Thermoelastic Stress Analysis of Inhomogeneous Composite Materials

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Abstract

In this work the effect of heterogeneity in woven composite materials is considered in the context of thermoelastic stress analysis (TSA). The approach is to consider the surface of a woven laminate as a ‘patchwork’ of orthogonally orientated unidirectional fibres. Assuming a state of uniform strain, the global strains are applied locally to predict the thermoelastic response of the woven material. A Cedip Silver IR system is used for the TSA measurements with a standard 27mm lens and a high resolution G1 magnifying lens. Experimental data shows that the strain field is non-uniform and closely related to the weave pattern of the fibre reinforcement. Out of plane deformations are identified as a possible explanation for the deviation between experimental data and theory.

Introduction

Thermoelastic stress analysis (TSA) is a well established experimental technique for quantifying the stress state at the surface of a component by means of the thermoelastic effect \cite{1}. It is a full-field, non-contacting technique that relates the small temperature change that occurs in a material subjected to elastic cyclic loading to the sum of the principal stresses $\Delta(\sigma_1 + \sigma_2)$. The heterogeneous nature of composite materials produces a non-uniform stress field. Typically in laminates constructed from layers of unidirectional material, this non-uniformity is only present from lamina to lamina, i.e. through the thickness of the laminate, as the material properties are uniform within a single ply. For these materials, i.e. two dimensional orthotropic materials, the small temperature change resulting from the thermoelastic effect can be expressed as follows \cite{1}:

$$\Delta T = -\frac{T}{\rho c_p} \left( \alpha^T [J] \Delta \sigma^e \right)$$  \hspace{1cm} (1)

where $\Delta T$ and $\Delta \sigma^e$ are the changes in temperature and the principal surface stresses, $T$ is the absolute surface temperature, $\rho$ is the density, $c_p$ is the specific heat at constant pressure, $\alpha$ is the coefficient of thermal expansion in the principal material directions and $J$ is the transformation matrix between material and principal stress directions. In deriving equation (1), it is assumed that the temperature change occurs in an adiabatic manner. To achieve adiabatic conditions the material is loaded cyclically at a sufficiently high frequency so that the thermal diffusion length is smaller than the measurement area defined by the spatial resolution of the infrared detector and lens.

In woven laminated composites the material properties are non-uniform within each ply. This leads to stress concentrations where the fibre bundles cross over. By reformulating equation (1) in terms of strain, it is possible to make use of global strains to evaluate the influence of the heterogeneity within woven plies. Initial work on this topic is presented in this paper that focuses on tensile specimens, manufactured from woven glass/epoxy laminated panels, which nominally have a uniform strain field. The thermoelastic data is collected using a new equipment for TSA manufactured by Cedip Infrared Systems, which incorporates a motion compensation routine that has been found to improve results when using high resolution optics. The implementation of the motion compensation routine is also described in the paper.
Theoretical Approach

The basis of the theoretical approach is the assumption that the global strain field is uniform in the tensile specimens used in the experimental work. The aim is to apply the global strains to the local regions in the woven structure. The local regions have different material properties and therefore according to equation (1) should have a different thermoelastic response. To confirm that equation (1) can be applied to heterogeneous structures, the theoretical thermoelastic response is compared with the experimental response. In this work adiabatic conditions are assumed, i.e. there is no heat transfer either from ply to ply or in the measurement plane. This assumption is considered reasonable as the thermal conductivity of both the epoxy resin and the glass used to construct the test specimens is very small.

To relate the principal stress changes in the specimen to the principal strain changes, $\Delta \varepsilon^p$, the following equation is applied

$$\{\Delta \sigma^p\} = [\overline{Q}][\Delta \varepsilon^p]$$  \hspace{1cm} (2)

where $\overline{Q}$ is the transformed stiffness matrix defined as [2]

$$[\overline{Q}] = [J]^T[Q][J]^{-T}$$  \hspace{1cm} (3)

where $Q$ is the stiffness matrix in the principal material directions. Substituting for $\overline{Q}$ in equation (2) and then for $\Delta \sigma^p$ in equation (1) gives the thermoelastic signal in terms of strain as

$$\Delta T = -\frac{T}{\rho c_p}([\alpha]^T[Q][J]^{-T}[\Delta \varepsilon^p])$$  \hspace{1cm} (6)

Using this formulation it is possible to use the global strains, which can be measured directly, to predict the thermoelastic response anywhere on the surface of the specimen, even if the local stresses are not known, thus making it possible to compare local variations in the thermoelastic response as a result of the local variations in the material properties.

