DEVELOPMENT OF A TECHNIQUE FOR EVALUATING DAMAGE IN COMPOSITE OVERWRAPPED PRESSURE VESSELS USING TSA

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ABSTRACT

Composite structures are at risk of low velocity impacts (LVI) during their service life, the effect of these on the load capacity and fatigue life has been widely researched. Of particular interest here is the redistribution of stresses around an area of damage caused by such an event. Composite overwrapped pressure vessels (COPV) were subjected to quasi-static indentation to impart damage of the type and level that may occur from an LVI at two different energy levels. The damage zone was inspected using X-ray computed tomography (CT) to provide information on subsurface damage, and thermoelastic stress analysis (TSA) to determine how the stresses were redistributed in the vicinity of the damage. TSA requires a change in stress state that usually involves cyclic loading. A test rig was designed that imparts an internal cyclic pressure on the damaged COPV. The rig is validated using a steel pipe section with simulated internal damage in the form of an internally machined slot. The TSA data from the pressure loaded pipe is calibrated into stress values, which compare well with that obtained from theory, with the stress redistribution clearly shown. A COPV was subjected to two levels of quasi-static indentation, representative of a LVI, and it is shown that TSA was able to identify the stress redistribution resulting from the indentation.

1 INTRODUCTION

The susceptibility of composite materials to low velocity impact (LVI) has been widely researched, e.g. [1], and it has been shown that these impacts can reduce the load carrying capacity and fatigue performance of composite structures. An important consideration in the residual life of a damaged structure is the effect of the damage on the redistribution of stresses. Here a composite structure, a composite overwrapped pressure vessel (COPV), was subjected to an interrupted quasi-indentation to impart progressively more severe damage representative of LVI. The aim of the paper is to develop an approach to evaluate the stress distribution on the surface of a COPV using full-field imaging techniques.

Thermoelastic stress analysis (TSA) [2] is a full-field technique that uses an infrared detector to measure the small temperature change that occurs in a material during a change in stress. Therefore, the technique requires a structure to be loaded to induce a change in the stress state. A cyclic load is used so that lock-in processing is applied reducing noise and enabling temperature changes of the order of 5 mK to be resolved. The lock-in processing allows the magnitude and phase of the temperature change to be obtained. The phase is the lag between the application of the applied load and the change in temperature and is useful in identifying damaged regions. The cyclic loading also prevents heat transfer and enables adiabatic conditions to be achieved in the test object. In the present paper the development of an experimental approach to apply the TSA technique to components subject to internal pressure is described. To this end, a specially designed rig that converts the linear movement of the actuator of a standard servo-hydraulic test machine to a cyclic internal pressure on a vessel type structure is designed. The use of the rig is validated on a metallic pipe with simulated 'damage'. The approach is then demonstrated on the progressively damaged COPV.

2 VALIDATION OF INTERNAL PRESSURE LOADING RIG

To facilitate the application of internal pressure to a test specimen a hydraulic pressurisation system was designed (see Figure 1). A hydraulic piston was positioned within an Instron 8802 servo-hydraulic test machine with each end gripped in the jaws. This was connected to a rig that housed a steel pipe specimen of 350 mm in length, 85 mm diameter and 10 mm wall thickness. The steel pipe was constrained between two flat plate fixtures using a sealing system that was such that it allowed axial movement of the cylinder, so that under the internal pressure only circumferential stresses were developed in the pipe. The system was filled with hydraulic oil and a hand pump was used to raise the pressure in the cylinder to a mean pressure. Then the internal pressure in the cylinder was cycled by movement of the actuator of the test machine. A series of calibration tests were conducted to determine the actuator displacement necessary for the desired pressure change. The pressure in the cylinder was measured using a digital pressure transducer. The rig was designed to develop pressures of 8 MPa, at frequencies of 10 Hz. However, the maximum frequency is dependent on the oil volume required and the desired pressure range.

