CMMT(MN)044

Determining the Skin-to-Core Bond Strength of Sandwich Constructions

This Measurement Note discusses on-going work on the development of test methods for evaluating sandwich laminates, in particular the skin-to-core bond properties. The conventional test for measuring the skin-to-core properties of sandwich structures is the climbing drum peel test, ASTM D1781. There are several deficiencies with this test including its inability to deal with thick skinned sandwich constructions typically used in the marine industry. High skin stiffnesses create the same difficulties. Alternative test configurations have been proposed for determining the skin-to-core bond strength of these types of materials. A variety of skin types and thicknesses in combination with Nomex honeycomb and PVC foam cores have been assessed in order to ascertain the robustness and applicability of proposed test methods.

One of the most promising alternative test methods, the Modified 3-Point Bend (MTPB) showed good agreement (for the Nomex honeycomb based materials) with a test method designed for thin skinned constructions, the Centre Notch Flexure (CNF) test. However results did not compare well with those generated using the climbing drum peel test. The CNF test method was unsuccessful when testing the foam based constructions due to unstable crack growth. The comparison of values for the same material system aimed at giving an acceptable level of confidence in the different test methods, has not yet been achieved. The National Physical Laboratory (NPL) and the University of Liverpool, are continuing to collaborate in these developments.

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1 Introduction

The increasing use of sandwich constructions, typically consisting of a low density core bonded to stiff carbon or glass fibre reinforced plastic skins, has fuelled the development of sandwich test methods and standards. A previous review [1] of the most comprehensive set of sandwich test methods (Section 2), the ASTM series, identified the need to develop a test method for determining the skin-to-core interfacial bond strength for sandwich structures consisting of relatively thick, stiff skins typical of those used in marine and other heavy duty applications.

The skin-to-core bond strength has traditionally been measured using the climbing drum peel test [2] where the skin is peeled from the core by being rolled onto a large radius cylinder. However, this test has limitations in that it is only really suitable for sandwich constructions comprising relatively thin, flexible skins and is generally only used to produce qualitative/ comparative results. In addition, the climbing drum peel test is not suited to high rate 'peel' which might be experienced by marine sandwich constructions facing wave slam loading.

The NPL and the University of Liverpool have collaborated in a programme of work to develop alternative methods to the climbing drum peel test. Various sandwich constructions were used in the validation.

2 Review of Sandwich Test Methods

A previous review of the ASTM series of sandwich test methods was carried out at NPL. The tests selected were all short term aimed at characterising the response under shear, tensile, compressive and flexural loads. The objective of the review was to use materials that would expose limitations in the test methods, for example relatively thick glass reinforced plastic skins, very dense or low density core materials, very thick or thin cores, anisotropic cores or skins, and asymmetric skins. The selected materials were chosen from a range of applications including automotive, aerospace and marine. Table 1 details the main comments and recommendations from this review. In addition, a test not in the ASTM series, the multiple flexure test, was identified as an alternative method for determining flexural and shear modulus data and was investigated. The multiple flexure method has been used at NPL and elsewhere previously, but is not standardised. It is primarily used to determine effective flexural and shear moduli for sandwich panels although moduli can also be calculated for the core and skins. The method is based on repeated 3-point elastic loading of a single specimen at different spans and then analysis of the data as straight line plots to yield moduli. A draft procedure has been written at NPL for the multiple flexure test and a round robin study completed to provide validation data. Results from this study show that the method has promise but needs further investigation and refinement.

Table 1 A summary of findings from the previous review of ASTM sandwich test methods

ASTM Standard Test Method	Comments	Recommendations
C273 - Shear Properties of Sandwich Core Materials	• specimen needs to be adhesively bonded to loading plates, • no provision for complementary shear stresses, • peel stresses induced.	• modify present jig to account for complementary shear stresses, • use alternative test method such as ASTM C393 or the flexure/shear classification test method for determination of shear properties.
C297 - Flatwise Tensile Strength of Sandwich Constructions	• ASTM recommended jig design not stiff enough, • bonding of specimens to loading blocks is critical to alignment, • difficulty in bonding thermoplastic matrix skins to loading blocks, • test report requires percentage of failed area of each specimen which is difficult to quote accurately.	• more guidance needed on types of adhesive appropriate to different matrix skins/cores, • re-design loading and bonding jig to improve alignment, • no need to include percentage of failed area of specimens.
C364 - Edgewise Compressive Properties of Sandwich Cores.	• not enough guidance on which type of end support to use for different materials.	• types of end support need to be recommended for different core types.
C365 - Flatwise Compressive Properties of Sandwich Cores.	• strength based on 2% strain value - not appropriate for some foam cores, • measurement of displacement (LVDT through hole in centre of specimen) may weaken specimen.	• use a 10% strain value for determination of strength as in ISO 844 - *"Cellular Plastics - Compression Test of Rigid Materials".*
C393 - Flexural Properties of Sandwich Constructions	• flexural and shear moduli calculated from the results of tests at only 2 spans.	• for measurement of moduli the multiple flexure test could be adopted as an alternative.
D1781 - Climbing Drum Peel for Adhesives.	• test not applicable to thick skinned sandwich structures, • for successful testing of cross ply skinned constructions the ply nearest to the core should not be orientated more than 45° from the loading direction. Otherwise the inner most ply is left on the core.	• a new test is required for thick skinned sandwich constructions, • an additional clause regarding the orientation of cross ply skins to the loading direction needs to be included.

