Application of optical measurement techniques to high strain rate deformations in composite materials

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ABSTRACT

Traditionally high strain rate material characterisations have been conducted using strain gauges and/or cross head displacements in servo-hydraulic test machines, and force transducers in split Hopkinson bar experiments. Non-contact full-field techniques for experimental stress/strain analysis have been available for many years and used extensively for structural analysis under static or quasi static loading. These techniques have the advantage that they are non-contact and high resolution, so damage initiation can be captured within the field of view and the material behaviour is not modified by the sensor. In the paper, one such technique known as Digital Image Correlation (DIC) is used to assess the material behaviour by using high-speed digital cameras to capture images from material subject to high strain rate events. The high strain rate loading is achieved using an Instron VHS high speed tensile test machine that allows the applied strain rates to vary from 12.5 s^{-1} to 125 s^{-1}. Although the strain rates that can be achieved are low in comparison to those achieved with the Hopkinson bar, the test machine provides better optical access and opportunities for illumination of the specimen necessary for the DIC. In the paper, a review of the literature associated with high strain rate testing using servo-hydraulic machines is first provided. Then, an experimental study of the high strain rate behaviour of the both composite material and the resin alone is described. The results from both the DIC and strain gauges are compared and discussed.

KEYWORDS: Composite Materials, High Strain Rate, Tensile Test, Digital Image Correlation (DIC).

1. INTRODUCTION

It is well-known that the properties of polymer composite materials are a combination of the individual constitutive materials properties and of their interface. In-service polymer composite materials must withstand severe static loads as well as high velocity events, such as shock and blast loading. The assessment and the modelling of composite materials are difficult because of their multi-scale nature, which can be described in the following ways:

1. As a bulk material where the properties are described simply as those of a homogeneous material.
2. As a laminated material by considering a sequence of stacked layers.
3. Each ply, or lamina, composed of two different phases with considerably different mechanical characteristics.

The behaviour of fibre reinforced polymer composites under quasi static loading is generally well understood. To extend the application of composite materials to primary structures in a cost effective manner, further investigation of their behaviour under high strain rate loading is required. In the paper, an experimental study of the high strain rate behaviour of both composite materials and the resin alone is described.

A complete, even if dated, review on techniques to test composite materials at high strain rate can be found in the work by Hamouda and Hashmi [1].The techniques used to assess the tensile properties of composite materials at different strain rates have been summarised by Sierakowski [2] and shown in Table 1.

Table 1: Experimental techniques, [1] and [2]

Technique	Strain rate (s^{-1})
Conventional Machine	≤ 0.1
Falling Weight	≤ 10
Servo-hydraulic	$0.1 \rightarrow 100$
Charpy pendulum	≤ 100
Split Hopkinson Bar	$100 \rightarrow 10^4$
Expanding ring	10^4
Flayer plate and ballistic impact	$\geq 10^5$

A detailed survey of the literature has shown, unsurprisingly, that the most widely used technique to test the high rate response of composite materials is the Split Hopkinson Bar. This approach allows very high strain rates to be achieved but presents criticality in the specimen connection to the machine and limits the size of the material to be tested to a relatively small coupon. Bardenheider and Rogers [3] stated that servo-hydraulic machines give access to an intermediate strain rate, difficult to access with the other testing techniques. Nowadays, servo-hydraulic high rate test machines allow cross-head displacement speed from quasi-static to 25 m/s to be achieved. This means the characteristic test duration may range from 10 to 10^{-5} s and strain rates between 10^{-3} and 10^{3} can be applied. The behaviour of composite materials within the strain rate range achievable with servo-hydraulic machines has not been investigated in great depth. Wang et al. [4] used an Instron VHS servo-hydraulic test machine to test glass and carbon reinforced epoxy specimens at strain rates between 15 and 43 s^{-1}. In the work of Fitoussi et al. [5], a servo-hydraulic machine was used to achieve strain rates between 0.5 and 60 s^{-1}. In [6], strain rates between 10^{-3} and 100 s^{-1} were achieved using specimens with gauge length and width of 12.7 mm^2.

Over the last decade, the development of high speed cameras has made it possible to capture images with high temporal resolution. The availability of such images allowed the development of new methodologies for obtaining the surface strains, such as the Digital Image Correlation (DIC). The advantages of such techniques appear evident:

- There is no mechanical interaction between the measurand and the sensor and therefore the system is not modified by the measurement process.
- Compromising between the measurement field and the resolution makes it possible to measure over a large area, allowing full-field measurements.

Grediac [7, 8] describes the importance of full-field methods for the modelling of composite materials. Full-field techniques enable the relaxation of the restrictions on specimen dimensions and loading conditions, to inform on the complete stress-strain field hence allowing the identification of heterogeneities in the field and enabling their inclusion in modelling. Furthermore, full-field techniques have the potential to reduce the number of experiments and sensors required to identify all the parameters for characterising an anisotropic material [7].

