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PRELIMINARY ANALYSIS OF DYNAMIC FREQUENCY & ARCHITECTURE ON THE FATIGUE LIFE OF TUBULAR BRAIDED COMPOSITES

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ABSTRACT

This study investigated the influence that the thickness, spacing, and orientation angle of fiber yarn reinforcements had on the fatigue life of tubular braided composite (TBC) structures. Kevlar/epoxy TBC specimens were manufactured with either 18 or 36 yarn bobbins at varying braid angles (35°, 45°, 55°) and mandrel diameters (7/16”, 3/8”) to manipulate the thickness, angle, and spacing of the braided yarns respectively. Specimens were subjected to tension-tension fatigue loading for 10^5 cycles at one of two load frequencies (5 Hz, 10 Hz) at stress amplitudes equal to 60%, 75%, or 90% of their ultimate tensile strength. The number of cycles to failure was recorded for each. For specimens that lasted the full experimental duration without failure, fatigue strength was assessed by way of the observed rise of their surface temperature via thermal imaging. TBC fatigue life was improved by increasing yarn thickness and decreasing yarn spacing in specimens with low braid angles and making opposite adjustments for specimens with high braid angles, mitigating the amount of unreinforced resin content between yarns and the angle of yarn crimping. Fatigue life also increased under higher-frequency fatigue cycles, a result validated by the collected surface temperature data. Near-zero temperature rise in specimens exposed to low stress amplitudes implies the existence of an endurance limit stress under which the TBCs may be exposed to near-infinite dynamic load cycles.

1 INTRODUCTION

Tubular braided composites (TBCs) are advanced material structures formed by interlacing fiber yarn bundles into a near-net shape cylindrical textile preform, then impregnating the preform with a polymeric matrix that is subsequently cured (Figure 1) [1]. The resulting hollow tube-shaped polymer boasts vastly improved directional stiffness properties due to the braided yarns reinforcing the structure while remaining at a low density. The braid angle, denoted as θ in Figure 1, can be readily altered during manufacturing to tailor the axial and transverse mechanical properties of the composite to fit one of many applications, most notably those in the aerospace, sporting goods, and biomedical industries. Outside of material selection, additional stiffness and strength modifications can be made by altering the diameter of the braided tube and the thickness of the preform yarns [1,2].

Figure 1. Dry tubular braided fiber preform (left) and fully-cured TBC impregnated with epoxy resin (right). The braid angle, θ, is defined as shown on the preform.

Whereas static loading mechanics have been examined on numerous occasions for TBCs of various preform geometry and material makeup [1-4], comparatively few studies exist on their behavior under cyclic loading scenarios. Prior research into the fatigue life and dynamic stiffness degradation trends of carbon fiber-epoxy biaxial braid structures with varying braid angles was conducted by Tate et al [5], in which specimens collectively experienced an inflection from low ($<10^{2.5}$ cycles) to high ($>10^{4}$ cycles) fatigue life over a range of stress amplitudes from 90-45% ultimate tensile strength (%UTS). Generally, the fatigue lives of fiber-reinforced polymer composites are also expected to depend upon the dynamic frequency of the applied load, in turn impacting their rate of self-heating due to strain energy losses [6,7]. Whether these phenomena still apply to TBCs with broader variations to preform architecture beyond the braid angle has yet to be investigated.

This study seeks to analyze fatigue life in Kevlar/epoxy TBCs of varying braid angle, diameter and yarn thickness, and how their number of cycles to failure changes in response to changing cyclic load amplitudes and frequencies. The relative temperature difference between the different braid architectures and their ambient surroundings will be simultaneously examined to assess the rate of strain energy loss, and expected fatigue life, of TBCs that exhibit high endurance against cyclic loads.

