UNIT CELL MODELING OF FAILURE BEHAVIOR FOR STATICALLY-LOADED KEVLAR FIBER TUBULAR BRAIDED COMPOSITES IN TENSION

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ABSTRACT

In this paper, the anticipated behaviors of Kevlar/epoxy tubular braided composites undergoing tensile failure are determined using a theoretical unit cell model. Through assessing the reaction of the different regions of the unit cell to a longitudinal tensile load, initial yielding was expected to initiate via cracking and degradation of regions of pure resin between interlocking yarns. This left only the undulating yarn regions of the unit cell intact which, as approximated by laminate plate failure theory, would fail by way of transverse cracking of the resin directly surrounding the yarn fibers, which would, in turn, progressively degrade the entirety of the resin in the yarn region. This was expected to make the yarn fibers lose their rigid shape and jam against one another. These theoretical expectations for composite tube failure behavior were verified by loading manufactured Kevlar/epoxy braided tube samples all the way up to full fiber fracture. By observing the resulting strain distribution on the tubular surface just before initial yield, the qualitative progression of damage along the length of the tubes, and the general load/displacement trends exhibited by each sample, the behavior of the theoretical unit cell model was shown to mirror the actual degradation process of the tubular composites it represented.

1 INTRODUCTION

Tubular braiding is a common method for manufacturing fiber-reinforced polymeric composite materials. Bundles of fibers are twisted together to form yarns, which are then woven together in an interlocking pattern along a cylindrical mandrel. This fiber preform is impregnated with a hardened polymer resin, resulting in a tube-shaped structure with fibers embedded in a polymer matrix. Tubular braided composites are lightweight but strong materials whose mechanical properties are easily tailorable by adjusting the angle at which yarns are woven together. They have several practical applications such as sporting goods and aviation equipment. Figure 1 displays what these composite materials look like before and after impregnation with a resin matrix

Braided tubular composites have limitations that make their behavior under loading difficult to predict. Since the fibers comprising the tube structure not only weave at an angle to the tube's longitudinal axis, but also undulate over and under neighboring yarns, the geometry of the structure is more difficult to incorporate into a theoretical model compared to simple unidirectional composite laminates. Additionally, the existence of distinct regions in the matrix through which fiber yarns do not pass means that the structure's stiffness and strain may easily vary with position [1]. In particular, little work has been done in the literature to assess the failure regimes of braided tubular composites in tension.

When considering the mechanical stress-strain properties of a composite material, it is useful to analyze the smallest repeating element of the material's structure, known as the unit cell [1]. Its properties are representative of the material as a whole, under the assumption that the material's geometrical properties remain constant along its entire length. The purpose of this study is to use a simple unit cell model of a Kevlar/epoxy braided composite tube to determine the mode by which it will initially yield under a tensile load, and to predict the means by which damage will progress in the structure beyond this point of yield**.** The estimated failure behavior will be compared to empirical test data gathered from Kevlar-epoxy composite samples of similar braid angle and yarn spacing. Should the analytical methods used in this study be combined with established mathematical formulae for failure analysis, they have the potential to further the usage of tubular braided composites in industry, as it would ease the process of determining whether or not said materials could be put under certain static loading conditions while avoiding failure.

Figure 1: Non-impregnated tubular braided composite yarn preforms (left) and fully-fabricated braided composite tubes impregnated with a resin matrix (right)

2 LITERATURE REVIEW AND MODELING STRATEGY

The representative unit cell for a tubular braided composite is shown in Figure 2, and contains one full weaving period for two adjacent yarns running in opposite directions, along with the matrix surrounding them. Here, s_{yarn} is the spacing between parallel yarns (hereafter known as yarn spacing), w_{yarn} is the yarn width, β is the braid angle, and r_i and r_o are the inner and outer radii of the unit cell, respectively.

