

Measurement Note

DEPC-MN 048

Assessment of a Compression-After-Impact (CAI) Test Method for Fatigue Loading

The well established but non-standardised compression-after-impact (CAI) test method is suitable for determining the residual compression strength for thin carbon fibre-reinforced plastic (CFRP) composite panels typically used in aerospace applications. For this type of material the governing type of impact damage is delamination that can propagate under compression loads. Traditionally, CAI tests have been performed under static loading i.e. the damaged panel is loaded in-plane at a slow rate until failure. However, this loading is not totally realistic as the component is likely to experience fatigue loading rather than, or before, a static overload. The damage is more likely to propagate to a large size, or catastrophically, under a long-term cyclic load rather than a one-off overload.

This Measurement Note details work undertaken to assess the suitability and practicality of adapting the static CAI test method for use under fatigue loading. The work characterises the CAI fatigue performance of two carbon fibre-reinforced epoxy material systems and provides a comparison to the plain compression fatigue response. The use of pulse thermography for monitoring damage growth is also detailed.

The results of the study have indicated that the CAI method can be successfully used under fatigue loading. Minimal changes in compressive stiffness of CAI fatigue specimens was observed until immediately prior to failure. In addition, pulse thermography was successfully used as a technique for real-time damage monitoring.

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

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INTRODUCTION

The use of the compression-after-impact (CAI) test method for laminated fibre-reinforced plastic (FRP) materials, 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 (or plain compression properties) in order to assess the susceptibility of a material to the growth of such delaminations under quasi-static compressive loading.

Traditionally, the compression phase has been performed under static loading i.e. the damaged panel is loaded at a slow rate until failure. However, this loading is not totally realistic as the component is likely to experience fatigue loading rather than, or before, a static overload. The damage is more likely to propagate to a large size, or catastrophically, under a long-term cyclic load rather than a one-off overload.

This Measurement Note is the second of two detailing work undertaken to assess the suitability of the Japanese Plastics Industry Federation (JPIF) compression-after-impact (CAI) test method proposed for ISO standardisation. The first Measurement Note [1] evaluated the repeatability of the method

under static loading and this second Note details work looking at the suitability of the method for use in fatigue loading.

EVALUATION OF CAI TEST METHOD UNDER FATIGUE LOADING

The following sections detail tests undertaken to assess the suitability of the JPIF CAI method for assessing the criticality of impact damage under long-term loading.

Materials

Two material systems were tested in this study supplied by Hexcel Composites Ltd and Gurit Holdings AG (previously 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 1.

Panel and specimen preparation

Test panels were manufactured at NPL according to the fabrication method given in [2] and following material supplier's guidance. Material 1 panels were autoclave cured at 120°C for 1 hour (3°C/minute ramp at 6 bar) and Material 2 panels 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 [3] (additional guidance on machining operations is given in [4]). Machining operations were performed using a Bennett diamond grit coated circular saw, with water used as a coolant/lubricant.

EXPERIMENTAL PROGRAMME

(A) CAI fatigue

(i) Impact resistance tests

For the creation of impact damage, route 2 of the JPIF proposed CAI method was used to determine the impact energy level required to cause barely visible impact damage (BVID), which is defined as a dent depth of 0.3 mm. This energy level, E_{BVID} , was determined by performing a series of impact tests over a range of energy levels and measuring the

Table 1 - Details of Materials Used in CAI Fatigue Tests

Material	Supplier	Generic Description	Measured fibre volume fraction V_f (%)
1	• Gurit Holdings AG	• unidirectional carbon fibre-reinforced epoxy	57.2
2	• Hexcel Composites	• autoclave cured • quasi-isotropic lay-up (+45/0/-45/90) _{2s}	56.5

resulting dent depths using a laser profilometer. By plotting impact energy against dent depth, the E_{BVID} levels for both materials were found by interpolation. It is noted that this route does not place a requirement on the user to determine damage area using ultrasonic inspection.

The impact procedure used is as follows. Rectangular specimens (150 x 100 x ~4-5 mm) were supported on a steel base plate containing a 75 mm x 125 mm cut out (detailed in [1]). 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 impact tests were performed. Prior to performing the impact tests the force transducer on the instrumented indenter was calibrated according to a method previously developed at NPL [5] (recommended in ISO 6603-2 [6] and used for UKAS calibrations). A second strike prevention device was employed to ensure that specimens received only one impact.

E_{BVID} for Material 1 was found to be ~29 J and for Material 2 ~22 J.

(ii) Residual CAI fatigue tests

For the residual CAI fatigue tests, the CAI support jig was used on an Instron 1251 hydraulic test machine (Figure 1). In order to improve the control of the test machine, the heavy base of the CAI support jig was inverted and bolted onto the load cell, which in turn was mounted on the stationary crosshead of the machine. The top loading plate was positioned on a compression platen screwed into the actuator.

