DAMAGE CHARACTERIZATION OF TRIAXIAL BRAIDED COMPOSITES UNDER TENSION USING FULL-FIELD STRAIN MEASUREMENT

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1 Introduction

Applying new lightweight materials, such as carbon fiber reinforced plastics (CFRP) in the automotive industry allows a significant reduction in structural weight and carbon dioxide emissions. In these high-volume production industries, current manufacturing technologies face a twofold challenge: cost and cycle time. Braiding combines an automated and reproducible process together with an excellent rate of material deposition for mass-production of high performance structures. Yarns of several thousand carbon fibers are intertwined and positioned on a mandrel to produce geometries with complex cross-sections. Triaxial braids comprise an integrated structure of yarns oriented in three in-plane directions, which makes them a well-suited choice for multi-axial loading. Their natural through-thickness reinforcement promises excellent specific energy absorption characteristics in combination with a high degree of delamination resistance. Mechanical in-plane properties, however, suffer from the textile nature of braids, as the intertwining yarns inevitably exhibit a certain degree of out-of-plane and in-plane waviness. Hence, a reduction of stiffness and strength can be observed compared to unidirectional composites, accompanied by a more complex damage and failure behavior. In addition, the textile process yields a heterogeneous fiber assembly, which can cause significant variations of the material properties across a braided composite structure. As a result, investigations on multiple textile architectures are usually inevitable.

The determination of representative mechanical properties for braided composites is a challenging task. Due to the complex textile architecture of braided composites, standard test methods developed for tape laminates may not be applicable. In order to obtain an accurate representation of the true material response, the specimen width must be large compared to the size of the material repeating unit cell (RUC).

Based on the ASTM D3039 standard, Masters and Portanova [1] proposed modified specimen dimensions for textile composites. Masters and Ifju conducted an experimental program to characterize the mechanical response and damage behavior of triaxial braided composites with a braiding angle ranging from 63° to 70° [2]. Multiple transverse cracks and delaminations were observed for testing in the transverse direction. Lomov et al. [3] proposed a methodology to study damage initiation and development in different textile composites...

Fig. 1. Triaxial braid (TB) architectures under investigation (a) TB30, (b) TB45, (c) TB60
using a combination of full-field strain measurement, acoustic emission, X-ray computed tomography (CT) and microsections on flat coupons exposed to specific load levels. Littell and Binienda [4] investigated the impact of the resins system on damage development in braided composites using digital image correlation (DIC) techniques. A reduced onset and extent of damage was observed for a toughened compared to untoughened resin system. The presented experimental study serves two major objectives. The first goal is to determine the impact of the braiding angle and off-axis angle on the mechanical properties of 2D 2x2 triaxial braided carbon/epoxy composites under tension. For this purpose, three different braid architectures (TB), with a braiding angle θ of 30°, 45° and 60° are each tested in their take-up (11), transverse (22) and braid yarn direction (1F), respectively. The described architectures are displayed in Fig. 1, where θ denotes the braiding angle and ψ is the angle between the principal material and the load direction.

Secondly, strong emphasis is put on the characterization of the complex material damage and failure behavior. Digital image correlation (DIC) measurement techniques are used to quantify the effects of the textile architecture on the strain field, identify and locate constituent failure mechanisms and investigate damage initiation and development. Microsections of the specimen are analyzed for the purpose of geometrical material characterization and assessment of failure mechanisms in thickness direction. This information shall serve as baseline for the development of a simulation model for predicting the constitutive behavior.

2 Materials

The materials investigated in this study feature 2D 2x2 triaxial braided preforms manufactured from Toho-Tenax® HTS40 F13 12K yarns for both the axial and braider direction in combination with a Hexcel HexFlow® RTM6 resin. All three braid architectures, with a nominal braiding angle of 30°, 45°, and 60°, were manufactured on a circular braiding machine with 176 bobbins. Single layers of triaxial braid were produced by overbraiding on a cylindrical mandrel, which was guided through the braiding point by a robot at constant axial take-up speed, as is displayed in Fig. 2. For each braiding angle, a different mandrel diameter was used in order to obtain full fiber coverage. As a result, similar fiber areal weights were achieved, which allows comparing different braiding angles. Machine parameters were optimized such that the yarn dimensions of all braid architectures match as closely as possible. In order to produce flat panels, each braid layer was cut along the axial yarn direction, removed from the mandrel and flattened.

