DEVELOPING A CAI TEST FIXTURE FOR CONSISTENT TESTING OF COMPOSITES AT REDUCED TEMPERATURE

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ABSTRACT

The influence of reduced temperature during the compression after impact (CAI) tests on the performance of glass fibre reinforced polymer (GFRP) is to be investigated. An approach is described that allows the application of digital image correlation (DIC) to CAI tests on thin composite plates with barely visible impact damage (BVID) at room and reduced temperatures. The overall aim is to use DIC to identify strain changes that indicate damage has occurred. A detailed review of the literature has been carried out which has enabled the design of a modified rig with the aim to improve the consistency of CAI tests on plates with thicknesses at the lower limit those specified in the ASTM standard. To compare outcomes tests have been conducted on GFRP plates ~ 3.5 mm in thickness with impact damage using a conventional ASTM rig and a modified rig. By applying DIC it was possible to show that the modified rig significantly reduces the amount of out-of-plane displacement during the CAI test that may influence the results. Additionally a series of trials were conducted on the use of DIC at reduced temperatures, -20 °C, which showed some of the challenges that may be faced in such work. Finally, an initial set of tests on thin composite plates, ~ 2 mm in thickness, with low levels of impact damage have been performed at both room and -20 °C using the modified CAI rig. There was a large variation in failure load even when considering plates with similar damage levels. The DIC revealed that the results were heavily influenced by out-of-plane displacement, with further work required to improve the testing arrangements for thin plates.

1 INTRODUCTION

Impact behaviour is an important consideration in understanding the failure behaviour of composite material. A common test used to define impact performance is compression after impact (CAI), which characterises the reduction in strength as a result of the impact damage [1, 2]. There is a wealth of literature on the topic of determining the extent and type of damage created by impact, and its evolution during the CAI test in composite plates. In [3] ultrasound C-scanning is used to determine the extent of damage in impacted composite plates and the growth of this damage after the CAI test. Bull et al [4] applied an interrupted CAI test on carbon fibre composite plates to allow the use of ex-situ X-ray computed tomography (CT) scanning to monitor damage growth near to, or at failure loads. The CT provided detailed information of both the extent and type of damage (in 3D) in the plates as it evolved. The damage was first assessed by CT when it was introduced and again after CAI testing, which also defined the final failure load. Jefferson Andrew et al [5] analysed damage evolutions during CAI tests on plates with repeated impacts using in-situ acoustic emissions (AE). The AE identified delamination and fibre break events in the CAI tests and correlated the frequency of these events with the residual strength of the impacted plates. Testing the compressive residual strength of glass fibre or carbon fibre composites after low energy impacts at low temperatures should be studied for a number of reasons, including the assessment of hail strikes upon composite aircraft structures (–50 °C) [6] and impact of composites for construction of cryogenic fuel tanks developed for aerospace and land vehicles (–150 °C) [7]. Cryogenic environmental chambers are commonly integrated as part of the drop weight tower systems, and enable controlled impacts to impart damage on composite coupons in this range of low temperatures. However, very few experimental studies have covered cases where the impacted coupons are subject to compression tests at similar low temperatures [8] and no studies have attempted to perform DIC at low temperatures to inspect the strain evolution of BVID impacts embedded within composite coupons.

The aim of the current paper is to test the feasibility of using a modified CAI fixture to improve the consistency of conducting the post impact compression testing and enable this test to be performed at reduced temperatures. 3D digital image correlation (DIC) is applied to track the evolution of damage in CAI tests on glass fibre reinforced polymer (GFRP) plates, and determine how damage changes the strain in the plates. A discussion of the influence of the modified test fixture is provided here, along with the use of DIC applied to reduced temperature testing. Finally, the results from a series of tests on thinner test laminates in the modified fixture are presented. In this work all impacts were conducted using an Instron Ceast 9350 drop tower instrumented with a 44 kN hemispherical tup.