DIC is a full-field, non interferometric optical technique that utilizes and tracks the grey scale contrast on a deforming surface. The correlation algorithm uses the tracking to provide deformation vectors, from which the surface strains are derived. All that is required for DIC is a high resolution image in the reference or undeformed state and one in the deformed state. To date there have only been a few works reported on using DIC on composite materials, e.g. [9- 12]. From these, the potential advantages of using DIC are identified as:

- The availability of the full strain-displacement field.
- The possibility of experimentally determining all the components of strain (normal and shear) on the observed surface.

These characteristics are particularly helpful in developing a constitutive theory. The knowledge of strain components and their spatial variation, on the fully measured surface is better than the local values obtained, for example, with strain gauges. At the same time, this technique allows the acquisition of data that are accurate enough to perform modulus calculations at low strains and to determine constitutive model parameters at larger strains. Despite these significant advantages, the limitation of DIC lies in the compromise between spatial resolution and strain resolution. Generally, increases in spatial resolution mean less precision in the strain measurement. Improving the resolution of the cameras (i.e. adding more sensors to the detector array) improves the spatial resolution, but at a cost of image processing time. Adding to this, the requirement for high speed image capture produces a further cost on strain resolution and spatial resolution. In most cases, increased image capture speed means reducing the size of the sensor array. Moreover as the pixel integration times are reduced, there is a need for increased lighting to obtain workable images. The constant improvement of imaging devices has meant that image capture speeds are now available with sufficient sensitivity to deal with small integration times. This combined with larger sensor arrays has provided the opportunity to apply DIC to high strain rate events.

2. METHODOLOGY

Tensile tests have been carried out on specimens of MTM28-1 epoxy resin, both unreinforced and reinforced with 32% E-GLASS-200 fibre content. The pure resin was supplied as sheets identical to those obtained with the pre-preg used to make the glass reinforced specimens. Both materials were supplied by Advanced Composites Group Ltd. Both the pre-preg and the pure resin specimens were prepared in autoclave following the same curing cycle. To avoid exothermic reaction, a pre-curing period of 1 hour at 90°C took place, then the temperature was increased to 120°C for another hour, a constant pressure of 5 bar was applied during the curing. The glass fibre specimen geometry is shown in Figure 1.

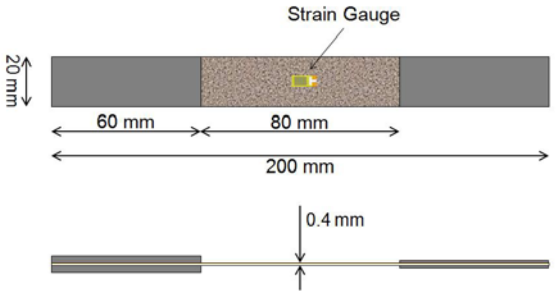

Figure 1: Test specimen geometry

The tests have been performed with cross head speeds, V, of 1, 5 and 10 m/s. Considering a useful length, L, of 80 mm, strain rates of 12.5, 62.5 and 125 s^{-1} were calculated as $\dot{\varepsilon} = V/L$.

The experimental apparatus used during these experiments is shown in Figure 2. The Instron VHS 80/20 is a high speed servo-hydraulic test machine able to develop cross head displacement speeds between 1 and 20 m/s. The machine works by accumulating oil at a pressure of 280 bar in a pressure tank regulated by a proportional valve. This valve is controlled by a system that releases the energy to move the actuator at the required testing speed. The actuator is capable of developing a force of 80 kN. To obtain a velocity of 20 m/s, an actuator acceleration travel of 150 mm is required. The Instron VHS is equipped with a fast jaw system to address the problem of the inertia of the system and to enable the specimen to be loaded at a constant rate once the actuator has reached the required speed. When mounting the specimen on the test machine, the jaw faces are kept apart by clamping them around two wedges and the tightening of four bolts. Initially the actuator accelerates downwards without touching the specimen, which passes freely between the grips as in Figure 3, a). At the desired position, two knock out pins, that are rigidity connected to the test machine, stop the wedges (Figure 3, b)) and the jaws are free to clamp the specimen (Figure 3, c)). The 100 kN Kistler piezo-electric load cell is connected to a charge amplifier from which data can be collected over four channels at a maximum frequency of 65 KHz.

