DEVELOPMENT OF THERMOELASTIC STRESS ANALYSIS AS A NON-DESTRUCTIVE EVALUATION TOOL

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SUMMARY

A modified methodology is proposed in which only a single transient load is used for the TSA measurement. Specimens with different damage severities are tested and it is shown that the modified TSA method has the potential to be applied in the field as a non-destructive evaluation tool.

Keywords: thermoelastic stress analysis, non-destructive evaluation

INTRODUCTION

Thermoelastic stress analysis (TSA) is a well established experimental technique [1] for measuring the surface stress field of a dynamically loaded component. The technique is non-destructive and non-contacting, requiring a minimum of surface preparation ranging from a coating of matt black paint to no preparation at all. The modern infra-red (IR) detectors used to measure the small temperature changes induced by the dynamic load are compact, robust systems that operate in conjunction with a standard PC. The technique therefore offers great potential as a non-destructive strain-based damage assessment tool, which could be used to assess components during routine inspections in the field. However, the current methodology presents a barrier that has hitherto tethered the technique to laboratory testing only: the requirement for a cyclic load.

In an orthotropic material under adiabatic conditions, the temperature change (ΔT) that occurs as a consequence of the thermoelastic effect is related to a change in the stress field by [2]:

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

where T is the absolute temperature, ρ is the density, C_p is the specific heat, 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 changes in the principal stresses.

The thermoelastic temperature change is very small; for example, a typical E-glass / epoxy composite specimen will exhibit a change in temperature of 1.5 mK for an induced stress change of 1 MPa. Modern IR detectors, such as the one used in this work, have a sensitivity of up to 4 mK within a noise of 15 to 20 mK. To increase the thermal resolution, current practice is to subject the specimen to a cyclic load and apply a lock-in amplifier to the measured IR signal, thereby providing the required filtering and temporal averaging to resolve stress changes as small as 1 MPa. It is the requirement for a controlled cyclic load and corresponding reference signal that presents a barrier to moving the technique from the laboratory into the field, significantly constraining the application range. The object of this work is therefore to consider a modified approach to TSA that circumvents this barrier. In the proposed methodology the component under test is subjected to a single transient load. In the current paper an impact method of imparting the transient load into fibre reinforced polymer composite specimens is defined that underpins the new methodology. The results from the new approach are then validated using both theory and the standard TSA method. Finally the potential of the new TSA methodology is demonstrated through application to the assessment of damage growth in three different polymer composite laminates.

TESTING PROCEDURE

TSA relies on a stress change to induce the thermoelastic effect and hence provide the small change in temperature that is measured by the IR detector. The cyclic loading is necessary to ensure that the temperature change occurs at such a rate so that dissipation into the surroundings is prevented. Conventionally this is done by applying a cyclic load using a servo-hydraulic test machine at such a rate that *pseudo* adiabatic conditions are achieved. A significant challenge in the current work is therefore to introduce a dynamic load into the component of sufficient magnitude to produce a measurable temperature change without the use of a test machine.

The transient loading approach addresses the aim of applying a load without a test machine and is based on a single controlled impact load. A test rig has been designed for this purpose and is based on the application of an impact load to a cantilever beam; the rig is shown in Figure 1. The impact is imparted into the specimen using a pendulum that is released from a known height, thereby providing a repeatable load. The impact test rig incorporates a mechanism that captures the impactor after the first rebound and prevents repeated loads from being applied. In the current work the magnitude of the applied load is determined by measuring the deflection at the end of the cantilever beam optically from above. However it is possible to incorporate a force transducer in the impactor and this is how the technique would be applied in the field.

