A COMPARISON OF THE USE OF 3D DIC AND THERMOGRAPHY IN DETERMINING THE SIZE AND GROWTH OF DELAMINATIONS IN WOVEN GFRP EPOXY LAMINATES

Osman Z. Ajmal\textsuperscript{1}, Andrew D. Crocombe\textsuperscript{1}, Michael R. L. Gower\textsuperscript{2}, David A. Jesson\textsuperscript{1}, Stephen L. Ogin\textsuperscript{1}

\textsuperscript{1}Centre for Engineering Materials, Department of Mechanical Engineering Sciences, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, UK
Email: o.ajmal@surrey.ac.uk; a.crocombe@surrey.ac.uk; d.jesson@surrey.ac.uk; s.ogin@surrey.ac.uk
Web page: \url{http://www.surrey.ac.uk/mes/index.htm}

\textsuperscript{2}National Physical Laboratory, Hampton Road, Teddington, Middlesex, UK
Email: michael.gower@npl.co.uk
Web page: \url{http://www.npl.co.uk/people/michael-gower}

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\textbf{ABSTRACT}

Digital Image Correlation (DIC) can be used to obtain full-field strain information on specimens under load. Through analysis of the resultant strain-contours, defects such as delaminations in composite materials can be detected, based on their effect on the deformation behaviour. This work focusses on the use of the DIC technique and two variations of active thermography (lock-in thermography and pulse thermography) for determining the lengths of delaminations in “milled-slot” specimens; for each technique, the measured delamination lengths have been compared with visually observed (i.e. photographed) delaminations grown under fatigue loading in transparent woven fabric GFRP specimens. In addition, the DIC results have been interpreted with the aid of a finite element model of the strain distribution in the milled-slot specimens.

It has been found that the DIC technique provides a reasonably good method for measuring the length of the fatigue-grown delaminations after an empirical fit is applied, with the aid of the FE analysis, to overcome complications caused by fibre-bridging. On the other hand, the results using both lock-in and pulse thermography showed reasonable correlations with the visually observed (i.e. photographed) delamination lengths without the need for an empirical fit, although some post-processing of the data was required. For both thermography techniques, there were difficulties in determining the delamination lengths close to the edge of the milled slot.

\textbf{1 INTRODUCTION}

As the range of composite material applications grows, it is becoming increasingly necessary to develop non-destructive evaluation (NDE) techniques that can be easily, rapidly and reliably deployed. In an effort to develop innovative methodologies to characterise the presence and propagation of defects in composite structural elements, the detection and growth of delaminations is being investigated using 3D Digital Image Correlation (DIC). 3D DIC is a full-field optical method capable of mapping surface strain contours on structural elements under load. These strain contours can be analysed to quantify the position and size of defects [1–4]. In this work, a 3D DIC system has been used to detect and monitor the fatigue growth of delaminations in woven glass fibre-reinforced plastic (GFRP) “milled-slot” specimens, fabricated using 8-harness satin weave (8-HSW) fabric and epoxy resin. A milled-slot specimen is a flat coupon which has a rectangular slot of a certain depth milled across the width of the coupon at the mid-length position. The design of the specimen is based on a specimen used in a previous NDE evaluation [5].
Comparisons of the measurements of the growth of the delaminations using 3D DIC have been made with lock-in thermography (LIT) [6, 7, 8] and pulse thermography (PT) [6, 9, 10]. This comparison is made as all three methods are non-contacting, provide full-field data and have high sensitivity to defects close to the surface.

2 EXPERIMENTAL METHODS

2.1 Specimen manufacture & damage generation

The specimens used in this work were coupons of 16 ply GFRP composite [0/90]₁₆₈ manufactured using 8-HSW fabric (supplied by Fothergill Engineered Fabrics Ltd) and an epoxy resin consisting of Epoxide 300 resin, MNA hardener and Ancamine K61B. Laminates with dimensions of 300 x 300 x 4.5 mm were made using a (wet) hand lay-up technique, as described in [11]. The similarity in the refractive indices of the glass and cured epoxy resin produces transparent laminates within which it is possible to observe visually the delamination growth. After curing, the laminates were cut into individual specimens 125 x 20 mm and a 2 mm wide slot was milled out from the top surface along the mid-length. The specimens were end tabbed with tabs having a length of 40 mm, giving a gauge-section shown in Figure 1. The slot was milled approximately two plies deep i.e. nominally 0.6 mm.