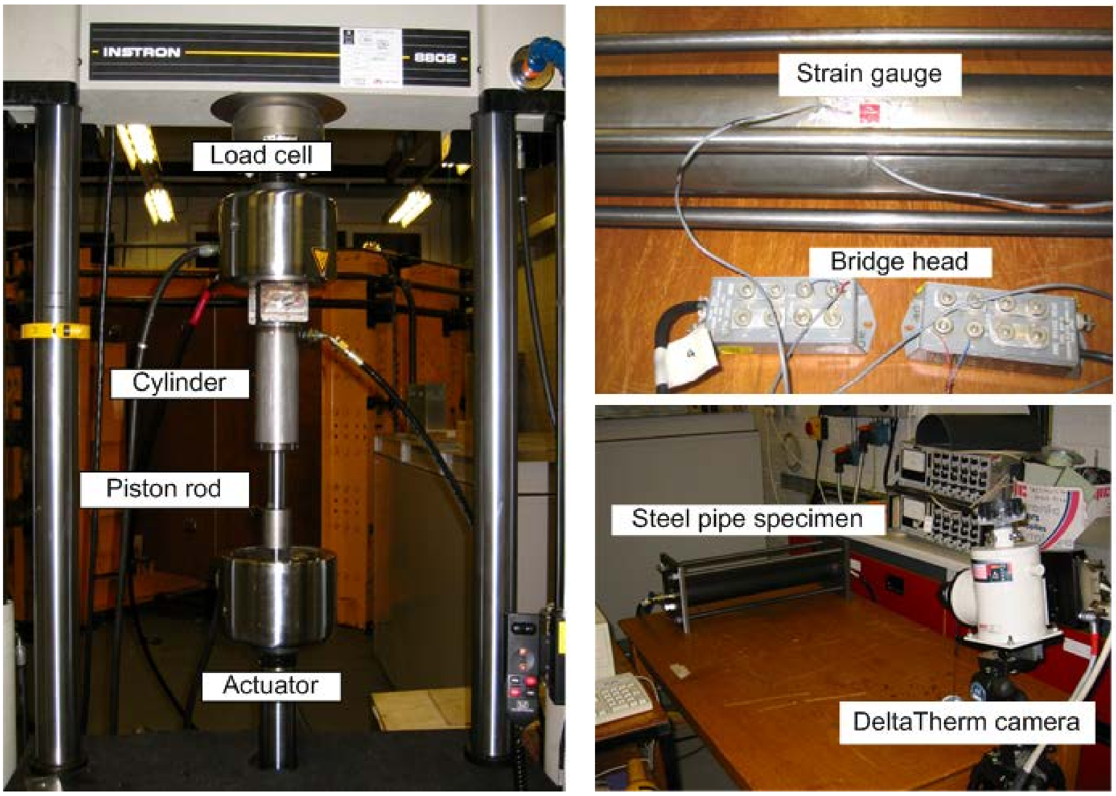

Figure1: Photographs of cyclic pressure rig setup for test on steel pipe specimen

To validate the rig, the steel pipe was pressure loaded at 3.2 MPa ± 1.9 MPa at 10 Hz. A Deltatherm 1000 IR detector was used to capture IR images of the surface. The temperature change from the surface of the specimen, ΔT, is directly related to the stresses in the cylinder as follows:

$$\Delta T = -\frac{\alpha}{\rho C_p}\Delta(\sigma_c - \sigma_a) \qquad (1)$$

where σ_a and σ_c are the axial and circumferential stresses respectively, α is coefficient of thermal expansion, ρ is the density and C_p is the specific heat at constant pressure; $\alpha/\rho C_p$ is known as the thermoelastic constant, K.

The thermoelastic constant was obtained for the steel by conducting a compression test on a section of the steel pipe, which provided a known stress condition that could be directly related to the ΔT

value obtained from TSA. Hence as $\Delta\sigma_a = 0$ in the pressure test on the cylinder it was possible to obtain a value of $\Delta\sigma_c$ during the cyclic pressurisation. To validate the rig, $\Delta\sigma_c$ was compared with the stress value derived from three methods. It was assumed that the cylinder conformed to a shell with a thick wall and $\Delta\sigma_c$ was derived. A 2D FE model was used to provide values of the $\Delta\sigma_c$. The pipe was also instrumented with a strain gauge and the measured strain data was converted to stress using a Young's modulus of 207 GPa. Table 1 shows the comparison, there is a good agreement between the four methods showing all are within 4% of the TSA measure.

Table 1: Comparison of $\Delta\sigma_c$ from TSA, theory, FEA and strain gauge measurements

Methods	$\Delta\sigma_{hoop}$ (MPa)	%error from TSA
Thick-walled theory	27.1	+4%
FEA	27.0	+4%
Strain gauge	24.9	-4%
TSA	26.0	-

Further tests were conducted on steel pipe sections that contained a slot machined on the inside of the cylinder using electrical-discharge machining, of dimensions 50 mm in length, 0.25 mm in width and 0.75 slot depth to wall thickness ratio, to simulate subsurface damage. The pipe was pressure loaded at 1.6 MPa ± 1.3 MPa. Figure 2 shows the ΔT and phase images from the TSA measurement on the pipe with pressure cycled at 8 Hz. The slot is clear in the phase image, but the variation in surface stress state around the slot is also visible in the ΔT image.