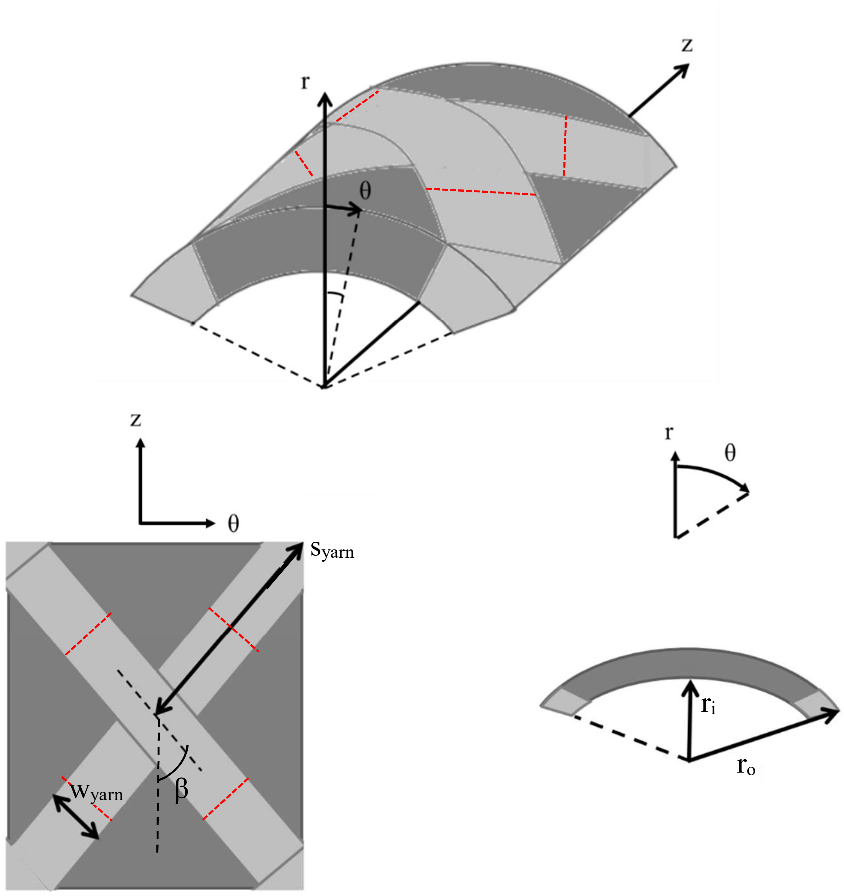

Figure 2: Isometric (top), overhead (bottom-left) and side (bottom-right) views of a tubular braided composite unit cell. Note that the unit cell is described in cylindrical coordinates. The light gray denotes regions where continuous fiber yarns undulate and weave past one another, while the dark gray indicates regions composed of pure, neat matrix material. The red lines denote where each yarn transitions from weaving over to weaving under the yarns it crosses, and vice versa. Note that there is still resin material in the yarn regions which old the fibers in place.

This curved variant of the braided unit cell, defined in cylindrical coordinates, was analyzed by Ayranci and Carey to determine its three-dimensional mechanical properties [2]. The yarn regions (light gray) along the unit cell were assumed to undulate with a sinusoidal pattern, and had their stiffness properties analyzed by treating each infinitesimal section as an angled fiber laminate, with fiber orientation defined by the yarn's undulation angle at that point. The stiffness properties of the neat resin regions (dark gray) between the yarns were accounted for as well, and a surface area average was taken along the entire unit cell to obtain its overall stiffness properties. Properties included the elastic moduli in the longitudinal, transverse, and through-thickness directions (E_z, E_θ, and E_r), Poisson's ratio in all directions ($\nu_{z\theta}$, ν_{zr}, and $\nu_{\theta r}$), and shear moduli in all directions ($G_{z\theta}$, G_{zr}, and $G_{\theta r}$). From this point onward, the z-θ plane of the unit cell will be treated as a flat plane, neglecting curvature, to simplify the modeling process; it was shown by Ayranci and Carey that it had little effect on properties [2].

Once the elastic properties of the braided composite are determined in this way, an estimate of how much a tubular composite sample will deform, transversely ($\varepsilon_{c,\theta}$) and longitudinally ($\varepsilon_{c,z}$), under a given tensile load, σ_z, may be found.

