TSA of Carbon/Epoxy Composite Laminates Under Cyclic Loading Using Harmonic Amplitude Characterization

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Abstract. The application of Thermoelastic Stress Analysis (TSA) for detecting internal and surface damage in carbon fibre reinforced polymer (CFRP) components is investigated. Under standard adiabatic conditions, TSA operates on the principle that the stress-induced temperature change is linearly proportional to the sum of the principal stresses. However, applying this to anisotropic materials like CFRP presents significant challenges due to complex heat transfer effects. Rather than treating this diffusion as a measurement limitation, this study actively exploits this frequency-dependent through-thickness heat transfer to non-destructively evaluate internal damage via TSA.

Theoretical Framework. Thermoelastic Stress Analysis (TSA) is a well-established full-field technique for evaluating structural stress distributions. Under ideal adiabatic conditions, the localized temperature change ΔT in isotropic materials is directly proportional to the change in the sum of the principal stresses $\Delta\sigma$, expressed via the classical relationship as:

$$\Delta T = -\frac{\alpha T_0}{\rho C_p}\Delta\sigma \tag{1}$$

where α is the coefficient of thermal expansion, T_0 is the absolute baseline temperature, ρ is the density, and C_p is the specific heat capacity.

While the surface thermal response of isotropic materials perfectly mirrors this global stress state, highly anisotropic CFRP laminates suffer from severe non-adiabatic heat transfer and sharp interlaminar stress gradients. To address this complexity, Wong et al. derived the following equation, which assumes that the measured surface temperature change ΔT_s is a superposition of the frequency-dependent thermal contributions diffusing from each individual embedded ply [1]:

$$\Delta T_s = T_0 \sum_{j=1}^{n} A_j \tau_j = -T_0 \sum_{j=1}^{n} \frac{1}{\rho^j C_p^j}\left(\alpha_1^j \Delta\sigma_{11}^j + \alpha_2^j \Delta\sigma_{22}^j\right)\tau^j \tag{2}$$

where A_j reflects the amplitude of the thermoelastic source in the j ply, $\Delta\sigma_{11}^j$ and $\Delta\sigma_{22}^j$ represent the normal stress changes in the longitudinal (fiber) and transverse directions of the j ply, and τ_j is the frequency-dependent surface temperature contribution from that ply. The value of τ_j is obtained by numerically solving the one-dimensional heat diffusion equation, typically using a finite difference or finite element scheme.

By applying the superposition framework in Eq. 2, this frequency-dependent through-thickness thermal conduction can be actively utilized to evaluate internal damage states directly from the surface TSA response.

Experimental conditions. To validate the proposed diagnostic framework, experimental investigation was conducted using multidirectional IM7/8552 coupon specimens. The experimental setup is illustrated in Fig. 1, and the corresponding material and loading configurations, including the $[\pm45]_{3s}$ and $[0/90/90/0/0/0]_s$ layups, are summarized in Table 1. Cyclic loading was applied below the First Ply Failure (FPF) threshold, with the loading frequency systematically varied from 0.5 Hz to 30.1 Hz to evaluate the frequency-dependent heat transfer characteristics. Furthermore, artificial damage was intentionally introduced into the specimens to explicitly investigate and characterize its influence on the resulting thermoelastic and thermal conduction behaviour.

Results and Discussion. The frequency-dependent surface temperature response is discussed using the $[\pm45]_{3s}$ laminate shown in Figure 2. At a low frequency of 1.1 Hz, the temperature distribution is uniform due to high heat transfer in both the in-plane and through-thickness directions. In contrast, at 5.1 Hz and 10.1 Hz, a distinct temperature pattern reflecting the interlaced ±45° fibres becomes visible. This indicates that at this intermediate frequency, the thermal response captured at the surface is still influenced to a certain extent by the heat generated in the subsurface plies. As the frequency increases to 20.1 Hz, only the 45° fibre orientation of the surface ply is prominently observed due to the shortened thermal diffusion length. This trend remains consistent even when the frequency is doubled to 30.1 Hz.