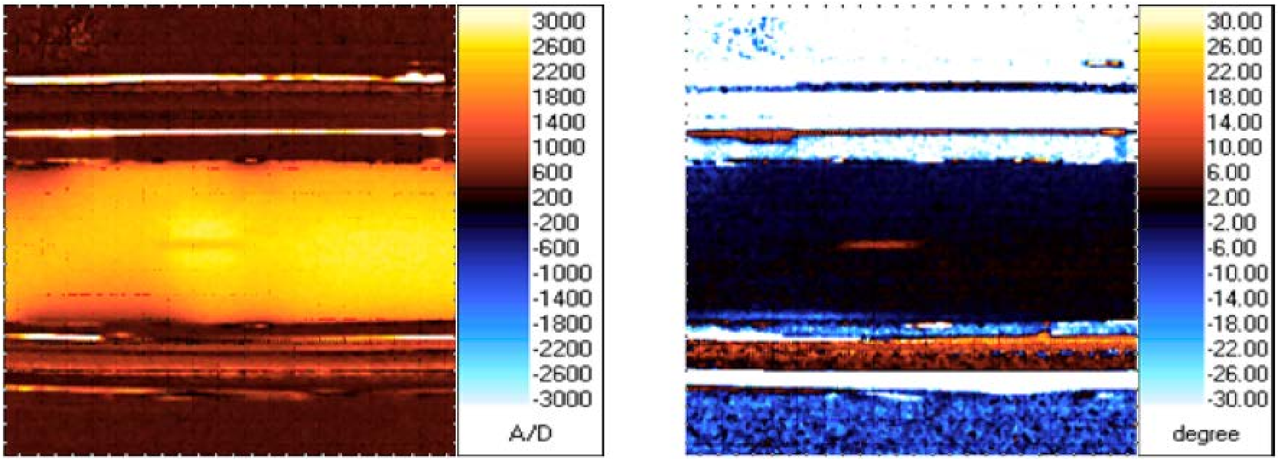

Figure 2: ΔT (in digital level) and phase image from pressure cycling on steel pipe with internal part-thickness slot representing 'damage'

3 ASSESSMENT OF DAMAGE IN COMPOSITE OVERWRAPPED PRESSURE VESSEL

The approach described above was applied to a COPV which was subjected to cyclic pressure loading using the test rig described in Section 2. The COPV was damaged using a progressive quasi-static indention methodology provide the types, and level of, damage caused by LVI [3, 4]. This approach allows the damage to be grown in the same test piece to various levels consistent with progressively higher impact energies. Here a COPV was positioned in a 'vee' block on an Instron electro-mechanical test machine. A hemispherical tup 16 mm in diameter was used to indent the COPV at two load levels sufficient to create damage. Additionally, CT scans were conducted to inspect the damage. The scans were completed on a Nikon Metrology HMX µCT scanner.

The damaged COPV was mounted in the pressure rig and a FLIR SC5500 photon detector was used to obtain IR images of the area around the damaged zone at a frame rate of 383 Hz so that TSA data could be obtained. To apply the TSA to the damaged COPV the vessel was filled with hydraulic oil and attached to the pressure rig described in Section 2. To determine a suitable pressure level for the loading a series of tests were conducted on a ring of material ring cut from a similar COPV, which was loaded under cyclic compression. By applying TSA to the ring of material during the compression tests, it was possible to determine the stress level required to provide a measurable ΔT and facilitate TSA. It was possible to extract a K value from the tests on the ring of material and hence determine the cyclic pressure required by assuming the COPV was a thin walled cylinder. A compromise was made between the pressure required to obtain a measurable ΔT and ensuring the cyclic pressure did not significantly grow the damage by fatigue. The pressure in the COPV was cycled at 1 Hz. This is lower than is usually considered necessary to obtain adiabatic conditions required to fulfil the assumptions of the thermoelastic equation. However previous work [5] has shown that TSA applied at lower cyclic frequencies can provide an indication of the stress state in a composite structure, and in this case it should be noted that the GFRP has a very low thermal conductivity minimising the influence from the subsurface.