3 The Climbing Drum Peel Test

The climbing drum peel test (ASTM D1781- 93), illustrated in Figure 1(a), is used to determine the peel resistance of the adhesive bond between the relatively flexible skin of a sandwich panel and its core, or between a relatively flexible adherend and a rigid adherend.

Test specimens are typically 76 mm wide by 350 mm long and are machined to have a 25 mm overhang of one skin at each end of the specimen. One end of the overhanging skin is clamped to the top of the apparatus whilst the other is clamped to the drum. The apparatus is configured so that as the test machine crosshead moves down (at a recommended rate of 25.4 mm/min) the drum is rolled upwards, peeling the skin from the core. A typical output trace from the test is shown in Figure 1(b).

Initially the load increases elastically until, ideally, skin/core interfacial fracture is initiated. The load versus displacement trace then levels out as the crack propagates along the skin-to-core interface. The ASTM standard requires that the 'peel strength' is calculated from the measured load as a torque resistance. The value of torque calculated depends on whether compensation has been made for the torque required to simply roll the drum up the apparatus and/or the torque required to roll the skin up.

In Figure 1(b), the drum resistance is shown as 115N, the glass fibre skin trace includes the drum contribution and the Nomex/glass trace includes both the skin and drum contributions. If the 'peel strength' of the adhesive alone is required then the above compensations are required. The peel strength is then the difference between the two torque values.

As the skin thickness and/or the stiffness increases, the torque due to the skin and drum alone increases as a proportion of the total torque measured. The difference between these two values should not fall too low (say, less than 50% of the total torque value) if the test is to maintain sensitivity, particularly if the output trace oscillates as shown in Figure 1(b). In addition, for a skin stiffness or thickness above a critical value, the load required to deform the skin around the drum will exceed the load capability of the jig.

If comparative values between panels are required then as long as the panels are identical no compensation will be required. The test is generally used for comparative purposes rather than for absolute measurements and therefore tends to be regarded as being a process/quality control test.

