Modelling the mechanical properties of as-manufactured composite components based on 3D non-destructive characterisation


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Abstract
During the composite component design process, and at the manufacturing stage, there is a requirement to understand the effect of defects in terms of their ‘knock-down’ in the structural performance. The result would be justifiably lighter designs, a better-informed concession process for manufacturing defects and improved in-service repair strategies. Such an understanding has been achieved for bulk-averaged porosity and delaminations but more subtle effects, such as in-plane fibre waviness, out-of-plane ply wrinkling, and 3D variations in fibre-volume fraction or porosity, have not received this level of attention. Recent developments in X-ray CT and ultrasonic 3D characterisation of composites offer the potential for a greater understanding of the effects of these material variations. In the composites community, work has been proceeding on the modelling of mechanical properties and failure modes in the presence of such variations. This paper will demonstrate the use of 3D NDT data to construct materials models of the exact as-built structures, including material variations and defects, in order to predict the effect on performance and better inform the design, concession and repair processes.

Keywords: Ultrasound, X-ray, computed tomography, finite element modelling, aerospace, carbon fibre composite

1 Introduction

1.1 Structural integrity background
The rate of increased use of composite materials in primary aircraft structure in the past 30 years has exceeded the rate of development of the desirable non-destructive characterisation (NDC) techniques. Ultrasonic C-scanning, developed for composites in the 1970s [1], is still used to detect gross manufacturing defects or give an estimate of through-thickness average porosity but provides little information about the conformance to design at a ply, or fibre tow, level. The risk posed by inadequately characterised components has been mitigated by designing in additional thickness, and hence weight. This increases the tolerance to damage until the maximum allowable strain will not cause any accidental damage to grow, unless it is clearly visible to the naked eye and, therefore, easily detectable. Thus the thorough understanding of the issues of damage growth under fatigue, or the large-area detection of invisible damage, have been unnecessary. The result for civil aircraft has been only a marginal efficiency/weight benefit over metallic construction. For military aircraft the additional benefits of aerodynamic performance and stealth provision have made composite construction easier to justify, but the performance benefit is still only a fraction of what may be possible if detailed 3D characterisation of the material itself were performed at manufacture, guaranteeing conformance to design.

A more recent problem has been the implementation of in-service repairs in order to restore the original designed performance or life. In the civil sector, a lack of confidence in adhesively bonded joints between composite adherends has resulted in the use of bolted, rather than bonded, repair patches – and these are often metallic. For military aircraft, an issue has been the lack of information about the original (classified) structural design, such as ply lay-up, to allow the optimised design of a repair patch. Characterisation of the original damage, conformance to design of the repair patch, and bond integrity are additional problems for composite repairs in both civil and military arenas.
1.2 Composite performance

As shapes of composite structures have become more complex and manufacturing methods more susceptible to local variations, the potential consequences of fibre-orientation deviations from design have caused greater concern. It is clear that no fibre is perfectly straight, and Bolotin [2] demonstrated the dependence of stiffness on average fibre misalignment. A significant reduction in performance, for both stiffness and strength, has been modelled and measured with relatively small angular deviations [3-4]. Budiansky [5] showed a dependence of compression failure stress on fibre waviness angle but strength is ultimately dependent on failure mechanisms and these vary with the shape of the fibre tows. Generally the greatest fibre curvature is the location of the largest stress concentration and it is near this that failure will occur [6]. The extent of the deviation from designed fibre orientation must be determined and compared with an allowable deviation based on modelling and experimental validation.

Various teams have modelled the dependence of performance on wrinkling, but issues exist with validating these models experimentally, such as how to determine exactly what the wrinkle shape and extent is before mechanically testing, and what parameters should be used to specify the wrinkle severity. For example Caiazzo et al [7] suggested using the following parameters to specify a wrinkle:

- Location of centre of wrinkle
- Shape of wrinkle (eg polynomial curve fit), \( h(x) \)
- Decay rate of waviness, \( \xi(x) \)

They felt limited by the non-destructive characterisation capabilities of the time, desiring “...more elaborate representations”. At a workshop on the NDT of ply wrinkling organised by the British Institute of NDT in 2010, it was proposed that the following parameters are also required in order to characterise a wrinkle defect:

- Number of wrinkles of a given shape
- Histogram of: %volume affected by >5°, > 4°, etc
- % unwrinkled fibres in each load direction.
- In-plane vs Out-of-plane wrinkle ratio (probably varies with depth in the structure).

1.3 Quantitative 3D fibre orientation and its visualisation

Due to the strong links between fibre orientation and mechanical performance of composites, the 3D fibre direction is the first parameter required for populating cells in a finite-element (FE) model of a composite component. It is this that dictates the orientation of the anisotropic stiffness axes. Any out-of-plane wrinkling must also be tracked by the element shapes in the FE mesh and this will be covered in the current paper.

