An examination of initial structural degradation in tubular braided composites through region-by-region strain analysis

Eric A Lepp and Jason P Carey

Abstract
The objective of this study was to characterize the early structural degradation behavior of tubular braided composites (TBCs) under quasi-static tension through direct quantification of the surface strains developed in their yarn-reinforced and unreinforced (resin-rich) material regions. Kevlar-epoxy TBCs with varying braid angles and numbers of yarns were analyzed through quasi-static testing and stereo digital image correlation (DIC) analysis to understand how the yarn-reinforced and resin-rich regions deformed under tensile loads up to the initiation of structural degradation within the braid structure. Structural weakening was confirmed to initiate in the unreinforced, resin-rich regions of the TBC specimens by way of a normal tensile failure mode, as the strains developed within these regions were the first to deviate from a linear-elastic growth trend and also exceed the expected strain to failure of their constituent material. Through two-way full-factorial ANOVA analysis with a 95% confidence interval, the stress required to initiate degradation within these regions was found to depend significantly upon both the quantity and angular orientation of the preform yarns, the former to a markedly lower extent. The maximum strain accumulated in the resin-rich regions upon their degradation was found to not statistically depend on either of these parameters, affirming that it is purely defined by the strength properties of the constituent neat resin material. To provide conservative and repeatable estimates of the stress to failure in TBC structures, it is recommended that this quantity be estimated from both the global stress-strain data of the entire specimen and the local stress-strain data measured exclusively within its resin-rich regions, with the lower of the two taken. Through these means, the relationship between a TBC’s preform geometry and its stress to failure may be optimally modeled using a polynomial regression trend.

Keywords
Composite materials, tubular braiding, structural degradation, strain distribution

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Background and objectives
Polymeric composite materials are advanced structures that use high-strength filler materials, typically of a micro-scale or nano-scale diameter, to reinforce a low-density polymer structure that, on its own, would have comparatively low strength and stiffness. Of the available filler types, continuous microfibers are often used as they are easy to form into a near-net shape, known as a preform,
before being impregnated with polymer resin.\textsuperscript{2,3} The bulk stiffness of these materials is greatly enhanced in the direction that the fibers in the preform are facing.

Two-dimensional (2D) tubular braiding is one method currently used to produce continuous fiber-reinforced polymer composites.\textsuperscript{1–3} In this process, groups of fibers are bundled into a series of yarns, which are interlaced along the outer surface of a cylindrical mandrel to create a near-net shape tubular preform. This structure is impregnated with a polymer resin and cured to produce a hollow, thin-walled tubular braided composite (TBC). These materials may be used in numerous high-strength applications for parts that require low material density, such as sporting goods or aerospace equipment.\textsuperscript{1,4} In addition to allowing the fiber architecture to better maintain its shape before resin impregnation, the crimping of the braided yarns enhances through-thickness stiffness properties in the final composite structure compared to conventional, unidirectional fiber-reinforced composite laminates. The tubular shape of these braided structures readily permits their use as shafts or structural supports compared to planar braid architectures.

An example of a typical TBC before and after resin impregnation is shown in Figure 1. Bounded by a black dotted box on the figure is the TBC unit cell, the smallest repeating volume element of the structure whose geometric and mechanical properties are representative of the entire braided tube. The unit cell itself features a variety of zones of interest, all of which either contain resin that is reinforced with preform yarns (yarn-reinforced content) or unreinforced resin through which yarns do not run (resin-rich content). Neat resin zones entirely composed of resin-rich content develop in the gaps between braided preform yarns. Crossover zones occur where two preform yarns overlap one another. As a result of this overlap, the resin in these zones is almost entirely reinforced by yarns. Finally, undulation zones occur everywhere along a yarn’s braiding path where it is not crossing over or under another yarn, during which the yarn experiences the largest degree of undulation (or crimping). Since only one yarn runs through these zones, there remains a significant amount of resin unreinforced by fibers, leading to a mixture of resin-rich and yarn-reinforced content. Being fully unreinforced, the neat resin zones undergo markedly greater deformation under loading relative to the zones around them.\textsuperscript{5} Generally speaking, the mechanical deformation response of the resin-rich TBC content is so different from that of the yarn-reinforced content that the two are often distinctly separated from one another when determining the TBC bulk mechanical properties through unit cell modeling.\textsuperscript{2,6–14}

For the purposes of this study, the term “resin-rich regions” will refer only to the neat resin zones, and “yarn-reinforced regions” will refer exclusively to the crossover zones. Undulation zones will not be considered due to the complexity involved in determining which of their resin-rich or yarn-reinforced portions contributes to the
mechanical behavior experimentally observed along their surface. Since the other two zones are mainly composed of either resin-rich or yarn-reinforced content, their behavior under tensile loading is assumed to be representative of how reinforced and unreinforced resin responds to applied stress.

