Applications of ultrasonic NDT to aerospace composites

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Abstract
Whilst existing composite aircraft designs carry additional weight to mitigate the risk of undetected non-conformance to design, new non-destructive characterisation (NDC) methods offer a leaner future for composite designs through complete verification of conformance. The structural-integrity philosophy for composites in current in-service aircraft does not directly accommodate any benefit from these new methods. Allowable strains are kept so low that non-visible defects will not grow and design life is not compromised. Hence the way forward to new lighter designs with greater allowable strains must include not just advanced 3D characterisation at manufacture but also a new structural-integrity philosophy including improved in-service non-destructive testing (NDT). The challenge for the aerospace industry is to make available all of these advances in readiness for the next generation of composite aircraft and give designers the confidence to design for their use.

In this paper, suitable 3D NDC methods will be presented together with manufacturing usage strategies such as 3D modelling of the mechanical performance of the as-built structure. Potential new in-service inspection methods will be reviewed and requirements for a new structural integrity philosophy will be presented.

Keywords: Ultrasound, non-destructive characterisation, aerospace, carbon fibre composite.

1. Introduction

The use of composite materials in primary aircraft structure has moved ahead faster in the past 30 years than the development of the desirable non-destructive characterisation (NDC) techniques. Ultrasonic C-scanning to detect gross manufacturing defects or give an estimate of through-thickness average porosity has been routinely applied but little knowledge of the conformance to design at a ply, or fibre-tow, level has been obtainable. The result has been non-optimised composite structures carrying additional weight to achieve the required certification. This paper presents a possible route to justifying leaner composite designs through improved NDC at manufacture and rapid accidental-damage detection in-service.

1.1 Structural integrity background

The risk posed by inadequately characterised components has been largely mitigated by designing in additional weight, thus increasing the tolerance to damage until the maximum allowable strain will not cause damage to grow unless it is clearly visible to the naked eye and therefore easily detectable. Thus the issues of damage growth under fatigue or detection of invisible damage have largely been neglected. Unfortunately 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 would 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 and design life. For military aircraft, an issue has been the lack of information on the ground about the original (often classified) structural design, such as ply lay-up, to allow the optimised design of a repair patch. Characterisation of the original structure, the damage itself, conformance to design of the repair patch, and bond integrity are 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 [1] 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 [2]-[3]. Budiansky [4] 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 this is indicative of where failure will occur [5]. The extent of the deviation from straightness or designed orientation needs to be carefully determined and compared with an allowable deviation based on modelling and experimental validation.

Literature studies show that teams have modelled the dependence of performance on wrinkling. Some issues with validating these models experimentally are: 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. Caiazzo et al [6] 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, $\xi(x)$

A workshop was run on the NDT of ply wrinkling by the British Institute of NDT in 2010 and the question of NDT ability to measure wrinkles was considered, along with the state of the art in modelling of mechanical performance of composites. 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).

More recent work by the authors has confirmed that curvature of fibres in the load direction is an indicator of stress concentrations and this suggests that curvature should also be mapped.

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 thing 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 cell 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 cannot be specific about where in the thickness of the structure each orientation exists. Ultrasound is an ideal method for determining and mapping local fibre orientation because its range of wavelengths covers most ply spacings 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 [7] used multiple short time windows to isolate the response from
each particular 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.

Later work by Hsu et al [8] demonstrated the potential for automatically determining the
dominant fibre angle from these images. This was extended by Smith et al [9] 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 – see Figure 2.

This has been successfully mapped in three dimensions by Smith et al, as was the out-of-
plane ply angles using a similar method but with B-scan slices through the 3D waveform data
[9] in two orthogonal directions, such as shown in Figure 3.
From these two orthogonal sets of ply angles (α and β), it is possible to reconstruct the profile of the wrinkle at each ply in the structure – see Figure 4. However, the integral calculus involved does not provide an absolute depth for a ply interface due to the inability to calculate an absolute integration constant. It is probably sufficient to assume equally spaced plied in a non-wrinkled region. Evaluation versions of the software – known as 3D-Validator – have been provided to composite aircraft manufacturers by the developers at QinetiQ Ltd in order to demonstrate the potential of this technology.

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 [12] of: ± (2º + 17%).

