# AN EXPERIMENTAL STUDY OF THE CREEP BEHAVIOR OF BRAIDED COMPOSITES

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## ABSTRACT

There are many composite manufacturing techniques, but recently braiding composites have been gaining popularity. Braided composites have been extensively studied – experimentally, analytically and numerically – in literature in terms of their tensile, compressive and torsional properties. No studies, however, have attempted to understand the creep behavior of these braided composites. Consequently, this work sought to investigate creep behavior of braided composites. Kevlar® braided samples were manufactured at three braid angles (35, 45 and 55 degrees) and loaded at three different percentages of the failure load (40 %, 50 % and 60 %) with loads sustained for two days. Strain was measured using a virtual extensometer. Strain versus time curves were plotted for the different samples and used to calculate the predicted time to failure. Results from this work show that Kevlar® braided composites do exhibit creep behavior which has not been shown before in literature. Furthermore, initial results indicate that braided composites at lower braid angles and lower percentages of the failure load have longer predicted functional life. Careful consideration needs to be made to braid geometry and loading conditions when using braided composites in applications where creep is relevant.

## 1. INTRODUCTION

Braiding has recently gained popularity due to the precisely controlled properties that can be achieved through altering the manufacturing parameters such as braid angle and choice of fiber and matrix. Braiding is not a new method of manufacturing composites. Braids are currently used extensively in the textile industry in the manufacture of heavy duty ropes, bullwhips and sports equipment. In braiding, a minimum of three or more yarns are intertwined to form an architecture. During the braid manufacturing process, yarns of the fiber are intertwined on a mandrel which moves in the axial direction of the desired part [1]. This produces a braided pattern with a hollow cross-section determined by the mandrel that is used [2].

### 1.1 Manufacture

Braiding is an automated process capable of very high deposition rates to produce tubular braided composites using a horizontal or vertical rotary braiding machine, similar to the one shown in Figure 1. The braiding machine is loaded with carriers of the yarn that is to be braided. These are attached to the mandrel at the center of the braiding machine which is moved along the axis of the braiding machine by a puller. The combination of the braider movement and puller results in a braiding production line similar to that shown in Figure 2.



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*Figure 1: Horizontal Maypole Braider with 36 carriers*

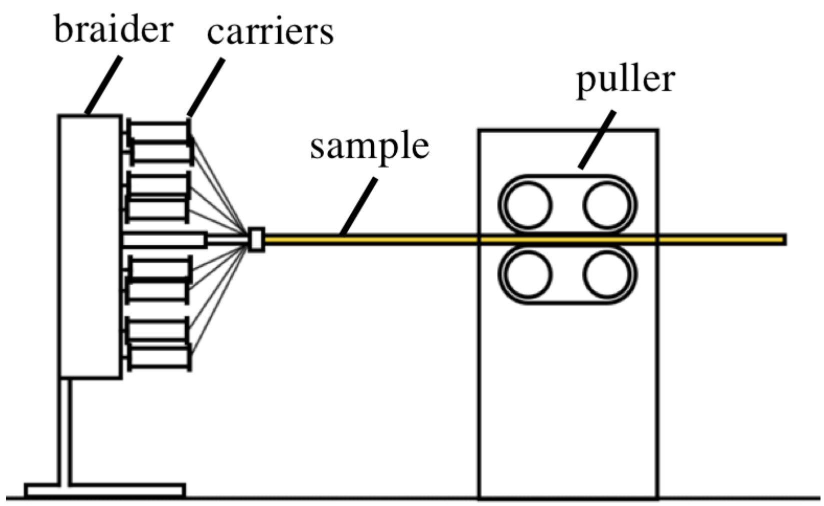



*Figure 2: Production Line for producing tubular braided composites*

By altering the rotational speed of the braider and the translational speed of the puller, different braid angles can be produced on the tubular braided composites. The braid angle is defined as the angle between the yarns and the axis of the produced tubular composite. This is shown in Figure 3. Furthermore, depending on how the carriers move during their rotary movement, different braid architectures can be produced by altering number and placement of overlapping yarns in a repeating element called a unit cell. The three types of patterns are show in Figure 4.

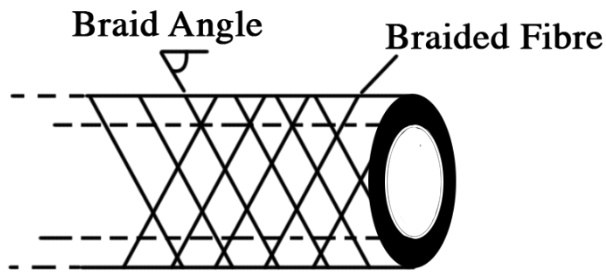



*Figure 3: Schematic representation of the braid angle of a tubular braided composite*

