MEASURING VISCO-ELASTIC BEHAVIOR OF COMPOSITES AT HIGH STRAIN RATES USING OPTICAL TECHNIQUES

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Abstract
Optical measurement techniques are used to investigate the effect of strain rate on fibre reinforced polymer (FRP) composites. It is proposed that at elevated loading speeds the viscoelastic nature of the polymer matrix causes localised specimen heating. Thus, a methodology that uses two optical techniques in a synchronised manner to measure the evolution of full-field strain and temperature is applied. The technique combines digital image correlation (DIC), on white light images from a high speed camera, and infra-red thermography (IRT). The approach is applied to glass fibre prepreg specimens in a crossply configuration, where the orientation of the surface ply is either 0° (longitudinal) or 90° (transverse). There are differences in the results from the specimen with the transverse surface ply and the longitudinal surface ply that can be attributed to the viscoelastic behaviour of the polymer matrix.

1 Introduction

The excellent specific strength and stiffness properties of fibre reinforced polymer (FRP) composites make them an attractive selection for designers to improve the structural efficiency of vehicles. Lighter vehicles are faster and more manoeuvrable, and importantly in the current environmental and economic climate will use less fuel and emit less carbon. For this reason FRP composites are also finding increased use in high performance applications, e.g. military structures, that are likely to be subjected to impact or blast events imparting high velocity loading. Whilst the behaviour of such materials subjected to quasi-static elastic loading is reasonably well understood, the response to high strain rate requires further investigation. To reduce and mitigate the risk of failure it is essential that knowledge of the behaviour of these materials under high velocity deformation is established. Hence the subsequent effects of damage on structural performance can be defined. Therefore the motivation for this work is the need to map the effect of high velocity loading on the overall structural performance. High velocity/strain rate deformations are usually accompanied by a temperature evolution. Therefore the material behaviour is a function of time, strain and temperature, so to fully understand the material structural performance the thermomechanical material constitutive behaviour is required. The overarching aim of the current research is to provide thermomechanical characterisations of glass and carbon fibre polymer composite over a range of strain rates, with the ultimate goal of inputting the constitutive behaviour into a finite element (FE) modelling approach.

Hamouda [1] and Sierakowski [2] discuss the range of approaches for high strain rate testing. The preferred technique is the split Hopkinson pressure (SHPB)bar that allows strain rates up to 10^4 s^{-1}. However in this work a specialised servo-hydraulic test machine (Instron VHS) is used, which allows moderate strain rates up to 10^2 s^{-1}. Whilst this machine cannot match the strain rates of the SHPB, it allows specimens of approximately 25 mm wide by 100 mm long to be used, unlike the much smaller coupons that must be used in conjunction with the SHPB. The specimens used with the VHS are of a similar size, and aspect ratio, to those recommended for quasi-static characterisation in testing standards and, therefore, provides a larger surface for the application of optical measurement techniques.

The complex behaviour of fibre reinforced composite materials lends itself to the use of full-field optical measurement techniques, as information from the entire specimen is obtained that allows the identification of failure zones, loading paths, etc. Digital image correlation (DIC) [3] is used to measure strain, and infra-red thermography (IRT) [4] to obtain the temperature evolution. One of the primary advantages of techniques such as DIC and IRT is that they are non-contacting, so the measurand does not affect the measurement by, for example, localised reinforcement or heating. However, it is essential that the images are synchronised temporally with any independent load or strain data collected from other sensors used in the experiment. Therefore the relative image capture rates, time delays and thresholding are important considerations. The aim of the current paper is to discuss the application of the synchronised optical measurement methodology to obtain the strain and temperature evolution of the surface of glass FRP composite specimens. The viscoelastic behaviour of crossply specimens with transverse and longitudinal surface plies are investigated, aiming to discern if the resin dominated transverse ply will heat more than the fibre dominated longitudinal ply.

2 High rate testing and synchronised optical technique methodology

2.1 Test and specimen setup

The FRP composite specimens were subjected to a controlled high velocity tensile load by a the VHS test machine [5], which is capable of actuator movements of up to 20 m/s at loads up to 80 kN. The machine uses a reservoir of oil, charged to 28 MPa, to move the actuator at high speed from the top of its travel to the bottom. There is no feedback in the system, and instead the speed is controlled by pre-set, calibrated, release of oil pressure. The actuator starts at rest, and hence requires time, and travel, to accelerate to the correct velocity. At 20 m/s, the actuator must travel up to 150 mm before the correct speed is achieved. Therefore a slack adaptor is used to remove the inertia effects of the acceleration, ensuring the specimen is not loaded until the actuator is moving at constant speed. The load is measured using a Kistler piezoelectric washer load cell 9071A, which is not as susceptible to load-cell ringing as resistance strain gauge based load cells at high loading speeds.