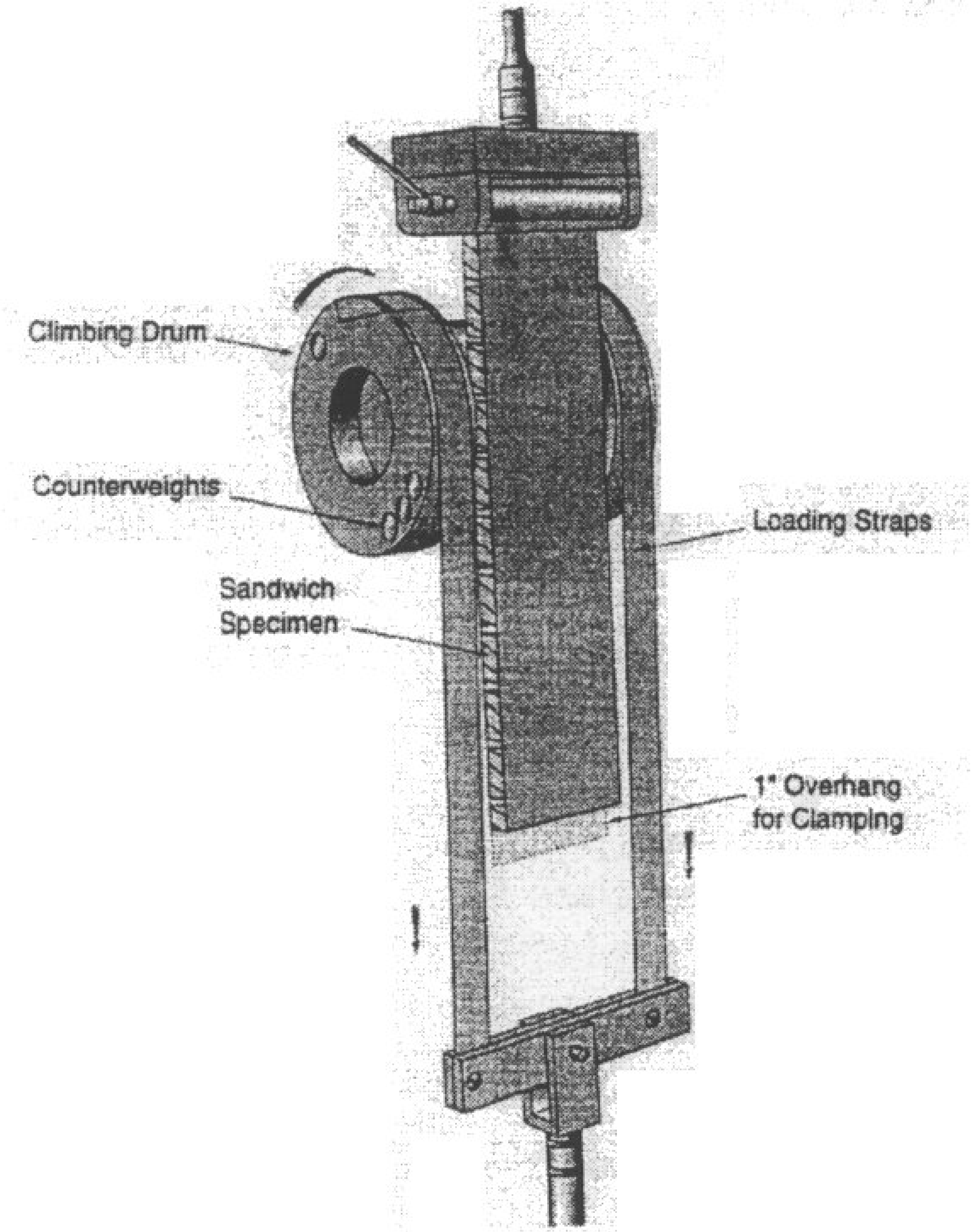


Figure 1 (a) Schematic of climbing drum peel test (ASTM D1781 [2]).