2 EXPERIMENTAL METHODS

Twelve different Kevlar/epoxy TBC configurations were created and tested, as graphically depicted in Figure 2. Specimens were produced by first interlacing Kevlar fiber yarns along a cylindrical mandrel using a maypole braiding machine (Steeger HS140/36-91, Steeger GmbH and Co., Wuppertal, West Germany), then impregnating the resulting near-net fiber preform with a 1:1 formulation of epoxy resin (EPON 826, Hexion Inc., Columbus, OH) and hardening agent (LS-81K, Lindau Chemicals Inc., Columbia, SC) through a hand lay-up technique. The wetted preforms were placed in an oven (Thelco 31480, GCA/Precision Scientific, Chicago, IL) and subjected to a complete curing cycle that began at a temperature of 60°C for 1.5 hours, increased to 80°C for 2 hours, and finished at 160°C for 3 hours. Each TBC configuration utilized one of two mandrel diameters and yarn bobbin quantities in their manufacture, with yarns oriented at one of three braid angles. Six replicates were made for each braid configuration. Each specimen was cut to a length of 4.5”, ensuring the axial deformation of each TBC during fatigue testing was mitigated while also allowing them to maintain a suitable gauge length.

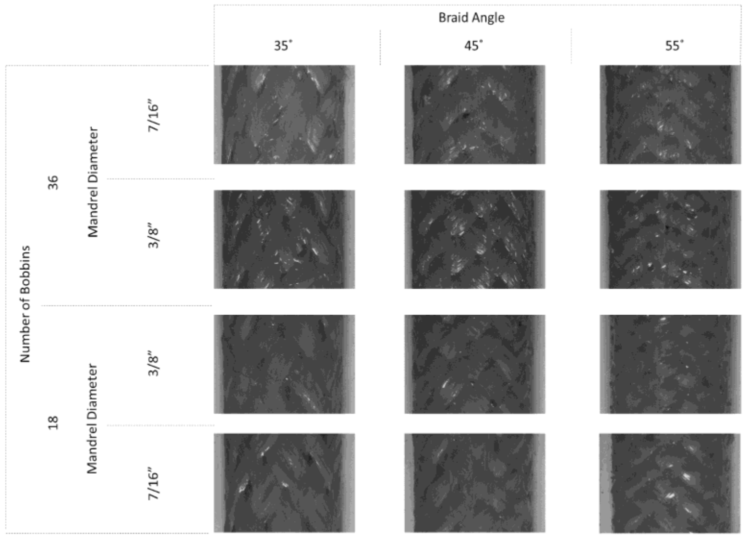

Figure 2. Sample images of each architectural braid configuration produced and tested in this study.

The composite tubes were mounted to a hydraulic load frame (MTS, Eden Prairie, MN). A 5-kN load cell (661.12B, MTS, Eden Prairie, MN) and a thermal imaging camera (X8500sc, FLIR Systems Inc., Nashua, NH) were positioned and configured to record tensile force and surface temperature readings from each specimen during cyclic fatigue testing. Once mounted to the load frame, specimens were subjected to tension-tension cyclic loading in accordance with ASTM Standard D3479, with a sinusoidal stress signal and a stress ratio of 0 [8]. Each of the six replicates of each braid configuration was subjected to peak load amplitudes of either 60%, 75%, or 90% of their ultimate tensile strength (UTS) at a cyclic loading frequency of either 5 Hz or 10 Hz. Specimens were subjected to cyclic loading until they experienced either of the macroscopic structural degradation scenarios shown in Figure 3, referred to here as “functional failure”. Either of these cases marked the point where fiber or matrix failure was so advanced that the specimen was no longer capable of functioning as a rigid structural member.

Figure 3. Characteristics of TBC functional failure in matrix-dominated (left) and fiber-dominated (right) modes. Note that in matrix-dominated functional failure, diameter reduction begins at one point along the tube’s length and progressively propagates outward.

Cyclic loading of specimens was also stopped if they reached 10^5 cycles without undergoing functional failure. Observation of fatigue properties beyond this point was not as valuable as in the mid-cycle fatigue regime ($10^{2.5}$-10^4 cycles), where rapid changes in fatigue life were anticipated to occur in response to gradual changes in stress amplitude [5].