Specimens were cut from a laminate manufactured from unidirectional (UD) glass prepreg, ACG MTM28-1\E-glass-200 in a symmetrical crossply configuration. The specimens were designed to be 1 mm thick, and therefore eight layers of the UD prepreg were required. The orientation of the surface ply on the specimen was selected to be longitudinal or transverse by cutting the laminate in two directions. The tests were performed at 5 m/s on the VHS providing a strain rate of ~ 50 s^{-1}.

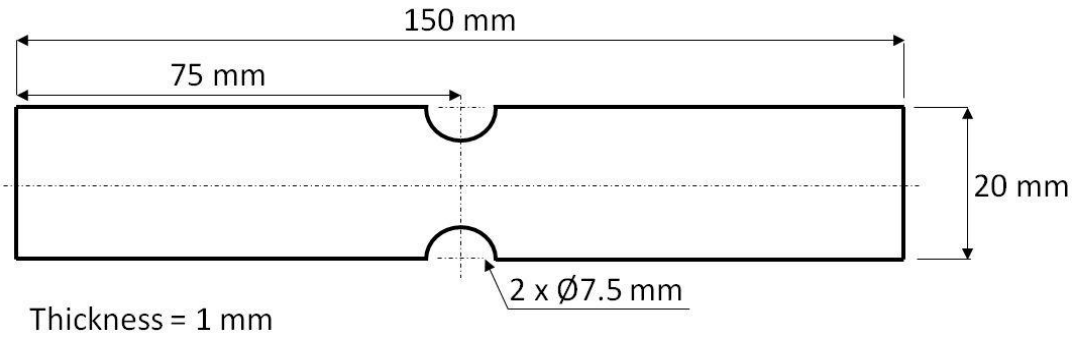

Figure 1. Wasted specimen dimensions to define failure zone for optical measurement

2.2 High speed digital image correlation

DIC is a full-field, optical method that measures the deformations and strains in a material or structure. DIC tracks the movement of a random surface pattern to monitor deformation or displacement. The random pattern is usually achieved by covering the surface of a component with a painted speckle pattern. Images of the deformation process are recorded using either one (2D DIC) or two (3D DIC) charge coupled device (CCD) cameras. The images are divided into discrete interrogation windows (or cells) and the displacement is obtained by tracking features within each cell [3]. Strain values are obtained by taking the measured displacement and dividing by the length of the undeformed cell. Strain resolutions are quoted as being as low as 40 μstrain [6], although this is highly dependent upon application and test conditions, such as lighting and alignment. The DIC technique has been successfully used to analyse the strains in heterogeneous engineering materials such as composites [7] and there is some reported work on the use of high speed cameras to collect images for DIC [8, 9]. Tiwari *et al* [8] described the use of high speed cameras for DIC, and the inherent limitations of such an approach. To apply DIC to high velocity testing, commercially available high speed digital cameras are used to record the images. In this work the images are then imported into the DaVis 7.4 (LaVision) software for analysis. The application of DIC to high speed imaging uses the same speckle analysis algorithm as that applied at quasi-static test speeds. The accuracy of the algorithm is the same as quoted above, but additional sources of error are likely, due to the acquisition of images using high speed cameras. To obtain images at the highest possible frame rates it is necessary to reduce the resolution of the sensor, therefore the user must accept a coarse strain map or use interrogation cells with fewer pixels which give greater uncertainty in the strain result. Secondly it is more difficult to obtain well illuminated images with high contrast at high speed as the integration time must be reduced. Therefore it is important to increase the lighting intensity which may have adverse effects such as specimen heating, or heat haze in the images.

In the work described in this paper images were recorded using a single Photron SA-3 high speed camera. The SA-3 has a maximum resolution of 1024 x 1024 pixels, and is capable of maintaining this resolution up to 2 kHz. However in these tests the images were sub-windowed to 512 x 256 pixels, providing a framing rate of 5 kHz and an acceptable compromise between spatial and temporal resolution. Figure 2 shows an example of the specimen in-situ alongside an example of the sub-windowed image. The images were processed using LaVision's Davis 7.4 software using a cell size of 64 x 64 pixels and 75 % cell overlap, therefore providing a strain map with 32 x 16 data points. Figure 2 (c) provides an example longitudinal strain map processed from the sub-windowed high speed image. The strain map is unsmoothed, and it is possible to see the individual integration cells.