Specimen and Materials

Tensile specimens were cut from a laminated panel made by vacuum assisted liquid resin infusion. The laminate consists of 5 plies of 2x2 twill woven roving (WR) and 4 plies of 300 g m$^{-2}$ chopped strand mat (CSM) with a 50 mm strand length arranged as [WR$_1$, CSM$_2$, WR$_3$, CSM$_2$, WR$_1$] and shown in Figure 1. The resin used in this work was a low viscosity epoxy, Prime 20 LV by Gurit. The fibre volume fraction of the laminate was calculated to be 48% for the laminate (55.0% and 35.8% for the WR and CSM respectively) from a burn-off test.

The reasons for constructing the laminate in this way were two-fold. Firstly to produce distinctive layers when examining the specimen in the through thickness direction to assess if the individual ply stresses could be determined using TSA. Secondly to isolate the surface ply from stress concentrations from those beneath it, as it is known that stress concentrations occur at the weave crossover points. In the through thickness direction, the effect of crimp and bunching of fibre bundles from different plies on the stress gradient were investigated. Since the effective resolution (ability of the detector to resolve small stress concentrations as opposed to simply the optical resolution in terms of mm/pixel) was not known, plies with large differences in stiffness were included that could readily be distinguished. At the surface the effect of the weave pattern on the stress distribution was investigated. The isotropic and much less stiff CSM plies effectively isolated the surface ply from the central WR plies. The specimens used in this work thus have distinct heterogeneity on both the surface and through the thickness.

In engineering applications, drapeability is often an important criterion in material selection. Twill weaves have better drapeability than plain weaves and are therefore commonly used in applications that require curved surfaces, which are typically found in the marine industry. The 2x2 twill WR used in this work was chosen because when using the high resolution
lens, one weave and weft unit (approximately 8 x 8 mm) fitted just within the frame projected by the detector array (i.e. 8 x 10 mm).

**Figure 1:** Sketch of the laminate composition

The laminate was manufactured on a sheet of glass so that one side of the laminate had a smooth finish with a resin rich surface layer (varying in thickness between 10 and 40 µm) whilst the other surface of the laminate was covered in peel ply, giving it a rough surface finish with only a very thin, broken layer of resin. The resin layer was removed with sandpaper from one region, exposing the fibres at the surface, to eliminate the possibility of the surface layer acting as a strain witness [3] and to allow the surface fibre orientation to be identified in the analyses.

The specimens were cut so that the warp and weft directions were aligned with respect to the loading axis. The overall dimensions of the specimens were 375 mm long (with 50 mm long steel end tabs giving a gauge length of 270 mm) 26 mm wide and nominally 3.2 mm thick. Thermoelastic data was taken from several regions near the centre of the specimen where the global strain was uniform.

**Theoretical Prediction of the Thermoelastic Response**

The weave pattern at the surface produces an image that can be likened to a patchwork of orthogonally orientated cells. In the following treatment the thermoelastic signal of each cell is considered to be a small area of unidirectional fibre composite. The strain is assumed to be uniform over the whole cross-section of the specimen. The global loading coordinate system has been denoted x and y whilst the local strain coordinate system has been denoted 1 and 2. In the patchwork representation of the woven composite material, the longitudinal cells are defined as those aligned with the x-axis (θ = 0°) and transverse cells are aligned with the y-axis (θ = 90°), see Figure 1. For each of the two cell orientations, longitudinal and transverse, equation (6) becomes

\[
\Delta T_L = -\frac{T}{\rho C_p} \left( (\alpha_{11} Q_{11} + \alpha_{22} Q_{22}) \Delta \epsilon_x + (\alpha_{11} Q_{11} + \alpha_{22} Q_{22}) \Delta \epsilon_y \right)
\]

