

# NON-LINEAR BEHAVIOUR OF TOWPREG TENSILE MODULUS FOR AUTOMATED FIBER PLACEMENT (AFP)

Massimo Carboni and Mehdi Hojjati  
Concordia Center for Composites, Concordia University  
Montreal, Quebec, Canada

## ABSTRACT

Modern composite manufacturing techniques using Automated Fiber Placement (AFP) technology incorporate simulations and Finite Element Analysis (FEA) prior to manufacturing of the part. In order to have acceptable results from the simulation, the material properties of uncured towpreg is required. One of those properties is tensile modulus. This study investigates the linear and non-linear behavior of the tensile modulus of a single uncured carbon fiber towpreg. Tensile tests were performed, and the force and displacement were monitored. Stress-strain curves were generated, and the modulus was calculated. It was observed that the modulus at the beginning of the load is nonlinear and as the load increases, it becomes constant and closer to the cured laminate. Additionally, investigation was made to determine the cause for the non-linear modulus through studying the fiber waviness of the uncured prepreg by microscopic observations. Comparisons were made between the waviness of untested and uncured carbon fiber tows with the tested uncured carbon fiber tows.

## 1. INTRODUCTION

In the domain of composite manufacturing, Automated Fiber Placement (AFP) and Automated Tape Laying (ATL) are new processes that are replacing traditional techniques such as hand lay-up. ATL and AFP are similar process which are faster, cost-efficient and provide a viable alternative in manufacturing large complex structures [1-3]. Both manufacturing techniques rely on process modeling simulations to predict the path of the fibers and to control the process parameters in order to avoid the formation of different types of defects. This process model can be used to control tape overlap/ gap as well as tow buckling and wrinkle formation. One of the limiting factors in process modeling for AFP & ATL is the reliance on using the cured composite material properties for process modeling when the material properties for the uncured state should be used instead [1]. Variability exists in the material properties between both states, with the properties of the uncured state being significantly lower [2]. This study will address the linear and non-linear behavior of the tensile modulus of uncured thermoset carbon fiber tows used in AFP and ATL simulations.

A few studies have been done to investigate the material properties of uncured carbon fiber prepreg. The variability of uncured carbon fiber epoxy prepreg were investigated where the tensile modulus was discussed [2]. While this study focused on all types of variability in prepreg including mass properties and waviness, measurements on the tensile response of uncured prepreg was also touched upon. They performed a uniaxial tensile test on a stack of 13 tows of unidirectional carbon fiber/ epoxy prepreg along the fiber direction and measured the stress/strain response using a 25 kN Instron test machine. The study attributed the tensile response to fiber misalignment in the

*Copyright 2020. Used by the Society of the Advancement of Material and Process Engineering with permission.*

prepreg and while a stress/strain plot was presented and characterized a “lead-in” area on non-linearity followed by a linear region. The lead-in area is attributed to the fiber waviness [4].

Researchers at North Western University, supported by a subcontract from the Ford Motor Company, published their findings on the mechanical response of woven composite prepreg during forming processes [3]. Focusing on the mechanical response and properties of the prepreg system, the uniaxial tension test was performed on uncured prepreg to obtain the tensile modulus. Similar to Ref [4], the stress/ strain plots of the tensile response, over varying temperatures, all exhibited a region of non-linearity followed by a linear region. This report studied the effects of temperature on the non-linear section of the plot and determined that as temperature increases, the area of non-linearity also increases. However, again the phenomenon and the reasoning behind the non-linear region were not addressed, and the stiffness represented by the linear region of the plot was selected to describe the response of the uncured prepreg [5].

