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A Study of Skin-Core Adhesion in Glass Fibre Reinforced Sandwich Materials

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Abstract. A test technique for measuring skin-core adhesion in fibre reinforced sandwich structures has been developed and applied. The test enables the interfacial fracture energy to be measured for most standard sandwich constructions. The technique has been subsequently employed to investigate skin-core adhesion in a number of sandwich structures similar to those currently used in the marine industry. It has been shown that the interfacial fracture toughness of a GFRP–crosslinked PVC sandwich structure can be as high as 2700 J/m^2; however, sandwich constructions based on balsa cores offered considerably lower values of interfacial fracture energy. Here it was found that pre-treating the balsa core prior to bonding of the composite skins has a deleterious effect on the measured fracture toughness. Finally, the results of these tests have been correlated with data obtained from conventional climbing drum and short beam shear tests.

Key words: sandwich materials, skin-core adhesion, interfacial fracture toughness, climbing drum test.

Introduction

The benefits of bonding strong, stiff composite laminates to low density materials such as polymeric foams and balsa have long been recognised. As a result, sandwich materials are now finding widespread use in major load-bearing components in both the marine and aeronautical industries, as described at several recent conferences [1–3]. The characterisation of the mechanical properties of these sandwich materials is complex. Previous work [4–7] has shown, however, that sandwich constructions are capable of absorbing considerable energy under impact loading. A common mode of failure in impact-loaded sandwich structures is skin-core debonding by interfacial crack propagation. Clearly, failure of the interface between the load-bearing skin material and the low density core may result in a total loss of structural integrity, almost certainly leading to complete structural failure of the part. To date, only a limited amount of work has been undertaken in a bid to characterise the strength a toughness of the interfacial region in sandwich materials. Traditionally, the climbing drum test has been widely used to evaluate the degree of bonding in these lightweight materials.

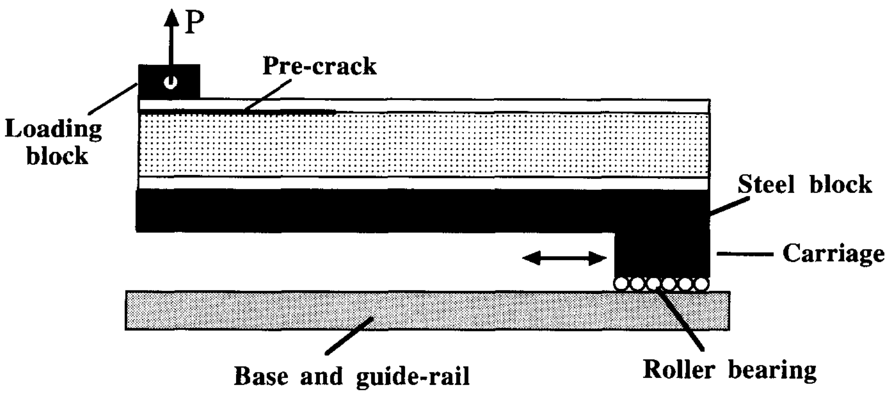


Figure 1. Schematic drawing of the test specimen and loading jig used to determine the interfacial fracture energy of the sandwich structures.

The test does, however, suffer several limitations, perhaps the most important being that it cannot be applied to structures having thick outer skins. Simple, short-beam flexural tests are also used to assess interface strength for quality control purposes, but tend to result in a mixture of failure processes (core shear, upper skin damage and interface debonding) making interpretation hazardous. Carlsson *et al.* [8] developed a cracked sandwich beam specimen for the study of interfacial failure in balsa-based sandwich materials. Their results indicated that the shear fracture toughness of a GFRP-balsa sandwich structure was intermediate between the interlaminar fracture toughness values for a brittle carbon fibre/epoxy and a tough carbon fibre thermoplastic composite. More recently, Prasad and Carlsson [9, 10] employed a modified double cantilever beam (DCB) specimen and a sandwich shear fracture specimen in order to characterise the interfacial fracture toughness of a series of aluminium–polymer foam sandwich structures. Zenkert also used cracked mode II specimens to look at crack propagation in foam sandwich composites, studying both the crack resistance of the core and the influence of disbonds at the skin/core interface on load-bearing capacity [11, 12].