The trend shown in Fig.2 demonstrates that higher frequencies effectively shorten the thermal diffusion length and restrict through-thickness heat conduction. These findings confirm that modulating the loading frequency allows for the selective non-destructive evaluation of internal versus near-surface damage.

Furthermore, the second-harmonic amplitude (2f) was analysed. These harmonic responses are generally associated with viscoelastic effects, localized friction, and damage. So, it is expected that analysing the 2f generation mechanism in CFRP will enable a more effective evaluation of internal damage. To observe these trends, the analysis was also extended to specimens from Table 1 in which intentional damage had been introduced.

References

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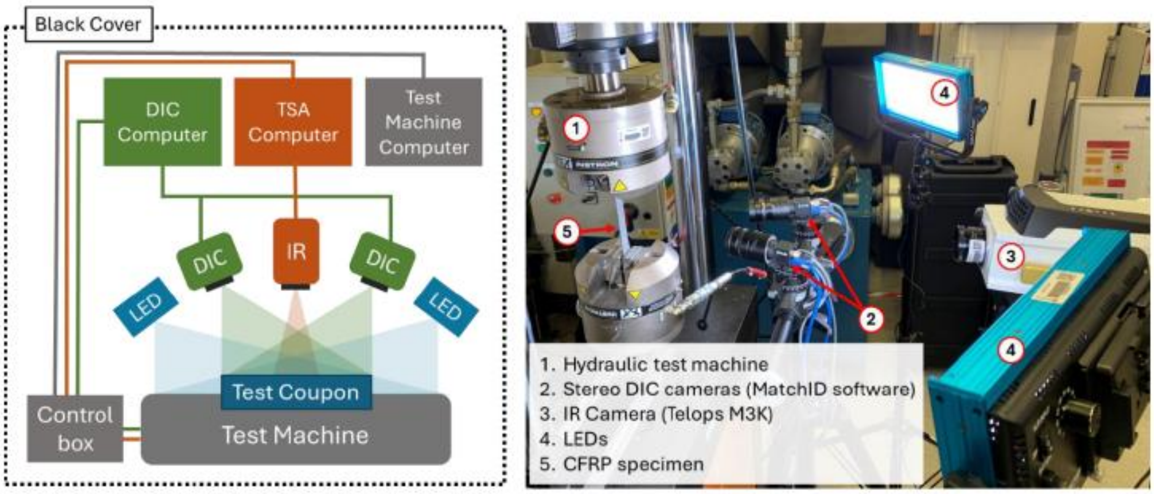

Figure 1 Schematic representation and realistic test setup.[2]

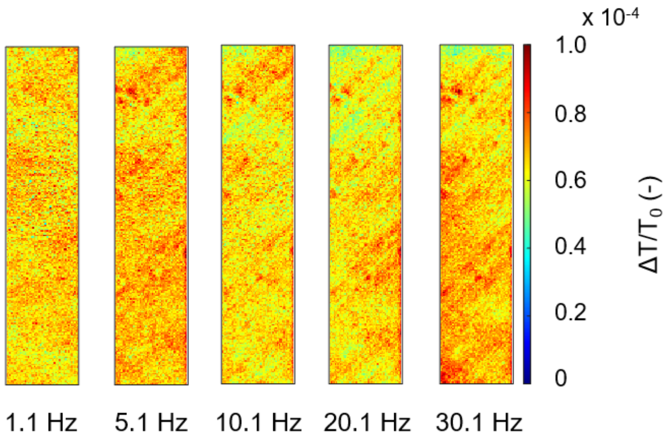

Figure 2 Full-field ΔTs/T0 from undamaged $[\pm45]_{3S}$ at different frequencies. [3]

Table 1 Material and loading conditions

Layup	L x W x Th (mm)	Loading frequencies [Hz]
$[0/90/90/0/0/0]_s$ $[\pm45]_{3s}$	200 x 20 x 1.62	0.5, 1.1, 3.1, 5.1, 7.1, 10.1, 12.1, 15.1, 20.1, 22.1,25.1, 27.1, 30.1