This report will concentrate on studying the tensile modulus of unidirectional (UD) thermoset, carbon fiber/epoxy resin systems, as it is one of the primary material properties required for AFP & ATL process modeling [1,5]. To measure the tensile modulus, uniaxial tensile testing was conducted and the engineering stress strain curve was derived from the force and displacement data acquired during the testing. This study will focus on classifying the non-linear region on the stress/strain plot of the tensile response, as this is the region the material will be exhibiting during AFP & ATL manufacturing. As seen in literature, in the uncured state, the material properties of carbon fiber prepreg are observed to be temperature dependent and, like cured composites, the fiber waviness also affects the material properties in the uncured state [4-8]. Testing temperatures should remain below 90 °C to prevent the excess curing during the lay-up. For our experiments, testing was conducted at room temperature 25 °C. Additionally, fiber waviness were measured through microscopic analysis before and after testing to study any variations in the waviness and its effect on the tensile modulus was discussed.

## **2. EXPERIMENTATION**

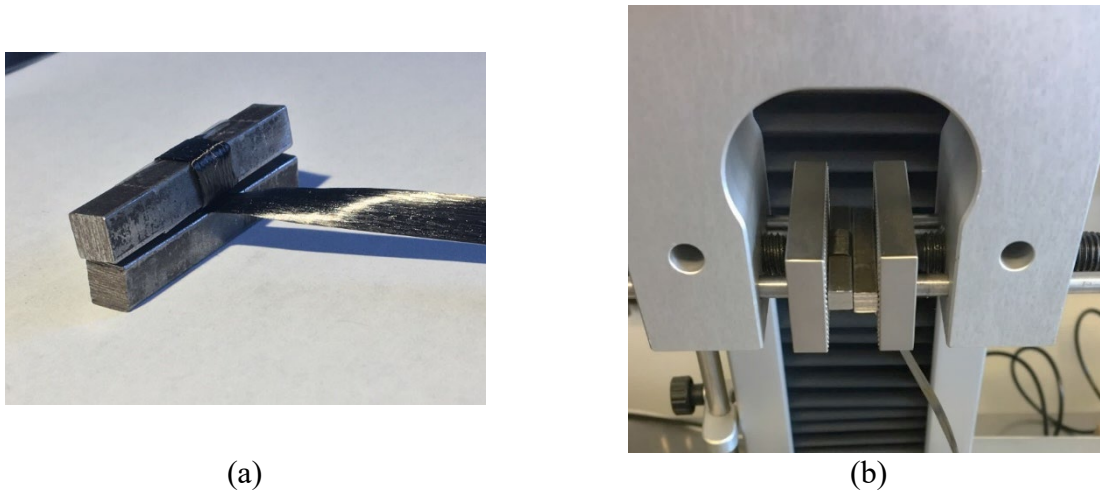
### **2.1 Material and Equipment**

The AFP prepreg used for experimentation in this study was manufactured by Solvay and consists of 12KHTS carbon fiber continuous filaments and a CYCOM 977-2 epoxy resin system. The prepreg used in AFP and ATL manufacturing are different than traditional prepreg as they are prepared as a several meter long and 6 mm wide continuous strip of material wound around a spool. This spool of prepreg is then able to be feed through the delivery head of an AFP or ATL machine and deposited onto a tool. For experimental tensile testing, samples of this prepreg with dimensions of 127 mm long, 6 mm wide and 0.127 mm thick were used. Samples were tested in a HOSKIN machine with a 5 kN load cell.

### **2.2 Tensile Behavior of Uncured Prepreg**

To characterize the tensile behavior of uncured carbon fiber prepreg, the tensile force and the displacement at the head of the machine were recorded to calculate the engineering stress and strain. Tensile force was applied along the fiber direction of the material (direction 1) and the machine was set to a displacement of 2 mm/min. Prior to testing, samples were removed from the freezer and left to sit at room temperature for 1 hour. The towprepg was wrpped around a steel block

to be used inside the tensile machine. It was reported that the main source of failure during tensile testing of uncured prepregs was caused due to the material slippage in the grips. The viscous nature and the low friction coefficient of the uncured epoxy can cause the material to slip out of the grips, resulting in an inaccurate reading of displacement/ strain in the results [4,5,10]. To prevent slippage from occurring, four short steel blocks were used in conjunction with the grips of the machine. The steel blocks were made from standard keystone of cross section 0.5 cm by 0.5 cm and a length of 4 cm. One side of the uncured prepreg was wound around a steel block, as shown in Figure 1a, and then compressed by the other steel block in the grips of the HOSKIN machine (Figure 1b). Between 4 cm to 5 cm of prepreg was used to wound around the block. The samples were first set up and clamped in the lower grip, then they were aligned and clamped in the upper grip. This was to insure no misalignment in the sample setup and to ensure the tensile load was applied in the fiber direction. This type of setup within the grips was able to prevent slipping as the grips viscous epoxy was no longer in contact with the grips, instead the force holding the sample in place was acting directly onto the steel blocks.



