

Measurement Note

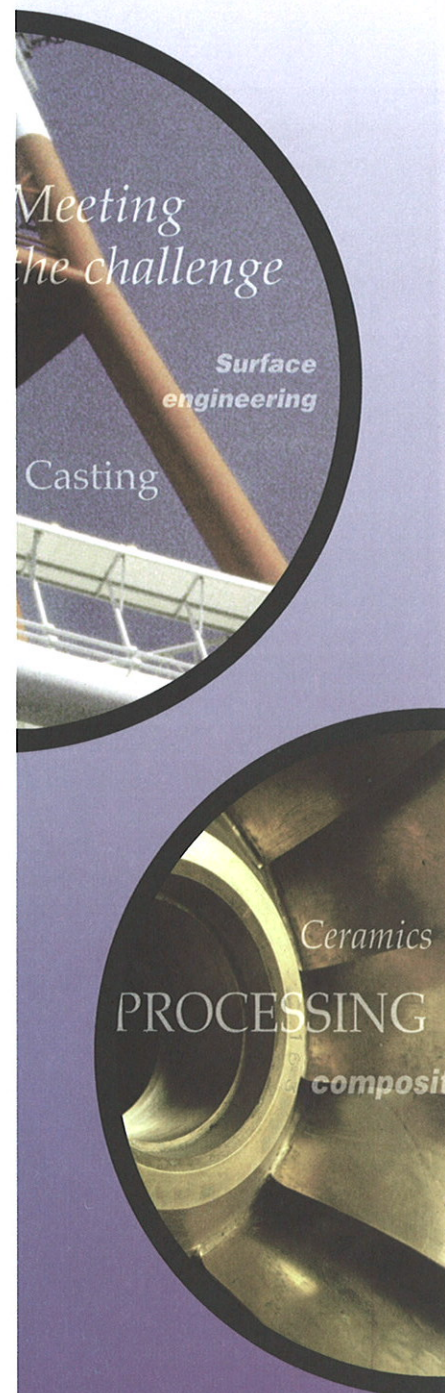
Evaluation of the Repeatability Under Static Loading of a Compression-After-Impact Test Method Proposed for ISO Standardisation

Damage tolerance to non-catastrophic impacts is a major issue for all classes of composite. This is one part of the wider problem of tolerance to damage or manufacturing defects under static or fatigue loads. At present, the most established residual property test is the compression-after-impact (CAI) test, which is well suited to thin, carbon-fibre based aerospace panels failing through minor impact by delamination. The test is conducted by impacting a test panel causing limited or barely visible impact damage (BVID), followed by a separate in-plane compression test on the impacted panel. There are several variations of the CAI test, but concerns still exist over both the range of applicability (e.g. thin panels, thick panels, sandwich structures) and the details of the test (e.g. test geometry, impact energy, method of damage characterisation, etc.). Hence, despite its widespread and routine use, only recently has activity commenced to standardise the test.

This Measurement Note details work undertaken to assess the suitability and repeatability of a compression-after-impact (CAI) test method proposed by the Japanese Plastics Industry Federation (JPIF) for ISO (International Standards Organisation) standardisation. Two carbon fibre-reinforced epoxy material systems were tested and the results indicated good levels of repeatability for both impact and residual compression tests.

M R L Gower, R M Shaw and G D Sims

December 2005



INTRODUCTION

The use of the compression-after-impact (CAI) test method for laminated fibre-reinforced plastic (FRP) materials, particularly where the critical loading mode (compression) is directly linked to the predominant and critical damage type (i.e. delamination), is common within the aerospace industry. Laminated wing skins are typically designed with compression performance as one of the main design drivers. Therefore, compression stress and/or stiffness/strain are key material properties that need to be characterised as they will be significantly affected by the presence of damage within the material.

Low velocity impact events such as tool drop or stone impact, often give rise to local delaminations within laminated composite structures. Even though the impact may be transverse to the laminate, damage often propagates along the planes between adjacent layers since these planes do not benefit from the reinforcing effect of the fibres. Growth of the defect will in many cases occur by extension of the delamination into the surrounding material that may not have been directly affected by the initial impact event.

The CAI method is typically used to compare residual compression properties to critical design values in order to assess the susceptibility of a material to the growth of such delaminations under quasi-static compressive loading.

Despite its widespread and routine use, the standardisation of the method has only just been initiated and several variations exist. A review of CAI test methods was presented in NPL Report CMMT(C)39 [1]. The non-availability of an agreed standard is due to a lack of industry consensus over the choice of test geometry, impact energy level for the CAI test and method of damage inspection and characterisation. However, different versions of the Boeing derived method has gained greatest acceptance and use.