The shape of the resin-rich regions in the tubular structure, much like the shape of the braided preform, is largely dependent on two parameters: the braid angle and the number of yarns per unit of the composite tube’s cross-sectional area. Both may be directly controlled and modified by the manufacturer through the preform fabrication process. The braid angle (β in Figure 2), of a preform is defined as the angle made between the interlacing yarns and the longitudinal axis of the preform. The quantity of yarns per unit of the structure’s cross-sectional area dictates the length of space between yarns running parallel to one another (labeled L in Figure 2) as well as the tube’s thickness, which itself affects the yarns’ maximum undulation angle. These two independent properties, and the geometric features of the fiber preform that they consequently influence, have proven significant in dictating the elastic moduli and ultimate tensile strength of the resulting composite structure.

While the linear-elastic properties and ultimate strength of TBCs have seen major study, the point at which these materials first start to show signs of structural degradation, and thus exit the linear-elastic deformation regime, has not been strongly examined. It is important to understand the level of applied stress required for this phenomenon to occur, as it indicates how far we may load TBCs before they begin to lose their structural integrity. Qualitatively, prior research has suggested that the resin-rich areas are the first regions of the TBC structure to cease their linear-elastic deformation behavior and structurally degrade. This is based on the tendency of the preform yarns to converge towards each other like a pair of scissors after initial structural failure, indicating a weakening of the interstitial matrix material between them facilitated by microcracking. However, these same studies have done little to numerically quantify the principal strain state developed locally within the resin-rich regions under increasing load, or the rate at which strain evolves within these regions compared to the yarn-reinforced regions or the braided tube as a whole. This is understandable, as current TBC research has been largely focused on assessing their effective linear-elastic properties for stiffness-critical applications, which does not require region-specific isolation of empirically-measured strains. By contrast, investigating the behavioral differences between the heterogeneous regions of a material is paramount in evaluating its aptitude for strength-critical applications, namely for understanding how structural failure will initiate and the means by which it will progress.

The aim of this study is to present a method for quantifying the region-specific evolution of surface strain along TBC specimens of varying preform geometry loaded in quasi-static tension. TBCs composed of Kevlar yarns and epoxy resin will be evaluated here, though the methodological approach will be applicable to other composite material combinations. This analysis will be used to:

- Verify that structural degradation indeed begins within the resin-rich regions between yarns, rather than within the yarn-reinforced regions themselves.
- Determine the failure mode experienced by the resin-rich regions at the point they cease to exhibit linear-elastic deformation, and which characteristics of the braided preform affect when this structural failure occurs.
- Assess the advantages and drawbacks of using the local stress-strain data gathered exclusively within a TBC’s resin-rich regions, as opposed to its global stress-strain data, to estimate the stress required to initiate degradation within the braided structure.

Though TBCs also experience strain effects in the through-thickness direction, these will not be a point of focus in this study. Based on the anticipated behavior of idealized unit cell representations of TBCs in prior work, as well as the lack of radial warpage observed along TBC surfaces previously loaded experimentally under tension, through-thickness strain is not expected to exhibit complex variation in different regions along the tubular surface like the surface strain does.

**Methods**

**TBC specimen preparation**

About 24 tubular braid preforms were fabricated using a maypole braider (Steeger HS140/36- 91, Steeger GmbH...
and Co., Wuppertal, West Germany) with carriers loaded with Kevlar fiber yarns (Kevlar49, 1420 Denier, Dupont, Mississauga, ON, Canada) following a process previously used by Melenka et al. When interlacing each preform, the machine was set at 1 of 3 distinct braider head and puller speed configurations, producing 1 of 3 possible braid angles for the structure (35°, 45°, or 55°). Braid angles were set at these values to sufficiently represent the full range of angles capable of being produced with the chosen manufacturing setup; yarns braided at angles lower than 30° and greater than 60° would run the risk of jamming against one another. In addition, the braider head was either loaded with eighteen or thirty-six yarn carriers in order to manipulate each preform's yarn count per unit cross-sectional area. This process allowed for preforms with 1 of 6 potential configurations of braid angle and yarn quantity to be produced. Four preforms were produced at each of these configurations. All preforms were interlaced in a diamond braiding pattern along the surface of a mandrel 11.1 mm in diameter and were cut to a length of 178 mm.

Figure 3. Fully-manufactured TBC specimens at each braid configuration.

Once braided and cut to an appropriate size, preforms were coated in a 1:1 mixture of epoxy resin (EPON 826, Hexion Inc., Columbus, OH) and hardening agent (LS-81K, Lindau Chemicals, Inc., Columbia, SC). The resin-hardener mixture was distributed along each preform specimen thoroughly via hand lay-up, ensuring all dry yarns were fully wetted. Next, specimens were placed in an oven (Thelco 31480, GCA/Precision Scientific, Chicago, IL) at 121°C for 1 h, allowing the wet resin to partially harden. This period of pre-curing was immediately followed by a vacuum bag resin consolidation process, where 67.7 kPa of vacuum pressure was applied to each specimen for 12 h. Specimens were removed from the vacuum bagging apparatus and once again inserted into the oven, this time at 160°C for 3 h to complete the resin cure. Figure 3 provides examples of what each braid configuration looked like after manufacturing was completed.