![Figure 1](image)

**Figure 1:** Schematic of a milled notch specimen placed under tension. (a) Front view of the specimen. (b) Side profile of the specimen, the dotted red line indicates the delamination growth path

In this work, delaminations were grown by placing the specimens under tension-tension fatigue loading with a peak load of 8 kN (i.e. 103 MPa), which corresponded to approximately 40% of the quasi-static failure load of the milled specimen; an R-ratio of R = 0.1 and a frequency of 5 Hz were used for the fatigue loading, using an Instron 1341 with a 50 kN loadcell.

2.2 Digital Image Correlation

The DIC system consisted of two 9-megapixel Allied Vision Technology Manta cameras, with LINOS MeVis-C 35 mm f/1.6 lenses, supplied by Correlated Solutions Inc. Each camera contains a 2/3” (16.9 mm) chip. When obtaining DIC data, the specimens were quasi-statically loaded from zero to 8 kN in 60 s, with DIC images taken every 2 s. In the post-processing of the DIC results, the subset grid was specified at 27 x 27 pixels and a step size of 5 was used for each set of results. The strain filter size used was 15 pixels.
2.3 Lock-In Thermography

The lock-in thermography equipment consisted of a FLIR SC5200 Silver 420M thermal camera with a resolution of 320 x 256 pixels, a frequency generator and two 1 kW halogen lamps. In this NDE technique, the sample is heated periodically with the halogen lamps using a power control that is modulated with a sinusoidal waveform from the function generator. The FLIR camera records the infrared (IR) emissions from the surface of the specimen during the testing period. The recorded IR emissions from the surface of the specimen correspond to the modulated input signal, where the interference pattern is caused by the interaction between the incoming thermal wave and a reflected thermal response from internal defects (in this case, the delamination) [12]. Lock-in testing was carried out at frequencies between 0.070 and 0.080 Hz. The duration of each test was limited to 3.5 periods as testing for longer increased the possibility that the camera used would lose synchronicity with the frequency generator, half a period of which was required to eliminate background temperature changes [8].

2.4 Pulse Thermography

The pulse thermography system consisted of a Phoenix Medium Wavelength Infrared (MWIR) 9705 IR camera (FLIR systems) and a xenon flash lamp with an energy output of ~2 kJ. The specimens were subjected to a high intensity flash of light for 30 ms. This pulse causes an increase in the surface temperature which decays as heat is absorbed from conduction into the specimen. The presence of discontinuities such as delaminations reflect the thermal energy, which in turn reduces the surface cooling rate adjacent to the defect. The contrast between the surface temperature above the defect compared with the surface temperature over a region not containing the defect can be used to determine the location and size of a defect such as a delamination [8].

For pulse thermography, lock-in thermography and DIC the surface being monitored required a coating. For both thermography techniques, the specimens were coated with an acrylic matt black paint. This was necessary due to the reflective nature of the uncoated GFRP surface. For the DIC investigations, the specimens were spray painted with an acrylic paint; initially matt white for the base followed by a matt black speckle, averaging 3-5 pixels per speckle and approximately 5 speckles per subset. This is required by the technique as the cameras monitor the movement of the speckles to determine the surface displacements, and hence the surface strains.

3 Finite Element Modelling

3D FE models of the specimens were created using Abaqus/Standard version 6.14 in order to model the strains developed in the specimens under load. The geometries and dimensions of the models replicated the experimental geometries. Each ply was tied to the adjacent plies in the specimen apart from the area over which the delamination was present. The models all used eight-noded brick full integration elements. The plies were each one element thick, and the in-plane dimensions of the elements were 0.5 mm x 0.5 mm. Each ply was assigned the properties given in Table 1, taken from [13].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$E_1$</td>
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</tr>
<tr>
<td>$E_2$</td>
<td>21 [GPa]</td>
</tr>
<tr>
<td>$E_3$</td>
<td>8.55 [GPa]</td>
</tr>
<tr>
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<tr>
<td>$v_{13}$</td>
<td>0.0305</td>
</tr>
<tr>
<td>$v_{23}$</td>
<td>0.075</td>
</tr>
<tr>
<td>$G_{12}$</td>
<td>3.7 [GPa]</td>
</tr>
<tr>
<td>$G_{13}$</td>
<td>3.5 [GPa]</td>
</tr>
<tr>
<td>$G_{23}$</td>
<td>3.5 [GPa]</td>
</tr>
</tbody>
</table>
The delamination lengths in the FE models were based on the measured delamination lengths in the transparent specimens at different stages of the fatigue cycling.