This Measurement Note details work undertaken to assess the suitability and repeatability of a compression-after-impact (CAI) test method proposed by the Japanese Plastics Industry Federation (JPIF) for ISO (International Standards Organisation) standardisation. The proposal is shown schematically in the flow chart of Figure 1 and is favoured by the UK's National Physical

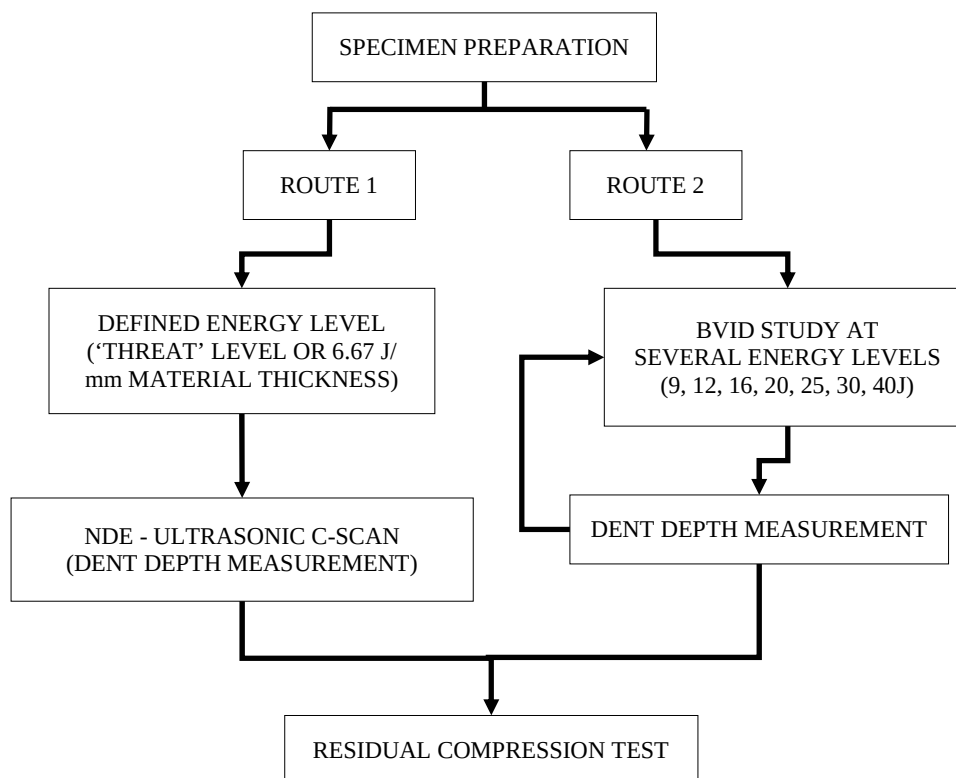


Figure 1 - JPIF proposal for ISO standardisation of the CAI test method

Laboratory (NPL). Initially, only Route 1 will be standardised in ISO, to harmonise with the ASTM approach. Route 2 will be standardised at a later date.

As with all variations of the CAI test method, the proposed method consists of three phases; (i) the impact resistance test; (ii) inspection and measurement of damage; and (iii) measurement of the residual compression strength. Specific details on the various aspects of the JPIF proposal for the CAI method are given in Table 1.

The initial JPIF proposal includes two routes by which the impact resistance and resulting level of damage can be evaluated. For impact resistance, Route 1 allows the user to set a specific impact energy level, which corresponds to the anticipated ‘threat’ energy level from an event, such as a tool drop during maintenance, or a value of 6.67J per millimetre of material thickness. The resulting damage area should then be determined non-destructively by ultrasonic C-scan as well as measurement of dent depth on the impacted face of the material. Route 2 requires the user to determine the impact energy level required

to cause barely visible impact damage (BVID), which is defined as a dent depth of 0.5 mm. This energy level, E_{BVID} , is determined by performing a series of impact tests over a range of energy levels and measuring the resulting dent depths. By plotting impact energy against dent depth, E_{BVID} can be found by interpolation. Route 2 does not place a requirement on the user to determine damage area using ultrasonic inspection. Route 2 agrees with the Airbus approach [2] and their input into the EN Aerospace version of the test.

EVALUATION OF JPIF CAI TEST METHOD PROPOSAL

The following sections provide details on the tests undertaken to assess the suitability and repeatability of the JPIF proposed CAI method. It is noted that the wider assessment offered by Route 2 has been followed for determination of the impact energy.

Materials

Two material systems were tested in this study and were supplied by Hexcel Composites Ltd

Table 1 - Details of Recommended CAI Method

Variable	Proposed detail		Comment
	Route 1	Route 2	
Test machine	Drop weight tower (instrumented)		Provides detail of impact event throughout
Support	Steel base plate with 75 mm x 125 mm cut-out		
Specimen	150 x 100 x ~4 mm		
Clamping	Specimen centrally positioned over cut out in base plate and held flat (not clamped) with four toggle clamps.		No allowance for lifting of specimen corners
Indenter	16 mm diameter hemispherical steel		
Impact energy	Defined energy level e.g. equivalent to perceived threat, 6.67J/mm thickness	9, 12, 16, 20, 25, 30, 40J. BVID energy determined for 0.5mm dent depth	Representative of tool drop or stone impact
Inspection	Ultrasonic C-scan (plus also measure dent depth)	Measure dent depth	Investigates relationship between dent depth and delamination area
Compression	Specimen edges simply supported in compression jig Loaded at 0.5 mm/min to failure		

Table 2 - Details of Materials Used in CAI Tests

Material	Supplier	Generic Description	Measured Fibre Volume Fraction V_f (%)
1	SP Systems	- unidirectional carbon fibre-reinforced epoxy - autoclave cured - quasi-isotropic lay-up $(+45/0/-45/90)_{2s}$	57.2
2	Hexcel		56.5

and SP Systems Ltd as industry co-funding contributions to the project. Both materials were unidirectional (UD) carbon fibre-reinforced epoxy pre-pregs.

The material systems used and measured fibre volume fractions are detailed in Table 2.

