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Multi-scale structure modeling of damage behaviors of 3D orthogonal woven composite materials subject to quasi-static and high strain rate compressions

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ABSTRACT

We proposed a multi-scale structure modeling scheme to analyze the damage behaviors of three-dimensional orthogonal woven composite materials subject to quasi-static and high strain rate compressions. The multi-scale structure model includes: (1) micro/meso/macro-structure model with periodic boundary conditions for homogenizing the heterogeneous fiber/resin system into unit cells, and (2) a macroscopic rate dependent plasticity model combined with critical damage area failure theory that accounts for the compressive deformation and failure strength of the composite material. The numerical results from the multi-scale structure model provide the locations of stress propagation and the progressive failure behavior within the 3D orthogonal woven composite material. The multi-scale model and the numerical simulation results are validated using compression test results at the strain rate range from 0.001 to 2100 s^{-1}. The methodology we proposed could be applied to understand the microstructure damage mechanisms of 3-D textile composite materials from meso- and macro-structure levels in simpler geometrical model and easier design approaches.

1. Introduction

Advanced composites have shown a rapid growth in recent years driven by civil aircraft programs such as Boeing 787, Airbus A350XWB and Bombardier C series. Three dimensional (3D) woven performs are particularly attractive because of the reduced part count, their ability to create near-net shapes as well as the presence of through-thickness reinforcement. Such kind of 3D woven fabrics and composites are usually applied to various strain rates occasions which may exceed the quasi-static strain rate range particularly under high velocity impact loading, such as military industries (Foglar and Kovar, 2013; Kulkarni et al., 2013), protective structures (Parsons et al., 2010), and aircrafts (Greenhalgh and Hiley, 2003). Understanding the mechanical behavior of composite materials at various strain rates is important for a wide variety of applications (Chen and Ghosh, 2012; Jia et al., 2012a). The recent years have seen a surge in researches on the 3D woven composite materials and structural responses subject to various strain rate loadings.

The mechanical behaviors of fiber reinforced composite materials under various high strain rates have been reported extensively. For example, the compressive behaviors under different strain rates have been previously investigated (Naik et al., 2010a; Ochola et al., 2004; Oguni and Ravichandran, 2001; Shokrieh and Omidi, 2009; Tarfaoui et al., 2009) using hydraulic testing machines (strain rates up

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Abbreviations: 3DOWC, 3D orthogonal woven composite; 3DWCs, 3D woven composites; CDA, critical damage area; FEA, finite element analyses; FEM, finite element method; MMWK, multi-axial multi-layer warp knitting; RUC, representative unit cell; SHPB, split Hopkinson pressure bar; SHTB, split Hopkinson tension bar; UMAT, user-defined material; VUMAT, vectorized user-defined material; VARTM, vacuum assisted resin transfer molding.

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to ∼100 s^{-1}) and split Hopkinson pressure bar (SHPB) apparatus for higher strain rates (strain rates up to ∼10,000 s^{-1}). Many materials show strain rate sensitivity that the dynamic strength and stiffness exhibited considerable increasing as compared with those in quasi-static condition (Malvar and Ross, 1998; Walley, 2010). Hosur et al. (2001) and Khan et al. (2002) also found this result in 2D fiber reinforced resin composite through investigating the compressive stress–strain responses of carbon/epoxy laminated composites at strain rates of 80–170 s^{-1}. As for 3D textile preform reinforced composites, most of investigations have been conducted under high strain rates loading conditions (Baozhong et al., 2010; Hao et al., 2008; Ji et al., 2007b; Liu et al., 2006; Shi et al., 2011; Sun and Gu, 2006a, 2007; Sun et al., 2007,2005; Sun and Gu, 2006b). These studies were mainly focused on the determinations of damage modes and strain rate sensitivity in experimental. In addition, the multi-axial multi-layer warp knitting (MMWK) composite has higher failure stress than the 3D woven composite and the 3D braided composite at the same strain rate. However, the failure strain of the 3D braided composite is higher than that of the 3D woven composite and the 3D knitted composite at quasi-static compression because of the quasi-isotropic structure feature in the 3D braided composite. The compressive failure modes of the 3D woven composite, the MMWK composite and the 3D braided composite are totally different because of the different preform structures (Sun and Gu, 2007). Experimental studies also include those by Kumar and Garg (1988) and Gerlach et al. (2012) who have tested fiber reinforced composite under dynamic compressive loading conditions to study the effect of fiber orientations on failure modes. They found that fiber orientations have significant influence on the failure modes. Several studies also focused on the high strain rate tensile testing of the composites (Majzoobi et al., 2005; Naik et al., 2010b; Schossig et al., 2008), using a split Hopkinson tension bar (SHTB) apparatus and high speed tensile testing machine. The strain rate dependent strength of the composites was reported to vary with the testing directions. The fracture modes of the composite materials were shown to be affected by the strain rate.