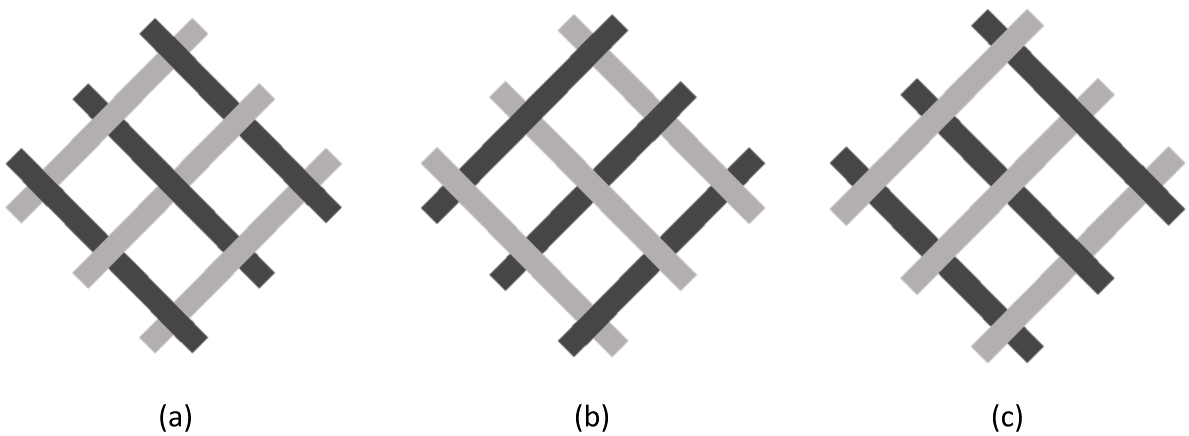



*Figure 4: The unit cells of the three types of braids in accordance to the intersection repeat showing a (a) diamond (b) regular and (c) Hercules braids*

## 1.2 Characterization

Several studies have attempted to characterize and model the mechanical properties of braided composites. Byun developed an analytical model to predict the mechanical properties and geometrical characteristics of tubular braided composites [3]. Shokrieh and Mazloomi also created an analytical method for calculating the stiffness of two-dimensional tri-axial braided composites [4]. In addition to the analytical studies attempting to characterize braided composites, there are several studies that experimentally investigated the mechanical properties and geometry of braided composites. Carey *et al.* used the classic laminate plate theory to predict the longitudinal elastic modulus of a 2D braided fiber composite with excellent agreement between the model and experimental results for Kevlar®/epoxy composites [5]. Ayranci *et al.* studied the elastic properties and behavior of two-dimensional open mesh braids. This included the longitudinal elastic modulus and shear modulus of Kevlar/epoxy and carbon epoxy composites [6]. In another study by Ayranci *et al.* the effect of the diameter of braided composites on the properties of the 2D braided composites was investigated. An analytical model was presented and compared against in-house experimental results, with good agreement seen [7]. Melenka *et al.* experimentally studied the properties of diamond and regular braided composites using digital image correlation. This included braids produced at three different angles and loading including both tensile and torsional loads [8].

Although several studies exist on the mechanical characterization of braided composites, very few studies have investigated the creep behavior of braided composites. Creep is the deformation of the material when exposed to a sustained load over a period of time [9]. A typical creep curve for a material is shown in Figure 5, with the three stages of creep behavior labelled.

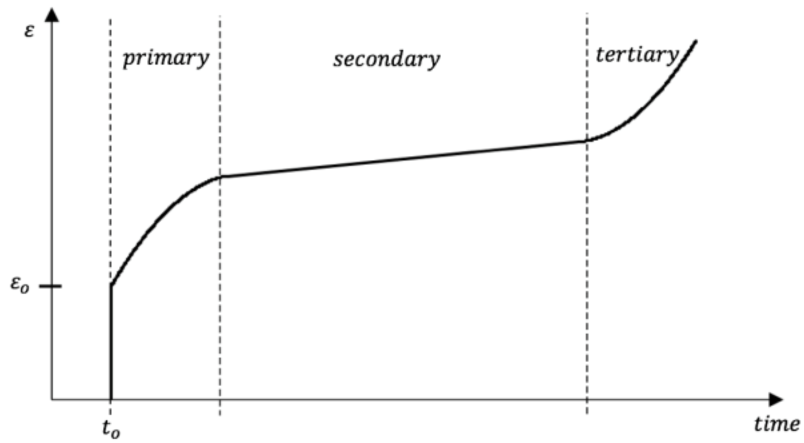



*Figure 5: Typical creep curve for a material with primary, secondary and tertiary phases labelled.*

In composites, the creep behavior is a combination of the creep behavior of the fibers and of the resin. After a period of time, a composite material may fail after the "endurance limit" which can be used to compare the performance of composites when exposed to sustained loads [9].

Studies on the creep behavior of individual fibres is abundant in literature. Walton *et al.* studied the creep response of Kevlar®-49 at room temperature, showing that the strains experienced were relatively low [10]. Ericksen performed a much more extensive study, investigated the creep behavior of Kevlar® fibres, epoxy and composites of the fibers and the epoxy [11]. Although there are other studies on the creep behavior of Kevlar and other fibres, very few studies are present on the creep behavior of braided composites. Jing *et al.* studied the creep behavior of 3D braided SiC composites at high temperatures and composites showed a steady secondary stage [12]. Other than the study by Jing *et al.*, no studies exist to the knowledge of the author.