Panel and specimen preparation

Test panels were manufactured at NPL according to the fabrication method given in [2] and following material supplier's guidance. All panels were autoclave cured at 125°C for 1 hour (3°C/minute ramp at 7 bar). The lay-up of the panels was quasi-isotropic $(+45/0/-45/90)_{2s}$. Specimens were extracted from test panels in accordance with [4] (additional guidance on machining operations is given in [5]). Machining operations were performed using a Bennett diamond grit coated circular saw, with water used as a coolant/lubricant.

Phase 1 - Impact resistance

For the impact resistance tests, rectangular specimens (100 x 150 x ~4 mm) were supported on a steel base plate containing a 75

mm x 125 mm cut out (Figure 2). Specimens were centrally placed over the cut out region and four toggle clamps with rubber tips were used to hold the specimens flat against the test jig. The impact support plate was positioned centrally under the aperture of a Rosand IFW5 drop weight impact tower and a series of impact tests were performed over a range of energy levels (9, 12, 16, 20, 25, 30, and 40 Joules). Prior to performing the impact tests the force transducer on the instrumented indenter was calibrated according to a method previously developed at NPL [6] (recommended in ISO 6603-2 [7] and used for UKAS calibrations). The drop mass and height were varied in order to give the correct level of impact energy. Each impact test was performed on a separate specimen and a second strike prevention device was employed to ensure that specimens received only one impact. Impact energy versus dent depth (see Phase 2 for details on how dent depths were measured) plots were used to determine E_{BVID} (energy to cause a dent depth of 0.5 mm) and a further 5 impact tests were then undertaken at this energy level.

Phase 2 - Inspection and measurement of damage

After impact and an initial visual inspection, specimens were further inspected to determine the depth of the dent caused by impact and damage area (i.e. delamination). The techniques used for determining dent depth and damage area are described in the following sections.

Dent depth: A laser profilometer was used to measure dent depths. The set-up is shown in Figure 3. Measurements were made immediately after impact and also 24 hours later to assess the effects of relaxation of the materials. For both materials the impact energy to cause a dent depth of 0.5 mm was

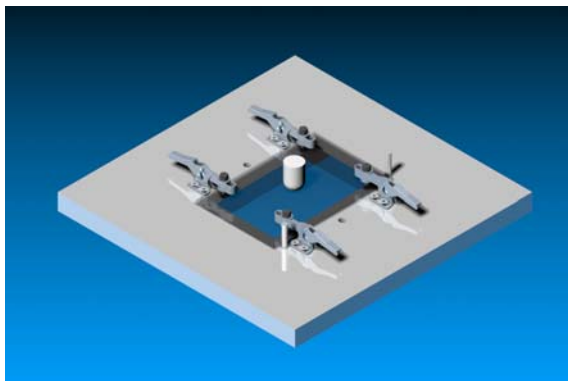


Figure 2 - Schematic of impact support plate for CAI tests



Figure 3 - Laser profilometer apparatus used for dent depth measurements

found by interpolation of plots of measured dent depth versus impact energy. This level of energy is defined as the energy to cause barely visible impact damage (E_{BVID}).

Damage area: A double through-transmission method was used to inspect all specimens and provide a measure of damage area. In this inspection mode, a single transmitter-receiver transducer scans along the material surface capturing signals that have propagated through

the specimen twice (Figure 4). The specimen is supported above a flat glass reflector plate and the inspection area, transducer and reflector plate are fully immersed in water. A short ultrasonic pulse passes through the specimen, normal to the surface, is reflected by the reflector plate and travels back through the specimen again to the transducer. The reflected signal is captured, amplified and displayed on an oscilloscope and the amplitude is measured and recorded.

Using the double-through transmission approach enhances the detection of near-surface flaws by directly monitoring the amplitude of the back-surface reflection rather than monitoring intermediate signals between the front and back reflections. The presence of a near-surface discontinuity will result in a reflected signal, and thus a reduction in energy of the transmitted pulse that propagates to the reflector and back. This effectively reduces the amplitude of the reflection.

The damage area was determined by measuring that area of the specimens which had a level of attenuation 6 dB below the average attenuation level of non-impacted material. This level corresponds to a signal loss of ~50%. This method of measuring the damage area is detailed in NPL developed procedures [8].

Phase 3 - Residual Compression Tests

Prior to conducting the compression tests, all impacted specimens were strain gauged in order to monitor the degree of bending during compression loading. Pairs of strain gauges were bonded to specimens in locations shown in Figure 5. CAI tests were then undertaken using the test rig shown in Figure 6. The JPIF proposal recommends the use of strain gauges to check the alignment and degree of bending of specimens, but it does not provide a value for the allowable level of bending. Therefore, guidance was taken from BS EN ISO 14126 [9], i.e. bending is acceptable if the difference between strains recorded on each face of the specimen throughout the duration of the test is less than or equal to 10%. This criterion is fairly strict especially when one considers that the percentage error in strain readings at low strain levels is higher than at higher strain levels and that immediately prior to failure