The as-manufactured braid angle of the specimens was determined by taking a high-resolution image of each using a CCD camera (Prosilica GT3400, Allied Vision Technologies GmbH, Stadtroda, Germany), then measuring the angular orientation of their yarns at ten different locations along the portion of their surface that was imaged. Next, each specimen’s inner diameter (dᵢ) and outer diameter (dₒ) was measured using a telescopic gauge (Mitutoyo Series 155, Mitutoyo, Kanagawa, Japan) and a Vernier micrometer (Mitutoyo 115-215, Mitutoyo, Kanagawa, Japan). From these measurements, the cross-sectional area of each composite tube, A, was calculated using the following formula:

\[
A = \frac{\pi}{4} \left( d_o^2 - d_i^2 \right)
\]
Each specimen’s yarn count per unit cross-sectional area was determined using this result. Finally, an extra TBC specimen was produced for each configuration and divided into three segments. Each segment was subjected to a resin burn-off test according to ASTM Standard D3171, from which measurements of the fiber volume fraction of each configuration could be obtained. The resultant measurements for all three of these quantities are detailed in Table 1.

Table 2 displays the mechanical properties associated with the fibers and resin comprising these braided composite specimens. Note that in this table, “strain to failure” refers to the strain at which the listed materials initially begin to structurally degrade and cease deforming in a linear-elastic manner. For the fibers, this is synonymous with the strain at which they fully fracture. By contrast, the epoxy resin may still be deformed well beyond the value listed before undergoing catastrophic breakage, itself typically occurring at approximately 5% tensile strain.

Preparation of specimens for mechanical testing

The ends of each specimen were attached to steel end-tabs using a two-part epoxy (Loctite E-60 HP, Henkel AG & Co., Rocky Hill, CO.) The shape and dimensions of the end tabs are shown in Figure 4.

For each, the two-part epoxy was applied to the tapered rod, which was subsequently inserted into one end of the composite tube. The taper was designed previously to provide better load transfer between the end tabs and the specimen. Once specimens were fully prepared for testing, the hole on the opposite side of each tab could be connected to a grip on the load frame via insertion of a dowel pin.

Next, specimens were coated with matte black spray paint (Painter’s Touch Flat Black, Rust-Oleum Corp, Concord, ON, Canada) along the entirety of their outer surfaces. Once dry, a speckled coating of white acrylic paint (4230 Transparent White, Auto Air-Colors, East Granby, CT), was applied to the surface of each specimen using an airbrush (Paasche H Series, Paasche Air Brush Co., Chicago, IL). This process gave each composite tube a high-contrast speckle pattern along its surface, allowing the deformation across said surface to be clearly visualized through stereo CCD camera imaging.

Quasi-static tensile testing and stereo camera imaging procedure

Specimens were attached to a calibrated load frame (Instron Model 1000, Instron Corporation, Canton, MA). As shown in Figure 5, a pair of CCD cameras (Prosilica GT3400, Allied Vision Technologies GmbH, Stadtruda, Germany) with 35-mm C-mount lenses (LM 35SC, Kowa Optical Projects Co., Tokyo, Japan) were focused upon a common region along each tube’s gauge length at an oblique viewing angle of 15°. These comprised a stereo digital image correlation (DIC) setup capable of measuring the strain along specimen surfaces in three dimensions.

Each camera was positioned to observe a field of view of 63.7 mm × 51.4 mm, with a spatial resolution of 53.3 pixels/mm. This allowed a variety of representative resin-rich and yarn-reinforced regions along each specimen to be observed at once, all while ensuring the surface area of both regions was encompassed within an ample quantity of pixels. An LED lighting system was placed above the cameras to enhance contrast in the camera images. Cameras were calibrated using a three-dimensional dot calibration target placed at the location of each specimen’s gauge length.

Table 1. List of unique braid configurations manufactured for experimentation, along with their key geometrical quantities.

| Configuration (nominal braid angle, number of yarns) | Measured braid angle (°) | Yarns per unit cross-sectional area (yarns/mm²) | Fiber volume fraction (%) | Quantity produced |
|-----------------------------------------------------|--------------------------|-----------------------------------------------|--------------------------|------------------|
| 35°, 18 yarns | 36.2 ± 2.6 | 0.97 ± 0.07 | 14.2 ± 3.2 | 4 |
| 45°, 18 yarns | 45.0 ± 1.0 | 0.99 ± 0.03 | 17.3 ± 2.0 | 4 |
| 55°, 18 yarns | 52.9 ± 1.5 | 0.92 ± 0.11 | 25.8 ± 5.0 | 4 |
| 35°, 36 yarns | 35.7 ± 1.5 | 1.39 ± 0.23 | 25.3 ± 4.3 | 4 |
| 45°, 36 yarns | 45.3 ± 1.3 | 1.37 ± 0.23 | 33.7 ± 5.1 | 4 |
| 55°, 36 yarns | 55.0 ± 0.6 | 1.34 ± 0.29 | 46.4 ± 9.9 | 4 |