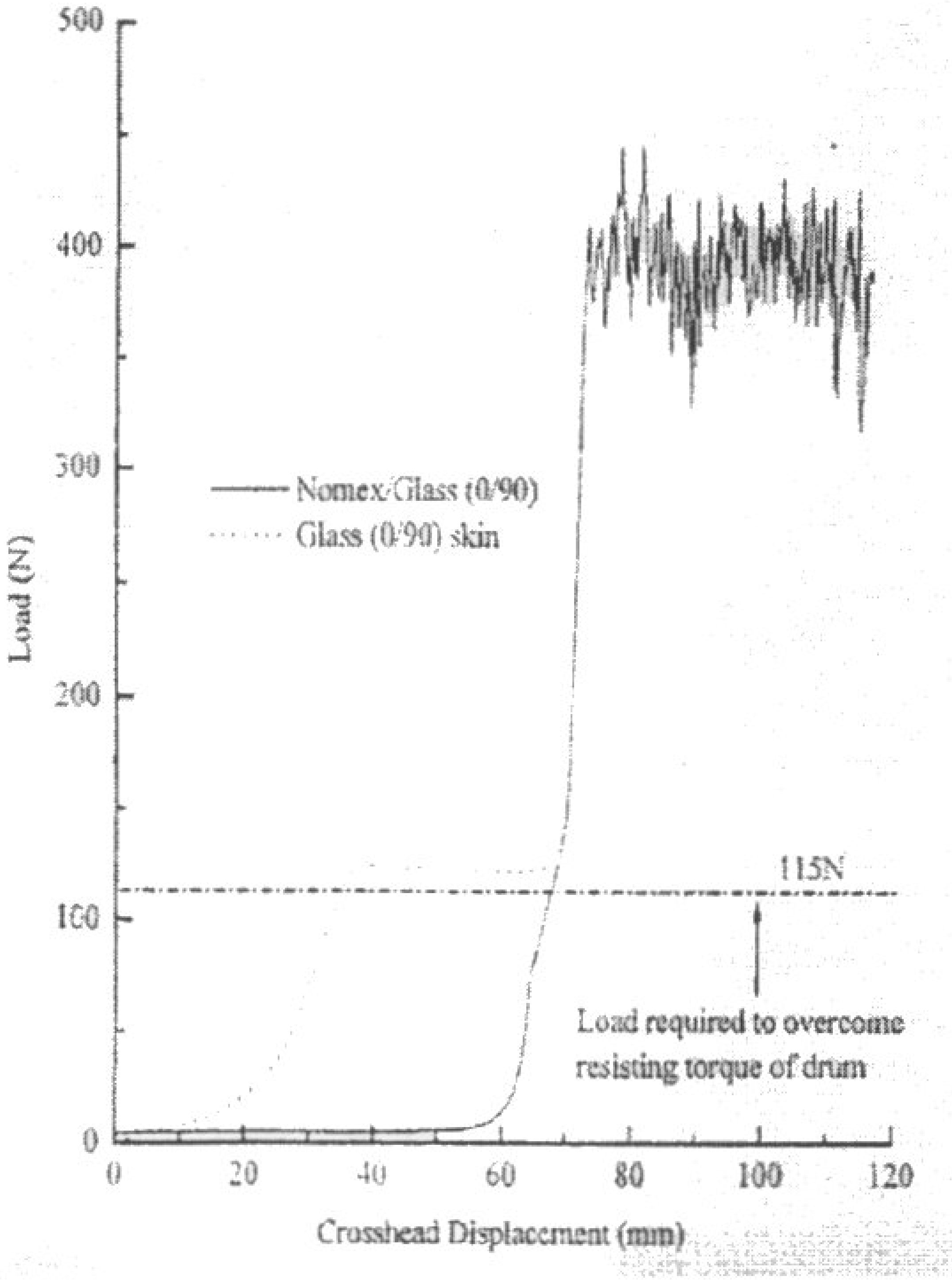


Figure 1 (b) Typical output from the climbing drum peel test for a UD glass fibre skin/Nomex panel.

4 Improvements To Climbing Drum Test Procedure

There are several areas where improvements to the climbing drum test procedure are suggested;

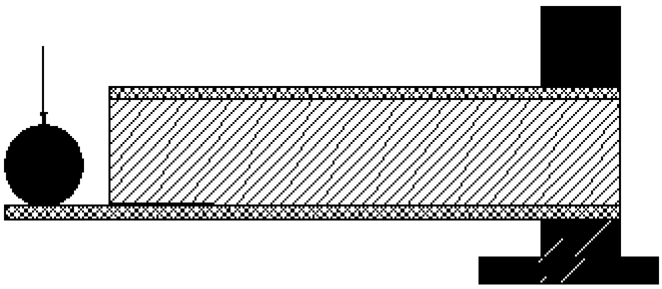
(a) the torque required to deform/roll the skin/drum should be limited to (say) 50% of the total value of the torque required to peel the skin from the core.

(b) the peel load (and consequently peel torque) should be calculated from the raw data using ISO 6133 [3] which gives a procedure for averaging oscillating load curves.

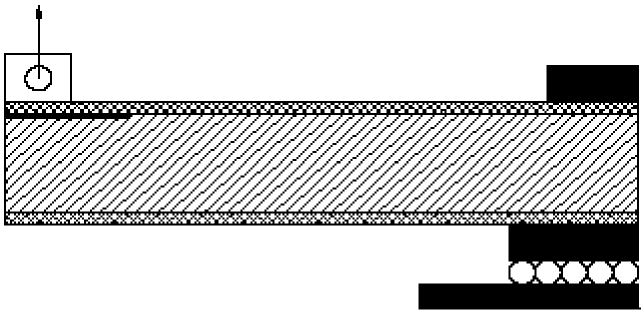
However, the current 'strength' as a torque value is unsatisfactory and an alternative analysis in terms of fracture energy would be preferred that would give improved correspondence with the new tests being developed. Fracture energies would give a better design opportunity, compared to the current 'peel torque' values, without effecting the current quality assurance use of the test.

5 Alternative Test Configurations

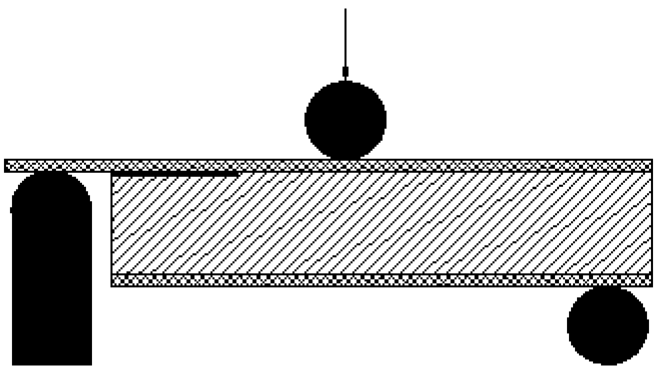
A variety of test configurations for determining the skin-to-core bond strength of sandwich panels have been proposed by various researchers [4, 5]. Some of the most popular geometries studied are shown in Figure 2. It should be noted that many of the test configurations for sandwiches have evolved from adhesive test methods [6] such as that shown in Figure 2(e).



