MATERIAL HETEROGENEITY OR STRESS CONCETRATION: THE THERMOELASTIC RESPONSE FROM WOVEN COMPOSITE MATERIALS SUBJECTED TO CYCLIC FATIGUE

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SUMMARY

A study of the growth of fatigue damage in 2 x 2 twill woven composite materials, subjected to cyclic tensile loading are described. Thermoelastic stress analysis (TSA) is used to monitor the stress field. As a result of the damage, a net reduction in the thermoelastic signal is observed. Laminates are found to be more resistant to fatigue.

Keywords: thermoelastic stress analysis, fatigue, woven composite

INTRODUCTION

The desire to improve structural performance often translates directly as a requirement to reduce weight. This has the consequence of increased stresses within the structure. The accumulation of fatigue damage is therefore a topic of great concern in most engineering applications. Reduced weight has been one the driving factors in the development of composite materials, in particular fibre reinforced polymers (FRP). The orthotropic nature of these materials, and the uncertainty regarding many aspects of their performance has meant that many of the design guidelines commonly applied in design with monolithic materials (i.e. metals) do not have reliable counterparts in the field of composite materials. Each component must therefore be subjected to bespoke evaluation, in the form of numerical simulation and experimental validation.

Woven composite materials are a popular class of engineering materials with widespread use in both construction and repair of damaged structures. Their popularity is in part due to ease of handling, ability to drape over complex curvatures, low cost and availability, and in part due to good mechanical performance in terms of the strength and stiffness to weight ratios.

Thermoelastic stress analysis (TSA) is a non-contacting, full-field stress analysis technique with well documented application to the study of stresses in composite materials [1, 2]. It has been shown that the thermoelastic response from an orthotropic material such as a FRP composite is dependent on the orientation of the fibres relative to the principal stress axis [3]. In composites with woven fibre reinforcements, two fibre orientations are present within each individual ply. Moreover, due to the interlacing pattern of the woven yarns, resin pockets are formed. As a result, even if a uniform strain field is assumed, as in a simple uniaxial tensile test, a non-uniform thermoelastic response would be obtained [4]. However, it is known that even under simple loading conditions, the strains in a woven composite are not uniform [5]. Hence, a significant challenge is the interpretation of TSA data from woven composite materials which results from both material and strain variations.

The motivation for using TSA to study FRP materials is that the measured data is directly related to the principal stresses at the surface of the material, and that the data can be obtained in quasi real time (less than 5 seconds per measurement) with almost no surface preparation. The measurement technique can therefore be applied directly to a component with minimal preparation time and data collected and analysed in situ, as the material is exposed to fatigue loading.

A cyclic load is required [6] to obtain a TSA measurement. To avoid fatigue damage accumulation, stresses are kept low relative to the failure stress of the material during TSA testing. However, a minimum stress amplitude must be achieved in the specimen to affect a measurement. In a typical E-glass / epoxy composite for which, in the fibre direction, a stress change of 1 MPa results in a temperature change of 1.5 mK, the minimum stress threshold is in the range of 10 to 20 MPa, below which stress concentrations cannot be resolved. Experiments involving a 2 x 2 twill woven E-glass / epoxy composite have shown a marked change in the thermoelastic response as individual specimens have been subjected to repeated testing. This indicates that fatigue damage is evolving during the cyclic load applied to the specimen as a normal requirement in TSA. The purpose of this paper is therefore to investigate the thermoelastic response from woven composite materials under low load (less than 20% of the failure load) fatigue conditions, to provide a deeper insight into the meaning of the measured TSA data with a view to understanding the mechanics and damage evolution in woven polymer composite materials.