It is clear from this brief review that improved test methods are needed to characterise the interfacial fracture properties of sandwich materials as these are critical to the optimisation of the sandwich structure. This paper presents results from the test technique shown in Figure 1 which has proved useful in recent studies aimed at improving skin/core bond integrity [13]. Results are presented from tests to assess the level of skin/core adhesion in a number of materials typical of those currently finding applications in the marine industry. Finally, results are compared with those from more traditional test methods obtained on climbing drum and short beam shear specimens.

Experimental Procedure

Table I and Figure 2 contain a summary of the materials examined during the course of this programme. Four glass/polyester balsa systems, manufactured using a hand lay-up process, and two vacuum bagged glass/epoxy PVC skinned foams were considered. The skins in materials A to D were based on composites containing two layers of stitched quadriaxial E-glass fibre fabric (areal weight 850 g/m^2) in an isophthalic polyester resin. The core material was an end-grain balsa having a density of 175 kg/m^3. Material A was considered to be a standard system in which the skins were cured directly on the as-supplied balsa core. Prior to applying the composite skins, the core in materials B, C and D was first sealed. Here, the polyester resin used as the matrix in the skins was applied to the balsa and allowed to gel. Material C contained a layer of chopped strand mat (areal weight 450 g/m^2) at the skin-core interface and material D a layer of fabric based on a thermoplastic polyester fibre (areal density 130 g/m^2). The skins in materials E and F were based on woven E-glass fibres in an epoxy resin. Materials E and F contained foamed cores, commonly known as 'PVC' but are in fact semi-penetrating networks of thermoplastic PVC with a thermoset polymer [14]. Material E contained a crosslinked core (density = 80 kg/m^3) and material F a linear core (density = 75 kg/m^3).

The interfacial fracture toughness of the sandwich materials was investigated using the modified peel test shown in Figure 1. Prior to testing, a 200 × 20 mm pre-cracked sandwich beam was bonded to a 10 mm thick metal substrate and placed on a movable chariot. In most cases, a pre-crack length of approximately 50 mm was used. Testing was carried out on an Instron 1122 screw-driven test machine at a crosshead speed of 5 mm/minute. Load was applied through an

Table I.

Material	Core	Skin	Areal weight of sandwich (kg/m^2)
A	Balsa[1]	Glass[2]/polyester[3]	11.5
B	Balsa	Glass/polyester	11.5
C	Balsa	Glass/polyester	13.7
D	Balsa	Glass/polyester	16.2
E	Crosslinked PVC[4]	Glass[5]/epoxy[6]	6.4
F	Linear PVC[7]	Glass/epoxy	6.4

[1] End grain balsa from Baltek Corp. (density = 175 kg/m^3)
[2] Quadriaxial glass fibres QX850 from Cotech.
[3] Isophthalic polyester resin 491PA from Scott Bader.
[4] H80 from Divinycell.
[5] 0°/90° Woven E glass fibres.
[6] 5052 epoxy resin from Ciba-Geigy.
[7] R63.80 from Airex.

