Validation of a Numerical Model for the Non-adiabatic Thermoelastic Stress Analysis of Composite Laminates

R. Cappello[1a], R. Ruiz-Iglesias[1], G. Olafsson[1], G. Pitarresi[2] , G. Catalanotti[3] and J. M. Dulieu-Barton[1]

[1]Bristol Composites Institute (BCI), University of Bristol, Bristol BS8 1TR, UK, [2] Dipartimento di Ingegneria, University of Palermo, Viale delle Scienze, 90128 Palermo, Italy, [3]Faculty of Engineering and Architecture, Kore University of Enna, Scientific and Technological Hub of Santa Panasia, 94100 Enna, Italy

[a]riccardo.cappello@bristol.ac.uk

Abstract. The interpretation of the thermoelastic response in carbon fibre reinforced polymer (CFRP) composites can pose significant challenges. In laminated multidirectional CFRP, the thermoelastic heat sources are driven by the anisotropic material properties which result in heat transfer, that are heavily dependent on the cyclic loading frequency used in the experiments. To provide further insight into interpreting the thermoelastic response from CFRP material, a modelling approach has been devised to simulate the thermoelastic heat sources at the lamina level and through-thickness heat transfer resulting from the laminated construction of the material. The numerical model is validated against experimental data obtained from multidirectional carbon fibre coupons and applied to a complex layup from a real structure.

Possible Sessions

10. Infrared & Thermal Methods, 14. Model Validation 24. Testing of Composite Materials

Introduction

The thermoelastic effect is a phenomenon that relates deformations in the a material's elastic range with reversible temperature variations. These temperatures changes can be measured via sensitive infrared cameras, and are directly related to the stress state of the material, if certain conditions are met [1]. A primary consideration is that the temperature change occurs adiabatically, usually met by using cyclic loading with a sufficiently high strain rate to minimize the opportunity for heat transfer.
The application of Thermoelastic Stress Analysis (TSA) to multidirectional laminated composite materials add a layer of complexity, as the anisotropic material behaviour causes the thermoelastic heat source ply-by-ply to be a step function. This is particularly true for carbon fibre composites (CFRP), where the highly anisotropic nature of the mechanical and thermal properties leads to significant stress induced temperature differences between adjacent plies, resulting in heat conduction through the thickness of the component. These temperature gradients, in thin *pre-preg* layers, cause heat transfer to take place also when relatively high loading frequencies are employed. In addition, the presence of a Resin Rich Layer (RRL), on the material surface caused by the manufacturing process influences the retrieved thermoelastic response [2, 3].
An investigation of thermoelastic effect in orthotropic composite laminates under cyclic loading is conducted, considering the influence of layup, loading frequency and surface resin-rich layer thickness. The main objective of the work is to validate the numerical model for the thermoelastic heat source [4] against experimental TSA data obtained from multidirectional CFRP coupons. It is demonstrated that the model can provide accurate predictions of the through-thickness temperature profiles across different testing conditions and laminate configurations. It is shown that the numerical results can be used to investigate the influence of the inner plies of the material on surface response, illustrating the potential to adjust testing parameters to minimize heat transfer effects or isolate responses from sub-surface plies.

Materials and Methods

Experiments. Four samples were manufactured using IM7/8552 *pre-pregs* in two layups ($[0,0,0,45,-45,0]_s$ and $[0, 45, -45, 0, 0, 0]_s$), with various resin layer thicknesses. These were tested under load control using an electrodynamic Instron E10000 testing machine, with frequencies ranging from 0.5 to 30.1 Hz. A cooled sensor infrared camera (Telops FAST M3k) was employed to measure temperature fluctuations. Also, a specimen taken from an actual structure having a more complex layup [45, -45, 45, -45, 45, -45, 90, 0, 90, 0, 90, 0] was studied, to demonstrate the capabilities of the model to aid analysis of a complex structure.
Simulations. The same testing conditions and layups defined for the experiments have been replicated in the numerical space. The numerical model described in [4] has been employed for the evaluation of the thermoelastic heat source at the element level and the heat conduction, in a coupled temperature-displacement analysis employing C3D8T elements. Both numerical and experimental results are presented as $\Delta T/T_o$ (ΔT is the thermoelastic temperature change and T_o is the mean temperature of the sample) averaged over the whole field of view.

Results and Discussion

The comparison between experimental and numerical results vs loading frequency is presented in Fig. 1 for the four specimens. A good match is found for all the considered cases, and the numerical predictions fall between the standard deviation of the experimental data, presented as error bars. It is clear that the RRL has a significant influence on the thermoelastic response, especially at higher loading frequency.

An advantage of employing a numerical model is the possibility to probe the behaviour of the internal plies of the laminate. Fig. 2 reports an example (for the specimen: [0, 0, 0, 45, -45, 0]$_s$, 5 μm RRL with 7.1 Hz loading frequency) of the temperature variation vs time of all the plies (left) as well as the same information expressed in amplitude and phase parameters (right). Understanding the behaviour of internal plies offers the opportunity to tune experimental setups and highlight specific ply responses to optimize tests on more complex structures so that subsurface behaviour could be revealed.