METHODOLOGY

TSA was used to measure the stress field at intervals during cyclic fatigue testing. An infra-red detector is used to measure the small change in temperature associated with a change in stress. Under cyclic loading it is possible to correlate the amplitude of the temperature signal to the amplitude of the applied stress changes in an orthotropic material by [3]:

$$\left|\frac{\Delta T}{T}\right| = \frac{1}{\rho C_p}(\alpha_1 \Delta\sigma_1 + \alpha_2 \Delta\sigma_2) \tag{1}$$

where ΔT is the amplitude of the temperature oscillation, T is the mean surface temperature, ρ is the density, C_p is the specific heat capacity, α_1 and α_2 are the coefficients of thermal expansion (CTE) in the principal material directions and $\Delta\sigma_1$ and $\Delta\sigma_2$ are the amplitudes of the principal stresses.

The fatigue behaviour of the twill woven textile composite was tested using tensile strips made from single and two ply material. Data was compared from two similar 2 x 2 twill woven composites. The specimens were fatigued under constant load amplitude (tension – tension) sinusoidal loading at 10 Hz. The load amplitude was set to cycle from nearly zero (2 to 6 MPa), to a peak stress of 10, 15 and 20 % of the failure stress for each material. The test was run for 12 hours (440000 cycles) at 10 % of the failure stress and for 5 hours (180000 cycles) at 15 and 20 % of the failure stress. TSA measurements were taken every 600 cycles for the first 4000 cycles and then every 6000 cycles. Each specimen was tested once only. Separate, identical specimens were used for setup and tuning of the servo-hydraulic test machine prior to each test. The displacement amplitude of the actuator was recorded at the start and the end of every test as an indication of a change in the global stiffness of the material.

TSA data was obtained in the form of calibrated temperature measurements. The mean surface temperature field was used to normalise the temperature change field in the form $\Delta T/T$. This enables direct comparison between different data sets by means of a non-dimensional stress metric. The data was evaluated both in terms of global and local changes in the thermoelastic response. The local accumulation of fatigue damage was best identified by subtracting each data set from the initial measurement taken from the 'virgin' material. Specimens were inspected under the microscope before and after fatigue testing to identify the formation of matrix cracks. Accumulation of fatigue damage identified in the TSA data could thus be correlated to the formation of cracks on the material surface. Differences in the accumulation and distribution of fatigue damage between the different materials could be related to differences in the textile structure and material composition.

SPECIMENS AND EXPERIMENTAL ARRANGEMENTS

The specimen dimensions were based around ASTM D 3039. The gauge length was increased from the standard 150 mm to 250 mm to enable access with the infra-red detector. Instead of clamped ends, the specimens were pin loaded at both ends to ensure uniaxial loading, and to eliminate the possibility of slippage in the grips. The tensile strips were nominally 25 mm wide, and fitted with 50 mm long end tabs of the same material. Additional 1.5 mm thick aluminium end tabs (40 mm long) were added to serve as a bearing material for the loading pin.

The two textiles used were WRE581T and RE400T, 2 x 2 twill woven roving E-glass textiles, both with a nominal fabric weight of 390 gm^{-2}. The WRE581T textile used 600 tex fibres with a yarn count of 5 ends per cm in the warp yarns and 4.6 ends per cm in the weft yarns. The RE400T textile used 68 tex fibres with a yarn count of 29.5 ends per cm in the warp yarns, and 136 tex fibres with a yarn count of 13 ends per cm in the weft direction. An important parameter that influences the severity of local stress concentrations is the fibre crimp. This was measured as the ratio of the out-of-plane deformation of the warp yarn, relative to the length of the weave unit. The WRE581T has slightly greater crimp in the warp yarns than the RE400T, due to the heavier fibres used. The textile dimensions are listed in Table 1.

Table 1: Textile dimensions

Textile	Textile weight (gm^{-2})	Warp yarn spacing (mm)	Weft yarn spacing (mm)	Warp yarn crimp
WRE581T	390	0.95	1.05	11%
RE400T	390	0.82	0.82	8%

The epoxy used to consolidate the composite was Prime 20 LV resin cured using the fast hardener. All materials were supplied by Gurit. The composite was manufactured as a flat panel by means of resin infusion, with consolidation at 1 atmosphere of pressure. The specimens were cut from the plate, had end tabs bonded and were then post cured for 16 hours at 50º C. Finally, 12 mm diameter holes were drilled through the end tabs.