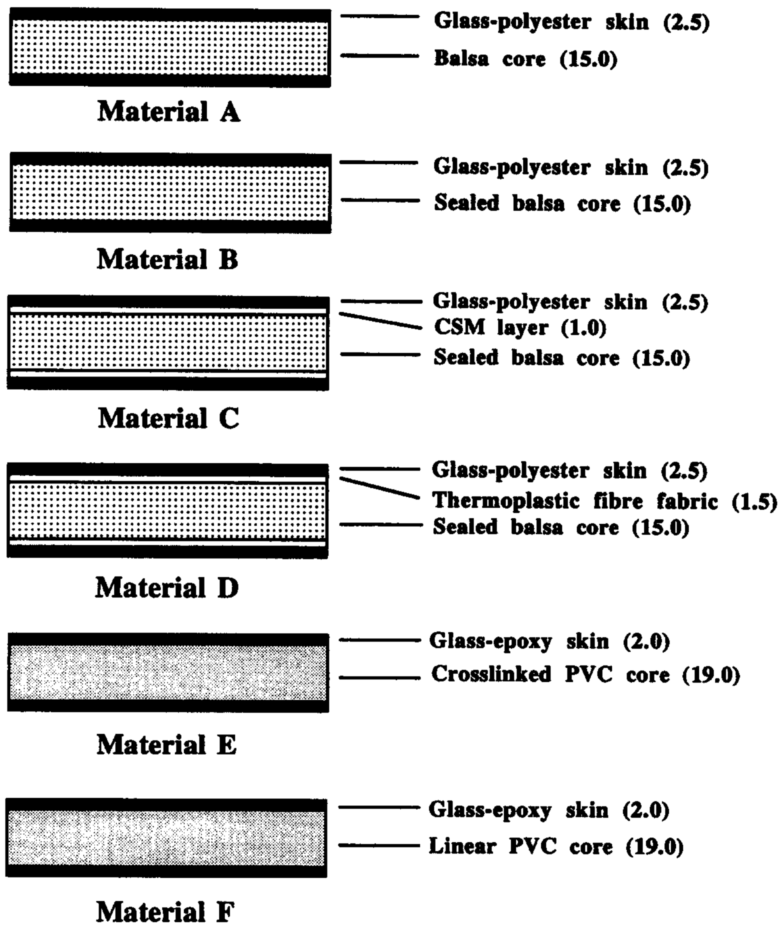


Figure 2. Summary of the materials examined in this study. The brackets contain the thicknesses of the relevant constituents.

aluminium hinge bonded to the end of the pre-cracked region and crack advance determined using a calibrated scale painted along the interfacial region. Typically, the crack was propagated fifty millimetres before the test was stopped and the specimen unloaded. Four specimens of each type were tested. The interfacial fracture energy was calculated in two ways. Firstly, an areas method was applied where the area under the load-displacement curve is divided by the resulting fracture surface area. A compliance calibration procedure based on the following equation was also used:

$$G = \frac{P^2}{2B}\frac{\mathrm{d}C}{\mathrm{d}a}.$$

It is likely that this loading regime involving fracture at a bi-material interface will result in a mixed-mode loading condition at the crack tip and that this ratio will vary with crack length [9, 10]. No attempt was made to determine the degree of mixity at the tip of the crack in these materials.

A series of climbing drum tests were conducted according to the DIN 53 295. Here, 300 $\times$ 20 mm specimens were machined, leaving 25 mm tongues at each end. One end of the specimen was held in steel grip and the other end fixed to the surface of a 100 mm external diameter drum. The subsequent movement of the drum relative to the lower end of the specimen resulted in the separation of the skin and core materials. The tests were undertaken at a crosshead speed of 25 mm/min.

A series of short beam shear tests were undertaken on the four balsa materials in order to characterise their apparent shear strengths based on the French standard NF T54-606. Here, 50 mm wide beams were supported on rollers positioned 200 mm apart. Load was applied by two central rollers rather than one, to avoid indentation. The loading rate was 5 mm/min. The shear stress at rupture was determined from the expression:

$$\tau = \frac{P}{(h + h_c) \cdot B}$$

with P the maximum force, h the total sandwich thickness and h_c the core thickness, B the beam width. Six beams of each type were tested.

Results and Discussion

Interfacial Fracture Tests

Failure in all of the materials except the crosslinked PVC, material E, occurred as a result of stable crack propagation. In material A, the crack propagated at the skin-core interface involving considerable amounts of fibre bridging between the balsa core and the glass fibre skins. Fibre bridging was less evident in system B even though the crack did propagate at the skin-core interface. In material C, the crack advanced largely within the CSM layer. In system D, the degree of adhesion between the polyester fibre fabric and the core material was so high that the crack propagated up through the fabric to the composite-fabric interface and then along it. Failure in material E occurred both at the interface as well as within the foam core whereas the crack propagated entirely within the core material in system F.

Load-displacement curves typical of those observed in balsa-core materials A and B are shown in Figure 3. The loading and unloading portions of the curves were fairly linear and the residual displacement after unloading was minimal. Material B exhibited a nonlinear response associated with large displacement effects. This is particularly apparent in the unloading curve. Figure 4 shows typical load-displacement curves for the foam-based sandwich structures, material E

