

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 significantly 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-ply, 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]:

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

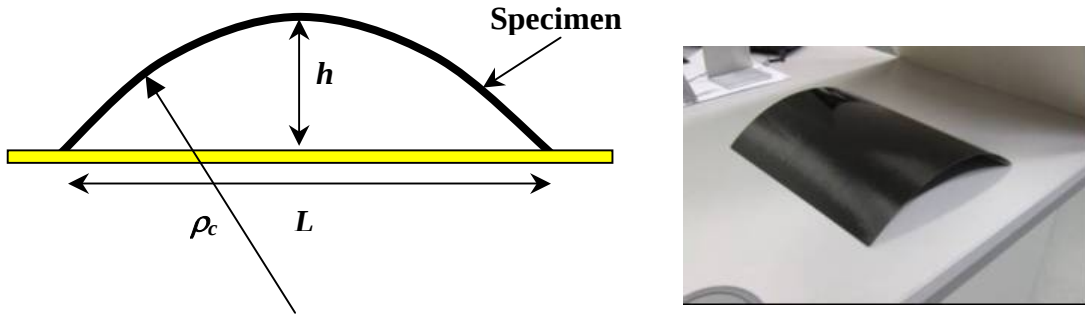


Figure 1 *Determination of curvature for an unbalanced laminate*

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]:

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

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 $\pm 2^\circ\text{C}$) 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 [0/90₂] 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 [0/90₂] laminates, had fallen by 28% and 58% to 20.2 MPa and 38.7 MPa, respectively.

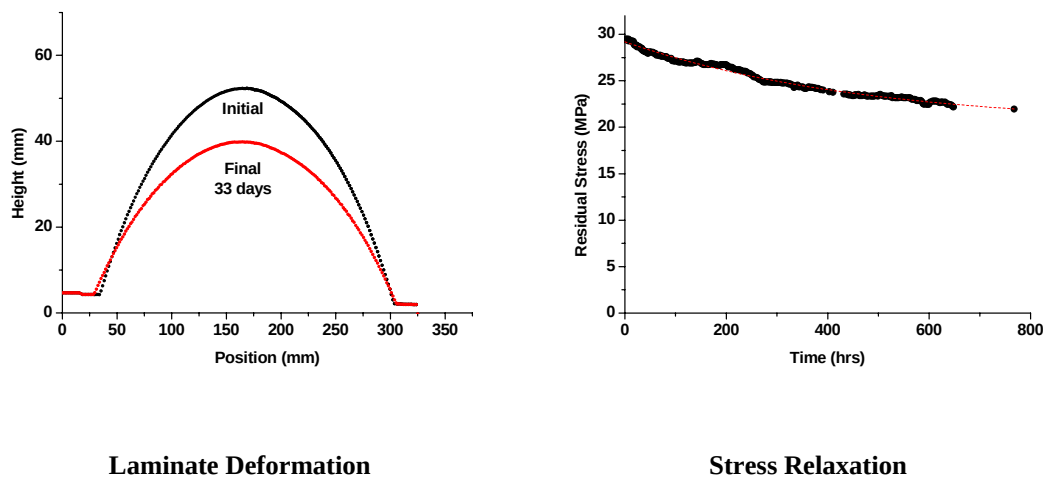


Figure 2 ***Residual Stress Relaxation for [0/90] SE 84LV CFRP Laminate***

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 $\sim 0.34 \text{ MPa}/^\circ\text{C}$. 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.

