Spring 5-5-2023

The Future is Now in Twisted Coil Polymer Actuators (TCPA)

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By

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Presented to the Faculty of the Graduate School of

Stephen F. Austin State University

In Partial Fulfillment

Of the Requirements

For the Degree of

Master of Science

Stephen F. Austin State University

May 2023

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Abstract

This thesis aimed to fabricate and test twisted coiled polymer actuators (TCPA) to understand the mechanical and thermal aspects of this artificial muscle fiber. The purpose of this thesis was to find a linear relationship using the LVDT sensor, fabricating TCPA fibers, and interpreting the data. The project tested whether nylon/polymer could be used as a better artificial muscle fiber.

This research accomplished three goals: (1) designing and fabricating a system capable of creating supercoiled muscle fibers consistently, (2) calibrating the Linear Variable Differential Transformer (LVDT) and Core, and (3) analyzing/interpreting the data of the Twisted Coiled Polymer Actuators (TCPA) fibers through the sensors. The proposed methods could be used to control the monofilament's twisting and tension through the four steps, measuring, coiling, annealing, and testing the TCPA fibers.

This thesis has built a foundation that can be used to fabricate TCPA fibers from nylon and evaluate their mechanical and thermal behavior while being measured within the LVDT sensor. The results provided a better understanding of the mechanical behavior of the TCPA fibers and provided the foundations to optimize a final building block to understanding this artificial muscle fiber.

Acknowledgements

I would like first to thank God for all my accomplishments, for without Him, I wouldn't be where I am today. This road that I have been on has been a journey; I am grateful for my friends, family, and brothers of my fraternity for sticking by my side through this process of getting my Masters. Thank you to my committee for serving on my committee and helping me when I needed it the most.

Thank you to the group of friends that I made along the way, Elie, Matt, Katie, Adam, Drue, Acacia, and more, that were always in the maker space, pushing me to finish this thesis. You all will forever have a special place in my heart, and without y'all, I wouldn't be here. Thank you, Dr. Ochoa, and I will find that pen eventually, but you have been a mentor to me, and I couldn't be more blessed to have a man like you help me get through this master's program.

Finally, I would like to thank the Department of Physics, Engineering, and Astronomy for helping me achieve my bachelor's and my master's program. All of you have pushed me to be a better student and a better man, to push past my limits, and to walk on that stage as a college grad eventually. Thank you again to everyone that believed in and supported me. Isaiah 41:10, for God, says to "Fear not, for I am with you; be not dismayed, for I am your God; I will strengthen you, I will help you, I will uphold you with my righteous right hand."

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Introduction

Prosthetics are an ancient piece of technology. Archaeological examples of artificial body parts include a 3000-year-old mummy with a wooden toe, many sets of early false teeth connected to intact teeth using metal bands, and perhaps the most famous ancient prosthetic limb in Europe, the Capua Leg. However, while these examples were impressive for their time and showed extraordinary craftsmanship, they were stop-gap solutions, offering little functionality.

It wasn't until around the 16th century that prosthetic design began to factor in functionality, design, and provide convivence. Innovative military surgeon Ambroise Paré pioneered a functional prosthetic design attempting to replicate the movement of biological limbs using pulleys, cables, hinges, and springs. His stand-out design was a mechanical hand that used catches and springs to simulate the direction of the finger joints. The design worked so well that a French Army captain wore a version of the prosthesis into battle, claiming he could grip and release the reins of his horse using the hand.

Leg prostheses are commonly used prosthetics that help many individuals continue daily tasks in their lives. Since World War One, prosthetics have been integrating springs to replicate the ability to store and release energy that mimics a muscle in the human body, and ever since then, engineers have wanted to be continued research on these extremities to improve prosthetics. The discovery and research of artificial muscles have been used to design and develop biomedical devices and biomimetic robots. However, the ideal biomimetic robots require specially designed actuators that can replicate the behavior of natural muscles. Natural muscles are impeccably capable of sensing, acting, and calculating. Such a replica of an artificial muscle is required for biomedical and robotic applications with advanced and higher performance.

For muscle fibers that react with the Myosin and Actin fibers in the skeletal system, the goal is to create an artificial muscle that can react sensitively to changes (Eccentric and Concentric contractions) similar to the skeletal muscles. For instance, the myofilament theory states, a suggested mechanism of contraction of striated muscles, actin, and myosin filaments to be precise, which overlap each other resulting in the shortening of the muscle fiber length. The length-tension relationship describes the amount of tension produced by muscle in relation to its length. The muscle will lengthen or shorten, changing the maximal force produced when tested under isometric conditions.

With this knowledge, in 2014, twisted polymer fibers were created in a laboratory at the University of Texas at Dallas (UTD), which were thermally constructed and fabricated to function as muscle fibers. In this development, most artificial muscles faced a limitation on one or another front and hence mainly failed to compete with mammalian muscles. This has led to further curiosity and accelerated research in artificial muscles. Recently, Haines et al. introduced a better alternative to expensive existing artificial muscles with better performances.

On May 22, 2016, The University of North Carolina came up with the idea that lightweight artificial muscle fiber can match the sizeable tensile stroke of natural muscle fibers. These fibers were produced by carbon nanotube yarn. This fiber was selected due to the anisotropy of the material. For thermally actuated muscles, the fiber expands or contracts due to thermal temperatures that create the TCPA to be "trained." This effect is most dramatic in certain aligned polymer fibers like nylon. This material expands in diameter but contracts in length when heated. This theory was also introduced at the University of Wollongong, where the diagram below shows the same process that the University of North Carolina did.

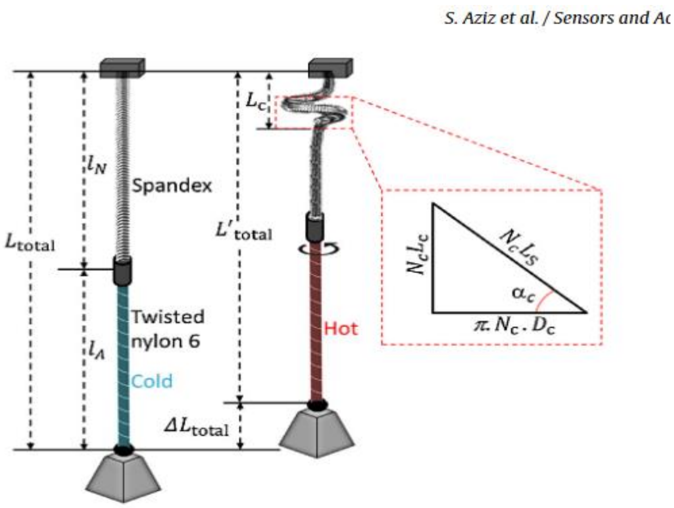

Figure 1: Schematic showing twist coil actator system that is heated to cause rotation.