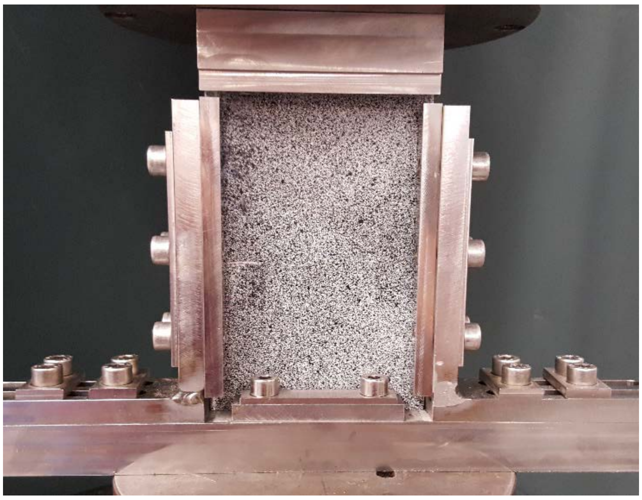
2 CONSISTENCY OF CAI TESTING

Typically the rig shown in Figure 1a is used for CAI tests on plates with thickness greater than 3 mm as per ASTM [1]; however even with relatively thick plates, failing the sample in pure compression in the centre of the plate is difficult for low levels of damage from a practical perspective. Small variations in the clamping forces and the application of the load can lead to out of plane displacement of the sample, and the resulting bending loads can lead to localised buckling or other failures occurring away from the damaged area. At low impact energies premature failure often occurs near the top of the plate in the unsupported zone. Previous authors [9] and [10] identified typical mechanisms of compression shear failures or crushing failures being the common causes of premature failure. As the impact damage is increased, failure in compression is easier to achieve because the load at which the damage will initiate the failure is lower, thus the propensity for premature failure due to parasitic effects of the loading rig is less likely. However, as the sample thickness and impact energies are decreased the influence of the constraints of the experimental setup become more important.

Currently there is no standardised method for testing plates that are less than 3 mm thick, therefore it is these that are of interest, alongside the application of DIC at low temperature. Furthermore, thin plates with low levels of damage, mean that the propensity to premature failure, due to buckling in the unsupported zone at the top of the standard rig, is increased. Some alternative methods have proposed modifications of the specimen geometry to include end tabs but this adds further complexity, due to localised stress concentrations and detachment of the end tabs. In [3], three new rig geometries were investigated, identifying that the rig design utilising a ‘picture frame’ approach successfully promoted failure in the region damaged by the impact. This design utilised thick anti-buckling plates to reduce the out of plane displacement of the specimen and the subsequent bending forces due to the applied load. In the present paper, a further modification of the rig designed in [3] has been made to improve control of the load transfer by incorporating a rail system following work described in [11]. Since the work proposed includes applying DIC within a chamber, extension bars are required to connect to the test machine. Subsequently, a cup-cone device has been incorporated at each end of the rig to reduce any detrimental effects caused by misalignment of the test machine amplified by the long extension bars. Considerations have also been made to account for differential thermal expansions between the specimen and fixture, to enable use in the reduced temperature environment. The modified rig is shown in Figure 1b.

Comparative tests on thick plates (~ 3.5 mm) were conducted to validate the modified rig design. Crossply plates of GFRP material manufactured from 6 layers of biaxial E-glass mat and Prime 20LV resin, from Gurit, machined to 150 x 100 mm in accordance with [1]. The plates were impacted at room temperature with an impact energy of 60 J. Following the impact the plates were subjected to a CAI test at a speed of 1 mm/min using an Instron electro mechanical test machine with a load capacity of 50 kN. Plates were loaded using either the original (Figure 1a) or modified (Figure 1b) CAI fixture. Two 5 MP cameras, equipped with Sigma 105 mm lenses, were used to capture images for 3D DIC applied to the impacted surface of the plate. The images were captured at a frequency of 1 Hz alongside the load and displacement data from the test machine and were processed using LaVision's DaVis software. The correlation was conducted using subsets of 41 x 41 pixels and a step size of 20 pixels with an image scale of ~ 17.5 pixels/mm. Figure 2a plots the out-of-plane displacement along a vertical line in the centre of the tested plates from an image close to, but not at, failure. The red line shows the out-of-plane displacement has been minimised below 0.25 mm, except for in the immediate locality of the impact damage (between ~ 40 and 65 mm). To analyse the effect of the influence of out-of-plane displacement the evolution of the longitudinal strains with time (or image number) has been plotted in Figure 2b. The longitudinal strain was averaged over an area of approximately 20 x 30 mm towards both the top and bottom of the plates, outside of the damaged region. The red lines, representing the plate tested on the original fixture, initially show good agreement, but quickly start to deviate, caused by bending of the plate. However, the black lines, representing the plate tested in the modified fixture, show good agreement throughout. By improving the alignment of the test plate with the load introduction and localising the unsupported section to the damaged zone the failures consistently occur at the damage site, by reducing the effect of the load introduction on the test outcome.