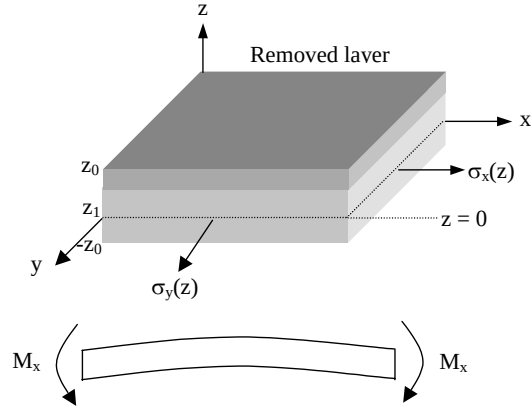


Figure 3 Co-ordinate system used in layer removal analysis [9]

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

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

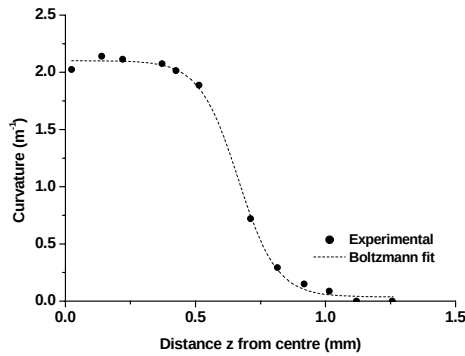
The general stress-curvature relationship for an isotropic material is given by [10]:

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

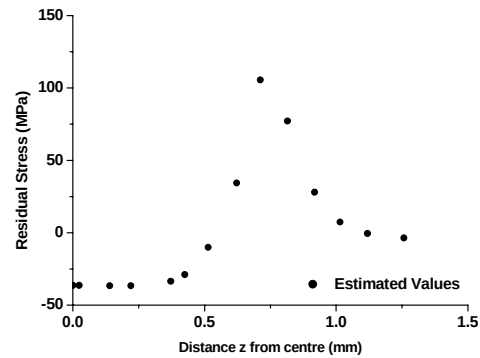
E is modulus and ν is Poisson's ratio, and ρ_x and ρ_y represent the curvature in the x and y direction, respectively. The above equation assumes that the elastic properties remain constant throughout the material. In fact, for orthotropic materials such as a composite laminate the elastic properties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

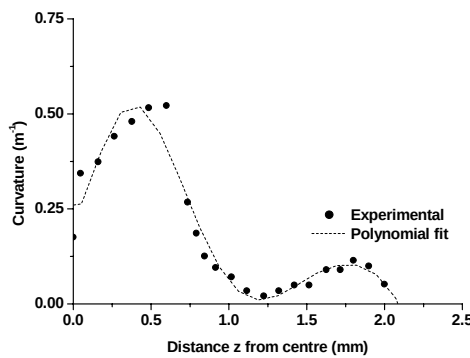


Laminate Curvature

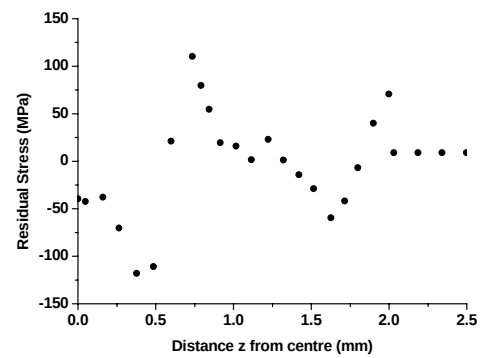


Residual Stress Distribution

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).