The CAI jig has only ever previously been used on a servo-electric test machine, where

good alignment is relatively easily achieved, but never on a hydraulic machine. As correct alignment of the loading jig is critical, checks were made before any tests were undertaken.

Two impacted specimens per material were strain gauged in order to check alignment by monitoring the degree of bending during loading. Pairs of strain gauges were bonded to specimens and trial compression tests were then undertaken, initially elastically to ~3000 microstrain and then to failure. In the ISO proposed CAI method, bending is deemed acceptable if the difference between average strains recorded on each face of the specimen throughout the duration of the test is less than or equal to 10 %. All alignment tests resulted in less than 10 % bending and it was therefore felt that the alignment of the CAI jig on the hydraulic machine was acceptable.

The ultimate CAI strength of both materials had previously been measured by undertaking tests at the quasi-static crosshead rate of 0.5 mm/minute. Unlike glass fibre-reinforced systems, the material properties of carbon

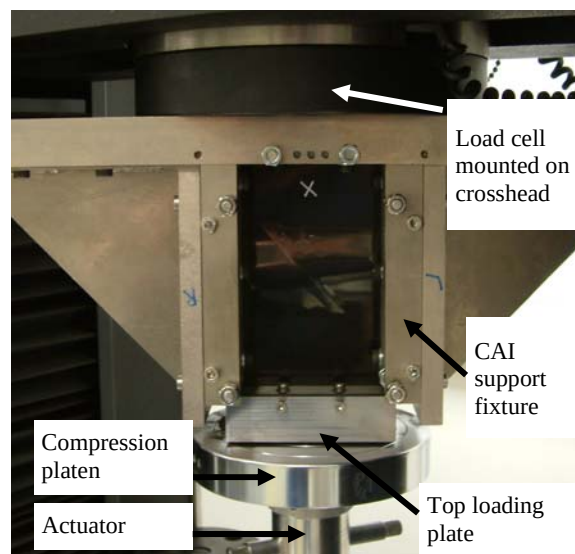


Figure 1 - CAI jig mounted on an Instron 1251 hydraulic fatigue machine (inverted)

fibre-reinforced plastics (CFRP) tend to be relatively insensitive to the testing rate, but in order to verify that this was the case specimens were also loaded at a rate equivalent to the fatigue rate. As expected, little difference between the strength values was observed for both the quasi-static and fatigue tests and the ultimate CAI strengths were used to determine the stress levels in the fatigue programme - Table 2.

Fatigue trials were also undertaken with strain gauged specimens to investigate whether strain data could be collected throughout the fatigue tests. Unfortunately the data logging equipment used was only capable of recording ~10 data points per second (10 Hz) and analysis of the data proved that this was not a sufficient recording frequency to fully define a load cycle. Thus measurement of displacement during the tests was performed using the actuator displacement. As the loading train for the CAI support jig is relatively short it was considered that there was a minimal amount of system compliance.

(N.B. Since the work detailed in this report was undertaken, data-logging facilities have been upgraded at NPL and are now capable of recording at 10 kHz)

For guidance on undertaking the fatigue tests, BS ISO 13003 [7] was followed closely and the reader is referred to this standard for more details on fatigue terminology and methodology. The fatigue regime used for all tests was compression-compression (Figure 2) with $R=10$, where R is;

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} = 10$$

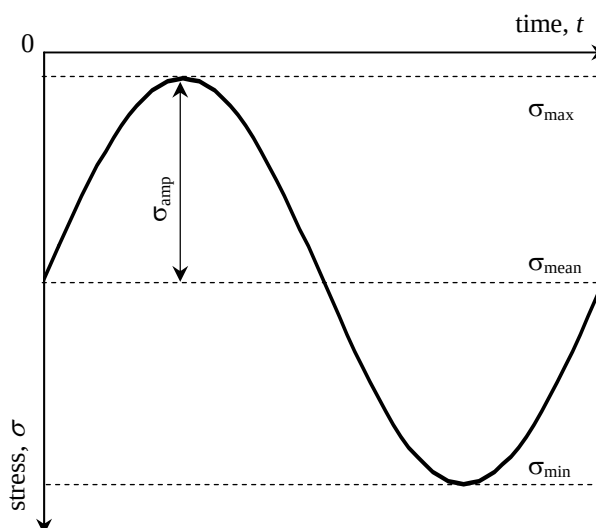


Figure 2 - Compression-compression sinusoidal waveform fatigue cycle

Values of $\sigma_{\min}$ were calculated as various percentages (50 to 85%) of the measured mean static CAI strength. The maximum, mean and amplitude stress values were then calculated using $R=10$. Initially, it was planned to undertake 5 tests at each of 5 percentage levels of $\sigma_{\min}$ (as recommended in [7]), however this was varied slightly to enable tests to be undertaken at additional stress levels (depending on material) so that a greater extent of the stress (S) versus number of fatigue cycles (N) plot could be investigated. The stress levels used are detailed in Table 2.