(a) (b)  
Figure 1. Test sample for uniaxial tensile testing wrapped around steel blocks to prevent slippage.

The gauge length of each specimen tested was kept at 127 mm, while the actual length of each sample was a maximum of 200 mm as the extra length of material was required to wound around the steel block. One ply of material was used, for a total thickness of approximately 0.127 mm and a width of 6 mm. In total, 24 samples were tested in this configuration. Engineering stress was calculated using the recorded reaction force in the load cell ( $F_1$ ) and the dimensions of the sample, width ( $w$ ), and thickness ( $t$ ) as:

$$\sigma_1 = F_1 / (w * t) \quad [1]$$

Engineering strain was calculated using the original gauge length of the sample ( $L_g$ ) with the displacement measured in the head of the machine ( $\Delta L$ ).

$$\varepsilon_1 = \Delta L / L \quad [2]$$

## 2.3 Microscopic Imaging

To investigate and observe the fiber waviness and fiber misalignment, microscopic images and analysis were performed on the prepreg samples prior to and post tensile testing. Samples were prepared by embedding them in an epoxy resin puck, and then polishing them until the sample was exposed on one end. Once the samples were polished, microscopic images were taken at 10x magnification. A MATLAB code developed at the Chalmers University of Technology was used for characterizing the degree of fiber misalignment in microscopic images [4]. Using this software, the change in misalignment and in turn the change in waviness before and after testing can be studied.

## 3. RESULTS & DISCUSSION

### 3.1 Uniaxial Tensile Testing

#### 3.1.1 Evaluation of Test Method

As there are no standards for testing uncured prepreg, the accuracy and reliability of our test method was evaluated. To conduct our evaluation, test samples were setup using the steel blocks and were subjected to an initial load of 100 N. Samples were then released and the tensile force was returned to a predefined load, where it held the samples for a short time before they were tensile tested once more. The return loads chosen for each sample were 40 N, 30 N, 20 N and 10 N respectively. Figure 2 shows the resultant plot for all 4 samples.

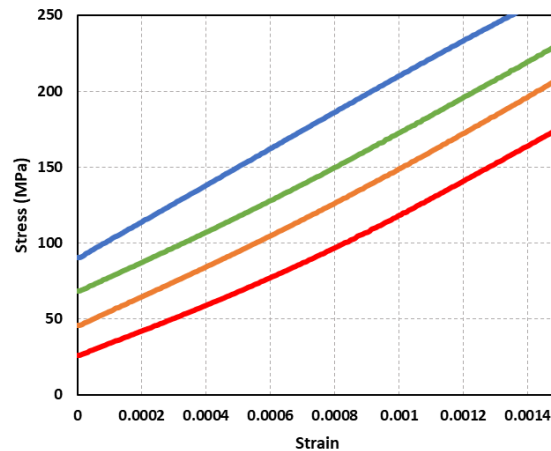


Figure 2. Experimental results for identification of slippage in the grips

Table 1. Maximum Young's modulus recorded in linear section of stress vs. strain plot

Sample #	Young's Modulus (GPa)	Sample #	Young's Modulus (GPa)
1	113.78	3	113.69
2	115.54	4	112.99

As shown in Figure 2 and Table 1, all samples tested exhibit a linear modulus with similar slope of approximately 114 GPa. The similarities in the slope indicate good repeatability of our test method. It was determined that samples should be loaded under a pre-load prior to testing. For this experimentation, the pre-load was selected to be approximately 100 N. The purpose of the pre-load is to ensure that the clamping force is sufficient, prevent any slippage in the system and to ensure that the same is properly aligned in the testing fixture.