To obtain the thermoelastic data from the infra-red detector it was necessary to collect thermal images from test specimens as they are subjected to the transient loading. The temperature was recorded from approximately one second before the application of the load and for approximately one second after. In the impact test the stress varies along the length of the specimen, so transverse lines 20 mm long (40 pixels) were plotted at 10 mm intervals along the length of the specimen. The average value of temperature from each line plot was used to give T at positions x_1 to x_8 along the length of the cantilever beam.
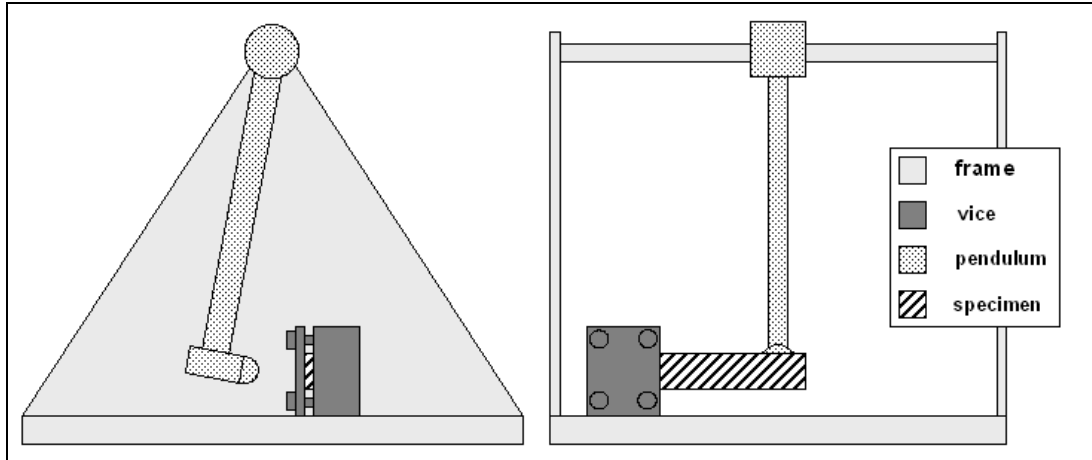
Figure 1: Schematic of the impact rig.

A typical plot of the temperature change during the impact is shown in Figure 2. T_1 was taken as the average of 50 frames of data and T_2 was taken as the maximum value of the temperature spike. (The measurement was taken on the compressive side of the beam and hence the impact results in a positive temperature change.) This approach differs significantly from standard TSA where proprietary embedded software is used to derive the temperature change data automatically by correlating the thermal data with a reference signal from the test machine. The 'lock-in' procedure rejects signals other than those at the reference frequency; this is not possible when using transient loading.
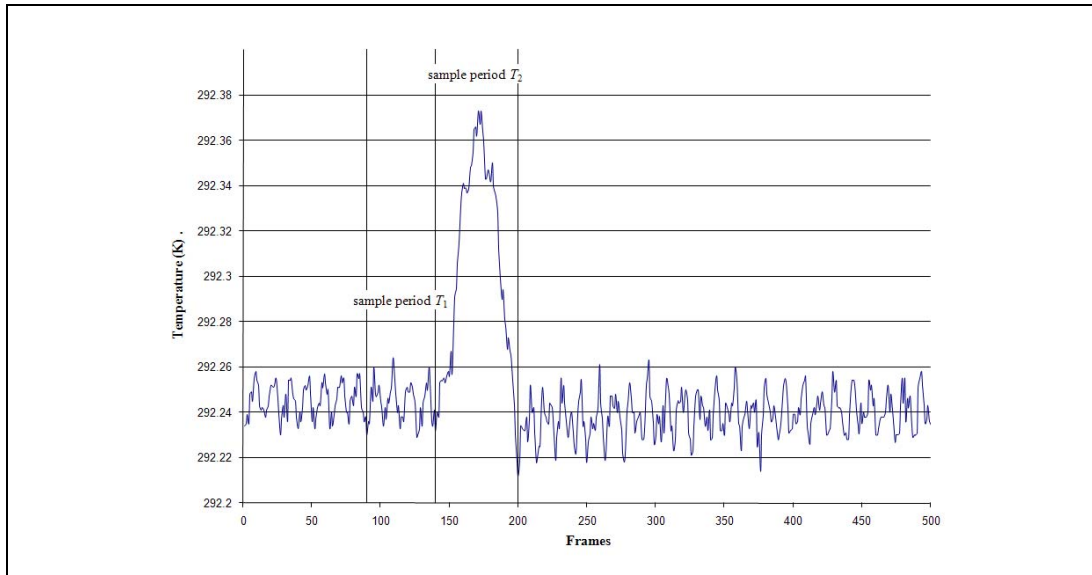