4 RESULTS

4.1 Introduction

In this section, the results of monitoring delamination lengths between each interval of fatigue cycling of the milled-slot specimens is presented, comparing the delamination lengths as determined by visual observations in the transparent coupons with the experimentally determined delamination lengths using DIC, LIT and PT, respectively. A total of four milled-slot specimens (i.e. eight different delaminations) were monitored for each interval of fatigue testing. In determining the lengths of the delaminations, the data were analysed only along the mid-line of the specimen as the quality of the results for thermography was diminished closer to the edges of the specimen.

4.2 Visual observations

As the specimens were transparent, the delaminations appeared in the images as lighter areas. Figure 2a shows images taken of one of the specimens after 100, 1000 and 3000 fatigue cycles, where the delaminations have grown from approximately 1.7 mm to 4.2 mm. Figure 2b shows a plot of the delamination length along the mid-line of the specimen, measured from the edge of the milled-slot, as a function of the number of fatigue cycles. After an initial period of rapid growth over about the first 500 cycles, the delaminations then grew at an approximately linear rate of about 0.8 µm / cycle. It is not clear why the delaminations in coupon 4 (i.e. 4A and 4B) were larger than the other specimens. This is possibly due to the milled slot depth being closer to the interface of the plies than for the other three specimens. Further investigation is required but for the work reported here (which is solely concerned with the NDE techniques), different delamination growth rates are not a concern.

**Figure 2**: (a) Digital images of a milled-slot specimen after different numbers of fatigue cycles. These images show the full width and length of specimen 1 (20 mm wide), showing delaminations A and B on either side of the milled slot; (b) delamination lengths determined visually along the mid-line of the milled-slot specimens at as a function of the number of fatigue cycles.
4.3 Digital Image Correlation

Digital image correlation requires the specimens to be mechanically loaded to measure the resultant surface strains. These surface strains have been shown to provide an indication of the position and size of delaminations in previous work on fully embedded delaminations in three point bending [1]. Figure 3 shows the DIC longitudinal strain results (i.e. parallel to the loading direction) for specimen 1; data for delamination 1A, for example, have been extracted along the dotted line. It is important to note that the DIC results within about 1 mm of the edge of the milled slot were omitted due to high errors caused by the subsets of speckles used in post-processing the DIC results picking up data from the recessed surface of the milled slot.

Figure 3: DIC longitudinal strain results of specimen 1 at different delamination lengths. The data line extracted for delamination 1A is shown as a dotted black line for delamination lengths of 1.7 mm, 3.0 mm and 4.2 mm.

For a complete delamination, in the sense that there is no fibre bridging between the faces of the delaminated material, the regions on the surface of the specimen above the delamination should show zero strain, as no load would be transferred to the material above the delamination. This is demonstrated in the FEA results; Figure 4a shows the surface strain of the test specimen in relation to one milled edge, and Figure 4b shows a screenshot of the FE model; the flap of material above the delamination undergoes some bending which physically separates the two delaminated surfaces, and there is a minimum point at the trough of compressive surface strain which occurs very close to the modelled delamination length. However, for the delamination grown in fatigue between the two plies of the woven fabric composite, bridging occurs (this would occur for quasi-static loading as well). As a consequence, some longitudinal strain is still carried by the flap. A comparison of the strain derived from the DIC data and the FE model is shown in Figure 4c.
Figure 4: (a) FE model surface strains over a schematic of a specimen. (b) FE image of bending surface, with the displacements magnified by 20. (c) Comparison of the FE model surface strains, for a delamination length of 3.6 mm, assuming no fibre bridging, and the actual strains as measured using the DIC.

Figure 5: (a) Longitudinal strains on the surface of a milled-slot specimen under 8 kN load for increasing delamination lengths predicted using the FE models; (b) DIC measurements of surface strains for increasing delamination lengths.

Figure 5a shows the change in the predicted (FE analysis) surface strain distribution with increasing delamination length, assuming no fibre bridging. Essentially, the strain distribution shifts along the y-position axis in proportion to the increase in the delamination length. However, this does not occur for the actual surface strains as measured using the DIC (Figure 5b); the minimum in the DIC surface strain remains in approximately the same spatial location with increasing delamination length, but there is a change in the slope of the strain/position curve with increasing delamination length.
In order to measure the length of the delaminations using the DIC measurements, a calibration has been made. It is found empirically that there is a reasonably good correlation between the minimum in the FE predicted strain profile and the visually measured delamination length at a DIC longitudinal strain of $\varepsilon = 0.0015$. This is shown by the dotted line in Figure 5b, and this close correlation is illustrated in Figure 4c. Consequently, for all delaminations, the DIC-measured delamination lengths were found using the y-position distances corresponding to a strain of $\varepsilon = 0.0015$, when the specimens were loaded to 8 kN. A plot of the DIC-measured delamination lengths as a function of the delamination lengths measured from photographs of the transparent laminates is shown in Figure 6; there is reasonable agreement between the two measurements. However, further work is required to model the bridging fibres of the delaminations so that the empirical method used for extracting the delamination lengths from the DIC strain distribution can be avoided.