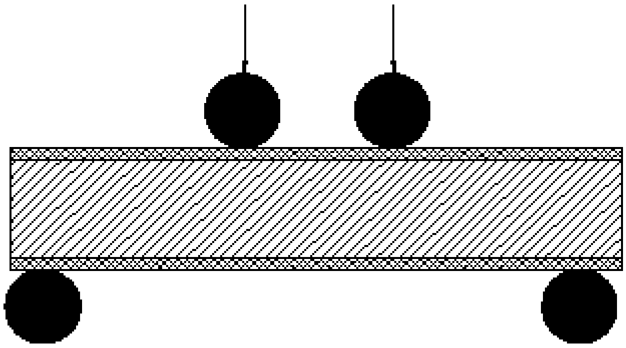
(a) single cantilever sandwich specimen



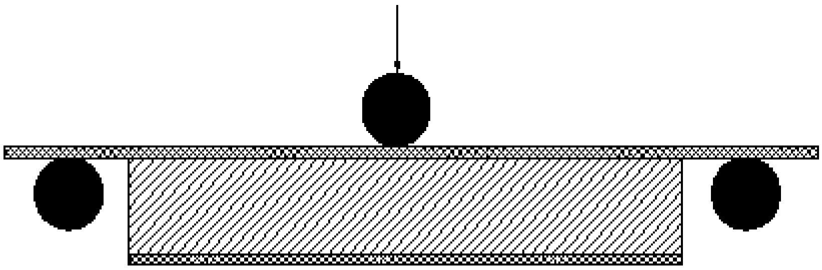
(b) end-loaded sandwich structure



(c) modified three point bend specimen



(d) short beam shear specimen



(e) adhesive test adapted to sandwich specimen

Figure 2 Alternative sandwich skin-to-core bond strength tests.

(a) The Modified 3-Point Bend Test (MTPB)

From previous work [7] the Modified 3- Point Bend (MTPB) configuration (figure 2 (c)) is considered to be a promising test method for sandwich constructions with thick skins and is investigated in this study. In this work, values of fracture energy, G_c, from 400-1000 J/m^2 were measured for four different glass-fibre based skins on the same balsa core. The specimen dimensions for the MTPB configuration are as follows: length=140 mm, span=120 mm and width=25 mm. Each specimen has 30 mm of the lower skin and core removed from one end. The MTPB configuration is preloaded to introduce an initial crack of approximately 10 mm prior to testing. Specimens are loaded at a crosshead speed of 2 mm/minute, and the pre-crack propagated to a desired length. The specimen is then unloaded and an areas method used to calculate values of G_c. The areas method of calculating G_c was used as it is suitable for non-linear as well as linear load-displacement responses.

(b) The Centre Notch Flexure Test (CNF)

The MTPB method, as it stands, is not suitable for sandwich constructions having thin, flexible skins, hence a different configuration must be used. One such configuration has been proposed [8] and is shown in Figure 3.

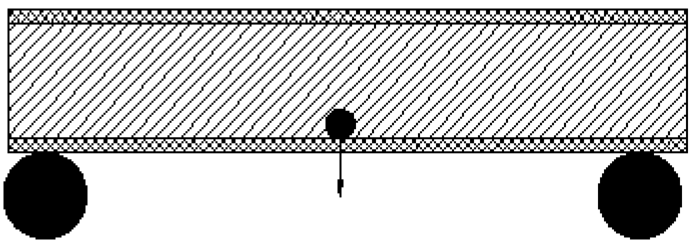


Figure 3 The Centre Notch Flexure (CNF) specimen.

The Centre Notch Flexure (CNF) specimen is a variation of the 3-point bend configuration. A hole is drilled through the core just above the bottom skin of the sandwich and a pin is inserted through the hole and loaded as shown in Figure 3. Like the MTPB test, the CNF configuration is pre-loaded to introduce an initial crack prior to testing. Specimen dimensions and loading speed are the same as for the MTPB test. Unlike the climbing drum peel test, fracture energy data for thin skinned constructions can be calculated from the CNF test which can be compared to MTPB data.

(c) The Flatwise Tensile Test (ASTM C297-94)

In addition to these alternative test methods, ASTM C297-94 'Standard test method for flatwise tensile strength of sandwich constructions' [9], is also considered as this method can be used to determine the bond strength between the skin and core as well as the tensile strength of the core, depending on the relative strengths. That is, the test will fail at the weakest link of core, skin or core-skin interface. It should be noted that this weakest link also applies to the other interface tests. Depending on the system, the interface may be a wider zone than the original physical interface due to, for example, resin impregnation of the core.

For the foam core material, 25 mm x 25 mm square specimens were tested and for the Nomex based materials, 55 mm x 55 mm specimens were used. The specimens were bonded to the loading blocks using a room temperature two part epoxy adhesive. A crosshead speed of 2 mm/min. was used.

6 Materials

Three sandwich constructions were selected for testing (see Table 2). These were: (i) [0°/90°] carbon-epoxy skins with a medium density Nomex core; (ii) [0°/90°] glass-epoxy skins with a medium density Nomex core; and (iii) [±45°] woven glass-polyester skins with a PVC foam core. The materials were supplied as finished panels by Hexcel Composites Ltd. and Vosper Thornycroft (UK) Ltd. respectively.