Various NDT methods have been proposed that are sensitive to fibre orientation, but many of these are either not quantitative [8] or cannot be specific about where in the thickness of the structure each orientation exists. X-ray computed tomography (CT) imaging has been shown by Nikishkov et al [9] to have potential for wrinkle mapping and subsequent formation of an FE mesh for modelling of performance. There are some components for which this may be a viable method, but X-ray CT with the resolution required is limited to relatively small components. Ultrasound is a more practicable method and is well suited to determining and mapping local fibre orientation because its normal NDT range of wavelengths covers the resonant frequencies of most ply thicknesses and the achievable focal spot sizes are of the order of a fibre-tow width. Storage of the full-waveform ultrasonic response at each point in
the scan provides the necessary 3D profiling ability and has been achievable for at least two decades. During that period, methods have been explored for analysing the waveforms to determine localised responses from a particular depth in the structure (time in the waveform).

In 1994, Smith and Clarke [10] used multiple short time windows to isolate the response from each interface between plies, resulting in C-scan maps of the amplitude response at a certain depth (see Figure 1). These C-scans showed clearly the ply orientations present within each short time window; the undulations are now known to be due to variations in thickness of the inter-ply resin layers caused by the fibre tows in the plies above and below the interface.

Later work by Hsu et al [11] demonstrated the potential for automatically determining the dominant fibre angle from these images. This was extended by Smith et al [12] to map the ply stacking sequence as a function of depth to over 18 mm in thickness in material with 0.25 mm thick plies. An extension of this for mapping in-plane waviness is possible by choosing a small group of waveforms and a short time window. Thus a volume element can be examined for local in-plane fibre-tow orientation, $\gamma$.

This has been successfully mapped in three dimensions by Smith et al [12], as was the out-of-plane ply angles using a similar method but with B-scan slices through the 3D waveform data in two orthogonal directions. From these orthogonal sets of ply angles, $\alpha$ and $\beta$, it is possible to reconstruct the profile of the wrinkle at each ply in the structure [14] - see Figure 2 (left).

![Figure 1. Amplitude C-scans to determine ply stacking sequence [9] - courtesy of QinetiQ Ltd. These amplitude C-scans are from successively deeper short time windows, showing plies at nominal angles - left to right: 135°, 135°/45°, 45°/90°, 90°/0°/135°.](image1)

![Figure 2. Out-of-plane ply wrinkling mapping; Pseudo-3D reconstruction (left) [14]. Comparison with optical scanning of the specimen edge (right) [13] – courtesy of QinetiQ Ltd.](image2)
However, the integral calculus involved does not provide an absolute depth for a ply interface due to the lack of an integration constant, so an assumption of equally spaced plies in a non-wrinkled region is used. A comparison of optical measurements (at a cut edge of a specimen) and the above ultrasonic analysis of out-of-plane wrinkles has suggested a total angular measurement uncertainty [13] of: $\pm (2^\circ + 17\%)$ - see Figure 2 (right).

1.4 Failure mode modelling

In a related project, Mukhopadhyay et al [15] have modelled the failure mechanisms in wrinkled composites. Three failure mechanisms have been modelled: transverse matrix cracking, fibre kinking and delamination. Matrix fracture under transverse tensile or compressive stress or in-plane shear has been discussed widely in the literature and is illustrated in Figure 3 (left). The matrix cracking model is based on the work of Pinho et al [16] with an improved initiation criterion for transverse tensile loading based on Catalanotti et al [17] and some additional refinements. Fibre micro-buckling or kinking is a failure that occurs under axial compression of high fibre volume-fraction advanced composites and is also illustrated in Figure 3 (right). The shear stress acting on the fibres during compression causes any initial misalignment in fibre orientation to rotate further, leading to the localised formation of a highly strained zone called the kink band. The fibre kinking model is again based on the 3D model of Pinho et al [16]. Inter-ply failure or delamination was simulated using the 8-node cohesive elements COH3D8 already available in Abaqus [18]. However, a user-defined constitutive law for the traction-separation response was used, as described fully by Jiang et al [19].

Experimental coupons with artificially created wrinkles were tested to failure under tension and compression (eg. Figure 3) loading. High-speed photography showed delamination, intraply matrix cracking and fibre kinking to be key governing mechanisms leading to complete failure. Test results showed that the modelling approach successfully predicted the final failure loads and also location and interaction of different damage mechanisms. The models were found to be particularly suitable because the embedded wrinkle defect produced stress concentrations in the region of the wrinkle which triggered failure initiation. Hence no artificial low strength ‘seed-element’ or statistical distribution of strength throughout the material was necessary to realize localized damage growth. The study also highlighted the need for observation and identification of all the primary and secondary failure modes that lead to final failure of a structure containing a wrinkle defect, as opposed to only post-test visual inspection. The incorporation of different damage mechanisms in the numerical framework and accurately modelling of their interaction during damage propagation resulted in successful prediction of failure loads.