$$\Delta L = \frac{I^2 \Delta T}{N}$$

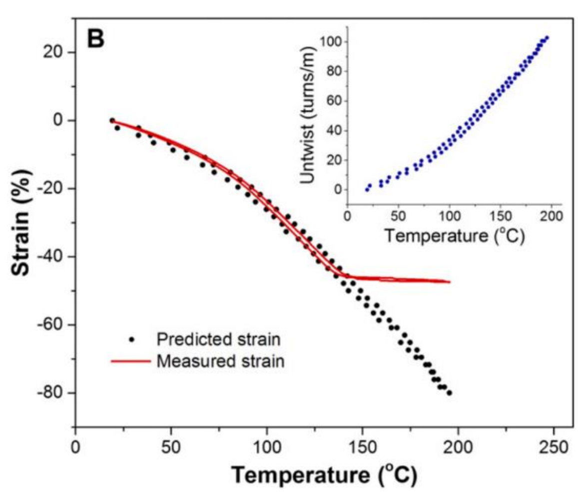

Figure 2: A plot of the tensile actuation measured from the coil vs temperature.

Figure 1 shows the overall length contraction (ΔL Total) of the twist coil actuator, which is the summation of the length changes (due to the coil formation) in the elastomeric and twisted fiber (due to untwisting). However, Witham Nicholas (UNC) used the equation from Figure 1 to find the tensile stretch of a coil spring instead of showing the apparatus in a geometric form. The parameters will be listed in the appendix. This research team also used a plot to find the tensile actuation measurements of the coil vs. the temperature (red) and the theoretical actuation prediction of the coil (black). Both teams complemented each other's research and aimed to find a productive artificial muscle through mathematical terms and precise plots.

Our research aims to fabricate the Twisted Coiled Polymer (TCP) actuators with nylon, calibrating the LVDT and Core sensor and deriving the data from the sensors. Finding a mathematical equation through statistical software (JMP) that predicts the muscle fiber's behavior will be the overall goal but not this research's goal. Fabricating the Twisted Coiled Polymer (TCP) actuators is mentioned thoroughly in the methodology, but these steps include four stages. The measurement, coiling, annealing, and testing stage aided our research by completing the first goal of this research, which is the fabrication of TCPAs. The next step is calibrating the Linear Differential Variable Transformer (LVDT) to acquire accurate linear measurements. Finally, after the calibration stage is the testing phase of each TCP actuator. Using an LVDT sensor in a closed heating chamber to measure the diameter of the muscle fibers' behavior. The fibers in the testing phase provide an array of data from the MATLAB code. This data aided the research team in interpreting the mechanical behavior. Once one trial is finished, MATLAB will display two graphs representing the actuator’s contraction. The data interpreted from MATLAB and JMP will display the TCP actuators' functionality and help find the overall goal for future research.

Background/Theory:

The Twisted and Coiled Polymer (TCP) actuator, generally categorized as a type of artificial muscle, is a linear actuator that can significantly contract its length under a mechanical load when subjected to thermal stimuli. The physical phenomenon behind the mechanism of this muscle is the anisotropic physical property of the highly oriented polymers such as nylon and polyethylene, which are the result of the oriented structure. Figure 3 shows a metallic spring and a TCP actuator to indicate their behavior in response to heat. The difference in the metallic helix vs. the polymer is the contraction change. For the left side of the figure (Metallic), the diameter contraction is much smaller than the right side of the figure (polymer). The metallic structure does not twist the same as the polymer due to its isotropic CTE properties, which doesn't allow the spring to twist when under thermal load. Thus, the research team is using this type of information to use this kind of material to get adequate results.

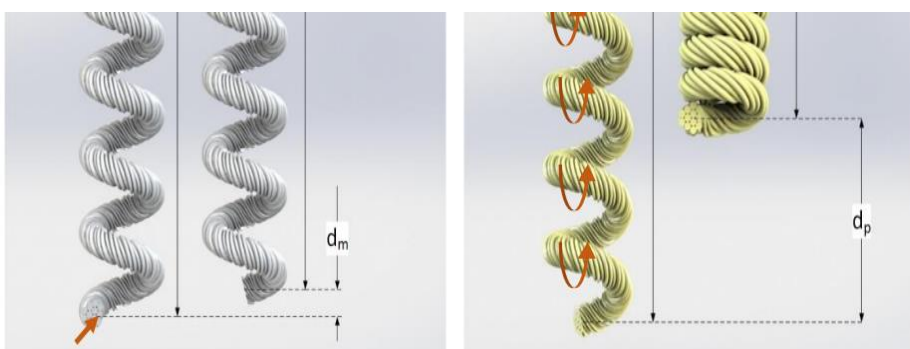

Figure 3: Effect of heat on the length of a metallic helix (left) and TCP (right) [Karami]

This theory is similar to the sliding filament theory proposed in the mid 1950s. Active muscle contraction involves the relative sliding between the thin (actin) and the thick (myosin) filaments in a sarcomere. Muscle contraction is caused by the brain from action potential causing an influx of calcium ions that bind to a protein on to the actin filament, causing a change in the actin (thin) and myosin(thick) binding sites. This mechanical driving process is the repetitive interaction of myosin heads on actin filaments. A cross-bridge attaches to actin, undergoes a confrontational change generating muscle force and power, and then detaches. This is called a power stroke, or in other terms, how our bodies produce force. This occurs when the sarcomere shortens and the muscles contract.

Figure 4 shows this mechanical cycle coupled with an enzymic reaction, hydrolysis of Adenosine Triphosphate (ATP). Energy is liberated during the release of the ATP hydrolysis and is converted into work and heat. This theory is still not fully understood, but muscle contractile response and function are sensitive to temperature.