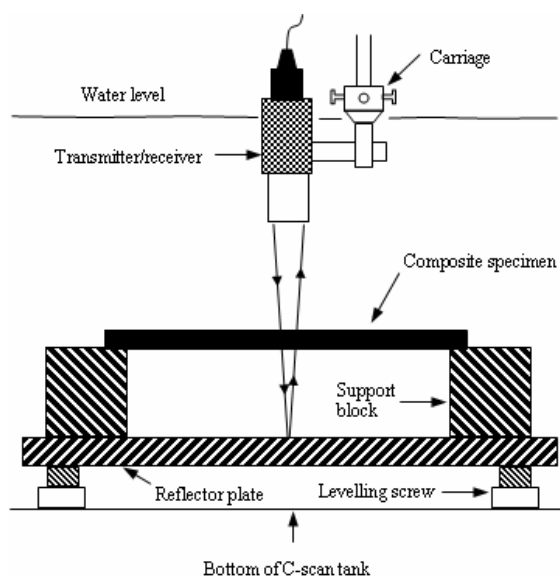


Figure 4 - Ultrasonic C-scan double through-transmission method (immersion)

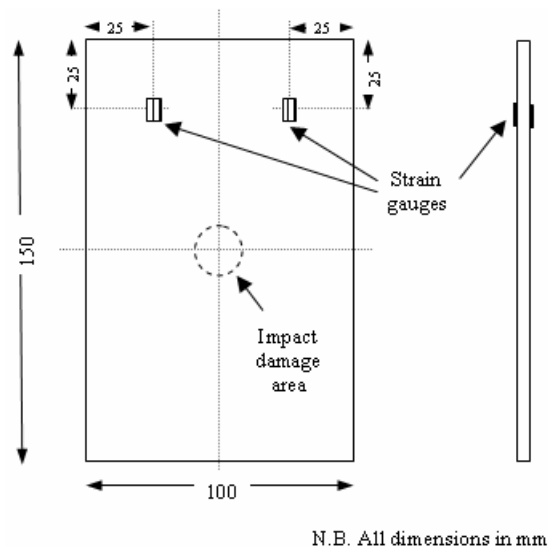


Figure 5 - Position of strain gauges on impacted test panels

strain readings often diverge drastically as the material starts to deform. Consequently, the bending criterion was relaxed slightly so that the difference in strain readings was only required to be less than or equal to 10% between 10 and 95% of the compressive failure stress. This modification is being considered for the BS EN ISO compression standard [9].

After careful positioning in the test rig (see Figure 6), vertical alignment was ensured using a spirit level and successful alignment checks of the jig made. Specimens were tested

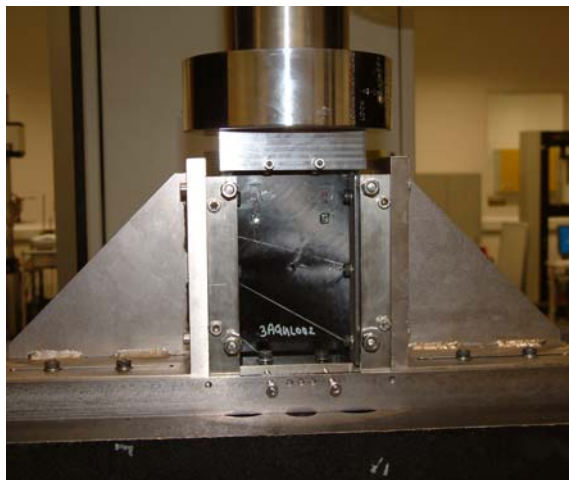
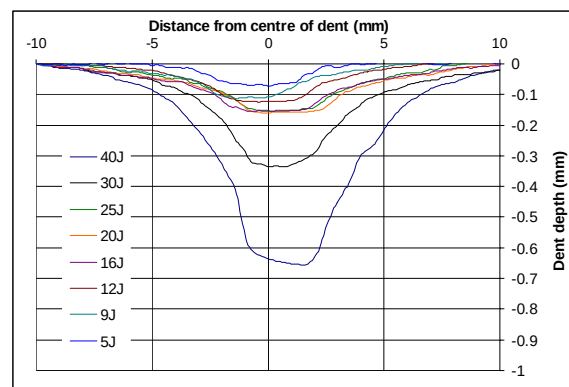


Figure 6 - CAI test apparatus

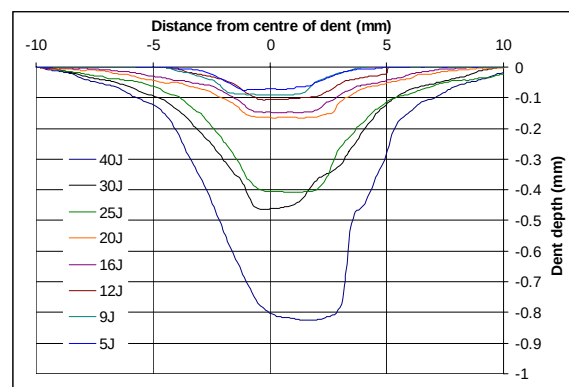
to failure at a crosshead displacement rate of 0.5 mm/minute. The CAI strength was calculated from the maximum load divided by the nominal specimen cross sectional area.

RESULTS

Immediately after impact (t_0) the dent depths for all panels were measured with the laser profilometer. Where possible the dent depths were also measured 24 hours later to determine the degree of relaxation of the material. Dent depth profiles are shown in Figure 7 indicating the increasing depth and extent of dent with impact energy. Example dent depth plots obtained using the laser profilometer are shown in Figure 8. In general the dent depth results shown in Tables 3 and 4 indicate that relaxation of both materials does occur, but that the degree of relaxation is quite small (~ 0.02 - 0.03 mm for a 40 J impact).