The woven yarn regions will alter in position in order to accommodate the change in length and diameter of the tube due to these strains, as illustrated in Figure 3.

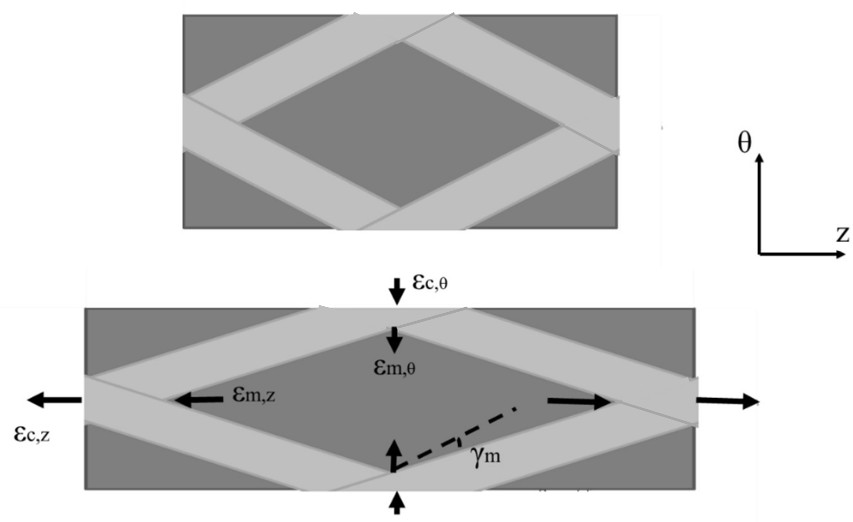

Figure 3: Schematic of tubular composite unit cell in an unstrained (Top) and strained (Bottom) state. As the unit cell as a whole is strained, the inner region of resin in between crossing yarns experiences a local strain state. Note that this figure shows only in-plane strains

As demonstrated in Figure 3, when put under a tensile stress, neighboring yarn regions in a tubular braided composite tend to experience a decrease in angular spacing between one another as they are extended in the direction of the applied force, a phenomenon known as scissoring [3]. Here, an assumption may be made that, since the tensile stiffness of embedded fibers in the composite is far larger than that associated with the resin material, the embedded yarn regions of the unit cell exhibit negligible strain due to the tensile load when compared to the neat resin regions between them. Under this assumption, the change in orientation of the woven yarn regions causes a significant change in shape for the diamond-shaped region of pure resin in between them. Depending on how far in the unit cell's planar directions the neighboring yarn regions migrate, and how much their angular separation decreases, a particular local strain reaction will evolve in the resin-rich pocket of material between the yarns. Since this region is expected to both receive the brunt of the strain in the unit cell while also exhibiting far lower strength properties than the yarn regions, this diamond of neat resin material may reasonably be expected to be the first portion of the unit cell to fail, giving way to yielding in the entire structure.

As shown in the figure, $\varepsilon_{m,z}$, $\varepsilon_{m,\theta}$, and γ_m are the longitudinal, transverse, and shear strains developed locally in the resin-rich pocket of the unit cell. By comparing the directional and angular displacement of this region to its original shape, a strain state like that shown in Figure 4 will develop. Note that the resin-filled region will also experience a through-thickness strain $\varepsilon_{m,r}$.

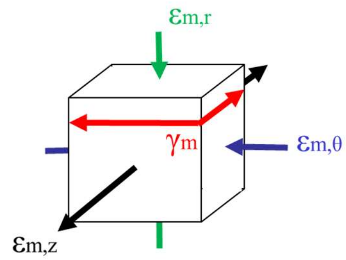

Figure 4: Illustration of the three-dimensional strain state acting upon an infinitesimal portion of the resin-rich region of the tubular composite unit cell, due to scissoring in the surrounding yarns.