Due to the typically extensive test durations involved with fatigue testing, it is desirable to use the highest test frequency possible. However, selection of the correct test

Table 2 - Percentage and Absolute Stress Levels for CAI and Plain Compression Fatigue Tests

Test	Material	Mean static strength (MPa)	$\sigma_{\min}$ for percentages of static compression strength (MPa)							
			50 %	62.5 %	70 %	72.5 %	75 %	77.5 %	80 %	85 %
CAI (ISO draft)	1	136	-	85	95	98	102	105	109	-
	2	200	100	125	140	145	150	-	160	170
Compression [8]	1	454	-	-	318	-	341	-	364	-

frequency is essential as too high a frequency can lead to excessive, self-generated heat (autogenous heating) leading to thermal damage of the material under test and hence incorrect measurement of material properties. The test frequency selected was 5 Hz and checks were made as to the extent of autogenous heating during loading. It was found that there was little or no rise in the temperature of specimens at this fatigue rate.

After careful positioning in the test rig (correct vertical alignment was ensured using a spirit level) specimens were tested under load control using Instron MAX software and a sinusoidal cyclic waveform (Figure 2). Using the minimum, maximum, mean and amplitude stress values for each percentage stress level and the individual specimen dimensions, the corresponding load values were calculated for each specimen and inputted into the MAX software.

Specimens were tested in fatigue until failure had occurred or 2×10^6 cycles had been reached. Specimens that reached 2×10^6 cycles without failure were classed as 'run-outs'. It is noted that some fatigue tests were run for longer than 2 million cycles to investigate how many additional cycles would be required for failure.

(N.B. for CFRP materials used for aerospace applications, 10^6 cycles is typically defined as the number of cycles equivalent to the material's design fatigue life).

The control software was used to record the time, load, actuator position and cycle number for each fatigue cycle logged. Due to the large number of loading cycles required to cause failure, data was logged on a logarithmic scale with a cycle interval of 5 i.e. data was recorded according to the following pattern of cycles 1, 2, 3, 4, 5, 10, 15, 20, 25, 50, 75, 100, 125, 250, 375, 500 etc. Logging of each cycle was also triggered when a 5 % change in the load amplitude was detected by the software.

(iii) Damage monitoring using pulse thermography

Pulse thermography is a non-destructive evaluation (NDE) technique that examines the thermal response (to heating or cooling) of

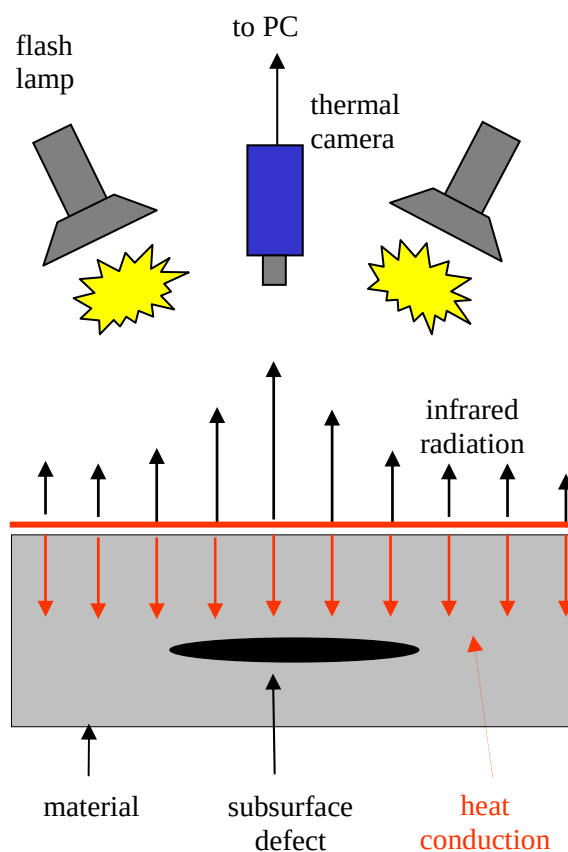


Figure 3 - Principle of pulse thermography technique for damage monitoring

a material or structure to determine the presence of subsurface defects and/or material properties of the target. The principle of the technique is shown schematically in Figure 3. When a material is momentarily exposed to a heat source, in this case via a halogen flash lamp, heat conducts into the material and is also reflected as infrared radiation. The presence of a sub-surface defect or damage reduces the amount of heat conducted through the material and therefore increases the level of infrared radiation in the location of the defect. By monitoring the level of infrared radiation emitted by the material using a thermal camera, the presence and size of damage can be determined.