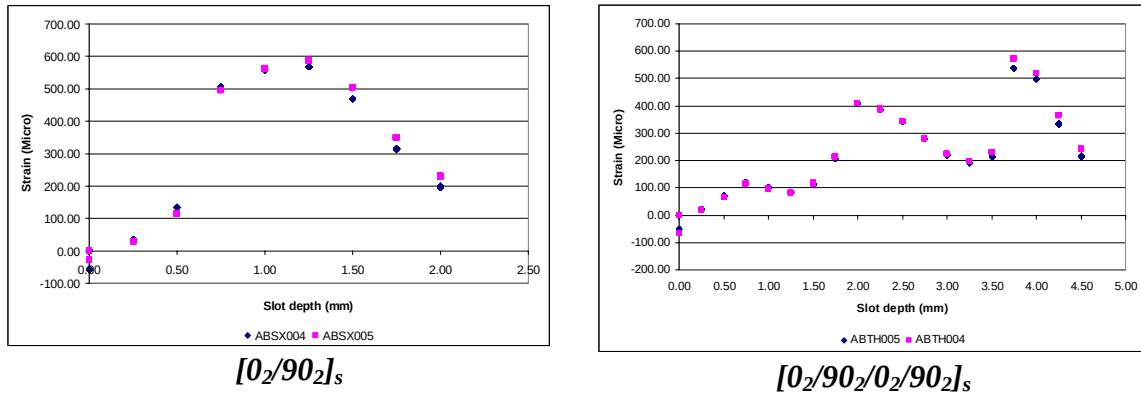


Figure 7 *Residual strain distributions using incremental slitting method*

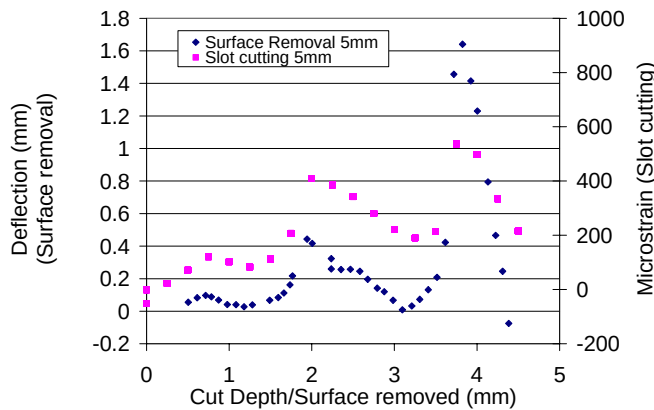


Figure 8 *$[0_2/90_2/0_2/90_2]_s$ laminate deformation obtained using incremental slitting and layer removal methods*

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

polymer composites using the hole drilling technique. To limit errors due to frictional heating or fibre pull-out, a drill bit that spins in an orbital motion around the hole was used. This reduces the drilling forces and allows air to circulate around the hole to cool the drill and prevent fibres becoming trapped in between the drill bit and the edges of the hole. Microscope images of the edges of the hole confirm that the drill bit has cut a clean hole into the composite without causing significant damage due to fibre pull-out (Figure 9).

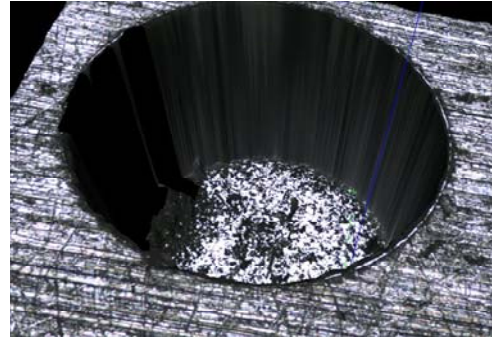


Figure 9 Image of a 1.95 mm diameter hole drilled in to carbon / epoxy composite with, no indication of fibre pull-out.

Measurements were made using three specimens of $[0_2/90_2]_s$ and $[0_2/90_2/0_2/90_2]_s$ carbon /epoxy composites, with nominal thicknesses of 2.56 mm and 5.12 mm, respectively. As can be seen in Figure 10, the repeatability of these results appears to be extremely good and would indicate that the concentric drill has overcome the problems of heating and fibre pull-out.

