Student Paper ☒

Reviewing the Experimental setup of Ultra-High-Speed and Low-Speed 3D Digital Image Correlation for composite CAI testing

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ABSTRACT

The use of composite materials in aircraft systems is increasing and to aid the development of Finite Element (FE) modelling of post-impact damage, there exists a requirement to increase the strain data output of compressive specimen testing. In order to capture more full-field strain data, three pairs of cameras have been employed to carry out Digital Image Correlation (DIC) of the front and rear faces of a composite test specimen as it is subjected to Compression After Impact (CAI) destructive testing. 3D DIC is captured from two pairs of cameras, with one pair pointed at the front and one pair pointed at the rear of the specimen respectively. They are able to capture full-field strain of the specimen in high spatial resolution over the lifetime of the test. A third pair of Ultra-High-Speed (UHS) cameras, focussed on the impact damage site, were also used to capture the failure event. The key technical considerations and challenges encountered while developing the test setup are presented in this paper.

Keywords: aircraft, composite, CAI, DIC, UHS, FE models, strain.

Introduction

Composite materials are increasingly becoming a key design material for advanced aerospace structures, given their high strength to low weight ratio, however they are susceptible to out-of-plane impact damage. This may stem from events such as bird strikes, hail damage or dropped tools resulting in barely visible impact damage which may lead to a significant reduction in material residual strength. While post-impact damage response of a composite material system can be determined from specimen destructive testing, it is difficult to incorporate this into Finite Element (FE) models without producing more in-depth strain data. To address this, Defence Science and Technology Group (DSTG) has employed 3D Digital Image Correlation (DIC) and utilised a dual Low-Speed (LS) and Ultra-High-Speed (UHS) camera setup to investigate the full-field surface strain and failure event of a carbon fibre test specimen while it is compressed to failure.

Composite materials created for aircraft applications are generally cured as a stacked ply sequence of pre-impregnated fibres. Material properties are in part determined by the individual fibre and resin properties, the individual ply orientations and the operator’s skill laying up the material. As each material system is different, there exists many challenges to accurately model the failure mechanisms of a composite material before accounting for boundary conditions, structural geometry and material defects. The increased strain data gathered by utilising DIC may assist in increasing the fidelity and accuracy of composite FE models.

One widely used method to measure the residual strength of a composite material is Compression After Impact (CAI) testing which is standardised under ASTM D7136 [1] and

D7137 [2]. A decrease in the strength of any given composite material can be estimated by simulating an out of plane damage event on a test specimen with a drop weight before compressing the specimen axially to failure. Typically, the load and displacement data is collected throughout the test, while the specimen is also instrumented with four back-to-back strain gauges. However, the gauges are bonded near the top of the specimen as they are primarily used to align the specimen in the test machine. As such, these strain gauges measure far-field strains, not localised to the damaged area of interest, limiting the suitability of this data for use in FE models.

To increase the amount of acquired strain data, 3D DIC was selected as a method to collect the surface strain across the entire test specimen. DIC measures strain by tracking the displacement change of a randomised speckle pattern against a contrasting background by analysing a set of images captured over time. DIC software is capable of monitoring surface strain in the plane of the specimen as well as the deformation normal to the specimen when used in conjunction with a pair of calibrated cameras. This allows the system to resolve out of plane displacements, minimising the impact this type of deformation has on the in plane strains measured [3]. Out of plane displacement can also provide a valuable insight into the propagation of a crack from impact damage, which is the expected failure generated from a CAI test, by producing a 3D deformation plot over the lifetime of the test.

In this study, full-field strain data was acquired on the impacted (front) face and rear face of the composite test specimen over the lifetime of the test via 3D DIC with two pairs of LS cameras imaging at 20 Frames Per Second (FPS). Additionally, two UHS cameras, capable of imaging up to 5,000,000 FPS, were used to capture the failure event, enabling the failure mechanism and strain gradients to be further investigated.

This paper describes the developed capability to simultaneously run three pairs of cameras to capture independent surface strains via DIC, including a blend of LS and UHS DIC systems. This capability can be applied to many research applications and is not limited to composite material testing. This paper also details a number of considerations inherent to optimising the experimental test setup while balancing the requirements of each camera system, as well as detail some challenges experienced. Testing has commenced on flat CAI specimens with a view to explore the use of this capability on a curved CAI specimen, which is more representative of aircraft structural components.