This technique was used to investigate the extent of damage (delamination) growth for several of the CAI fatigue tests. A ThermoScope™ pulse thermography system (supplied by LOT-Oriel Ltd.) was used for these tests. One of the key advantages of pulse thermography for damage detection compared to other techniques such as ultrasonic C-scan

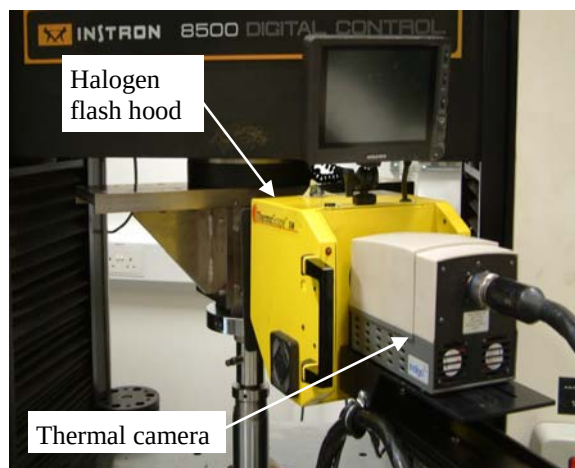


Figure 4 - Pulse thermography system adjacent to CAI jig mounted on fatigue machine –(supplied by LOT-Oriel Ltd.)

and X-ray, is that the inspection can be performed without the need to remove the specimen from the loading jig. The ThermoScope™ equipment is shown in Figure 4. After various numbers of fatigue cycles had been completed, tests were stopped and the specimen under test was held briefly at the maximum compressive load (σ_{min}). The specimen was then interrogated using the ThermoScope™ equipment before the fatigue test was resumed.

(B) Plain end-loaded compression fatigue to BS EN ISO 14126

In order to compare the compression fatigue performance of CAI specimens to the



Figure 5 - End-loading compression jig mounted on hydraulic fatigue machine

undamaged fatigue performance, a number of fatigue tests were also undertaken on plain compression specimens. It is noted that this was only performed on Material 1.

Tests were undertaken on un-impacted coupons with the same dimensions as the CAI specimens i.e. 150 x 100 x ~4-5 mm using the CAI support jig. As expected these tests proved unsuccessful with specimens failing by buckling rather than compression. Therefore undamaged compression tests were carried out using the specimen dimensions (125 x 25 x ~4-5 mm) and end-loading jig detailed in BS EN ISO 14126 [8].

The four pillar die set end-loading compression jig was mounted on an Instron 1251 hydraulic test machine as shown in Figure 5. The alignment of the jig on the test machine was set using a ground steel bar to ensure that the top and bottom loading blocks were correctly aligned.

A number of static tests to failure were undertaken to determine the mean ultimate compression strength, and the maximum, mean and amplitude stress values for a range of percentage (of ultimate) stress levels were calculated (Table 2).

As for the CAI fatigue tests, a sinusoidal cyclic waveform was used and tests were run at a frequency of 5 Hz. All tests were run in load control using MAX software and the same data logging sequence was also used.

ANALYSIS OF FATIGUE DATA

As well as recording the number of cycles to failure, stiffness properties of each specimen were monitored throughout the test at each logged cycle. This was carried out to see whether changes in stiffness occur due to growth of the damage throughout the fatigue tests, and whether if there was a change in stiffness, where in relation to the failure cycle it occurred.

The stiffness of each specimen was calculated using two methods; (i) from the minimum and maximum actuator positions corresponding to minimum and maximum load levels and (ii) by monitoring the hysteresis loops of logged cycles to determine the storage and loss

Table 3 - CAI Fatigue Results for Materials 1 and 2

Material 1					Material 2				
Specimen number	$\sigma_{\min}$ (MPa)	Normalised peak stress*	Cycles to failure, N	Log_{10} (N)	Specimen number	$\sigma_{\min}$ (MPa)	Normalised peak stress*	Cycles to failure, N	Log_{10} (N)
5AQUL002	139.7	1.03	0.5	-0.30	3AQUN009	202.2	1.01	0.5	-0.30
5AQUL003	131.9	0.97	0.5	-0.30	3AQUN010	193.2	0.97	0.5	-0.30
6AQUL006	108.6	0.80	10,887	4.04	4AQUN001	170.0	0.85	3,292	3.52
6AQUL007	108.6	0.80	59,962	4.78	4AQUN002	170.0	0.85	2,056	3.31
6AQUL008	108.6	0.80	7,907	3.90	4AQUN003	170.0	0.85	1,072	3.03
4AQUL001	108.6	0.80	22,245	4.35	4AQUN009	170.0	0.85	2,346	3.37
5AQUL012	105.2	0.78	35,433	4.55	4AQUN004	160.0	0.80	8,407	3.92
6AQUL002	105.2	0.78	11,227	4.05	4AQUN005	160.0	0.80	16,443	4.22
6AQUL003	105.2	0.78	52,959	4.72	4AQUN006	160.0	0.80	32,038	4.51
6AQUL004	105.2	0.78	149,597	5.17	4AQUN008	160.0	0.80	18,611	4.27
6AQUL005	105.2	0.78	103,307	5.01	4AQUN010	160.0	0.80	17,642	4.25
3AQUL010	101.8	0.75	115,161	5.06	3AQUN001	150.0	0.75	241,129	5.38
5AQUL004	101.8	0.75	72,195	4.86	3AQUN002	150.0	0.75	28,584	4.46
5AQUL005	101.8	0.75	261,805	5.42	3AQUN003	150.0	0.75	170,982	5.23
5AQUL006	101.8	0.75	86,116	4.94	3AQUN007	150.0	0.75	230,149	5.36
5AQUL007	101.8	0.75	231,818	5.37	4AQUN007	150.0	0.75	46,316	4.67
4AQUL003	98.4	0.73	156,280	5.19	3AQUN011	145.0	0.73	3,202,899	6.51
4AQUL004	98.4	0.73	46,419	4.67	3AQUN012	145.0	0.73	2,000,000	6.30
4AQUL005	98.4	0.73	19,468	4.29	3AQUN005	140.0	0.70	605,703	5.78
3AQUL003	95.1	0.70	460,729	5.66	3AQUN006	140.0	0.70	1,478,957	6.17
3AQUL006	95.1	0.70	999,615	6.00	3AQUN008	140.0	0.70	1,649,892	6.22
3AQUL007	95.1	0.70	2,000,000	6.30	3AQUN004	125.0	0.63	4,328,050	6.64
3AQUL008	95.1	0.70	197,251	5.30	2AQUN010	100.0	0.50	2,125,403	6.33
3AQUL009	95.1	0.70	632,587	5.80	* - normalised with respect to the mean UCS determined by quasi-static tests grey shading indicates run-outs				
3AQUL004	84.9	0.63	1,788,290	6.25					
3AQUL005	84.9	0.63	2,000,000	6.30					
5AQUL001	84.9	0.63	2,000,000	6.30					
5AQUL008	84.9	0.63	2,000,000	6.30					
5AQUL009	84.9	0.63	2,000,000	6.30					