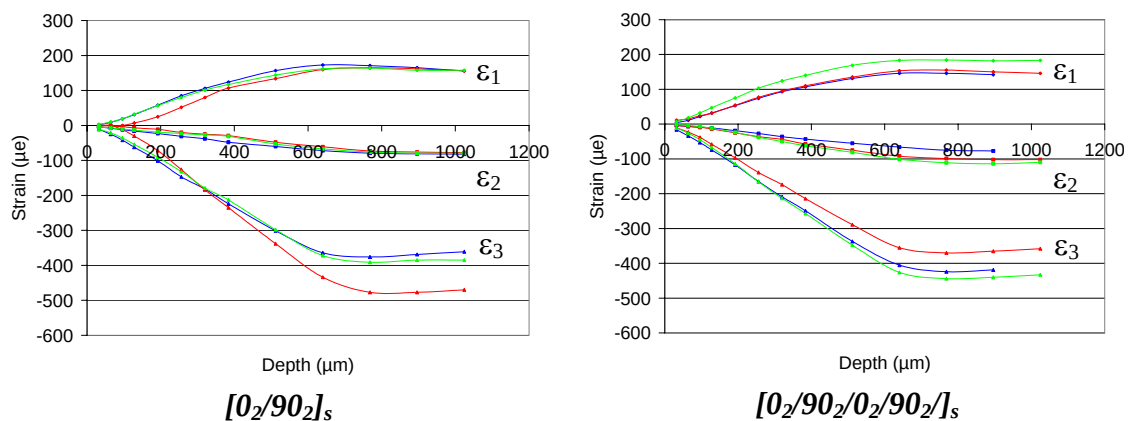


Figure 10 Strain gauge readings obtained at different depths within a carbon fibre composite using the hole drilling technique ϵ_1 is parallel to the fibres, ϵ_2 is at 45° and ϵ_3 is perpendicular to the fibres

The main limitation of the hole drilling technique is that measurements can only be made to depths up to half the diameter of the hole [15], which in the current work is 1.0 mm deep. As a consequence, the hole drilling technique is unable to distinguish any difference between the $[0_2/90_2]_s$ and $[0_2/90_2/0_2/90_2]_s$ laminates as the lay-up of these two composites is identical down to 1.2 mm. These results therefore indicate that although residual strain measurements can be obtained from the hole drilling technique the technique is limited to near surface measurements.

2.5 RAMAN SPECTROSCOPY

Raman spectroscopy is based on the inelastic scattering of monochromatic light from non-metallic materials. Laser light causes the bonds in the material to vibrate and by comparing the frequency of the scattered Raman light to the incident laser light it is possible to obtain information about the chemical and physical structure of the material [16-18]. Application of stress to a material will change the inter-atomic separation of the bonds, resulting in a corresponding change in the vibrational frequency of the bonds and hence a shift in the wavelength of peaks in the Raman spectra. This effect is particularly strong in crystalline materials and can be used to detect strains in both carbon or aramid composite fibres.

The magnitude of the Raman peak shift that occurs due to residual strain in the composite was determined by applying known levels of uniaxial tensile strain to a single carbon fibre and monitoring the position of the Raman peak (1607.4 cm^{-1}) associated with the carbon fibre. As can be seen in Figure 11 the effect tensile strain had on the Raman peak was to shift the peak to lower wavenumbers in the spectra. Furthermore, this shift in the Raman peak was found to be linear with the position of the peak shifting down 3.9 cm^{-1} wavenumbers per 1% strain. It would therefore appear possible to determine strain in a carbon-fibre composite by measuring the shift in the Raman peak. Unfortunately, although the Raman peak could clearly be detected in the carbon fibre composite (1607.25 cm^{-1}) only a minimal shift in the Raman peak was observed (0.15 cm^{-1}). It would therefore appear that although the Raman technique can detect the presence of large applied strains in a carbon fibre composite, the resolution of current Raman equipment is insufficient to detect the level of strains that typically result from residual stresses.

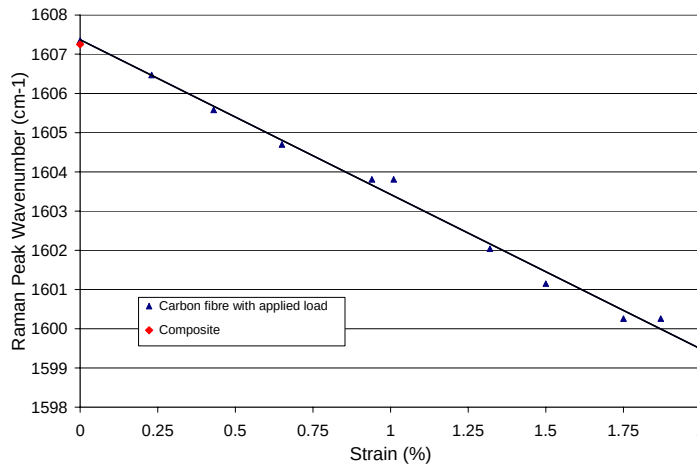


Figure 11 Shift of Raman peak as a function of strain in carbon fibres

2.6 FIBRE BRAGG GRATINGS

Fibre Bragg Gratings (FBG) are sections of optical fibre treated to behave as narrowband filters which reflect a portion of incident light as a peak of finite bandwidth [19-20]. The reflected wavelength varies linearly with changing strain or temperature, shifting the peak position. Conversely, using the magnitude and direction of the reflected peak shift, the strain or temperature change, which caused it can be