Fig. 2. Robot assisted braiding

Composite plates were produced with a total of four triaxial braid plies each. For resin infusion, the vacuum assisted process (VAP) technology was selected to minimize void content and to yield similar fiber volume fractions in all plates as a result of constant compaction pressure. The resin system for all braid architectures consisted of a Hexcel HexFlow® RTM 6 resin. This matrix material is a one-part untoughened 180° C cure epoxy system designed for the RTM process. Fiber volume fractions for each panel were obtained from three locations using the acid digestion technique. The TB30 braid architecture panels had a fiber volume fraction ranging from 57-59%, the TB45 55-57% and the TB60 56-57%.

3 Experimental Methods

All monotonic tensile tests were performed according to ASTM D3039 with the recommendations provided by [1]. A specimen width of 25mm was selected in order to cover a minimum of two unit cells, as defined by [5]. An electromechanical H&P testing machine capable of loading 250kN was operated under displacement control with a constant head speed of 2mm/min.
For proper load introduction, fiberglass fabric tabs of 50mm length were bonded to the specimen grip region, leaving a total gage length of 150mm. In case the applied load was not aligned with any of the orthotropic axis, oblique tabs according to Sun [6] were used to minimize stress concentrations due to the presence of material shear-extension coupling.

Full field measurement of surface strains was undertaken using the commercial digital image correlation (DIC) system GOM ARAMIS in 2D mode with a maximum camera resolution of 4 MP. A comprehensive description of DIC can be found in [7]. The field of view was centered at the coupon midpoint and covered approximately 70 mm of the gage length and the entire specimen width. Average stress-strain curves were generated by averaging the entire surface strain field.

4 Analytical Modeling

The overall impact on the elastic properties due to the textile architecture can be approximated by comparing experimental data with equivalent tape laminates using classical lamination theory (CLT). For triaxial braided composites, an equivalent laminate can be constructed by virtually separating all axial and braid yarns and modeling each yarn direction with a single discrete ply of unidirectional, continuous fibers. Hence, no textile architecture is considered, and a quantitative assessment of the mechanical property knockdown may be made in the linear elastic regime. The ratio of axial to total fiber volume content in an equivalent tape laminate can be represented by the individual ply thicknesses:

\[ \frac{t_{AV}}{t_{LAM}} = \frac{\rho_{AV} \cdot \mu_{AV}}{2 \cdot \rho_{BY} \cdot \mu_{BY} \cdot \cos(\theta) + \rho_{AY} \cdot \mu_{AY}} \]

where \( \theta \) is the braiding angle and \( \mu \) and \( \rho \) are the linear density and mass density of the braid and axial yarns, respectively. Using the analytical homogenization by Chamis [8] with the fiber and matrix properties from Table 1, the effective elastic properties can be obtained as a function of the braiding and off-axis angle.

Table 1: Fiber and matrix properties

<table>
<thead>
<tr>
<th>Fiber: Toho Tenax HTS 40</th>
<th>Resin: RTM 6</th>
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</thead>
<tbody>
<tr>
<td>( E_{1f} )</td>
<td>221.9 GPa</td>
</tr>
<tr>
<td>( E_{2f} )</td>
<td>16.4 GPa</td>
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<td>( V_{12f} )</td>
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<td>( E_M )</td>
<td>2.75 GPa</td>
</tr>
<tr>
<td>( \nu_{m} )</td>
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</tbody>
</table>

5 Experimental Results and Discussion

5.1 Elastic behavior

The linearized elastic properties of the three braid
architectures are calculated from the measured stress-strain data for a homogenized longitudinal strain range of \(<\varepsilon> = 0.001\) and 0.003 in accordance with ASTM D3039 [9]. A linear approximation in this strain region allows a reasonable representation of the initial elastic properties for all measured stress-strain curves. The impact of the off-axis angle on the longitudinal Young’s modulus is displayed in Fig. 3. Experimentally obtained values are normalized to a fiber volume fraction of 60% and compared against an analytical prediction using classical lamination theory (CLT). Error bars indicate one standard deviation.