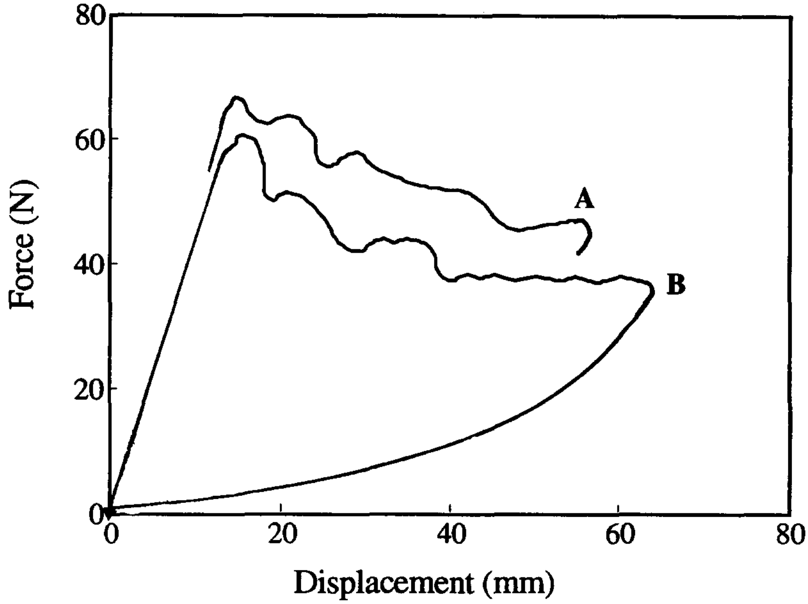


Figure 3. Typical load-displacement traces for the standard GFRP-balsa sandwich structure, material A and the pre-treated balsa system, material B.

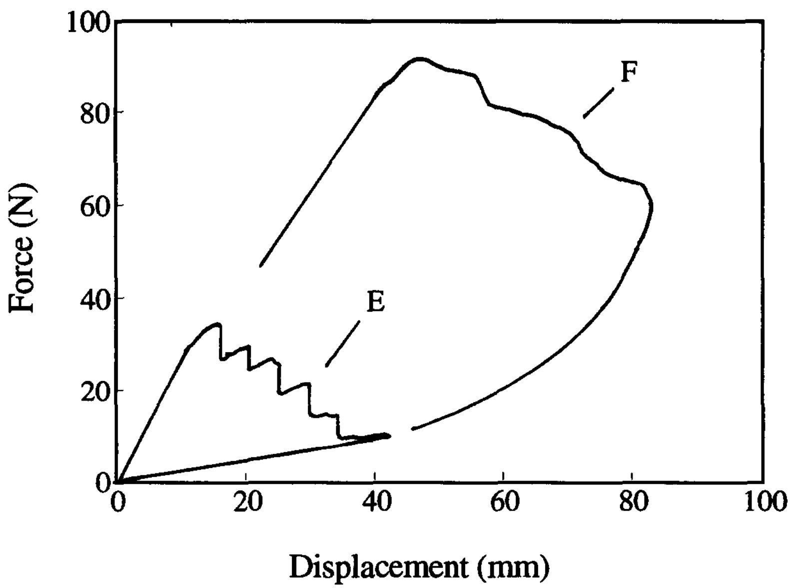


Figure 4. Typical load-displacement traces for the crosslinked PVC sandwich structure, material E, and the linear PVC system, material F.

and F. The linear PVC exhibited a stable mode of crack growth whereas the crack propagated in a stick-slip mode in the crosslinked PVC system. The displacement of the upper composite skin was so great in the former that the unloading curve exhibited considerable non-linearity. Further, since a significant amount of permanent deformation occurred in the foam during the fracture process, the unloading curve did not return to zero but exhibited a small permanent displacement.

Figure 5 shows typical R-curves for materials A, B and E. The variation in the results for the two balsa-based materials as the crack proceeds is probably caused by the periodic fracture of fibre bridges and the heterogeneity of the balsa core which is made up of small blocks. The scatter in the PVC foam results from a tendency for the crack to propagate either within the interfacial region or else entirely within the foam, the latter mode of failure yielding slightly higher values of fracture energy.

Table II contains a summary of the mean interfacial fracture energies measured on the six materials examined in this study. An examination of the data indicates that the fracture energies determined using the areas method are greater than those determined using the compliance calibration technique. This disparity becomes more pronounced as the interfacial fracture energy increases. It is believed that at least part of this difference is due to energy dissipation in permanently deforming the core material. Indeed, the linear PVC foam exhibited considerable permanent deformation after unloading. The presence of extensive fibre-bridging particularly in material A may also have influenced the compliance calibration procedure. It is also likely that the large displacements occurring during the fracture of materials A and F will have affected the accuracy of the calculated data.

From Table II it is apparent that of the four balsa-based sandwich structures, material A exhibited the highest value of interfacial fracture toughness. This superior behaviour is probably a result of the significant amount of fibre bridging occurring between the skin and core materials during the crack propagation process. Figure 6a shows the lower surface of a GFRP skin for material A. Clearly, many of the longitudinal fibres have been pulled out of the polyester matrix during the bridging process. It is very likely that the debonding and pull-out mechanisms associated with the bridging process have consumed significant amounts of energy resulting in an increased fracture toughness.

