

# Characterization and Validation of a Precursor Drawn Monofilament for Twisted Polymer Actuators and Free Torsion Actuation Data

BY

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# Introduction to Research Topic

It was recently shown that drawn polymer monofilaments, such as Nylon fishing line have the ability to supply linear actuation when it is configured as a coil Twisted-coiled Polymer Actuator (TCPA) [8]. However, it has not been clearly explained what the primary driving mechanism of these axial actuators is. Dr. Ray Baughman and his team at the University of Texas in Dallas [8] claim that axial actuation in TCPAs is caused by anisotropic thermal expansion in the radial and axial directions. Since, no clear explanation has been presented, suggesting no final demonstration has been achieved.

In the interest of achieving a suitable model for nylon actuators, our team has looked toward understanding how twisted nylon fibers react when a temperature gradient is applied. Here we present the straight twisted polymer actuator (STPA), which is a precursor fiber that is twisted about its central axis but still remains straight. Even though the twisted precursor remains straight, after the twisting process of manufacture, the polymer chains will be helically oriented about the central axis.

We consider this configuration the first step to take in order to model more complex nylon actuator configurations as TCPAs. So far, two models have been presented for STPAs: Shafer's [4] and Aziz's [9] model. These two models use the thermo-mechanical properties of the precursor fiber to predict torsional actuation. The purpose of this thesis is to characterize the thermo-mechanical properties of the precursor fiber and obtain accurate prediction by using the two mentioned models of torsional actuation under no load. This work also involves the process of experimentally validating the model and properties to ensure its accuracy.

## Objectives

### -Thesis Objectives

1. Complete a literature review on the body of the work on smart axial and torsional actuation, as well as a review on the material modeling of mechanical properties and behavior of the precursor material.
2. Qualitative and quantitative characterization of the precursor material known as drawn monofilament of Nylon 6.6 with the brand name of "Berkley Super Strong Trilene" as a function of the variables, which play an important role in the mechanism of actuation of Twisted Polymer Actuators, including its elastic and viscoelastic behavior. The following properties must be studied in depth to fully predict the actuation of TPAs:
  - Axial modulus as a function of temperature
  - Radial modulus as a function of temperature
  - Shear modulus as a function of temperature
  - Poisson ratio
  - Thermal axial contraction
  - Thermal radial expansion

3. Compare experimental torsional actuation of a Twisted Polymer Actuator under no load with the previous found properties by using the Shafer's and Aziz's mathematical models.

## **Relevance to this Field**

### **Torsional actuation with Smart Materials**

Many different smart materials have been studied to create torsional actuation. Some renowned smart materials in this engineering field are CNT (Carbon Nanotube), SMA (Shape Memories Alloys), EAP (Electroactive Polymers) and SMP (Shape Memory Polymer), and the one study here, STPA (Straight Twisted Polymer Actuators). However, other non-smart materials but innovative torsional actuators can be mentioned like PAMs (Pneumatic Torsional Actuators) and HAMs (Hydraulic Actuators).

All of these smart materials are unique in behavior and properties. The mechanism of activation differs from one type to other due to the coupling that occurs between different fields of the materials (electric, magnetic or thermal field), in the case of STPAs there is a thermo-mechanical coupling, which is the driving force of actuation.

All of these materials can play similar roles in torsional actuation, but the affordability of STPAs is an aspect to highlight, this feature put nylon actuators in a competitive position regard the rest of the smart material on the market.

The features table 1 has been attached to this proposal to give a better understanding of the main actuation properties to study in torsional actuation, as well as provide a comparison between the different current technologies in this field.

Table 1: Main features of torsional actuators

Ref.	Type of Torsional Actuator	Activation Mechanism	Specific gravity	Free torsion. ( $\frac{\circ}{mm}$ )	Torque normalized by cross sectional ( $\frac{N}{mm^2}$ )	Magnitude of activation
[1,2]	CNT	Temperature	1.6	15 ~ 80	0.5 ~ 1.8	0 ~ 90°C
[3]	SMA	Temperature	6.5	0.18	100 ~ 200	0 ~ 100°C
[4]	STPA	Temperature	1.12	~12.7	0 ~ 119	0 ~ 90°C
[5]	EAPs Ion-based actuation	Electricity	1.12	0.01	N/A	0 ~ 4 V (Alternating Current)
[6]	PAMs (Antagonistic Torsion Shape Actuators)	Pneumatic (Pressure)	...	0.287	0 ~ 1.43	50 ~ 90 kPa
[7]	PAMs (Peano Actuators)	Pneumatic (Pressure)	...	0.315	0 ~ 0.713	50 ~ 90 kPa
[8]	SMP Shape Memory Polymers	Temperature	1.12	~1.8	~1	0 ~ 62°C
N/A	HAMS	Hydraulic	N/A	N/A	N/A	N/A