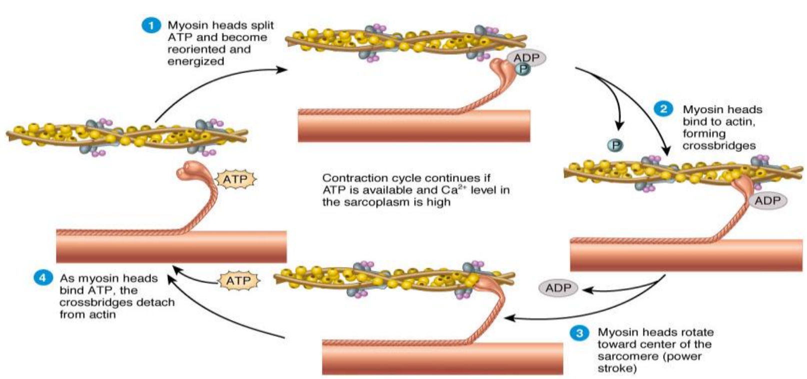

Figure 4: Myofilament/sliding filament theory [Karki]

With this knowledge of biology, the idea is to create an artificial muscle that can replicate muscles' contraction (shortening) and eccentric (lengthening) through temperature changes. TCPAs are finding several applications through biomedical and robotics research that could revolutionize modern prosthetics. For example, the University of Texas at Dallas "proposed a robotic hand powered by a TCP muscle through a tendon-driven mechanism, which reduced the weight of the hand compared to the ones driven by servo motors. In another work, Saharan et al. demonstrated an exoskeleton hand orthosis driven by a set of TCP muscles to help people with an impaired nervous system having assisted hand movements." [UTD]

The first step is to calibrate the Linear Differential Transformer (LVDT) and the core to continue to find the overall goal. This helped the research by finding a linear function from the TCPA fibers and calibrating the sensors, which ensures reliable linear measurements. The LVDT sensor is a position transducer that uses a trio of transformers to provide linear displacement measurements shown in Figure 5.

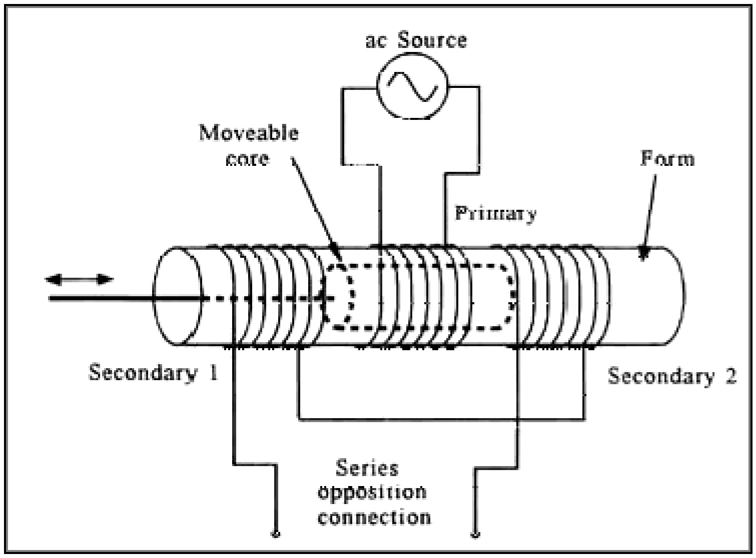

Figure 5: Linear Displacement Measurements [Ni.com]

The moving element of an LVDT is a separate tubular armature of magnetically permeable material. This is called the core, which is free to move axially within the coil's hollow bore, and mechanically coupled to the object whose position is being measured. The core will measure the displacement of the TCPA fibers within the LVDT sensor to determine the muscle fiber's contractive state in millimeters. As Figure 6 demonstrates, once the core is within the LVDT sensor, a MATLAB code will give an array of data that will give a graph similar to Figure 7.

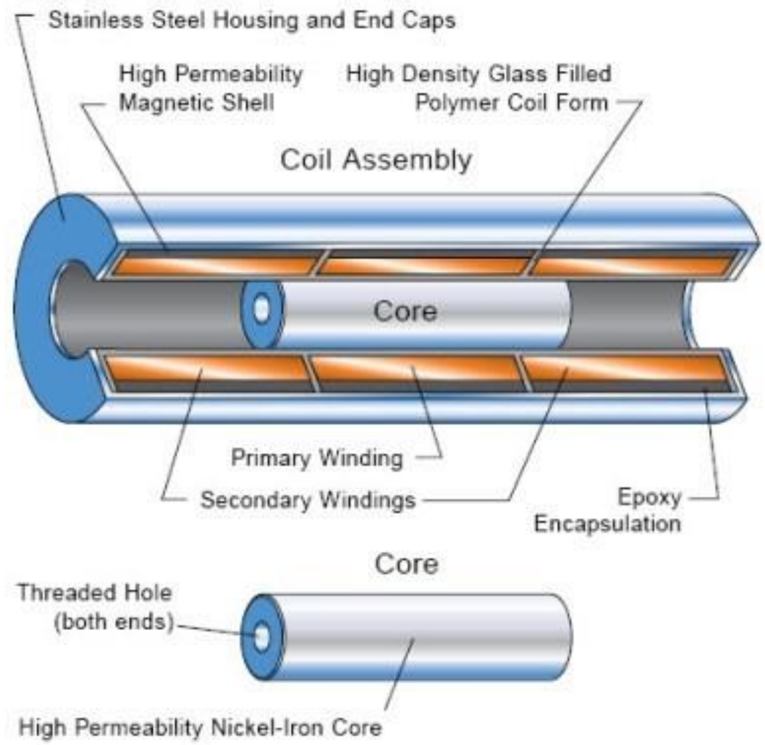

Figure 6: LVDT Sensor With the Core [NI.com]

To summarize, "The LVDT closely models an ideal zeroth-order displacement sensor structure at low frequency, where the output is a direct and linear input function. It is a variable-reluctance device, where a primary center coil establishes a magnetic flux coupled through a central core to a symmetrically wound secondary coil on either side of the primary. Thus, by measurement of the voltage amplitude and phase, one can determine the extent of the core motion and the direction, that is, the displacement." (NI, 2022) Figure 6 shows the linearity of the device within a range of core displacement. Note that the output is not linear as the core travels near the boundaries of its range. This is because less magnetic flux is coupled to the core from the primary. However, because LVDTs have excellent repeatability, nonlinearity near the boundaries of the range of the device can be predicted by a table or polynomial curve-fitting function, thus extending the range of the device.