(a)



(b)

Figure 7 - Dent depth profiles for (a) material 1 and (b) material 2

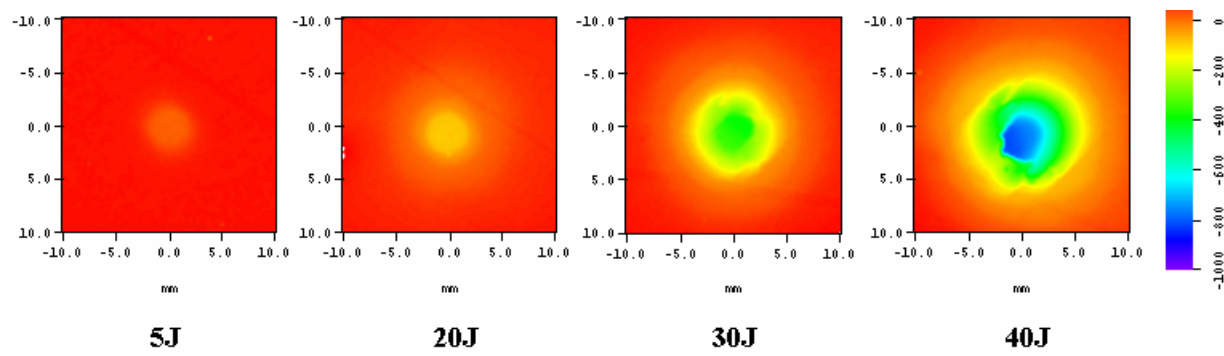


Figure 8 - Laser profilometer dent depth plots for Material 2

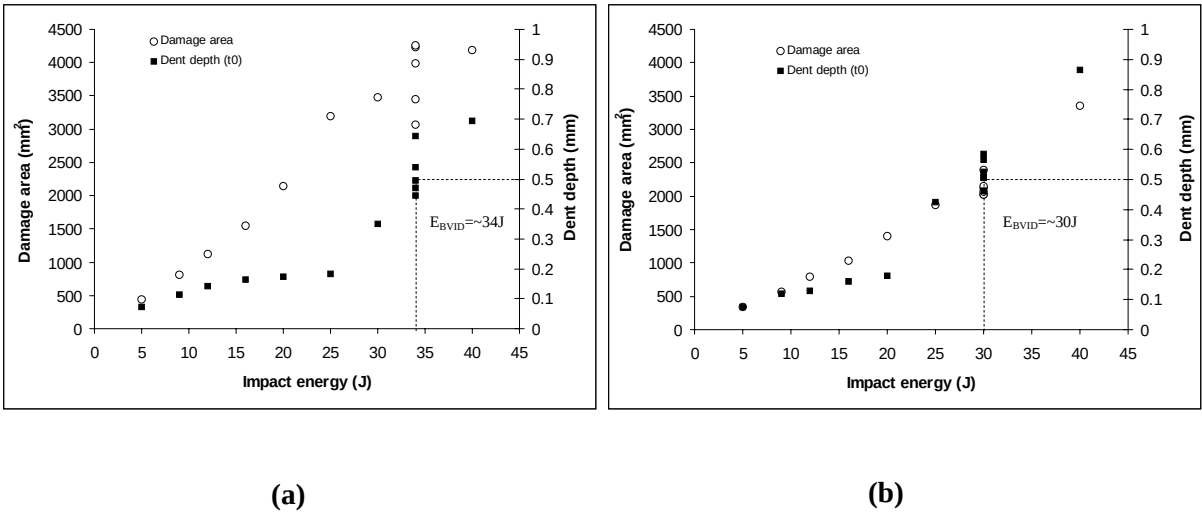


Figure 9 - Dent depth and damage area results for; (a) Material 1 and (b) Material 2

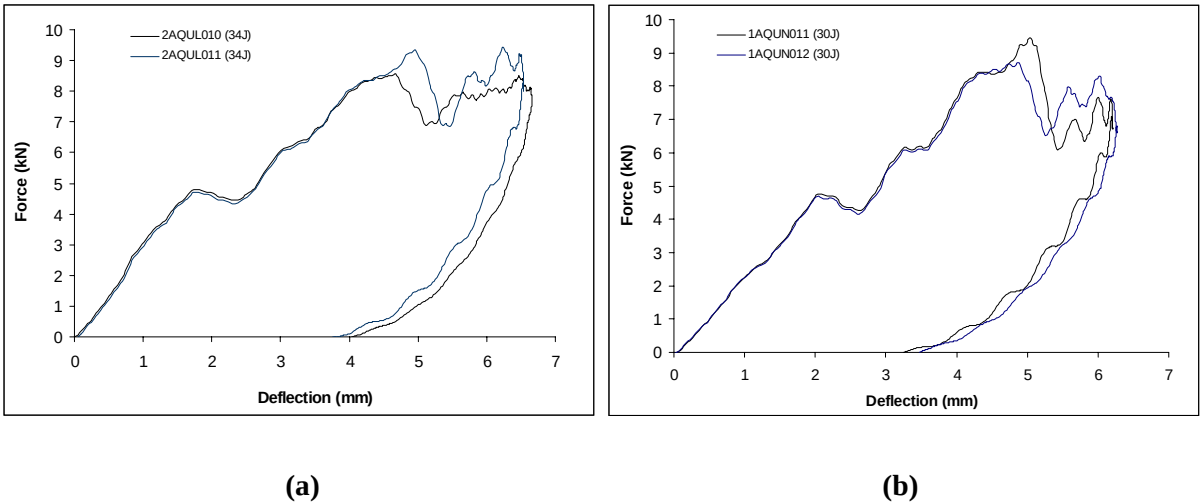


Figure 10 - Force vs. deflection for BVID energy level impacts; (a) Material 1 and (b) Material 2