Table 4 - Plain Compression Fatigue Results for Material 1 (End-Loaded, R=10)

Specimen number	$\sigma_{\min}$ (MPa)	Normalised peak stress*	Cycles to failure, N	Log_{10} (N)	Specimen number	$\sigma_{\min}$ (MPa)	Normalised peak stress*	Cycles to failure, N	Log_{10} (N)
3AQUL012	457.1	1.01	0.5	-0.30	ABDQ017	363.6	0.80	36,204	4.56
3AQUL013	464.8	1.02	0.5	-0.30	ABDQ012	340.8	0.75	138,318	5.14
3AQUL014	441.5	0.97	0.5	-0.30	ABDQ013	340.8	0.75	204,240	5.31
ABDQ018	386.3	0.85	37,901	4.58	ABDQ014	340.8	0.75	178,464	5.25
ABDQ019	386.3	0.85	18,084	4.26	ABDQ010	318.1	0.70	3,459,001	6.54
ABDQ015	363.6	0.80	30,731	4.49	ABDQ011	318.1	0.70	1,575,779	6.20
ABDQ016	363.6	0.80	37,521	4.57	ABDQ009	318.1	0.70	576,000	5.76

moduli. The first method is relatively simple, although the use of actuator position to calculate strain can lead to errors due to machine/loading train compliance. The second method is described in the following section.

Monitoring specimen stiffness via hysteresis loops

When a material is subjected to fatigue loading the stress-strain response observed is related to its ability to store and dissipate energy. Figure 6 shows stress-strain responses for (a) perfectly elastic behaviour and (b) viscoelastic behaviour.

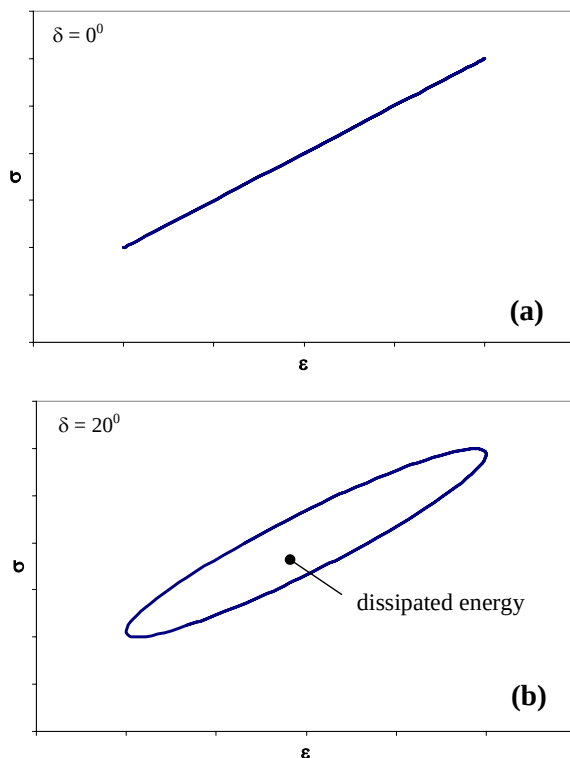


Figure 6 - (a) elastic response, stored energy and (b) viscoelastic response

For sinusoidal waveform loading, Figure 7, changes in the response of the stress and strain curves over time, indicate changes in the mechanical properties of the material. These changes are measured by looking at the change in amplitude and phase angle (δ) of the two curves. For a perfectly elastic material the mechanical energy stored during loading is returned completely when the specimen is unloaded. Thus the stress and strain curves for the material are completely in phase with each other i.e. $\delta=0^\circ$, resulting in no hysteresis (Figure 6(a)). Conversely, a perfectly viscous