Table 2. Key mechanical properties of the braided composite specimens’ material constituents.

|                     | Longitudinal elastic modulus (GPa) | Transverse elastic modulus (GPa) | Major Poisson’s ratio | Shear modulus (GPa) | Strain to failure (%) | Density (kg/m³) |
|---------------------|-----------------------------------|---------------------------------|-----------------------|---------------------|----------------------|-----------------|
| Kevlar 49 fibers    | 112                               | 7.30                            | 0.36                  | 2.86                | 2.4                  | 1.44            |
| EPON 826 Epoxy       | 2.73                              | 2.73                            | 0.30                  | 1.05                | 0.75–1.5a           | 1.16            |

*Approximated from existing tensile test stress-strain curves of EPON 826.
Specimens were placed under stroke-controlled quasi-static tensile loading in accordance with ASTM Testing Standard D3039. The load frame applied a constant crosshead displacement of 2 mm/min, ensuring each braided tube experienced failure within 1–5 min. As each specimen was gradually strained, the cameras simultaneously captured images of its surface at a rate of 0.25 Hz (Figure 6).
During each test, a 5-kN load cell connected to a data acquisition terminal (NI-USB 6211 DAQ, National Instruments, Austin, TX) recorded the tensile load applied to each specimen at a rate of 10 Hz. Specimens were loaded for 5 min or until they underwent full catastrophic fracture, ensuring the end of their linear-elastic deformation regime was encompassed by the test data. Through this method, a full data set was generated for each specimen describing the change in applied tensile load as a function of time elapsed during each test. By dividing the load values recorded over each test by the cross-sectional area measured from their respective specimens, a stress versus time curve was obtained for each braided composite tube.

**Measurement of principal strains in resin-rich and yarn-reinforced material regions via stereo digital image correlation**

The CCD image pairs captured for each tested specimen were imported to a stereo digital image correlation processing program (DaVis version 8.2.0 StrainMaster 3D, LaVision GmbH, Gottingen, Germany). The intrinsic and extrinsic parameters of each camera were calculated using the images of the calibration target taken from each camera in conjunction with the pinhole camera model. These parameters were subsequently used to combine and convert the local, 2D pixel coordinates of the cameras to an equivalent set of global, 3D physical (metric) coordinates. Applying the new coordinate system to the imported image pairs allowed a 3D reconstruction of each specimen’s surface, as visualized by the stereo setup during testing, to be generated.

Prior to evaluating specimen deformation, an intensity normalization filter and sliding average Gaussian filter were applied to all image pairs. The former rescaled the grayscale intensities in each image to follow a standard normal distribution. The latter “smoothed” image grayscale data by evaluating the convolution of 3-pixel × 3-pixel segments of each image with a Gaussian distribution kernel. Combined, these filters ensured consistent image contrast and reduced grayscale noise. Then, for each specimen, a least-squares matching algorithm was applied to every image pair to track the incremental 3D displacement of white speckles across the tubular surface relative to their initial position before loading. The algorithm calculated 3D displacement vectors within a 31 pixel × 31 pixel subset window with a step size of 8 pixels, leading to the generation of a full displacement vector field across the entire specimen surface at each point an image pair was captured.

The multidirectional surface strain fields associated with this displacement data were calculated using the equations (2) to (4). Here, \( d_u \) and \( d_v \) are the change in vector displacement and spacing between adjacent displacement vectors, and \( d_x \) and \( d_y \) are the longitudinal and transverse spacing between adjacent displacement vectors.

\[
\varepsilon_{xx} = \frac{d_u}{d_x} \tag{2}
\]

\[
\varepsilon_{yy} = \frac{d_v}{d_y} \tag{3}
\]

\[
\varepsilon_{xy} = 0.5\left(\frac{d_u}{d_y} + \frac{d_v}{d_x}\right) \tag{4}
\]

For both the longitudinal and transverse directions, changes in vector displacement and spacing were adjusted by the DIC software to always be measured tangent to the contour of the specimen surface, with reference to their reconstructed 3D surface geometry. This accounted not only for subtle changes in surface depth due to yarn undulation, but also the cylindrical curvature of the specimen.
In essence, the cylindrical strain evolved along each specimen surface was approximated by a series of contour-adjusted Cartesian strain calculations made across small portions of the specimen gauge length. Each of these strain values are important to consider in order to appreciate the full extent of deformation occurring within each region of the braided composite specimens. Since TBCs contain obliquely-angled reinforcing fibers, shearing effects in particular may create a non-negligible impact on their strain response, and therefore the magnitude of their contribution must be evaluated and verified. To assess the combined influence of these multidirectional strains, the resultant maximum principal strains across each specimen’s surface was approximated by a series of contour-maps. Since TBCs contain obliquely-angled reinforcing fibers, shearing effects in particular may create a non-negligible impact on their strain response, and therefore the magnitude of their contribution must be evaluated and verified. To assess the combined influence of these multidirectional strains, the resultant maximum principal strains across each specimen’s surface was approximated by a series of contour-maps.

