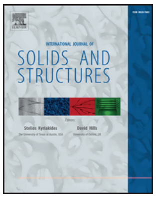
International Journal of Solids and Structures 97–98 (2016) 1–15

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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



Effect of temperature on the failure modes of a triaxially braided polymer matrix composite

Amine El Mourid[a], Rajamohan Ganesan[b], Myriam Brochu[c], Martin Lévesque[a,*]

[a] *Laboratory for Multiscale Mechanics (LM^2), CREPEC, Département de Génie Mécanique, École Polytechnique de Montréal, C.P. 6079, Succ. Centre-ville, Montréal, H3C 3A7, Canada*
[b] *Concordia Centre for Composites (CONCOM), Department of Mechanical & Industrial engineering, Concordia University, Montreal, H3G 1M8, Canada*
[c] *Département de Génie Mécanique, École Polytechnique de Montréal, C.P. 6079, Succ. Centre-ville, Montréal, H3C 3A7, Canada*

ARTICLE INFO

Article history:
Received 1 September 2015
Revised 14 June 2016
Available online 12 August 2016

Keywords:
Mechanical behavior
Elevated temperature
Finite element analysis
Textile composites
Analytical models
Mechanical properties
Failure analysis

ABSTRACT

The temperature effect on the tensile behavior of a triaxially braided composite was investigated in two different loading directions. The damage evolution was monitored and the results were explained with the help of experimental, analytical and numerical methods. The evolution in the constituent elastic properties was responsible for stress redistribution within the composite explaining the differences in crack initiation and Ultimate Tensile Strength for both directions and testing temperatures. The study also revealed the potential of quick and efficient analytical homogenization models to explain failure paths in textile composites.

1. Introduction

Textile composite can be tailored for specific applications by carefully choosing the fabric type (e.g., woven, braided, knitted, etc.) or microstructure parameters (e.g., volume fraction, yarns spacing, etc.) to obtain desired mechanical properties. Textile composites have already been successfully used in jet engine fan blade components and outer cores where service temperatures are moderate. Recently developed polyimide matrices suitable for Resin Transfer Molding (RTM) have rated operating temperatures of up to 350 °C. This paves the way for textile composites use in higher temperature applications, especially in jet engines. Baseline properties, as well as predictive design models, must be available for service conditions to enable the successful deployment of polyimide-based textile composites in high temperature structural applications. For example, thermo-oxydative stability, viscoelastic response (creep/relaxation), fatigue response and damage evolution must all be understood and predicted to develop optimized designs.

Damage evolution in textile composites has been studied by numerous authors at room temperature (Ivanov et al., 2009; Lomov et al., 2008) and is relatively well documented. During a tensile test, damage is typically initiated by transverse cracks in yarns oriented at an angle with respect to the loading direction (called transverse yarns). Then, as the load increases, the cracks size and density increase. This phenomenon is associated with a decrease in the composite's stiffness. The accumulation of damage creates local yarn/matrix debonding areas. Finally, fibre damage causes material failure. Yu et al. (2016) observed the same damage patters in tension-tension fatigue loading of woven composites with the help of time-lapse tomography. Additionally, several authors (Böhm et al., 2010; Ernst et al., 2010; Ivanov et al., 2009; Karkkainen and Sankar, 2006; Zhang et al., 2014) worked on the damage modeling of textile composites. For instance,Ivanov et al. (2009) extended the Ladeveze damage model (Ladeveze and LeDantec, 1992) to textile composites. However, these models require an extensive experimental campaign at several directions. Böhm et al. (2015) studied damage textile composites with the help of in-situ tomography and observed that cracks were significantly larger under load. They concluded that accurate damage diagnosis should be performed under load.

The influence of elevated temperature (i.e., above 125 °C) on composites behavior has also been studied by numerous authors. For example, Odegard and Kumosa (2000) reported decreases of 10% in the axial stiffness (i.e., E_{11}) between room temperature and 316 °C for an unidirectional carbon/PMR15 composite submitted to σ_{11}. The deterioration in properties was more pronounced for E_{22} and G_{12}, with decreases of 27% and 80%, respectively, as well as for ultimate strength in the transverse (σ_{22}^{u}) and shear directions

---

[*] Corresponding author.
E-mail address: martin.levesque@polymtl.ca (M. Lévesque).

http://dx.doi.org/10.1016/j.ijsolstr.2016.08.005
0020-7683/

(σ_{12}^u). Kobayashi and Takeda (2002) studied the damage mechanisms in carbon/Bismalmeide (BMI) laminates, both at room temperature and 180 °C. They observed that matrix cracks initiated in transverse plies. However, the damage initiated earlier at high temperature and crack density at failure was lower when compared to that measured at room temperature, probably due to matrix softening. Selezneva et al. (2011) studied qualitatively the influence of temperature on the failure of carbon/BMI off-axis woven textile composites, for temperatures ranging from 25 °C to 205 °C. They observed that the areas affected by necking and delamination were significantly larger at elevated temperatures than at room temperature.

