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Mesh morphing methodology for strength predictions in composites

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ABSTRACT

This work presents a methodology based on mesh morphing techniques for transfer of high-fidelity X-ray computed tomography (CT) data, including manufacturing defects information, into finite element (FE) models for failure prognosis in composite structures. An IM7/8552 carbon/epoxy hat-section element with complex layup is considered. Failure initiates at the location of seeded defects, including in-plane and out-of-plane fiber waviness, representative of irregularities that could occur during manufacturing of composite parts with complex layup and geometry. The ability of the method to efficiently transition high fidelity CT data into structural models for assessment of the effects of manufacturing defects is essential for condition-based structural substantiation. Stress-based failure criteria are considered for prediction of matrix-dominated failure under quasi-static loading. FE results are compared with experimental data, including correlation with CT-based post-failure damage information.

1. Introduction

Progress in computer hardware and simulation software have led to a growing interest in using three-dimensional (3D) finite element (FE) models for predictions of failure in composites. Stress-based failure criteria that consider specific failure mechanisms and can include contribution of stresses in all principal material planes, such as the set of LaRC criteria [1], have achieved wide acceptance for FE-based prediction of failure initiation in multidirectional composite laminates. Development of characterization methods for assessment of 3D material constitutive properties of composite materials also seems on the right track. New methods based on full-field measurements of deformation [2,3] enable better understanding of the complex deformation of composite materials all the way till material failure; and can serve as the basis for the development of three-dimensional FE models used in stress-based failure analysis. Combination of accurate 3D material properties with physics-based failure criteria has been successfully used for strength and fatigue life predictions in test specimens at the coupon scale [4–7], increasing confidence in the development of FE-based virtual test methods [8]. Along with these developments, advanced methods for non-destructive inspection (NDI) of composite structures have also seen major improvements. Emerging 3D imaging techniques, such as high-resolution X-ray computed tomography (CT), have demonstrated their unique ability to accurately detect and quantify critical subsurface irregularities, such as voids [9], waviness [10,11], and service damage [12,13] in composites. It has become apparent that fidelity of NDI needed to quantify manufacturing defects and damage in composites is extremely important. Recent works have shown that residual structural performance can be largely impacted by the size, location and three-dimensional geometry of critical individual irregularities in the material [9,14].

While significant progress has been made in the respective areas of failure predictions, integrating 3D material characterization and NDI of composites at the coupon scale, such integration into a comprehensive methodology applicable to failure prognosis of composite structures has yet to be developed. Significant improvement of the capabilities of industrial CT scanners as well as ongoing development of new methods for 3D volume reconstruction, such as limited angle X-ray computed tomography [15], increase the confidence in the ability to break through the current limits of X-ray CT and enable high-fidelity NDI of larger composite structures. Once the condition of a fabricated part is known and material constitutive properties are fully understood, a fundamental shift from statistics-based to condition-based structural substantiation could be achieved. Such transition could significantly lower the cost and increase the efficiency of composite parts qualification through reduced testing and increased reliance on analysis methods [16].

The objective of this work is to contribute to the development of such an integrated approach to composite structural substantiation and propose a methodology that combines high fidelity X-ray CT measurements with 3D stress-based FE analysis for strength evaluation in a complex composite structural element in

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presence of manufacturing defects. One of the key challenges to the methodology is the transfer of high fidelity NDI information, including defect geometry and features, into a numerical FE model suitable for stress-based failure analysis. Due to the large amount of data produced by CT reconstructions, generating a 3D FE mesh from voxel-based CT data may require a lot of manual effort and can be extremely time consuming. To overcome this limitation, automatic or semi-automatic methods for CT-based mesh generation have been developed, particularly in the medical field, with an overview of current methods proposed in Ref. [17]. However, these methods typically generate unstructured meshes or meshes with uniform element size, resulting in an extremely large total number of elements necessary to achieve accurate stress calculation in critical areas. Another limitation resides in the methods used for automatic model segmentation. For instance, ply interface partitioning is normally required for failure predictions in laminated composites using 3D FE models and physics-based failure criteria. Most automatic segmentation methods for medical applications are based on material density, which is related to voxel intensity metrics in the CT data. Such segmentation methods fail to partition laboratory CT-generated models of carbon/epoxy composite structures at ply interfaces, since the difference in density between plies and resin-rich regions at the interface is typically very low or not well defined.