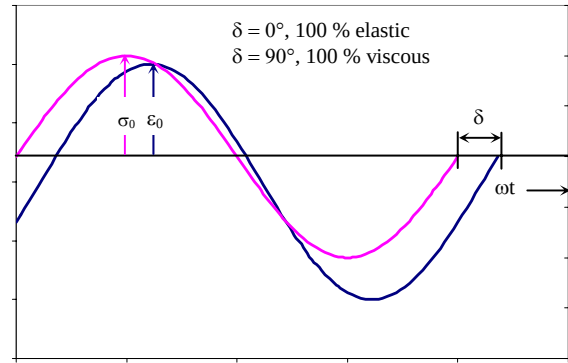


Figure 7 - Out of phase stress-strain response for viscoelastic material, $\delta=20^\circ$

material ($\delta=90^\circ$) which exhibits no elasticity, results in all of the mechanical energy being dissipated and the stress-strain curves being out of phase with each other. Materials that fall between these two categories are classified as viscoelastic.

For viscoelastic materials subjected to cyclic fatigue, a proportion of the mechanical energy per cycle is converted to heat with the rest of the energy being stored and returned on unloading. This produces stress and strain curves which exhibit a phase lag (Figure 7) and a hysteresis loop results of which the area enclosed within the ellipse is equal to the dissipated energy per cycle, Figure 6(b).

The viscoelastic behaviour for stress and strain can be represented as:

$$\epsilon = \epsilon_0 \sin(t\omega) \quad \text{and} \quad \sigma = \sigma_0 \sin(t\omega + \delta)$$

Where:

ϵ = strain, σ = stress, ω = period of oscillation, t = time and δ = phase angle (radians).

To monitor the changes in material during fatigue, individual fatigue cycles can be investigated for changes in: (i) the *storage modulus*, which is as a measure of the elastic properties of the material i.e. the ability to store energy, and (ii) the *loss modulus*, which is a measure of the viscous component of the material i.e. the energy dissipated as heat. Where:

$$\text{Storage modulus} = M' = \frac{\sigma_0}{\epsilon_0} \cos \delta$$

$$\text{Loss modulus} = M'' = \frac{\sigma_0}{\epsilon_0} \sin \delta$$

The *damping factor* can also be used as an indication of the viscous component of the material. If damage formation and growth occurs under fatigue loading, the storage and loss (damping factor) moduli can be expected to decrease and increase respectively with an increasing number of fatigue cycles.

For the fatigue tests conducted, each logged cycle was analysed to calculate the elastic, storage and loss moduli, and damping factor. The method of data analysis is not described here, but can be found in [9].

RESULTS

The number of cycles to failure for CAI and undamaged plain compression fatigue are detailed in Tables 3-4 and Figures 8-9. Figure

9 shows normalised compressive stress against $\log_{10}(\text{fatigue cycles to failure})$. (N.B. the scale on the y axis goes up to 1.1 as the compressive stresses were normalised with respect to the mean ultimate compressive strength (UCS)). In general the CAI fatigue S-N plots for both materials were very flat as is typically the case for CFRP materials. The plain compression S-N curve for Material 1 exhibited a slightly steeper gradient to the CAI curve but this was thought to be due only to the fact that fewer specimens had been tested.

Figure 10 shows plots of: (a) normalised elastic storage modulus against the log of fatigue life, and (b) normalised storage modulus and damping factor. It is noted that the y-axis normalised scales extend to 1.1 as there tended to be some degree of noise in the