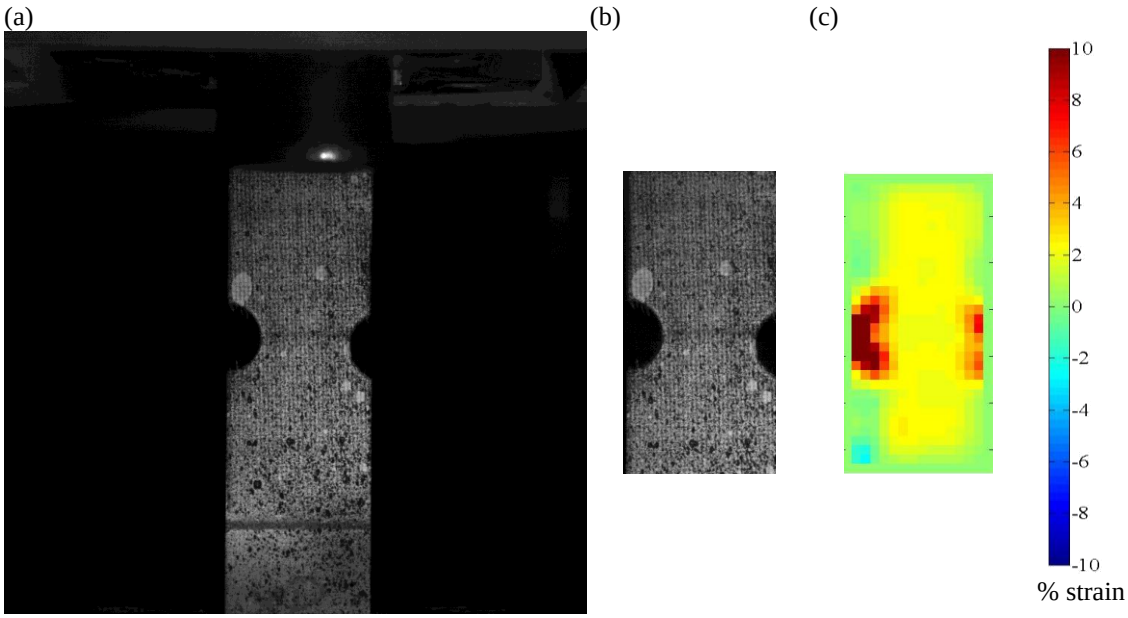

Figure 2. (a) example image of full window from Photron SA-3 of wasted specimen in VHS machine, (b) example of sub-windowed image, (c) example of longitudinal strain from DIC

2.3 High speed infra-red thermography

Infra-red thermography uses an infra-red (IR) detector to monitor the emissions from the surface of a structure, from which the surface temperature is derived. IRT is therefore a full-field non-contacting technique for temperature measurement that has a sensitivity determined by the thermal resolution of the IR detector, and spatial resolution determined by the number of elements in the detector array. IRT has a large range of commercial uses for non-contact temperature measurement, such as detecting hot-spots in structures that may identify sub-surface damage in non-destructive testing [4]. Commercially available IR detectors, such as those from FLIR systems, are capable of image capture speeds of 100s Hz with detector array sizes upwards of 320 x 256. Using these detectors to capture data at higher frame rates has the same limitations as the white light high speed cameras used for DIC. The internal electronics that control data transfer from the detector elements into digitised values enforce a limit on the total number of samples from all elements per second. Therefore to improve the frame rate the number of detector elements utilised must be reduced.

An important factor in high framing rate optical measurement is the integration time. To achieve higher framing rates it is necessary to reduce the integration time to avoid overlap between successive images. A reduction in integration time will lead to a low response due to a reduction in the photons exciting the sensor. In white light imaging, it is possible to counter the effects of lower integration times by increasing illumination and therefore maintaining an adequate amount of photons striking the CCD array. However, IRT is a special case, and is dependent on the finite amount of energy emitted from the materials surface due to its temperature. The amount of photons and the sensitivity of the detector elements therefore limit the minimum integration time and hence the maximum frame rate given that the integration time must be equal to or less than the reciprocal of the frame rate. There is little research reported in the literature on the use of high speed IR; however a couple of examples found used specifically designed systems. Noble [10] described the use of a thermal scanning camera to measure the temperature change occurring during high strain rate test on ductile iron at a rate of 1600 s^{-1} in a split Hopkinson bar rig. The scanner was an AGEMA 880LWB that used a liquid-nitrogen cooled CdHgTe detector with a temperature resolution of ± 2 K.