This three-dimensional strain state is equivalent to a stress state in the unit cell's z-θ plane ($\sigma_{m,z}$, $\sigma_{m,\theta}$, τ_m). A planar stress state is assumed here since the yarns of the unit cell do not contact or border the resin-rich regions in the r direction, and thus would not be expected to transfer load to the region through scissoring. This, in turn, is equivalent to a pair of planar tensile and compressive principal stresses, σ_1 and σ_2, which dictate when the neat resin region will fail in a brittle fashion to initiate yielding in the composite tube.

Once a braided composite tube initially yields and ends its elastic regime, a damaged region of reduced diameter forms around the point of yielding which steadily begins to propagate through the length of the sample under a state of constant stress, as observed by Harte and Fleck [3]. The exact nature of how this damaged region propagates may be further elaborated upon by once again considering the newly-yielded unit cell.

In the unit cell's state after initial yield, only the non-degraded yarn regions remain to be considered. For the yarn regions depicted in the unit cell, it is known that the fibers are oriented furthest from the unit cell's longitudinal axis approximately halfway between their crossover points with neighboring yarn regions (shown in red in Figures 1 and 5) where they transition between weaving over and weaving under the unit cell's midplane. Both the undulation and braid angle of the yarn cause fibers at these points to experience a largely transverse loading state even when a tensile longitudinal load is applied to the entire unit cell. By idealizing the yarn regions as angled laminate plates, as was done by Ayranci and Carey, these transition points may be examined using the partially discounted stiffness method of progressive laminate failure [2,4]. Under the assumptions of this failure criterion, the transition points are highly likely to fail first via transverse cracking in the matrix directly surrounding the yarn fibers, which should progressively break down the remainder of the resin in the yarn region within a short time. Once all the resin immediately surrounding the yarns in the unit cell cracks and degrades the yarns will be unable to maintain their rigid shape and will slide into one another. This "locked" state in which yarns directly contact one another and impede each other's movement is known as jamming [5]. The entire damage propagation in the unit cell is summarized in Figure 5. When considering an entire composite tube, this jamming effect will steadily move across the material as more and more transition points along its length progressively break down in this same manner under the same loading value, until eventually the entire sample jams. This signifies the point past which further loading of the composite tube should be critically avoided, as past this point catastrophic fracture of the yarn fibers is imminent