The thickness of the skins for each of the configurations was chosen with the following rationale in mind. For the climbing drum test to be unsuitable, a skin was considered to be too thick if the torque required to roll the skin up the climbing drum apparatus was more than 50% of the value of the torque required to peel the skin from the core, (see Figure 1(b)). By calculating the force required to bend a skin of a known modulus around a radius of curvature equivalent to that of the drum in the climbing drum apparatus, the thickness of a skin requiring 50% the value of the torque required to peel the skin from the core could be calculated (N.B. the climbing drum skin/core peel strengths for the material systems chosen were known from a previous programme of work [1]). This critical skin thickness was considered to be the border-line "thick/thin" case. Sandwich constructions were chosen with skins of, or as near to this thickness as possible, together with laminates having skin thicknesses less than and greater than this critical thickness. Due to the pre-preg ply thickness and anticipated exotherm difficulties when producing thick epoxy skins, the thickest skin requirements could not always be met and slightly thinner skin constructions were fabricated.

7 Test Regime

The test regime consists of each of the material combinations in Table 2 being evaluated using the following test methods; (i) climbing drum peel test (ASTM D 1781); (ii) flatwise tensile test (ASTM C297); (iii) MTPB test; and (iv) CNF test. It was hoped that by testing the range of skin thicknesses with each test method the advantages and disadvantages associated with each test method will be clear and that the optimum test conditions for thick skinned constructions could be determined.

Table 2 Sandwich constructions and geometries

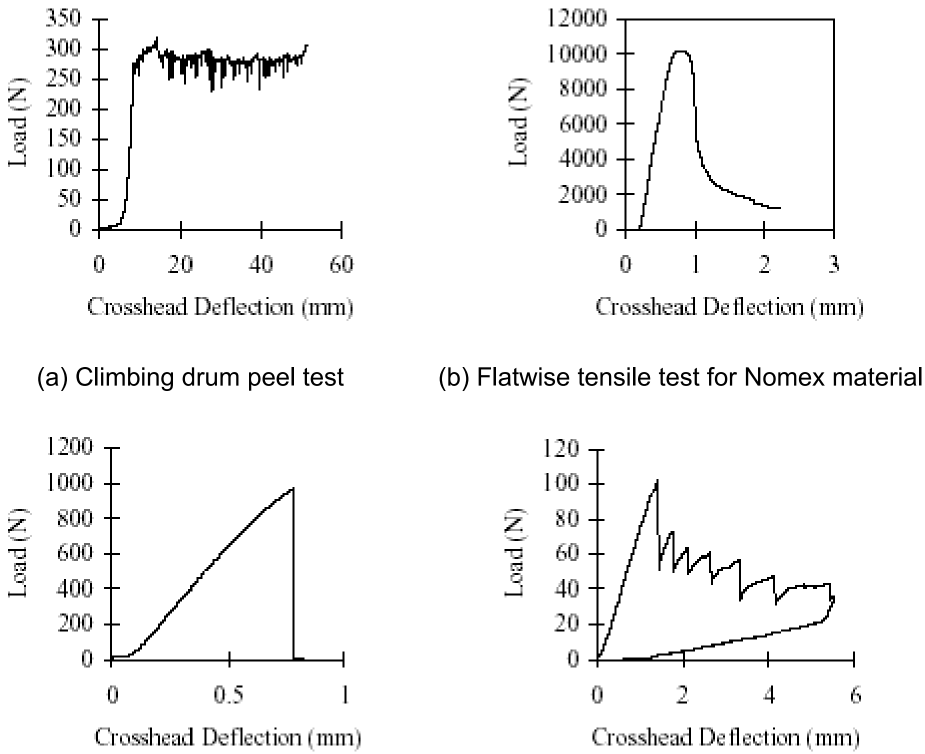
Material	Skin	Core	Skin thickness	Core thickness
A	[0°/90°] UD glass/epoxy	medium density Nomex	~1.1mm	~10mm
B	[0°/90°] UD glass/epoxy	medium density Nomex	~1.8mm *	~10mm
C	[0°/90°] UD glass/epoxy	medium density Nomex	~2.1mm	~10mm
D	[0°/90°] UD carbon/epoxy	medium density Nomex	~0.5mm	~10mm
E	[0°/90°] UD carbon/epoxy	medium density Nomex	~1.0mm *	~10mm
F	[0°/90°] UD carbon/epoxy	medium density Nomex	~1.3mm	~10mm

G	[±45°] woven glass/polyester	PVC foam core	~1.0mm	~30mm
H	[±45°] woven glass/polyester	PVC foam core	~2.0mm *	~30mm
I	[±45°] woven glass/polyester	PVC foam core	~4.0mm	~30mm

(* = critical skin thickness for 50% torque level in ASTM D1781)

8 Results and Discussion

Typical load versus deflection plots for the tests carried out in this study are shown in Figure 4.



(a) Climbing drum peel test

(b) Flatwise tensile test for Nomex material

(c) Flatwise tensile test for foam material

(d) MTPB and CNF for foam material

Figure 4 Typical output traces for tests investigated in this study.