RESULTS

The measured stress fields (shown in Figure 1) from the two single ply specimens and the WRE581T two ply specimen showed very similar patterns in the virgin state. This diagonal banding of local stress concentrations between adjacent transverse fibres is commonly observed in composites made from 2 x 2 twill textiles. It can be noted that the stress concentrations in the WRE581T material with the greater yarn crimp are much more pronounced than in the RE400T material. The RE400T two ply specimen however shows a markedly different pattern. This suggests that there is interaction between the two plies, leading to reduced stress concentrations.

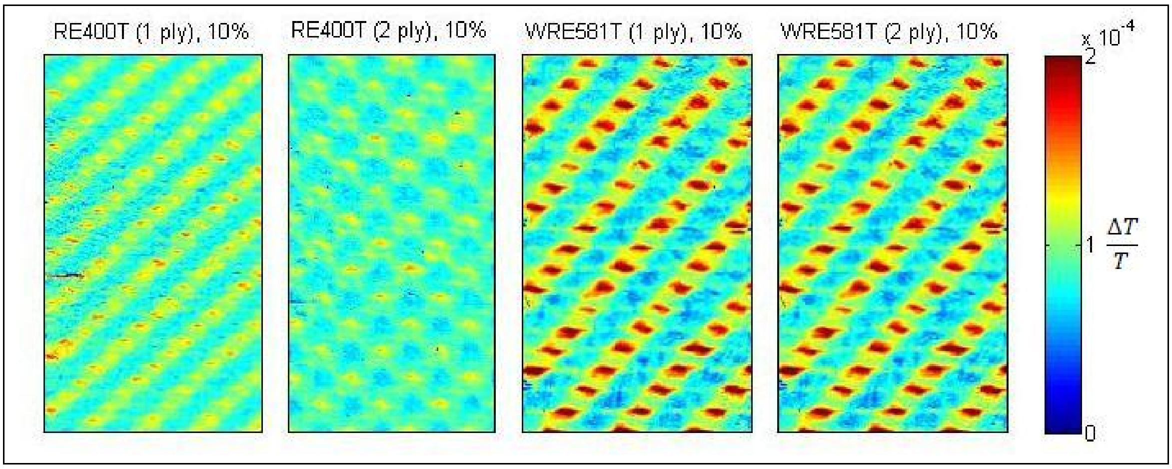

Figure 1: Measured non-dimensional stress field from virgin material

Figure 2 shows the global average thermoelastic response from each specimen, from the virgin material, through to the end of the test. (Note that the specimens were not tested to failure.) The global average was obtained by taking data from an area equivalent to that shown in Figure 1 which represents a box of 45 mm in length by 25 mm wide. The data has been normalised against the virgin data for each test case. The two ply RE400T specimen, which shows the lowest level of stress concentrations in the virgin data, also shows the least change in the net thermoelastic response as a result of the fatigue cycling. The single ply RE400T specimen and the two ply WRE581T specimen display a comparable decrease in the net thermoelastic response. The greatest change is observed in the single ply WRE581T specimen.

Both single ply specimens show a gradual linear decrease in the net thermoelastic response for the 10% loading case. For the two ply specimens the 10% loading case shows no net decrease. For the 15% and 20% loading cases, both single ply specimens show an initial rapid decrease in the net thermoelastic response, followed by a transition to a stable value approximately 20% and 30% lower than the initial data for the RE400T and WRE581T respectively. By contrast, both of the two ply specimens display an approximately linear decrease in the net thermoelastic response for the same two loading cases. This suggests that there is an interaction between the two plies, common to both weave types, which leads to improved resistance to the accumulation of fatigue damage.