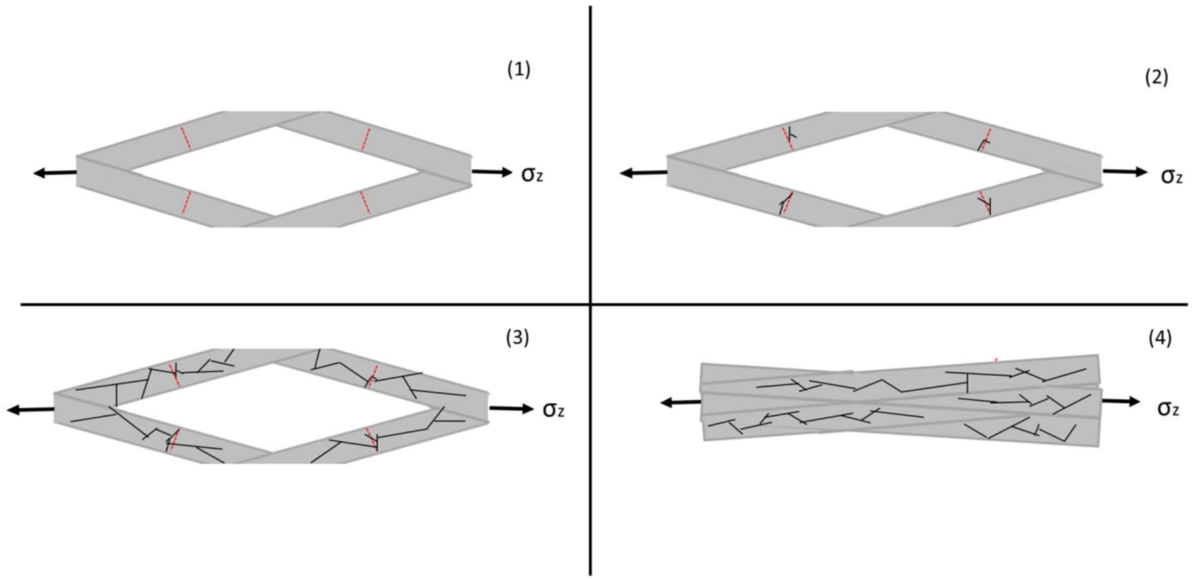

Figure 5: Steps in the unit cell's damage propagation process. (1) Yielded resin-rich regions are fully discounted, leaving only the yarn regions intact. (2) Transverse matrix cracking initiates at the transition points of the yarns (3) Cracking progressively moves through the remainder of the yarn regions, degrading the matrix material around the fibers (4) The yarn regions lose their rigid shape and jam together

3 TESTING METHODOLOGY

As a means of comparing the actual failure conditions of tubular Kevlar/epoxy braided composites to the unit cell model above, six test samples to be subjected to quasi-static loading conditions up to the prescribed failure points were produced. All samples were created with an 11.1-mm internal diameter, a 45° nominal braid angle, and a circumferential spacing between parallel yarns of 3.89 mm.

The first step of creating each tubular composite sample was to weave a series of Kevlar fiber yarns into an interlocking preform. Spools of 1420 Denier Kevlar fiber (Kevlar 49, Dupont, Mississauga, ON) were mounted to half (18) of the carriers of a maypole braiding machine (Steeger USA, K80-72, Inman, SC). Each spooled fiber bundle was attached to an 11.1 mm-diameter mandrel, which was pulled forward as the maypole braider head wove interlocking yarns along its surface.

After all of the preforms were fabricated, each sample was impregnated with thermoset epoxy. First, each sample preform was fit onto a cylindrical plastic mandrel, where the resin (EPON 825, Momentive Specialty Chemicals Inc., Columbus OH) and hardener (Ancamine 1482, Air Products, Allentown PA) components of the epoxy were mixed in a 100:19 ratio and applied to the interlocking yarns through hand lay-up. The wetted samples were then heated in an oven for three hours at 120 °C to fully cure the epoxy. Once fully cured, all samples were cut down to a length of 7" (177.8 mm). As only qualitative observations and general load-displacements trends were desired from testing these samples, measurements of their inner and outer diameters, as well as their yarn spacing and yarn width, were not required.

Five of the six samples were directly tested in quasi-static tension. Each tube was connected to a calibrated tensile load frame (Instron 1000, Instron, Norwood, MA) with a 1000-lb (5-kN) load cell. Samples were strained at a quasi-static rate of 2 mm/min, with the corresponding tensile stress measured by the load cell being recorded to a MATLAB data file by way of a digital acquisition terminal (NI-USB 6211 DAQ, National Instruments, Austin, TX).. Once failure initiated in the sample and it ceased to behave elastically, the sample was strained until full fiber fracture occurred. The shape of the load-displacement curve produced by each of the five samples could therefore be tracked all the way from elastic deformation to final failure.

The remaining sample was loaded in a similar manner, but only up to its initial yielding point at a stroke rate of 1 mm/min. Before this trial began, the sample was coated with matte black spray-paint (Krylon 51602 Flat Black Interior- Exterior Paint), with white acrylic paint lightly applied overtop with an airbrush (Custom Micron-B, Iwata-Medea Inc., Portland, OR) in order to produce a fine, high-contrast speckle pattern on the sample surface Then, while this sample was stressed in the elastic regime, a high-resolution CCD gigE Vision camera (Prosilica GT3300, Allied Vision Technology, Stadtroda, Germany) was used to capture images of the strained tube every ten seconds. The movement of the speckle pattern on the sample surface, as captured by the camera images, was converted into a strain field measurement via a digital image correlation (DIC) program (DaVis, LaVision, Ypsilanti, MI). These results served to show how strain was distributed across the sample during initial elastic loading.