## 1.3 Motivation

Due to the lack of studies investigating the creep behavior of braided composites, the objective of this research was to present a method to measure the creep behavior of braided composites. Braided composites have recently been considered in structural applications where loads are sustained for extended periods of time. Understanding the creep behavior will be paramount in applications where creep is an important aspect of performance. Different braid angle parameters were to be tested with different loading conditions to further understand how these braided composites behave under creep loading.

# 2. EXPERIMENTATION

## 2.1 Manufacturing and Sample Preparation

To manufacture the braids, a braiding process similar to that of Melenka *et al.* was followed [8]. Preforms were produced using a maypole braiding machine (Steeger HS140/36-91, Steeger GmbH and Co., Wuppertal, West Germany) which was shown in Figure 1. 36 carriers were loaded with Kevlar®-49 yarns and used to manufacture regular braid preforms on a 7/16'' diameter aluminum mandrel. A sample preform is shown in Figure 6. Braid parameters were controlled to produce braided preforms at three angles (35, 45 and 55 degrees). Preforms were then placed on Teflon mandrels (as shown in Figure 7) and resin (Epon 826, Hexion Inc., Ohio, USA) and hardener (Lindau LS-81k, Lindau Chemicals Inc., South Carolina, USA) were mixed in a 1:1 weight ratio and manually applied onto the preforms.

*Figure 6: 35$^o$ preform produced from the braidtrusion process.*

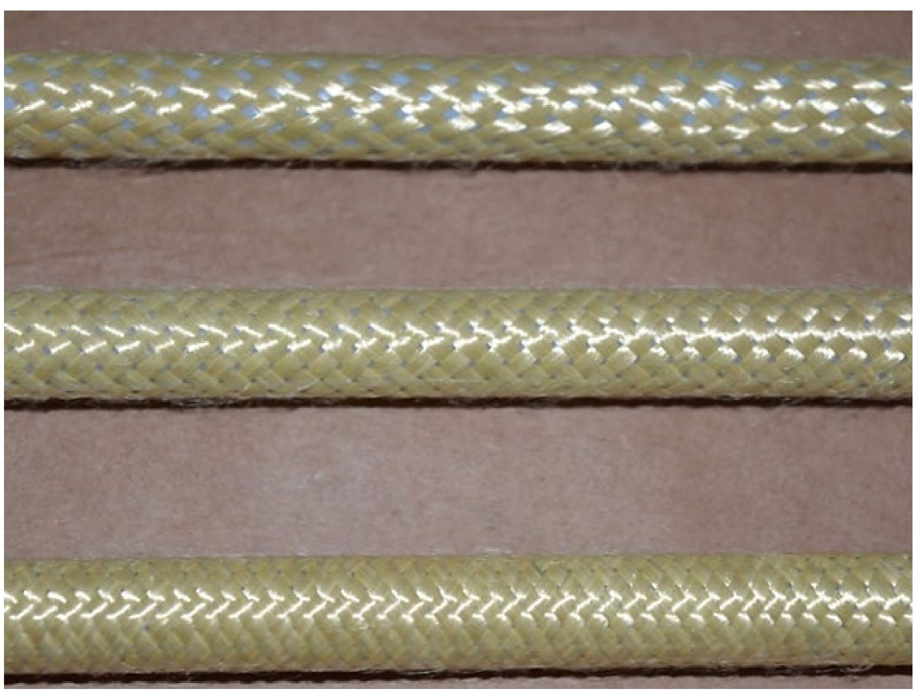


*Figure 7: Preforms placed on Teflon mandrels before impregnation with resin and hardener.*

Once impregnated, samples were placed in an oven and cured in a three-stage cycle as specified by the resin manufacturer [13]. Samples were heated to 66 ºC and maintained for 1.5 hours, then the temperature was raised to 85 ºC and held for 1 hour and finally the temperature was raised to 150 ºC and held for 3 hours. Once complete, the oven was turned off and samples were allowed to gradually return to room temperature. By the end of this stage, the composites were manufactured. Tubular braids, produced at three different angles as a result of this process, are shown in Figure 8.

*Figure 8: Preform placed on Teflon mandrel before impregnation with resin and hardener.*

Creep tests required that samples be loaded to a particular percentage of the failure load. Accordingly, tubular braided samples were attached to end tabs using high strength two-part Loctite epoxy (Henkel AG & Company, KHaA, Düsseldort, Germany). Tabbed samples were clamped on aluminum rails and left to cure for 24 hours as shown in Figure 9. This ensured sufficient time for complete setting of the two-part Loctite epoxy.