Figure 2: Change in temperature during a cantilever impact test

To demonstrate that a single transient excitation is sufficient to perform an accurate and repeatable measurement of the stress induced temperature change the methodology was validated against ΔT values determined from simple bending theory and the known material properties.

Once the viability of the technique is established a stress raiser is introduced into the specimen and the transient TSA applied. More damage is evolved in the specimens by further cyclic loading. The damage is assessed by comparing the data from the damaged and undamaged states.

TEST SPECIMENS AND MATERIALS

Three materials types have been used in the current work: two pre-preg laminates and one resin-infused woven roving. In all cases the fibre reinforcement is E-glass. The fibre configuration, laminate stacking sequence and manufacturing process are given in Table 1. Glass-epoxy composites were used as they have a low thermal diffusivity, which means that heat transfer is minimised hence providing a basis for assessing the transient loading approach.

Table 1: Materials and manufacturing processes

Specimen	Resin	Reinforcement	Lay-up	Process
UD	(epoxy)	UD fibre	8 (7) plies, 0°	pre-preg [*]
LAM	(epoxy)	UD fibre	[0,25,-25,0]$_S$	pre-preg [*]
TW	Prime 20 LV with fast hardener (epoxy)	2 x 2 twill woven roving 500 gm^{-2}	6 plies, 0°	VARTM [**]

[*]   Autoclave consolidated pre-impregnated glass fibre matt
[**]   Vacuum Assisted Resin Transfer Moulding

The unidirectional pre-preg autoclave consolidated material was chosen for two of the specimens (UD and LAM) as this provides the most consistent material properties. The pre-preg material (manufactured by Primco) was cured in an autoclave at 125 °C under 3 bar of pressure. The UD specimen also has the advantage that the opportunity for heat transfer is reduced further as both the in-plane and through thickness stresses are uniform. The only heat transfer that might take place in this specimen is between the fibres and the resin at the micro-scale, which will not be visible because of the scale of the measurement. The second configuration (LAM) is a [0, 25, -25, 0]$_S$ laminate and provides comparison with an off-axis configuration. For both the UD and LAM materials the stress state in the surface ply can be calculated using classical laminate theory (CLT) thereby enabling the calculation of ΔT to be compared to experimentally derived values.

The third material is a 2 x 2 twill woven composite (TW). The epoxy resin system was Prime 20 LV with a fast hardener manufactured by Gurit. The consolidation was by liquid resin infusion at room temperature (~20 °C) and atmospheric pressure. This was included to investigate if the influence of the weave pattern on the stress field could be detected using the transient TSA methodology. Local variations in the stress field in the woven material prevent a simple calculated solution for the stresses from being formulated. Therefore it was decided to use this material only in the damage assessment.

Material properties for calculating the thermoelastic response based on the known stress in the surface ply were measured using samples of the UD material. The Young's moduli (E_1 and E_2) were obtained from quasi-static tensile tests according to ASTM

standard D 3039. The coefficients of thermal expansion (α_1 and α_2) were measured using a strain gauge technique described in Ref. [3] over the range from 20 to 40 °C. The density (ρ) was measured using microscope images of the material cross-section from several regions cut from a UD specimen and the specific heat capacity (C_p) was measured using differential scanning calorimetry (DSC). The material properties are summarised in Table 2.