4 MODEL VALIDATION RESULTS

The load-displacement curves generated for the five samples loaded to full fracture are shown in Figure 6. All curves consistently show the samples undergo the same expected failure procedure described in the unit cell modeling process: a linear-elastic deformation regime which ends at a clearly-defined peak yield strain, after which material strain and damage carries on and propagates at an approximately steady, level load value until the entire sample's length jams.

Once these samples experience jamming across their entire gauge length (at the end of the steady-state damage propagation region on the associated plots), the Kevlar fibers generally experienced linear deformation until full fracture (in the case of sample 3, fracture may have occurred early due to imperfections in consolidating the yarns and the matrix material, or the existence of excessive voids in the matrix material itself, which potentially hampered the even distribution of load to individual yarn fibers) . This is a consequence of the jammed fibers, barely supported by a degraded matrix, being elastically deformed, and demonstrates that, past the point of full sample damage and yarn jamming, failure of the samples happens in a sudden, catastrophic manner akin to any neat brittle material. As such, the strain at full yarn jamming is an important quantity to determine, as it signifies the point past which the sample should never be loaded further in order to avoid the risk of unexpected and catastrophic failure.

If, in the future, the unit cell model were to be used to mathematically determine the stress and strain values associated with the different stages of failure in composite tubes, a series of failure-based milestones could be extracted from these plots, as listed in Table 1, that would be useful to quantify. As described above, any milestones past the point of full yarn jamming are not as pertinent to explore, as by this point the tube has fully lost its shape, making it not only dangerous, but also highly impractical, to use any further.

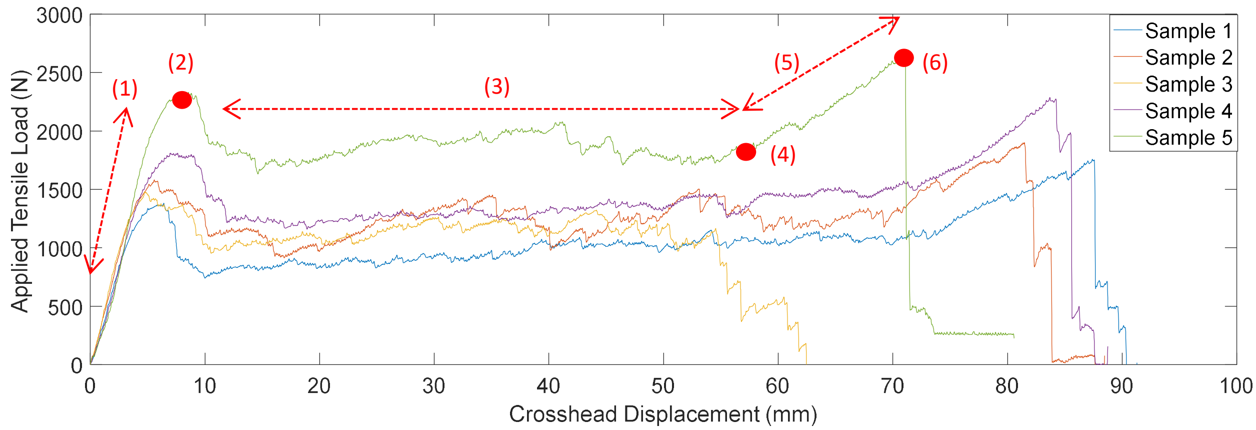

Figure 6: Load-displacement curves generated for Kevlar/epoxy tubes loaded to fracture

Ref #	Quantity
1	Elastic deformation region used to calculate elastic modulus using constant cross sectional area
2	Stress/strain point of initial yield based on gauge length and constant cross sectional area
3	Near constant load bearing region during damage propagation
4	Deformation at full tubular jamming
5	Elastic response of fully-jammed sample
6	Load and deformation at final fiber fracture

Table 1: Quantifiable properties of tubular braided composite behavior to failure (as denoted on the curve for sample 5)

The DIC strain field gathered from the remaining sample, just before the onset of initial yielding, is shown in Figure 7. Here, it may be seen that, as predicted by the unit cell model, strain accumulates mainly in the resin-rich regions between undulating yarns, which themselves exhibit a comparatively negligible amount of strain (roughly less than or equal to 10% of what is experienced in resin-rich regions).The small holes in the middle of some of these resin-rich regions where no strain field data exists are where openings have already begun to form in the sample's surface, suggesting predictably that cracking begins in these regions of resin well before the yarn regions see any noticeable damage.

