Fast two-scale computational model for progressive damage analysis of fiber reinforced composites

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1 Introduction

Micromechanics based failure analysis of composite structures is a competent tool to model damage progression as it can effectively capture explicit variation in constituent properties along with their non-linearities [1]. The paper presents a fast two-scale finite element framework based on a class of refined finite beam models called Carrera Unified Formulation (CUF) [2]. The energy based crack band theory (CBT) is implemented within framework to predict the damage propagation in individual constituents [3, 4, 5]. The efficiency of the framework is derived from the ability of CUF models to provide accurate three-dimensional displacement and stress fields at a reduced computational cost (approximately one order of magnitude of degrees of freedom less as compared to standard 3D brick elements).

2 Carrera Unified Formulation

Carrera Unified Formulation (CUF) expresses the displacement field as an expansion of generic cross-section functions, $F_\tau(x,z)$ with the displacement, $\mathbf{u}_\tau(y)$,

$$\mathbf{u}(x,y,z,t) = F_\tau(x,z)\mathbf{u}_\tau(y,t) \quad \tau = 1,2,.,T$$

where T is the number of terms in cross-section expansion function F_τ [2]. In this work, 1D CUF models based on Lagrange Expansion (LE) functions are utilized. Bi-quadratic nine-noded L9 Lagrange elements are used to model the cross-section. The displacement field within an L9 element can be expressed as

$$\begin{aligned} u_x &= F_1 u_{x_1} + F_2 u_{x_2} + ... + F_9 u_{x_9} \\ u_y &= F_1 u_{y_1} + F_2 u_{y_2} + ... + F_9 u_{y_9} \\ u_z &= F_1 u_{z_1} + F_2 u_{z_2} + ... + F_9 u_{z_9} \end{aligned}$$

where $u_{x_1}, ..., u_{x_9}$ represent the translational displacement component of each of the nine nodes in the L9 element. The beam is discretized using the classical finite element technique. Therefore, the displacement vector can be expressed as

$$\mathbf{u}(x,y,z) = F_\tau(x,z)N_i(y)\mathbf{u}_{\tau i}$$

where N_i stands for the FE shape function, F_τ for the cross-section expansion function.

Component-Wise (CW) approach is an efficient and powerful tool which allows to model each component in an complex structure via 1D CUF LE models by enriching the kinematic field [6, 7]. In this work, CW approach is utilized to model the sub-scale representative volume element (RVE) of a uni-directional fiber-reinforced composite as illustrated in Figure 1. With CW approach, the RVE can be discretized into any number of L9 elements with individual constitutive properties (eg.: fiber and matrix). Periodic boundary conditions are applied for the displacement unknowns along the outer faces of the RVE. CUF RVE models

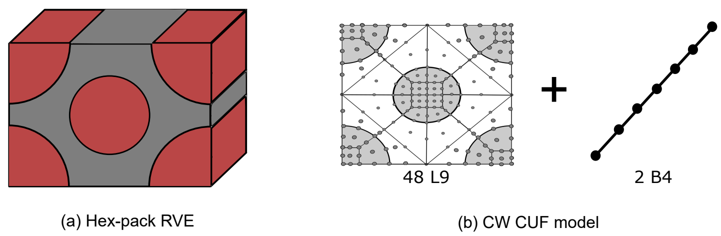

Fig. 1: CW modeling of a hex-pack RVE

are able to compute local stress concentrations at the micoscale with great computational accuracy as illustrated in Fig. 2. The local strain and stress fields are computed using the local constitutive laws and the overall stiffness, strain and stress field is obtained by volume averaging the quantities over the RVE dimensions. Fiber is assumed to be linearly isotropic and brittle. Therefore, a maximum longitudinal stress criteria is used and upon satisfaction the stiffness is reduced to zero. Matrix is assumed to be isotropic and maximum principal stress criteria is used as failure envelope. Upon damage initiation, matrix stiffness degrades linearly based on crack band model [3, 4]. The algorithm for the damage degradation is illustrated in Fig. 4.

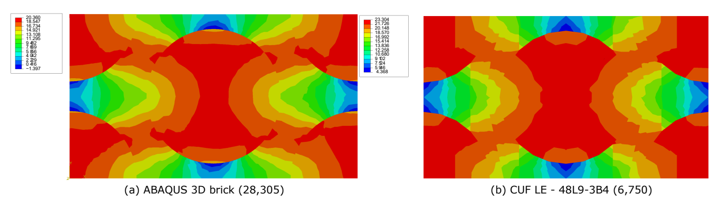

Fig. 2: Transverse stress contour (σ_{xx}) for hex-pack RVE under transverse strain (ϵ_{xx}) (Number of degrees of freedom is mentioned in brackets)

3 Two-scale framework

The two-scale framework consists of a macro-level model to define the structural-level components via ABAQUS, interfaced with a sub-scale model at fiber-