Recent years have also witnessed the increasing interesting in the developments of macroscopic mechanical properties of heterogeneous materials by multi-scale and multi-level computational methods. The multi-scale models can be defined as constitutive models in which the global constitutive behavior of composite material is determined simultaneously throughout the analysis based on the behavior of the constituents and their interactions. This is considerably advantageous in the case of evolving microstructure, since the evolution of the microstructure depends on loading history in most practical occasions. Furthermore, it can be analytical or computational, since analytical solutions (Ha-Minh et al., 2013; Naik et al., 2001; Tan et al., 2000) for practical problems are limited to simple geometries and generally do not account for evolutionary damage growth (Souza et al., 2008). Therefore, computational models, especially those based on the finite element method (FEM), have been widely applied.

Several multi-scale 3D finite element models with rate-dependent damage evolution equations have been developed to ascertain the damage due to fiber/matrix debonding, fiber breakage, matrix cracking, and delamination in fiber-reinforced composites under explosions and impact loading (Batra and Hassan, 2007; Chen and Ghosh, 2012; Cuong et al., 2011; Ellyin and Xia, 2001; Nilakantan et al., 2012; Souza et al., 2008). Lee and Pyo (2007, 2008) proposed a micromechanics based elastic damage model to predict the effective elastic behavior and weakened interface evolution in particle composites. Then a multi-level elastic damage model based on a combination of a micromechanical formulation and a multi-level damage model was proposed to predict the effective elastic behavior and progressive weakened interface in particulate (brittle) composites. Their multi-level damage model in accordance with the Weibull's probabilistic function described the sequential, progressive weakened interface in the composites. Horstemeyer and Bammann (2010) reviewed the development and the usage of internal state variable theory for polymers, composites and multi-scale modeling which is definitely helpful for use in practical engineering applications.

Generally, the numerical analyses of woven textile composites are often carried out in two scale models (meso-scale and macro-scale) (Cuong et al., 2011; Ha-Minh et al., 2013; Smilauer et al., 2011). The meso-scale model represents detailed fiber tows in a fabric and it can predict the responses of fiber tows: tensile, shear and compression failures. The macro-scale model is considered as a homogeneous material block. Thus the macro-scale model can only describe basic and global responses of composites. However, the meso-scale model is a key model which enables one to take into account the damage mechanism easily as well as to simulate complicated structures used in the industry. A bridge between the micro- and meso-mechanics of delamination for fiber-reinforced composites was described by Ladeveze et al. (2006). In the cases of meso-model for 3D textile composites, most of the models (Buchanan et al., 2010; Ji et al., 2007a; Luo et al., 2007; Naik et al., 2001; Sun et al., 2009; Tan et al., 2000; Tang et al., 2011) are based on a representative volume element (RVE) homogenized finite elements (Khdir et al., 2013; Nakamachi et al., 2007) to derive the mechanical properties, due to the consequence of their structural complexity and non-linear material constitutive models. The meso-scale finite element modeling of textile composites have been also reviewed and grouped (Lomov et al., 2007).

Recently, a set of constitutive equations for large rate-dependent elastic–plastic-damage (Bruenig and Gerke, 2011) and nonlinear viscoelastic with damage (Jia et al., 2013) materials have been developed. These models are based on the concepts of continuum damage mechanics, and are able to analyze adiabatic, high strain rate dependent deformation processes for a wide range of stress triaxialities. Multi-scale models of textile fabrics based on hybrid element analysis (Nilakantan et al., 2010) and a discretization of the yarn geometry accounting for the yarn-yarn interactions at the yarns crossing points (Assidi et al., 2011) were developed. The predictions of the mesoscopic models regarding the impact of yarn geometries and mechanical properties on the overall behaviors provide a guideline for the design of woven fabrics. A homogenization theory for non-linear time-dependent materials is rebuilt for periodic elastic–viscoplastic materials with misaligned internal structures, by employing a