DAMAGE EVOLUTION TEST MACHINE CONTROL BASED ON THERMOGRAPHY

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Keywords: Composite, Fatigue, Infrared, Thermography, Control

Abstract
It has been shown that as damage grows within a composite material, there is a local temperature increase that can be measured with an infrared (IR) detector. The possibility of controlling the rate of damage evolution during a cyclic test, using infrared thermography (IRT), is investigated. Unlike the point or local monitoring achieved by strain gauges, IRT is a full-field technique which can be used to monitor the surface of the whole test specimen. To control the damage evolution rate, the IR response (i.e. temperature change) associated with material damage must be identified, characterised and quantified, before a control methodology can be developed. The results of a series of tests conducted to establish the relationship between the recorded temperature change and damage condition in composite materials is described. Two types of glass reinforced epoxy specimens are studied with layup $(0, 90)_{3S}$ and $(+/-45)_{3S}$ under fatigue loading.

1. Introduction

During fatigue testing of composite materials and structures there is a recognised need to control the damage evolution rate and to establish more effectively when the material has failed. As damage evolves, the strain increases for a given load, or in displacement control the stress decreases. The damage evolution rate accelerates towards final failure when in load control and decelerates when in displacement control. A more appropriate form of test machine control, for composite testing, could be termed 'damage evolution control' where the load or displacement rate is adjusted to give a constant damage evolution rate. This type of approach is well established for crack propagation in metals, using controlled level and variation, in crack tip stress intensity [1]. It is well-known [2] that as damage occurs in a composite material, there is a local temperature increase in the area of the damage growth. It is proposed that the temperature increase, detected with an infrared (IR) camera, could be used for test machine damage evolution control.

Unlike the point or local monitoring achieved by strain gauges, infrared thermography (IRT) is a full-field technique which can be used to monitor, record and output real-time temperature changes over the entire specimen surface. The ability to monitor full-field is essential when considering unnotched composite specimens, where the damage initiation point is not known. The material damage type and the corresponding temperature evolution must be identified, characterised and quantified, before a control methodology can be developed. The specimen temperature evolution during damage

Excerpt from ISBN 978-3-00-053387-7

progression is sufficient to be detected using IRT, however to identify the damage type further information is required. Therefore, during these initial studies a technique known as thermoelastic stress analysis (TSA) [3] is applied to provide more data, to assist the identification of the damage type and link to the IRT measured temperature changes. The thermoelastic response is proportional to stresses and enables the stress redistribution due to damage to be visualised and quantified. When capturing IR images during a fatigue test, it is also possible to post-process the images and apply TSA. The surface temperature captured in the IR images can then be directly compared with the damage type identified by the TSA and by visual inspection, to provide the specimen temperature change at which a certain damage type occurs.

Two types of glass reinforced epoxy specimen were used. A panel with a layup of $(0, 90)_{3S}$ was prepared. On-axis specimens were produced to, generate progressive defects through the fatigue cycle, i.e. matrix cracking, longitudinal splitting, delamination and finally fibre breakage. The second type of specimens were cut at 45° to the fibre directions to generate internal shear damage. The specimens were fatigue tested to failure under a sinusoidal, load-controlled waveform, at a load ratio of R=0.1, during which the temperature was mapped and recorded. The paper presents results from the two specimen types and the relationship between the damage type (from the TSA) and temperature changes measured during damage evolution is discussed.

2. Methodology

Previous studies have shown that IRT can be used with a (+/- 45) fibre lay-up, to detect matrix disbonding and delamination's during fatigue tests [4], and matrix cracking is the dominant failure mechanism [3]. Visible surface damage evolution can be created by using a lay-up of (0, 90). It has been shown [5] that axial cracks and delaminations form during tensile testing, that the specimen fractures orthogonal to the tension axis with 0° fibre failures [4] and that there is axial cracking of the matrix, with internal matrix cracking and delamination [3]. Although IRT is a full-field technique, in this initial study it was decided to localise the damage in the specimen to allow the detector to focus on a smaller area and hence improve the spatial resolution of the data. It has been shown that an open hole concentrates the damage and its evolution within a localised area [5], [6], therefore a stress concentration in the form of a central circular hole was used. The test specimens were 250 mm in length. The width of the specimen was determined based upon the British standard BS ISO 12817 [7] and BS ISO 14603 [8] for open hole compression of fibre-reinforced plastic composites and open hole tension of continuous fibre ceramic matrix. Both standards suggest a specimen width to hole diameter ratio of 6. It is also suggested a hole diameter of 6 mm is used giving a specimen width of 36 mm. Therefore the specimens were manufactured using E-glass fibre (1062) pre-impregnated with a MTM28-1 resin system material with an autoclave consolidation to the dimensions shown in Figure 1.