\[
\Delta T_T = -\frac{T}{\rho C_p} \left( (\alpha_{11} Q_{11} + \alpha_{22} Q_{22}) \Delta \epsilon_x + (\alpha_{11} Q_{11} + \alpha_{22} Q_{22}) \Delta \epsilon_y \right)
\]

where subscripts L and T denote the longitudinal and transverse cells respectively. To estimate the magnitude of the thermoelastic temperature change the global strains in the test specimen and the material properties for a unidirectional composite, are required. Values for the material properties, obtained from the literature, for a unidirectional E-glass/epoxy with a 55% fibre volume fraction [4, 5] are provided in Table 1. The specific heat, \(c_p\), was calculated using the rule of mixtures, following the procedure of Ref. [6], using the individual values for E-glass [7] and epoxy resin [8]. The material property values are summarised in Table 1.

**Table 1:** Material properties of generic unidirectional E-glass/epoxy composite

<table>
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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>GPa</td>
<td>GPa</td>
<td>10(^{-6}) K(^{-1})</td>
<td>10(^{-6}) K(^{-1})</td>
<td>kg m(^{-3})</td>
<td>2100</td>
<td>857.5</td>
<td></td>
</tr>
<tr>
<td>38.6</td>
<td>8.3</td>
<td>0.26</td>
<td>0.056</td>
<td>7</td>
<td>65</td>
<td>2100</td>
<td>857.5</td>
</tr>
</tbody>
</table>
At a load of 3 kN strains of 0.18|\x| and -0.03|\y| were measured in a static test using a biaxial extensometer. Applying these strains to equations (7a) and (7b) gives the theoretical temperature change for the longitudinal and transverse cells as 0.085 K and 0.041 K respectively. By a similar process, it is possible to predict the response from a resin surface. Based on the uniform strain assumption this response should be uniform over the whole surface, with the resin acting as a strain witness [3]. Using the material properties for the resin system supplied by the manufacturer [8] a temperature change of 0.179 K was obtained.

Experimental Work

Experimental Setup

Thermoelastic data was collected using the Silver 480M infrared detector manufactured by Cedip Infrared Systems using two optical configurations. A 27 mm lens was focused on a region approximately 100 x 80 mm, to examine the whole specimen width. A G1 magnifying lens, working in combination with the 27 mm lens, was then used to provide detailed views of chosen areas, 10 x 8 mm in size. The test parameters for the data capture using the Cedip system were also optimised during preliminary testing. The thermoelastic data in this work was derived from video recordings of 1000 frames collected at rates of either 103 Hz or 269 Hz, with a 3700 ms exposure for each frame. The detector operates with two overlaid arrays, thereby permitting nearly seamless data capture at 269 Hz.

Tests were conducted in an Instron 8501 servo-hydraulic test machine with the end tabs of the specimen clamped in hydraulic grippers. Several loading conditions were tested in a preliminary set of experiments to determine the optimal testing conditions, i.e. load cycle and frequency. Figure 2 shows the frequency dependence of the TSA signal from a box of data from the central region of an unpainted specimen, away from the influence of the ends of the specimen. This data was from motion compensated images using the zoom lens. This shows that the thermoelastic signal is constant for loading frequencies greater than 8 Hz. A load cycle of 2 ± 1.5 kN at a frequency of 10 Hz was selected for the tests described in this paper.

![Figure 2: Frequency dependence of the thermoelastic data](image)

Motion Compensation

Van Hemelrijck et al. [9] demonstrated, using the SPATE 8000 system, that localised viscoelastic and frictional heating, coupled with motion, could lead to spurious thermoelastic data. However, by using known geometrical features, for instance, when looking at stress concentrations around holes, it was possible to remove the effect of these errors during post-processing operations. In the Cedip system the effects of motion are compensated for in a preprocessing stage by means of an image correlation routine. Two surface features (e.g. pencil marks or other visible features of the surface) are identified by the user and joined by a vector in the first frame of a video recording. The software package then tracks the motion of these features from frame to frame and subsequently moves, rotates or distorts the frames so that the vector remains stationary throughout the video. In this way translational and rotational displacements as well as tensile and shearing distortions are removed from the raw infrared data. The motion compensation package is most effective when displacements are relatively large, greater than a single pixel between frames in the video recording. Smaller displacements require sub-pixel interpolation.
and it was found that this could introduce noise in the analysis. Motion compensation was therefore only used for the high
resolution data, where the displacement of the specimen during testing was equal to several pixels.

