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Dynamic micromechanical modeling of textile composite strength under impact and multi-axial loading

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ABSTRACT

Micromechanical finite element modeling has been employed to define the failure behavior of S2 glass/BMI textile composite materials under impact loading. Dynamic explicit analysis of a representative volume element (RVE) has been performed to explore dynamic behavior and failure modes including strain rate effects, damage localization, and impedance mismatch effects. For accurate reflection of strain rate effects, differences between an applied nominal strain rate across a representative volume element (RVE) and the true realized local strain rates in regions of failure are investigated. To this end, contour plots of strain rate, as well as classical stress contours, are developed during progressive failure. Using a previously developed cohesive element failure model, interfacial failure between tow and matrix phases is considered, as well as classical failure modes such as fiber breakage and matrix microcracking. In-plane compressive and tensile loading have been investigated, including multi-axial loading cases. Highly refined meshes have been employed to ensure convergence and accuracy in such load cases which exhibit large stress gradients across the textile RVE. The effect of strain rate and phase interfacial strength have been included to develop macro-level material failure envelopes for a 2D plain weave and 3D orthogonal microgeometry.

1. Introduction

For inhomogeneous materials such as woven and textile composites with relatively complex microgeometries, finite element micromechanical analysis tools can be employed in highly detailed simulations of material failure behaviors. Investigation of non-uniform through-volume stress distributions and subsequent micromechanical failure analyses can shed great insights which can be used to optimize or tailor the mechanical response of a material system. In dynamic loading cases, further complexities arise due to non-periodicity of loading, material rate effects, as well as impedance mismatching of stress wave propagation. Failure modeling must account for dynamic loading effects and consideration of multiple failure modes to accurately simulate structural or impact mechanical performance.

Two-dimensional (2D) and three-dimensional (3D) textile composites can offer advantages over laminated composites and often greatly alleviate the delamination failure mode, especially in the case of thick-section composites. Such microgeometries are of critical importance to delamination resistance, an otherwise common weak point of thick composite structures. The out-of-plane undulation of a 2D or the direct through-thickness tows of a 3D woven composite both provide delamination resistance and generally increase through-thickness properties [1,2]. However, there is an unavoidable trade-off, as this also leads to loss of in-plane properties, as the weaving leads to interruption of in-plane fiber tows less in-plane aligned reinforcement.

The increased microstructural complexity of textile composites also leads to increased complexity of characterization and analysis, as well as a need for non-traditional analysis methods. Composite laminate theories and simple approximations will no longer apply. An accurate model must accommodate the fact that 3D woven composites exhibit multiple potential failure mechanisms [3], which depend upon the loading conditions and particulars of the layup and materials. 3D weaves show improved damage resistance, as well as more capacity to absorb multiple strikes before perforation and show less damage localization [4] in comparison to 2D weaves. This can be of particular interest in armor applications, and related modeling has addressed issues surrounding the computational needs required to reflect the energy absorption modes and damage progression [5].

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Textile composite structures are often designed based upon traditional well-known phenomenological failure criterion, such as the maximum stress criterion, maximum strain criterion, and quadratic interaction criterion such as the Tsai-Hill and Tsai-Wu failure theories [6,7]. Other failure theories for orthotropic composites include the strain invariant failure theory (SIFT) [8,9] and failure mode concept (FMC) [10] approach.

Dedicated analysis of 2D and 3D textile composites has been effectively approached before [11–15], but strength prediction is still a topic of current research and ongoing development. FEM micromechanical methods for strength modeling of textile composites have been explored in previous works by the authors [16–18]. Therein, it was shown that many common assumptions and traditional micromechanical analysis techniques break down, due to the size and complexity of a textile representative volume element (RVE) in comparison to a unidirectional composite RVE, thus improvements to these techniques have been presented. Further work developed additional consideration of interface failure effects [19] such as tow pullout, and extension of these efforts into the dynamic regime [20].

The current work involves application of FEM micromechanics to 3D orthogonal weave and 2D plain weave textile architectures to provide detailed strength analysis for failure prediction. Loading cases and failure envelopes developed in Ref. [20] have been expanded to include some multi-axial cases. Further, a great deal of scrutiny has been applied to investigate differences between the applied nominal strain-rate actuated through boundary conditions and the local strain rates calculated (by rate of deformation tensor within a finite element formulation) within an RVE in an inherently inhomogeneous response. Explicit dynamic finite element modeling has been employed to investigate failure of 2D and 3D textile composite RVEs. Parametric investigation includes: 2D plain weave vs. 3D orthogonal textile microgeometry, two different loading rates (1000 and 10,000 strain/s), and both tensile and compressive loading, including some multi-axial cases.