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 its possible presence in test samples and manufactured
components being strategically allowed for in design strategies, resulting in additional weight. Thus there is no need to detect wrinkles in components where this strategy has been employed and so there is no requirement 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. A subsidiary requirement is for the design and characterisation of bonded composite patch repairs to ensure restoration of the design life. This could be just as relevant for in-service aircraft of the heavier designs currently in use.

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 with the measured orientations of the orthotropic stiffness axes, followed by fibre volume fraction.

2. COMBINED IN-PLANE AND OUT-OF-PLANE WAVINESS

2.1 Methodology

It is necessary to combine the out-of-plane ($\alpha$ and $\beta$) and in-plane ($\gamma$) measured fibre angles to achieve two useful results. Firstly, the depth of each inter-ply interface, where the fibre angle changes significantly at the transition between two plies, must be determined. These transitions can then be tracked throughout the data to determine the out-of-plane wrinkling of the plies. Secondly, the local 3D fibre orientation, represented by a unit vector $\mathbf{F}$ must be mapped at each point in the specimen.

The tracking of ply interfaces by producing a 3D scalar volumetric data set is shown in Figure 5 for a 19-ply specimen containing both out-of-plane and in-plane waviness.

![Figure 5. 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 ($\alpha$ and $\beta$) are sufficient to define the local plane of a ply and can be determined from the ultrasonic full-waveform data – see Figure 6.
\( \alpha \) and \( \beta \) can be used to describe two unit vectors \( \mathbf{1} \) and \( \mathbf{2} \) which lie in both this ‘ply’ plane and the y-z and x-z planes respectively.

\[
\begin{align*}
\mathbf{1} &= \begin{pmatrix} \cos \alpha \\ 0 \\ \sin \alpha \end{pmatrix} & \mathbf{2} &= \begin{pmatrix} 0 \\ \cos \beta \\ \sin \beta \end{pmatrix}
\end{align*}
\]  \hspace{1cm} (1)

A unit vector \( \mathbf{3} \) is then determined as a cross product of \( \mathbf{1} \) and \( \mathbf{2} \) and is orthogonal to the ply.

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

Finally, the in-plane fibre angle, \( \gamma \), is used to find a unit vector \( \mathbf{1}' \), which is in line with the fibres, and, using a cross product with \( \mathbf{3} \), a unit vector \( \mathbf{2}' \), which is perpendicular to the fibres but in the plane of the ply.

\[
\mathbf{1}' = \begin{pmatrix} \cos \theta_f \cos \gamma \\ \cos \theta_f \sin \gamma \\ \sin \theta_f \end{pmatrix}
\]  \hspace{1cm} (3)

where:

\[
\tan \theta_f = \cos \gamma \tan \alpha + \sin \gamma \tan \beta
\]  \hspace{1cm} (4)
Figure 7. Diagram showing the unit vectors $1'$ (parallel to the fibres) and $2'$ (orthogonal to the fibres) in the local 'ply' plane, shown as a plane with diagonal 'fibre tow' lines. The fibre direction is represented by unit vector $F$, which must lie in the ply plane.

2.2 Vector Maps

The unit vector $1'$, 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 8 shows an example of stream tubes for the same specimen as Figure 5.
Figure 8. Vector field data for the unit vector field $1'$ (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) 135° plies are shown. Note the aspect ratio used exaggerates out-of-plane distances with 10x magnification.

2.3 Fibre Volume Fraction

Finally, the local fibre volume fraction could be applied to refine the cell properties. Local ply thickness has been used to infer local fibre volume fraction given an assumption that fibres do not move laterally in a ply [10]. However, in the presence of in-plane waviness as well, such as in the example used in Figure 8, it would be necessary to allow for three-dimensional fibre movement. In essence, the vector field described above contains all the information required to determine local fibre volume fraction trends. This is similar to determining local volumetric flux in a fluid-flow model but with fibres instead of streamlines. An appropriate analogy can be drawn with a compressible fluid where its motion is governed by a velocity vector field. The fluid density can then be related to the fibre volume fraction $\psi$ and fluid velocity to the fibre-orientation unit vectors $\mathbf{F}$. For a steady (time-invariant) flow, advective flux of a conserved quantity can be expressed as:

$$\nabla \cdot (\psi \mathbf{F}) = 0$$  \hspace{1cm} (5)