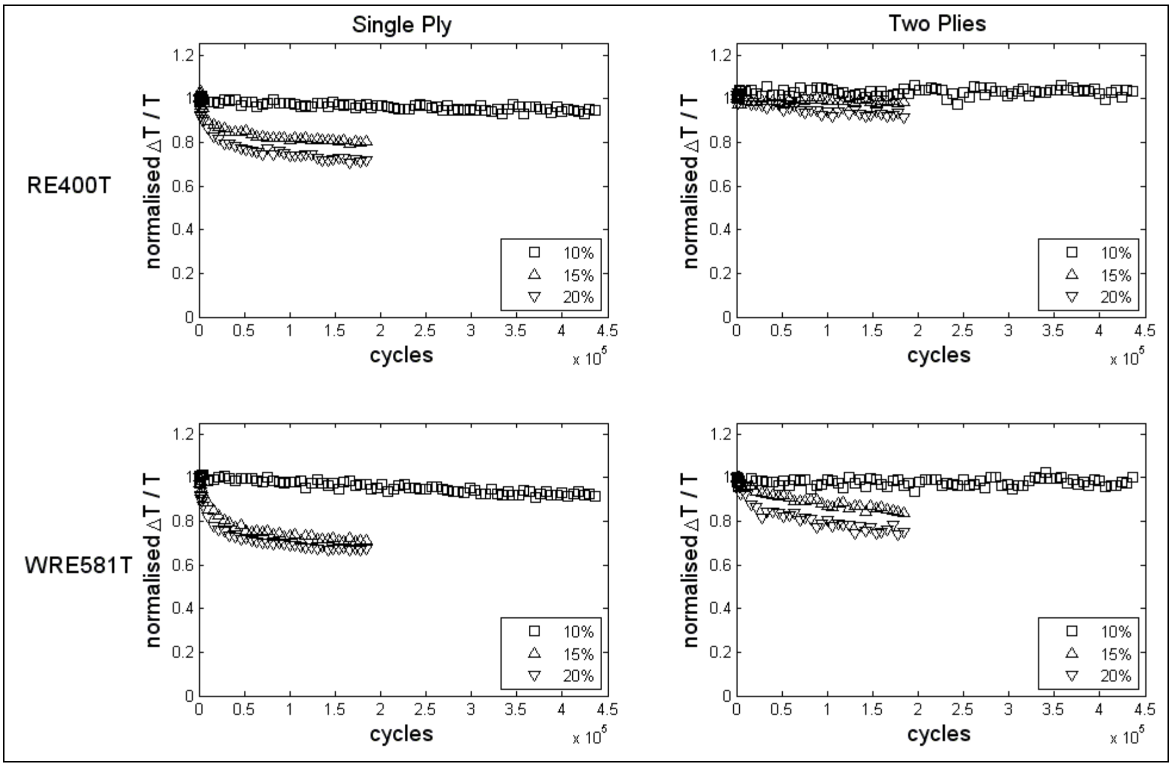

Figure 2: Global averaged thermoelastic response

As damage progresses, stresses previously carried by one part of the material are redistributed to other parts of the material. It might therefore be expected that the variation in the thermoelastic response will increase with fatigue progression. The standard deviation in the two ply RE400T specimen increases in a roughly proportional manner with the increase in the stress, and remains fairly constant throughout the fatigue loading, as shown in Figure 3. However, in the specimens that display damage accumulation, the standard deviation does not increase with the number of cycles, i.e. a local reduction in the thermoelastic response is not accompanied by a corresponding increase in another part of the specimen. In fact, the standard deviation decreases over time such that it remains roughly proportional to the average global signal. Therefore the globally averaged thermoelastic response does not provide a full picture of the nature of the damage evolution.

