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Progressive damage analysis and strength properties of fiber-bar composites reinforced by three-dimensional weaving under uniaxial tension

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ABSTRACT

A new geometric model is reported for fiber-bar composites reinforced by three-dimensional weaving (FBCR3DW) having 0/90, 45/135 and 0/90/45/135 weavings. An anisotropic progressive damage analysis model is proposed based on the Hashin-type failure criterion and the Murakami–Ohno damage theory, with shear nonlinearity considered in the stiffness matrix of the yarn and fiber-bar. Finite element models coupled with a progressive damage analysis model were developed to study the progressive damage behavior and strength properties under uniaxial tension. A cohesive zone model was adopted to evaluate the effect of the strength of the interface between the matrix and the fiber-bar on the tensile properties of the FBCR3DW. Several specimens were prepared and used in tensile testing. The stress–strain curves and strengths obtained by the numerical simulations were in good agreement with the experimental results. The failure mechanisms of the composites were revealed in the simulation studies. The numerical results showed that the main damage modes of FBCR3DW were matrix damage, yarn transverse damage and yarn longitudinal breakage, which were in good agreement with the experimental findings.

1. Introduction

Three-dimensional (3D) woven composites are the combination of a traditional two-dimension (2D) textile weaving process, a 3D braiding process and advanced composite technology. They are receiving increasing attention for load-bearing structures as a new, lightweight and advanced material, which overcomes certain disadvantages of conventional laminated composites such as relatively poor mechanical properties in the thickness direction, and has better mechanical properties such as higher out-of-plane stiffness and strength, higher damage tolerance and good impact and fatigue resistance [1]. Three-dimensional woven composites are uses widely in aviation, aerospace and marine applications. However, because of the complicated weaving structures, the failure mechanisms of 3D weaving composites are not well understood. For improved safety and application design, a better knowledge of their damage and failure behaviors under different loading conditions is essential.

With the development of studies on the damage mechanisms of composites, multiple failure criteria for composite have been generated by researchers, e.g. Tsai–Wu criterion, Hoffman criteria, Hashin criterion [2], Puck criterion [3], and then lots of remarkable achievements have been obtained on the research of damage mechanics of laminate, 2D textile weaving and 3D weaving composites. Pinho et al. [4,5] developed a 3D failure criterion for laminated fiber-reinforce composite, based on a physical model for each failure mode and considering non-linear matrix shear behavior. The physical model for matrix compression is based on the Mohr–Coulomb criterion and also predicts the fracture angel. Maimí et al. [6,7] developed and used damage activation function based on the LaRC04 failure criteria to predict the different failure mechanisms occurring at the ply level. The model is based on four possible ply fracture planes related to fiber tensile fracture, fiber kinking, and matrix cracking with fracture planes oriented at two angles. Camanho et al. [8] presented new 3D failure criteria for fiber-reinforced composite materials based on the transversely isotropic yield function. The criteria have an invariant quadratic formulation based on structural tensors that accounts for the preferred directions of anisotropic material. Catalanotti et al. [9] proposed a failure criterion for polymer composites that predicts the onset of the different failure mechanisms and that provides additional information on the type of failure and on the orientation of the fracture plane.

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The continuum damage mechanics (CDM) method, which can provide a tractable framework for modeling damage initiation and development as well as stiffness degradation, is one of the important and effective methods for modeling the progressive damage behavior of fiber reinforced composites. Camanho et al. [10] examined the use of a CDM to predict strength and size effects in notched carbon-epoxy laminates. It is found that, the CDM proposed predicts with good accuracy hole size effects in composite laminates subjected to tension. The CDM provides not only the final failure load, but also information concerning the integrity of the material during the load history. Maimí et al. [6,7] developed a CDM able to represent the quasi-brittle fracture of laminated composite structures, from the onset of non-critical failure mechanisms up to final structural collapse. Based on CDM approach and Murakami–Ohno damage evolution model, Gorbatikh et al. [11] suggested a new property degradation procedure where the size of an inhomogeneity and properties of the surrounding material were taken into account. Green et al. [12] adopted voxel method and CDM in a finite element analysis to compute stress–strain curves for an orthogonal 3D woven composite under tensile loading. Visrolia and Meo [13] proposed a finite element model using the asymptotic homogenization method to distribute marco-scale stress to the micro-scale, i.e. yarns and matrix, where the stressed in the yarns and matrix were then used CDM to determine localized stiffness degradation. Zhong et al. [14] used CDM for predicting the damage initiation and development in three-dimensional woven composites, in which the damage initiation and propagation criteria are based on the Puck criteria for the fiber yarn and the paraboloidal yield criterion for the matrix. Martín-Santos et al. [15] proposed a constitutive behavior model based on CDM for the simulation of fabric-reinforced composites. Greve and Pickett [16] presented a combination of the elasto-plastic CDM constitutive model proposed by Ladevèze and the Puck criteria to treat in-plane failure of carbon non-crimp fabric reinforced composites under combined in-plane loading conditions.