The vector field $\mathbf{F}$ is given, and a method can be constructed based on artificial compressibility to determine $\psi$ from the divergence: $\nabla \cdot \mathbf{F}$. Equation (5) is applied as an ‘elastic’ constraint by solving a Poisson equation:

$$\nabla^2 \Phi = \nabla \cdot \mathbf{F}$$  \hspace{1cm} (6)

where $\Phi$ is a Lagrange multiplier on the constraint (5), and in our fluid analogy this plays the role of pressure. One could proceed to modify the vector field $\mathbf{F}$ according to:

$$\frac{d\mathbf{F}}{dt} = -\nabla \Phi,$$  \hspace{1cm} (7)

ie.,

$$\mathbf{F}_1 = \mathbf{F}_0 + \nabla \Phi dt,$$  \hspace{1cm} (8)

to restore the constraint (5) on $\mathbf{F}$ progressively over some notional time $dt$. However, here the artificial compressibility model is used to infer a constitutive relation between fluid pressure and fibre volume fraction $\psi$ at any point, which can be described in general simply as:

$$\psi = f(\Phi).$$  \hspace{1cm} (9)

Given a known or nominal fibre volume fraction at some location, suitable boundary conditions can be imposed on $\Phi$ and the Poisson equation solved to obtain the fibre volume fraction throughout the interior.
3. MATERIALS MODELLING

3.1 Finite-element mesh generation

The mesh was generated in MATLAB from the 3D vector field described above, as a list of cells, each one specified as eight vertices (see Figure 9). 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.

An example of the mesh generated from the vector field shown in Figure 8 is given in Figure 10.

Figure 9. FE cell definition using eight vertices (left) and combined into an example mesh (right). Note the aspect ratio used here shows out-of-plane distances (z) with approximately x10 magnification.

Figure 10. FE mesh generated for the vector field shown in Figure 8. Note the unity aspect ratio showing realistic cell dimensions of approximately 0.4 x 0.4 x 0.125 mm.

3.2 Population with local stiffness axes

The vector field of fibre orientation is sufficient to populate each cell of the model with the orthotropic stiffness axes appropriate for fibre-reinforced composite. An example of this is shown in Figure 11.
3.3 Population with fibre volume fraction

The actual stiffness in each of the stiffness axes will be dependent on the stiffness of fibre and matrix and the local fibre volume fraction. The above discussion about generating a map of fibre volume fraction from the vector field of fibre orientation will be key to being able to populate the model with the appropriate stiffness values for each cell. However, there will be other defects that affect fibre volume fraction such as gaps between tapes and tows caused during tape or fibre placement. The ideal situation would be a non-destructive measurement of fibre volume fraction directly, but that is not possible at present. When the map of fibre volume fraction has been generated, a property of the cells can be populated which can then be used to determine the correct stiffness along each axis using mixture rules for anisotropic media.

3.4 Failure mode modelling

Starting prior to this work was a project by Mukhopadhyay et al [11] to model 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 12 (left). The matrix cracking model is based on the work of Pinho et al [12] with an improved initiation criterion for transverse tensile loading based on Catalanotti et al [13] 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 12 (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 (Figure 5a). The fibre kinking model is again based on the 3D model of Pinho et al [12]. Inter-ply failure or delamination was simulated using the 8-node cohesive elements COH3D8 already available in Abaqus [14]. However, a user-defined constitutive law for the traction-separation response was used, as described fully by Jiang et al [15].

Experimental coupons with artificially created wrinkles were tested to failure under tension and compression (eg. Figure 12) loading. High-speed photography showed delamination, intra-ply 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.
4. CONCLUSIONS

This paper gives a summary of progress on the use of 3D ultrasonic 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. This vector field has then been used to create a finite-element mesh that matches the out-of-plane wrinkling with one cell depth per ply. The vector field of fibre orientations was then used to populate each cell with the measured stiffness axis orientations. Finally, the fibre volume fraction needs to be added to the cell properties and this should be calculable from the vector field using an advection analogy.

ACKNOWLEDGEMENTS

The authors acknowledge the support of the Engineering and Physical Sciences Research Council for funding Prof. Smith’s Fellowship in Manufacturing: ‘NDT for High Value Manufacturing of Composites’, also QinetiQ Ltd for making available the information and images for the introduction to this paper, and the Brazilian government for funding the undergraduate research project of Guilherme Roldo at the University of Bristol – Guilherme contributed to the combination of FE modelling with DT information.

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