(a)



(b)

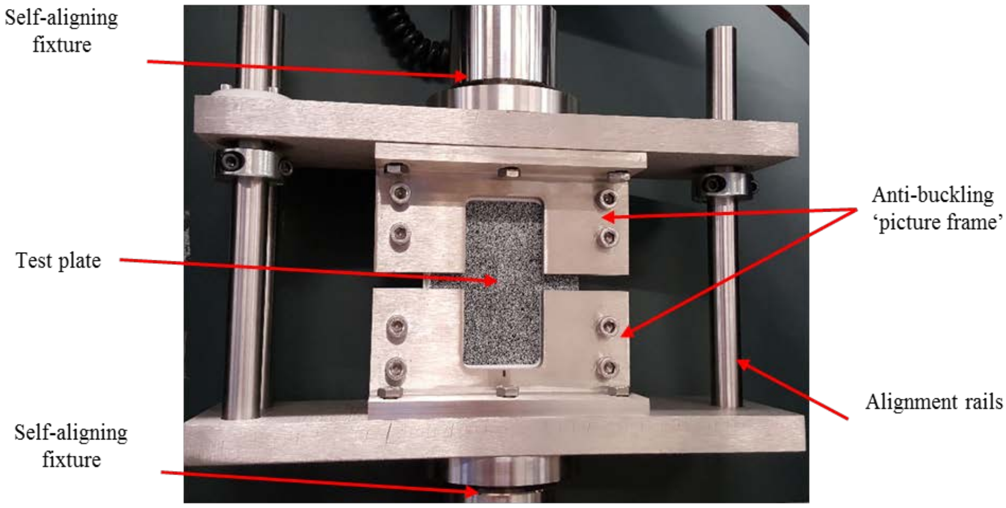


Figure 1: Comparison of CAI fixtures (a) original, and (b) modified

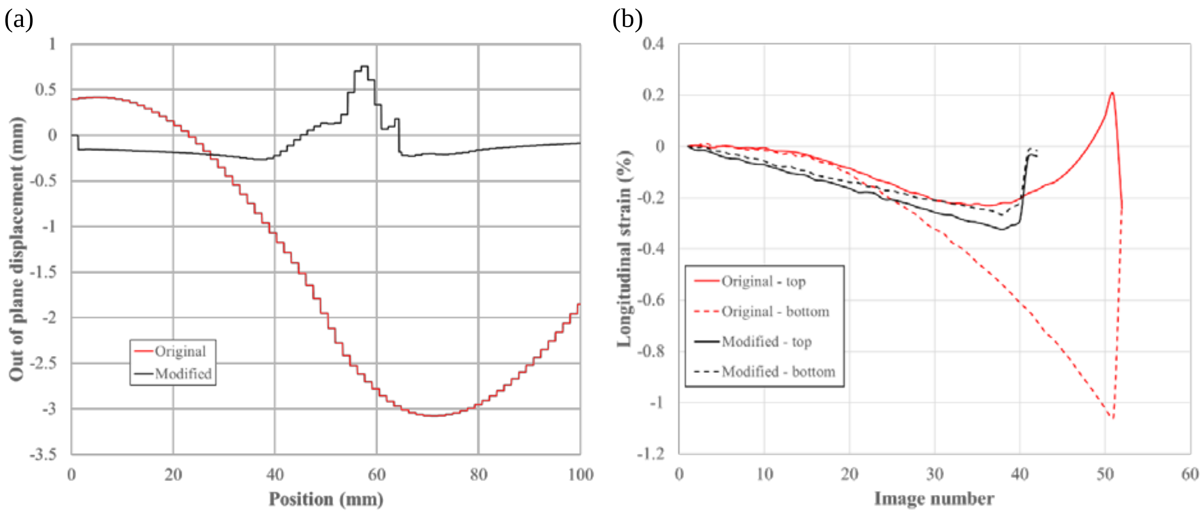


Figure 2: (a) Comparison of out-of-plane deformation during CAI tests conducted on both original and modified fixtures, (b) comparison of longitudinal strain evolution across the surface of the specimen tested using both the original and modified fixture.

3 CONDUCTING CAI TESTING AT LOW TEMPERATURES WITH DIC

The CAI tests have been performed at low temperatures in well-insulated environmental chambers designed to inject liquid nitrogen against a metal plate. The cold gas generated from the vapourising liquid is distributed around the chamber by an electrically driven fan. This process of cooling is not very effective given the poor heat transfer properties of the gas. The mass of metal fixtures in the chamber increases the time required to achieve thermal equilibrium at the desired test temperature. Performing DIC at low temperatures also requires viewing access (through a window) and sufficient lighting to illuminate the test specimen. The stereo DIC setup used here had additional lighting to illuminate the specimen externally.

The inclusion of windows in a cryogenic chamber increases radiative heat transfer into the cold space and the time required for cooling. Windows included in the chamber are typically double-walled (two panes of glass sandwiching a void space filled with nitrogen or argon gas) to provide some insulation and also heated by an electrical heating element to avoid condensation forming on the window. As the application of DIC at low temperatures is new, the effects of the heated double-wall window and vapourised gas stream flowing within the chamber upon DIC techniques has not been assessed.

A series of trials were performed in a cold chamber at –20 °C. The DIC was affected by the circulation of cold vapour around the chamber and haze caused by the heated window in the chamber, which was included to avoid condensation. To investigate the effect of performing DIC under these conditions a series of images of the speckled specimen whilst