Measurement Note

NPL Report MN 7

Measurement of Residual Stresses and Strains in Carbon Fibre Composites

An investigation has been carried out to assess a range of different techniques for the measurement of residual stresses and strains in composite laminates. Residual stresses are introduced into composites during their manufacture and can significantly reduce both the performance of the material and the lifetime of the product. Residual stresses can also be extremely difficult to measure, as there are no well-established techniques for measuring their presence in these materials. For this reason, designers and engineers have often been forced to use higher margins of safety to prevent in-service failure, leading to both "overdesign" of structures and increased weight. With the continuous drive to optimise material performance and minimise component weight, there is an increasing need to understand the role of residual stress in composites. This report assesses some of the most promising measurement techniques, which include curvature measurement of unsymmetric panels, layer removal, incremental slitting, hole drilling, Raman spectroscopy and Fibre Bragg-Gratings.

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1 INTRODUCTION

Residual stresses are tensile or compressive stresses that exist in materials without an external load being applied to the component. Their presence in a composite can have a significant influence on both its mechanical properties and resistance to internal damage. For polymer composites in particular, residual stresses introduced during fabrication are one of the most significant problems associated with the processing of these materials. Residual stresses can affect the stress-strain behaviour as well as degrading the strength resulting in cracking, delamination and lower fatigue and fracture toughness performance. Residual stresses also impact post-manufacture warpage or ‘spring back’, which can lead to difficulties in subsequent component assembly.

During the curing process, a composite is subjected to high temperatures and pressures causing the matrix to liquefy, flow, gel and then solidify. The onset of gelation is the key point at which load is transferred between the matrix and the reinforcing fibres. The fact that gelation marks the onset of induced stresses is crucial for understanding theoretical approaches, as these require a ‘stress-free’ temperature [1]. The chemical and thermal shrinkage in thermoset resin matrices is opposed by the reinforcing fibres. This subjects the fibres to mechanical stresses and results in lower chemical and thermal shrinkage deformations parallel, as compared to transverse, to the reinforcing fibres [1-3]. These generate residual stresses at the microscale level even in purely unidirectional material [2]. Similarly, at the macroscale, residual stresses at ply level are induced in multidirectional laminates due to the anisotropic characteristics of the ply [1-2]. Residual stresses can also originate from interactions between the mould and laminate where CTE differences create high stresses at the tool surface on cooling. These are gradually redistributed to the outer plies leaving the upper surface of a cured laminate free of stresses and reaching a maximum value near the surface in contact with the mould [1].

Due to the difficulty of assessing residual stresses, designers and engineers are often unable to determine their magnitude, forcing them into using higher safety margins, which can significant increase the weight of the structure. With the continuous drive to optimise material performance and minimise component weight, there is an increasing need to understand the role of residual stress in composites.

A wide range of different techniques for the measurement of residual stress in composites has been proposed. A number of these techniques have been examined and a summary of the results obtained is presented in this Measurement Note. Techniques considered include curvature of unsymmetric panels, layer removal, incremental slitting, hole drilling, Raman spectroscopy and Fibre Bragg-gratings.

2 MEASUREMENT TECHNIQUES

2.1 CURVATURE OF UNSYMMETRIC PANELS

One of the simplest and most commonly used methods of determining the build-up of residual stresses in a composite material is through the measurement of curvature in an unbalanced composite laminate [4-7]. As each ply in a composite laminate cools down after cure it attempts to contract, primarily in the transverse direction of the fibres. If the composite is built-up of a symmetric series of cross-plies, the adjacent plies will constrain each other resulting in a build-up of residual stress. In an unbalanced cross-ply laminate this contraction is not constrained, thus resulting in curvature of the panel (Figure 1). By measuring the curvature that occurs in an unbalanced laminate it is possible to determine the macroscopic residual stress within the laminate. The radius of curvature, ρ_c, can be determined from the height, ***h***, and the length, ***L***, of the strip (Figure 1), according to the following formula [7]:

$$h^2 - 2h\rho_c + \rho_c^2 \sin^2\left(\frac{L}{\rho_c}\right) = 0 \qquad (1)$$

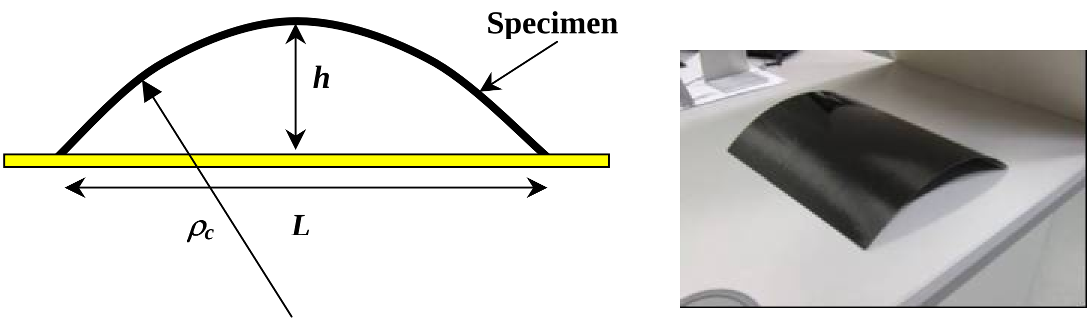


Figure 1 Determination of curvature for an unbalanced laminate

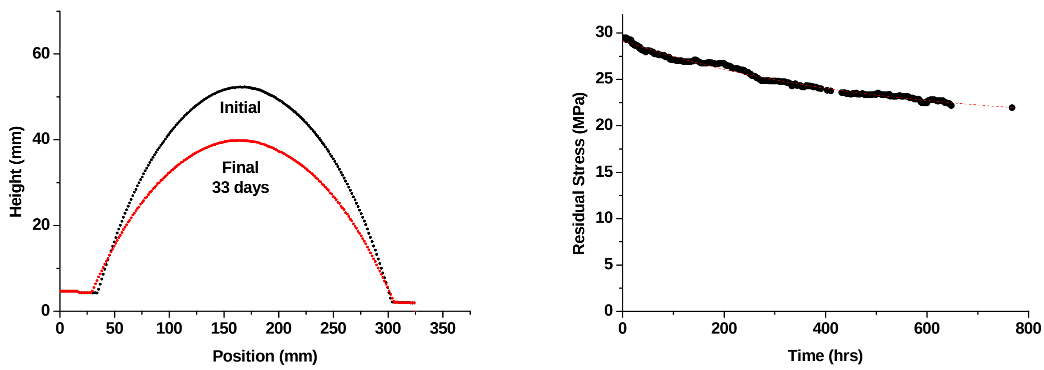
The residual stresses that would exist in a symmetrical (balanced) composite laminate can be calculated using classical laminate analysis from the deformation that is observed in the unbalanced laminate. Knowledge of the longitudinal and transverse moduli E_{11} and E_{22}, and the radius of curvature ρ_c at the test temperature are required to determine the residual stresses σ_r, using the following equation [7]:

$$\sigma_r = \frac{E_{11}E_{22}h}{\rho_c\left(E_{11}h + E_{22}k\right)}\left[\frac{b+d}{2} + \frac{E_{11}b^3 + E_{22}d^3}{6\left(b+d\right)}\left(\frac{1}{E_{11}b} + \frac{1}{E_{22}d}\right)\right] \qquad (2)$$

Where, the thickness of the longitudinal and transverse plies in the unbalanced laminate are denoted by ***b*** and ***d***, respectively while ***h*** and ***k*** are the corresponding ply thicknesses in the symmetrical lay-up.

A series of tests were conducted on unbalanced [0/90] and [0_2/90] SE 84LV carbon fibre-reinforced epoxy panels (300 mm x 300 mm) to determine the residual stress build-up during cooling from cure temperature (120°C), the resultant residual stress at room temperature and stress relaxation following laminate manufacture. The thickness of the individual plies was 0.32 mm; Gurit supplied the carbon/epoxy prepreg. The panels were cured in accordance with the manufacturer's specifications. Deformation (panel height, ***h***) measurements following cure and cooling to room temperature were measured using a MEL MIKROELEKTRONIK GmBH laser distance sensor M3L/50 (laser 670 nm, red visible), which has a spatial resolution of 0.05 mm. The laser was scanned across each panel at its mid-section at a step rate of 9 mm/sec. Panel height was recorded at 1.5 mm step intervals. Panel deformation was measured routinely each hour for approximately 1 month. To determine the build-up of residual stress with temperature that occurs within the laminate during cooling, the composite panels were heated in an air-circulating oven to 120 °C at a ramp rate of 3°C/min and then allowed to cool down to room temperature. A Temposonics linear variable displacement transducer with a resolution of 0.02 mm was used to measure the panel height at the specimen mid-section. Sample temperature (within ± 2°C) was recorded via a thermocouple positioned close to the sample and recorded on a Pico TC-08 thermocouple logger.