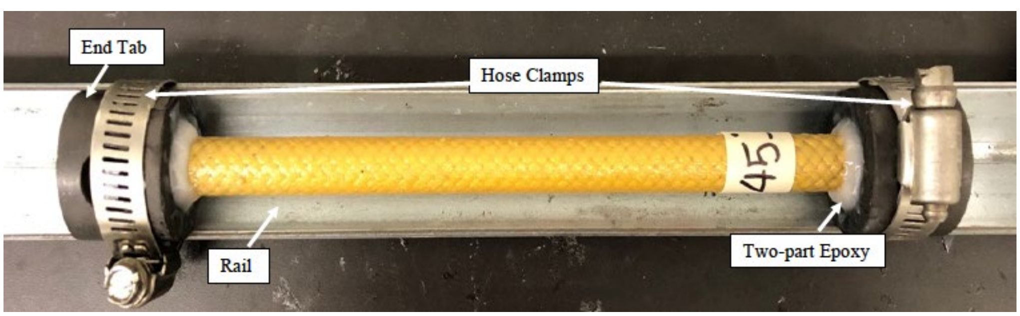
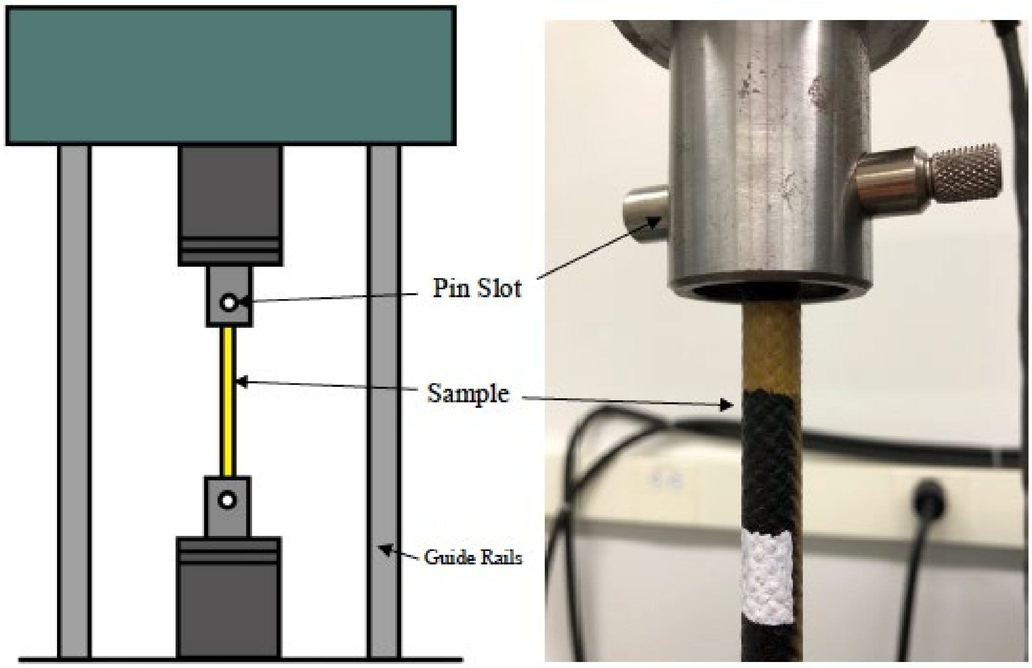



*Figure 9: Preform clamped to aluminum rail and attached to end tabs with two-part epoxy*

## 2.2 Creep Test Experimental Design

### *2.2.1 Experimental Setup*

In creep tests, samples are loaded to a percentage of the failure load sustained for a period of time. Due to the absence of any studies on the creep behavior of braided composites in literature, an experimental design was setup to test the Kevlar® braided composites. End tabs from sample preparation were pinned in the grips of a hydraulic MTS machined to transfer loads from the machine to the braided samples. For all tests conducted, a 4400 N load cell was used. Figure 9 shows a labelled schematic of the machine setup and a picture of the loaded sample.




(a) (b)

*Figure 10: Preform placed on Teflon mandrel before impregnation with resin and hardener.*

ASTM D7337 standard for tensile creep testing of Fiber Reinforced Polymer Matrix composites was followed for guidelines on conducting the test. According to the standard, load must be maintained with ±1 % of the required load for the duration of the test and samples must be ‘instantaneously’ loaded within 5 minutes of starting the test. The hydraulic MTS was calibrated accordingly to meet these requirements.

### *2.2.2 Testing Parameters*

To identify suitable testing parameters for this study a pilot test was conducted. Pilot loading showed that samples could sustain lower percentages of their failure load. Accordingly, 3 percentage loads were selected for this study, 40 %, 50 % and 60 %. Pilot testing on braided composites confirmed that this was a suitable range for this work.

To identify the duration of testing, it was important to identify how quickly samples reached the secondary stage. Preliminary testing of the 35º braids at 60 % of their failure load (the highest load in all samples to be tested) showed that after four days of testing, samples had reached the secondary stage within the first day. To normalize testing between the different samples, two days (48 hours) was selected as the testing times for these creep tests. The experimental matrix used in this work is shown in Table 1.

*Table 1: Braided composite test sample experiment matrix*

| Angle (degrees) | Percentage of Failure Load (%) | Number of Samples Evaluated |
|---|---|---|
| 35 | 40 | 3 |
| | 50 | 3 |
| | 60 | 3 |
| 45 | 40 | 3 |
| | 50 | 3 |
| | 60 | 3 |
| 55 | 40 | 3 |
| | 50 | 3 |
| | 60 | 3 |

### *2.2.3 Strain Measurement*

To measure strain a virtual extensometer was used in this work. The setup for the virtual extensometer is shown in Figure 11.