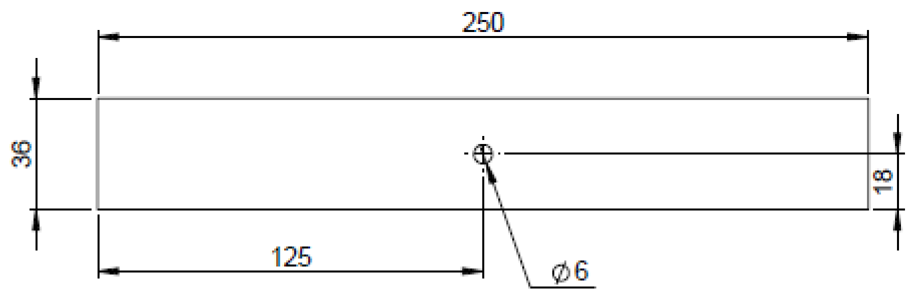

Figure 1. Dimensioned drawing of the composite open hole specimen.

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Specimen thickness was an important consideration as the detection of internal damage using IRT becomes more challenging with increasing thickness. It was decided that a 12 ply stacking sequence would be used, giving an approximate thickness of 1.8 mm. This was based on [3] where IRT was used successfully on laminates of E-glass epoxy with 13 plies. Laminates of $(0, 90)_{3S}$ were manufactured and the $(+/-45)_{3S}$ laminate was cut at 45° to the principal material axis. The front surface of all test specimens was sprayed with matt black paint to provide a uniform emissivity for the IRT.

The (+/-45) specimen was cyclically loaded, in load control, using a 5 Hz sinusoidal waveform. A maximum load of 6.1 kN (R=0.1), was applied. A FLIR SC5500 series photon detector was used to record the IR images for 1000 frames at 383 Hz, every 100 cycles until 1200 cycles and then every 50 cycles, to monitor the accelerating damage evolution. The (0, 90) specimen was loaded at the same frequency and R ratio, to a maximum load of 10.45 kN. Images were recorded every 1000 cycles until just before failure, when images were recorded after an audible ping.

3. Results

The TSA data was processed as follows to eliminate the effect of the surface temperature increase:

$$\frac{\Delta T}{T} = -K(\sigma_1 + \sigma_2) \tag{1}$$

where ΔT is the change in temperature, K is the thermoelastic constant, T is the absolute temperature of the specimen, and σ_1, σ_2, are the changes in the principal stresses.

The temperature evolution from the (0, 90) specimen is shown in Figure 2. In the early parts of the test the temperature did not change, so the data recorded, before 92,000 cycles is not presented. Instead the audible pings from the localised failure of the material were used to select the data. Between 92,000 and 118,000 cycles there is a steady increase in temperature data around the hole, but no definition of the damage type. In comparison to the $\Delta T/T$ images, where the damage evolution could be clearly observed, with a crack developing from the lower right hand quadrant of the hole. The last two image sets in Figure 2 shows the damage evolution just before failure. The IR image clearly shows an increase in temperature at the damage site. What is more revealing is the $\Delta T/T$ data which clearly shows how the stress is redistributed as a result of the damage progression. Local to the hole all load carrying capacity is lost as the delamination progresses away from the hole. The remaining intact material has to carry the load and this is signified by the increased response at the edge of the delamination. Figure 3 shows photographs of the front and back of the specimen at the end of the tests. Full failure occurred after 140,922 cycles. Here the TSA has revealed areas of sub surface damage that are not visible in the photographs. In Figure 3(b), the curvature of the delaminated area can be seen on the right hand side of the hole, corresponding with surface damage on the front of the specimen.