For all three braid architectures, the stiffness predicted by CLT is generally higher compared to the experimental results. For loading in the 11 direction, minor reductions in stiffness can be observed. Here, the elastic properties are governed by the behavior of the predominantly straight axial yarns. A maximum relative error of approximately 10% in this direction may be attributed to two geometrical phenomena: the presence of minor fiber undulations in the axial yarns caused by the braiding process in combination with nesting and uneven compaction. Secondly, axial yarns tend to spread in regions where they are primarily surrounded by matrix pockets and lack support from adjacent braid yarns. The Young’s moduli in the 1F direction are significantly lower compared to their equivalent laminate counterparts. This critical load condition yields the biggest impact on the overall mechanical properties, as the heavily undulated braid yarns are loaded in their longitudinal direction. Fig. 4 illustrates the effect of the braiding angle on the elastic properties. With increasing braiding angle, experimental and predicted moduli in 1F direction deviate progressively. The accompanying increase in braid yarn content contributes more and more to a reduction in mechanical properties. The same effect can be seen inversely for the modulus in the 11 direction. The transverse modulus for the TB30 braid is matrix dominated and therefore largely unaffected by fiber undulations. However, the braid yarns contribute severely to the transverse modulus of the TB45 and TB60 architectures. A maximum relative error of 26% can be observed for the TB45 case.

![Fig. 4: Comparison of experimental and predicted Young's modulus as a function of the braiding angle θ](image-url)
5.2 Non-linear behavior and damage characterization

5.2.1 Loading in 11 direction

The non-linear mechanical behavior of triaxial braided composites is highly anisotropic. Depending on the external state of loading, a degradation of the tangent modulus can be attributed to a combination of constituent damage and plasticity mechanisms. The application of full-field measurement allows to investigate the characteristic damage morphology in terms of crack initiation and propagation on the specimen surface and to assess the impact on the non-linear material response.

Typical tensile stress-strain curves are presented in Fig. 5 for loading different braid architectures in the 11 direction. In addition, the local strain fields in load direction are displayed for a first visible surface crack and right before ultimate failure of the specimen. Crack locations can be identified by artificially high local strains. Dotted lines represent the initial elastic properties. For the TB30 and TB45 architecture, a slight decrease in tangent modulus can be observed. Although the 11 direction is largely dominated by the predominantly straight axial yarns loaded in fiber direction, the braid yarns are subjected to a state of multiaxial stress. Hence, they contribute to the overall nonlinearity. No surface cracks were registered in the TB30 and TB45 braid. The TB60 architecture shows almost linear elastic behavior up to a global threshold strain level of approximately 0.009. Up to this point, strain concentrations intensify at the lateral yarn interfaces until first inter-yarns cracks initiate parallel to the braid fiber direction. As the load is further increased, a combination of inter and intra-yarn cracks form at multiple locations on the specimen surface. Within each yarn, they grow along one braid fiber direction until they are deflected at the adjacent intersecting braid yarn. Hence, a zig-zag crack pattern forms across the specimen width. Above the threshold strain, crack development can be directly correlated with a bulge in the stress-strain curve, accompanied by a sudden decrease in Young’s modulus. Ultimate failure for all architectures occurs within a strain range from 0.013 to 0.015. Damage accumulation causes several braid yarns in the fracture area to lose their capability of supporting shear, which finally triggers rupture of the axial yarns, as is shown in Fig. 6.