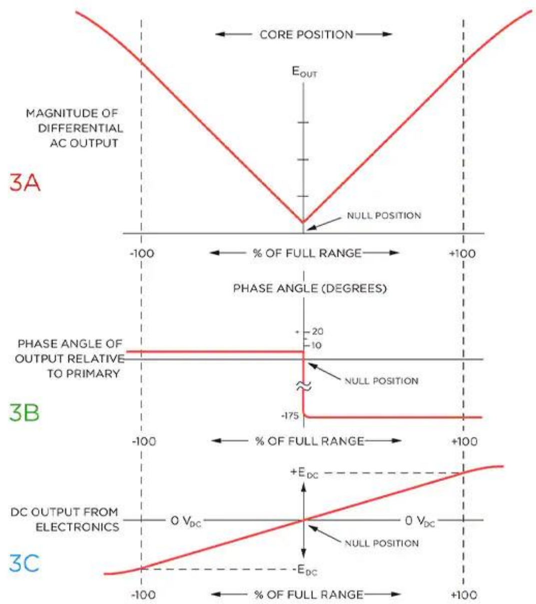

Figure 7: Proportionally linear LVDT Response to Core Displacement

The goal is to make an artificial muscle fiber that fits the magnitude of the differential AC output (Figure 7) to justify our equation. This will be achieved by calibrating first the LVDT sensor with the core. The core will be lowered approximately 4 millimeters (mm) for about 30 minutes. Once the 30 minutes are up, the core will be lowered another 4mm until the core reaches the bottom of the LVDT sensor. This test provides the range of the sensors to be accurate and whether it will be a positive or negative slope. The equation will come from a set of data points from our statistical software JMP, which will provide an array of data to interpret the change of displacement within the LVDT sensor. Figure 8 represents the change of displacement of the core within the LVDT sensor to demonstrate its functionality. Using a MATLAB code, the data that was provided is in five categories, Time, Voltage 1 (X), Voltage 2(Y), Z (voltage difference), and millimeters(mm).

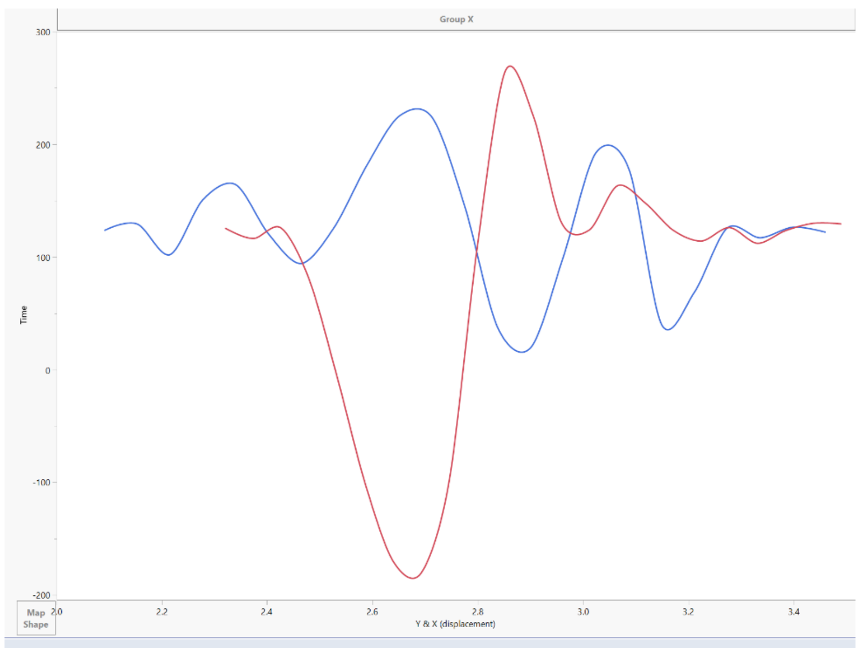

Figure 8: Voltage 1(X) and Voltage 2(Y) vs Time

This graph is identical to Figure 8 in the ranges of [2.4,2.8] regarding the magnitude of the two voltages. This graph shows the behavior of the core descending into the LVDT sensor and producing the image you see above. This represents how the core should behave when testing the artificial muscle fibers on the core.

Now that the core and LVDT sensor have been calibrated, the next step is finding a material that can be used to create TCPA fibers. Research has shown that nylon is the most used for this purpose due to its flexibility. Nylon is perfect for this research because it shrinks or contracts in length but expands in diameter when heated. Using an ordinary fishing line, and twisting the fibers with some tension, will fabricate TCPA fibers, as shown in Figure 9.

Figure 9: TCPA Muscle Fiber

This is one of the thirty muscle fibers created for this research. The polymer muscles will be used to find an array of data using MATLAB and JMP. The TPCA muscle fibers will need to be annealed or trained before testing. The annealing process trains the muscles to contract at high temperatures to maintain a specific shape. It relieves the internal stresses and maintains the twisted shape fibers. The data recorded from the testing phase of the devices will be used to generate mathematical models that would characterize the performance of these muscle fibers.

One issue found with this research, which will be discussed in the closing statements, is the magnitude was found that matched our plot in Figure 8. However, the research identified that the phase angle was not found due to the limitations of the MATLAB code. This was not a significant issue, but that phase angle determines whether that slope is either positive or negative on that absolute curve. To solve this issue for future research, the research team aims to add a program to identify the phase angle in the MATLAB code to ensure the identity of which side of the curve it is on. Considering this issue, the data was still sufficient to interpret the mechanical behavior of the TCP actuators.

Methodology

Fabrication

The nylon fishing line was chosen as the optimal material for the TCPA fiber. This was motivated by the material's low bulk cost and broad accessibility. An in-house device preemptively cut the fibers to a consistent length of approximately 6 inches or 16 centimeters. A knot is used to create a loop at one end of the muscle, and the loop at the other end is secured using a metallic 'collet' shown in Figure 10. An image of fiber ready to be coiled is shown in Figure 11. Once measured and the loops are secured, the nylon filament will then be coiled using the custom device with an Arduino to create a TCPA fiber. These steps are necessary to ensure that the data collected from the artificial muscles remains consistent throughout the experiment.