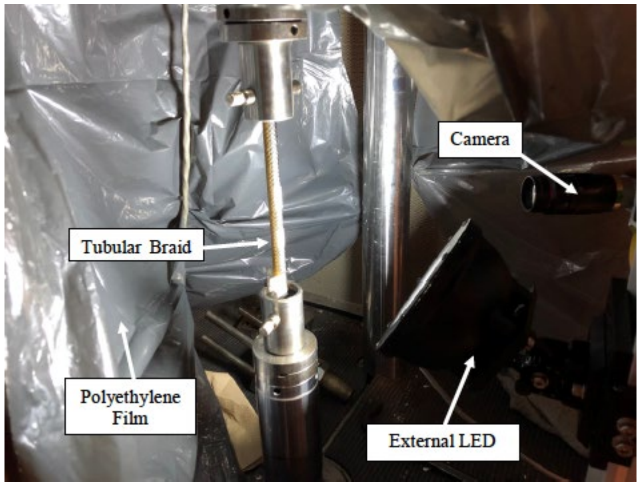
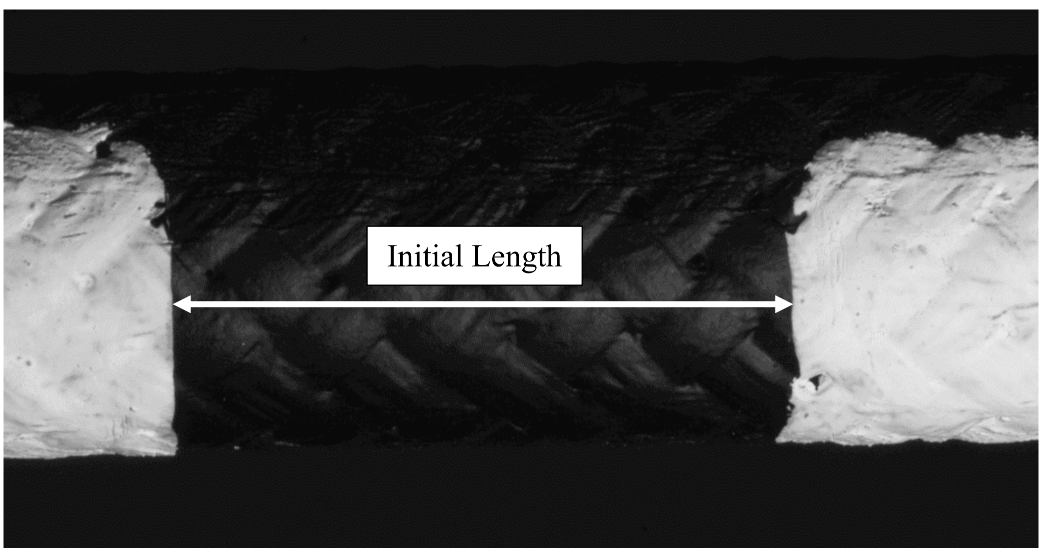
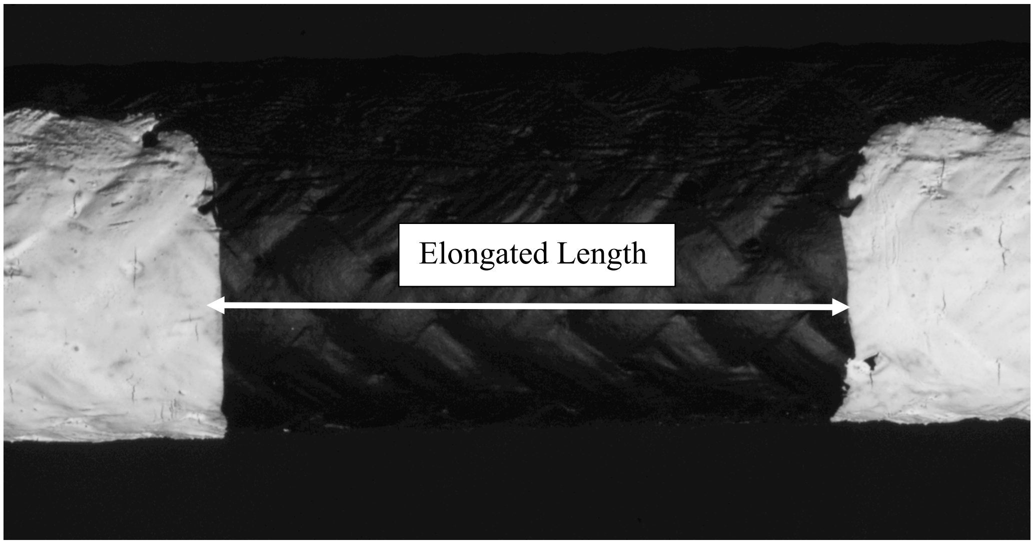



*Figure 11: Virtual extensometer for measuring strain over the duration of the creep tests*

The sample is painted in black and two contrasting marks are placed on the sample. Images are taken over the duration of the test using a scientific camera (Basler acA3800-10gm, Basler AG, Ahrensburg, Germany) and an error function is fitted to each of the images to measure the displacement of the marks over the duration of the test. The shift in the error function relative to the first image (which is taken before applying the load) is used to calculate the strain over the duration of the test. The shift in the contrasting marks in the sample can be seen in Figure 12.