Figure 3 shows the ΔT/T and phase image for the damage zone after the first quasi-static indentation. From the CT it was possible to observe multiple damage modes; delamination, tensile cracks near the interface with the liner and 45° shear cracks in a cone pattern. From the TSA (Figure 3) it is possible to see the indentation site, and there is some influence of the damage in a surrounding darker area showing a change in stress state. However this is highly localised and there is not significant measurable alteration to the stress state further from the damage zone. Figure 4 shows the ΔT/T and phase image for the damage zone after further quasi-static indentation. This represents a highly complex damage state with influence on the stress state from composite surface damage, composite subsurface damage. In the higher load case, the extent of the damage was found to have progressed significantly from the CT scan. The effect of the more severe damage is also evident in the TSA data. The TSA images in Figure 4a and b show a data-rich evaluation of the stress state around a large damage zone from an indentation representative of an impact. In particular, it is possible to identify an inner circle, which represents the area that came into direct contact with the tup. Around this area is a dark ring that indicates a region that is no longer able to carry load. This corresponds to the area captured by the CT data showing significant damage. Immediately surrounding the darker region is a ring of high ΔT/T response showing large localized stresses have occurred as a result subsurface damage.

(a) (b)

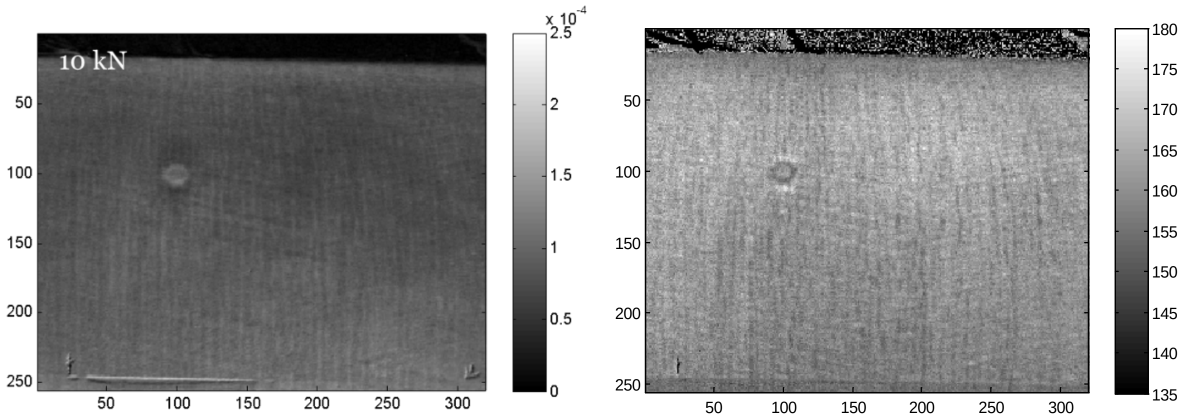

Figure 3: Images for damage zone in COPV after the first indentation (a) ΔT/T (K), (b) phase

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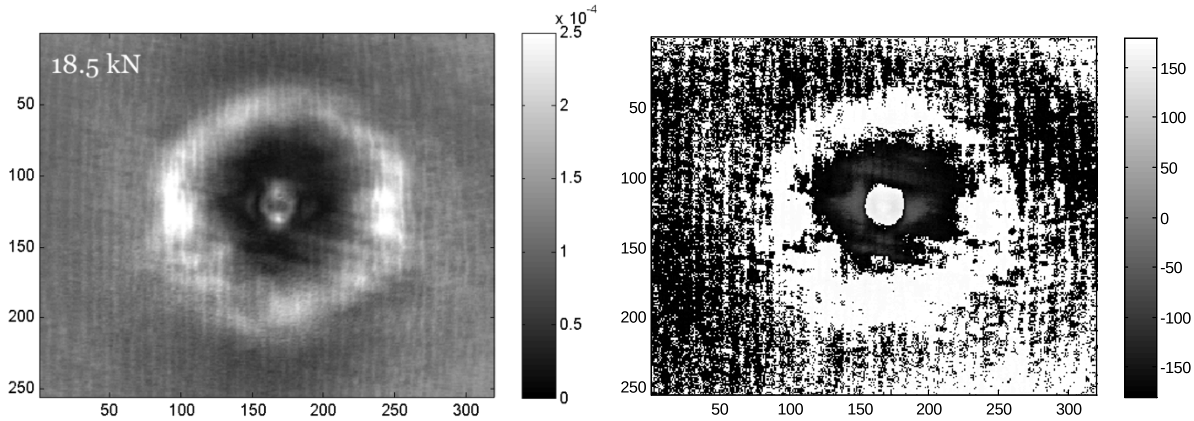

Figure 4: Images for damage zone in COPV after the second indentation (a) $\Delta T/T$ (K), (b) phase

4 CONCLUSIONS

A rig has been used to apply a cyclic pressure to a progressively damaged COPV to enable the application of the data rich infra-red technique TSA to provide an insight into the stress redistribution after quasi-static indentation. This has been used alongside X-ray CT inspections to link the stress redistribution to particular features in the subsurface damage.

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