The measured and predicted residual stresses of the [0/90] laminate immediately following panel manufacture were 29.4 MPa and 28.7 MPa, respectively. The corresponding measured and predicted residual stresses for the $[0/90_2]$ laminate were 49.6 MPa and 53.5 MPa. The onset of stress relaxation was immediate on cooling the panels to room temperature (see Figure 2). After 1 month, following panel manufacture, the residual stresses for [0/90] and $[0/90_2]$ laminates, had fallen by 28% and 58% to 20.2 MPa and 38.7 MPa, respectively.



Laminate Deformation **Stress Relaxation**

Figure 2 Residual Stress Relaxation for [0/90] SE 84LV CFRP Laminate

Residual stress was observed to build-up linearly with temperature as the laminate was cooled down from the cure temperature. For the [0/90] laminate, the build-up in residual stress with temperature was ~0.34 MPa/°C. The shape of the deformed laminates resembles a saddle (non-cylindrical), indicative of anticlastic bending. Each panel can assume one of two possible shapes when cooling, which are interchangeable by a snap-through moment. It is possible to manually manipulate the panel to take on either shape. The curvature was different for the two shapes. Curvature depends on the mechanical and thermal loads applied to upper and lower laminates surfaces during processing. Although the laminates are relatively thin, a residual stress gradient will be imprinted on the laminate due to differences in temperature and mechanical forces present at the upper and lower surfaces of the laminate during processing.

2.2 LAYER REMOVAL

The layer-removal technique [8] is a relatively simple technique for the measurement of residual stresses in plates, which involves measuring the curvature of specimens following the progressive removal of thin layers from the surface. In response to removal of a layer the sample restores equilibrium by warping to a shape, which closely resembles a circular arc. The measured curvature as a function of the depth removed can be used to calculate the stress distribution through the thickness of the sample prior to layer removal. The generalised relationship relating the bending moments M_x to the residual stresses σ_x, is given by the following expression [9], the co-ordinates of which are given in Figure 3.

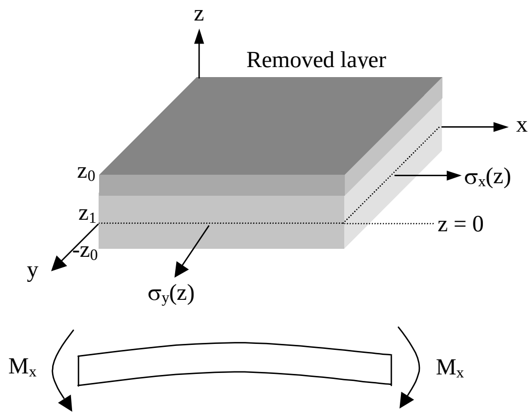


Figure 3 Co-ordinate system used in layer removal analysis [9]

$$\sigma_x(z_1) = \frac{2}{z_0 + z_1}\frac{dM_x(z_1)}{dz_1} + \frac{2M_x(z_1)}{(z_0 + z_1)^2} - 4\int_{z_1}^{z_0}\frac{M_x(z)}{(z_0 + z)^3}dz \qquad (3)$$

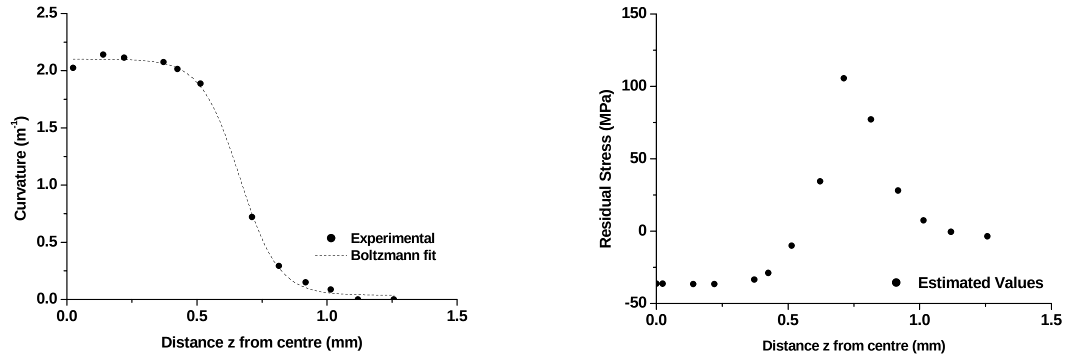
where z_0 is half thickness, and z_1 is the thickness from the original centreline to the removed surface.