## Characterization of a Precursor Drawn Monofilament of Nylon 6.6

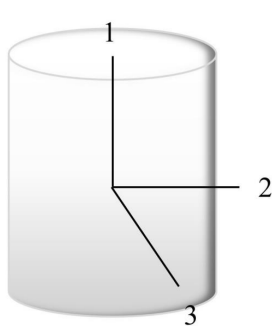
In terms of free torsional displacement actuation only two properties of the precursor fiber are required; axial and radial thermal expansion. However, for other actuation scenarios where a load is involved, the rest of properties will play a role in the equation of actuation.

In the characterization of a material mechanical properties there are a couple of considerations that are key in order to obtain reliable properties. In this respect, we consider the precursor fiber a transversely isotropic material, where the material is perfectly characterized by finding the properties in the radial and axial directions.

Another aspect to consider is how the material is going to behave when stresses are applied. Two different behaviors are studied in this thesis: Linear elasticity and viscoelasticity. It is worth mentioning that linear elastic behavior (Hooke's Law) is easier to model than viscoelastic behavior; nonetheless, we will state when elastic behavior is a great approximation under certain circumstances.

### Linear Elastic Behavior

In this section, the 3D stress-strain relationships for transversely isotropic materials will be considered within a linear range.



$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_1} & \frac{-\nu_{12}}{E_1} & \frac{-\nu_{12}}{E_1} & 0 & 0 & 0 \\ \frac{-\nu_{12}}{E_1} & \frac{1}{E_2} & \frac{-\nu_{23}}{E_2} & 0 & 0 & 0 \\ \frac{-\nu_{12}}{E_1} & \frac{-\nu_{23}}{E_2} & \frac{1}{E_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{2(1+\nu_{23})}{E_2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{12}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \times \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{13} \\ \tau_{12} \end{Bmatrix}$$

Figure 1: Transversely Isotropic Compliance Matrix.

Illustration 1 shows a transversely isotropic material. Configuration, where the 2 and 3 axis (radial directions) are assumed to be planes of isotropy. Thus all properties in the radials directions are going to be the same. This fact can be translated to the compliance matrix that is well defined with only five independent variables.

### Viscoelastic Elastic Behavior

Most of the polymers materials exhibit a combination of elastic and viscous responses when external loads and deformations are applied. This behavior is more complicated than

Hookean solids. Some models that have been studied are: Boltzman superposition, spring-dashpot configurations or complex modulus notation model. In this thesis we will work through these models and obtain the closest fit for the precursor fiber.

## Validation of Shafer's and Aziz's Model with the Obtained Properties using Experimental Results

The models that have been presented in journal articles so far are the Shafer's model in the DASL at the Northern Arizona University and Aziz's model at the University of Wollongong. These are the model that we are going to be testing for validation.

### Shafer's Model

This model predicts the free rotation of a STPA as a function of thermal load under the main assumptions of: considering the precursor monofilament a transversely isotropic linear-elastic material, constant pitch angle as a function of the radius, and the fibers at each radii are free to expand/contract due to thermal loading without stress.

The model uses precursor drawn fiber axial thermal expansion,  $\varepsilon_{11}^t$ , and the radial thermal expansion,  $\varepsilon_{22}^t$  to predict the untwist ( $\Delta\phi$ ) and change in length ( $L_f - L$ ) of the polymer monofilament under thermal loads.

This model is based on a transformation of coordinate system of the chain polymer (1 & 2 directions) to the radial (r), tangential ( $\theta$ ), and axial (z) coordinates direction by using the pitch angle. As a matter of simplification a non-dimensional initial twist;  $x = \frac{r\phi_o}{L}$ , is defined where "r" is the radial position of a particular fiber,  $\phi_o$  is the initial twist into the fiber, and L the initial length of the monofilament.