### 3.1.2 Uniaxial Tensile Test Results

Eight specimens from two distinct batches of material were tested. The results indicate that the tensile response of an uncured carbon fiber can be characterized as a non-linear behavior at the beginning of the test followed by a linear region. The same behavior has been reported in the literature where the non-linear region is described as a lead-in region of the reduced modulus [2]. From experimental observations, the lead-in (non-linear) region of the stress strain curve for our prepreg material was observed up until 0.2% strain where it then followed by a linear trend. Due to the observed failure in the prepreg at a force of over 500 N, in the form of fiber splitting and tearing of the fibers, the tensile response was plotted up to 0.5-0.6% strain. Figure 3 shows the average stress strain plot generated from all 8 samples.

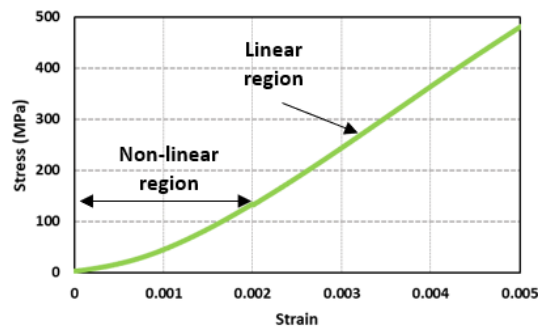


Figure 3. Experimental Results of Tensile Behavior of Uncured Prepreg

It is important to note that Figure 3 represents an average of all sample and when comparing the stress strain curve over individual samples and even over the two different batches of identical material, there is a large standard deviation between results. Figure 4 shows the tensile response between two batches of identical Solvay prepreg. While both plots exhibit the same characteristic lead-in area followed by an area of linear response, the two plots have their own distinct behaviour.

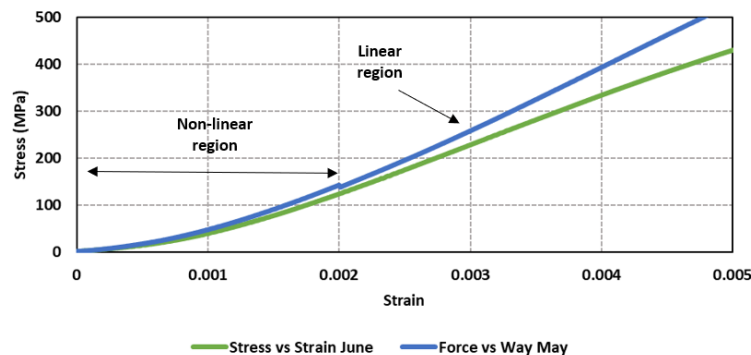


Figure 4. Difference in Tensile Response Between two different spools of towpre materials.

It is possible that the variations in tensile modulus are attributed to the differences in waviness between the samples. As the waviness in uncured prepreg can change due to the ease of fiber movement within the uncured viscous epoxy, the angle of misalignment will then vary per sample, and in turn introduces a source of variability in values for the tensile response. This can be further supported when comparing the tensile response of each sample individually. The tensile response between samples, even those within the same batch of material, have a high standard deviation between each other. Each sample was cut from the same roll of AFP prepreg and theoretically should have the exact same properties. However as recorded experimentally, each sample exhibits a different tensile response due to the varying waviness and misalignment of the fibers between each sample caused by the movement of the fibers in the viscous epoxy matrix. One aspect of the tensile response curve that stays constant between all samples are the lead-in and linear regions caused by the re-aligning of the misaligned fibers. As all samples experience a certain degree of misalignment, they in turn all display a non-linear gain in modulus as the fibers align themselves along the direction of the applied load.