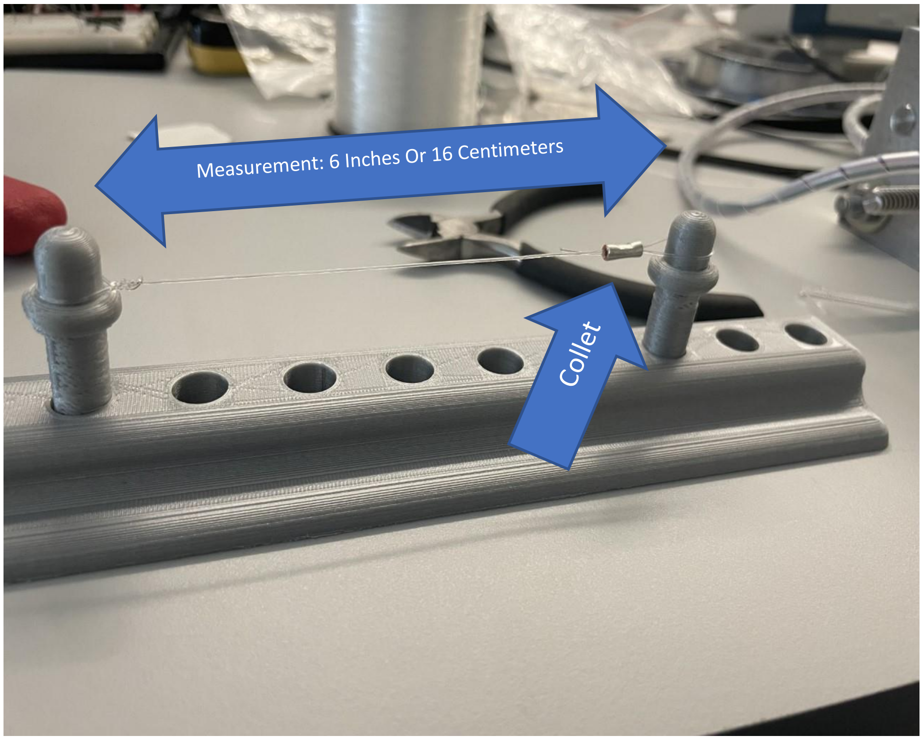

Figure 10: Measurements of the Nylon before twisting

Coiling

Once the filaments are of equal length and have been secured from each end, the next step is to coil the fibers to create a TCPA fiber. These fibers were created using our muscle twisting apparatus, equipped with a force sensor and PID controller using an Arduino. The Force Sensor is designed to provide precise and reliable force-sensing performance to the targeted object. The Arduino connected to the pressure sensor reads the pressure while the cart moves to provide consistent tension through the filament. The

Oscilloscope shows the output voltage from the force sensor, which is proportional to the tension of the coiling filament. As the filament slowly coils, tension builds in the line of the filament, causing a rise in voltage. This continues until one coil of the filament is complete resulting in a voltage drop. This periodically occurs until the filament is completely coiled. Once the filament has finished coiling, it must be annealed, which is needed to lock the shape of the muscle. A total of 30 artificial muscle fibers were fabricated for this research project. From these 30 fibers, three groups of 10 were created, where each group was fabricated with a different tension.

This was performed to observe the different parameters that affect TCPA fibers. For instance, the first group of fibers was fabricated with a tension of 227 (g). For the first group, the research team observed that the length was 17.6(mm). For the second group, the tension was 300 (g), and for the third group, the tension was 400 (g). The average number of coils and diameter were roughly the same for each group. Similar results were found for the muscle fiber length and pitch angle of the coil. The first group of muscles had an average length of 17.6 (mm) with a pitch angle of (15.37), the second group of muscles had an average length of 15.9 (mm) with a pitch angle of (16.2), and the third group of muscles had an average length of 14.3 (mm) with a pitch angle of (16.7). As the tension increases, the loops take a bit longer to form, causing the structure to shrink in length and increase the pitch angle of the TCPA fibers. The numbers are shown in Table 1-3.

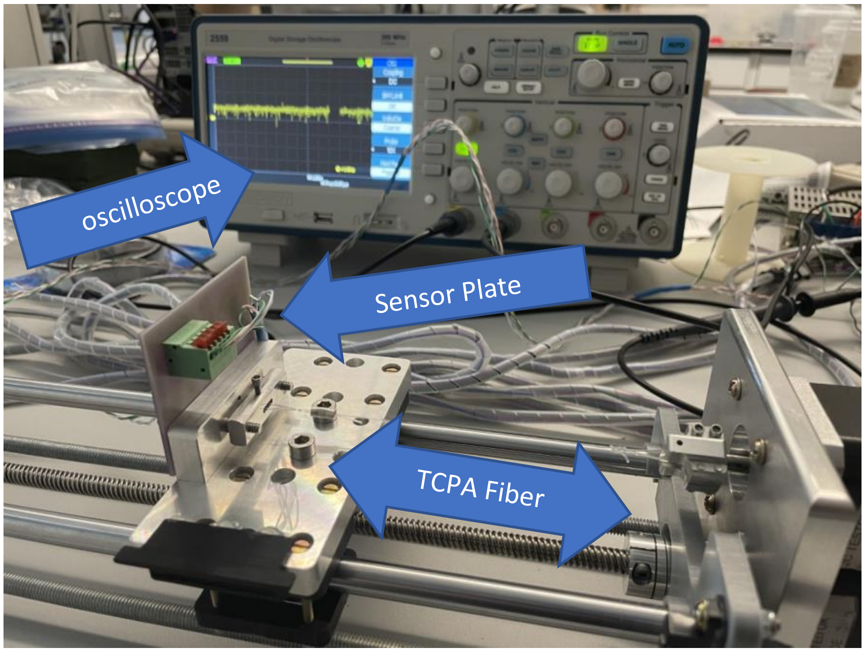

Figure 11: Filament Coiling Process

Annealing process (with physical data)

The annealing process trains the muscles to contract at high temperatures to maintain the helix shape. It relieves internal stresses and provides a twisted shape. In other words, the internal fibers have a new orientation defined by the given pitch angle, α, which is the angle defined by the new internal fiber orientation with respect to the horizontal. This angle α depends on the radial position within the twisted monofilament. The activation temperatures are defined in a range from room temperature (22◦C) and 100◦C. The maximum activation temperature is 20◦C lower than the annealing temperature to avoid new rearrangement in the microstructure of the actuator. The fiber will descend from our homemade hooks in the heating chamber. Once the fiber is set up on the hook, the weight of 100-150 grams is attached to the TCPA fiber. Once correctly set up, the annealing process takes about thirty minutes to reach 95-100 degrees Celsius and then an hour to properly train the fibers at that temperature. This whole process takes about an hour and thirty minutes. This stage provides the fibers to maintain a helix-type structure in thermal load; without this step, the fiber will release the loops and return to a linear-type structure.

Figure 12: The heating Chamber for the Annealing process

Once the fibers are fully annealed, the physical measurements of each TCPA are taken. The following is a list of the measurements taken

- Length (mm),
- Number of Coils(N)

- Pitch angle (α)
- Coil Diameter (mm)

The results from these measurements are shown in Table 1-3. Once all the measurements were collected and the training had been completed. The artificial muscles were tested to collect data regarding their physical response to changes in temperature. This last step is understanding the artificial muscle fibers' mechanical behavior and functionality.