This work presents a semi-automatic method based on mesh morphing techniques for transfer of CT data, which includes manufacturing defect information, into a local FE model of the composite structure. Mesh morphing has been extensively used in computer graphics and animation techniques where the primary problem was in identification of a smooth or natural-looking transformation between the source and final shapes [18]. Other examples of using mesh morphing techniques are probabilistic analysis of design variables for durability of aerospace structures [19] and in X-ray CT-based finite element analysis for medical applications [20,21] where morphing techniques were used to rapidly create patient-specific structural models of skeleton. Mesh morphing was also recently used in Ref. [22] by the authors to generate CT-based local FE models for static and fatigue failure predictions in a rectangular-section laminated carbon/epoxy element including void and out-of-plane waviness defects. The major advantage of mesh morphing over other methods used for CT-based FE mesh generation is that the construction of a ply-segmented structured FE mesh is straightforward, even for complex geometries. In this work, a more complex IM7/8552 carbon/epoxy hat-sectioned laminated element is considered and both in-plane and out-of-plane manufacturing-induced fiber waviness defects are modeled. Multiple failure mechanisms are considered for static strength predictions based on modified LaRC04 failure criteria [1,7]. FE results are compared with experimental data, including correlation between FE contour plots of failure indexes and CT-based post-failure damage information.

2. Specimen and test description

A 762 × 165 × 45 mm (30 × 6.5 × 1.8 in.) hat-section element was manufactured by Bell Helicopter Textron from Hexcel IM7-carbon/8552-epoxy prepreg material cured in an autoclave at 350 °F per prepreg manufacturer's specifications [23]. Such specimen is representative of a stiffened component used in structural designs for aerospace applications. Fig. 1 shows details on the geometry and ply layup of the element cross section.

Fig. 2 shows a custom four-point bend test fixture which has been used in a servo–hydraulic load frame at a constant 1.27 mm/min (0.05 in./min) crosshead displacement rate until failure. The bottom and top supports lengths were 600 mm and 229 mm (23.625 in. and 9.0 in.), respectively. As illustrated on Fig. 2, glass/epoxy tabs at the bottom supports and fillet edges around all contact surfaces of the top supports were used to prevent crushing and indentation failure at the supports.

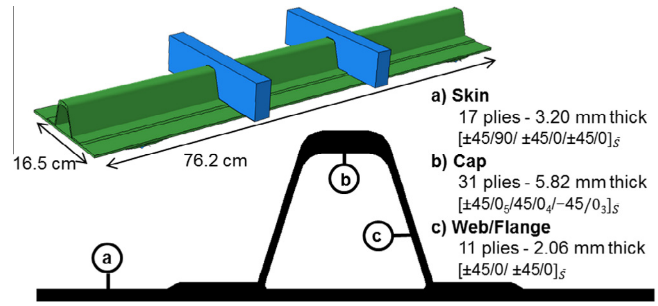

Fig. 1. A 76.2 cm long IM7/8552 specimen with hat-stiffened cross section.

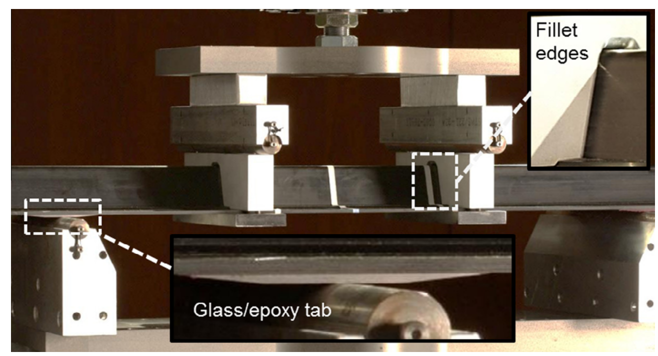

Fig. 2. Experimental set-up with four-point bend custom test fixture.

Fig. 3 shows seeded flaws, representative of fiber-waviness manufacturing defects in composite structures, in the cap section at element mid-length. The maximum defect dimension in the laminate thickness direction is approximately 1.4 mm (0.04 in.), which represents about 25% of the cap thickness. In-plane characteristic defect dimensions are approximately 20 × 10 mm (0.8 × 0.4 in.) in the longitudinal and transverse directions, respectively.

The load–displacement data was recorded until specimen failure. Failure initiation occurred at 35.8 kN (8050 lbs), with an apparent drop in the load–displacement curve. It is worth noting that no external damage was visible after the initial load drop. However, post-failure CT-scans of the specimen revealed significant sub-surface damage. CT scans were performed using a 225 kV-capable microfocus X-ray CT system manufactured by North Star Imaging. A 50 kV tube voltage was used with 500 μA target current and 0.9 frame per second (fps) speed for an average of three frames per angle increment and 9.6× magnification. North Star Imaging efX-CT software was used for 3D reconstruction of the scanned volume with a pixel resolution of approximately 13 μm (5×10^{-4} in.). Fig. 4 illustrates the post-failure reconstructed volume with 2D CT slices taken along the axial direction in the cross-sectional plane showing details of the damage in the defect area. Multiple delaminations and matrix cracks can be observed. It is worth noting that the sub-surface structural damage did not expand beyond the vicinity of the defect area. The element mid-length section exhibits a global compression state due to bending in the four-point bend test fixture. Failure is initiated by local stress gradients, including in-plane shear stress due to in-plane fiber misalignment, and interlaminar shear and tensile stresses due to out-of-plane ply waviness.