(a) The Climbing Drum Peel Test

Initial tests on materials A-F (Nomex core) resulted in global deformation of the specimens due to the low shear modulus of the core. In order to prevent this, thick backing plates were bonded to the skin not being peeled with a two part room temperature epoxy adhesive. When tested with backing plates, this deformation was avoided and the skin was peeled from the specimen with crack propagation through the core region at a depth corresponding to the tips of the adhesive fillets on the core. Undeformed skins were also tested so that compensation could be made for the load required to roll the skin and drum up the apparatus. As well as the torque values calculated for these tests, a value of G_c was calculated for each specimen by equating the work done by the externally applied load to the energy required to create the resulting fracture surface area. The energy required to bend the skin and the roll the drum up the apparatus was taken into account and compensation was made for this. The values of G_c are shown in Table 3. It can be seen that apart from materials B and C, the G_c values are in good agreement for the climbing drum test. It was observed that the failure region for materials B and C was slightly further into the core region than for the other materials. This would lead to a larger peel force as more core material was removed from the sandwich as the skin was peeled away. The slight change in failure region may have been due to slightly larger adhesive fillets observed on the core.

Results for materials G and H (Table 3) show a significant amount of scatter and do not show good agreement.

Crack growth was unstable and therefore the areas method of calculating G_c is not strictly applicable without addition of a kinetic energy term. Hence the values of G_c quoted in Table 3 are only approximations and should not be compared to other results. Crack growth occurred in a region corresponding to the interface of resin impregnated foam and unimpregnated foam. It was felt that some regions of material had a slightly higher proportion of resin impregnation of the foam than others.

Tests on the skins alone, resulted in higher peel loads than for skins being peeled from the core. This could have been due to a higher proportion of resin impregnation of the core or a variation in skin stiffness/thickness across the panel. Skin only specimens should be machined from the same area of the panel that complete specimens are taken from, and the skins peeled in both the skin only and complete sandwich tests should be from the same facing of the panel. The requirement of having to compensate for the load required to bend the skin and roll the drum, has for this material resulted in a lack of sensitivity for the case where the difference between the peel load of the skin and of the system is small. Material I could not be tested with this method as the load required to bend the skin exceeded the capacity of the jig.

(b) The MTPB and CNF tests.

For materials A to F (Nomex core), it is clear that the fracture energy values achieved with each test method are in fairly close agreement, with material C being the only exception - see Table 3. In addition, the fracture energy values for each panel geometry are in close agreement. This is as expected as all the specimens tested exhibited steady crack growth in the core material in a direction parallel to the skin-core interface.

The composition of the carbon-epoxy skin/Nomex based materials differ only in skin thickness. The same is true for the glass-epoxy skin/Nomex materials. The tests showed that as the skin thickness increases, the load at which crack initiation occurs increases and the displacement at the load application point decreases. With consideration given to linear elastic fracture mechanics, the load required to begin crack propagation increases with skin thickness and hence the stored internal elastic energy at crack growth initiation increases. At the same time, as the skin thickness increases the work done by the applied load will decrease per unit area of crack growth due to more internal elastic energy being stored within the thicker skinned construction. As the crack area produced in the tests was approximately the same for all specimens, the fracture energy would be expected to be constant for constructions of the same core material exhibiting crack growth in the same region. The results for the Nomex based materials verify this as being the case.

Results for the PVC foam based constructions tested in the MTPB configuration show some differences in values for fracture energy. For all specimens, crack growth occurred in a region corresponding to the interface of resin impregnated and unimpregnated core close to the skin/core interface. The crack growth was not as steady as for the Nomex based materials, cracks tended to grow in a stick-slip fashion. Again, for unstable crack growth, the application of an areas method without a kinetic energy term for determination of G_c is not strictly correct and values calculated are therefore only approximations. The values of G_c for materials G and H (see Table 3) show a fairly close agreement but for the 4mm thick skin construction (material I) the value is significantly higher.

Visual examination of the specimens showed that the region of resin impregnated core for material I was significantly larger than for materials G and H. This was thought to be as a result of the fabrication process used and may be the cause of the larger values of G_c achieved. Tests on materials H and I using the CNF test proved unsuccessful with rapid crack propagation along all specimens resulting in removal of the skin from the core. It should be noted here that thick/stiff backing plates were used for both the MTPB and CNF tests to prevent global deformation of the specimens.

(c) Flatwise Tensile Test Results

The flatwise tensile tests are not designed to provide any fracture energy data. However, the test does give an indication of where the weakest link lies within the sandwich laminate. For the Nomex core material, the results show that the weakest link is within the core and not the skin-to-core interface. In these tests failure occurred in the same region as for the MTPB and CNF tests. Similarly the foam core material failed in the core, however the failure initiated in a region corresponding to the interface of resin impregnated and unimpregnated foam, and crack propagation then occurred into the core. Strength values are given in Table 3.

