

Analysing thermally induced macro-scale residual stresses in tailored morphing composite laminates



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ABSTRACT

An approach for predicting and extracting through-thickness residual stresses in tailored composite laminates (*i.e.* laminates with local variations in lay-up sequence and/or thickness) is presented. Tailored composite laminate configurations can be explored in some novel structural applications (*e.g.* morphing laminates) by incorporating unsymmetric laminate lay-up sequences. In such cases, the presence of and variation in through-thickness (*i.e.* macro-scale) residual stresses can considerably influence the structural geometry, strength and multi-stable behaviour of these laminates, and thus require consideration at a design stage. In this context, a combined numerical-experimental approach was used to analyse residual stresses in tailored laminates. Laminates with local unsymmetric cross-ply lay-ups and/or varying thicknesses were manufactured at elevated temperatures and experimental measurements (of cured shapes at room temperature) were used to develop laminate-level finite element models. The cured laminate shapes were measured using a full-field non-contact technique. The numerical models were calibrated and subsequently used to extract through-thickness residual stresses in the laminates. It was shown that the current approach can be successfully applied to predict the cured shapes of and the through-thickness residual stresses in tailored laminates.

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1. Introduction

It is known that uni-directional fibre–matrix composites with unsymmetric lay-up sequences become warped following the cool-down from elevated cure temperature to room temperature. This is due to a mismatch in the coefficients of thermal expansion (CTE) between transverse and longitudinal plies, which, when stacked adjacently, introduce residual stresses [1]. This warping following cure is generally undesirable in structural applications and thus laminates with unsymmetric lay-up sequences are largely avoided in conventional designs. However, it is possible to use unsymmetric laminates beneficially, such as in stiffness tailoring [2] or in morphing applications (*e.g.* aeronautical or wind turbine) [3–7]. In the case of morphing technologies, a likely solution to integrate a multi-stable laminate into a structure entails the use of tailored lay-ups, whereby the orientations of individual plies within the laminate are discontinuous, resulting in a changing ply lay-up sequence along the length or width of the laminate [8,9]. This could be done, for example, to couple the multi-stable laminate into the

surrounding structure [6] or to maximise the multi-stable configurations available [5,8]. In addition, laminate asymmetry may occur as a consequence of geometric requirements, such as ply-drop off cases where plies are prematurely cut short at discrete locations leading a taper being formed, which in turn can lead to local asymmetry in the lay-up sequence [10,11].

The change in lay-up sequence will introduce through-thickness residual stress variation along the length of the laminate. This can influence the laminate shape, multi-stable behaviour and structural performance. An approach is thus required to correctly predict residual stresses through-out the transition in lay-ups. The curvatures developed by unsymmetrical composite laminates have been previously used to measure macro-scale residual stresses by using classical laminate theory [12]. However, such analytical techniques to predict and analyse cured shapes become challenging and time consuming when complex laminate lay-ups and geometries are considered. Numerical modelling (using the finite element method) offers flexibility in this regard and has been used in the past to characterise multi-stable laminate behaviour, particularly with the use of shell models [9]. When a detailed analysis is sought (*e.g.* when studying the interactions with local structures and actuating systems, or damage) it can be advantageous to use a solid

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continuum approach. Additionally, complex environmental factors that influence residual stresses (such as moisture absorption) can require a transient analysis, to which a continuum approach lends itself by use of the analogy between heat transfer/thermal expansion and moisture diffusion/moisture-induced swelling [13–15].

This work aims to build upon a previously developed experimental–numerical approach to predict dry and saturated through-thickness residual stresses (and thus the shapes) of unsymmetric laminates [15] by expanding it to predict tailored lay-up laminate shapes, and subsequently extract and analyse macro-scale through-thickness residual stresses. A number of different laminate configurations are explored with varying laminate thickness and discontinuous ply orientations (with the transition being both normal to the laminate thickness and tapered). The changes in through-thickness residual stresses due to the tailored laminate configuration were analysed at both the centre of lay-up partitions and at the boundary between changing lay-ups. The effectiveness of the numerical model in predicting cured laminate shapes is described in more detail by means of a full-field study of the variations.

Tailored laminates were manufactured from uni-directional pre-preg (carbon fibres with epoxy resin) material. The lay-ups featured sections with both unsymmetric and symmetric lay-up sequences, and at least one multi-stable region. Numerical models of the laminates were then developed, and the cool-down from cure temperature to room temperature was simulated to reproduce the warped laminate shapes. The orthotropic material expansion coefficients used in the numerical models were then calibrated to reproduce the experimentally observed laminate shapes. Equivalent CTE values were employed to eliminate the need to precisely account for individual contributors to residual stresses (such as imperfections or manufacturing effects [16–20]), which can have an effect on thin composites panels [8]. Subsequently, the ability of the present technique to correctly predict the cured laminate shapes was investigated by means of a detailed shape comparison. The through-thickness residual stresses at different positions of the tailored laminates were then extracted from the models and analysed to gain insight into the effect of tailored laminate configuration on residual stresses.