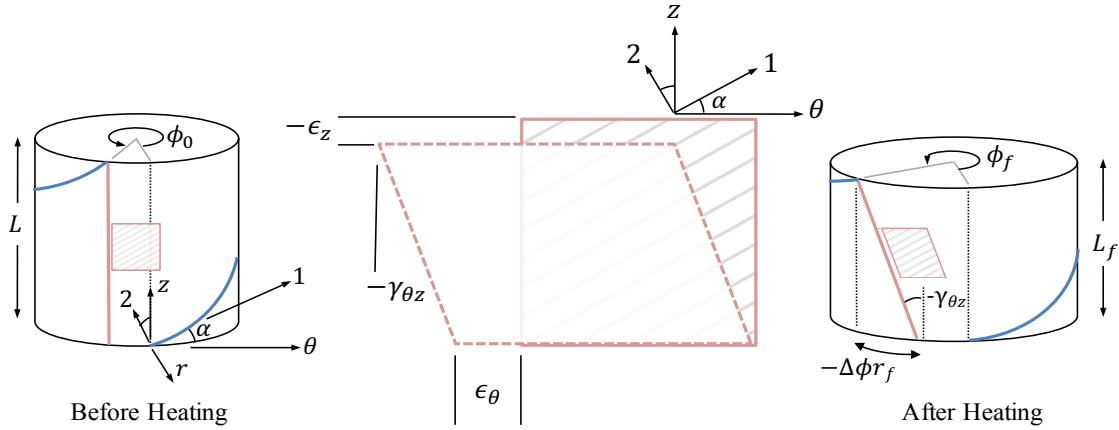


Figure 2: Transition of a STPA under thermal load with principal and converted coordinate systems.

As a result of this coordinate transformation and simplifications, the change in length can be predicted as the equation 1 shows:

$$\Delta L = L_f - L = \varepsilon_z^t L = \frac{\varepsilon_{22}^t x^2 + \varepsilon_{11}^t}{1 + x^2} L \quad (1)$$

And the change in untwist can be calculated as the equation 2 shows:

$$\frac{\Delta\phi}{\phi_0} = \frac{(\varepsilon_{11}^t - \varepsilon_{22}^t)}{1 + x^2} \quad (2)$$

### Aziz's Model

Another model has been presented, where torsional actuation is attributed to the radial thermal expansion. This model neglects changes in length in the axial direction and is not valid for temperatures in the range of 26 to 62 °C. In this model the torsional stroke in turns for fiber length was claimed to be  $\Delta T$  :

$$\Delta T = \frac{n_o}{l_o} \left( \frac{d_o}{d} - 1 \right) \quad (3)$$

In the equation 3,  $n_o$  is the initial number of twists,  $d_o$  is the initial fiber diameter,  $l_o$  length of the fiber, and  $d$  is the fiber diameter as a function of temperature.

Equation 3 can be converted in terms of untwist in radians ( $\Delta\phi$ ) and the radial thermal expansion ( $\varepsilon_{22}^t$ ) in order to be able to analyze a general case. The prediction of the untwist fiber is given by  $\Delta\phi$  in radians, in the equation 4:

$$\Delta\phi = -\phi_o \frac{\varepsilon_{22}^t}{\varepsilon_{22}^t + 1} \quad (4)$$