Figure 3. Two successive frames captured by high-speed camera just before final failure in a compression test [15], showing development of matrix crack and delamination (in red ellipse, left), and post failure fibre kinking in axial plies (in red ellipse, right). Maximum angle was approximately 11°.
1.4 The challenge ahead.

Whilst the importance of avoiding fibre waviness has been understood, the inability to detect or quantify it has resulted in the risk of its presence in test coupons and manufactured components being mitigated in design strategies, resulting in additional weight. Thus there is no need to detect wrinkles in existing components or for extant designs.

The main industrial pull for quantification of waviness comes from the desire to design leaner next-generation structures backed up by rigorous non-destructive characterisation (NDC). Thus, it is necessary to incorporate this NDC capability from the modelling and testing stages through the determination of design allowables and the planning of a new structural integrity philosophy suited to higher-strain lighter structures.

This paper presents a pathway to the use of this quantitative non-destructive 3D fibre orientation information in all these stages of the lifecycle, by using it to create models of actual structures including all the deviations from perfect fibre alignment. The first stage is to combine the in-plane and out-of-plane waviness maps in such a way that a finite-element mesh for a materials model can be generated. The second stage is to populate it the measured orientations of the orthotropic stiffness axes, followed by fibre volume fraction and porosity.

2 Fibre orientation vector maps

It is necessary to combine the out-of-plane (α and β) and in-plane (γ) measured fibre angles to achieve two useful results: firstly, the depth of each inter-ply interface, thus determining the out-of-plane wrinkling; secondly, the local 3D fibre orientations, represented by a vector map of unit vectors $F$. The tracking of ply interfaces by producing a 3D scalar volumetric data set is shown in Figure 4 for a 21-ply specimen with ply lay-up: [45°, 0°, -45°, 90°, -45°, 0°, 45°] containing both out-of-plane and in-plane waviness.

![Figure 4. A 3D scalar volumetric data set showing local fibre orientation on a colour scale where: Blue ~0°, Green ~45°, Red ~90° and White ~135°. Ply interfaces are at significant changes in colour. Note the aspect ratio shows out-of-plane distances with 10x magnification.](image)

The two out-of-plane angles (α and β) are sufficient to define the local plane of a ply and can be determined from the ultrasonic full-waveform data – see Figure 5. α and β can be used to describe two unit vectors $1$ and $2$ which lie in both this ‘ply’ plane and the y-z and x-z planes respectively.
Figure 5. Diagram showing the unit vectors 1 and 2 in the local ‘ply’ plane, shown as a plane with diagonal ‘fibre tow’ lines, and the unit vector 3, which is orthogonal to the ply.

A unit vector 3 is then determined as a cross product of 1 and 2 and is orthogonal to the ply.

\[
\mathbf{1} = \begin{pmatrix} \cos \alpha \\ 0 \\ \sin \alpha \end{pmatrix} \quad \mathbf{2} = \begin{pmatrix} 0 \\ \cos \beta \\ \sin \beta \end{pmatrix} \quad \mathbf{3} = \begin{pmatrix} -\sin \alpha \cos \beta \\ -\cos \alpha \sin \beta \\ \cos \alpha \cos \beta \end{pmatrix}
\] (1)

Finally, the in-plane fibre angle, \( \gamma \), is used to find a unit vector \( \mathbf{F} \), in line with the fibres.

\[
\mathbf{F} = \begin{pmatrix} \cos \theta_f \cos \gamma \\ \cos \theta_f \sin \gamma \\ \sin \theta_f \end{pmatrix}
\] (2)

where:

\[
\tan \theta_f = \cos \gamma \tan \alpha + \sin \gamma \tan \beta
\] (3)

The unit vector \( \mathbf{F} \), which represents the direction of the local fibre orientation, can be mapped in three dimensions as a vector field and then imaged using various methods including stream lines and tubes to represent the fibre tows. Figure 6 shows an example of stream tubes for the same specimen as Figure 4.