The specific sampling percentages used in this study were arrived upon by running this data collection procedure through multiple iterations, each time highlighting the location of the sampled pixels in each region to observe how well they adhered to the above stipulations. The quantity of strain values sampled within each region was reduced until minimal-to-no outlier pixels were found to be highlighted in unexpected areas (including undulation zones), while ensuring data was still being gathered at a sufficient number of locations along each specimen surface.

In each specimen, for both the resin-rich and yarn-reinforced regions, the mean of the sampled strain values was found to determine the average maximum principal strain evolved at each captured image frame. These values were matched with the corresponding stress values recorded from the specimen at each image frame in order to generate stress versus principal strain curves for both regions.

The normal longitudinal strain fields and shear strain fields generated for each specimen through equations (2) and (4) were additionally imported in MATLAB. Their data was sampled at exactly the same pixel locations as data in the current analysis methodology.

Each specimen’s full set of maximum principal surface strain data generated at each imaging frame was imported into a mathematics and data processing program (MATLAB R2016a, The Mathworks Inc., Natick, MA), where the local strain values uniquely evolved in each braided tube’s yarn-reinforced and non-reinforced regions were identified and recorded over the course of the entire tensile test, as described in Figure 8. For each image frame of a specimen, the upper 1.5% of strain values along its surface was taken to represent the local strain within the resin-rich areas of the composite tube, while the lower 20% of strain values was taken to represent the local strain within the tube’s yarn-reinforced regions. Through this process, strain values in each of these distinct regions could be identified at a variety of locations along the specimen surface, as shown in Figure 9.

In general, the chosen data sampling percentages allowed for at least 10 resin-rich regions and at least 20 yarn-reinforced regions on each observed specimen surface to be analyzed. A larger number of regions reinforced with yarn fibers were sampled in order to account for potential changes in strain magnitude amongst them due to subtle variations in fiber orientation along the specimen surface. To avoid erroneous sampling of strains outside of their corresponding regions, the percentage of the specimen surface that was sampled for each region was kept significantly lower than the percentage of the surface that the region actually occupied. For example, from preliminary measurements of yarn width and spacing in each specimen, all configurations were known to have resin-rich regions that occupied approximately 10% of the structure or greater by surface area, which is far greater than the 1.5% of the specimen surface sampled for resin-rich strain data in the current analysis methodology.

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with the maximum principal strain fields, the average values within each region at each imaging frame were found, and the results were plotted in relation to the corresponding tensile stress values recorded during testing. This way, the relative contribution of normal and shear strain effects on principal strain development in each region could also be monitored.

**Measurement of global stress-strain curves for TBC specimens**

In addition to the region-specific (local) strain data gathered in Sections 2.3 and 2.4, the overall (global) tensile stress-strain behavior of each TBC specimen was also determined.

The evolution of global tensile strain across the full gauge length of each specimen, as observed from the stereo image pairs imported to DaVis, was recorded through application of a virtual strain gauge function. This function
selected 2 points approximately 10 unit cells apart along the centerline of each specimen’s surface, tracked their relative displacement from one another across each image frame, and compared it to their original separation distance. For each specimen, its global strain was measured in this manner at each point during the tensile test where a stereo image pair was taken. The results were paired with the corresponding stress values measured during the test to obtain a global stress-strain curve, which described the bulk tensile stress-strain response of the composite tube.

Results and discussion

Preliminary evaluation of DIC strain fields

Figures 10 and 11 depict the principal surface strain fields computed from one specimen of each braid configuration at various stages of tensile testing. A commonality between all configurations, as expected, was the rapid development of strain in the neat resin regions relative to those fully composed of yarn-reinforced content. As the specimens continue to endure greater tensile deformation, presumably beyond the inception of structural degradation, the elevated strain values developed in the resin-rich regions appear to expand outwards to the adjacent undulation zones, and also very gradually into nearby crossover zones. Knowing that significant portions of unreinforced resin exist within the undulation zones, this suggests that after non-linear deformation begins in the TBCs, elevated surface strains grow along a “path of least resistance” where a minimal amount of yarn-reinforced content will be encountered. Though not explicitly detectable with the DIC camera setup, this trend of accelerated strain growth in unreinforced resin is expected to similarly occur internally throughout each specimen’s thickness. While these observations provide initial qualitative support for non-linear material deformation beginning within the resin-rich regions, we cannot confidently confirm which region is first to exit a linear deformation regime without direct quantification of their local strain development. This underscores the importance of the region-specific strain calculation steps taken in this study.