Studying the tensile response of all samples as an average, shown in Figure 3, the lead-in region of non-linear modulus lies between 0%-0.2% strain and 0-100 MPa of stress. Correspondingly, this relates to a maximum of 50 N of applied uniaxial tensile force. In AFP & ATL manufacturing, tensile loads are expected to be close to 25 N, however it is difficult to measure exactly what the applied loads are during this process. Nonetheless, during AFP & ATL manufacturing, the tensile modulus of the uncured prepreg is expected to be in the non-linear region of its response and thus modeling of the manufacturing process must consider the waviness, misalignment and the changing modulus in this region. Microscopic analysis provides clear observations of what is happening at the micro level of the prepreg and is a means of developing a microscale model to support the experimental results.

### **3.2 Microscopic Observations**

To capture the effect of fiber waviness and misalignment in the prepreg, microscopic analysis was done on the prepreg samples prior to and post tensile testing. Figure 5 represents microscopic images of one sample at 10x magnification. Visually, the waviness is shown to have changed after the sample was tested in uniaxial tension. The waviness appears to have diminished along the fiber direction and the overall misalignment of the fibers has been reduced. To further support the visual observations, the photos were processed using the MATLAB software developed by D. Wilhelmsson as mentioned in the previous section [4].

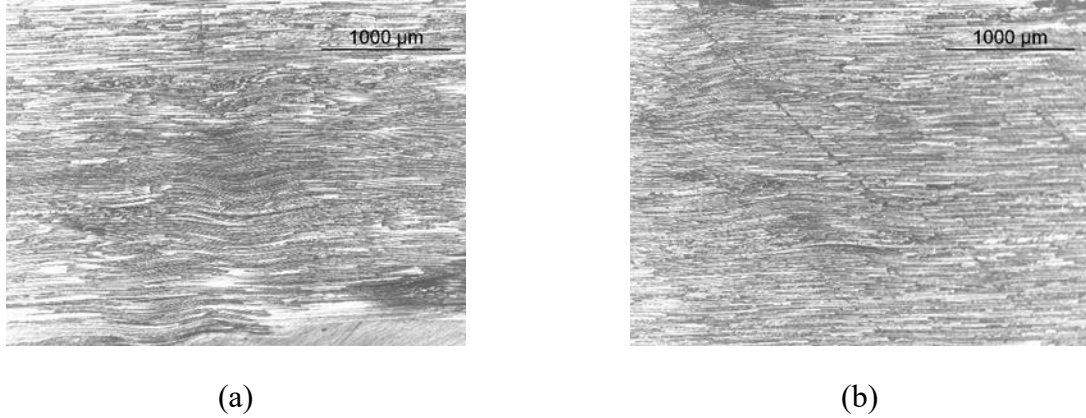


Figure 5. Microscopic images of an uncured carbon fiber tow prepreg a) before and b) after uniaxial tensile testing

The results of the MATLAB analysis shown in Table 2 support the visual findings of the microscopic images. The overall mean misalignment angle, the maximum misalignment angle and the standard deviation of angles have all been reduced after uniaxial tensile testing. Following classical lamination theory, this means that the theoretical tensile modulus of the same prepreg sample after testing is higher than if no uniaxial load was applied. Additionally, the Figure 4 justifies the assumption that there is an event of fiber re-alignment during the tensile testing experiment and that the lead-in area of the tensile response plot is attributed to this movement of fibers.

Table 2. Results of Fiber Misalignment Within Carbon Fiber Prepreg Before and After Uniaxial Tensile Testing

	Sample Prior to Testing	Sample After Testing
Successfully Measured Area	89.1%	93.4%
Mean Angle (Deg)	1.750	1.170
Mean Misalignment Angle (Deg)	3.722	2.773
Maximum Misalignment Angle (Deg)	15.500	11.904
Standard Deviation of Angles (Deg)	4.696	3.575

### 3.3 Mathematical Model

Using the experimental data obtained through uniaxial tensile testing, a mathematical equation was derived to predict the modulus of the uncured prepreg at different load levels. The model is based on the derivative of a second order polynomial fitted to the average stress vs. strain plot of all the samples. Figure 6 represents the average stress vs. strain plot over all samples along with the second order polynomial fitted to the non-linear region of the graph. The trend-line was fitted at a starting Strain value of 0.0002, as to remove any initial noise or possible testing error that can occur at the start of the experimentation. The trendline and resulting equations will be able to predict the initial stress & strain points and the expected modulus of the uncured prepreg at 0 N.