determined. Even changes in the reflected spectrum can describe changes in the host material's internal strain state since non-uniform or non-axisymmetric stress/strain fields can exhibit spectral disturbances such as multiple peaks, peak broadening (chirping) or peak splitting [3, 21].

In these experiments a $[0_2/90_2]_5$ laminate was prepared using carbon epoxy prepreg. A thin PTFE release film was used between the base plate and the laminate to minimise frictional stresses due to coefficient of thermal expansion (CTE) mismatch. The residual strains and temperatures developed in the composite during processing were obtained using embedded FBGs and thermocouples respectively, located as shown in Figure 12. The FBGs were monitored with a W4-5 SmartFibres interrogator with a resolution of 1 pm using W4 SmartSoft datalogging software. Thermocouples were placed beside the gratings, as temperature compensation is critical for accurate strain measurements.

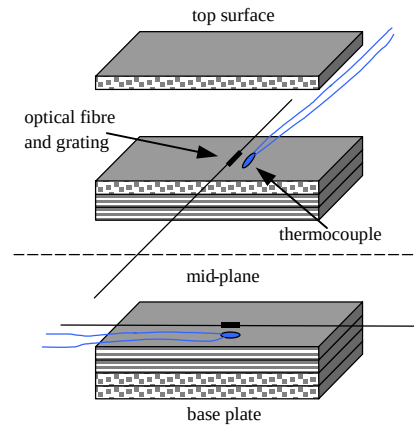


Figure 12 Schematic of panel lay-up showing positions and orientations of plies, FBGs and thermocouples

No information was obtained during cure, however, Figure 13 presents the spectral response of the two FBGs compared to their respective original bare fibre spectra prior to lay-up. The spectra in all cases seem undisturbed, with no sign of peak splitting or chirping suggesting that the stresses experienced by the gratings were axisymmetric and uniform. The discrepancy between the peak wavelength of the bare fibre at the original zero strain condition and that after lay-up, for the FBG in the surface plies, indicates pre-straining unlike the mid-plane FBG where the spectra are seen to overlap almost perfectly.

The fabrication strains measured for the FBGs are given in Table 1. These show the large, dissimilar strains exhibited by the gratings as a result of the autoclave curing process at different locations within the lay-up. These are consistent with similar lay-ups and materials available in the literature summarised in Table 2, establishing the presence of non-linear residual strain gradients through the thickness of multidirectional laminates.

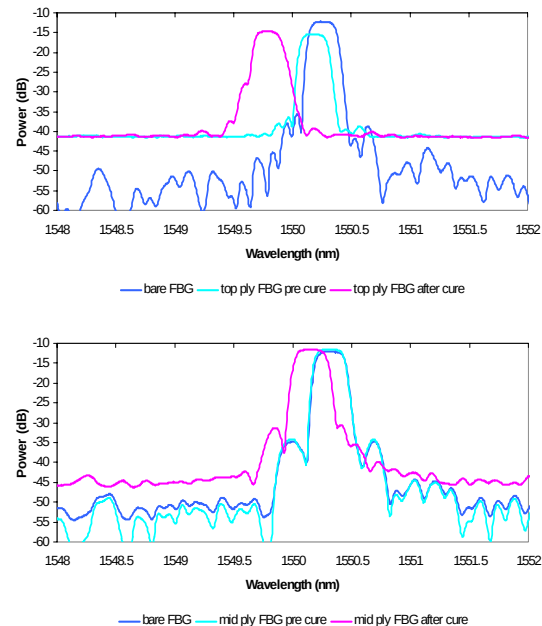


Figure 13 Typical FBG spectra before embedding, after embedding and post-fabrication: between top two plies (upper) and at the mid plane (lower)

