Using Thermoelastic Stress Analysis for Damage Quantification on CFRP laminates

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Abstract
Thermoelastic Stress Analysis (TSA) is a full-field non-contact infrared imaging technique based on the monitoring of temperature distributions in components subjected to cyclic loading. While traditionally regarded as a surface technique, recent work has shown that the subsurface thermoelastic response could be obtained at low loading frequencies where through thickness heat transfer occurs. The paper expands on TSA previous work by embracing the full-field nature of thermal data that permits a novel full-field damage parametrization methodology, by combining data sets obtained from thermal imaging and from digital image correlation (DIC). For the first time it is shown that the TSA damage parameter offers a detailed full-field degree of damage inspection in both surface and subsurface plies of Carbon Fibre Reinforced Polymer (CFRP) laminates.

Introduction

Thermoelastic stress analysis (TSA) is a non-contact full-field technique that utilises infra-red (IR) imaging. It is based on the measurement of a small temperature changes (ΔT) on the surface of a material that occurs when a material is cyclically loaded in its elastic region. Temperature variations are captured using a sensitive IR detector, which can then be related to the stress changes on the surface of a component. The relationship between ΔT and the stress changes in orthotropic materials is defined as [1]:

$$\Delta T= \frac{-T_0}{\rho C_p}(\alpha_1 \Delta\sigma_1+\alpha_2 \Delta\sigma_2) \tag{1}$$

where T_0 is the material mean temperature, ρ is the density, C_p is the specific heat capacity, α_1 and α_2 are the coefficients of linear thermal expansion in the principal material directions (α_6 = 0) and $\Delta\sigma_1$ and $\Delta\sigma_2$ are the stress changes in the principal material directions.

Equation 1 is only valid when adiabatic conditions are met when components are cyclically loaded at frequencies sufficient to prevent heat transfer. It has been recently demonstrated that TSA as a method, need not be limited to the surface, and indeed subsurface thermoelastic response can be obtained using low loading frequencies, where heat transfer occurs in the form of through thickness heat diffusion [2].

To interpret the thermoelastic response in terms of the damage severity, a theory has been proposed [3]. A damage parameter, D_{TSA}, that accounts for micro-cracks, defects, and voids, under uniaxial stress conditions is related to the thermoelastic response by:

$$\frac{\Delta T}{T_0} = K_{Undamaged} \cdot \frac{\Delta\sigma}{(1 - D_{TSA}^2)} \tag{2}$$

where $K_{Undamaged}$ is the thermoelastic constant of the undamaged laminate and $\Delta\sigma$ is the stress change across the laminate during the cyclic analysis.

The procedure is developed by investigating CFRP laminates at low loading frequencies so that through thickness heat transfer is encouraged. D_{TSA} is also compared with a more conventional approach based on material stiffness reduction as damage accumulates [3–5] obtained from the DIC. In the present paper controlled damage is introduced into multidirectional laminates, and it is shown how tuning the loading frequency enables damage quantification to reveal features in the interior plies.

Materials and methodology

Damage initiation and propagation in laminated composites can occur in both surface and subsurface plies, so a testing campaign was devised that promoted both scenarios. CFRP (IM7/8552) $[0,90]_{3S}$, $[90,0]_{3S}$, $[0,45,-45,0,0,0]_S$, and $[0,0,0,45,-45,0]_S$ strip specimens were cut from autoclave cured pre-preg panels. Phase 1 of the experiments commenced with an inspection of the undamaged coupons by cyclically loading below the first ply failure (FPF) with a frequency of 3.1 Hz and carrying out TSA and DIC simultaneously. $K_{Undamaged}$ was obtained experimentally for all the layups as D = 0 in the undamaged state. In Phase 2 incremental uniaxial tension loads introduced damage of increasing severity and DIC was employed to obtain the strain fields and hence calculate the laminates stiffness at each damage level. Phase 1 loading conditions are then used after each incremental load is applied to obtain ΔT and hence calculate D_{TSA}.

Results and discussion

D_{TSA} is displayed in Figure 1 for all the CFRP configurations. The plot shows how D_{TSA} evolves with the incremental load levels. First, an inspection is carried out at 31% of the UTS to corroborate the undamaged state of the configurations. At this level, the D_{TSA} is close to zero as FPF has not occurred and hence confirming that damaged is not induced.