Considering the surface of the composite comprising small cells of unidirectional material, it is observed that the thermoelastic response from cells running parallel to the loading direction (longitudinal cells) have a weaker thermoelastic response than those running transverse to the loading direction. The red regions in Figure 1 correspond to the boundary between two transverse cells. The response from the transverse cells is of the order of 1×10^{-4}, while the response from the longitudinal cells is approximately 30% less. As the material begins to fatigue, a sharp reduction occurs in the thermoelastic response from the transverse cells. Individual cells 'fail' independently of each other, and this can happen very early in the fatigue process. In the case of the single ply WRE581T loaded at 20% of the failure stress, significant fatigue damage was observed already after only 200 cycles. The thermoelastic response falls sharply at first, until a point is reached where no further decrease in the thermoelastic response occurs.

This continues until all transverse cells have failed in this way. Because this reduction in the thermoelastic response is not accompanied by a corresponding increase in the response from the longitudinal cells, the global average thermoelastic response decreases as shown in Figure 2.

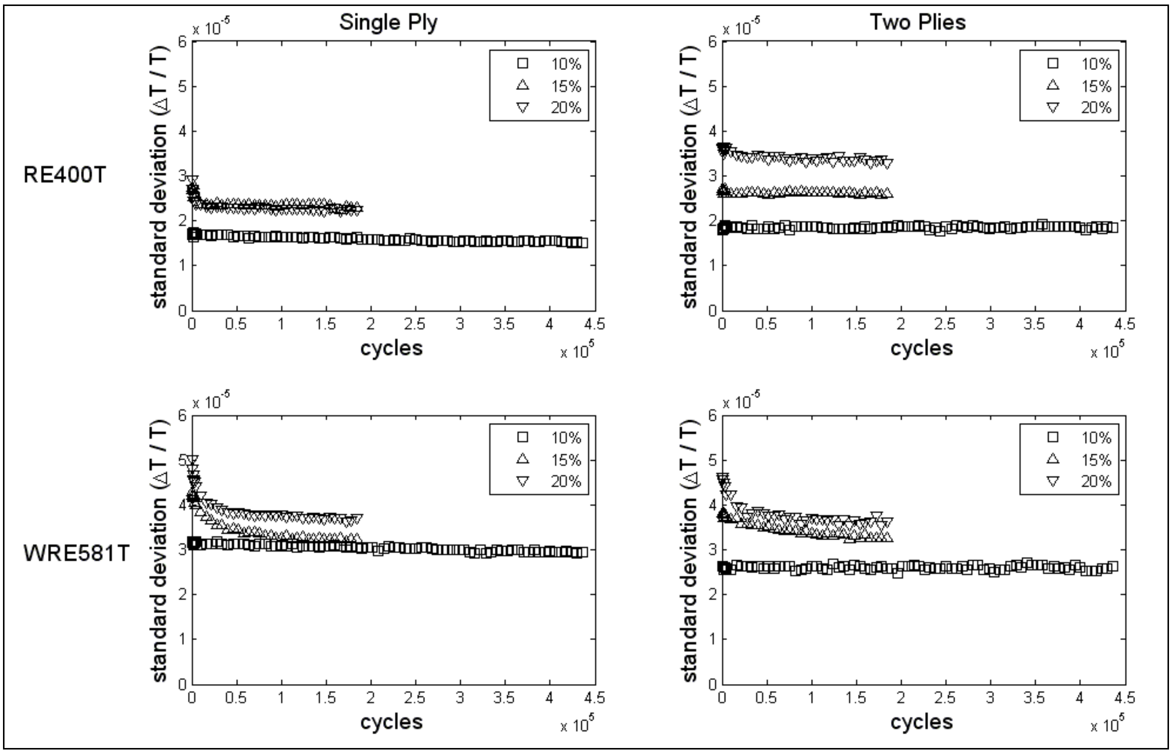

Figure 3: Standard deviation of globally averaged thermoelastic response

The data in Figure 4 shows two data sets from the single ply WRE581T material at two different stages in the fatigue process. The data from the fatigued specimen has been subtracted from the corresponding virgin material data to produce the images in Figure 