Table 1 *Strain changes experienced by the embedded FBGs after processing, with relaxation time and on subsequent heating (to 120 °C)*

FBG location	Strain after manufacture ($\mu\epsilon$)	Δ strain after 8 weeks ($\mu\epsilon$)	1st heating cycle Δ strain ($\mu\epsilon$)	2nd heating cycle Δ strain ($\mu\epsilon$)
Between surface plies	-421	+77	-13	-18
Between mid-plyes	-173	+92	-28	-15

In fact, the residual strain in composite materials is defined as the difference between the measured fabrication strain and the ‘free strain’ (unrestricted shrinkage/thermal contraction as measured biaxially on a unidirectional material) [22]. This explains the larger apparent strain observed in the surface plies. Since these are less influenced by adjacent plies or metal moulds, they are free to contract to a greater extent than the central plies which experience a greater level of constraint. This would therefore suggest that the ‘residual’ strains (or those which have been induced by the stresses built up by preventing free contraction) are actually much lower at the surface than at the mid-plyes.

Table 2 *Summary of cure or residual strain measurements made using embedded FBGs obtained from the literature*

Material	FBG location	Fabrication strain ($\mu\epsilon$)
Fiberite HyE 6049U carbon/epoxy [23]	[0 ₅ /90 ₅ /FBG/90 ₅ /0 ₅]	-430
T300/F155 carbon/epoxy [21]	[90 ₄ /FBG ⁽¹⁾ /90 ₄ /0 ₄ /FBG ⁽²⁾] _s	-20 ⁽¹⁾ /-385 ⁽²⁾
Hexcel 920 carbon/epoxy [22]	[0 ₈ /FBG ⁰ /FBG ⁹⁰ /0 ₈] [0/FBG ⁽¹⁾ /0 ₃ /90 ₄ /90 ₃ /FBG ⁽²⁾ /90/0 ₄]	-40/-4800 -270 ⁽¹⁾ ≡-230 ^{res} /- 370 ⁽²⁾ ≡+4430 ^{res}
Hexply M21 T700 carbon/modified epoxy [1]	[0 ₄ /FBG/0 ₄] [90 ₄ /0/FBG/0/90 ₄]	+101 -1093

After manufacture, the FBGs were monitored intermittently for an extended period to determine whether any relaxation of the “frozen in” strains could be observed. Figure 14 shows the gradual decrease in compressive strain experienced by both sensors with time. Subsequent short duration heating cycles showed small increases in compressive strain suggesting some degree of post-cure occurring. The opposite effect would be observed if the strain were being released as the material passed through the glass transition temperature (T_g) on heating.

Whilst FBG determination of residual strain holds great promise, there is a requirement for a better fundamental understanding of the measurement process and its interpretation. Clearly FBG strains need to be correlated to strains in the surrounding composite by generating relevant analytical models and numerical simulations. These need to include viscoelastic effects, elastic moduli of fibre and resin and thermal expansion / contraction coefficients of both the composite materials and

tooling with both temperature and chemical conversion. These need to accommodate the anisotropic and non-homogeneous nature of residual strains, which is not taken into account in classical laminate theory where the stress-free temperature (gelation) is assumed constant throughout the laminate. In addition, the accuracy and reproducibility of the experimental data needs to be validated and the conversion of the measured strains into stresses is also important.

3 SUMMARY

The simplest of the techniques that have been studied is the measurement of curvature in unsymmetric panels. This technique enables the average residual stress in a ply to be determined allowing different composite materials to be compared. The technique does not, however, allow you to assess the variation of residual stresses within a ply and is therefore not suitable for design purposes. The layer removal and incremental slitting techniques enable residual stresses to be determined at different depths throughout the thickness of the composite. The importance of this is clearly demonstrated by the complex distribution of residual stresses that have been measured using these techniques (Figure 4, 5 and 8). However, these techniques can only be used on standard test pieces and cannot therefore be used for actual components. The hole-drilling technique can be used to determine the residual stress at any position on the surface of an actual component. However, it is limited due to the complex calculations that are required to determine the residual stresses in the material and that it is unable to detect stresses at shallow depths.