Test Specimen Design

A composite panel was manufactured from a high-modulus unidirectional carbon fibre/epoxy prepreg with a 36 ply stiff-orthotropic lay-up and was approximately 5.1 mm thick. Each specimen machined from the panel measured 177.8 mm by 254 mm aligned longitudinally with the loading direction and was impacted with approximately 30 J using a drop-weight in accordance with [1]. The specimen dimensions used here were increased from the standard [2] as impacting standard specimens of the same material led to the damaged area interacting with the drop-weight boundary conditions. Strain gauges were bonded to the specimen, then it was painted matte white in preparation for the application of the black speckle pattern.

Development of Test Setup

DIC has been extensively employed as a measure of change in displacement and hence measure of strain, but the accuracy of the data produced is heavily influenced by the test setup [4, 5]. As the objective was to pair both LS and UHS imaging systems to record strain throughout the same test, the test setup must be configured to meet the independent requirements of each camera system without compromising the output strain data.

Two pairs of 12 Megapixel (MP) Basler cameras acquiring at 20 FPS were focussed on the specimen centre, with one pair looking at the front face and one pair pointed at the rear (shown in Fig. 1a). Additionally, two 0.1 MP UHS Shimadzu HPV-X2 cameras were positioned facing the impacted face of the specimen and acquired at 350,000 FPS. A macro 100 mm lens was installed onto each camera using an adaptor and each camera was vertically aligned with and focussed on the centre of the specimen.

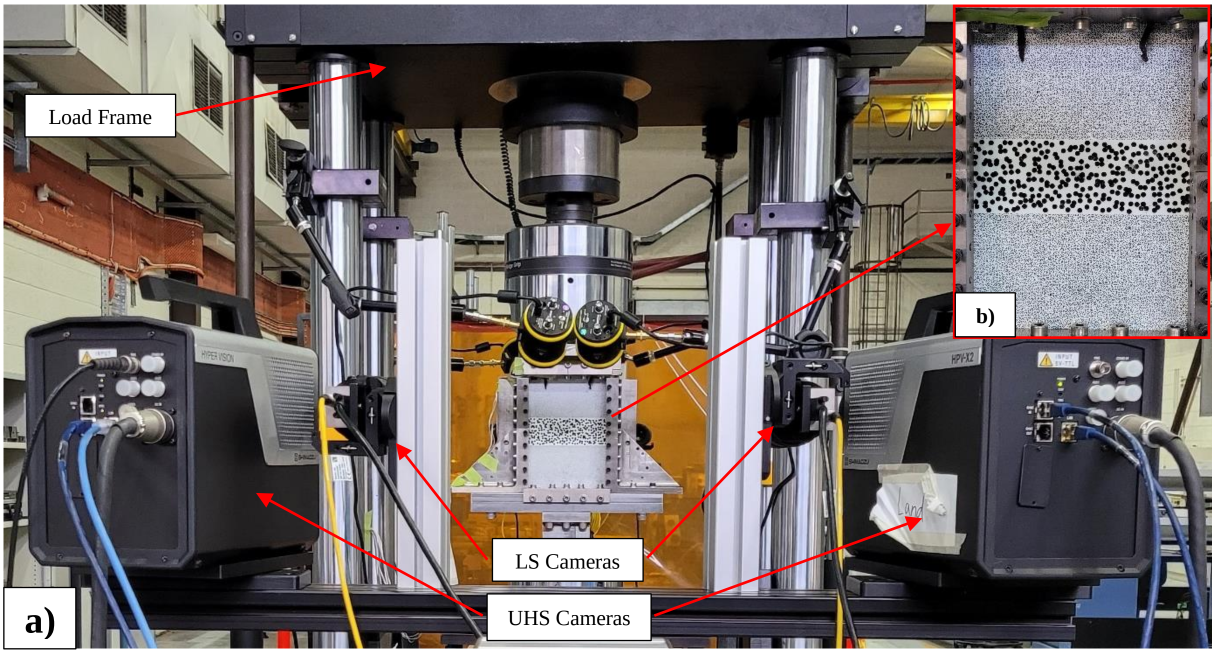

Figure 1a: The test setup indicating the two LS and two UHS cameras facing the front of the impacted specimen (foreground). The test specimen installed in the CAI fixture is visible in the background. Figure 1b: The specimen front face installed in the CAI fixture prior to commencement of test which demonstrates the two different speckle patterns.