The effect of motion in the current work is illustrated by Figure 3, which shows an image from the through thickness direction
of the painted laminate. In Figure 3(a) a single glass fibre can be seen protruding from the edge of the specimen (highlighted
with a circle in the figure), as well as two scratches on the specimen surface (indicated with arrows). These features
demonstrate that the specimen is moving by approximately 6 pixels with the extremities of the applied loading cycle. A motion
compensated image is shown in Figure 3 (b). Here the effectiveness of the motion compensation software is apparent as the
“blurring” in the image of Figure 3(a) has been removed, and the material structure (as shown in Figure 1) is clearly visible.

![Figure 3: TSA data through the thickness of the specimen a) raw data b) motion compensated data](image)

**Results and Discussion**

Thermoelastic data from four regions has been considered in this work. Where the peel ply has left its imprint is termed the
rough surface and where this “roughness” was removed to expose the fibres is termed the exposed surface. The reverse side
of the specimen, which had been in contact with the mould during manufacture is termed the smooth side. Here the surface
resin layer has filled out the unevenness of the weave to produce a flat surface. Finally measurements were also taken from
the side of the specimen; these have been termed the through thickness view.

The Cedip system is radiometrically calibrated, thereby allowing temperature measurements to be taken directly. A value of 1
has been assumed for the emissivity of the specimen's. The temperature change was obtained from each of the three in plane
surface preparations using the 27 mm optics. Average values of the temperature change were taken from areas of
approximately 35 x 25 mm. These values are reported in Table 2 and show no correlation with the theoretical values
presented above for the longitudinal, transverse or resin rich surface.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Temperature Change (K)</th>
</tr>
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<tbody>
<tr>
<td>Rough</td>
<td>0.084 ± 0.009</td>
</tr>
<tr>
<td>Smooth</td>
<td>0.094 ± 0.014</td>
</tr>
<tr>
<td>Exposed</td>
<td>0.109 ± 0.014</td>
</tr>
</tbody>
</table>

The theoretical approach predicts a uniform response from the in-plane surface, which is clearly not the case in the
experimental data shown in Figure 4. By applying a low-pass spatial filter to the data, both diagonal and horizontal banding on
a scale corresponding to the weave pattern is apparent in the images. The fact that the same pattern is observed on both the
rough and the smooth surfaces with the resin rich layer suggests a non-uniform strain field. From a thermal image of the
exposed surface it was possible to identify the longitudinal and transverse cells. In a comparison of the average thermoelastic
signal temperature values from each of these cells, the signal from the longitudinal fibres was 11.6% (± 13%) greater. The
signal noise is clearly too high to attach any significance to this finding and so it was considered necessary to obtain data at
higher resolutions.

Using the G1 high resolution lens it was possible to focus on clusters of 4 cells. The bands of strong thermoelastic response
noted in Figure 4 appear to be from what might be termed resin interspersions, i.e. the small regions of resin separating the
longitudinal and transverse cells. Figure 5, taken with the high resolution optics, highlights this phenomenon. The first image
shows a thermal image in which the longitudinal and transverse cells can clearly be seen and on which the areas for
measurement have been defined. The second image shows the corresponding thermoelastic response. Areas 1 and 3 are
resin interspersions, 7 and 8 are transverse cells and 4, 5, 6 and 9 are longitudinal cells.
The difference in the thermoelastic response from the longitudinal and transverse cells in the in-plane data is small with respect to the spread of the data. A gradient in the longitudinal directions is also noticeable in some of the longitudinal cells in Figure 5. A possible explanation could lie in the surface preparation which consisted of sanding the surface until the peel ply imprint was no longer visible to the eye. This may lead to some of the fibres being broken at the surface, particularly where the specimen had a greater thickness. Furthermore the emissivity value of 1 was chosen for consistency but may be different for the exposed glass and the epoxy. Table 3 shows average values of temperature change from four sets of data obtained from these regions. The theory predicts a factor of approximately two between the longitudinal cells and a resin-rich region. However, the signal from the resin interspersions on the exposed surface is only 30% greater, and the response from the longitudinal and transverse fibres is practically equal, as opposed to the factor of 2.10 given by the theory.