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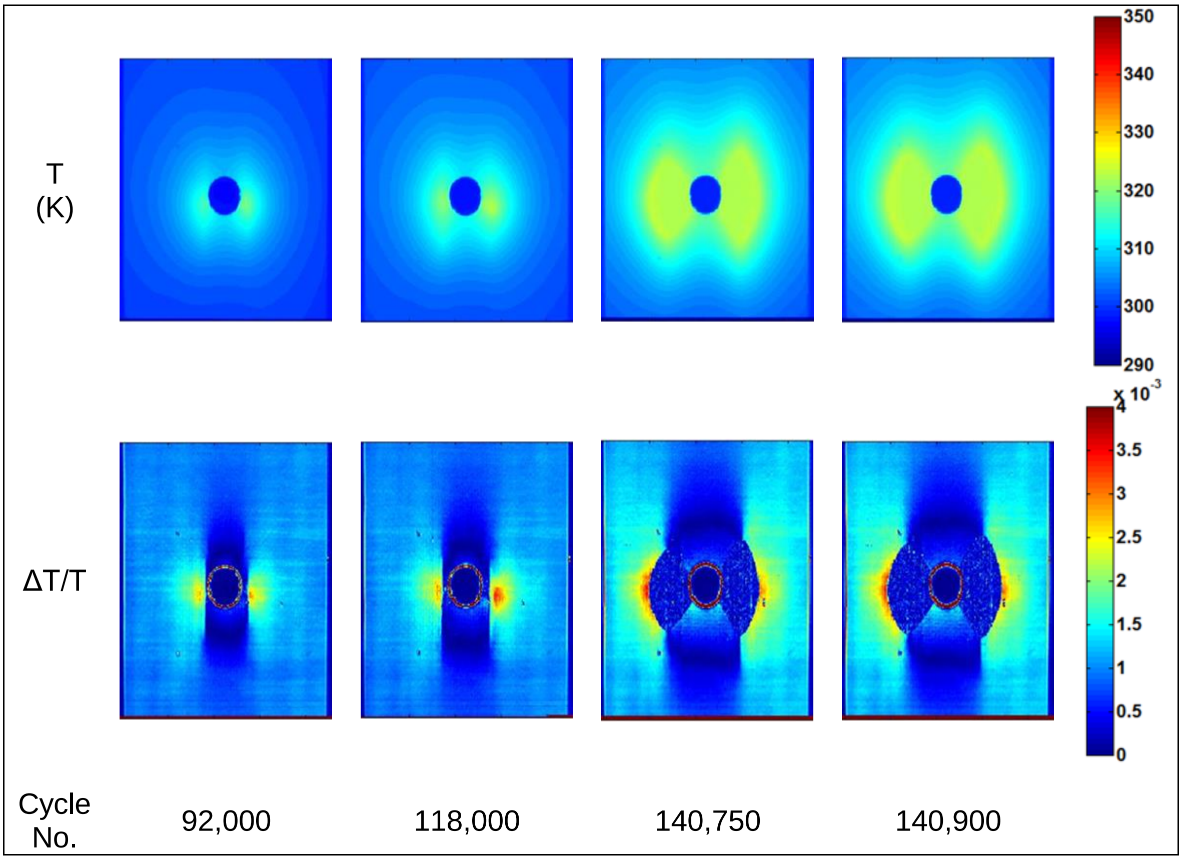
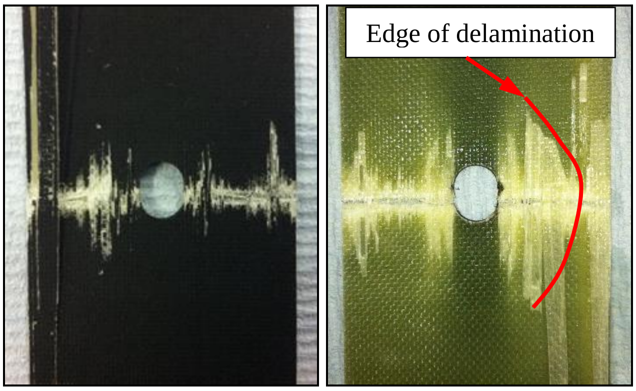


Figure 2. (0, 90) Specimen temperature evolution.



(a) (b)

Figure 3. Photo of the failed (0, 90) Specimen, after 140,922 cycles (a) front face (b) back face.

Figure 4 shows the temperature evolution of (+/-45) specimen. Deformation of the hole during the test can be clearly seen, along with deformation along the edge due to the shear coupling. The entire specimen shows an increase in temperature as well as the damaged areas, due to the gross deformation occurring as a result of the specimen fibre orientation. In the $\Delta T/T$ images, the damage evolution is evident. A crack is growing from the hole signified by the stress concentration, as well as delamination, signified by the triangular area shown in images. Figure 5(a) is a photograph of the failed specimen, showing a kink in the surface damage on the right side of the hole, which corresponds well to the damaged regions in the $\Delta T/T$ image. The deformation of the specimen edge is also clear in the image.