![Diagram showing DIC-measured delamination lengths vs visually observed delamination lengths](image)

**Figure 6:** A comparison of the actual delamination length in the milled-slot specimens measured from visual observations with the delamination lengths determined from the DIC results. The dashed line indicates the ideal relationship.

### 4.4 Lock-in Thermography

Lock-in thermography produces two main types of outputs; amplitude and phase images [14]. In this work, the phase images have been used because the phase lag caused by the delaminations in the thermal response indicates the location and size of the delaminations [14, 15]. Figure 7a shows the grey-scale phase image of one of the specimens with a delamination length of 4.2 mm. In order to determine the delamination length, the grey-scale values were extracted along the mid-line of the specimen, starting from the edge of the milled slot; in Figure 7b, the beginning of the delamination is indicated by the blue line. The grey-scale value is initially high close to the milled slot and decays to a mean value after about 11 pixels, which corresponds to a physical distance of approximately 4.95 mm. The length over which the grey-scale values decay to a mean value away from the delamination has been found to be a good measure of the length of the delamination. Analysing all of the LIT results for all of the delamination lengths in this way (see Figure 8) shows that there is a reasonable correlation between the LIT-measured delamination length and the lengths measured from the photographs.
Figure 7: (a) LIT results of 4.5 mm long delamination in a milled-slot specimen. Data extracted along the dotted red line i.e. the mid-line of the coupon. (b) Decay of the grey-scale values to the mean away from the delamination.

Figure 8: A comparison of the actual delamination length in the milled-slot specimens measured from visual observations with the delamination lengths determined from the LIT results. The dashed line indicates the ideal relationship.

4.5 Pulse thermography

The output of a pulse thermography test consists of a series of thermal images. In this work, after the pulse, the camera used recorded the IR emissions from the surface of the specimen at a rate of 50 Hz. As described in [9], a defect at a certain depth, \( z \), can be resolved by considering the thermal image taken at time, \( t \) according to Equation 1.
\[ t = \frac{y^2}{\pi\alpha} \]  

(1)

Here, \( \alpha \) is the thermal diffusivity of the material, taken to be as constant. There is some debate in the literature about the value of \( t \), but a value of \( t = 2.4 \) s has been used here.

In pulse thermography, complications arise because of specimen edges where extra thermal losses occur. Due to the proximity of the delaminations to the edges of the milled slot in the specimen, the delaminations were difficult to resolve. However, taking the second derivative of the heat amplitude with respect to time increased the contrast when comparing non-damaged and damaged regions. A further improvement was found by subtracting the second derivative image of the undamaged specimen from the second derivative image for the damaged specimen; an example of this subtraction is shown in Figure 9a. By extracting a data line starting from the edge of the milled slot, the length of the delamination can be determined as shown in Figure 9b, using a similar procedure to that described for LIT above. Using this approach, the results for all the delaminations considered in this work are shown in Figure 10. In a small number of cases, the delaminations could not be resolved using the technique described above and have been omitted from the figure.

![Figure 9](image-url)  

**Figure 9:** (a) PT results of 4.2 mm long delamination in a milled-slot specimen and the post processing done to highlight damage. Data extracted from dotted red line. (b) Results from the data line determining the length of the delamination as measured from PT.
Figure 10: A comparison of the actual delamination length in the milled-slot specimens measured from visual observations with the delamination lengths determined from the PT results. The dashed line indicates the ideal relationship.

5 CONCLUDING REMARKS

The three NDE techniques considered, i.e. DIC, LIT and PT, demonstrated the ability to measure the length of growing delaminations in milled-slot specimens. For the DIC, an empirical fit (required as a consequence of bridging fibres in the milled-slot delamination), enabled a reasonably good correlation to be made between the measured delamination length and the actual length. Both of the thermography techniques, on the other hand, were not affected to the same extent by the presence of fibre-bridging and showed reasonable correlations between the thermography-measured delamination lengths and the visually observed (i.e. photographed) delaminations, with LIT showing less scatter in the results than PT. However, it is important to note that there are difficulties when measuring delamination lengths close to the edges of the specimen using these techniques.

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REFERENCES