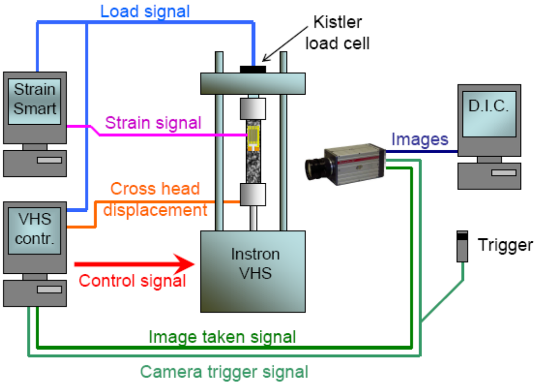

Figure 2: Experimental set-up

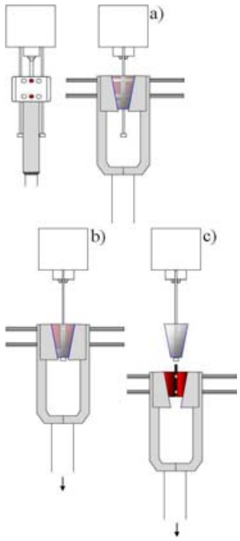

Figure 3: Fast Jaw system operation: a) The actuator accelerates, the specimen is not clamped. b) The wedges hit the knock out pins, the specimen is clamped c) The specimens is loaded

All the specimens were equipped with a CEA-06-240UZ-120 Vishay strain gauge (see Figure 1), which comprises a 6 mm long active grid on a polyamide backing. This gauge type is the standard choice for composite material testing and can withstand strains up to 3-5%. According to the results of quasi-static tests, this is greater than the ultimate tensile strain. The strain gauges were bonded on the specimens using a cynoacrylate adhesive. To optimize the adhesion, the bonding surface was roughened with a silicon-carbide paper, degreased and conditioned according to the strain gauge manufacturer's instructions.

The strain gauge data was collected using a Vishay Strain Smart 6000 data acquisition system. This system allows data to be recorded at a maximum sampling rate of 10.2 kHz. In these experiments, two channels were used: a strain channel to acquire the strain reading from the strain gauge installed on the specimen and a high level card to record the load signal from the load cell, making it possible to record simultaneously the strain and the associated load.

To perform the DIC, a Redlake Motion Pro X3 high speed camera was used to acquire the images and the DaVis 7.4 software from LaVision for the image correlation. The camera is monochromatic and able to acquire images over frame rates of 1 kHz with a resolution of 1280 × 1024 pixel up to 64 kHz with a resolution of 1280 × 16 pixel. In the present paper, a resolution of 1280 × 300 pixel was used; this enables an image of the whole specimen surface to be captured at a frame rate of about 7 kHz. The camera can capture a preselected number of frames before and/or after receiving a trigger signal. At the same time, it is capable of generating a signal every time a frame is recorded. In this configuration the camera can constantly record images of the specimen. The tests (from start to specimen failure) take only 1 ms to complete, hence it is vital that the camera captures images during this period. To facilitate correct image capture, after the specimens failed, the camera was triggered and images from the 3 seconds prior to failure, and therefore of the test itself, were acquired. To evaluate the stress-strain curve, it is necessary to synchronise the images and, consequently, the strain evaluated with DIC with the load recorded by the load cell. To provide sufficient illumination to capture images with the appropriate contrast for DIC, a high power halogen lamp was used to illuminate the specimen.

DaVis 7.4 software has been used to perform 2D DIC on the acquired pictures. An array of 4 × 16 interrogation cells of 64 × 64 pixel with no overlapping with the neighbouring cells has been chosen. The speckle pattern was applied using aerosol spray of white and black paint on a surface that was uniformly painted in grey. On average, a single speckle is sampled by an array of 7 × 7 pixels. It is believed that this configuration allows a strain resolution of 200 µstrains. The strains are calculated relative to a reference image of the unloaded specimen.

3. RESULTS

Typical stress-strain curves obtained from the tests on the glass fibre and pure epoxy specimens are shown in Figures 4 and 5. It can be seen that there is some scatter in the data but in general there is good correspondence between the strain gauge results and the DIC. The results from the three glass fibre specimens show good correspondence; there is more scatter in the results from the pure resin. Both types of strain data collected allowed the evaluation the Young's modulus. Increasing test speed reduced the amount of data collected but was sufficient to calculate the modulus. The value of modulus was obtained from quasi-static test as 42.2 GPa for the glass fibre material; Table 2 summarises the modulus values obtained from the high speed tests. It can be seen in general that the Young's modulus is greater at higher strain rates, which is consistent with reports in the literature. However, the values from the strain gauge show a decrease in modulus with increasing strain rate, whilst the DIC shows an increase. The unexpected results from the strain gauges could be attributed to sampling rate and will be investigated in future work. However, there is no doubt that the DIC is producing 'sensible results' of the correct order; these will be fully verified in future work.