unloaded were captured, and correlated using DaVis, using the same parameters as in Section 2. Figure 3 shows a longitudinal strain map for three unloaded cases; Figure 3a shows the resultant strain map from the specimen directly viewed, Figure 3b shows the resultant strain map from the specimen viewed through the chamber window with no influence of the heated screen, and Figure 3c shows the resultant strain map from the specimen viewed through the chamber window with the heated screen turned on. Additionally Table 1 lists the maximum strain deviation in each image, and the standard deviation across that image. The correlation from the specimen viewed directly shows a deviation of ± 250 μstrain, the inclusion of the chamber window increases this deviation to ± 500 μstrain. However the “rippling” in the images captured when using the heated screen was significant, causing a deviation of ± 10000 μstrain, which is greatly in excess of that required for any kind of quantitative work. It was found that shutting down the fan once at the test temperature did not resolve the imaging errors, and therefore it was also necessary to disconnect the heating element attached to the window to improve the stability of the captured images. Unfortunately, disabling the window heater caused condensation to form rapidly on the window. The chamber was purged with dry nitrogen gas to remove air (containing water vapour) prior to cooling. However, this process did not prevent the condensation forming within the void space due to failure of the sealing encapsulating the window assembly. The chamber itself had other unsealed edges and larger clearances around the top and bottom openings to connect the fixture to machine bed and crosshead. Unless a positive pressure was maintained inside the chamber during cooling, air from outside the chamber was drawn back inside. These problems did not prevent the DIC from being used, but limited the lowest test temperature and the time available to conduct the test. Further efforts are required to improve the cooling methodology to reduce the influence on the DIC and reduce the test temperature further.