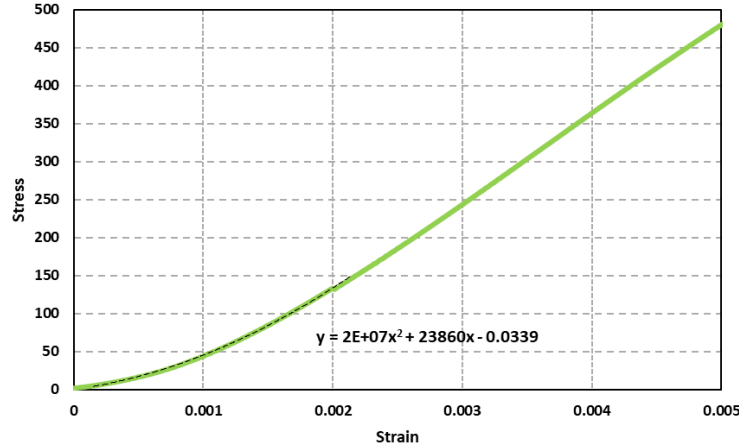


Figure 6. Experimental Results of Tensile Behavior of Uncured Prepreg with trendline

$$y = ax^2 + bx + c \quad [3]$$

$$\frac{dy}{dx} = 2ax + b \quad [4]$$

$$(1/a * f) = ax^2 + bx + c \quad [5]$$

$$x = \frac{-b \pm \sqrt{b^2 - 4a[c - (1/a * f)]}}{2a} \quad [5]$$

$$\frac{dy}{dx} = 2a \left( \frac{-b \pm \sqrt{b^2 - 4ad}}{2a} \right) + b \quad [6]$$

$$E^{eff} = \left| \sqrt{23860^2 - 4(2 * 10^7)(-0.0339 - 2.22f)} \right| \text{ (MPa)} \quad [7]$$

Equation 7 represents a mathematical solution for calculating the effecting Young's Modulus of the uncured prepreg system in terms of force  $f$  in Newtons. This equation is valid only between strain values of 0-0.2% and is only applicable for the material used in our experimentation. Applying Equation 7 to AFP or ATL manufacturing, where the expected applied tensile load is approximately 25 N, the resultant Young's modulus is calculated to be approximately 70 GPa. At 0 N, the modulus is approximately 24 GPa.

Studying the geometry of a single fiber, a mathematical model was also developed to predict the force based on the amplitude and period of the waveform. The fiber was modelled with the assumption that waviness follows a sinusoidal function with a period ( $k$ ), and amplitude ( $a$ ) as seen in Figure 7.

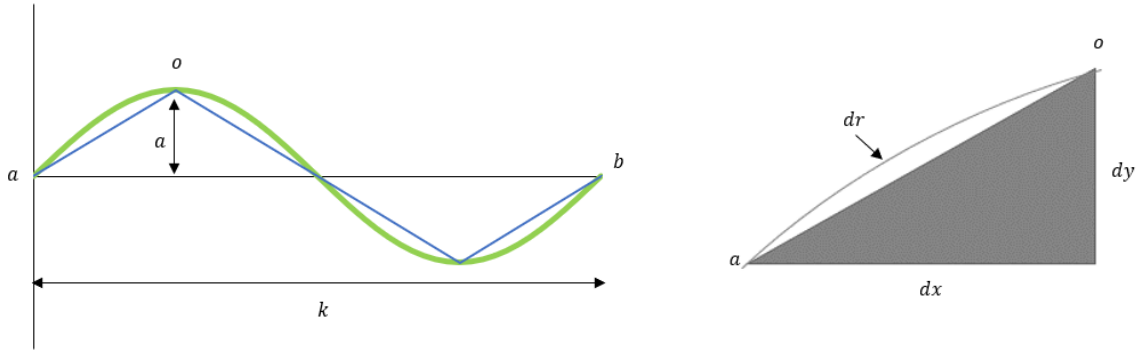


Figure 7. Generalized Sinusoidal Waveform of a Single Fiber.