Table 3: Temperature change values from the thermoelastic data from individual cells and resin interspersions from the exposed surface.

<table>
<thead>
<tr>
<th>Optical Configuration</th>
<th>Longitudinal</th>
<th>Transverse</th>
<th>Resin Interspersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>0.11 K</td>
<td>0.116 K</td>
<td>0.150 K</td>
</tr>
</tbody>
</table>

The same diagonal banding pattern was clear in images from the rough and smooth surfaces, but the longitudinal and transverse cells could not be distinguished in the infrared images in the same way as for the exposed surface because the resin surface layer masked the fibres. In the images from the smooth side of the plate the high signal associated with the resin interspersions was much more pronounced. This indicates that the strain field in a woven composite structure is inhomogeneous and dependent on the architecture of the weave. Clearly a new approach to analysing this data is required for quantitative TSA studies.

An explanation is proposed that considers bending moments introduced by the crimp. The tensile strain in the longitudinal fibres will produce a bending moment as shown in Figure 6 which introduces a compressive strain on the outside surface of the fibre, thereby reducing the stress and consequently also the thermoelastic response. By contrast, the transverse fibres are subjected to a compressive load that introduces a state of tension on the outside surface and increases the thermoelastic response. Since both fibres are in a net state of tension, the bending effect in the transverse fibres will bring the relative
magnitudes of the thermoelastic responses of the longitudinal and transverse cells closer together, and the stronger the crimp, the larger the relative magnitude of the transverse cells compared with the longitudinal cells will be. This bending also introduces a tensile strain in the resin interspersion adjacent to the longitudinal cells, which would lead to an increased response in these positions, while adjacent to the transverse fibres the reverse effect would occur. Thus both the equal response of the longitudinal and transverse cells and the diagonal distribution of signal peaks in the resin interspersions are accounted for in a qualitative sense. However further work is required to confirm this experimentally.

![Diagram of bending](image)

**Figure 6:** Schematic diagram of the bending induced by tensile and compressive strains in woven fibres

In examining the through thickness response of the specimen TSA data of the type shown in Figure 6 was obtained. A ‘macroscopic’ optical image of the specimen through thickness surface is also shown in Figure 6. The layers of CSM and WR are clearly distinguishable in the TSA data and match the optical image. However, it is not possible to identify the individual layers of WR definitively in the TSA data. There are distinct peaks in the TSA data, which could correspond with the ends of transverse rovings, indicated by circles in Figure 7, although it was not possible to correlate these exactly with the optical data.

![Image of microscopy and TSA data](image)

**Figure 7:** Microscope image and corresponding TSA data from the through thickness direction.

Taking the mean TSA value from each ply it was found that the through thickness temperature profile matched well with a classical laminated plate theory (CLPT) prediction of the ply averaged stresses. However, the three profiles indicated in Figure 7 and plotted (normalised against the mean temperature change or the stress change in the central three plies) in Figure 8, show that locally there is significant deviation from the CLPT prediction. The data from line 1, where the longitudinal rovings are relatively straight, shows the best correspondence with the CLPT. The other two lines cross signal peaks and demonstrate that the material heterogeneity plays an important role. However it is possible to identify ‘signal concentrations’ resulting from the roving ends; future work will investigate these concentrations and establish if they play a role in component failure.

**Closure**

This paper has described some initial work on the thermoelastic assessment of woven composite structures. The work has shown that:

- TSA can be used to assess macroscale inhomogeneous materials
- High resolution data can be obtained from these complex materials and interpreted in a quantitative manner
- Successful motion compensation has been carried out that significantly improves the quality of the data
In attempting to analyse the woven characteristics of the material it was shown that a uniform strain field cannot be assumed because of possible out of plane deformation.

Further work is required to identify more precisely the source of the thermoelastic response from the woven surface, specifically to characterise the response from the resin rich regions and from areas where the rovings were exposed.

A further feature of the work demonstrated that the manufacturing procedure plays an important role as the response was significantly different from the mould and peel ply sides of the test specimens.

References


Figure 8: Normalised through thickness stress distribution from CLPT and measured TSA data