The fracture toughness of material B was approximately 15% lower than that of material A. Prior to the laying-up process, the balsa core in this material was sealed using a polyester resin. This sealing process is employed to reduce the overall weight of the component but it prevents the polyester resin present in the composite skins from seeping into the core material to form mechanical anchors. Further, a weak interfacial zone may be present between the pre-cured layer of polyester resin on the surface of the balsa and the composite skin. A lack of a strong bond may reduce the amount of fibre bridging occurring during the failure process. Indeed, an examination of one of the specimens during failure

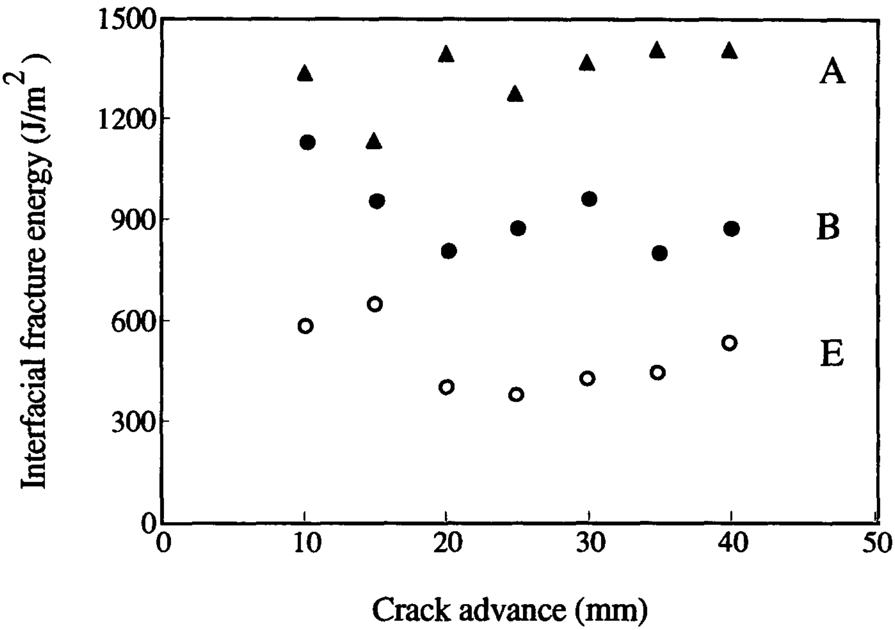


Figure 5. R-curves for the balsa-based materials A and B and the crosslinked PVC system, material E.

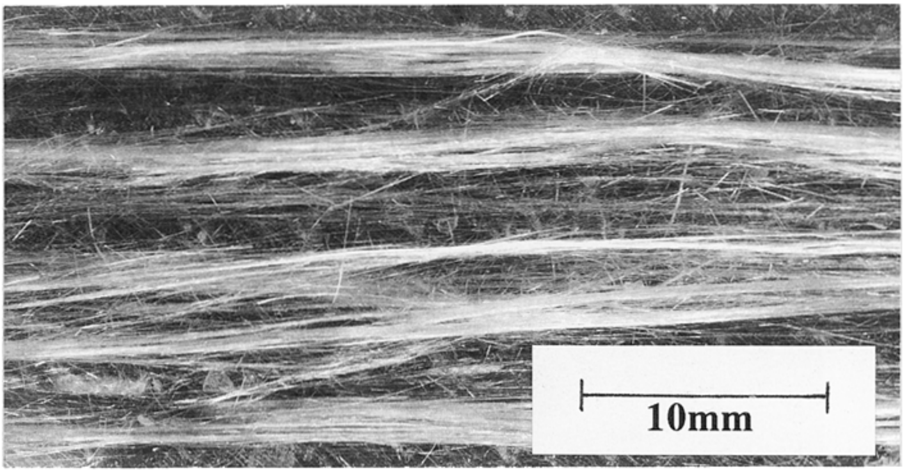
Table II.