$$L = \int_a^b \sqrt{1 + \left(\frac{dy}{dx}\right)^2} dx \quad [8]$$

$$y = a * \sin[k(x)] \quad [9]$$

$$\left(\frac{dy}{dx}\right) = k * a * \cos[k(x)] \quad [10]$$

$$L = \int_a^b \sqrt{1 + (k * a * \cos[k(x)])^2} dx \quad [11]$$

$$\int_0^{950} \sqrt{1 + \left(\left(\frac{2\pi}{b}\right) * 36.8871 * \cos\left[\left(\frac{2\pi}{b}\right)(x)\right]\right)^2} dx = 963.982 \mu m \quad [12]$$

$$L = \int_a^{b+\Delta b} \sqrt{1 + ((k + \Delta k) * (a + \Delta a) * \cos[(k + \Delta)(x)])^2} dx \quad [13]$$

Using Equation 11 to calculate the true length of the sinusoidal graph, the rate of change of the amplitude  $a$  as the length  $b$  can be numerically determined using Equation 13. MATLAB was used to numerically solve for the change in amplitude by equating the integral in Equation 13 to the arc length solve for in Equation 12. Figure 8 represents the resultant values.

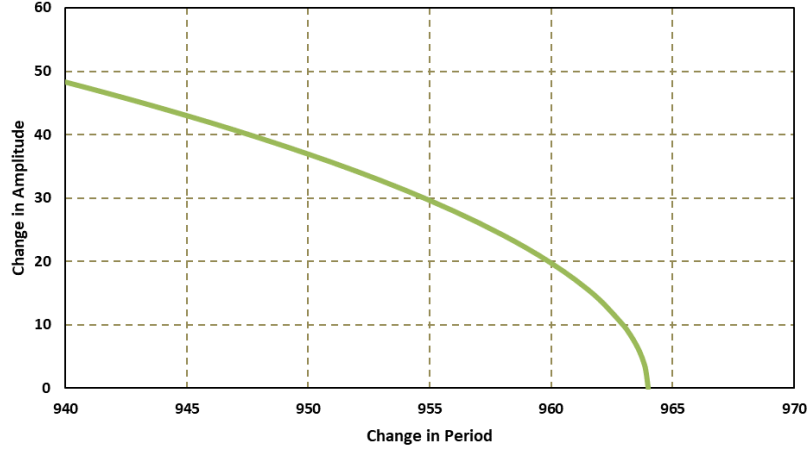


Figure 8. Ratio Between the Change in Amplitude & the Change in Period

Based on the graphical results in Figure 8, the ratio between the change in amplitude vs wavelength follows a non-linear trend. The sharp drop in amplitude as the period approaches the arc length is attributed to the values approaching the node of the periodic function. Uses these values, and the stiffness equations developed by M. Geers et al, an equation based on the geometric wave of a single fiber can be developed to solve for the axial force and the bending moment exerted on the system [5].

$$\begin{Bmatrix} N \\ M_2 \end{Bmatrix} = \begin{bmatrix} a_{11}^{hom} & a_{13}^{hom} \\ a_{31}^{hom} & a_{33}^{hom} \end{bmatrix} * \begin{Bmatrix} E^E \\ E^{C_1} \end{Bmatrix} \quad [14]$$

In Equation 14,  $N$  represents the axial force while  $M_2$  represents the bending moment.

$$\begin{cases} a_{11}^{hom} = \frac{E \cos \theta}{\frac{\cos^2 \theta}{A} + \frac{x_1^2}{I}} \\ a_{33}^{hom} = EI \cos \theta \\ a_{13}^{hom} = a_{31}^{hom} = 0 \end{cases} \quad [15]$$