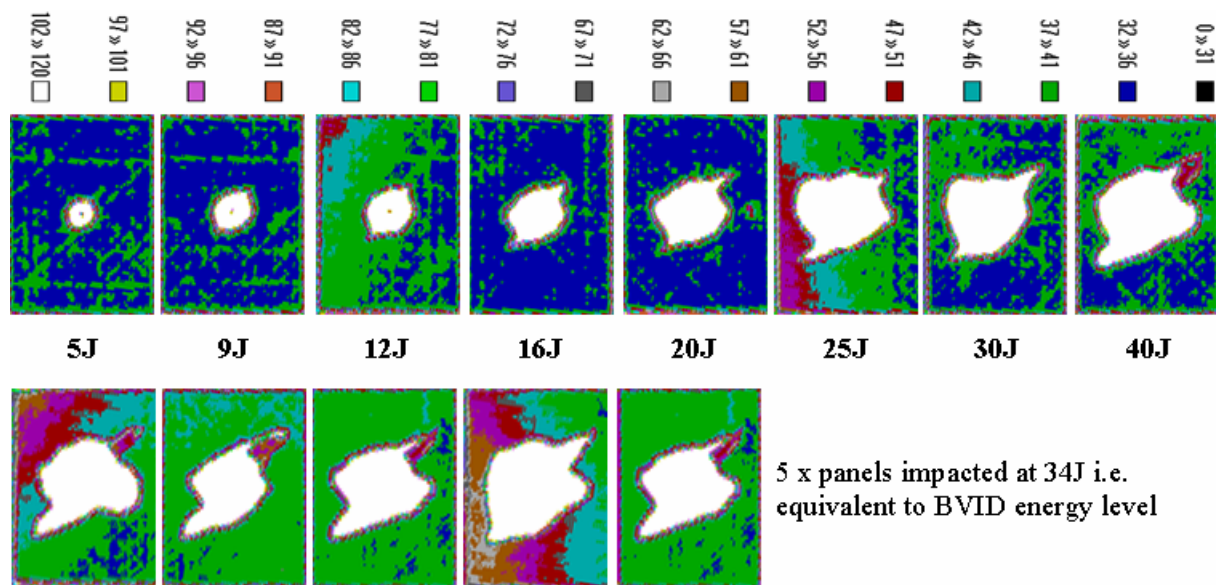


Figure 11 - Damage as determined by ultrasonic C-scan inspection for Material 1

In order to determine E_{BVID} , plots of dent depth (at t_0) versus impact energy were constructed (Figure 9) and the energy corresponding to a 0.5 mm dent depth was found by interpolation (E_{BVID} for Material 1 was ~34 J and ~30J for Material 2). Five further impacts per material were performed at these E_{BVID} energy levels. It is noted that if Route 1 had been followed in order to determine impact energy (i.e. 6.67J per material of material thickness) then the energy level for Material 1 would have been ~32J and for Material 2 ~28J). Examples of force-

deflection impact traces are shown in Figure 10 for both materials. In general, the impact tests showed good levels of repeatability and the coefficient of variation in peak force was less than 6% for both materials. After impact, all panels were ultrasonically C-scanned and the damage areas measured (Figures 11 and 12, Tables 3 and 4). One or two of the C-scan images in Figure 11 show considerable changes in colouration, however this was found to be due to the panels not lying flat on the glass reflector plate rather than due to damage. It was noted that at E_{BVID} , all panels