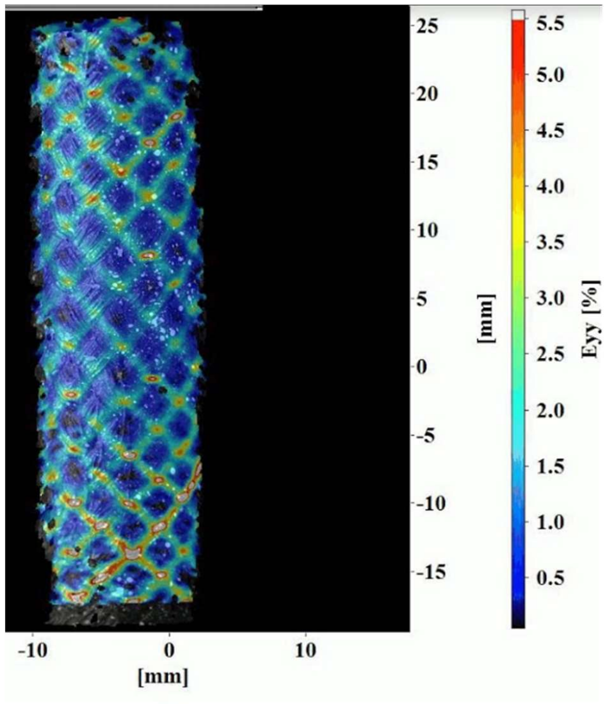

Figure 7: DIC strain fields gathered from a Kevlar/epoxy composite tube just before) initial yielding. Longitudinal strain is quantified.

Past the initial yield point, the five fully-tested samples were qualitatively observed to demonstrate the damage propagation procedure predicted by the proposed model. The initial damaged portion of the material grew and moved along the gauge length of each sample as demonstrated in Figure 8. Each time the damaged region grew, a clearly audible cracking occurred in the matrix surrounding the yarns, followed by said yarns slipping and jamming against one another. This behavior is consistent with the assumption that these yarn regions would fail by transverse cracking in the matrix holding them together, thereby degrading their ability to maintain their shape. Such a reaction is one that may easily be modeled using progressive laminate failure analysis and the partially discounted stiffness method, which is the reason it was employed when considering the unit cell.

Figure 8: Growth of a damaged region in a manufactured composite tube sample shortly after initial yielding. Notice how, when damaged, the yarns immediately move to their jamming angle.

5 CONCLUSION

The objective of this study was to theoretically determine the means by which braided composite tubes will cease to behave elastically and begin to fail based on the reaction of a representative unit cell model to tensile stress. This same unit cell was also examined to describe, in detail, how the subsequent regime of damage propagation along the composite tube would progress. Tensile testing to fracture, along with strain field measurement of samples in the elastic deformation region, were used to validate that the behaviors that may reasonably be observed in the composite unit cell were consistent to how composite tubes behaved in reality.

For future work, previously-devised mathematical failure criteria will be applied to the presented models of tubular yielding and damage propagation in order to predict specific stress and strain values at which they occur, purely based on the material and geometric properties of the fiber and resin constituents. Such a model would permit engineers and manufacturers to more easily assess the loading limitations of composite materials, in order to ensure they operate safely with elastic stress-strain behavior. Past initial failure and yielding, the additional quasi-static information to be gathered for this model would provide limitations on how much stress could be applied to the material to prevent the spread of a necking region across the entire tube, and would identify how much the tube would deform before transitioning to a regime where catastrophic fiber fracture is likely to occur. Put together, the stress-strain quantities that are sought through this modeling procedure would also allow the general shape of a composite tube's stress-strain curve to be predicted in great detail.

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