Figure 6. Vector field data for the unit vector field \( \mathbf{F} \) (parallel to the fibres) with fibre-tow ‘tubes’ illustrating the wrinkling and in-plane waviness in each ply. (a) 90°, (b) 0°, (c) 45° and (d) -45° plies are shown. Note the aspect ratio used exaggerates out-of-plane distances with 10x magnification.
### 3 Materials modelling

An Abaqus [18] finite-element mesh was generated in MATLAB from the 3D vector field described above (Figure 6), as a list of elements, each one specified by eight nodes or vertices (see Figure 7). The eight vertices follow the wrinkling of the interfaces above and below a ply. The cell height is therefore one ply thickness whilst the width and length are equal to the original ultrasonic scan pitch; this is also the pitch of the vector field. The vector field of fibre orientation is sufficient to populate each element of the model with the orthotropic stiffness axes appropriate for fibre-reinforced composite (see example in Figure 8).

![Figure 7. FE element definition using eight nodes (left) and combined into an example mesh (right). Note the aspect ratio used here shows out-of-plane distances (z) with approximately x10 magnification.](image)

Figure 8. A portion of the FE mesh populated with stiffness axes based on the vector field of fibre orientation generated from ultrasonic data (Figure 6). The blue axis in each element is vector $F$ the fibre direction.

An example of the mesh generated from a portion of the vector field (Figure 6) is shown in Figure 9(a). The stress maps, $S_{11}$ and $S_{33}$, as a result of tensile strain in the x-direction ($0^\circ$) are shown in Figure 9(b) and Figure 9(c) respectively. The $S_{11}$ stresses (parallel to the load in the $0^\circ$ direction) show how the $0^\circ$ fibres produce the highest stiffness (stress per unit strain), whilst the lowest stiffness is in the $90^\circ$ ply. The maximum $S_{33}$ stress (parallel to the laminate through-thickness axis) is expected at a wrinkle but this real component contained a complex combination of both out-of-plane and in-plane fibre waviness and the resulting stress field is complicated and difficult to evaluate. For this reason, it was necessary to develop a simulation capability, allowing the systematic study and validation of the modelling process.

![Figure 9. Stress maps showing tensile strain in the x-direction ($0^\circ$).](image)
Simulated ply wrinkling and fibre waviness

The main aim of the current project is to demonstrate the complete route from 3D non-destructive characterisation through materials modelling to the determination of the predicted performance of as-manufactured structures including any out-of-plane ply wrinkling or in-plane fibre waviness. In order to test and evaluate each part of that process systematically it is important to be able to simulate the data inputs of each stage. To this end, a simulator has been developed in MATLAB to create the 3D data sets that could be generated from the ultrasonic data – ply surface-height maps and in-plane fibre-orientation maps (Figure 10). This is for insertion at the stage represented by Figure 4 – the determination of the fibre-tow vector map. This can then be used to test the next two stages – the conversion to Abaqus [18] input files for the mesh and the stiffness axes orientations, and then the modelling of the structural performance under load (Figure 11).

Figure 10. A MATLAB simulator creates files necessary for modelling of controlled wrinkled and wavy laminates.
The results of running the model are shown in Figure 11 and provide confidence that the model is satisfactorily predicting the response of the structure to induced strains. The largest $S_{11}$ stresses (ie parallel to the load in the $0^\circ$ direction) are shown to be in the $0^\circ$ plies, as expected, and especially in the double ply in the centre. The through-thickness stress, $S_{33}$, which is red for tensile and blue for compressive stresses, is greatest in the region of the wrinkle and it is this stress (when combined with through-thickness shear stress) that is most likely to cause failure. Also, the tensile strain has caused the wrinkle to straighten, resulting in a dip in the top surface (bottom-left) and a bulge in the bottom surface (top-right). Stress concentrations on the far right of the image can be ignored due to application of the model boundary conditions.

5 Conclusions

This paper summarises progress on the use of 3D non-destructive characterisation information to specify finite-element meshes and populate models of composites with stiffness axes and fibre volume fraction. The various stages of the process have, until recently, progressed independently but this work is bringing them together to demonstrate the benefits for prediction of mechanical performance of wrinkled composites, based on actual measured waviness. Ultrasonic full-waveform data has been used to generate out-of-plane ply-orientation and in-plane fibre-orientation information, which has then been converted into a vector field mapping the 3D fibre direction throughout a specimen. X-ray CT data could similarly be used. This vector field has then been analysed to create a finite-element mesh that matches the out-of-plane wrinkling with one element depth per ply. The vector field of fibre orientations was then used to populate each element with the measured stiffness axis orientations. The model was run with an increasing tensile strain in the zero-degree direction and maximum through-thickness tensile stresses were predicted by the model at the wrinkle location. In order to better understand the results from complex real specimens with both in-plane and out-of-plane wrinkling, a simulator has been developed. This creates vector maps of fibre orientation using known values of wrinkling parameters such as amplitude, wavelength and Gaussian-envelope functions. This has been shown to provide a level of confidence in the modelling stage for out-of-plane wrinkling, but in-plane waviness can also be studied.

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