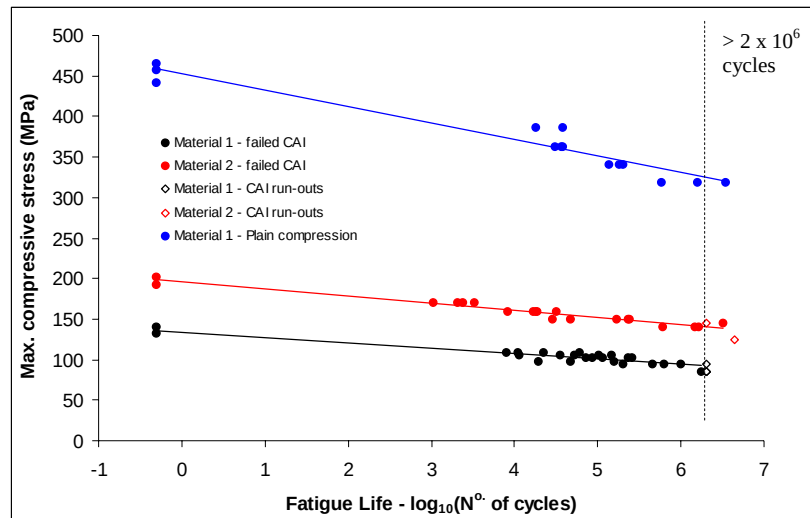


Figure 8 - Fatigue results for CAI and plain compression tests

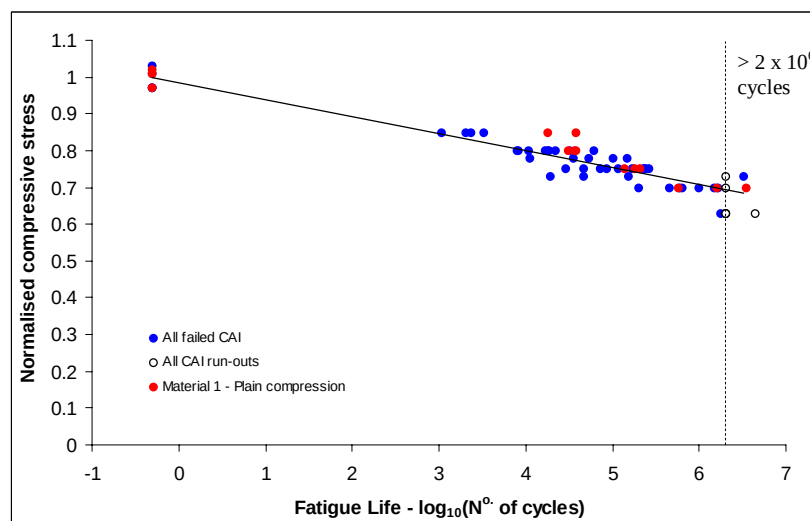


Figure 9 - Normalised fatigue results for CAI and plain compression tests

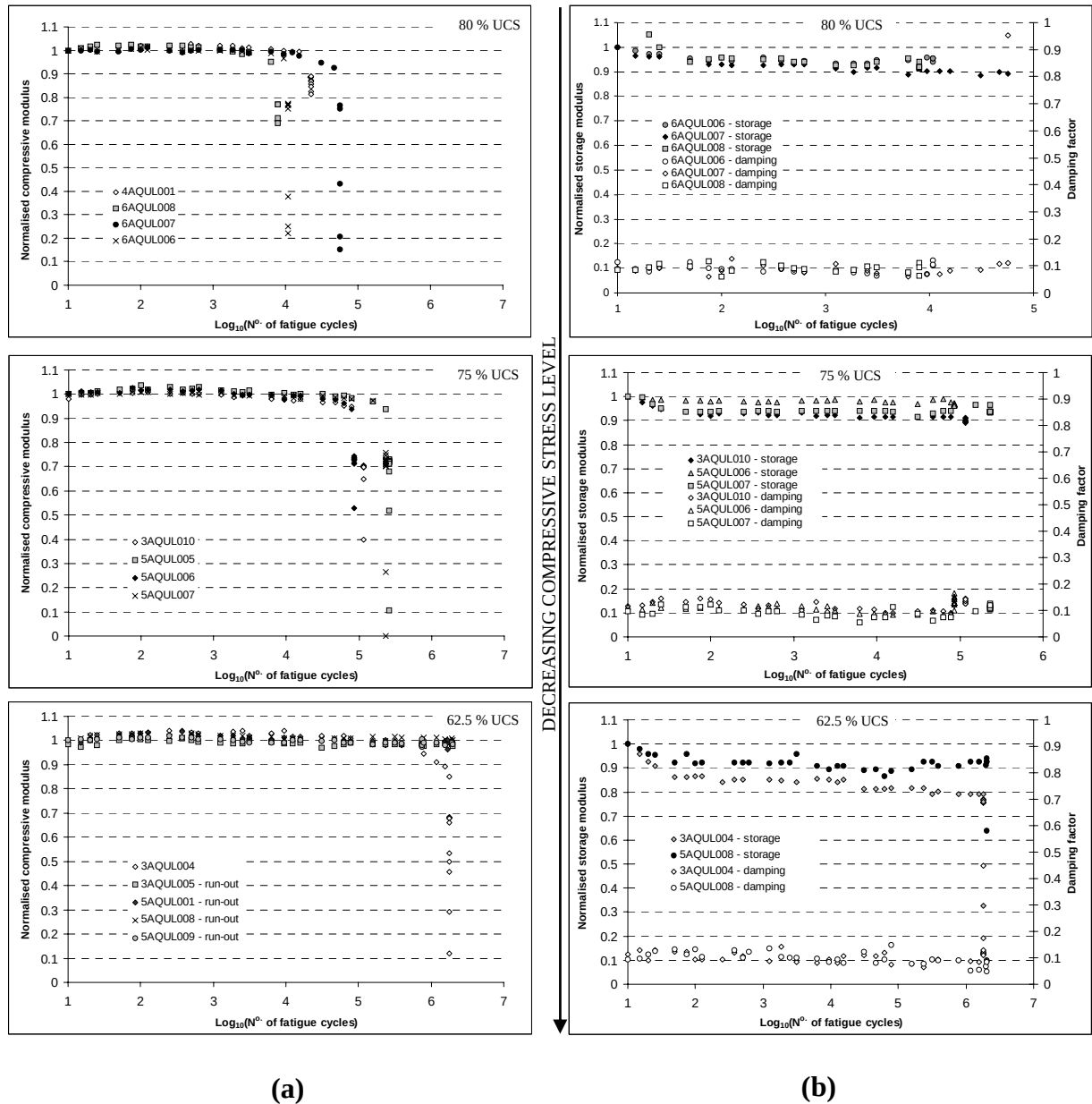


Figure 10 - Material 1 results: (a) normalised compressive modulus vs. $\text{Log}(\text{fatigue cycles})$ and (b) normalised storage modulus and damping factor vs. $\text{Log}(\text{fatigue cycles})$

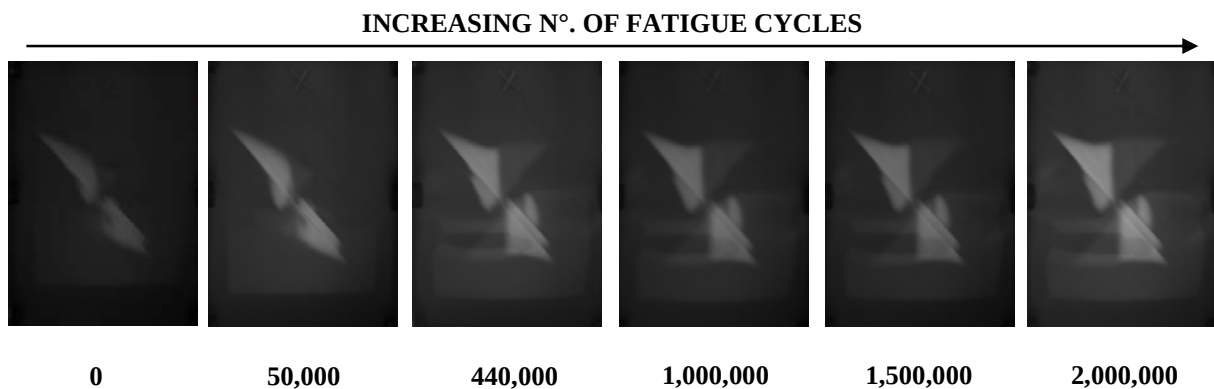


Figure 11 - Pulse thermography images of CAI fatigue specimen (72.5 % of static UCS)

data. Plots of the loss modulus were very noisy and hence the damping factor has been plotted instead. Results have only been shown for Material 1 here but the same trends were observed for Material 2. It can be seen from Figure 10(a) that the normalised compressive modulus shows very little change over the fatigue life until very close to failure. This is true for all of the percentage stress levels tested. Figure 10(b) also indicates that there are minimal changes in the storage modulus and damping factor over the fatigue life, again until just prior to failure.

Finally, images obtained from pulse thermographic inspection of a CAI specimen fatigue tested at 72.5 % of UCS after various numbers of fatigue cycles are shown in Figure 11. Careful inspection of the damage area visible in the images indicates that there is some growth of delaminations within the specimen but to a fairly minimal extent.

CONCLUSIONS

The results of this study have evaluated the suitability and practicality of adapting the static CAI test method for use under fatigue loading. A number of key observations and conclusions can be drawn from the work undertaken:

- In general it was found that the static CAI method required minimal adaptation for use under fatigue loading, and there were no problems encountered in using the support jig on the fatigue machine.
- The plain compression and CAI S-N curves were found to be of similar gradient. Therefore it is reasoned that it would be possible to calculate the CAI fatigue life from a 'knock-down' factor applied to the plain compression fatigue performance and knowledge of the ultimate CAI strength.
- The use of the normalisation framework approach to fatigue has been previously used for glass-fibre based systems [10] and is incorporated into the CoDA predictive composites software [11].
- Failure of CAI fatigue specimens tended to occur suddenly with little or no reductions in compressive and storage moduli or increase in damping factor. The accuracy of calculated stiffness values could be increased by using strain gauges for direct measurement of strain rather than using values derived from the actuator displacement.
- Pulse thermography has been demonstrated to be a useful technique for 'on-line' damage monitoring, as it does not require the user to remove the specimen from the test jig.

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For further information contact:

Mr Michael Gower
 Polymers and Modelling Group
 Industry and Innovation Division
 National Physical Laboratory
 Hampton Road, Teddington
 Middlesex
 TW11 0LW
 Telephone: 020-8977 3222 (*switchboard*)
 Direct Line: 020-8943 8625
 Facsimile: 020-8943 6177

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