FPF load levels are exceeded for all the layups at 59% of the UTS, which is accompanied by an increase in. The $[90,0]_{3S}$ laminate appears to be as the most damaged, with a D_{TSA} of 0.19. Also, the full-field damage distribution in Figure 1 shows that the surface ply is severely damaged, indicated by the horizontal stripes. Damage in the other configurations has occurred in the subsurface plies, which explains the increase in D_{TSA} for $[0,90]_{3S}$, $[0,45,-45,0,0,0]_S$ and $[0,0,0,45,-45,0]_S$. Interestingly, the full-field TSA plot for the $[0,90]_{3S}$ laminate shows subsurface damage in the form of horizontal strips at 59% of the UTS. The TSA results reveal that when the ±45 plies are in the 2nd and 3rd ply in the stack D_{TSA} shows a value of 0.15, being smaller (0.03) when the ±45 plies are the 4th and 5th position in the stack.

The degree of damage then increases after reaching 75% of the UTS. Following the same trend, the $[90,0]_{3S}$ reveals a D_{TSA} of 0.29. The increase in damage is visible in the full-field map shown in Figure 1. Moreover, both surface and subsurface damage are visible in the $[0,90]_{3S}$ full-field map, which is shows an average D_{TSA} of 0.09. Diagonal damage patterns are observed for the $[0,45,-45,0,0,0]_S$ which correspond to damage in the ±45 plies. Although a rounded feature is found at the centre of the coupon for the $[0,0,0,45,-45,0]_S$ with D_{TSA} close to 0.

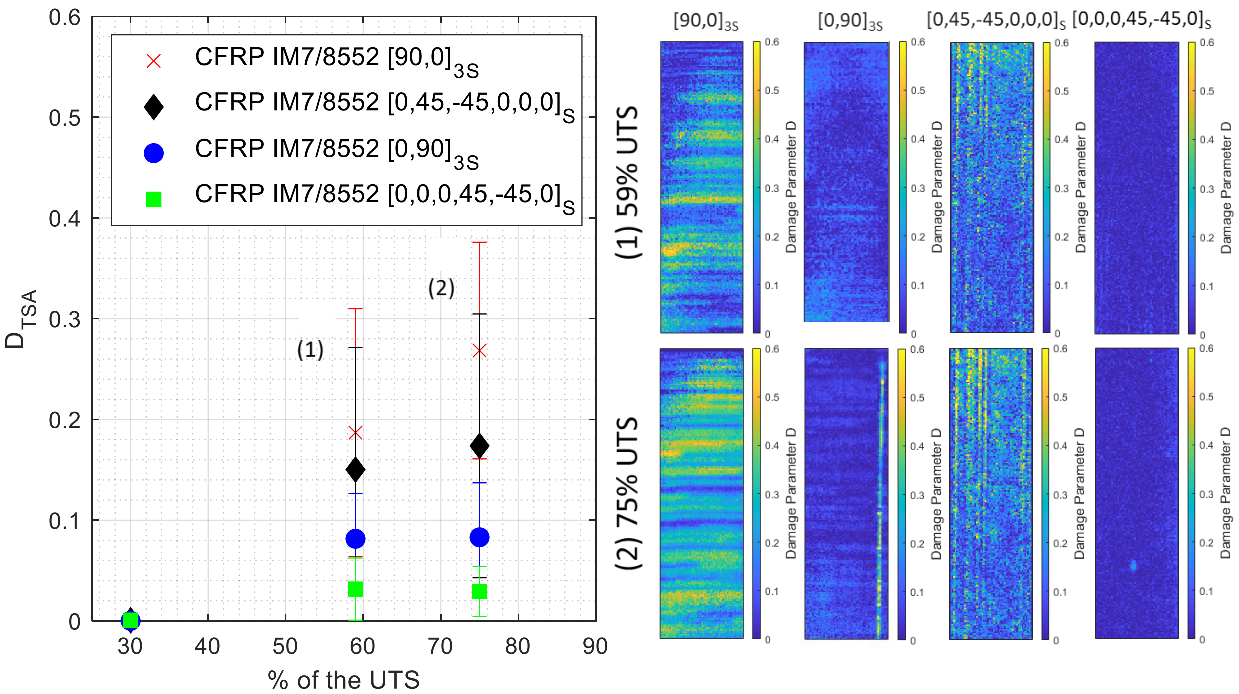

Figure 1. Averaged and full-field D_{TSA} for $[0,90]_{3S}$, $[0,45,-45,0,0,0]_S$, $[90,0]_{3S}$ and $[0,0,0,45,-45,0]_S$.

Conclusions

In the present paper, CFRP specimens are subjected to increasing levels of damage, and a damage parameter obtained from TSA is employed:

- The $[90,0]_{3S}$ specimen reveals the highest degree of damage as FPF occurs in the surface.
- Both surface and subsurface damage is included in $[0,90]_{3S}$, $[0,45,-45,0,0,0]_S$ and $[0,0,0,45,-45,0]_S$.
- Full-field subsurface damage is revealed for $[0,90]_{3S}$ and $[0,45,-45,0,0,0]_S$ configurations.

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