The temperatures of the specimen surface and the surrounding ambient air were also monitored throughout each fatigue trial. The thermal imaging camera, fitted with a 50-mm focal length lens and 35-mm extension tube, captured the tubular surface within a 26.9 mm X 21.5 mm field of view with a spatial resolution of 0.0210 mm. Temperature-mapped images of the specimen surface were captured at the intervals shown in Figure 4. Twenty images were taken during each image collection period, with each individual image separated by five load cycles. These methods allowed for fatigue-related temperature changes to be monitored throughout an entire cyclic load test while economizing on the quantity of image data collected.

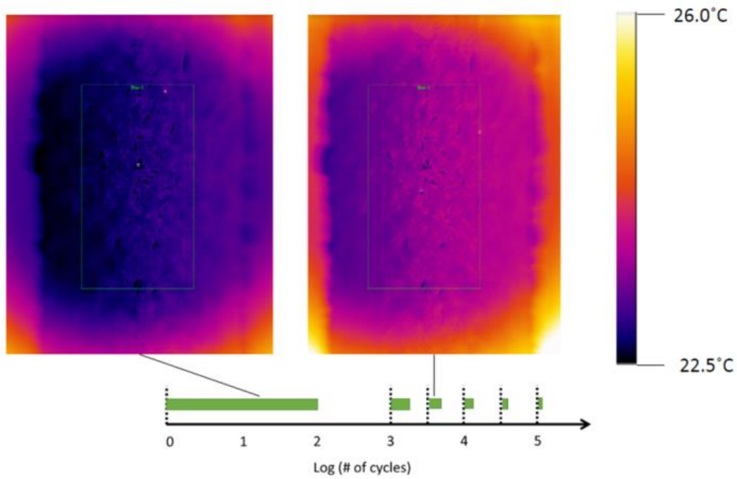

Figure 4. The green bars each represent a period during dynamic testing where 20 images were taken every five loading cycles. Examples of thermal camera images captured at various sampling periods are also shown.

The average rise in temperature achieved across each test specimen's surface was calculated as a function of the number of dynamic load cycles the specimen had endured. For specimens that endured without failure for the duration of fatigue testing, this plotted surface temperature tended to stabilize towards a constant value as fatigue cycles progressed. Thus, in lieu of a cycle-based fatigue life measurement, the stabilized surface temperature rise was reported for these particular specimens as this quantity was expected to be directly proportional to the specimen's hysteresis-based strain energy losses per dynamic load cycle [7].

3 RESULTS AND DISCUSSION

The measured fatigue lives of each test specimen, as well as stabilized temperature rise of the specimens that endured fatigue loading beyond 10^5 cycles, are listed in Table 1. As previously noted, specimens with a larger temperature rise were expected to incur greater hysteresis-based strain energy losses and, therefore, approach functional failure under fewer fatigue cycles. Results indicated that fatigue life improved in TBC specimens with a lower braid angle when the thickness of the preform yarns increased and the spacing between them decreased. However, similar improvement was observed in TBC specimens with a larger braid angle when the thickness of the preform yarns decreased and the spacing between them increased. Such observations suggest that the strength of the TBCs against fatigue loading was optimized when the cover factor was adjusted to a moderate value. Implementing thicker, closer-spaced yarns in TBCs with a low cover factor reduces the proportion of unreinforced resin content between yarns [1,4]. Using thinner, further-spaced yarns in high-cover factor TBCs reduces the crimp angle of yarns as they traverse the fiber preform [1]. Large unreinforced resin regions and yarns with steep crimp angles on a braided composite may therefore be seen as factors that increase the vulnerability of braided composites to fatigue failure, as mitigating both geometric features without exacerbating one proved to bolster fatigue life. Fatigue life across all braid configurations improved under an increased cyclic loading frequency. This suggests that TBCs undergo viscoelastic strengthening in the resin matrix under higher load application rates, which stands in agreement with previous observations in fiber-reinforced polymer composites [6].

Table 1. Fatigue life of each braid configuration under all experimental load amplitudes and frequencies. Results in red indicate failure before 10^5 cycles and the number of dynamic load cycles to failure. Results in green indicate survival beyond 10^5 cycles and the stabilized surface temperature rise at the test's conclusion.