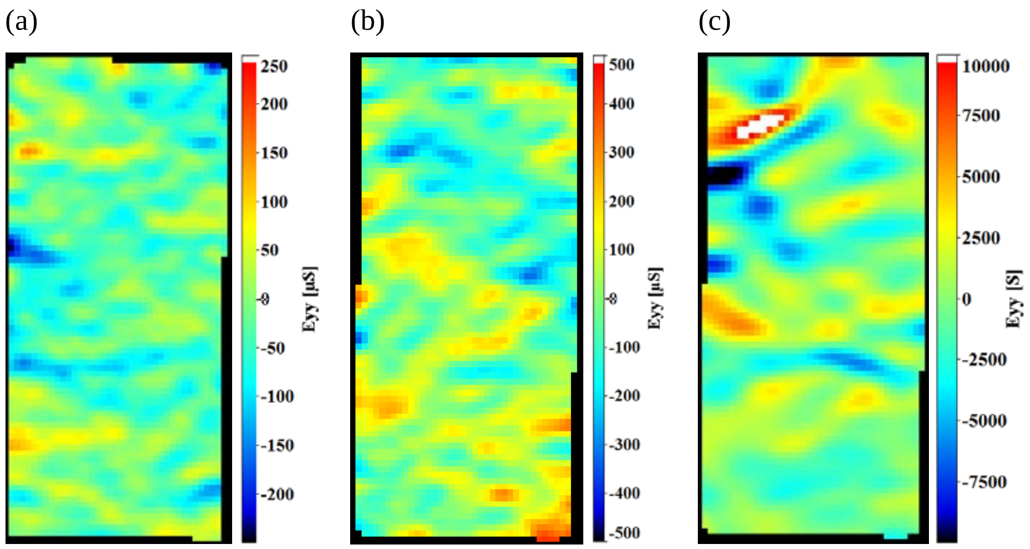


Figure 3: Longitudinal strain plots showing noise in unloaded data for test setup (a) outside of chamber, (b) through chamber window, and (c) with heated screen

Table 1: Evaluation of strain resolution for application of DIC at cold temperatures

Test setup	Maximum strain deviation (µstrain)	Standard deviation of single image (µstrain)
Outside of chamber	± 250	50
Through chamber window	± 500	200
With heated screen	± 10000	3000

4 THIN PLATES/BVID

Despite some of the challenges encountered in applying DIC to the reduced temperature tests a series of CAI tests on thin plates with low energy impact damage have been conducted. Crossply plates of ~ 1.8 mm thickness were manufactured from 8 plies of UD glass prepreg from PRF Composites cut to 150 x 100 mm. The plates were subjected to CAI tests using the modified fixture in an undamaged state, or with impacts with energy of 5 J or 15 J. All impacts were conducted at room temperature, with CAI tests conducted at room temperature or -20 °C. All tests were conducted with the DIC setup and parameters described in Section 2.

Table 2 lists the tests considered here with impact energy and CAI test temperature, alongside the failure load for each CAI test. There is a lot of scatter in the failure loads, even when specimens tested under similar conditions are considered. There does not appear to be a correlation between impact damage and failure load. It was noted during testing that at, or around, failure the upper picture frame moved significantly away from the plane of the test specimen as the thin plates started to show out-of-plane displacement. It is hypothesised that the cup-cone ends at both the top and bottom of the fixture allow for too much freedom for the test plate to determine the movement of the rig rather than the other way around. This was also evident in the DIC data where distinct out-of-plane movement was measured in the plates that were 50 % the thickness of those tested in Section 2. It is evident that the failure is being heavily influenced by the out-of-plane movement, and loads are not being reached that would show an influence of impact damage.

Figure 4 plots the longitudinal strain vs compressive load for each CAI test. The longitudinal strain is a spatial average across an area 30 x 20 mm in the damaged region. All tests show an initial linear response before a sharp change in gradient at ~ 0.4 % strain with a second linear period of a much shallower gradient to failure. The point at which the gradient alters is considered to be the onset of significant out-of-plane movement with an improvement at the load when this occurs due to a change in the procedure used for loading specimens in the fixture. Further investigation is required on the influence of the fixture and out-of-plane movement on the failure loads achieved, and on the freedom imparted by the use of dual cup-cone fixings.

