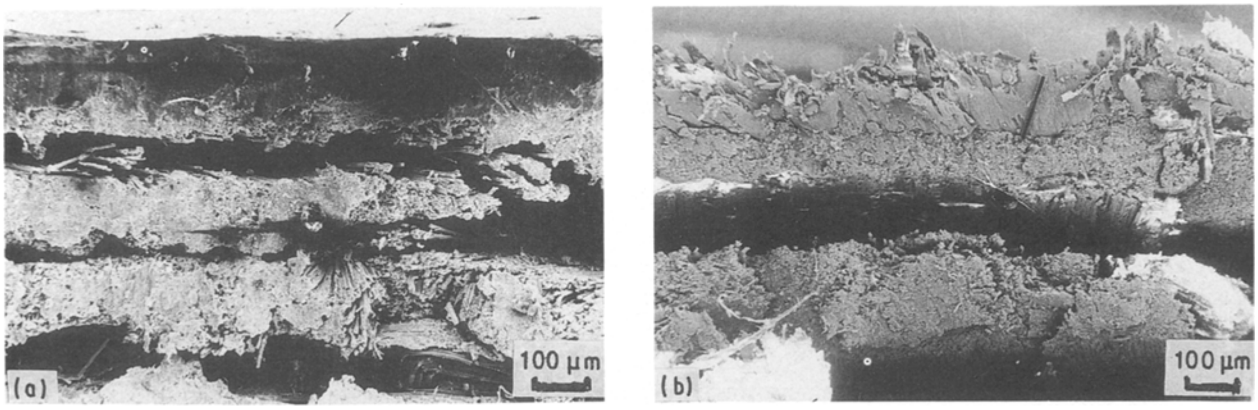

Figure 7 SEM fractographs showing (a) irregular and discontinuous delaminations in type A; and (b) regular and continuous delaminations in type B composites.

63% increase, at the lowest and the highest loading rates, respectively, over those of plain specimens. This increase in the E_B values is attributed to the high ratio of $E_C 0°/90°/E_K \pm 45°$ for this composite. It is noteworthy that despite an E_C/E_K of 0.7 (i.e. less than unity), an improvement in the modulus (and strength) was noticed for the type A composite.

SEM fractography was carried out on the failed bimaterial specimens to study their delamination patterns. The carbon-layer failure, due to the action of the loading nose in the compression face, shows either a rounded or a stepped delamination for carbon-layer orientations corresponding to $\pm 45°$ (type A) and 0°/90° (type B), respectively. This is illustrated in Fig. 6a and b. Delaminations [10] in the compression face of the samples seem to be more regular and continuous in type B than in type A (Fig. 7a and b). This can be mainly attributed to the effect of the orientation-related rate of deformation of the two types of fibre layers employed. Regular and continuous delaminations in the type B samples are a result of large deflections shown by Kevlar in the $\pm 45°$ orientation, compared to its carbon reinforcement in the 0°/90° direction. Resin-rich regions between the carbon and Kevlar layers show fracture features similar to that shown in Fig. 8. These chevron-like marks [11] appear prior to delamination due to the resin thickness being much smaller than the width or length. Further, these marks are irregular, even though the

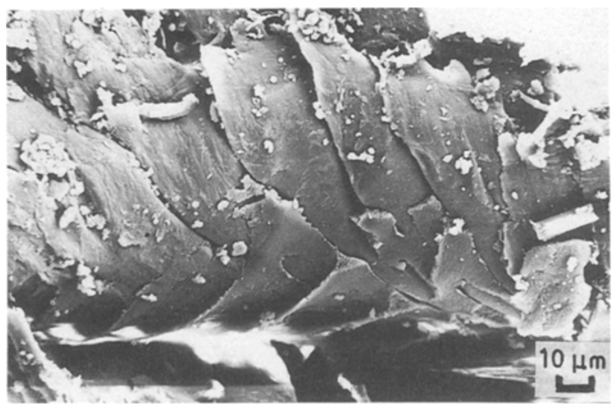

Figure 8 Chevron-like patterns in a resin-rich area in the carbon–Kevlar interface.

rate of defomation of fibres is distinctly different for type A and type B composites. The absence of distinct patterns could be due to the fact that the resin always experiences a high compressive stress, as it is just beneath the carbon layer. Also, shear damages were produced in the Kevlar layer close to the carbon layer as a result of relative misorientation and the difference in deformation characteristics of carbon and Kevlar.

Fractography also revealed that, despite the improvement in flexural properties, the failure of the asymmetric hybrid composite was still dominated by the compressive failure of the carbon fibres for both type A and type B samples. This can be inferred from the load deflection plots also. The observed improvements, in the flexural properties are mainly due to the higher modulus and compressive strength of carbon fibres, compared to Kevlar.

5. Conclusions

1. Asymmetric hybridization of Kevlar fabric with carbon fabric on the compression face improves the flexural properties of the composite. The improvement in flexural modulus depends on the E_C/E_K ratio and the strength on the higher compressive strength of carbon fibres. The carbon layer enables development towards the true ultimate tensile strength of Kevlar. The improvements in E_B values are more impressive than those in MFYS values for an asymmetric hybrid of Kevlar and carbon, for a small percentage of carbon fibres ($P_C = 0.06$).

2. The loading-rate sensitivity of the bimaterial does not show an increasing trend like the plain composite. The bimaterial arrangement is more effective, by and large, at lower loading rates.

3. Fractographic investigations reveal regular and continuous delaminations in type B composites compared to type A composites. Resin-rich regions in the carbon/Kevlar interface show chevron-like fracture features. Shear damage is caused due to the fibre misorientation and differences in rate of deformation.

4. As in plain Kevlar/epoxy specimens, the failure of asymmetrical hybrid composites is also dominated by the compressive failure, but to a lesser extent due to the presence of carbon fibres in the compression face.

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