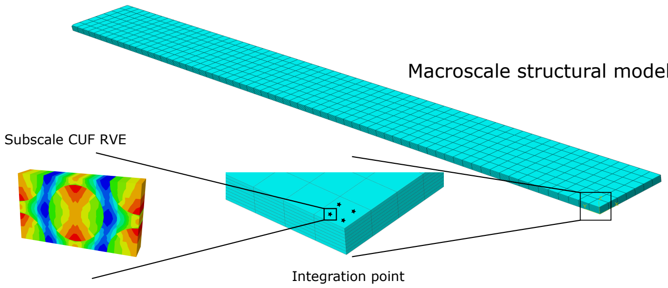

Fig. 3: Workflow of the two-scale framework built within ABAQUS via UMAT/VUMAT interface

matrix level using CUF micromechanics module as illustrated in Fig. 3. The communication between the two scales is achieved through exchange of strain, stress and stiffness tensor at every integration point via ABAQUS UMAT/VUMAT call.

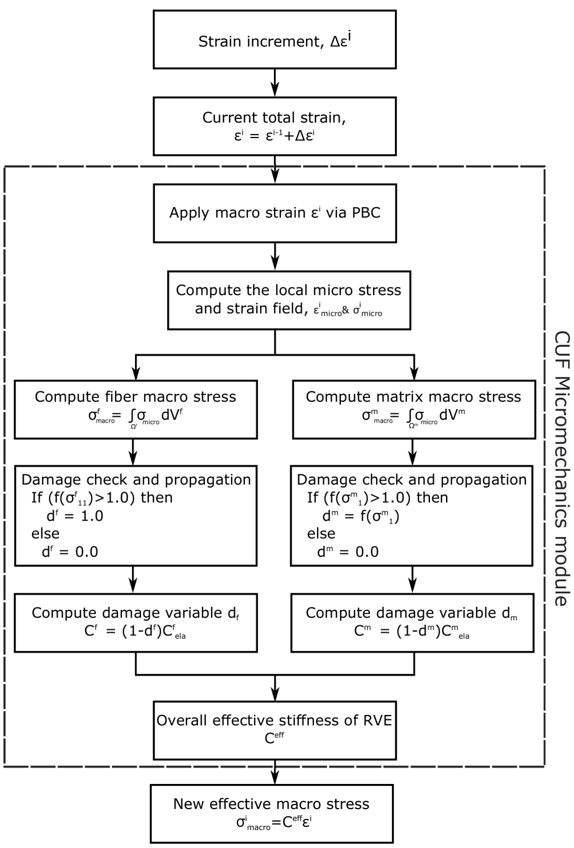

Fig. 4: Algorithm for two-scale progressive damage analysis

4 Numerical results

An unnotched $[0]_8$ coupon under uniaxial tension is simulated. A triply periodic RVE (see Fig. 1) is used for analyzing the composite coupon. The volume fraction of the RVE is 65% and it is made of IM7/977-3 material configuration [1]. Structural coupon was modeled in ABAQUS using C3D8 brick element and CUF-RVE micromechanical module is called at every gauss point for material response. The stress-strain response for a $[0]_8$ laminate is presented in Fig. 5.

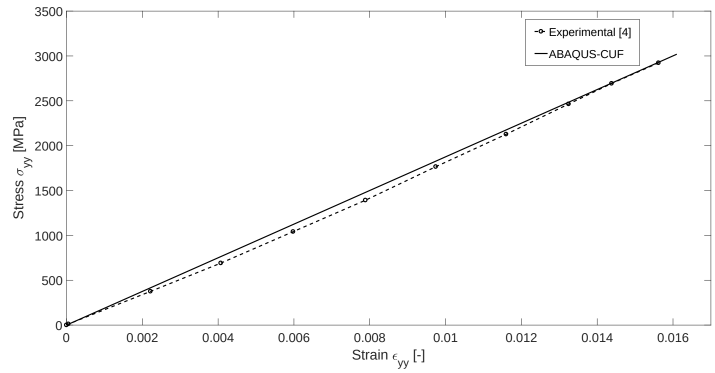

Fig. 5: Uniaxial stress-strain curve for laminates $[0]_8$

5 Conclusion

A novel micromechanics-based two-scale analysis for progressive damage analysis of composite is presented. The micromechanics module integrated into the framework is based on a class of refined beam models called Carrera Unified Formulation. Efficiency of CUF beam models to produce accurate displacement and stress fields is exploited for micromechanical analysis. The energy based crack band theory (CBT) is implemented within micromechanical framework for predicting the damage propagation. Result for an unnotched $[0]_8$ coupon under uni-axial tension is presented. The result is validated against experimental data. Future results shall include a set of different layups (notched and unnotched) under tensile and compressive loading conditions. Predictive capabilities along with the efficiency of the presented two-scale framework shall be highlighted.

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