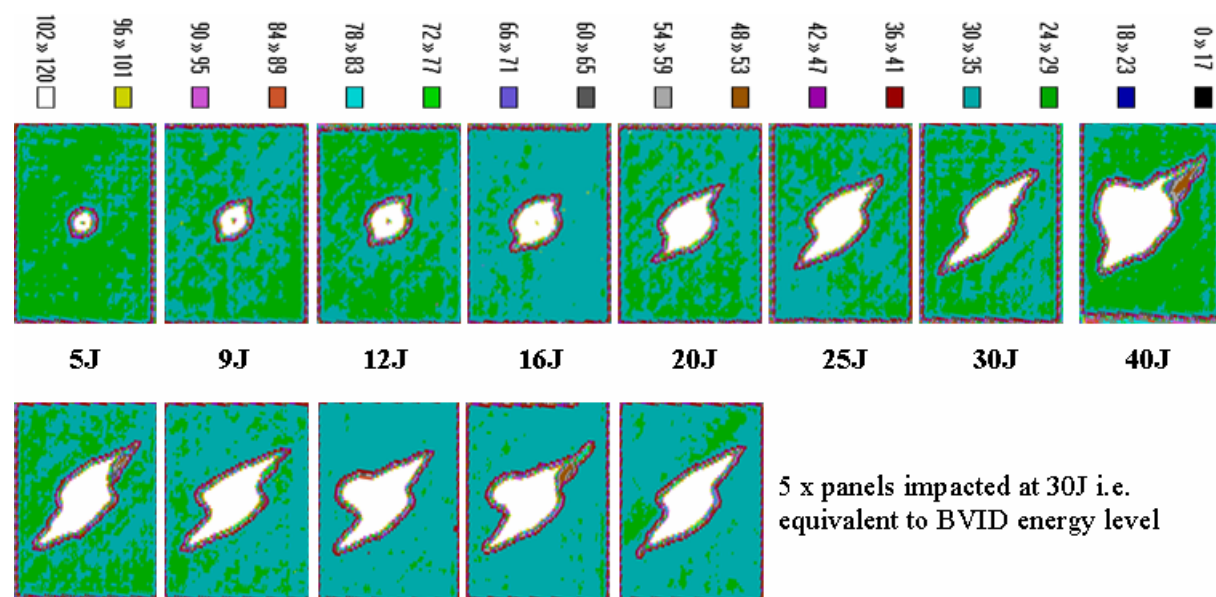


Figure 12 - Damage as determined by ultrasonic C-scan inspection for Material 2

Table 3 - Results for Material 1

Specimen	Impact Energy (J)	Peak Force (kN)	Dent Depth (mm)		Damage Area (mm ²)	Failure Strain (%)	CAI Strength (MPa)
			t ₀	t _{+24hrs}			
2AQL001	5	4.430	0.073	-	441	0.69	294
2AQL002	9	5.549	0.113	-	814	0.53	241
2AQL003	12	6.547	0.142	0.137	1118	0.53	228
2AQL004	16	7.493	0.165	0.159	1542	0.49	217
2AQL005	20	8.954	0.175	0.166	2147	0.41	183
2AQL006	25	9.814	0.183	0.173	3195	0.34	147
2AQL007	30	9.239	0.350	0.332	3481	0.31	139
2AQL008	40	9.561	0.694	0.666	4186	0.28	128
BVID Impact Tests - Impact Energy of 34 J							
2AQL010	34	8.554	0.644	-	3064	0.36	160
2AQL011	34	9.439	0.540	-	3446	0.32	145
2AQL012	34	9.918	0.446	-	4230	0.29	134
3AQL001	34	9.731	0.495	-	4263	0.29	137
3AQL002	34	9.828	0.469	-	3984	0.30	141
<i>Mean</i>		9.494	0.519	-	3797	0.31	143
<i>Standard deviation (±)</i>		0.555	0.078	-	524	0.03	10.2
<i>Coefficient of variation (%)</i>		5.9	15	-	14	9.5	7.1

Table 4 - Results for Material 2

Specimen	Impact Energy (J)	Peak Force (kN)	Dent Depth (mm)		Damage Area (mm ²)	Failure Strain (%)	CAI Strength (MPa)
			t ₀	t _{+24hrs}			
1AQN009	5	4.063	0.077	-	345	0.70	309
1AQN001	9	5.304	0.120	0.101	571	0.60	270
1AQN002	12	6.290	0.130	0.109	798	0.59	265
1AQN004	16	7.386	0.161	0.158	1027	0.56	252
1AQN005	20	8.675	0.178	0.172	1407	0.45	211
1AQN006	25	9.218	0.423	0.414	1866	0.39	182
1AQN007	30	8.551	0.505	0.474	2025	0.39	179
1AQN008	40	9.255	0.866	0.844	3356	0.35	160
BVID Impact Tests - Impact Energy of 30 J							
1AQN007	30	8.551	0.505	-	2025	0.39	179
1AQN010	30	9.159	0.524	-	2390	0.38	173
1AQN011	30	9.451	0.463	-	2124	0.38	176
1AQN012	30	8.700	0.584	-	2152	0.40	185
2AQN002	30	8.571	0.566	-	2073	0.39	181
<i>Mean</i>		8.886	0.528	-	2153	0.39	179
<i>Standard deviation (±)</i>		0.400	0.048	-	141	0.01	4.6
<i>Coefficient of variation (%)</i>		4.5	9.1	-	6.6	2.2	2.6

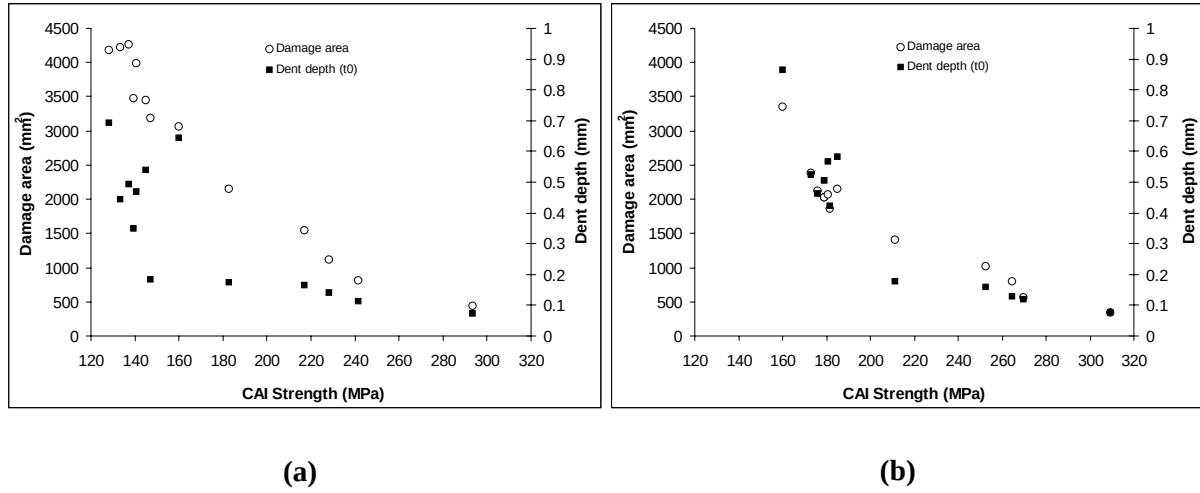


Figure 13 - CAI strength against dent depth and damage area results for;
(a) Material 1 and (b) Material 2