In recently, progressive damage model (PDM) was proposed and applied in the analysis of failure behaviors of composites under different loading condition by researchers. Simultaneously, cohesive zone approach was successfully implemented by applying cohesive element between two adjacent surfaces of two neighboring components in composite. Zako et al. [17,18] developed a theoretical anisotropic damage constitutive equation based on damage mechanics and proposed a PDM based on damage theory established by Murakami. The model was employed to reveal damage mechanisms for unidirectional fiber reinforced composite materials as well as plain woven fabric composite. Turon et al. [19] presented a PDM for fiber-reinforced composites based on the fragmentation analysis of the fibers, where the stiffness loss of unidirectional composite comes from the parameters of the Weibull distribution of the fiber strength and the mechanical properties of the fiber, matrix and the interface. In Costa et al.'s work [20], a stress corrosion model for composite materials reinforced with environment sensitive fibers was developed and incorporated into a PDM, and a mechanistic damage model for the stiffness loss during the first stage of fatigue degradation was presented. Lapczyk and Hurtado [21] proposed an anisotropic PDM suitable for predicting failure and post-failure behavior in fiber-reinforced materials. The damage evolution of this model is based on the fracture energy dissipated during the damage process and the increase of a damage variable is governed by an equivalent displacement appropriately defined for each failure mode. Tserpes et al. [22] proposed a PDM, which is able to predict the residual strength and final failure mode of bolted composite joints by using a step-wise simulation of damage accumulation from the point of initial component failure until catastrophic failure. Huysmans [23] presented a PDM for knitted fabric composites based on a Mori-Tanaka or self-consistent elastic framework, in which matrix non-linearities are implemented using the secant stiffness method and Yarn/matrix debonding is investigated using a simple interfacial failure criterion. Labeas et al. [24] developed a PDM capable of predicting the interaction effects between the post-buckling behavior and the various failure modes of composite plates. In the model of Xu et al. [25], a PDM was used to the fatigue damage analysis of textile composites on meso-scale. Su et al. [26] proposed a PDM with continuum shell elements representing each ply and cohesive elements modeling the delamination for the open-hole fiber reinforced composites subjected to tension. Chen et al. [27,28] developed a PDM, which consists of a combined elastoplastic damage model for simulating the in-plane failure mechanisms and plastic deformations of the composite layers and a cohesive zone model for modeling delamination. Fang et al. [29] proposed an anisotropic PDM based on Murakami–Ohno damage theory, and used it to evaluate the non-linear behavior of the 3D four-directional braided composites. The failure locus of 3D four-directional braided composites was also obtained by progressive damage analysis of a representative volume cell under biaxial loading in finite element model [30]. In Zhou et al.'s work [31], the PDM was implemented to study the damage and failure behaviors of 2D plain weave composites under various uniaxial and biaxial loadings. In the mode of Zhang et al. [32], the progressive damage behavior of a single-layer triaxially braided composite was analyzed by using a 3D mesoscale finite element model with an anisotropic PDM based on Murakami–Ohno damage theory and an interlaminar tow-to-tow cohesive zone.

As the same as CDM and PDM, many special methods and models were developed and effectively used to study the damage and failure behavior of 2D and 3D woven composites. Bogdanovich [33] presented a multi-scale methodology to illustrate 3-D stress/strain analysis of the Mosaic unidirectional composite and developed a 3-D progressive failure analysis of generic 3-D Mosaic structure using ultimate strain criterion. Lee et al. [34] proposed an evaluation method for the initial and progressive failure of composite laminates based on the Puck failure criterion and damage mechanics. Zaïri et al. [35] adopted a micromechanical approach for the elastic-damage prediction of glass mat reinforced polymer composites. In this approach, void onset and evolution, induced by progressive interfacial debonding, are integrated into a micromechanically derived model to estimate the overall mechanical behavior in connection to the microstructure. Cousigné et al. [36] developed a new nonlinear numerical material model based on Ramberg–Osgood formulation to predict the failure behavior of woven composite materials. Pineda et al. [37] implemented the smeared crack band theory with the high-fidelity generalized method of cells micromechanics model to capture progressive failure within the constituents of a composite material. Römelt and Cunningham [38] suggested a numerical procedure to simulate the macro-behavior of 2D woven laminates, in which nonlinear springs were used to model the stiffness degradation due to damage and cohesive element were used in the full finite element analysis to model damage initiation and progression. Hu et al. [39] proposed a new peridynamic model for fiber reinforced composite laminate and applied it on the analysis of the progressive damages in composite laminate with notch or open hole. However, up till now, the mechanisms that lead to failure in composite materials are not fully understood yet. Due to the complicate microscopic geometrical structures and the complexity of damage mechanisms of components interior the composites, the analyses of the damage and failure behaviors of fiber reinforce composites are difficult and complex.

The main objective of the present study was to characterize the damage and failure behavior of fiber-bar composites reinforced by 3D weaving (FBCR3DW) under unidirectional tensile loading. A