Table 1: The measurements of each TCPA fiber at a Tension of 227 grams

1st Test (227g)		Table A		
Number	Length (mm)	Number of Coils (N)	Pitch angle (α)	Coil Diameter (mm)
1	29.2	24	16	1.92
2	23.9	22	21	1.95
3	13.9	17	14	1.32
4	17.5	23	21	1.8
5	14.94	20	13	1.9
6	16.85	22	15	1.85
7	15.42	20	10	1.77
8	12.32	18	16	1.94
9	15.01	22	13	1.86
10	14.2	14	14	1.82
Averages	17.6	20.8	15.37	1.812

Table 2: The measurements of each TCPA fiber at a Tension of 300 grams

B: 2ndTest (220-300g)		Table B		
Number	Length (mm)	Number of Coils (N)	Pitch angle (α)	Coil Diameter (mm)
1	18.71	20	13	1.85
2	14.65	22	14	1.78
3	16.83	22	18	1.86
4	13.08	19	15	1.81
5	13.52	18	15	1.81
6	18.44	21	24	1.88
7	17.13	23	12	1.82
8	14.52	20	19	1.8
9	17.12	20	18	1.86
10	15	21	14	1.81
Averages	15.9	20.6	16.2	1.828

Table 3: The measurements of each TCPA fiber at a Tension of 400 grams

3rdTest (150-400g)		Table C		
Number	Length (mm)	Number of Coils (N)	Pitch angle (α)	Coil Diameter (mm)
1	16.51	22	16	1.86
2	14.13	23	19	1.91
3	11.54	20	17	1.87
4	14.85	22	15	1.74
5	17.42	23	13	1.91
6	15.69	21	18	1.97
7	12.74	16	18	1.7

8	12.49	18	18	1.88
9	12.68	20	16	1.98
10	15.24	20	17	1.95
Averages	14.3	20.5	16.7	1.877

The research team identified one key aspect during the annealing phase that can alter the testing phase. During the testing phase, some of the samples would produce irregular results similar to those seen in sample 6 (figure 13). The issue with this particular sample was not annealed long enough, to solve this issue the TCPA was annealed again for an hour and a half. Once the fiber was annealed again, the fiber produced the logarithmic shape as desired.

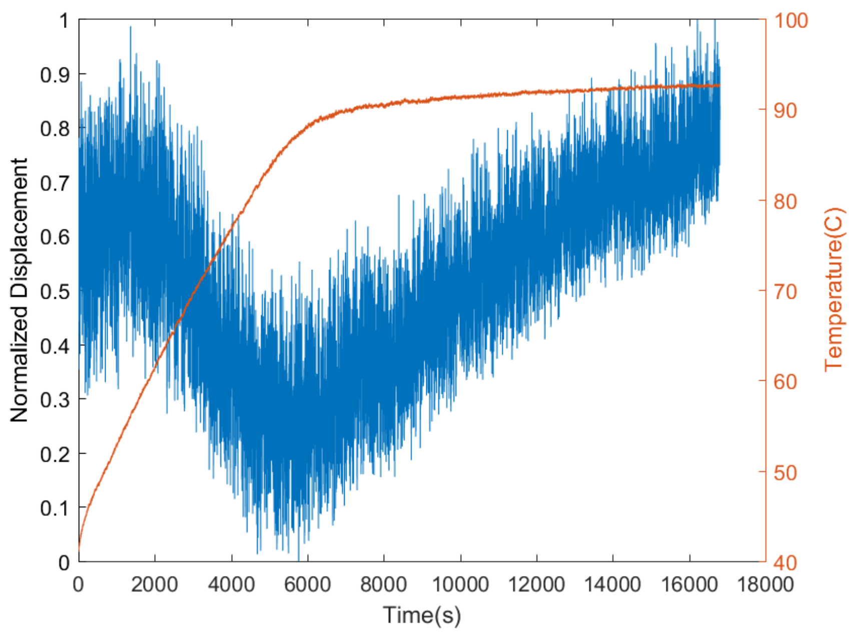

Figure 13: Irregular shape in Sample 14 of Tension 300 grams

Testing the Muscles in the LVDT

Figure 14 demonstrates the testing process of the TCP actuators in the heating chamber. However, instead of 600 grams, it will be 150 grams of weight. The TCPA fiber will be attached to the hook at one end and the weight at another. While the temperature increases to about 96 degrees Celsius, the LVDT sensor will read the core displacement position from the TCPA fibers contraction. It will be interpreted through MATLAB, giving us two graphs.

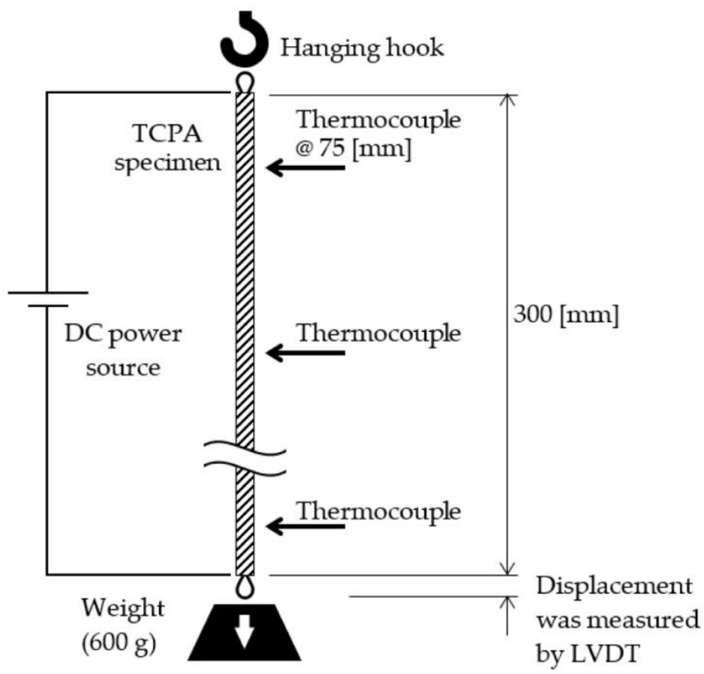

Figure 14: Schematic of TCPA Measurements with LVDT and Core Sensor (Kikuta)

This is the same process as the annealing stage; however, the LVDT sensor and core will be used to find an array of data representing their mechanical behavior. The DC power supply is connected to the Arduino, which transfers the data collected from the LVDT sensor and core to the MATLAB code generate components mentioned in Figure 9. The direct current (DC) power supply is set up at 13 Volts powering the Arduino. From there, the LVDT sensor will gather the collected data from the contractive state of each artificial muscle fiber, which will result in a change in diameter due to a thermal and mechanical load. Once completed, MATLAB will generate a figure of the TCPA fibers displacement and temperature readings. The measurements of the TCPA fiber's Normalization Displacement and Temperature (°C) vs. Time (Sec). In some instances, the response will rise and produce a positive or a negative linear slope. This is due to the placement of the core within the LVDT sensor. If the core is on the lower end, it will produce a negative slope, and on the higher end, it will produce a positive slope.