2. Materials, manufacturing and testing

2.1. Manufacturing of tailored laminates

A range of tailored laminates were manufactured featuring different tailored lay-ups. The material used was Hexply HTA 6376 (uni-directional carbon fibre with impregnated epoxy resin). Hand lay-up techniques were used, followed by autoclave (TC1000LHTHP, LBBC, UK) curing at 178 °C temperature under 7 bar pressure. Five different lay-up configurations were manufactured. Each configuration featured partitions along the length (x -direction) of the laminate (see Fig. 1, showing a single partition). The cross-section of each laminate is presented in Fig. 2(a)–(e) along with the corresponding cured shape. For convenience, each lay-up configuration will be referred to by the corresponding numbers given in Fig. 2 (i.e. Laminate 1–5). As all the laminates featured a multi-stable property, with two or more stable shapes being obtainable, only the shapes depicted in Fig. 2 are analysed in this work.

2.2. Recording laminate shapes

In order to make detailed comparisons against numerical models, a full-field non-contact shape measuring technique was required. Optical methods, based on the fringe projection technique, have been used in the past to record shapes of unsymmetrical

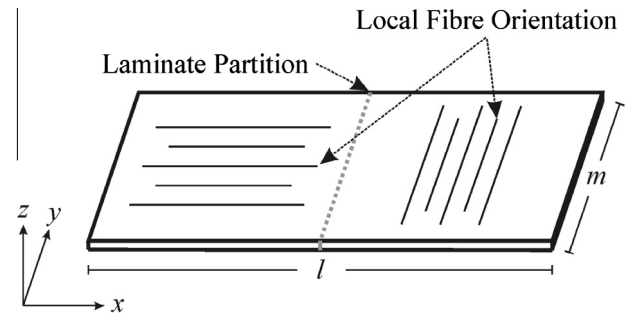


Fig. 1. Typical configuration of manufactured tailored laminates, featuring partition along the x -axis. In all cases, $l = 200$ mm, $m = 100$ mm. Only cross-ply (0° or 90°) ply orientations were used.

laminates [21]. As no contact is involved, distortion of the laminate during measurement is eliminated. Additionally no assumptions on the measured displacement fields are needed [22]. This is important as the cured shapes of the laminates used feature varying curvature along their lengths, due to their tailored nature. In this work, laser scanning was used to measure laminate shapes. A flat laser line was swept over the laminate, and a camera was then used in conjunction with specialist software (David-Laserscanner 3.9.1) to record the distortion of the laser line as it sweeps over the laminate. The experimental set-up used in this study is shown in Fig. 3. A full description of the technique can be found in [23]. Following a scan of the laminate's surface, a point cloud of co-ordinates describing the surface was obtained. The accuracy of this technique is stated to be 0.5% of the object size. To determine the accuracy of the experimental set-up used in this work, a calibration plate with patterns of known dimensions (item (e) in Fig. 3) was scanned. The plate was manufactured using identical methods and materials to those of the laminates, so as to give an identical scanning surface. The plate was scanned and a point cloud obtained. Using this point cloud, the dimensions of the patterns were compared against the actual dimensions. It was found (due to the resolution of the point cloud) that an error of 2 mm is possible when calculating in-plane distances, depending upon the point cloud spacing. However, the important metric required in this work is the accuracy of the co-ordinates (specifically, in the out-of-plane direction) of each point in the point cloud. As the calibration plate was flat (save for a slight warping), the variation in the measured out-of-plane co-ordinates was checked. The maximum variation was between +1.4/–1.8 mm. This was deemed acceptable as: (a) the calibration plate was not completely flat and (b) the advantages of this technique (simplicity, full-field, non-contact) made it the most attractive shape measuring technique.

3. Numerical modelling

The thermal deformation of each laminate following the cure cycle was modelled using the finite element software Abaqus (version 6.11). The models incorporated the temperature drop following cure, which induces thermal deformation in the model due to the material's orthotropic CTEs. The models were developed as flat three-dimensional solids to the nominal dimensions of the manufactured laminates ($l = 200$ mm, $w = 100$ mm, ply thickness = 0.125 mm). The models were then partitioned to create each ply as well as the tailored sections. A local material orientation was then assigned to each ply according to the ply stacking sequence for that laminate. Orthotropic and linear-elastic material properties were used to represent the HTA 6376 material, as in Table 1 [15]. The material's longitudinal CTE (α_L) was deliberately left undefined at this stage, and was later used as a calibration parameter to

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