Table 2: Material properties

E_1	(GPa)	34.2
E_2	(GPa)	10.0
P	(kgm^{-3})	1880
C_P	(Jkg^{-1}K^{-1})	843
α_1	(K^{-1})	9 x10^{-6}
α_2	(K^{-1})	31 x10^{-6}

Surface preparation is typically not required for epoxy composite materials due to the high emissivity of material. However, it is important that the surface is matt to avoid reflection sources influencing the measurement. To achieve a matt finish, the surface was lightly abraded by hand using a medium grade 3M Scotch-Brite scouring cloth. This imparts a dull finish to the surface without damaging any of the fibres below.

VALIDATION

To enable direct comparison between the measured and the calculated TSA data, the measured data was converted into a non-dimensional form by taking equation (1) and dividing through by the specimen static temperature. The calculated non-dimensional temperature change is then given by:

$$\left| \frac{\Delta T}{T} \right| = \frac{1}{\rho C_p} [\alpha_1 \Delta \sigma_1 + \alpha_2 \Delta \sigma_2] \tag{2}$$

Tests were conducted using the UD and LAM specimens. Using the material properties in Table 2, the stress state in the surface ply was calculated using simple cantilever beam theory and the measured maximum deflection. In the case of the UD material, the force (P) at the free end of the beam is related to the deflection (δz) by the following equation:

$$P = \frac{3(\delta z) E_1 I}{l^3} \tag{3}$$

where I is the second moment of area, E_1 is the Young's modulus in the longitudinal direction and l is the distance from the fixed end to the point at which the force acts. Using the measured deflection, equation (3) was used to calculate the corresponding force at the free end of the beam at the maximum deflection. This could then be used to calculate the stress in the surface ply at any distance (x) from the fixed end using:

$$\sigma_u = \frac{P(l - x)h}{I} \tag{4}$$

where h is half the thickness of the beam. In this case $\Delta\sigma_1 = \sigma_x$ because the beam is initially at rest. For the UD material $\sigma_2 = 0$. For the LAM material, E_1I in equation (3) is replaced by the laminate bending stiffness, and instead of equation (4), the bending moment at each distance x was taken and CLT was used to calculate σ_1 and σ_2.

The impact test was repeated five times for each material, but only for one pendulum release height. The results are shown in Figure 3 for the UD material and Figure 4 for the LAM material. Notably the experimental data lies below the calculated data, by approximately 10% at the fixed end. Both the UD and the LAM specimens show a slightly steeper stress gradient at the fixed end, which then becomes nearly parallel to the line of calculated values.

Uncertainties regarding the emissivity and material properties are not sufficient to produce the discrepancies shown in Figures 3 and 4. However, two further effects may explain the lower experimental values. Firstly, flexibility in the clamped end would result in a lower stress. Secondly, the thin beams have a sharp through-thickness stress gradient. It has been shown that temperature dissipation between plies in specimens loaded in uniaxial tension can be neglected in E-glass / epoxy specimens, even at low loading rates [4]. However, sharp stress gradients exist within the surface ply; the stress in its outer surface is 25% higher than the stress at its inner surface. The average surface ply stress is therefore 13% lower than the stress at the outer surface. Taking this into account, the calculated and measured stress data correlate very well, as do the results from the two validation methods, confirming that the modified procedure provides a valid means of evaluating the stress field in composite components.
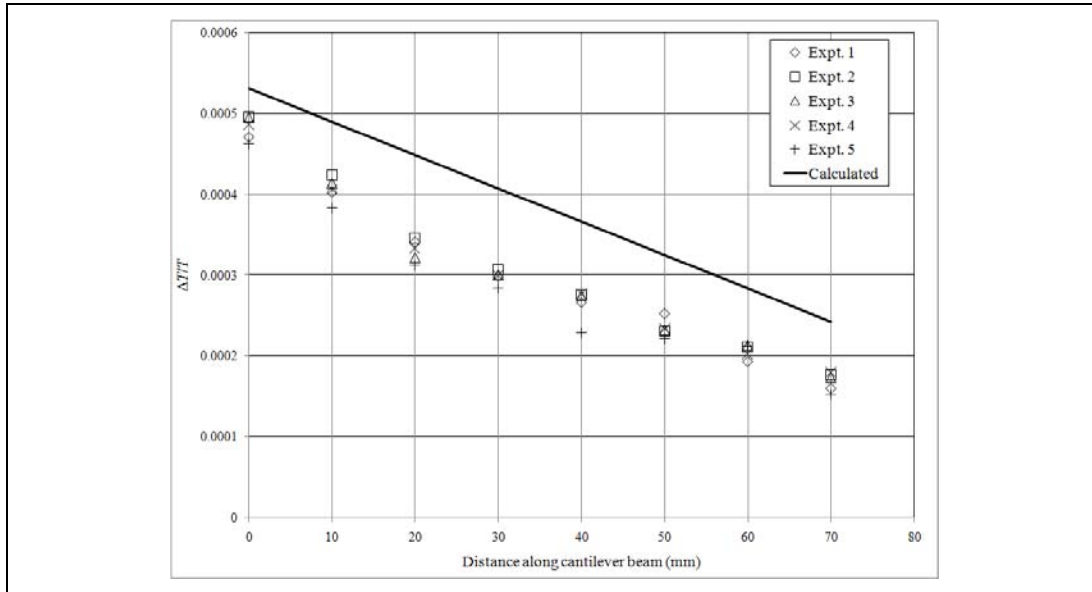