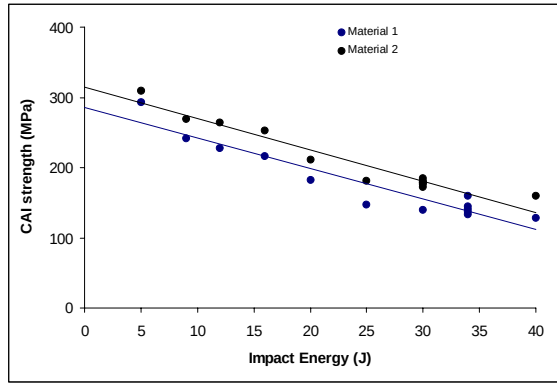


Figure 14 - CAI strength versus impact energy

exhibited considerable back face damage, including ply splitting and delamination, whilst the impacted surfaces of the panels all sustained fracture of the surface ply at the bottom of the dent. The variations in dent depth and damage area indicate a lesser degree of repeatability and this is reflected in the lack of agreement between force-deflection traces after peak force has been reached (Figure 10). In general, whilst damage area and dent depth increased with increasing impact energy, there was no clear trend between dent depth and damage area.

The CAI strength and failure strain results are detailed in Tables 3 and 4. The strength results are plotted as a function of dent depth and damage area in Figure 13 and impact energy in Figure 14. All specimens failed

catastrophically under compression loading by growth of delaminations across the width of the panels perpendicular to the loading direction. Failure strength and strain results showed good levels of repeatability - less than 10% for strain and 7.1% for strength.

CONCLUSIONS AND FURTHER WORK

The results of this study have evaluated the suitability and repeatability of the JPIF proposed CAI method. A number of salient conclusions can be drawn from the work undertaken:

- The JPIF method provides the user with the option of choosing how to set the impact energy, i.e. Route 1 or 2. The results have shown that levels of E_{BVID} determined by Route 2 were in fairly close agreement with those calculated from setting the impact energy to 6.67J/mm (Route 1).
- It is considered that the 0.5 mm dent depth corresponding to a level of barely visible damage is too large as for both materials fracture of the top ply occurred in the bottom of the impact dent. Considerable back face damage was also observed at this energy level.
- In general, there was no discernible correlation between dent depth and damage area.

- The impact and residual compression tests showed good levels of repeatability despite a large amount of scatter in dent depths and damage area.

Although the repeatability of the JPIF proposed CAI method has been assessed in this work, the reproducibility (i.e. the variation in results obtained between different test sites) needs to be investigated. An international round-robin (to be led by NPL) aimed at generating reproducibility data is planned as part of further work within project F12 - "Development of test methods for determining the criticality of defects in composite materials systems under long-term loading". In addition it is emphasised that whilst the CAI is currently used for static testing, in reality damage is more likely to propagate to a large size, or catastrophically, under a long-term cyclic load rather than a one-off static overload. Therefore work is also being undertaken within project F12 to assess the suitability of the CAI test method for fatigue loading.

REFERENCES

1. Gower, M.R.L. and Sims, G.D., "Damage Tolerance Testing of Composites: A Standard Procedure for the Introduction of Impact Damage", NPL Report CMMT(C)39, October 1998.
2. AITM 1.0010 - Fibre Reinforced Plastics - Determination of Compression Strength After Impact.
3. BS ISO 1268 Plastics - Preparation of Glass Fibre Reinforced, Resin Bonded, Low-Pressure Laminated Plates or Panels for Test Purposes.
4. BS EN ISO 2818 Plastics - Preparation of Test Specimens by Machining.
5. Davies, A., Foreman, A., Shaw, R. and Sims, G.D., "Fibre Reinforced Plastic Composites - Machining of Composites and Specimen Preparation", NPL Measurement Good Practice Guide N^o 38, 2001.
6. Money, M.W., and Sims, G.D., "Calibration of Quartz Load Cells; An In-Situ Procedure for Instrumented Falling Weight Impact Machines.", Polymer Testing 8, 1989, 429-442.
7. ISO 6603-2, Plastics - Determination of Puncture Impact Behaviour of Rigid Plastics, Part 2: Instrumented Puncture Testing.
8. prEN 1330-4 European Standard on Non-Destructive Testing - Terminology - Part 4: Terms Used in Ultrasonic Testing.
9. BS EN ISO 14126 Fibre-Reinforced Plastic Composites - Determination of Compressive Properties in the In-plane Direction.

ACKNOWLEDGEMENTS

The research reported in this Measurement Note was carried out at NPL as part of the Performance Programme funded by the United Kingdom Department of Trade and Industry (National Measurement System Directorate). The authors would like to express their gratitude to the Industrial Advisory Group, and colleagues Bill Broughton and Bruce Duncan.

For further information contact:

Mr Michael Gower
 Process Materials Group
 Division of Engineering and Process Control
 National Physical Laboratory
 Queens Road, Teddington
 Middlesex
 TW11 0LW
 Telephone: 020-8977 3222 (*switchboard*)
 Direct Line: 020-8943 8625
 Facsimile: 020-8943 6177

© Crown Copyright 2005. Reproduced by permission of the Controller of HMSO.