The camera was only capable of scanning at 2500 Hz, and therefore was not fast enough to record temperature evolution during the test. Instead the camera recorded the temperature change approximately 0.5 ms after specimen fracture. The nature of the material tested, and the high speed applied, produced temperatures up to 573 K at the necking site. Three possible error sources were identified that could account for uncertainty of ~ 100 K; movement of the specimen with respect to the camera, change of specimen orientation and changing emissivity during deformation. Improvements in electronics allowed Zehnder [11, 12], to produce a system capable of 1 MHz with 64 HgCdTe detector elements in an 8 x 8 planar array. Studies of the temperature rise near the tip of a notch in high strength steel subjected to an impact showed thatthe system was capable of a temperature resolution of approximately ± 2 K.

In the current work infrared data were recorded using a commercially available Silver 480M (FLIR systems) detector. The Silver 480M uses a dual layer InSb sensor with 320 x 256 pixels. At maximum resolution it is possible to capture data at 383 Hz, and by windowing down to 48 x 4 pixels it is possible to achieve 20 kHz. It was decided to operate the detector at 15 kHz with a window of 64 x 12 and an integration time of 60 μs as a compromise between spatial, temporal and temperature resolution. When operating the detector outside of its standard configuration it is necessary to perform calibration and non-uniformity correction procedures different to those provided by the manufacturers. These processes set up the detector and the internal electronics for use at higher speeds, and altered window size, to allow calibrated temperatures to be measured. Full details of the calibration and non-uniformity techniques, and their requirement, are discussed in [13]. Figure 3 demonstrates the importance of the in-house calibration and non-uniformity, providing an example of data before and after the procedure. The data pre-calibration is shown in digital levels, and the specimen is not discernible; some artefacts of the sensor are visible in vertical striations. After the calibration the shape of the wasted area of the specimen is evident, with the cooler background in contrast.

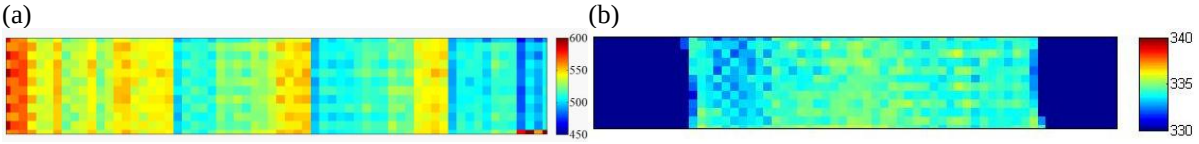

Figure 3. (a) example of uncalibrated IR in digital levels (DL), (b) example of calibrated IR in Kelvin (K)

2.4 Synchronised high speed optical testing approach

It has been previously noted that the overall goal of the research is to obtain full-field temperature and strain information from composite materials subjected to high velocity loading. Previous work [5, 13] has shown promise from the two techniques separately applied at high framing rates, although further work is required to improve consistency and confidence in the results. The next step is to develop an approach that will allow both systems to capture data concurrently. In the literature there is little mention of the use of white light imaging and IRT together, particularly at high speed. Noble [14], used the IR system mentioned above and a white light high speed camera during a test on iron in a split Hopkinson bar rig. The white light camera was used to obtain deformation information by monitoring the change in shape of the specimen, and did not provide full-field strain. The IR system did not operate at a high enough sampling rate to capture temperature evolution during the test. Instead it was triggered shortly after the specimen failure to measure the maximum temperature at the fracture site.

In the current tests an approach is required to synchronise the capture of load data from the VHS controller, strain data from the DIC system and, temperature data from the IRT system. The white light cameras and IR detector can be triggered from a digital pulse with a known jitter of the order of 100 ns. Therefore a pulse generator is used to monitor the actuator displacement of the VHS for a user pre-set value, at which point a trigger signal is sent to all three systems. The entire operation is illustrated in the schematic shown in Figure 4.