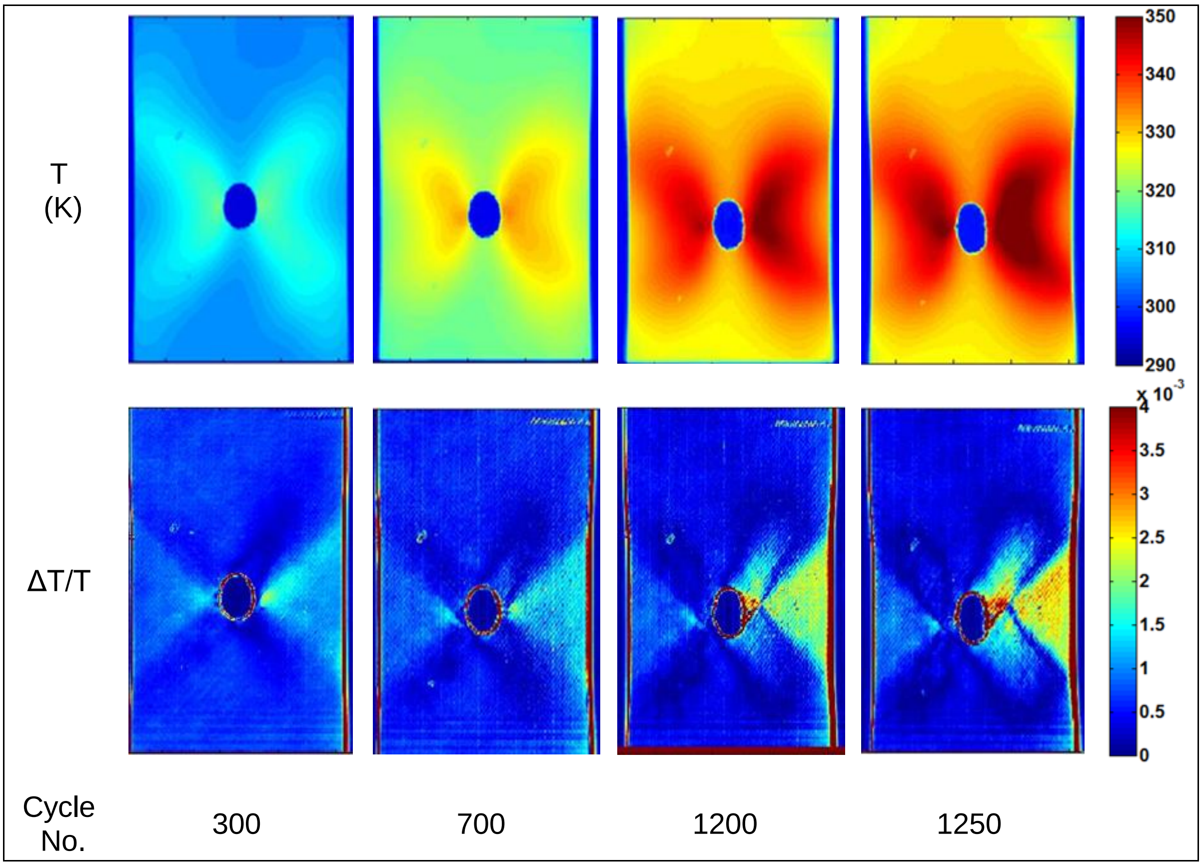


Figure 4. (+/-45) Specimen temperature evolution.

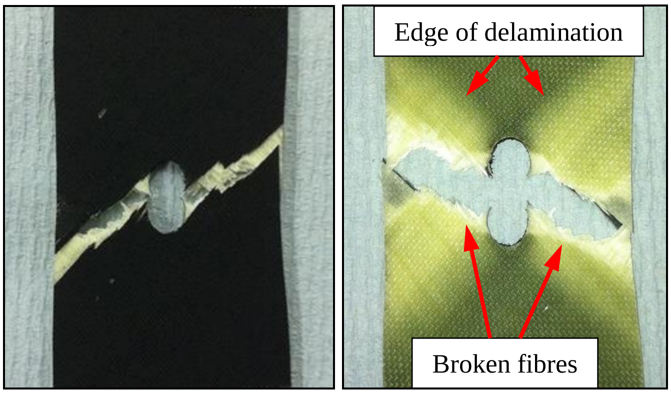


Figure 5. (+/-45) Specimen failure image after 1291 cycles. (a) front face (b) back face.

4. Discussion and future work

It has been demonstrated that the surface temperature changes obtained from an IR detector can monitor damage evolution in a composite material. It is clear from this work that identifying, characterising and quantifying the damage and its severity using the surface temperature change is a difficult if not impossible proposition. The difference in the temperature changes between the (+/-45) specimen and the (0, 90) specimen is as expected as the shearing causes a greater increase in

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temperature. The temperature difference between delamination, matrix cracking and fibre breakage as seen in the (0, 90) specimen is not detectable. Only by applying the TSA is the actual damage state revealed. Therefore it is necessary to link this with the surface temperature data, which will be the object of further investigations.

To characterise and quantify the IR data from the detector, a bespoke LabView program will be written. The program will monitor and characterise the detector output, using the link between the surface temperature and the damage state. Quantify the data into two output channels and then output the data channels into Instron's Wavematrix, test control software, adjusting the displacement and/or load levels, to maintain an constant damage evolution rate.

Acknowledgments

The author would like to thank the Engineering and Physical Sciences Research Council (EPSRC) and Instron Dynamic Systems, Instron Division of ITW Ltd. for funding this research.

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