Table 2: Young's modulus of the glass fibre specimen

Strain rate [s^{-1}]	Young's Modulus [GPa]	
	From strain gauge	From DIC
12.5	69.3 ± 5.8	55.6 ± 6.7
65.5	59.9 ± 1.9	61.2 ± 3.2
125	54.9 ± 5.2	64.8 ± 1.3

4. CONCLUSIONS

The work in the paper has demonstrated that it is feasible to obtain stress-strain data using DIC from relatively low resolution images. The critical issue in the methodology is the synchronisation of the images with the load data. Currently this is done in a rather empirical way. Further development of the experimental apparatus will involve the possibility of automatically associating the images to the corresponding load. It is also necessary to achieve a greater sampling rate. More tests are required on more specimens to reduce the uncertainty and improve the quality of the stress-strain curves for the material characterisation. Future work also will investigate different laminate configurations and strain rates.

References

[1] A. M. S. Hamouda and M. S. J. Hashmi. Testing of composite materials at high rates of strain: advances and challenges. Journal of Materials Processing Technology, 77(1-3):327-336, 1998.
[2] R.L Sierakowski. Strain rate effects in composites. ASME, 1997.
[3] R. Bardenheider and G. Rogers. Dynamic Impact Testing. Instron, 2003.
[4] W. Wang, G. Makarov, and R. A. Shenoi. An analytical model for assessing strain rate sensitivity of unidirectional composite laminates. Composite Structures, 69(1):45-54, 2005.
[5] J. Fitoussi, F. Meraghni, Z. Jendli, G. Hug, and D. Baptiste. Experimental methodology for high strain-rates tensile behaviour analysis of polymer matrix composites. Composites Science and Technology, 65(14):2174-2188, 2005.
[6] M. M. Shokrieh and M. J. Omidi. Tension behavior of unidirectional glass/epoxy composites under different strain rates. Composite Structures, 88(4):595-601, 2009.
[7] M. Grediac. The use of full-field measurement methods in composite material characterization: interest and limitations. Composites Part A: Applied Science and Manufacturing, 35(7-8):751-761, 2004.
[8] M. Grediac Importance of full-field measurement techniques for better models in solid mechanics. Experimental Analysis of Nano and Engineering Materials and Structures, 13-14. 2007.
[9] J.N. Perie, S. Calloch, C. Cluzel, and F. Hild. Analysis o a multiaxial test on a c/c composite by using digital image correlation and a damage model. Experimental Mechanics, 42(3):318-328, 2002.
[10] G. P. Mogadpalli and V. Parameswaran. Determination of stress intensity factor for cracks in orthotropic composite materials using digital image correlation. Strain, 44(6):446-452, 2008.
[11] D. R. Hufner and M. L. Accorsi. A progressive failure theory for woven polymer-based composites subjected to dynamic loading. Composite Structures, 89(2):177-185, 2009.
[12] D. Lee, H. V. Tippur, and P. Bogert. Quasi-static and dynamic fracture of graphite/epoxy composites: An optical study of loading-rate effects. Composites Part B: Engineering, In Press, Corrected Proof, 2010.

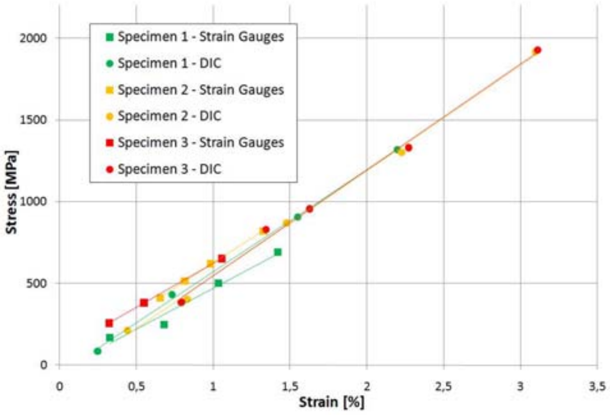

Figure 4: Glass reinforced epoxy at 125 s^{-1}

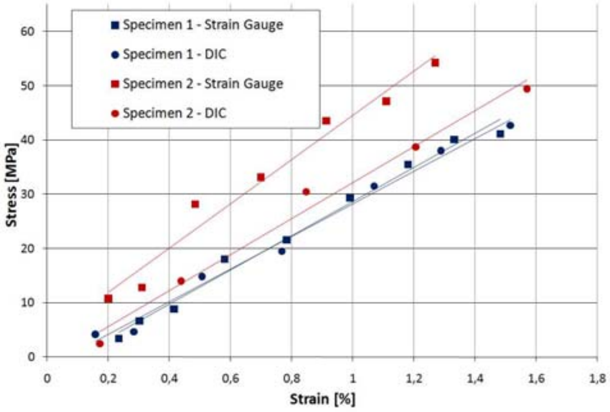

Figure 5: Pure epoxy at 12.5 s^{-1}