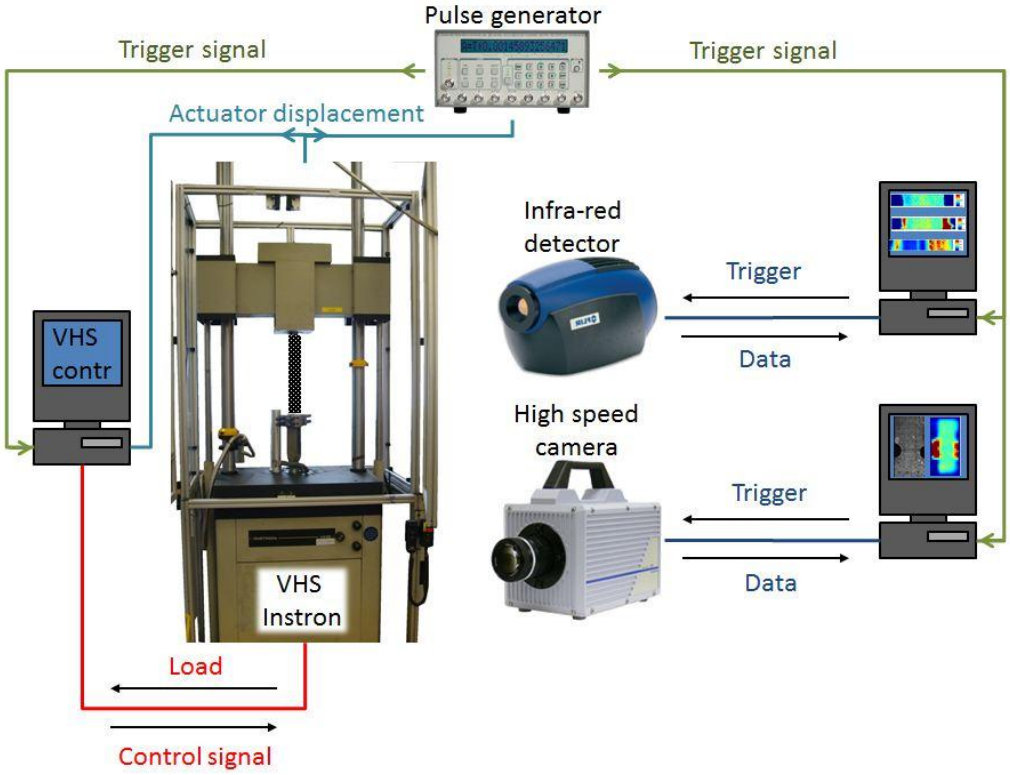

Figure 4. Schematic of approach for synchronised capture of strain and temperature data from tests on VHS Instron machine using optical measurement techniques

A further challenge in synchronising the two optical techniques is in the physical collection of the white light and IR images. DIC requires the specimen surface to be coated with a speckle pattern, whilst, to obtain the best results, IR requires a specimen with a uniform and matt surface free from reflection. Furthermore, the lights required to utilise the dynamic range of the sensors in the white light imaging cause a heating effect measureable by the IRT. The specimens tested here were prepared with a coat of matt white paint, and then speckled with matt black paint. It had been previously found that this type of speckle provided images with good contrast for DIC even in lower illumination conditions. However, it is possible that such a paint coating may adversely affect the IRT measurement in terms of temperature lag or attenuation. The next section presents initial results from the combined DIC/IRT technique to ascertain if it is feasible to obtain a noticeable difference between specimen types.

3 Results and discussion

For comparison the temperature and strain data from a test on a crossply specimen with a longitudinal surface ply and a specimen with a transverse surface ply has been plotted in Figure 5 against the stress derived from the load cell data and specimen cross section. The temperature and strain are averaged across an area approximately 5 data points by 10 data points in the centre of the wasted section. Although this approach loses some of the benefits