5.2.2 Loading in 22 direction

Severe nonlinearities exist in all braid architectures for loading in the transverse (22) direction. The TB60 and TB45 braid exhibit a gradual decrease in stiffness. However, compared to the TB45 case, no

![Fig. 5. Stress-strain response and strain fields for loading in axial (11) direction](image)
discrete cracks appear on the specimen surface of the 60° braid (with exception of edge initiated cracks). Multiple sites of high strain concentrations at elevated load levels correlate with the positions of the underlying axial yarns, possibly indicating subsurface transverse failure events in the specimen. This phenomenon was directly identified in the TB45 braid, as minor gaps in this braid configuration allow local camera vision onto small segments of axial yarns, where most of the initial occurrences of cracks are identified.

Fig. 6: Final failure of a TB30 specimen

Fig. 8 provides a detailed view on the damage development in the surrounding area of an uncovered axial yarn. Fig. 8 (a) highlights the strain concentration located on the axial yarn. A straight crack opens in Fig. 8 (b), running parallel to the axial fiber direction across the entire length of the visible uncovered axial yarn section. In Fig. 8 (c), the crack further develops along the braid fiber direction in opposite directions at the upper and lower boundaries with the braid yarns. The TB30 braid features the most complex damage behavior within this study. Here, the material response can be separated into three distinct domains up to final failure: the elastic domain, the damage progression domain and the saturation domain. As the applied load is increased in the elastic domain, strain concentrations arise in the resin rich areas between adjacent yarns, thus exposing the underlying textile architecture, as is displayed in detail in Fig. 9 (a).

Minor nonlinearities present at the end of the elastic domain are attributed to matrix plasticity. When a critical load level is reached, first inter-yarn cracks form at the boundaries of adjacent yarns at a specific location across the specimen length.

Fig. 7: Stress-strain response and strain fields for loading in transverse (22) direction
Their initial appearance can be correlated with the first major load drop, which marks the point of damage initiation at the end of the elastic domain. As the strain further increases, the load level exhibits a stable plateau as a result of progressive damage development. This behavior is associated with the continuing development of inter-yarn and also intra-yarn cracks across the entire specimen length, originating from the initiation location. Fig. 9 (b) displays a typical crack pattern in the damage progression domain.

When the entire specimen is saturated with cracks, a small increase in load can be observed. In this domain, the existing cracks exhibit further growth. Final failure of the specimen occurs, where multiple cracks coalesce across the specimen width.

5.2.3 Loading in 1F direction

The textile architecture has the greatest impact on the mechanical response for loading in the braid fiber direction, as is shown in Fig. 10. Up to a homogenized strain level $\langle \varepsilon \rangle \approx 0.006$, all braid architectures exhibit approximately linear stress-strain behavior. Beyond this threshold point, distinct load drops can be attributed to a progressive mixed mode failure mechanism intrinsic to the textile architecture: as the external load is coincident with the 1F direction, the aligned braid yarns straighten along their longitudinal direction. Hence, intersecting axial yarns are subjected an out-of-plane movement, which is at first inhibited by the overlying non-aligned braid yarns. As the load is increased, transverse cracks and delaminations develop in these areas. A similar effect was observed by [3]. This process continues, until multiple inter- and intra-yarn cracks appear in the braid yarns along the path of a single underlying axial yarn. Finally, the braid yarns lose their capability to resist the out-of-plane movement, resulting in a sudden delamination of individual fibers.
axial yarns across the entire specimen width. This mechanism is repeated, until all axial yarns have debonded over the specimen length, causing global delamination of the coupon. As a result, separation of braid plies can occur during ultimate failure of the coupon, as is displayed in Fig. 11.

Fig. 11. Ply separation during ultimate failure of TB45 coupon

6 Conclusion

This paper investigated the mechanical response of 2D 2x2 triaxial braided carbon/epoxy composites under tensile load. The decrease in elastic properties of triaxial braided composites was found to be most severe for loading in the 1F direction. This direction also exhibited the most complex damage behavior. A combination of transverse cracks and progressive delamination can significantly reduce ultimate tensile strength in this direction.

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