Validation of location and mode of initial structural degradation in TBCs

The aggregate stress versus principal strain curves determined in the resin-rich regions and yarn-reinforced regions for each unique braid configuration are shown in Figure 12. All curves and their associated error bars display the average and standard deviation of the region-specific stress versus principal strain data measured from their four representative test specimens. At the end of each curve, the associated test specimens reached a point of such extensive resin microcracking that DIC surface strain measurement data could no longer be sufficiently gathered and plotted. While specimens continued to be loaded in tension until they underwent large-scale structural collapse (either by the propagation of resin cracking across the entire composite tube or by catastrophic fiber fracture), the surface damage they accumulated at this point prevented the camera pair from accurately identifying the displacement of the speckles patterned their observed gauge lengths. Nevertheless, each TBC’s transition from linear to non-linear deformation behavior was encompassed within the plotted data range.

From this region-specific principal strain data, along with the data from Table 2, we can verify that the resin-rich regions of the specimens are the first to experience mechanical degradation compared to the yarn-reinforced regions. The yarn-supported portions of the composite tubes are shown to maintain a linear principal strain profile long after the resin-rich areas stop demonstrating linear strain evolution and begin to exhibit degradation in mechanical performance. The fact that the resin-rich areas in each configuration surpass 1.5% strain (the predicted best-case failure initiation strain for pure epoxy resin) well before the yarn-reinforced areas reach even 0.75% strain (the predicted worst-case failure initiation strain for either material constituent) supports the argument that the resin-rich areas are critical when considering a first-region-to-failure analysis.

The yarn-reinforced regions not only fail to reach 0.75% strain by the time the resin-rich regions reach a strain of 1.5%, but they also barely reach (or slightly fall short of) half of that value. This suggests that even for a relatively weak fiber additive like E-glass, which has a Young’s modulus only 65% to 75% as high as Kevlar’s while exhibiting a comparable strain to failure, it can still be expected for the resin-rich regions to structurally degrade first. Thus, the results here are likely to apply to a wide assortment of synthetic linear-elastic braided fiber yarn materials when impregnated with a Bisphenol-A resin, such as EPON 826. Natural fiber braided composites, while shown to exhibit similar macroscopic failure behavior upon exiting the linear-elastic deformation regime, are notably weaker in stiffness than even E-glass in their yarn-reinforced regions. As a result, these braided structures in particular may require further investigation, perhaps on a case-by-case basis, to determine whether structural degradation still initiates in the resin-rich regions.

Figure 13(a) and 13(b) depict the aggregate growth of longitudinal and shear strain within the same set of resin-rich regions sampled from the four specimens of each braid configuration. Both of these strain components contributed to the maximum principal strain profiles shown in Figure 12(a).

This data shows that normal strain developed in the direction of the applied tensile load made a far more dominant contribution to principal strain evolution in the
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resin than any shear strain effects. As such, the resin-rich regions should be expected to undergo a predominantly normal tensile failure mode as they begin to degrade. This conclusion is supported further by existing research into the behavior of EPON 826 epoxy resin under pure tensile, compressive, and shear loading.\textsuperscript{30} The principal strain profile

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**Figure 10.** Progression of principal surface strain along 18-yarn braid configurations under increasing tensile stress.
obtained in the resin-rich regions of the TBCs in the current study match most strongly with the behavior previously observed for EPON 826 under pure tensile loading, since the resin loses linearity at a similar strain value and does not exhibit the same stress relaxation beyond the linear-elastic regime as was observed under pure compression or shear.
Though not as pronounced as tensile normal strain, shear strain in the resin-rich regions still makes a non-zero contribution to the resultant principal strain. Therefore, it is still recommended that the maximum principal strain be recorded in its entirety within these regions when tracking the evolution of their deformation, so as to properly account for both the relevant normal and shear strain effects altogether. The cause of this shear development is likely due to the fact that the reinforcing fibers apply force to the surrounding resin along their bonding interface, which runs at an oblique angle to the TBC’s longitudinal axis. As braid angle increases, so do the severity of these oblique shearing forces. Though the applied shearing forces from yarn fibers running in opposite directions should theoretically offset one another, subtle differences in angle between adjacent yarns can facilitate the observed non-zero shear strain development. With yarns in typical TBCs anticipated to exhibit misalignments of up to $\pm 3^\circ$ from their intended value, unbalanced shear deformation in their resin-rich zones should always be thoughtfully considered.\textsuperscript{31}

**Effect of braid preform manufacturing parameters on failure initiation in TBCs**

The applied tensile stress required to initiate structural degradation in each specimen’s resin-rich regions was measured by determining the proportional limit of their associated localized stress-strain curve. First, the linear-elastic portion of the specimen’s resin-rich deformation profile was fit to a least-squares linear regression function (using five data points comfortably within the linear-elastic

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**Figure 12.** Local growth of maximum principal surface strain in each braid configuration in the (a) resin-rich and (b) yarn-reinforced regions when placed under increasing tensile load.

