Composite Structures 94 (2012) 1590–1604

Contents lists available at SciVerse ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Modeling the response, strength and degradation of 3D woven composites subjected to high rate loading

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ARTICLE INFO

Article history:
Available online 5 January 2012

Keywords:
Hopkinson bar
High strain rate
3D woven
RUC modeling
Material characterization

ABSTRACT

Experimental results which were obtained using a split Hopkinson pressure bar (SHPB) apparatus to determine rate dependent effects, and reported by the authors in [1] are used as the basis to perform dynamic simulations of 3D woven composites (3DWCs) using representative unit cells (RUCs). The input material properties for the RUC simulations were determined from the concentric cylinder model (CCM) in conjunction with the geometry of the textile architecture, mechanical properties of pure epoxy samples and fiber mechanical properties. The RUC model incorporates rate dependent plasticity. Additionally, linear-eigen perturbations that correspond to buckling modes are used to seed imperfections in the RUC model to capture buckling and subsequent failure that was observed in experiments. The RUC model results showed good agreement with experiment and correctly captured the observed modes of failure while pointing to transitions in failure modes.

1. Introduction

Polymer matrix 3D woven composite materials (3DWCs) are being inserted into applications that expose them to uncertain external loading scenarios including loads applied over very short durations subjecting the material to a high loading rate environment. The ability to tailor the architecture of these material appropriately has lead to the development of many different types of 3DWCs, that are summarized in [2].

Classical laminated plate theory (CLPT) [3] has been used extensively and works well for simple layered composites, such as pre-preg based polymer matrix laminated composites. With the explosion of new 3DWCs, new analytical models are needed to predict mechanical performance. An extension of CLPT to 2D in-plane woven composites has been accomplished in [4] with an extension to 3DWC being reported in [5]. Since the Z-fiber is the hardest constituent to model in 3DWCs, some have attempted a simplified approach to model the sinusoidal Z-fiber tow, however the method relies on a newly derived special element [6] and a solution strategy similar to that of the finite element method has been used. These models, however, because of their homogenized nature are not suitable for modeling failure mechanisms (such as kink band formation in compression [7–9], or localized stress concentrations that occur from fiber tow undulations) that are dictated by the textile tow architecture. Many of the textile weaving companies use their own in-house codes to predict the initial, linear elastic in-plane mechanical properties, with some able to predict failure of the material using simple failure initiation criteria [10]. However, available analytical models are incapable of capturing architecture dependent failure, such as fiber tow kinking (and buckling) and/or matrix cracking in matrix rich pockets. In these instances, there is a need to develop a validated methodology that can be implemented numerically.

To capture mechanism based failure modes, finite element codes have been written to accurately represent the 3DWC architecture and to include non-linear material constitutive models [11,12]. A detailed model incorporating consolidation of the various layers has been incorporated into RUC modeling of textile composites producing good experimental correlations [9,13,14]. Many different models have been proposed based on the geometry of a representative unit cell [15–24]. However each of these models tends to simplify the geometry or neglect certain aspects of the material. Often the Z-fiber is turned into a rectangular element, seen as the block approach, to fit into a grid of warp and weft fibers [25,17], neglecting the crimp and actual path followed by the Z-fiber. Other types of models break the individual elements into representative sub-cells showing the type of fibers that occurs in each [19], however each sub-cell must be calibrated and are approximate for the geometry. Periodic RUC's have been investigated for stitched material [26], however the modeling does not account for damage due to stitching, and has many issues related to predicting the correct shear response of the material.

In many of the models referred to earlier, the simulations use simple block geometry, whereas the actual architecture will have

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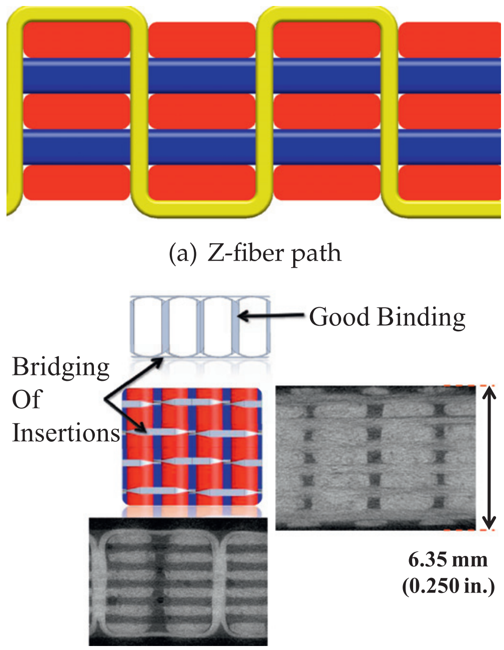
doi:10.1016/j.compstruct.2011.12.010