Two techniques that offer the possibility of in situ, non-destructive measurement of residual strain in actual components are Raman spectroscopy and Fibre Bragg gratings (FBG). The advantage of Raman spectroscopy is that it can measure the strain of actual carbon fibres within a composite. The sensitivity of this technique is, however, too low to detect the levels of residual strain typically found in composites. FBG are far more sensitive to low levels of strains allowing them to be used to detect the levels of strain typically induced by residual stresses. These gratings can be positioned at any position within the composite allowing the possibility to strain map the material. Furthermore, as the measurements are non-destructive the sensors can be used throughout the life of the product for structural health monitoring. This technique would appear to be the most promising of all the techniques studied although it is expensive and further work is still required to assess its accuracy and repeatability. Less expensive techniques that also show great promise and could be more widely used in manufacturing are the incremental slitting and hole-drilling techniques. The advantages and disadvantages of each of the techniques that have been examined in this study are summarised in Table 3.

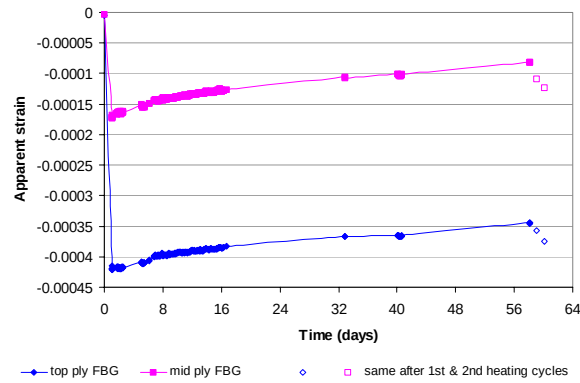


Figure 14 *Graph of changes in strain with time for both FBGs. The strain changes experienced after short duration heating cycles are also plotted*

Table 3 *Summary of advantages and disadvantages of the different residual strain/stress measurements techniques under investigation.*

Techniques	Advantages	Disadvantages
Curvature of unsymmetric panels	- Minimal equipment required - Computation of residual stresses from strains straightforward	- Limited to plain laminates - Cannot measure stress gradients - Assumes residual stress in unsymmetric panels same as in symmetric panel
Layer removal	- Residual stress distributions can be obtained throughout the composite - Computation of stresses from deformations straightforward	- Limited to simple flat panel specimens - Destructive - Expensive in terms of time and labour
Incremental slitting	- Stress distributions can be obtained - Less time and labour consuming than layer removal technique	- Destructive - Stiffness of strain gauges can affect results - Calculation of residual stresses from strains complex
Hole drilling	- Equipment widely available and relatively low cost - Strain mapping across surface possible - Strain gradient can be measured down to 1 mm	- Measurements can only be made down to typically 1 mm - Stiffness of strain gauges could affect results - Calculation of residual stresses from strains complex
Raman	- Measurement of large strains possible >1% - Mapping of large strains along the length of a fibre possible - Non-destructive measurement of surface fibres possible - Minimal specimen preparation required	- Extremely low sensitivity means most residual strain cannot be detected - Measurements limited to surface fibres - Only applicable to carbon and Kevlar fibres - Strain measurement rather than stress
Fibre Bragg gratings	- Measurements in situ and internal - Small size, means fibres are minimally intrusive - Multiple sensors on single fibre allows strain mapping - High strains are measurable, strain limit >1% - Non-destructive measurement allows monitoring in service - Non-uniform and non-unidirectional strain information obtained from full spectral response	- Sensors and interrogation expensive - Sensors strongly influenced by temperature so that strains need temperature compensation - Uneven bonding or intermittent contact can cause strain measurement problems - Strain measurement rather than stress - No strain detectable prior to gelation - Orientation of fibres in adjacent plies can affect spectra response

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