The general stress-curvature relationship for an isotropic material is given by [10]:

$$\sigma_x(z_1) = \frac{-E}{6(1-\nu^2)}\left[\begin{array}{l}(z_0 + z_1)^2\left\{\frac{d\rho_x(z_1)}{dz_1} + \frac{\nu\, d\rho_y(z_1)}{dz_1}\right\} + 4(z_0 + z_1)\times \\ \{\rho_x(z_1) + \nu\rho_y(z_1)\} - 2\int_{-z_0}^{z_1}\{\rho_x(z) + \nu\rho_y(z)\}dz\end{array}\right] \qquad (4)$$

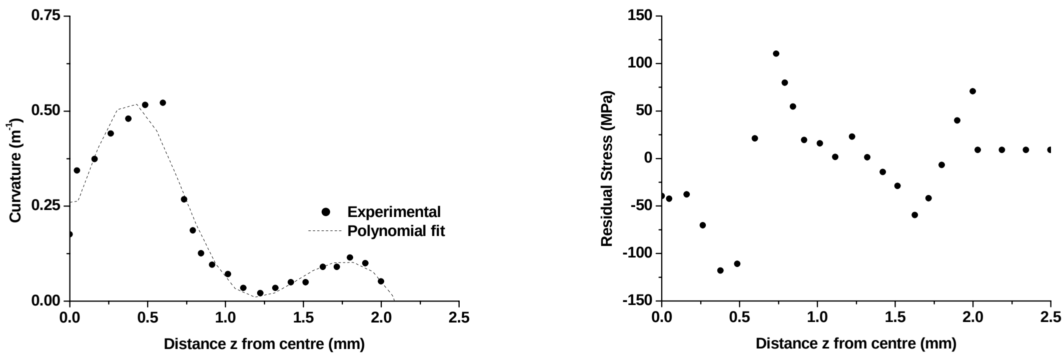
E is modulus and ν is Poisson's ratio, and ρ_x and ρ_y represent the curvature in the *x* and *y* direction, respectively. The above equation assumes that the elastic properties remain constant throughout the material. In fact, for orthotropic materials such as a composite laminate the elastic properties may vary through the laminate thickness but this can be calculated.

A series of trials were conducted using the layer removal method to determine the through-thickness residual stress distribution in symmetric $[0_2/90_2]_s$ and $[0_2/90_2/0_2/90_2]_s$ SE 84LV carbon/epoxy specimens. The nominal thickness for the two laminates was 2.56 mm and 5.12 mm, respectively. The specimens were 80 mm long and 10 mm wide. Tests consisted of removal of 0.1 mm thick layers at a time and then measuring the resultant height of the arc at the specimen mid-length. Arc height was measured using a shadow graph (0.01 mm resolution). The elastic modulus and Poisson's ratio of the remaining laminate, after removal of each layer, was calculated using classical laminate analysis. It was assumed that the contribution to the curvature in the transverse direction was small. The curvature was then calculated. Figures 4 and 5 show the curvature and residual stress distribution for a half-thickness of the $[0_2/90_2]_s$ and $[0_2/90_2/0_2/90_2]_s$ laminates.



Laminate Curvature ***Residual Stress Distribution***

Figure 4 ***Curvature and residual stress distribution in a $[0_2/90_2]_s$ laminate***



Laminate Curvature ***Residual Stress Distribution***

Figure 5 ***Curvature and residual stress distribution in a $[0_2/90_2/0_2/90_2]_s$ laminate***

Residual stress distribution, as shown in Figures 4 and 5, is complex and is dependent on factors, such as laminate lay-up and thickness, and processing conditions. Residual stresses tend to increase substantially around the interface of plies of differing orientations. It was difficult to measure near surface residual stresses for the thick sections (relatively straightforward for thin sections), as changes in arc height could not be resolved until a few millimetres of material had been removed. Experimental measurements are time consuming, although computation is straightforward and moderately time consuming. The analysis is further complicated by the fact that the elastic properties vary through the specimen thickness. For improved accuracy, curvature measurements are required in both directions and it would be necessary to measure the bending moment required to straighten the specimen after every layer is removed. A practical concern is that handling of the specimen needs to be kept to a minimum in order to avoid damaging the specimen or contributing to the specimen deformation.