2. Methods

2.1. Textile composite RVE formulation and analysis

A representative volume element (RVE) is the smallest geometrical unit which represents the textile microstructure when arrayed or repeated, and the analysis of which can accurately determine the material continuum behavior. Figs. 1 and 2 depict both a 2D plain weave and 3D orthogonal RVE as implemented into a finite element mesh. Corresponding dimensions and material properties are listed in Table 1 through 4.

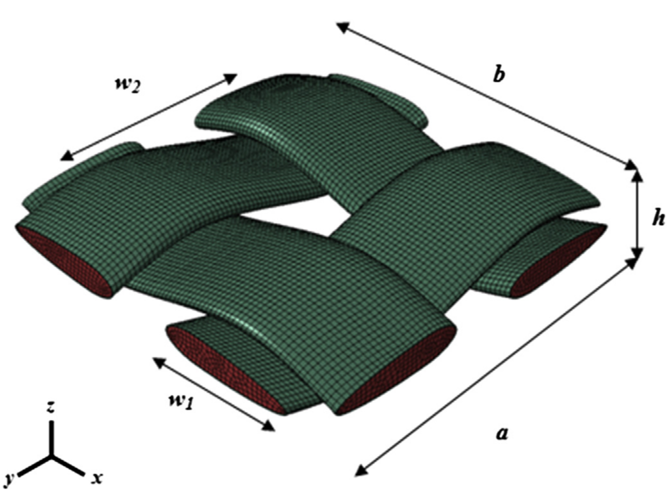

Fig. 1. Representative volume element for a 2D plain weave composite.

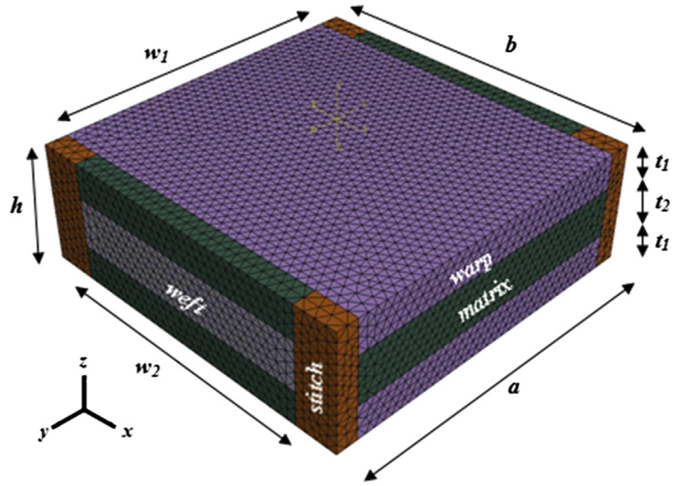

Fig. 2. Representative volume element for a 3D orthogonal woven composite.

Effort was taken to investigate RVE geometries with some reasonable parity of dimensions. Note that the fiber tows themselves have a roughly 65% volume fraction and thus total volume fraction is less than 50% given that interstitial matrix is present between tows. In the case of the plain weave tow which exhibits some out of plane undulation (around 13.5° from horizontal at maximum), material properties are assigned to multiple local coordinate systems which follow the undulation angle.

To implement the interface failure model, each fiber tow has been surrounded with cohesive elements which essentially comprise a "sleeve" that binds the tow phase to the interstitial matrix. The 2D plain weave mesh (Fig. 2) consists of 248,351 total elements. Of these 43,813 are linear hexahedral elements of type C3D8R which comprise the fiber tows, while 186,212 linear tetrahedral elements represent the matrix (the meshed region is sufficiently complex that meshing algorithms require tetra elements) region, and 18,326 cohesive COH3D8 elements are used for the interface regions. A cohesive element is not indifferently symmetric and must be oriented such that its integration points lie along the bondline, thus defining inward and outward normals to the potentially debonded surface. Failure to do so will result in very inaccurate results. Note that for the 2D plain weave geometry, automatic meshing routines were not adequate to proper definition of the cohesive mesh regions without significant time consuming user adjustments. These meshing issues were not present in the case of the 3D orthogonal mesh, which was geometrically simpler (orthogonal, symmetric, non-undulating) in composition. The 3D orthogonal mesh consists of 221,190 total elements. Of these 38,406 are COH3D8 cohesive elements representing the interfaces, and 182,784 are C3D8R elements representing the fiber tows and interstitial matrix regions. Mesh density was chosen to be comprehensively dense for proper representation of inhomogeneous distributions and gradients in stress, strain, and strain rate.

Table 1
Plain weave RVE dimensions (mm).

Dimension	a	b	h	w_1	w_2
Description	RVE width	RVE depth	RVE height	tow width	tow spacing
Value (mm)	6.0	6.0	1.38	2.11	4.60