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Determination of ply level residual stresses in a laminated carbon fibre-reinforced epoxy composite using constant, linear and quadratic variations of the incremental slitting method

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ABSTRACT

Measurement of residual stresses in FRP composites is by no means a trivial task and there are no commonly applied or standardised methods currently available. As a result, characterisation of residual stresses is often avoided, resulting in the use of conservative safety margins, which has consequently resulted in structures being overdesigned. In the work described here, the incremental slitting method has been demonstrated to be a technique suitable for measuring residual stress in thin (~0.3 mm) plies of a $[0°_2/90°_2]_{4s}$ carbon fibre-reinforced epoxy laminate. The stresses measured using a constant stress approximation approach provided the best agreement with measurements obtained using the layer removal technique and stresses predicted using a semi-coupled transient-thermal and structural model.

1. Introduction

Residual stresses are those stresses that are present in a material in the absence of any external load being applied. For fibre-reinforced plastic (FRP) composites, residual stress development during processing can cause significant fabrication, assembly and in-service performance problems resulting in part distortion, matrix cracking, delamination, adverse effects on the stress-strain behaviour of the material [1–5], and reduction in fracture toughness [6], impact and environmental resistance.

The extent and magnitude of manufacturing induced residual stresses will strongly depend, amongst other factors, on the properties of the matrix and fibres, the orientation of plies within a laminated component and the temperature at which the material is processed. During the cure of a thermosetting composite, the material is typically subjected to elevated temperatures and pressures and these conditions result in the matrix liquefying and flowing around the fibre reinforcement, followed by gelation and finally vitrification. At the intra-ply level, as gelation initiates, load transfer between the fibres and matrix can occur and the chemical shrinkage of the resin due to crosslinking of molecular chains is partially resisted by the fibres. On cooling from the cure temperature, vitrification occurs and the thermal shrinkage of the resin is partially opposed by the fibres in the axial direction due to the difference in their coefficients of thermal expansion (CTE). The chemical and thermal shrinkage resistance of the fibres causes stress along their length resulting in lower resin shrinkage parallel to the fibre direction compared with the transverse direction [7–9]. These mechanisms are responsible for the development of residual stresses at the micro-level and explain the occurrence of residual stresses in unidirectional material [8]. For multidirectional laminates, at the inter-ply level, macroscale stresses are generated on cooling from the stress free cure temperature due to anisotropy of the thermal expansion of the plies in the longitudinal and transverse directions [7,8]. Another key mechanism by which residual stresses can develop during processing is from interactions between the tooling (e.g. mould or caul plate) and the laminate due to differences in the CTE of tooling material and composite part [8].

A review of potential techniques for measurement of residual stress in FRP composites was undertaken by Maxwell et al. [10]. Of the methods reviewed, the most commonly used for laminated composites were identified as curvature measurements of unsymmetric laminates [11–14] and layer removal [15–18]. The first technique has the advantages of requiring only simple measurement equipment and a straightforward method for calculating residual stress from the measured curvature. A key disadvantage of the technique however, is that it is limited to continuous fibre-reinforced laminates; it also requires a special laminate

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lay-up and cannot be used for measuring the residual stress in individual plies. The layer removal method can be used to determine ply level residual stresses and has the advantage that the computation of the stresses from measured back-face strains is relatively straightforward. However, the complete removal of thin layers of material is in practice a difficult task to perform and can be extremely labour and cost intensive. The technique is limited to flat coupons and as the method for derivation of residual stresses is based on classical laminate theory (CLT), the measurement of stresses in thick laminates (>10 mm) requires proportionately large specimens i.e. >100 mm × 100 mm, increasing the difficulty of layer removal further.

One of the most promising techniques reviewed [10], was the incremental slitting method or compliance technique. Incremental slitting has primarily been developed and used for determining residual stress in a range of metallic samples including cylinders [19], welded plates [20,21], and laser and shot-peened specimens [22]. The technique involves machining a narrow slit of increasing depth into a rectangular coupon of material so that the stresses normal to the plane of the slit are relieved. The resultant deformation, measured at the back-face, is used to determine the residual stresses in the coupon prior to machining. The technique has seen limited but successful application for the measurement of residual stress in laminated composites. Ersoy and Vardar [23] used the technique to determine residual stresses in heavily blocked $[0°_{10}/90°_{10}]_s$ APC-2 thermoplastic laminates. They compared incremental slitting measurements to layer removal measurements on the same material, as well as residual stress predictions using a model developed by Lawrence et al. [24]. The method is in principle similar to the layer removal method [16–18], however the advantage is that much less material has to be removed and it is therefore simpler to perform experimentally. The technique requires a model to convert the measured strains into stresses; a data reduction method that is considerably more complex than that required for the layer removal technique. However, as the stress derivation is not based on CLT, the method can be used on relatively thick laminates without the need to use samples with correspondingly large planar dimensions. It should be noted that in general, the measurement of residual stresses in thick laminates is difficult to perform using techniques that rely on the measurement of small changes in back-face strain on removal of relatively thin plies of material.