During this phase, the research team discovered that the thermocouple wire was cut/burnt out producing erratic temperatures readings as seen in figure 15. The temperature readings were not necessary for some samples due to their erratic behavior; thus, the normalization displacement will be shown for some samples such as sample 18. The research team also noticed a bit of noise disturbance during the testing phase, this was caused by the electrical and seismic power supply which transmits electrical noise through the connection from the sensor. This will be resolved using a lowpass filter in future research.

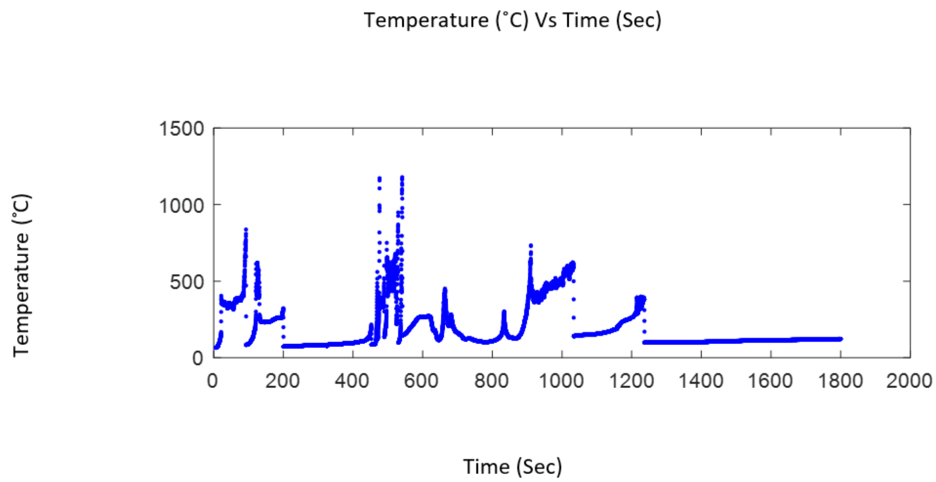

Figure 15: Erratic temperature readings from sample 18

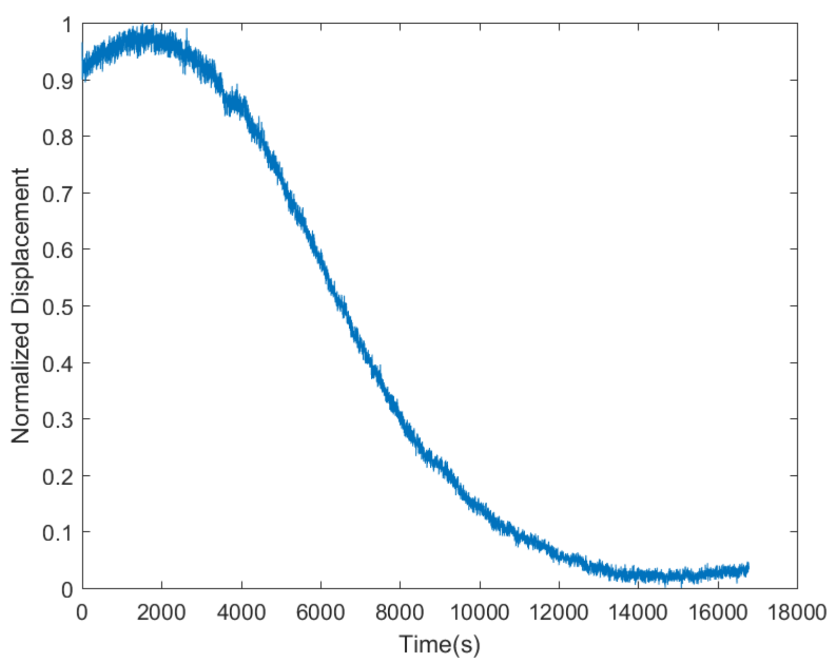

Figure 16: No Temperature, Sample 16, 300 grams of Tension

Results

The first result is the Core and LVDT sensor calibration shown in Figure 17. This figure shows the positive and negative slopes as the core descends in the sensor, as shown in Figure 8. Each trial lasted about 30 minutes before lowering the core, approximately 4(mm) after each trial. The vertical axis demonstrates the voltage difference between secondary 1 (X) and secondary 2 (Y), and the horizontal axis demonstrates the change in millimeters per trial. This step ensures the reliable linear measurements of each TCPA fiber and identifies which side of the absolute curve it is on.

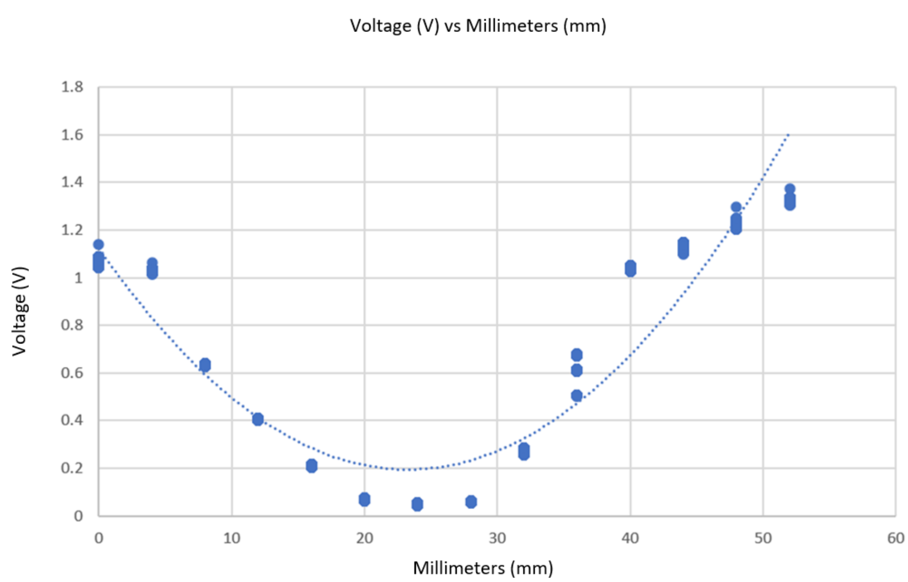

Figure 17: Testing of the LVDT sensor and core

Using MATLAB, this graph demonstrates the core positioning in the sensor, as demonstrated in Figure 8. This graph shows whether the muscle fiber is on the positive or negative side of the slope based on the core positioning and will aid in providing the overall goal, the mathematical model. After accomplishing all the steps in the methodology, MATLAB produced one graph during the training stage of the methodology. This graph is a control system of the muscle fiber in a contracting state that was normalized to represent the Y-axis from 0 to 1. This was implemented in the graph to show the fibers mechanical and thermal behavior as the temperature rises thus including both displacement and temperature in the same graph. These results will be subdivided into three categories labeled in the figures that will correlate with the amount of tension the TCPA fiber was tested with. The blue line will represent the TCPA fibers displacement, and the red line represents the temperature.