In Equation 15,  $L$  represents the period length,  $I$ , the moment of inertia,  $E$ , the Young's Modulus, and  $\theta$ , the cross-section inclination angle as shown in Figure 7. Using Equation 14 [5], and the results in Figure 8, the axial force and the moment in a single fiber can be determined based on the geometric properties of the sine waveform. Furthermore, with initial microscopy of a sample and knowing the relationship between the change in amplitude and the change in wavelength, the average axial force and bending moment in the prepreg can be predicted based on the initial average wavelength on the fibers. Using these resultant calculated force and moment, the effective Young's Modulus of the uncured prepreg system can be determined by outside of experimental testing. Future work is still in progress to further develop the equations for calculating force in a fiber following a periodic functions based on the research of E. Syerko et al. and P. Cartraud et al. [6], [7].

## 4. CONCLUSIONS

Studying the mechanical response of uncured carbon fiber prepreg systems is important for AFP and ATL manufacturing, as these properties will be used to simulate the process and predict the overall quality of the part. Inaccurate simulations can lead to defects in the automated manufacturing process which results in a negative time and cost incurrence. The behavior of uncured towpreg under tensile testing was investigated. It was shown how at the beginning of its tensile response, the fibers in the uncured prepreg system exhibit a moment of re-alignment and movement in which the waviness and the angle of misalignment within the system is corrected. This movement within the uncured and viscous epoxy system results in a non-linear tensile response, until a certain point where the majority of the fibers are aligned to the direction of the force, and the tensile modulus turns linear. This change in modulus due, to the change in angle of the fibers, can be mathematically solved using classical lamination theory and was recorded in experimentation over 24 samples from 2 batches of material. Microscopic imaging was performed to capture this change in fiber angle in the towpreg. Using images of an uncured prepreg sample at 10x magnification taken prior to, and after uniaxial tensile testing shows a clear change in the angle of misalignment and the waviness of the carbon fibers. A mathematical equation was proposed to predict the towpreg modulus at different load level.

### **Acknowledgments**

The authors would like to acknowledge the financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC). Material was provided by Bombardier Aerospace.

## 5. REFERENCES

- [1] D. Leutz, M. Vermilyea, S. Bel, and R. Hinterhölzl, “Forming Simulation of Thick AFP Laminates and Comparison with Live CT Imaging,” *Appl. Compos. Mater.*, vol. 23, no. 4, pp. 583–600, Aug. 2016, DOI: 10.1007/s10443-016-9475-6
- [2] K. Potter, C. Langer, B. Hodgkiss, and S. Lamb, “Sources of variability in uncured aerospace grade unidirectional carbon fibre epoxy preimpregnate,” *Compos. Part A Appl. Sci. Manuf.*, vol. 38, no. 3, pp. 905–916, Mar. 2007, DOI 10.1016/j.compositesa.2006.07.010
- [3] W. Zhang *et al.*, “Experimental Methods to Characterize the Woven Composite Prepreg Behavior During the Preforming Process,” in *Proceedings of the American Society for Composites--Thirty-First Technical Conference*, 2016.
- [4] D. Wilhelmsson and L. E. Asp, “A high resolution method for characterisation of fibre misalignment angles in composites,” *Compos. Sci. Technol.*, vol. 165, pp. 214–221, 2018, DOI: <https://doi.org/10.1016/j.compscitech.2018.07.002>
- [5] M. Geers *et al.*, “Computational homogenization of structures and materials To cite this version: HAL Id: hal-01419916 Computational homogenization of structures and materials,” pp. 0–12, 2016.
- [6] E. Syerko, A. A. Diskovsky, I. V. Andrianov, S. Comas-Cardona, and C. Binetruy, “Corrugated beams mechanical behavior modeling by the homogenization method,” *Int. J. Solids Struct.*, vol. 50, no. 6, pp. 928–936, 2013, DOI: 10.1016/j.ijsolstr.2012.11.013
- [7] P. Cartraud and T. Messenger, “Computational homogenization of periodic beam-like structures,” *Int. J. Solids Struct.*, vol. 43, no. 3–4, pp. 686–696, 2006, DOI: 10.1016/j.ijsolstr.2005.03.063