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Mechanical behavior and failure micromechanisms of hybrid 3D woven composites in tension

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ABSTRACT

The deformation and failure micromechanisms of a hybrid 3D woven composite were studied in tension. Plain and open-hole composite coupons were tested in tension until failure in the fill and warp directions, as well as fiber tows extracted from the dry fabric and impregnated with the matrix. The macroscopic evolution of damage in the composite coupons was assessed by means of periodic unloading–reloading (to obtain the elastic modulus and the residual strain), whereas the microscopic mechanism were established by means of X-ray computed microtomography. To this end, specimens were periodically removed from the mechanical testing machine and infiltrated with ZnI-containing liquid to assess the main damage modes as a function of the applied strain. The experimental observations and the predictions of an isostrain model were used to understand the key factors controlling the elastic modulus, strength and notch sensitivity of hybrid 3D woven composites in tension. It was found that the full contribution of the glass fibers to the composite strength was not employed, due to the premature fracture of the carbon fibers, but their presence increased the fracture strain and the energy dissipated during fracture. Thus, hybridization of the 3D woven composite led to a notch-insensitive behavior as demonstrated by open-hole tests.

1. Introduction

Fiber-reinforced polymers stand out among the most successful structural materials due to the combination of low density, high stiffness and strength and reasonable damage tolerance and impact resistance. In addition, their performance can be optimized for specific applications by choosing the fiber type, volume fraction and orientation, stacking sequence, etc., normally within the framework of 2D laminates. However, more sophisticated strategies are available to further improve the composite behavior for specific applications. They include hybrid composites containing two or more fiber types and 3D fiber architectures.

Hybrid composites in which carbon fibers are used in combination with higher strain-to-failure fibers have consistently demonstrated better damage tolerance under impact, reduced notch-sensitivity and improved fracture toughness than their carbon-fiber counterparts [1–6]. Fiber architecture has an even stronger influence on the mechanical response [7]. The baseline materials for comparison are conventional multidirectional laminates manufactured from unidirectionally-reinforced pre-preg sheets. They show excellent in-plane properties due to the lack of crimping, but low delamination resistance under out-of-plane loads. This problem can be partially overcome with 2D fabrics, although the in-plane stiffness and strength are reduced, while non-crimp fabrics provide properties in between these fiber architectures.

More radical differences (and a much wider design space) is achieved when textile manufacturing techniques are applied to create 3D fiber preforms. The huge variety and the complexity of the 3D fiber architecture makes the prediction of mechanical properties of 3D composites a challenging task, as their deformation and failure mechanisms are very complex and can show large differences as a function of the loading conditions and of the 3D fiber preform. Early studies [8,9] showed that 3D woven composites presented higher failure strains than conventional multiaxial laminates, together with lower notch sensitivity and higher work of fracture. Following this pioneer work, there were many papers available in the literature on the mechanical response of 3D composites, but detailed studies focussing on the comprehensive assessment of the dominant damage micromechanisms in different 3D fiber preforms have appeared recently. For instance, Gerlach et al. [10] studied the effect of the volume fraction of through-the-thickness binder on the in-plane and out-of-plane properties of 3D woven composites as a function of the strain rate.

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Bogdanovich et al. [11] and Ivanov et al. [12] carried out a comprehensive experimental analysis of the elastic constants and damage micromechanisms of 3D non-crimp orthogonal woven composites loaded in tension. They showed that non-crimp 3D orthogonal woven composites have significantly higher in-plane strengths, failure strains and damage initiation thresholds than the 2D woven laminated counterparts [12]. The effect of 3D reinforcement on delamination was studied by Pankow et al. [13], whereas Seltzer et al. [14] performed a detailed investigation on the damage mechanisms under low-velocity impact of various 3D orthogonal woven composites and highlighted the differences between those observed in 2D woven materials. This latter study demonstrated that state-of-the art 3D characterization techniques, such as X-ray microtomography (XCT), are extremely useful to understand the initiation and progression of damage in these materials in which failure processes are inherently 3D.

While the analysis of the failure mechanisms in hybrid or 3D composites has been studied in the past, there are few comprehensive studies on this topic for hybrid 3D composites containing two or more fiber types [15]. This was the main goal of this investigation, which presents a detailed analysis of the failure micromechanisms in tension of a hybrid 3D orthogonal woven composite. The evolution of damage as a function of the applied strain was monitored by means of progressive reduction in stiffness and the increment of the residual strain as well as by XCT. The composite properties (stiffness, strength) were compared with predictions obtained from the actual properties of the fiber tows, which were measured independently. All this information provides a comprehensive picture of the effect of fiber hybridization, 3D fiber architecture, crimping and damage on the mechanical behavior in tension of hybrid 3D woven composites.