4. Figure 4a shows the difference in the thermoelastic response after 3200 cycles. The dark blue regions are individual transverse cells in which damage has occurred. Two transverse cells have been highlighted, one for which damage development has progressed considerably (black box), the other just at the onset of damage growth (red box). In both cases a small region of increased thermoelastic response is visible on either side of the central reduction in the signal. This symmetry is shared by all the transverse cells visible in Figure 4a, and occurs only as the damage is progressing. Once damage accumulation is complete, these regions of increased signal become more diffuse, as shown on the example after 184000 cycles in Figure 4b.

Inspection of microscope images from the fatigued specimens reveals the formation of cracks running along the transverse yarns, as shown in Figure 5, circled in red. The cracks form as a single crack through the centre of the yarn, in some cases accompanied by smaller parallel cracks along the yarn edges. These grow until they reach a longitudinal cell where they stop. The regions of increased thermoelastic response in Figure 4a have a similar signature to those observed at a crack tip, as in reference [7]. It is therefore proposed that the formation and propagation of these cracks is the cause of these small regions. The cracks then serve to disconnect the transverse yarns from the mean strain of the specimen, resulting in the local reduction in the thermoelastic response.

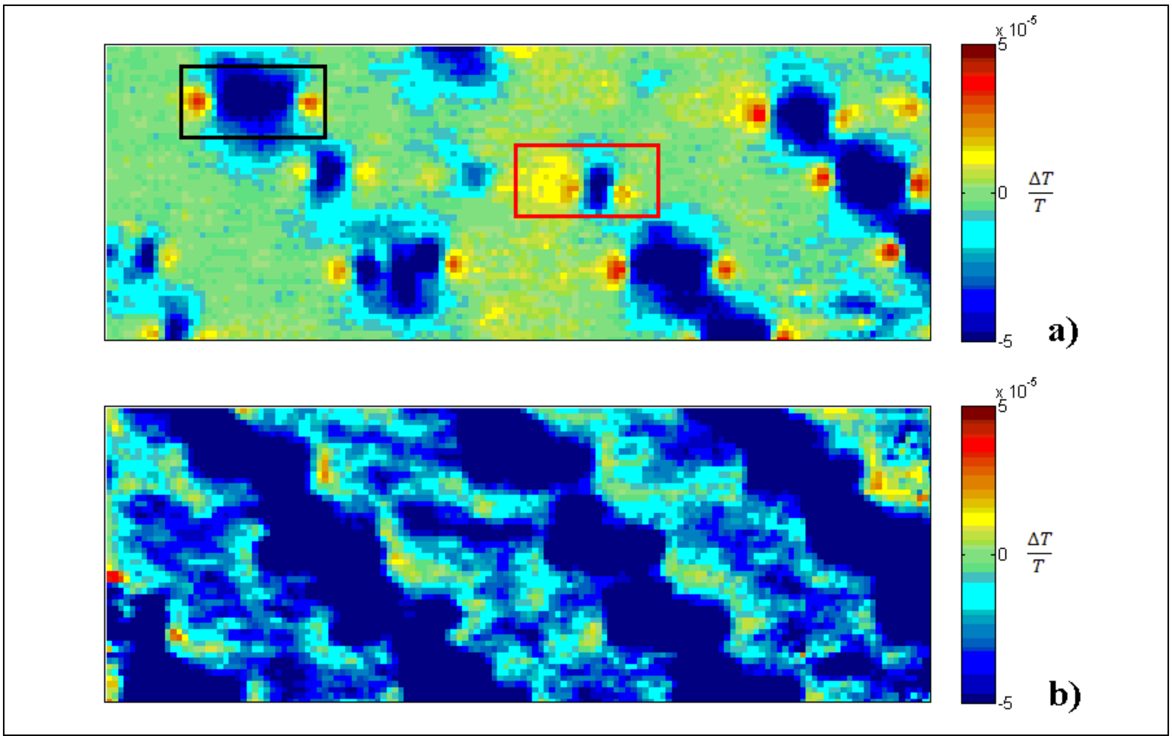

Figure 4: Subtracted thermoelastic image of single ply, WRE581T specimen after a) 3200, and b) 184000 cycles, loaded at 15% of failure stress.