In this paper, measurements of residual stresses in individual plies of a $[0°_2/90°_2]_{4s}$ laminate fabricated from SE84 LV carbon fibre-reinforced epoxy material have been undertaken using a variant of the incremental slitting approach detailed in [23]. Residual stresses derived from incremental slitting measurements have been compared to measurements made using the layer removal technique and predictions calculated using a semi-coupled transient-thermal and structural analysis.

2. Incremental slitting measurements

The incremental slitting method detailed in this paper consists of the following stages; (i) the experimental measurement of a set of strain, ε_k^m, $k = 1, 2, \ldots, K$ associated with known slit depths a_k, $k = 1, 2, \ldots, K$, (where K is the number of slit depths and the superscript m indicates measured strain); (ii) finite element (FE) models to calculate the strain equivalent to the measured strain, $\varepsilon_{k,i}$ for the same slit depths a_k under a defined set of residual loading ply stresses σ_i, $i = 1, 2, \ldots, M$ that are used to characterise the residual stress where M is the number of functions used to characterise the residual stress, and; (iii) a Matlab routine to derive the ply level stresses from the measured strains and the results from the FE models. The following sections provide more detail regarding the approach taken.

2.1. Material details and laminate manufacture

The material used in this study was SE84 LV (Toray T700 UD HS) carbon fibre-reinforced epoxy unidirectional tape, supplied by Gurit (UK) Ltd. The nominal cured ply thickness was 0.3 mm. A 300 × 300 × ~10 mm thick $[0°_2/90°_2]_{4s}$ laminate was prepared by hand lay-up and autoclave processed. The material supplier's recommended cure cycle is only suitable for laminates <5 mm thick, and therefore an optimised cure cycle, developed at the National Physical Laboratory [25] was used. The mean elastic properties, which are required for the incremental slitting modelling approach to convert measured strains to ply level residual stresses, are detailed in Table 1.

2.2. Experimental procedure

The procedures detailed in this section were followed to generate a series of experimentally determined strains, ε_k^m, each associated with a known slit depth a_k. Rectangular specimens, 100 × 30 × ~10 mm thick were machined from the laminate using a diamond grit coated circular saw with water as a coolant. Five specimens were extracted with the longitudinal axis aligned to the 0° fibre direction (defined as *X* specimens) and two specimens were extracted with the longitudinal axis aligned to the 90° direction (defined as *Y* specimens) so that the residual stresses in the fibre and transverse directions for each ply could be determined. Two sets of measurements are required on samples of laminate cut in different directions as the incremental slitting method cannot be used to make measurements of residual stresses in both in-plane ply directions simultaneously. The reason for testing only two *Y* specimens was due to the limited amount of material available. For consistency of measurements, care was taken to ensure that the top face of each specimen corresponded to the surface of the laminate that was in contact with the upper steel caul plate during cure. Details of the specimen dimensions, directions and slitting tests undertaken are provided in Table 2. For one specimen (*X*5), slits were machined to quarter-ply depths in order to provide sufficient strain readings to determine linear and quadratic, as well as constant stress variations per ply (Section 3). For all other specimens, slits were machined to single-ply depths. The time required to perform shallower cuts was otherwise prohibitively long (~2 days compared to ~few hours) as four times as many cuts need to be machined compared to tests in which plies are notched in their entirety.

The long edges of each specimen were ground to ensure they were square and parallel. Optical measurements were made of the thickness of each ply using a Nikon MM-60 microscope at 5× magnification. Ply thickness measurements were made on both sides of each specimen at mid-length corresponding to the position at which the slit was to be machined. For each ply, the thickness was calculated as the mean of the two measurements.

A 2 mm uniaxial strain gauge (Tokyo Sokki Kenkyujo Co. Ltd. Type: FLA-2-11, gauge factor 2.09, gauge resistance 120 Ω) was bonded using a cyanoacrylate adhesive to the centre of the back-face of each specimen. A polyurethane coating (Micro-Measurements M-COAT A) was then applied to the surface of the strain gauge and lead wire connections to ensure that carbon dust produced during the slitting operation did not short the electrical connections. Strain gauges were wired into a quarter-bridge configuration via a National Instruments (NI) data logger and NPL designed logging software.

To monitor the temperature variation of each specimen during slitting and compensate for the effects of any fluctuations in labo-