(a)




(b)

*Figure 12: Images showing how the initial strain was calculated between the (a) Image 1 and (b) Image 2 in a sample set of images*

### *2.2.4 Creep Curves and Endurance Limit Calculation*

A MATLAB® code was written to convert the values of strain obtained from the virtual extensometer images into a plot of strain against time. The first plot for the 35º at 40 % of the failure load is shown in Figure 13.

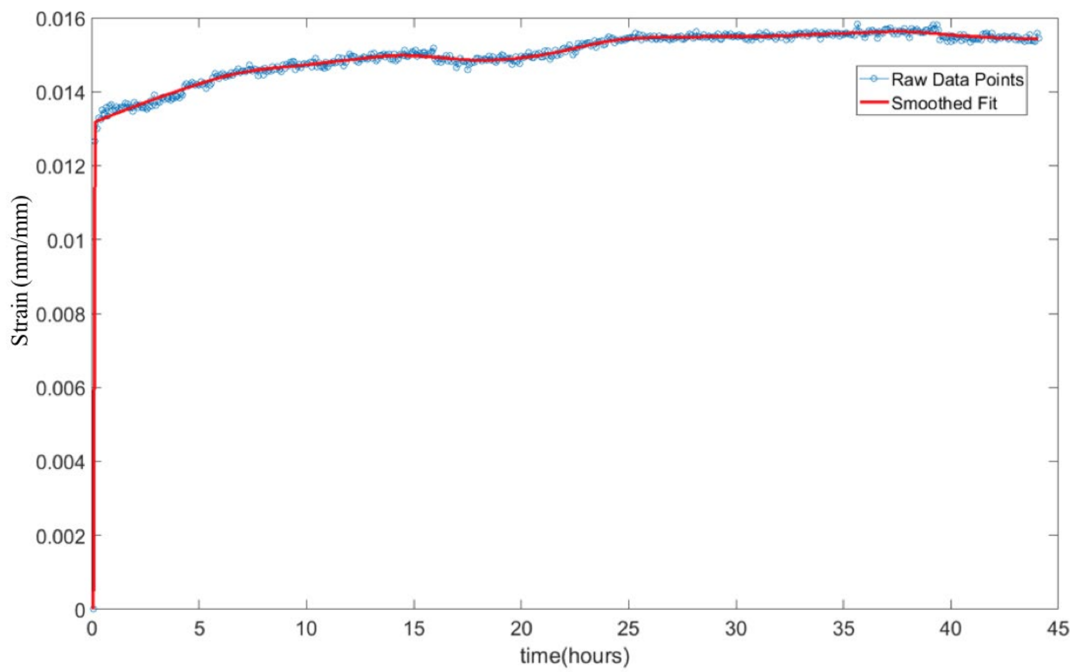



*Figure 13: Creep curve obtained from conversion of virtual extensometer data to strain against time data*

As previously mentioned, endurance limit is defined as the time after which the composite fails under a sustained load. The general equation for the strain experienced by a material at the point of failure exposed to a constant load can be described by equation 1.

$$\varepsilon_f = \varepsilon_o + \beta \log(t_f) \quad (1)$$

where $\varepsilon_f$ is the strain at failure, $\varepsilon_o$ is the initial strain experienced upon instantaneous loading, $\beta$ is the creep rate parameter and $t_f$ is the time to failure.

Using equation 1, the time to failure, $t_f$ can be calculated by rearranging the equation. $\beta$ is the slope of the curve when the logarithm of strain is plotted against time. Accordingly, the above plot can be converted to an isostress curve and the creep rate parameter calculated. Values of $\varepsilon_f$ are found from literature and $\varepsilon_o$ is the initial strain which can be read from the creep curve shown in Figure 13. Using these values, the time to failure, $t_f$ can be calculated.

## 3. RESULTS

Using the above techniques, creep curves were plotted and used to interpret the behavior of 2D braided Kevlar composites when exposed to sustained loads for long periods of time. The results obtained from this initial work are presented in this section.

## 3.1 Strain Development

With the lack of research on measuring the creep performance of braided composites, it was important to see if the virtual extensometer could measure the strain values experienced by the sample. Figure 14 shows the strain values reported by the virtual extensometer for the 35° braid tested at 40 % of the failure load.