Material	G (J/m^2) (Compliance method)	G (J/m^2) (Areas method)
A (balsa)	1320	1860
B (balsa)	1130	1460
C (balsa)	960	1120
D (balsa)	1300$^+$	*
E (C/linked PVC)	510	530
F (linear PVC)	*	2770

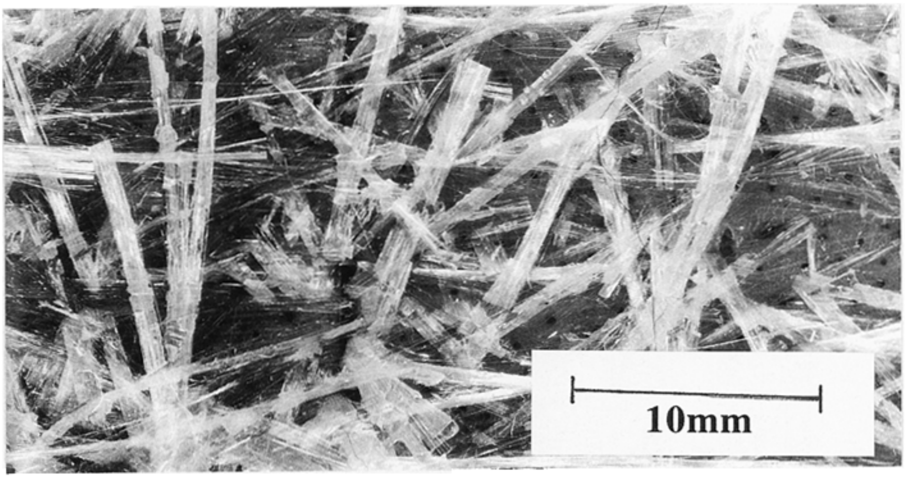
$^+$ = Failure at the skin-fabric interface.
* = Not calculated.

indicated that the amount of fibre bridging occurring during crack propagation was significantly less that in system A.

Of the four GFRP-balsa structures, material C exhibited the lowest value of interfacial fracture toughness. A post-failure examination of the core indicated that the crack had propagated ostensibly within the CSM-skin layer, Figure 6b. Clearly, the fibres in a layer of chopped strand mat are both relatively short and oriented in a random manner. The scope for appreciable amounts of fibre bridging to occur is therefore limited and this may explain the lower value of toughness measured on this material.



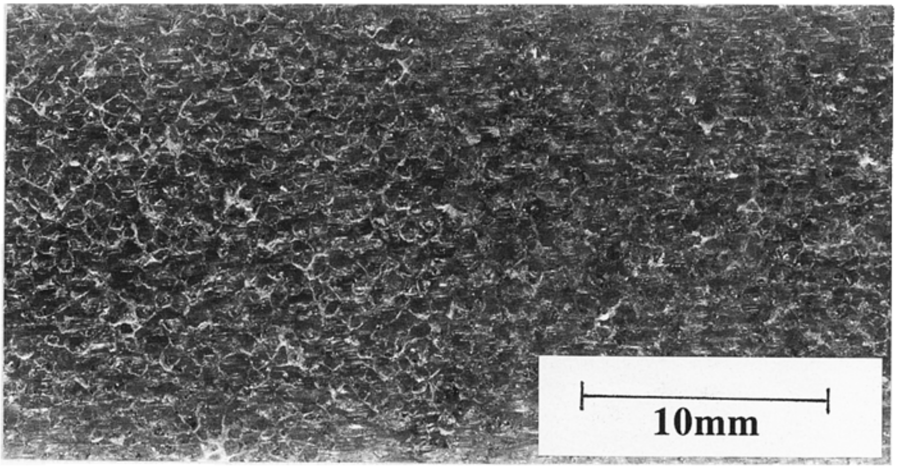
(a)



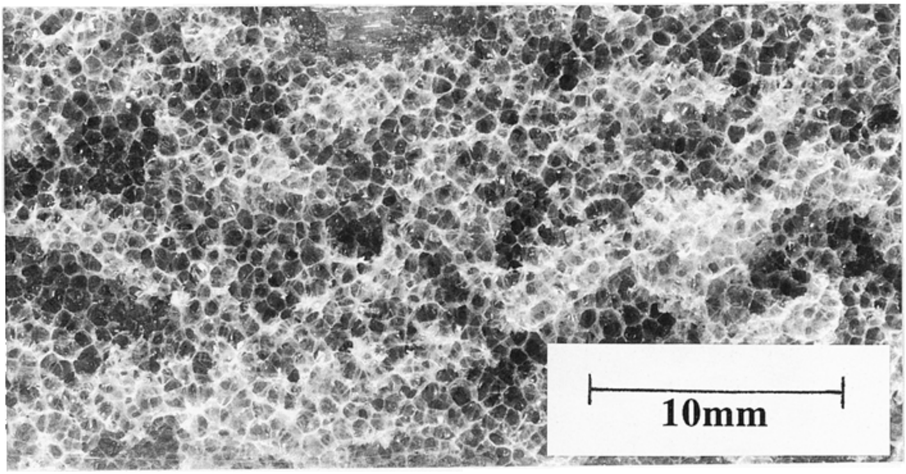
(b)

Figure 6. Fracture surfaces of failed samples: (a) the lower surface of the GFRP skin in material A; (b) the balsa core with remnants of the CSM layer in material C.