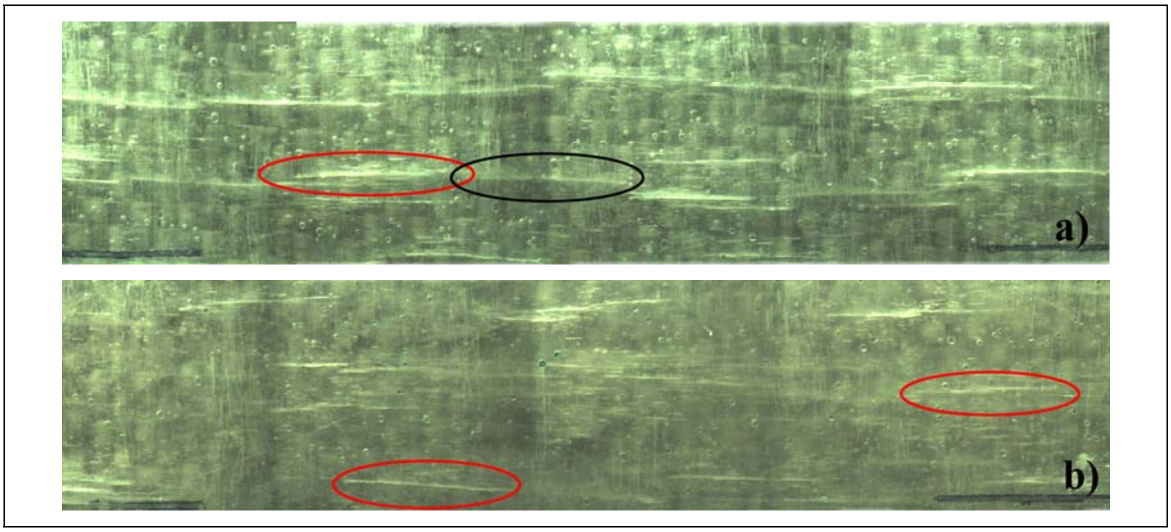

Figure 5: Microscope images from WRE581T a) single ply, b) two ply specimens after 184000 cycles

The specimens were illuminated at an angle to show subsurface defects. In Figure 5a can be seen that the cracks continue on the opposite side of the single ply specimen, circled in black. The same is not observed in the two ply material shown in Figure 5b. This retardation of the crack growth on both sides of the woven ply, due to the ply interface in the middle of the specimen may partly explain the differences observed in the thermoelastic response from the single and the two ply specimens.

CONCLUSIONS

The study highlights the potential for fatigue damage to accumulate rapidly in woven composite materials, even at low stress levels. The problem is even more pronounced in single ply ‘laminates’ such as can be used as the face sheet material in sandwich structures. While the development of matrix fatigue cracks did not reduce the specimen global stiffness or strength, the presence of cracks at the surface may lead to greater susceptibility towards environmental degradation, such as the ingress of water, and this study has highlighted how this damage can be observed and might be quantified. Conversely, the study also shows that small differences in the textile, for example the use of a different yarn, can result in greatly improved resistance, despite the weave architecture and fabric weight being nearly identical.

The potential to identify the growth of small scale damage by means of TSA has been clearly demonstrated. However, the interpretation of the data with regard to quantitative stress measurement remains an area for further investigation. Nevertheless, the technique provides a suitable means for evaluating new materials and complex components. By considering the thermoelastic response in a non-dimensional form, data obtained under different conditions (i.e. collected at different ambient temperatures) can be reliably compared. TSA thereby provides a robust tool for rapid evaluation of new materials.

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