The LS camera field of view was defined as the specimen geometry and led to the cameras being positioned 1676 mm from the face of the specimen. This distance allowed the LS cameras to achieve a full-field view of the entire specimen geometry and the UHS cameras to concurrently achieve a full view of the specimen width while focussing on the impact damage. A balanced aperture was adopted, with each lens set to F/8 while the stereo angle of the three camera pairs was measured to ensure consistency between the two LS systems and that it was within the Correlated Solutions Vic-3D 8 Manual and Testing Guide recommendations [6].

The exposure time of the DIC system is variable depending on the light available on the camera sensor but is also influenced by the camera frame rate. As the UHS cameras capture at a far higher frame rate than the LS cameras, the lighting requirements were dictated by its required exposure time (approximately 2,500 ns). Several high-intensity LED lights were mounted from the test machine to supply sufficient light to capture images at UHS frame rate, while the exposure time of the LS cameras was adjusted to prevent overexposure.

The LS camera systems were calibrated individually using the calibration plates supplied by Correlated Solutions. To achieve this, the specimen was replaced with the calibration plate and images were captured of the plate at a number of translational and rotational orientations. Care was taken to ensure that the grid was in view at all times and not overexposed under the LED lights. The resolution of the UHS cameras relative to their distance from the specimen meant that they could not recognise the fiducial points on the Correlated Solutions plates, which are used as reference points of a known offset by the system to create the calibration model. To overcome this, a custom plate was created with larger calibration dots and fiducial points which could be recognised at the cameras given resolution and the pair were calibrated. The projection error for all views was lower than 0.05 for each pair of cameras which was considered an acceptable error score [6].

The design of the test coupon speckle pattern used during DIC is an imperative part of experimentation. The speckle pattern directly influences the noise floor inherent within the process. The most impactful factors defining an optimal speckle pattern can be summarised as a stark black to white contrast, an approximate 50 % distribution between contrasting dots and backgrounds, a random distribution of the features to prevent false matching and a consistent minimum feature diameter of at least 5 pixels to prevent aliasing [6]. Within the design of the speckle pattern, strain resolution and spatial resolution must be considered in order to produce high quality strain measurements. As strain resolution is inversely proportional to spatial resolution [7], a minimum diameter was chosen that suitably accounted for the physical camera resolution limitations while also considering the test field of view.

The LS cameras have a resolution of 3000 x 4000 pixels whereas the UHS cameras have a resolution of 400 x 250 pixels. Rather than compromising the strain quality, two separate speckle designs were developed specific to each system. It was ultimately calculated that an ideal speckle for the LS cameras was approximately 0.3 mm in diameter and approximately 2.25 mm for the UHS cameras. It should be noted if the images are captured with cameras that are pixel binned, this will influence what the software recognises as an optimal speckle pattern.

In order to enable the application of a quantifiably random but repeatable dot pattern to the test specimen, the development of a stencil was necessary. This enabled painting of the black dots while also providing some protection to the white space integrity which is critical to achieve a stark contrast required for quality DIC results. A random dot pattern of 75 % density and 75 % variability was generated using the Speckle Generator Tool [8] and laser cut into a sheet of mylar film using a Trotec Speedy 400 Laser Engraver. The power, velocity and wavelength settings are able to be varied and hence an iterative approach was employed to determine the settings which produce an optimal stencil. A number of small sample speckle patterns were cut into a mylar film with varied laser settings, which were then evaluated under a microscope. Settings which had pierced the film well without burning the edges and showed a consistent dot diameter were selected and the others discarded.

Once optimal laser settings were identified, a stencil was produced which matched the specimen geometry and the speckle was applied to the specimen. The rear face was painted entirely with the speckle specific to the LS system. For the front face, a 54 mm x 177.8 mm band in the centre was painted with the speckle pattern specific to UHS cameras and the remaining 100 mm x 177.8 mm areas were painted with the smaller speckle pattern (as viewed in Fig. 1b).