2.3 INCREMENTAL SLITTING

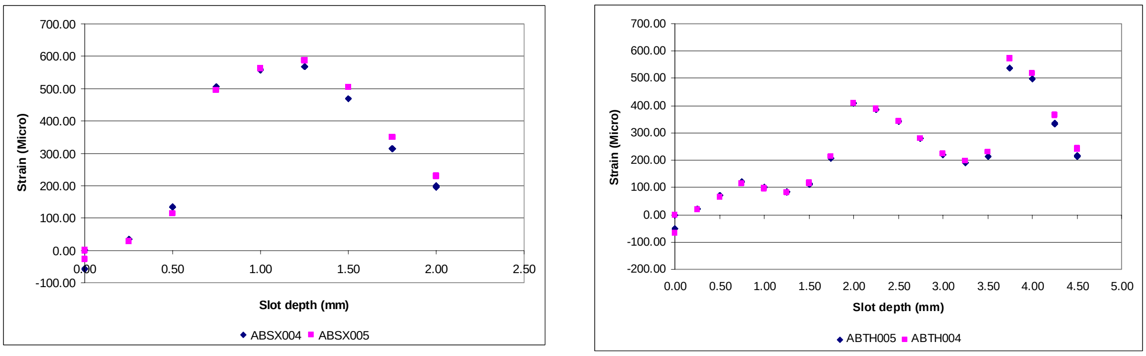
The incremental slitting method [11-13] involves making thin cuts of progressively increasing depth into a material to release the stresses along the plane of the cut and relating the resulting deformation to the residual stresses in the part before it was cut. A computational model is required to relate the deformation produced by the cutting process to the residual stresses that were in the material that has been removed. These relationships are known as compliance functions and can be obtained either experimentally using fracture mechanic solutions or by using finite element analysis. The compliance function can be obtained experimentally by applying a known load to a specimen and measuring the strains that are produced around the cut section, provided the specimen is undamaged and no permanent deformation occurs.

Once the compliance functions are known a slot can be cut into a specimen containing unknown levels of residual stress at incremental depths to release the stresses causing deformation. By measuring the strain next to the slot (or on the back-plane of the specimen) it is possible to determine the residual stresses at each depth within the material by using the compliance functions. Strain gauges are bonded to the specimen for this purpose. The top gauge provides good sensitivity for shallow cuts and the bottom gauge provides improved sensitivity for deep cuts. The incremental slitting method is, in principle, similar to the layer removal method. The advantage of the method is that less material has to be removed to determine the residual stresses. This makes the method simpler to perform and less time consuming. The disadvantage of the technique is that the compliance functions that are required to convert the strains into stresses are considerably more complex. The incremental slitting method can be used to measure both near surface and through-thickness strain release [11].

Figure 6 Incremental slitting method

Testing involved progressively cutting a slit (1 mm wide) of increasing depth in specimens identical to those used for the layer removal method and measuring the resultant strain on the back surface of the specimen (Figure 6). A strain gauge was bonded to the specimen surface for this purpose. The notch depth was increased in 0.1 mm increments. Due to the complexity of the composite lay-ups and analysis required no attempt was made to convert the strain measurements to residual stresses. Figure 7 shows the residual strain distributions through the thickness of $[0_2/90_2]_s$ and $[0_2/90_2/0_2/90_2]_s$ laminates. The results indicate good repeatability between specimens.

The trends in laminate deformation measured using the incremental slitting and layer removal methods are very similar (Figure 8).



$[0_2/90_2]_s$ *$[0_2/90_2/0_2/90_2]_s$*

Figure 7 Residual strain distributions using incremental slitting method

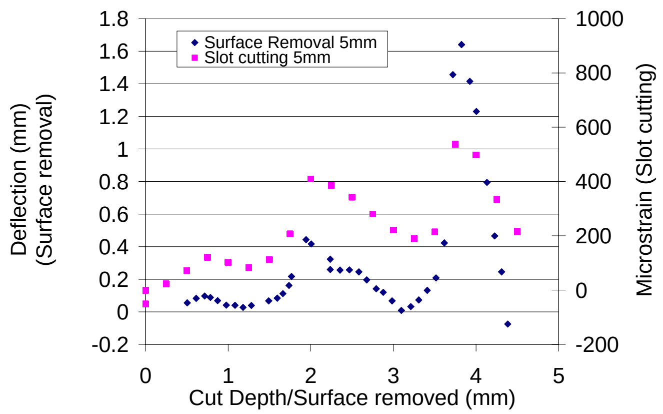


Figure 8 $[0_2/90_2/0_2/90_2]_s$ laminate deformation obtained using incremental slitting and layer removal methods

2.4 HOLE DRILLING

The hole drilling technique involves fixing a rosette of three strain gauges to the surface of the specimen and then drilling a hole precisely through the centre of the rosette. The strains produced at the surface reflect the residual stresses that have been removed during the drilling process. Hole drilling is potentially a more useful technique than either the layer removal or the incremental slitting techniques, due to the fact that it is able to determine values of residual stress at different positions within a component. The technique is relatively quick and unlike layer removal and slitting is applicable to specimens of various geometries.

Whilst hole drilling is widely used for the measurement of residual stress in metals and ceramics [14] its use with composites has been limited due to the sensitivity of resins matrix to changes in temperature and fibre pull-out during the drilling process. This investigation assesses whether reliable strain measurements can be obtained from