of using a full-field technique, it is a useful tool for an initial comparison. The most interesting observation is the difference between the temperature evolutions in the two specimens. Although both show a trend of temperature increase, the resin dominated transverse surface ply heats up significantly more than the fibre dominated longitudinal surface ply. Observing the IR data just before failure from the two specimens, shown in Figure 6, it is possible to discern their failure mode. In Figure 6 (a), the specimen with longitudinal surface ply, there is localised heating on one side of the specimen as fibres fail. Conversely Figure 6 (b), with a transverse surface ply, shows more the temperature evolution taking place across the width of the specimen indicating transverse matrix cracking. Some caution should be applied when interpreting these results as the recorded temperature evolutions are relatively small. In the region of interest selected to average the strain and temperature results, i.e. the centre of the wasted section, the temperature rises only ~ 0.5 K and ~ 1 K for the longitudinal and transverse specimens respectively. These are low compared to values reported in [13], although the material tested was glass fibre chopped strand mat and hence may behave differently. The tests conducted in [13] used the high speed IRT in isolation, and therefore was not affected by the issues of heating from illumination or measurement through a painted speckle pattern. Neglecting the values of temperature recorded, the differences in heating distribution are an encouraging indicator of the promise of the technique. Hence, more investigation is warranted of the use of technique and the possible viscoelastic behaviour alluded to by the results presented here.

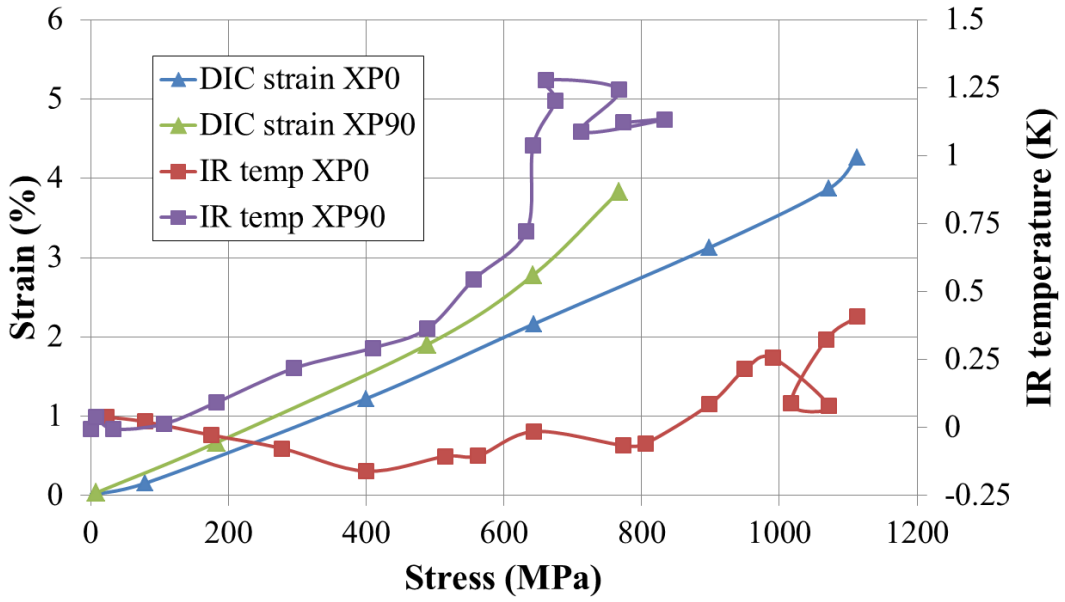

Figure 5. Plot of DIC strain and IR temperature against stress for crossply specimens with longitudinal surface ply (XP0) and transverse surface ply (XP90)

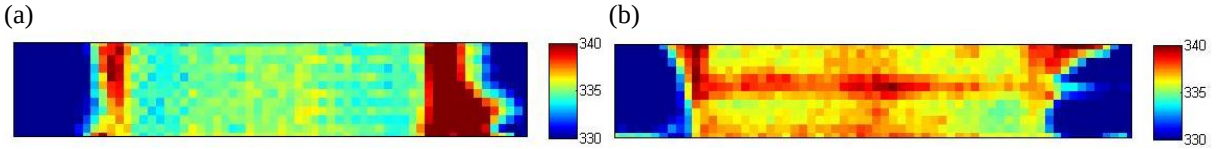

Figure 6. Temperature (K) plot close to specimen failure measured using IRT (a) longitudinal surface ply, (b) transverse surface ply

4 Conclusions and future work

A synchronised approach using two optical techniques, DIC and IRT, has been applied to high speed tests on crossply glass fibre specimens to measure strain and temperature evolutions synchronously. The results show an apparent difference between specimens with a fibre dominated longitudinal surface ply and a resin dominated transverse surface ply. A reasonable explanation for this is the viscoelastic nature of the polymer resin. Questions remain over the consistency of the IRT data measured in conjunction with the illumination required for high speed white light imaging, and the speckled paint coating required for DIC. These will be addressed through further testing and the identification of illumination and speckle coatings that can be used for both techniques.

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