Table 3 Results for MTPB, CNF, climbing drum peel and flatwise tensile tests.

Material	System	G_c (J/m^2)		Climbing Drum	Flatwise Tensile

	(skin thickness, mm)	MTPB (mean, (SD))	CNF (mean, (SD))	(J/m^2) (mean, (SD))	(MPa) (mean, (SD))
A	UD glass/Nomex (1.1)	3073 (113)	2794 (178)	1049 (28.2)	3.305 (0.289)
B	UD glass/Nomex (1.8)	3068 (358)	2679 (127)	1359 (117)	3.754 (0.063)
C	UD glass/Nomex (2.1)	4261 (1147)	2360 (153)	***1294 (81.3)***	3.535 (0.143)
D	UD carbon/Nomex (0.5)	2886 (556)	2787 (340)	1051 (37.8)	3.469 (0.117)
E	UD carbon/Nomex (1.0)	2445 (188)	2807 (421)	1058 (39.7)	3.431 (0.100)
F	UD carbon/Nomex (1.3)	2877 (298)	2732 (448)	***1094 (77.1)***	3.529 (0.040)
G	GRP/PVC foam (1.0)	124 (33.2)	107 (23.9)	58.2 (23.3)	1.527 (0.084)
H	GRP/PVC foam (2.0)	143 (5.5)	×	295 (75.4)	1.497 (0.077)
I	GRP/PVC foam (4.0)	254 (20.1)	×	×	1.716 (0.070)

(i) Results in bold italics are results that would have been impossible to obtain if the maximum desired skin thicknesses had bee n possible to fabricate. Pre-preg ply thickness and exotherm difficulties encountered when making thick epoxy skins necessitated thinner skins to be fabricated.

(ii) Shaded boxes indicate approximate results due to values of G_c being calculated by areas method without kinetic energy term being take n into account. Materials G-I showed unstable crack growth for tests with shaded boxes.

9 Concluding Comments

The work described in this measurement note is still in progress. The climbing drum peel test method for determining the skin-to-core bond strength of sandwich structures has certain limitations, and although the test method can be improved, most beneficially by re-specifying the data analysis calculations and output, it is not suitable for testing thick skinned structures. Table 4 lists some of the advantages and disadvantages of the methods studied.

Table 4 Summary of test methods studied.

Test Method	Output	Comments
Flatwise Tensile Test (ASTM C297-94)	Flatwise tensile strength (MPa) of sandwich constituents depending on weakest kink.	• gives indication of weakest link of sandwich construction, • provides only strength data and no energy based criteria, • small specimens, but need to be adhesively bonded to loading blocks in loading jig, • test alignment critical.
Climbing Drum Peel Test for Adhesives (ASTM D1781-93).	Torque resistance of skin to peel loading. (Nmm/mm)	• large specimens needed, • compensations need to be made for load required to roll skin and drum,

		• tests show non-linear responses, • unsuitable for thick skinned sandwich panels,
MTPB	Fracture energy, G_c, (J/m^2)	• small specimen size, • specimens easy to prepare, • not suitable for thin skinned sandwich panels, although stiff backing plates can assist, • tests show non-linear responses.
CNF	Fracture energy, G_c, (J/m^2)	• small specimen size, • specimens easy to prepare, • not suitable for all materials, • tests show non-linear responses.

Salient comments arising from this study are;

- promising agreement of results was achieved for the Nomex materials using the MTPB and CNF tests. The MTPB and CNF tests were less successful when testing the foam based materials due to unstable crack growth, however this is a property of the material and not the test method,
- thin skinned specimens can be tested using the MTPB test as long as stiff backing plates are used,
- for the tests studied, most load-displacement responses were non-linear. In order to keep the data analysis techniques relatively simple, the areas method was chosen to calculate values of G_c as this method holds for non-linear responses,
- for the foam based materials crack growth was unstable and a more complex data reduction technique is needed to include a kinetic energy term,
- the climbing drum test is recommended as only being suitable for QA purposes as it stands,
- the flatwise tensile test can be used to provide an indication of where crack growth is likely to occur when using these types of test methods,
- agreement between the values of G_c calculated for the MTPB/CNF and climbing drum peel tests is poor. The validity of the areas method used for calculating G_c for the climbing drum peel test needs to be investigated.

10 Recommendations For Further Work

Further work must be undertaken before a new test method can be recommended for standardisation. At this stage of the work it is considered unlikely that a single method could be used to test all sandwich material combinations and geometries. Additional investigation is needed in the following areas to ensure that;

- tests are not excessively non-linear in nature and that relatively simple and universal energy based data reduction techniques can be used,
- the loading conditions produce the desired mode of fracture,
- proposed test methods can be used for high rate tests.

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Determining the Skin-to-Core Bond Strength of Sandwich Constructions
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