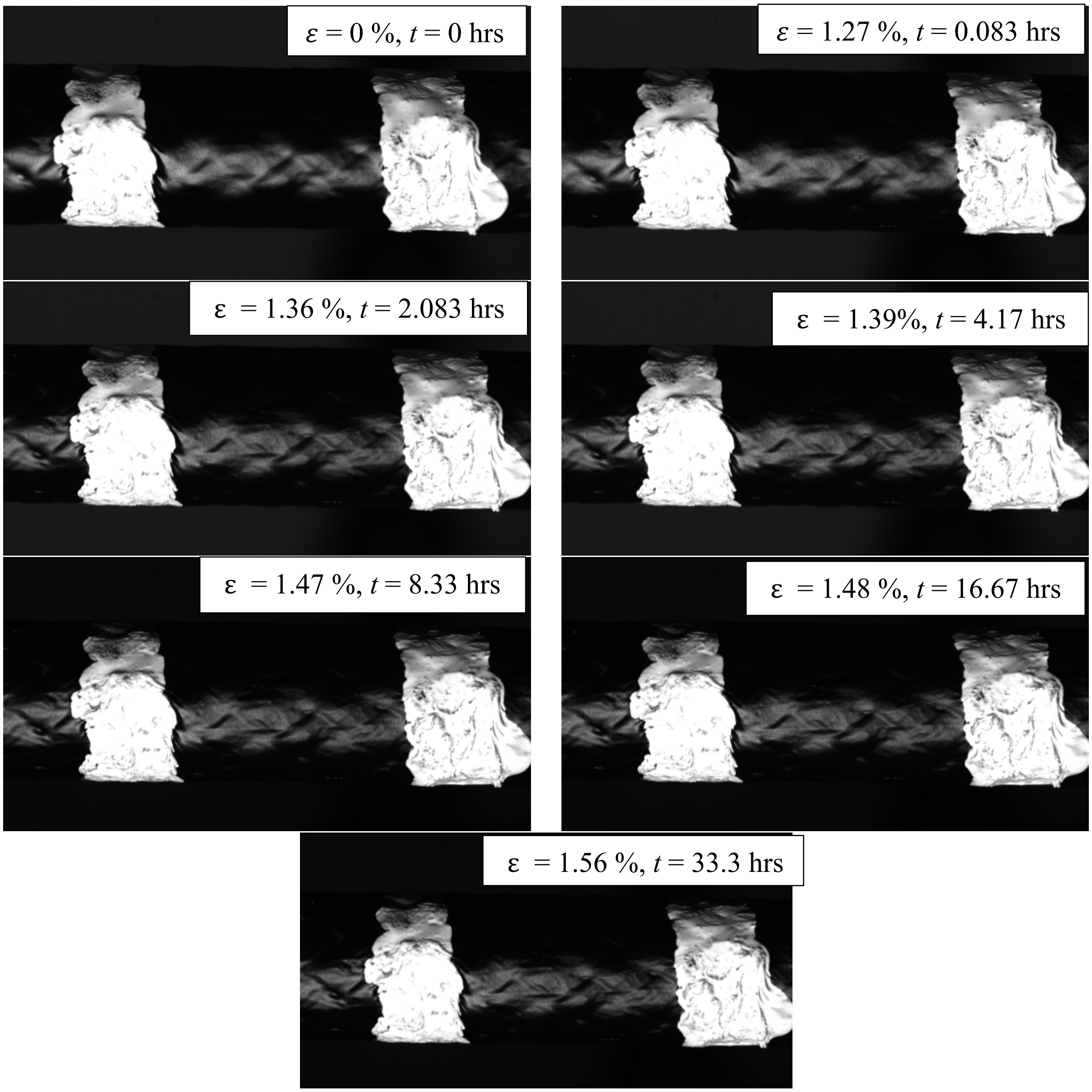



*Figure 14: Set of images taken at different times during testing for the 35° braid loaded at 40 % with strain values and time recorded on images*

Initial observation shows that as expected, over the duration of the test, the strain experienced by the samples increases. Also, changes in the strain values reported are initially higher than towards the later part of the test. This matches the expected behaviour of a material exposed to a sustained load. This indicated that the virtual extensometer could in fact be used to measure strain data of braided composite creep samples.

Another initial result obtained from testing the different samples showed that the initial strain was lowest for the 55 degree braids and highest for the 35 degree braids. These results matched the previous results obtained in the work highlighted in the literature [8]. The initial strain values obtained from one of each of the samples tested is shown in Table 2.

*Table 2: Initial strain values for the representative single samples at different percentages of failure load*

| Angle (°) | Percentage of Failure Load (%) | Initial Strain, $\varepsilon_o$ (mm/mm) |
|---|---|---|
| 35 | 40 | 0.0132 |
| | 50 | 0.013 |
| | 60 | 0.015 |
| 45 | 40 | 0.0104 |
| | 50 | 0.099 |
| | 60 | 0.0168 |
| 55 | 40 | 0.0081 |
| | 50 | 0.0076 |
| | 60 | 0.0077 |

### 3.2 Creep Rupture

Although all tested samples showed primary and secondary stages, the 45° specimens showed premature failure. Often during the test or a few hours after the start of the test, braided composites at 50 % and 60 % of the failure load would fail. Images from the progressive failure of these braids are shown in Figure 15. Upon close inspection of the failed specimens, failure occurs at the resin-rich areas. As the load on the sample increased, the resin rich areas begin to progressively fail. A behavior similar to necking is seen in these failed specimens.