(a) Z-fiber path

(b) 6% Z-fiber architecture

Fig. 1. Details of Z-fiber architectures. (a) Z-fiber path, the yellow color path represents the course that the Z-fiber follows during the weaving process. (b) Details of 6% Z-fiber architecture [1].

continuous curves that can be represented by splines. Block geometry models cannot capture fiber tow undulations and other byproducts of the weaving process. Therefore, new, more accurate models must be implemented to better predict the actual mechanical properties. The proposed models are extensions of investigations reported in [8,9], where the true measured geometry is used. These references have shown good correlations with 2D in-plane woven systems for determining deformation response, and also in describing progressive damage. Extensions of these studies to 3DWC are the logical starting point.

In this paper, 3DWCs are modeled using a RUC model. Results from SHPB tests are used to validate the model. The model incorporates rate dependent plasticity. Additionally, linear eigen perturbations that correspond to RUC buckling modes are used to seed imperfections in the RUC geometry. The deformation response of the imperfection seeded RUC is shown to lead to progressive failure and collapse of the RUC, much like what has been observed in the experimental study [1].

2. Material

A 3DWC architecture that uses a 6% Z-fiber reinforced architecture is studied. The architecture consists of a strict system of warp and weft fibers (the word "fibers" is used to refer to fiber-tows as was used in the previous paper [1]). Fig. 1a shows a schematic of this, the red fibers are the weft while the blue[1] represent the warp. The yellow fiber representing the Z-fiber binds all of these layers together. The 6% refers to the fact that 6% of all the fibers being used in the binding process are used as Z-fibers. Fig. 1b shows the actual architecture from the 6% Z-fiber material along with details of the actual path followed by the Z-fibers. Details of the weaving process are provided by the authors in [1].

[1] For interpretation of color in Figs. 1–5 and 7–26, the reader is referred to the web version of this article.

Table 1
Individual mechanical properties for pure S-2 glass fibers.

E_{11} (GPa)	G_{12} (GPa)	ν_{12}
114.2	46.5	0.22

2.1. SC-15 Material

The material used as resin to infuse the panels is SC-15 epoxy, a thermoset polymer. SC-15 is a low-viscosity two-phased toughened epoxy resin system consisting of part A (resin mixture of diglycidylether epoxy toughener) and part B (hardener mixture of cycloaliphaic amine poluoxylalkylamine) [27]. Details of the mechanical properties are provided later.

2.2. S-2 Glass

S-2 glass was chosen as the material for the fibers. The mechanical properties of S-2 glass are different compared to E-glass in that they are 30% stronger and about 15% stiffer. The fibers are made by pulling molten glass through tiny holes at the base of a furnace [28]. They are part of the Magnesium–Alumina–Silicate glass family of fibers. The individual properties under static loading are reported in Table 1 which is obtained from Ref. [29].

It has been shown that the glass fibers are typically linear elastic in their response, while the matrix exhibits rate dependent behavior which is modeled through the Cowper–Symonds overstress model, which will be described later [30].

3. Proposed models

A finite element (FE) model was developed to understand how the fiber tows carry load for different woven architectures. To obtain the RUC geometry, 3DWC specimens were polished and then observed under an optical microscope to extract microstructural geometric details. The images were analyzed to determine the average dimensions of each of the fiber tows, the separation between tows, and any other dimension required to accurately recreate the RUC for the architecture. These dimensions were then turned into three dimensional models in SolidWorks 2009, see Fig. 2. The dimensions are provided in Table 2, where the Z-fiber consisted of a spline fit that would wind around the architecture, holding a constant cross section of $0.104\ \text{mm}^2 (1.61 \times 10^{-4}\ \text{in.}^2)$. The constant cross section is held to ensure that fiber volume fraction is constant so that the properties are not changing as a function of the position, see Fig. 3. The SolidWorks model was then imported into ABAQUS version 6.8. The ABAQUS finite element (FE) model is comprised of quadratic tetrahedral elements. The mesh size chosen is dependent on geometry and computation size. There is ultimately a trade off that needs to be effected. The finer the mesh size is, the more computation time is needed. A "relatively" coarse but "converged" mesh is used in the present study because of the end goal of dynamic simulations, and in order to reduce computational time. The RUC model used consists of 70,000 3D elements. The percentage of fibers along each direction is reported in Table 3 along with the overall fiber and matrix volume fractions which are presented in Table 4. The small deviations between actual and model being attributed to the distributions in individual fiber volume fractions that will be discussed later.

3.1. Tow interactions

Two methods for characterizing the tow interaction have been investigated to determine how to properly model the complex woven architecture. Idealizing the architecture requires some