Figure 3: Non-dimensional temperature change distribution in the cantilever beam UD, deflection 17.5 mm
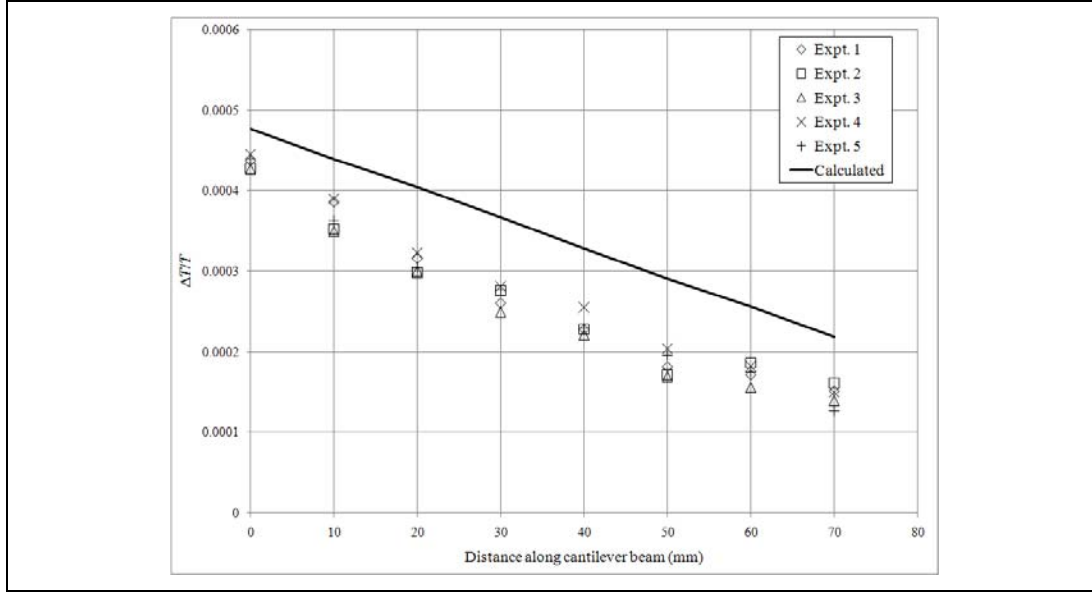
Figure 4: Non-dimensional temperature change distribution in the cantilever beam
LAM, deflection 18.2 mm

DAMAGE ASSESSMENT

The spatial averaging used in the previous section to improve the effective thermal resolution is not practical for the purpose of damage assessment for which full-field data is desired. In the following tests, the method of obtaining ΔT was as described above, except that the temperature measurement was taken on a pixel by pixel basis to provide an image of the non-dimensional ΔT field.