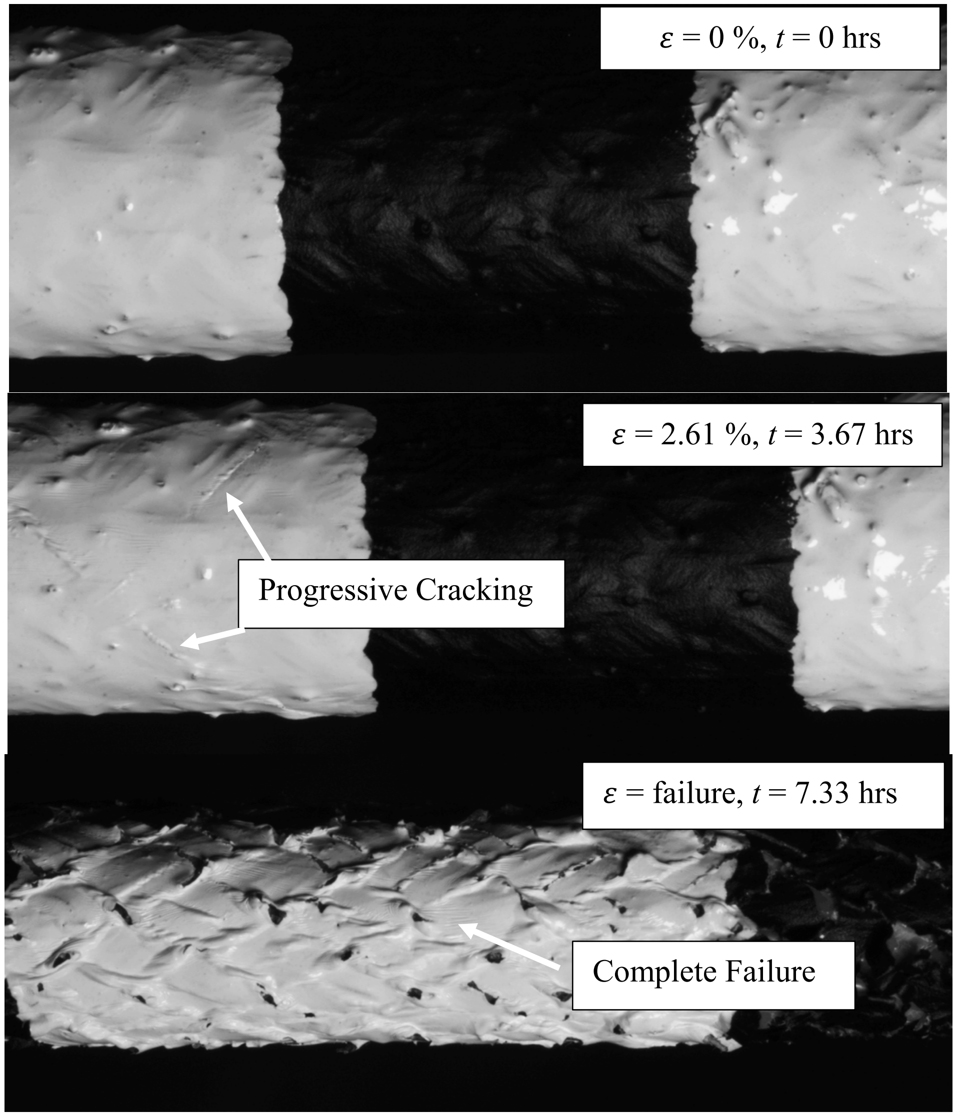



*Figure 15: Progressive Failure of 45° braids at 60% of failure load*

The premature failure shown in Figure 15 did not occur for the braided composites samples which were manufactured at 35° and 55° degrees. At lower braid angles the fibres contribute more to the overall behavior of the composite. At higher braid angles, the resin is geometrically dominant in the overall behavior of the composite. At 45°, the behavior is not completely understood and further analysis is required in the future. Neither fibre nor matrix is geometry preferential in determining the behavior of the composite. This could explain the behavior exhibited by the 45° braids.

## 4. CONCLUSIONS

This study presented the initial work to investigate the creep behavior of braided composites. Although several studies have experimentally and analytically investigated the mechanical properties of Kevlar® braided composites, no studies have reported how braided composites behave when exposed to sustained loads. Kevlar® braided composites were manufactured using a braiding process. Braids were manufactured at three angles (35, 45 and 55 degrees). To test the behavior under creep, each configuration of braids was exposed to three percentages of the failure load for 48 hours (40, 50 and 60 %). During this time, images are taken of painted samples and used to calculate the strain developed in the samples during the test. From this initial work done, a few conclusions were made:

- Tubular Kevlar® braided composites present creep behavior. Loaded samples show an initial strain and a decreasing strain rate until a secondary stage with a steady strain rate is seen.
- A virtual extensometer can be used to measure the strain in the braided composites during creep, but further studies need to be conducted to verify its accuracy.
- Careful consideration is recommended for braid architecture. 45° braids failed prematurely when tested at 50 % and 60 % of the failure load.

# 5. REFERENCES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