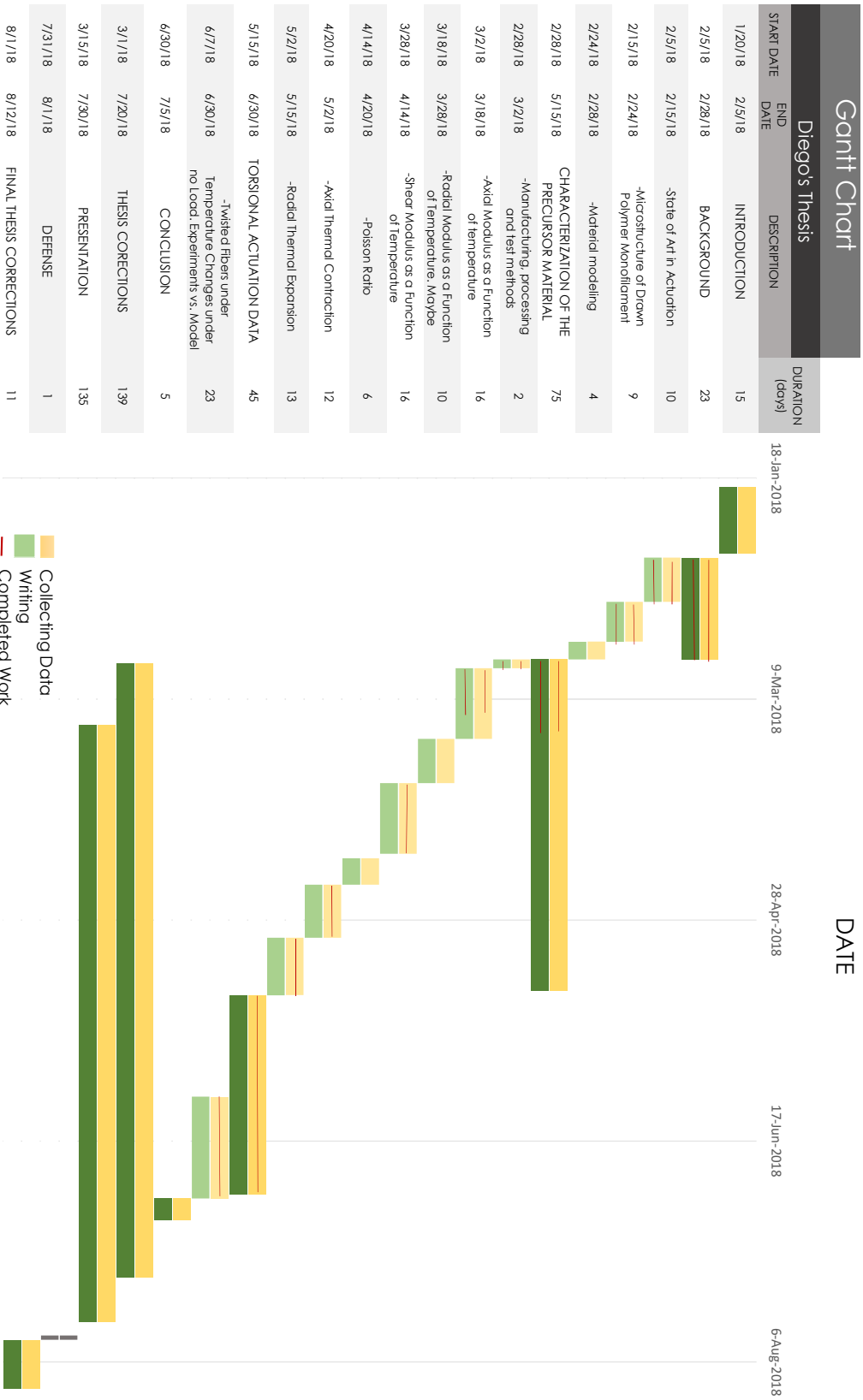
where  $\phi_o$  is the initial twist in radians.

### Completed Work

A complete literature review and characterization of nylon actuators will be submitted as a part of this thesis work, as well as an analysis of the microstructure of drawn monofilament of nylon 6.6.

An assessment of the obtained properties in the models will be presented and experimentally validated. To date, no reliable properties of the precursor fiber of nylon 6.6 have been published and this is a crucial work that need to be done in order to predict the actuation of STPAs. For this reason, in this work the properties of the precursor fiber will be found as a function of temperature. In addition, an study of the behavior of the precursor material will be done in order to analyze how the monofilament performs as a function of temperature or other parameters that might be critical in the characterization process.

Finally, we will use the obtained results to predict the actuation of STPAs with different numbers of inserted twists to see how they perform as a function of the pitch angle and validate these results with experimental data.



# Time Line



## Future Work

After the characterization of the precursor material and modeling of the actuation under no load, the model will be expanded to account for actuation with applied loads, being this case that will be presented in real life applications. This upgraded model will predict torsional stroke and developed torque as a function of temperature.

In terms of modeling, a new model could be created for predicting the actuation of axial nylon actuators. This is considered the most complex model; nevertheless, it is expected for this model will follow the same principles of torsional actuators models.

After characterization and modeling of the material, implementation is the final step. Different type of configurations can be built in order to create different applications. In implementation, activation method is another topic to consider, since more of the efficiency drop is due to thermal losses between the thermal source and the nylon actuator.

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