Damage assessment was conducted on the TW material. Firstly data was collected from the strip specimen. Then a stress concentration was introduced in the form of a 4 mm diameter hole in the centre of the strip and a second measurement was made. Finally the specimen was subjected to a tensile sinusoidal load at constant load amplitude for two sets of 18000 cycles and a TSA measurement was taken after each set.

The TW specimen enables a qualitative evaluation the resolution of the TSA transient loading methodology, as the interlacing of the fibres in the textile results in stress concentrations at a small scale. Fatigue of the textile composite leads to a change in the distribution and magnitude of these stress concentrations. The aim here is therefore to verify if such fine details in the stress field can be resolved using the modified TSA method.

The data in Figure 5 shows that the stress concentration around the hole can be identified using the impact method. The deterioration in the weave structure is however not picked up by the impact method to the same extent as by the standard method. A slight decrease in the magnitude of the signal, in particular towards the free end, can be identified. This data shows that further refinement of the technique will be necessary to enable small scale features in the stress field to be identified using the impact method.
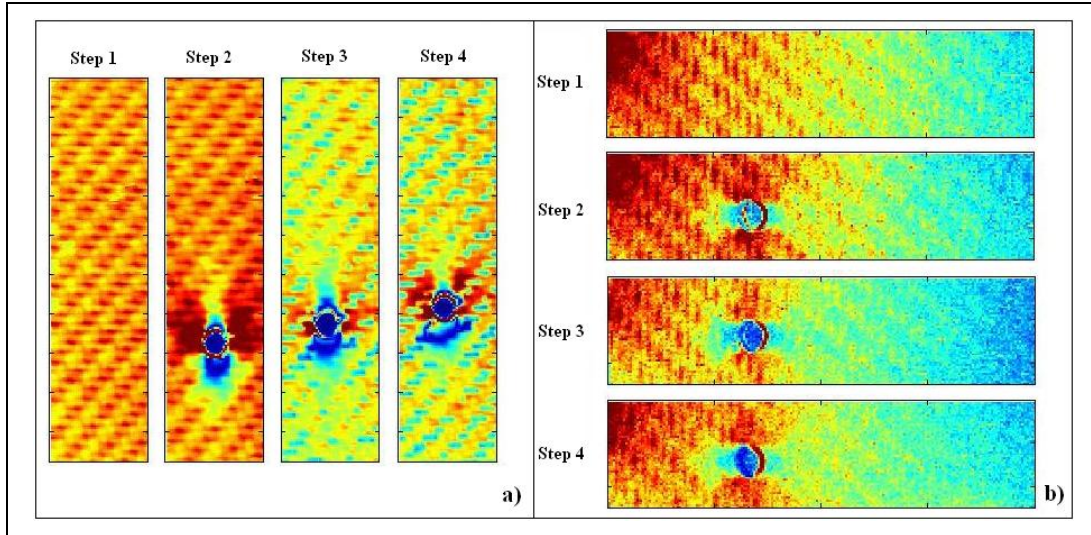
Figure 5: Progression of damage around a hole and within the weave structure in the TW material using a) the standard method and b) the impact method

CONCLUSIONS

The results show that quantitative data can be obtained using a single transient load with a comparable accuracy to the standard TSA method. The rate and magnitude of the stress change must exceed a minimum threshold which will vary depending on the material. In the case of E-glass / epoxy composites, relatively low loading rates and magnitudes are sufficient.

With regard to the identification of damage, the technique relies on a stress redistribution in the surface ply. This is no different from the standard method. However, the greater simplicity of the modified technique provides improved flexibility for introducing load into the specimen. The greatest difficulty will always be to generate a realistic loading scenario, and sufficient load amplitude. Development of the filtering of the thermal data to improve the effective thermal resolution of the technique is required to enable small scale stress concentrations to be identified; these challenges will be the subject of future work. The present study has confirmed the feasibility of applying TSA as a damage assessment technique for in-service components. The work represents an important initial step in taking the TSA technique away from the laboratory and opens a new application range of significant industrial relevance.

References

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