Material D contained a layer of thermoplastic polyester fibre fabric between the composite skins and the balsa core. Here, adhesion was so good that the crack propagated up through the fabric layer to and then along the skin-fabric interface. It is not clear why the degree of bonding between the fabric and the core was so high. It may be that some of the thermoplastic fibres infiltrated along with the polyester resin into the balsa core to form a very strong mechanical bond. The fracture toughness of the skin-fabric interface was roughly the same as that measured in material A.



(c)



(d)

Figure 6 (Continued). (c) the GFRP skin from crosslinked PVC system, material E; (d) the GFRP skin from the linear PVC system, material F.

Crack propagation in the crosslinked PVC sandwich structure, material E occurred in a stick-slip mode involving limited amounts of stable crack propagation. Figure 6c shows the lower surface of the GFRP skin following fracture. The right-hand side of the photo shows a region of unstable crack propagation where failure occurred either at or very close to the skin-core interface. The left-hand portion of the photo shows a region in which stable crack propagation occurred. Here, the cellular structure of the PVC foam is more apparent suggesting that fracture took place entirely within the core material.

The linear PVC, material F, offering an interfacial fracture toughness in excess of 2700 J/m^2 proved to be the toughnest of the six systems examined in this study. In most cases, the crack propagated entirely within the foam core as shown on the fracture surface of the composite adherend, Figure 6d.

CLIMBING DRUM TESTS

As a result of the excessive skin thicknesses of the materials C and D, climbing drum tests were only undertaken on materials A, B, E and F. The two balsa-core materials, A and B, as well as the linear PVC system, material F, exhibited a stable mode of fracture. The crosslinked PVC system failed in a mixed stable/unstable mode as was observed during the peel tests reported above. The results of the climbing drum tests are summarized in Table III. Clearly, the linear PVC/GFRP sandwich, material F, offered by far the highest value of specific moment, M. The crosslinked PVC material even though failing in the core rather than at the interface offered a relatively low value of M. The two balsa materials exhibited intermediate values of specific moment. The values for M of the four materials as well as that for another GFRP-linear PVC system are compared with their corresponding values of interfacial fracture toughness in Figure 7. The figure suggests that there is a good correlation between the two fracture parameters. Materials offering higher values of M also exhibited superior fracture toughness properties. One advantage of the peel test over the climbing drum test, however, is that it enabled the interfacial properties of the thick-skinned materials C and D to be characterised.

SHORT-BEAM SHEAR TESTS

In all materials, initial failure occurred between the balsa blocks in the core material extending up to the skin-core interface at higher loads. Figure 8 shows typical force-displacement histories for the four balsa materials. Crack propagation in materials A, B and D was unstable whereas failure in system C containing a layer of chopped glass fibres occurred in stable manner. The resulting shear strength data are summarised in Figure 9. An examination of the data indicates that the average shear strength values for the four materials are quite low (the interlaminar shear strength of the skins is around 30 MPa) and that the scatter

Table III.

Material	Specific moment (Nm/m)
A (balsa)	88
B (balsa)	91
E (crosslinked PVC)	59
F (linear PVC)	162

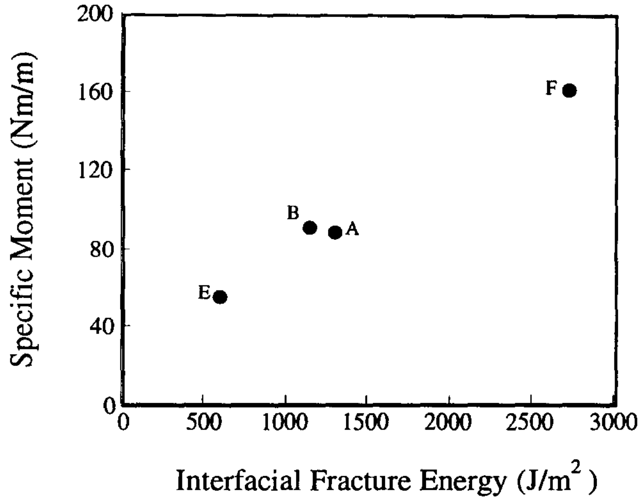


Figure 7. Correlation between the specific moment measured using the climbing drum technique and the interfacial fracture energy determined using the peel test. The letters indicate the particular material.