Very few studies focused on the mechanical behavior of braided composites at high temperature. For example, Montesano et al. (2013) studied the fatigue damage evolution in triaxially braided carbon/polyimide composites, in the warp direction. They concluded that crack density was significantly lower at high temperature in the warp direction, and postulated that it was due to the increased ductility/softening of the matrix at elevated temperatures. Most of these studies (Kobayashi and Takeda, 2002; Montesano et al., 2013; Selezneva et al., 2011) focused on properties along a single direction and neglected the effect of anisotropy.

Analytical and numerical homogenization aim at predicting the effective properties of composites by considering the orientation, mechanical behavior and volume fraction of each constituent (Bornert et al., 2001). Most analytical models rely on Eshelby's solution to the problem of an inclusion embedded into an infinite medium. The most widely used schemes are that of Mori-Tanaka (Benveniste, 1987) and self-consistent techniques (Hill, 1965). These techniques can also estimate the spatially averaged stress tensor in each phase (Benveniste, 1987) and could potentially be used to explain local damage initiation. The mechanical behavior of composites can also be predicted by simulating the mechanical response of unit cells describing the exact morphological features of the studied microstructure. This topic has received considerable attention, especially for textile composites (El Mourid, 2011; Gommers et al., 1998b; Lomov et al., 2007; Verpoest and Lomov, 2005; Wong et al., 2006). In particular, `Wisetex` software provides efficient tools for creating solid or meshed representations of the yarns in 2.5D textiles that can be directly transferred to ANSYS. The first step consists of generating a proper 3D volume representation of the textile composite. The second step aims at obtaining an optimized unit cell through symmetries and periodicity. Finally, periodic boundary conditions are imposed and the effective and local fields are computed. However, the numerical modeling of textile composites presents challenges for high fibre volume fractions, especially for braided architectures (Lomov et al., 2007). In this case, most volume representations present yarn interpenetrations that have to be taken care of manually before meshing the architecture. High yarns densities can also hinder the matrix phase meshing due to the lack of space between the yarns to create a proper matrix box. In order to solve these problems, several authors (Blacklock et al., 2012; Naouar et al., 2014; Rinaldi et al., 2012) developed new techniques to model textile RVEs based on tomography imaging imaging. These advances provide fascinating insights on the possibilities of textile FE modeling, since they enable the inclusion of defects that are present in real materials as well as the modeling of high volume fraction textile composites. However, they require extensive access to tomography equipment.

The objectives of this study are to:

- Test up to failure and carefully monitor damage evolution in braided composite samples at different temperatures and along different material orientations.
- Analyze the influence of stress redistribution inside the yarns with analytical and numerical models to explain room temperature and elevated temperature failure sequences.

Table 1
Braided composite microstructure.

Property	Dimension
Yarns width	2.2 mm
Yarns thickness	0.212 mm
Distance between 60 ° yarns	2.7 mm
Distance between 0 ° yarns	3.4 mm
Yarns fraction at 60 °	40%
Yarn fraction at -60 °	40%
Yarns fraction at 0 °	20%
Fibre volume fraction	56%
Yarns packing factor	71%

The experimental methododology is presented in Section 2. The experimental results are presented in Section 3. The modeling procedure and its results are presented in Section 4. The paper ends with a discussion and a summary of the findings.

2. Experimental investigation

2.1. Material characterization

The studied composite was a tri-axially braided preform infused by RTM with Maverick's MVK10 high temperature polyimide resin. The preforms were fabricated by tri-axially braiding multiple plies of Cytec T650-35 6K dry carbon fibres on a tubular mandrel at 0/±60 ° (±3 °). The fabric plies were subsequently laid flat, consolidated and placed in a RTM test panel mould to the desired thickness. Fibre volume fraction was aimed to be at 57% (±3%). Preforms were moulded at a pressure of 1700–2100 kPa. The materials were manufactured by ITT Corporation, who withheld the details of the manufacturing process. All the composites were C-Scanned after manufacturing to check for major defects and passed the quality requirements. Test coupons were cut from two 342mm × 381mm × 3mm composite panels.

Small samples were sent to Southampton University to perform Computed X-Ray Microtomography (µCT) observations. A Nikon XTH 225 L scanner with a Perkin Elmer PE1621 detector and a Molybdenum target, with an accelerating voltage of 55kV and a beam current of 157 µA, were used to create the 3D representations. Fig. 1 displays the results of the tomography and shows the microstructure of the yarns in the composite. These observations allowed for determining the yarns' width, height, separation distances and volume fractions. The fibre volume fraction was evaluated to be 56% based on acid digestion tests. The yarns packing factor (i.e., the fibre volume fraction in a given yarn) was evaluated with the help of image analysis. A 200 × magnification image of a 0 ° yarn cross-section was transformed into a biphasic image through thresholding. Fig. 2 shows the raw and thresholded images. The fibre packing factor was then evaluated to be 71%. Table 1 reports the results and Fig. 3 provides an approximate three-dimensional representation of the fabric obtained with `WiseTex` software. In the sequel, Direction 1 is that aligned with the straight yarns while Direction 2 is perpendicular to it, as shown in Fig. 3. Angles are also measured from Direction 1.

Table 1 reveals that 80% of the yarns were oriented at ±60 °, while only 20% were at 0 °. This led to a composite that was stiffer in Direction 2 (i.e., perpendicular to the straight yarns).

MVK10 dry-glass transition temperature was provided by the manufacturer and was over 300 °C. Samples were fully water satu-