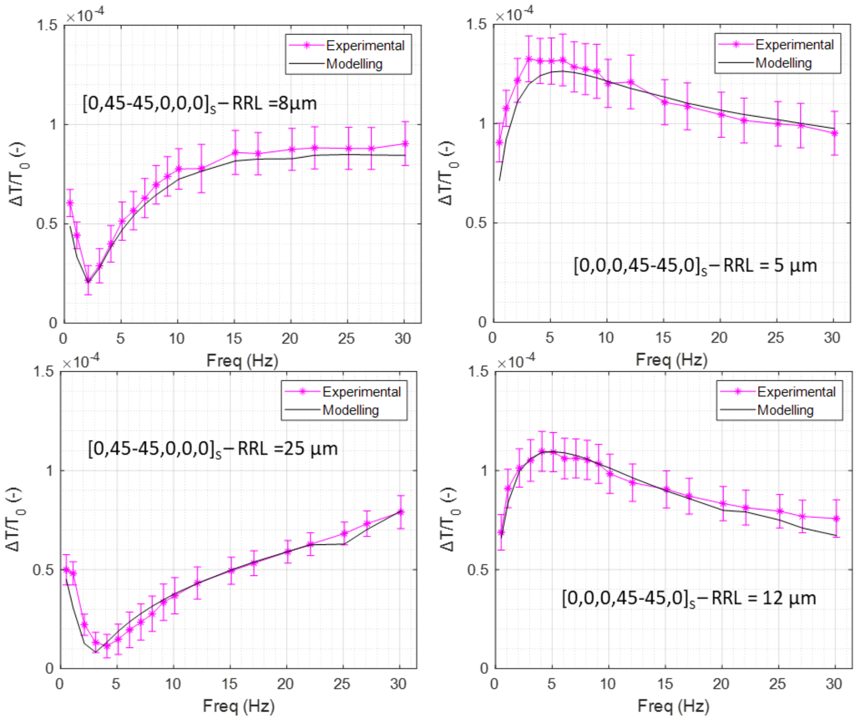

Figure 1. Modelling and experimental results for different layups, loading frequencies and RRL thicknesses.

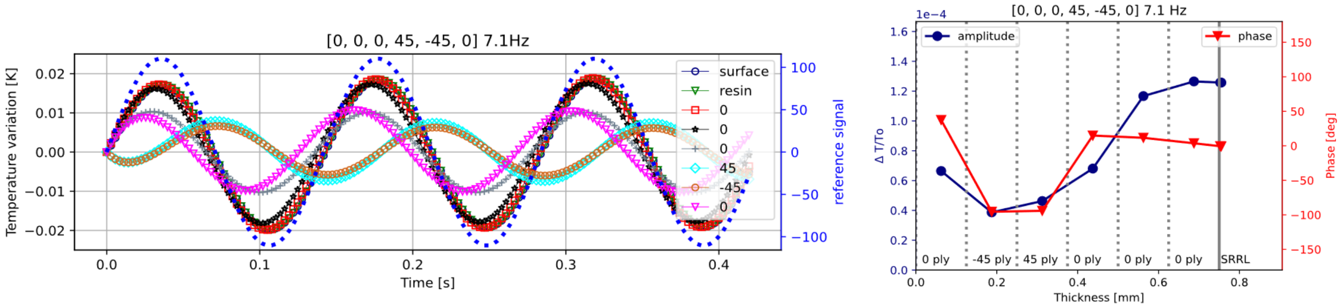

Figure 2. Temperature variation of the internal plies in the laminate in a) time b) frequency domains.

Conclusion

The numerical model for the thermoelastic effect has been validated against a range of experimental results, also when non uniform temperature distributions are generated. The power of numerical modelling opens new perspectives for the application of TSA to CFRP laminates. The modelling approach offers an opportunity to tune experimental setups to reveal sub surface information on damage progression. It is also shown that a more detailed understanding the thermoelastic heat sources can enable improved TSA based model validations.

References

[1] Dulieu-Barton, J. M. "Thermoelastic stress analysis." Optical Methods for Solid Mechanics: A Full Field Approach (2012): 345-366.

[2] Pitarresi, G, Found, M.S., Patterson, E.A. “An investigation of the influence of macroscopic heterogeneity on the thermoelastic response of fibre reinforced plastics.” Composites Science and Technology, 65-2 (2005): 269-280.

[3] Jiménez-Fortunato, I., Bull, D. J., Thomsen, O. T., & Dulieu-Barton, J. M. "On the source of the thermoelastic response from orthotropic fibre reinforced composite laminates." Composites Part A: Applied Science and Manufacturing 149 (2021): 106515.

[4] Cappello, R., Pitarresi, G. and Catalanotti, G.. "Thermoelastic Stress Analysis for composite laminates: A numerical investigation." Composites Science and Technology (2023): 110103.