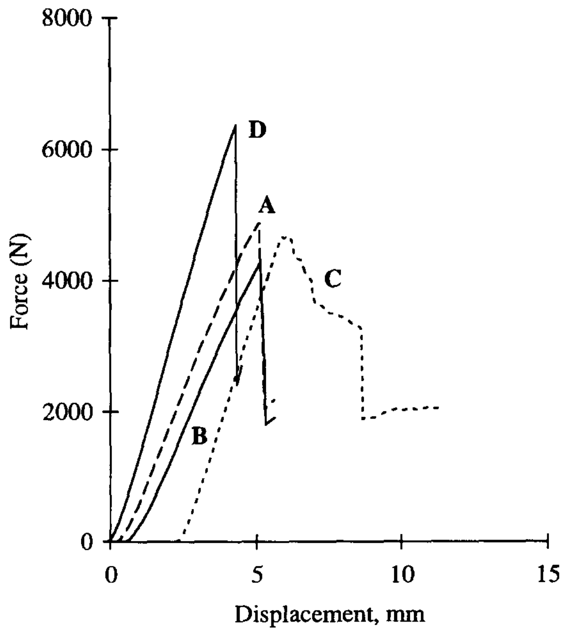


Figure 8. Short-beam shear force–displacement curves for the four balsa materials.

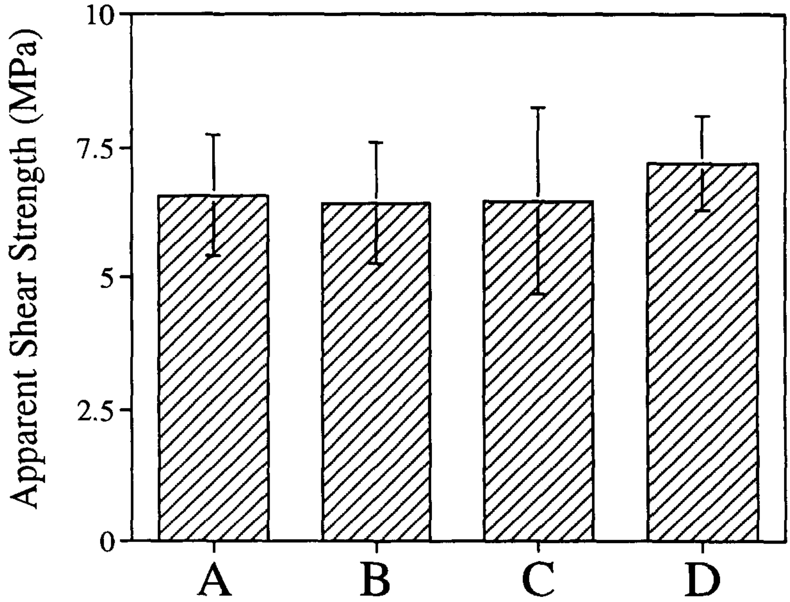


Figure 9. Short-beam shear strengths for the four balsa materials.

is quite large as shear crack initiation depends on the position of joints between blocks. Material D containing the thermoplastic fibre interlayer yielded the greatest value of shear strength, this being in agreement with the observations from the peel tests reported above.

This test is used as a quality control check in shipyards and can indicate problems with a facing-core interface. However, the very different interfaces of the four materials studied here all yielded similar apparent shear strengths so this test is of limited use in more detailed studies of interface behaviour.

Conclusions

A peel test for characterising the interfacial fracture properties of sandwich materials has been presented and applied. The test enables the skin-core properties of a wide variety of both thin and thick-skinned materials to be characterised. It has been shown that the application of a polyester primer to a balsa core can result in an appreciable reduction in interfacial properties. Similarly, the incorporation of a layer of CSM fibres at the interface does not result in any improvement in skin-core bonding. The use of a low density thermoplastic polyester fibre fabric dramatically increased the toughness of the skin-core interface at the expense of increased sandwich weight. The linear PVC-based material exhibited the greatest degree of skin-core bonding. Finally, a good correlation was observed between the results of the climbing drum tests and the interfacial fracture tests suggesting that the latter can be used with confidence to characterise adhesion in lightweight sandwich structures.

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