Table 2: List of CAI tests considered here and the failure load

Test specimen	Impact and test temperature	Failure load (kN)
02	5 J, room temperature	30.7
03	5 J, room temperature	37.6
04	5 J, -20 °C	38.3
05	15 J, room temperature	30.8
06	15 J, room temperature	37.1
08	15 J, -20 °C	37.4
09	Undamaged, room temperature	28.9
10	Undamaged, room temperature	30.3
11	Undamaged, room temperature	37.8
12	Undamaged, room temperature	33.6
15	30 J, -20 °C	36.1

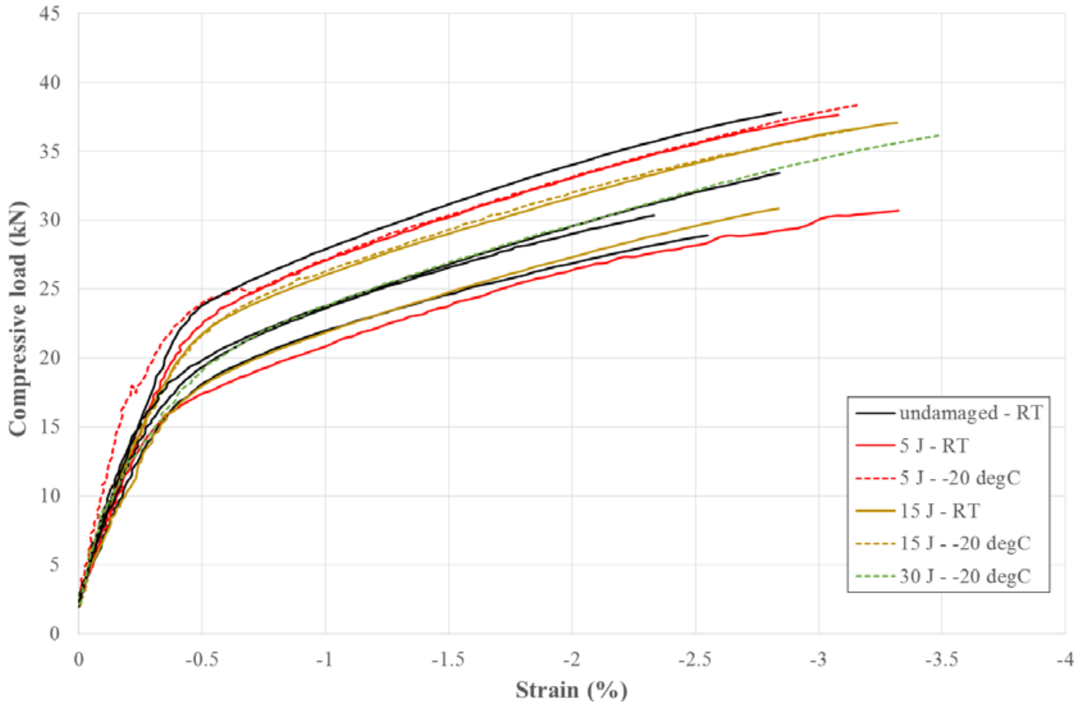


Figure 4: Load vs strain at damaged region for all thin plates tested

5 CONCLUSIONS/FUTURE WORK

An approach has been described that uses a modified CAI fixture to enable DIC to be conducted on thin composite test plates during CAI tests at both room and reduced temperatures. The modified fixture has shown improved consistency and reduction of the amount of out-of-plane movement when using plates ~ 3.5 mm or at the lower limit of the ASTM [1]. However there are concerns of the performance and amount of out-of-plane movement occurring when applied to much thinner plates, ~ 50 % the thickness of the ASTM limit. In particular the out-of-plane movement on the thinner plates appears to have a large influence on the failure loads obtained and is potentially masking any influence of the damage caused by impact. It is considered that the inclusion of cup-cone joints at both the top and bottom of the fixture have introduced further parasitic effects because this enable extensive freedom of movement and is to be investigated further.

Additionally, some initial work has been conducted to determine a methodology for applying DIC to mechanical testing conducted at reduced temperatures. Here, the tests were cooled using the application of cold nitrogen gas which produced significant vapour and convection effects. The effect of applying the DIC through the window of an environmental chamber, and that with a heated screen have shown that although the window itself has little influence, the haze produced by the heated screen make the DIC data unusable. Further work is required to determine a better approach to cooling and ensuring the environment is dry, to avoid air currents, vapour and condensation.

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