Mechanical Testing

The painted test specimen was installed in an adjustable CAI fixture and mounted in a 250 kN Instron load frame. The top compression platen was shimmed to balance the alignment, guided by the strain gauge output. An approximate 10 % variance between the gauges was considered acceptable. Reference images of the unloaded specimen were captured prior to the test commencing. The specimen was loaded in compression at a rate of 0.5 mm/min until failure. The time, displacement, load and strain gauge readings were recorded. Additionally, the test was recorded using the camera setup described above using Vic-Snap 9 with a view for the results to be analysed using Vic-3D 9.

Discussion

A number of technical challenges were encountered while developing the camera system setup. The UHS cameras when used as a stereographical pair have limited memory storage. The camera is able to capture only 128 frames on a continuously looped on-board memory chip and requires a trigger pulse to stop over-writing the images. After the test, the images were downloaded from the camera memory chip to the PC hard drive. The MTS FlexTest 40 test controller which operates the servo-hydraulic machine was unable to send a pulse trigger fast enough to the camera to capture the failure event as it is limited to a maximum system update rate of 6,144 Hz. This was overcome by developing a dedicated trigger box, which interfaced directly between the load cell and the controller. It intercepted the drop in voltage (i.e. load), which occurred at specimen failure, and sent the pulse to the cameras before the controller received the signal. The selection of the frame rate was heavily influenced by the limitation of 128 frames storage capacity and the speed which the trigger pulse was received.

The speckle pattern for each camera system was determined using non-pixel binned images. To produce a 0.3 mm diameter speckle on the specimen, the laser settings were required to be varied to cut a stencil with 0.4 mm diameter holes. To achieve the ideal 2.25 mm diameter speckle for the UHS system, density was varied to 85 % and the stencil hole diameter was increased to 2.7 mm.

To interrogate optimal speckle parameters a specimen painted with trial speckle patterns was placed in front of the DIC cameras, configured per the proposed test setup, on an X/Y table which can be translated via a micrometre. The speckle sample was evaluated by translating the specimen a known distance using the micrometre, in five 1 mm increments, and comparing these values with the displacement determined by the DIC software. The DIC displacement confidence margins were then evaluated for each speckle sample and the speckle with the highest confidence and lowest error was selected. This process was undertaken for both the LS and UHS speckle patterns. This iterative process reduces measurement noise and the possibility of aliasing, which increases the integrity of the strain output.

Powerful lights are necessary to meet the lighting requirements of the UHS cameras. These lights were initially mounted to the load frame and therefore were close to the optical pathway. The heat produced from these lights distorted the air medium within the optical pathway and was observed as heat haze in the captured images resulting in noise being introduced into the DIC data. Very little can be done to remove this distortion when processing the data and hence it must be minimised in the test setup. As the majority of heat from the lights is generated from the unit itself, repositioning the lights further away from the optical pathway would eliminate much of this distortion. Ideally, the lights should be positioned behind or above the camera units. If this is not possible, introducing a fan to mix the air across the optical pathway may reduce or eliminate the image distortion from heat haze, which is recommended in the DIC Correlated Solutions Manual [6]. The presence of heat haze across the optical pathway can be checked by taking a number of static images prior to testing and analysing the images for relative movement of the speckle pattern [9].

Conclusion

A carbon fibre test specimen was subjected to an approximate 30 J impact and painted matte white before a random matte black speckle pattern was applied using a stencil. The specimen was subjected to CAI testing while load and displacement data was captured and three pairs of cameras recorded full-field strain using DIC at both LS and UHS. To optimise the test setup a number of requirements independent to each imaging system were critically evaluated in order to setup the test in a manner which did not compromise the data produced by either system. The speckle size was interrogated for each camera system and two different speckle patterns were selected that enabled the highest quality full-field strain data to be output via DIC. Establishing the test setup presented a number of technical challenges which have been evaluated and solutions have been recommended to address each of these challenges.

Acknowledgements

The authors would like to acknowledge the technical expertise of Greg Beziuk from DSTG for developing the UHS camera trigger box, and acknowledge Michael Forsey from RMIT University, Kasi Metcalfe and Loc Tran from QinetiQ for their technical advice of the DIC setup. Gratitude is expressed to Katherine Grigoriou from RMIT University and Jordan Carroll from DSTG for their technical input during the writing of this paper. Finally, the authors would like to acknowledge the support of Ben Main from DSTG and Simon Barter and Pier Marzocca from RMIT University for supporting the increased cooperation between RMIT and DSTG in composites research, and the Fatigue and Fracture Laboratory at DSTG for providing resources for this testing.

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