**Figure 13.** (a) Longitudinal normal strain and (b) shear strain evolved in the resin-rich regions of every TBC configuration.
regime to construct the fit line). Then, the corresponding proportional limit was defined as the point at which the measured applied stress deviated from its expected linear growth (as dictated by the regression line) by a value exceeding δ:

\[ \delta = S \ast t_{0.025,4} \]  

where \( S \) is the standard deviation in stress of the five data points from their associated regression line and \( t_{0.025,4} \) is the value of the two-tailed student’s t-distribution for five data points (four degrees of freedom) at 95% confidence. Through this technique, it was assured that a numerically-quantifiable, statistically-sound estimate of the proportional limit could be determined. Both the applied stress on the specimen and the principal strain within the neat resin regions were recorded at the proportional limit once it was located. Figure 14 provides a graphical demonstration of the above-mentioned calculation technique.

The applied tensile stress and resin-rich strain developed in each specimen at their specified local proportional limit are displayed in Figure 15, with respect to their preform braid angle and yarn count. These data plots were constructed using the empirically-measured braid angles of the specimens, rather than their nominal braid angle values.

Previous research and analysis has shown that both the braid angle and yarn quantity in a TBC have a noticeable impact on the rate of global and local strain development in the whole structure and its resin-rich regions, respectively. However, it is not yet known if they similarly affect the applied tensile stress required to initiate local structural degradation within these structures, or the local strain developed in their resin-rich regions upon the beginning of their degradation regime. Thus, a full factorial analysis of variance (ANOVA) test with a 95% confidence interval was carried out using the proportional limit data collected from the specimens to determine whether the modifications made to their braiding angle or their number of yarns per unit cross-sectional area had any significant effect on the value of applied tensile stress, or local strain, required to induce structural weakening of their resin-rich regions. Statistical analysis was limited only to these two factors as they are the two most prominent mutually exclusive parameters affecting preform geometry, fiber deposition density, and fiber/matrix volume fraction that are able to be directly and deliberately manipulated through the manufacturing process. Most other methods of quantitatively and qualitatively representing TBC geometry change as a direct consequence of the manipulation of these two factors.

Only the linear effects of these two braiding parameters, as well as their interaction, were assessed for statistical significance, as preliminary ANOVA tests showed that quadratic effects for both parameters held negligible significance.

To analyze the applied stress required to degrade the resin-rich regions via ANOVA, the data points from Figure 15(a) were assigned to one of three braid angle factor levels (35°, 45°, or 55°) and one of two yarn quantity levels (18 yarns or 36 yarns), based upon the nominal braid angle and yarn count of the specimen they were obtained from. This created a full factorial dataset with four replicates appropriate for statistical evaluation. The same process was carried out with the data points in Figure 15(b) to perform ANOVA testing for the strain developed in the resin-rich regions upon degradation. In Table 3, the \( p \)-values of the two factors and their combined interaction, as calculated from each ANOVA test, are displayed with respect to the response variables of applied stress and resin-rich strain measured at the proportional limit.

A \( p \)-value of 0.05 or less denotes that the parameter/interaction holds a statistically significant influence over the global stress or local resin-rich strain at the proportional limit of the TBCs.

The results indicate that the tensile stress required to initialize structural weakening in the resin-rich regions of the TBCs is significantly influenced by both the angular orientation of the braided preform yarns as well as the quantity of yarns built into the structure. Of these two parameters, the proportional limit stresses of the TBCs are particularly sensitive to braid angle modification. Unit cell modeling is often used to determine the directional elastic moduli of TBCs, which have a similarly prominent dependence on the orientation angle of the braided yarns. Thus, such techniques may serve as an equally valid starting point for analytical prediction of the required stress to induce degradation in the resin-rich portions of TBCs. Alteration of the quantity of yarns per unit area, by contrast, is much less prominent in affecting the stress to failure of the TBC specimens despite still demonstrating statistical significance. In addition, the interaction of the two preform manufacturing parameters does not show significance within 95% confidence. These are also important factors for calculating TBC...
elast properties through construction of unit cell models. As a result, altering the number of yarns in a TBC’s construction, despite affecting a clear change in its overall linear-elastic deformation under load, may not cause an equally noteworthy change in the tension required for its linear deformation regime to end. When manufacturing a braided composite structure, changing the quantity of yarns within the preform may be a useful technique for finely adjusting its proportional limit strength without compromising its desired braid angle value.

By contrast, the maximum principal strain developed within the resin-rich regions at the end of their linear-elastic regime was determined to not be significantly influenced by either manufacturing parameter nor by their interaction. Therefore, it may be concluded that the local proportional limit strain within these critical regions is fully dependent on the inherent material properties of the pure epoxy that comprises them. Figure 15(b) supports this as no definitive increasing or decreasing trend is seen in the data across differing braid angles and yarn counts. The resin-rich proportional limit strain across all specimens works out to an average value of 1.08%, well within the expected range of proportional limit strain values for EPON 826 resin as seen in Table 2. Ergo, should the proportional limit stress and strain be predicted analytically, it should prove especially useful to approach the problem with a strain-based brittle material failure criterion, since failure in the resin-rich regions is anticipated to occur by their deformation reaching an unchanging material-specific threshold.