2. Material

A flat composite panel was manufactured by vacuum infusion of an epoxy-vinylester resin (Derakane 8084) into a hybrid 3D orthogonal woven composite. Both the dry perform and composite panel were provided by 3TEX, Inc. (Cary, North Carolina, USA) with the commercial name p3w-d00001-hx21. The preform was non-symmetric and consisted of three warp (0) and four fill (90) fiber layers stacked as a cross-ply laminate [90_c, 0_c, $90_{c/s2}$, 0_{s2}, 90_{s2}, 0_{s2}, 90_{s2}]. The schematic of the 3D fiber preform is shown in Fig. 1. The fibers in each layer were distributed in yarns rectangular in shape. The top four layers were made up of S2 glass fibers and the bottom 2 layers of AS4C carbon fibers. The hybrid layer (containing glass and carbon fibers) oriented in the fill direction was located between the glass and the carbon layers. Each tow of this layer contained both AS4C and S2 glass fibers, which were not intermingled but separated in two different zones of the tow (i.e. one half of the tow was formed by carbon fibers and the other half by glass fibers). It should also be noticed that every other tow was missing in the carbon layer oriented in the warp direction. In addition, the composite panel was reinforced in the through-thickness direction by z-yarn binders made up of ultra-high molecular weight polyethylene (PE) fiber (Dyneema SK75) that went from top to bottom layers in the warp direction. Note that consecutive z-yarns were in *antiphase*.

The nominal thickness of the dry fabric was 3.02 mm and its areal density was 4.24 kg/m^2. The nominal thickness of the composite was 4.1 mm, with an areal density of 6.44 kg/m^2. The overall fiber volume fraction in the composite was 47% and the porosity, as measured by XCT, was 11.6%. The volume fraction of each type of fiber in each direction (warp or fill) is shown in Table 1. It was determined from the areal density of the individual plies and the fiber density, which were provided by the manufacturer. In addition, the matrix volume fraction was determined from the matrix density and the weight of the composite panel before and after infiltration and this is also given in Table 1.

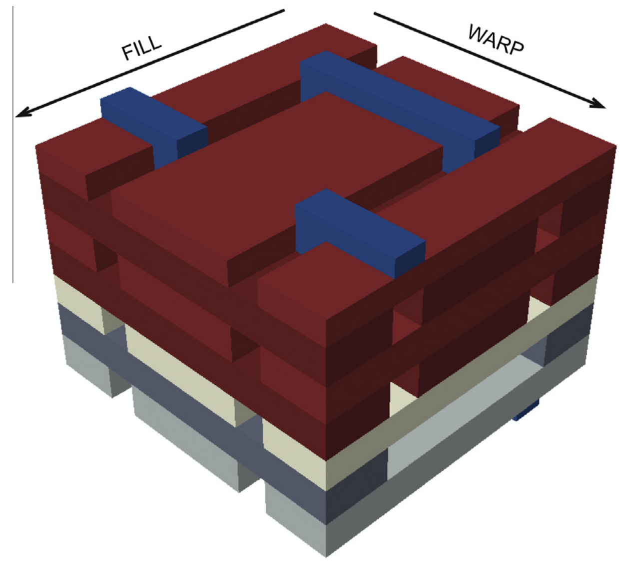

Fig. 1. Schematic of the unit cell of the hybrid 3D woven fiber preform. Carbon fiber bundles are shown in gray (dark gray for the warp direction and light gray for the fill), hybrid bundles in white and glass fiber bundles in red (dark red in the warp direction and light red in the fill direction). PE z-yarn binders in the warp direction are plotted in navy blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Density (ρ) and volume fraction of matrix and fibers as a function of fiber type and orientation within the hybrid composite.

Material	ρ (g/cm^3)	Warp (%)	Fill (%)	Total (%)
Glass S2	2.48	15.4	14.7	30.1
Carbon AS4C	1.78	4.3	10.7	15.0
Polyethylene SK75	0.97	1.9	–	1.9
Total fibers		21.6	25.4	47
Matrix	1.02			53

3. Experimental techniques

3.1. Mechanical characterization

Rectangular specimens of 250 × 25 × 4.1 mm^3 were machined from the plate with the longest dimension aligned in either the warp or fill direction for the mechanical tests. Glass tabs of 50 mm in length were glued to the specimens, leading to a free length of 150 mm. They were tested in tension in an electromechanical universal testing machine (Instron 3384) following the recommendations of the ASTM Standard D3039 [16] and of the ASTM Standard D5766 [17] for rectangular coupons with a central hole of 4.1 mm and 11 mm in diameter. Tests were carried out under stroke control at 2 mm/min and the load was continuously measured during the test with a load cell of 150 kN. Since composite is non-symmetric (and coupling between bending and extension might occur), the longitudinal strain was recorded on both faces of the specimen using an extensometer of 50 mm gage length on one face and digital image correlation (Vic2D) on the other. The strain reported with digital image correlation was that corresponding to a virtual extensometer, whose gage length was equal to that of the actual extensometer on the other side. Periodic unloading–reloading was carried out in one test in each direction (warp or fill)