		Number of Yarn Bobbins											
		36						18					
		Mandrel Diameter						Mandrel Diameter					
		7/16"			3/8"			7/16"			3/8"		
Load	Load	Braid Angle			Braid Angle			Braid Angle			Braid Angle		
Frequency	Amplitude	35	45	55	35	45	55	35	45	55	35	45	55
5 Hz	60% UTS	1.07 °C	3.24 °C	$1.70*10^{1}$	2.66 °C	$9.00*10^{0}$	< 1	$3.16*10^{4}$	1.49 °C	1.58 °C	1.66 °C	0.680 °C	0.984 °C
	75% UTS	1.74 °C	$2.45*10^{4}$	< 1	3.39 °C	$3.00*10^{0}$	< 1	$6.06*10^{3}$	1.61 °C	2.54 °C	$6.76*10^{4}$	1.36 °C	< 1
	90% UTS	$3.39*10^{4}$	< 1	< 1	$5.76*10^{4}$	< 1	< 1	$3.00*10^{0}$	2.78 °C	1.73 °C	$1.97*10^{4}$	2.09 °C	< 1
10 Hz	60% UTS	0.966 °C	0.630 °C	$2.39*10^{4}$	2.06 °C	$1.60*10^{1}$	< 1	0.181 °C	2.03 °C	0.241 °C	-0.180 °C	0.510 °C	0.295 °C
	75% UTS	1.55 °C	1.83 °C	< 1	2.64 °C	$9.00*10^{0}$	< 1	2.20 °C	1.01 °C	1.34 °C	-0.0925 °C	1.24 °C	$1.00*10^{1}$
	90% UTS	2.02 °C	< 1	< 1	4.41 °C	< 1	< 1	0.298 °C	1.99 °C	1.33 °C	1.54 °C	0.584 °C	< 1

	Number of cycles to functional failure (for specimens that failed before reaching 10^5 cycles)
	Stabilized surface temperature rise (for specimens that endured 10^5 cycles without functional failure)

For TBC configurations that endured beyond 10^5 cycles, the stabilized temperature rise tended to be greater when loaded at lower frequencies or larger stress amplitudes, which aligns with the trends seen from the remainder of the fatigue life data. The presence of negative and near-zero surface temperature rise values for particular specimens suggests that they have the capability to register near-zero strain-energy loss under low-amplitude loading scenarios and thus achieve a near-infinite fatigue life, similar to what was observed in prior braided composite S-N curve data [5]. Certain specimens registered notably larger stabilized temperature values inconsistent with the above trends, which may indicate that surface temperature concentrations developed in the visualized area of these specimens that were not representative of temperature rise across the full structure. Additional tests at a broader field of view are a feasible way of assessing these anomalous observations in greater depth.

4 CONCLUSION

This study conducted a preliminary investigation on the rate-dependent relationship between fatigue strength in tubular braided composites and the geometric properties of their fiber yarn preform. Fatigue life of each TBC specimen was gauged by the number of cycles they endured before undergoing functional failure or, if they endured for the full experimental duration of 10^5 load cycles, the stabilized temperature rise registered on their outer surface once cyclic testing had concluded. Fatigue life was optimized when the cover factor of the specimens was raised in low-braid angle specimens and lowered in high-braid angle specimens. Higher load frequency also bolstered fatigue life for the TBCs. Near-zero temperature rise values in specimens exposed to low-amplitude fatigue patterns suggest that Kevlar/epoxy TBCs are capable of being loaded for infinite cycles under low cyclic loads.

These results confirm that several phenomena seen in basic fiber-reinforced polymers and carbon-reinforced biaxial braided composites apply to Kevlar-reinforced braided composites as well. With the knowledge that the yarn spacing, thickness, and orientation do impact TBC fatigue life, further focus can be specifically placed on how these factors quantifiably alter stiffness degradation under low-cycle and high-cycle fatigue.

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