Table 3. ANOVA test results for each preform braiding parameter with respect to applied stress and local principal strain at the initial structural degradation point of TBCs.

| Parameter                        | Calculated p-value for                |
|----------------------------------|---------------------------------------|
|                                  | Applied stress required to initiate non-linear deformation in resin-rich regions | Principal surface strain in resin-rich regions upon initiation of non-linear deformation |
| Braid angle (A)                  | $<0.001$                              | 0.715                       |
| Number of yarns per unit cross-sectional area (B) | 0.009                                 | 0.118                       |
| Interaction between A and B      | 0.273                                 | 0.398                       |

Bold numbers indicate a significant difference at $p < 0.05$.

Figure 15. (a) Applied tensile stress and (b) local, resin-rich principal surface strain measured at each test specimen’s proportional limit, plotted with respect to their braid angle and preform yarn count.

Comparison of failure stress values estimated from local and global stress-strain curves

Figure 16 displays the global stress-strain curves measured from each braid configuration. Once again, the curves and...
their error bars are based upon the average and standard deviation of the global stress-strain data measured from their four representative test specimens. The same proportional limit measurement technique from the previous section was applied to these curves in order to determine how the proportional limit stresses estimated from the global TBC data compared to those determined locally within the failure-prone resin-rich regions. The globally-estimated proportional limit stresses of each individual specimen relative to their empirically-measured braid angles are given in Figure 17.

Compared to the values measured locally in the specimens’ resin-rich regions in Figure 15(a), the proportional limit stress values estimated from the global stress-strain curves were generally less consistent between specimens of the same nominal preform configuration. Though consistency in the measurements for specimens with 36 yarns was approximately equal between values estimated from the global curves and those estimated from the local resin-rich region data, the globally-determined data experienced a dramatic drop in relative consistency in the specimens with 18 yarns. However, the majority of specimens yielded a lower proportional limit stress estimate from the globally-determined curves, which would be more pertinent to report for the sake of engineering safety. These results highlight the advantages of estimating the damage initiation stress of TBCs using either dataset. Since it is measured across the entirety of the braided structure’s observed surface, the global stress-strain data contains lower systematic error, meaning that a loss of linearity can be detected with statistical confidence sooner and low, conservative proportional limit stress estimates may be made. By contrast, stress-strain data gathered locally within only the resin-rich regions data experienced a loss of linearity due to braid angle variations. The lower of the two values determined on a specimen-local basis was considered in tandem, with the more conservative of the two values determined on a specimen-local basis. The lower of the globally and locally-determined stress values for each specimen, as a function of their measured braid angle, is given in Figure 18.

As envisioned, this data ensures proportional limit stress values are kept as low as possible while also presenting measurement repeatability comparable to what was seen with the failure stresses determined solely within the resin-rich regions. Ergo, it may be concluded that the optimal way to estimate the stress required to initiate structural degradation in TBCs is to apply the presented proportional limit determination methods to both their global and local, resin-rich stress-strain curves, taking the lower of the two values.

These conservative and repeatable failure stress estimates may prove beneficial to use in conjunction with the Ramberg-Osgood equation, which has been shown to adequately predict the shape of the full global stress-strain profile of TBCs. Though the equation typically uses the yield stress of the material-of-interest as an input variable, proportional limit stress values determined through the current method could be inserted in its place as they are a more relevant durability metric for the brittle resin material constituting TBCs.

**Conclusion**

This study used a region-by-region surface strain quantification technique to determine the nature of heterogeneous strain evolution TBCs up to their initial structural degradation. From the analysis, the following key points were validated:

- Structural weakening was confirmed to initiate in the resin-rich regions of TBCs rather than yarn-reinforced regions, and occurred via a normal tensile failure mode. The applied stress required to reach the proportional limit in these regions was dependent upon both the braid angle of the preform yarns (to a great extent) and the proportion of yarn content in the composite structure (to a lesser extent). Neither of these parameters caused significant variation in the surface strains evolved in the resin-rich regions upon the initiation of their localized degradation, suggesting that the strain to failure within these regions is purely based on a material-specific brittle failure threshold.
- The stress required to initiate structural degradation in TBCs may be estimated using either stress-strain data collected locally within its resin-rich regions or global stress-strain data measured across the structure’s gauge length. The former yields results with superior repeatability between specimens of a similar configuration, while the latter tends to produce lower,
more conservative results. To reap the benefits each of these strategies offers, it is recommended that the lower of the two estimated values be considered for each specimen.

The ability of this analysis method to relate global loading to localized deformation may prove useful for further research into mechanical analysis of TBCs or similar heterogeneous composite material structures. In addition, the data gathered here suggests that unit cell modeling may be a feasible avenue for future research into analytically estimating the point at which non-linear deformation and structural damage initiates within the resin-rich regions of TBCs.

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ORCID iD
Eric A Lepp https://orcid.org/0000-0002-1820-7718

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