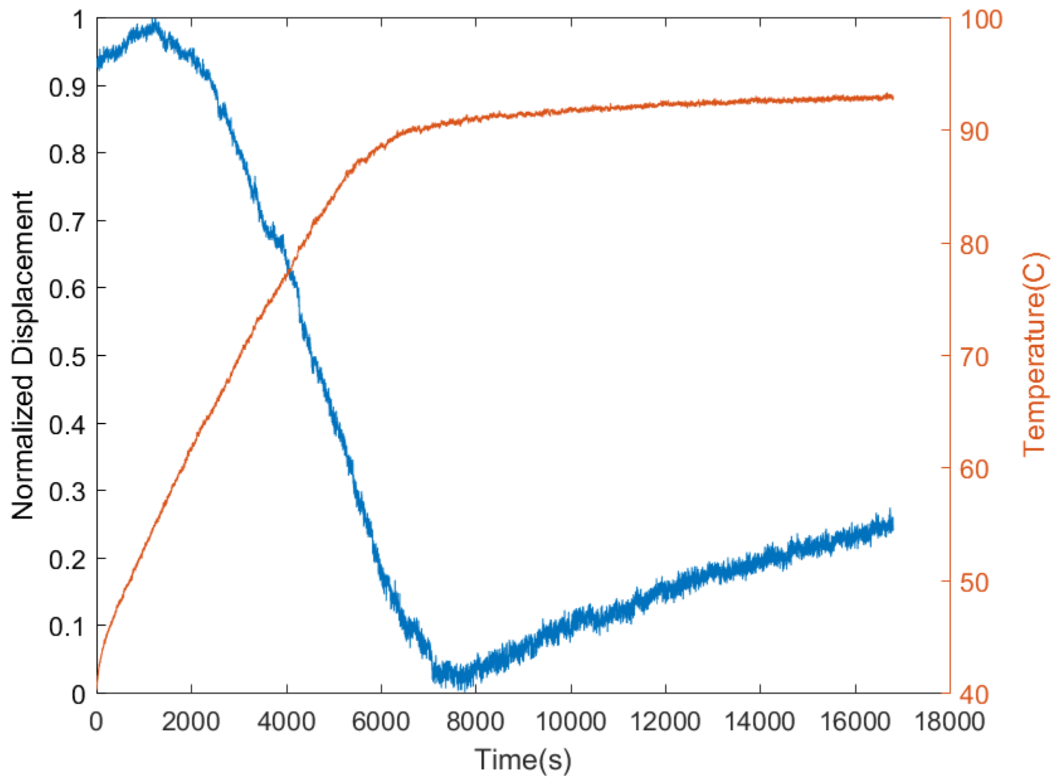

Figure 18: Sample 15, 300 grams of Tension

This graph indicates that the TCPA fiber is on the lower end of the core, giving us this negative logarithmic curve for displacement. As the temperature increases over time, the curve will begin to be linear for approximately 800 seconds (about 13 and a half minutes) until the temperature reaches 96 degrees Celsius, this is when a plateau begins, and the muscle fibers cease to contract. This mimics myofilament theory, in which a muscle fiber is contracting until the fiber is fully shortened. For instance, think of a bicep curl; at the bottom of the movement, the fiber is full lengthened (like in our graph). Once initiating the curl, the fiber begins to shorten and contract, and the fibers create enough force to overcome the external resistance.

This example is similar to the experiment and the data shown above. The TCPA fiber was measured for approximately 1800 seconds. This gave the fiber enough time to show muscular contractions as the temperature increased. This sample perfectly represents how the myofilament theory works and mimics actual muscular contractions of muscular fibers. Four samples will be shown from each tension, three samples will be represented with a displacement and temperature as shown in figure 18 and the other sample will be without a temperature reading. The rest of the samples that were not shown in the results will be located in the appendix.

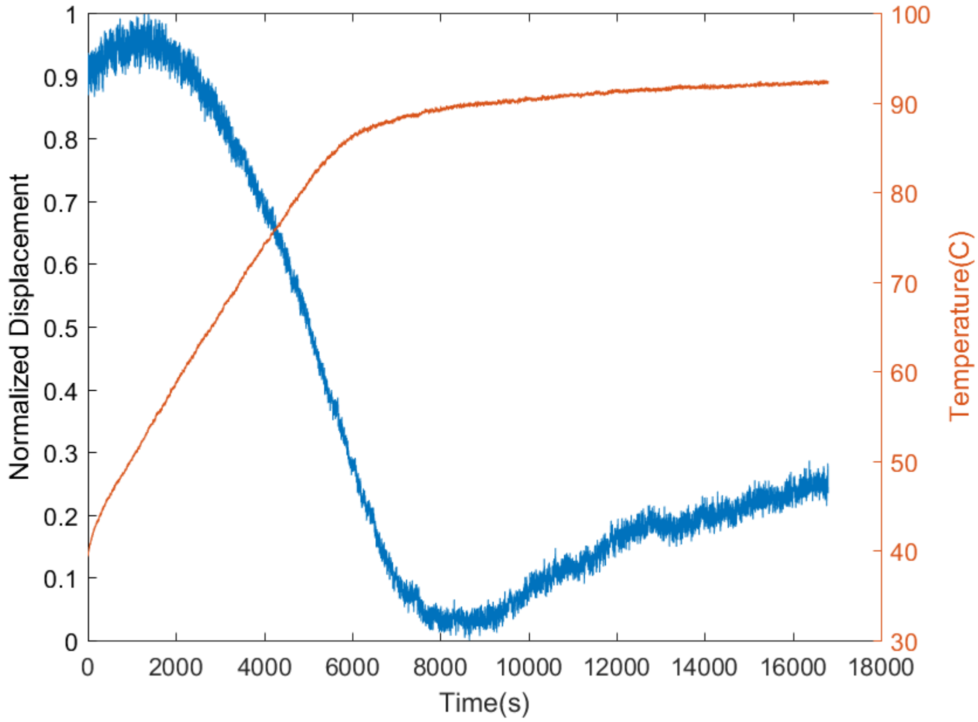

Figure 19: Sample 5, 227 grams of Tension

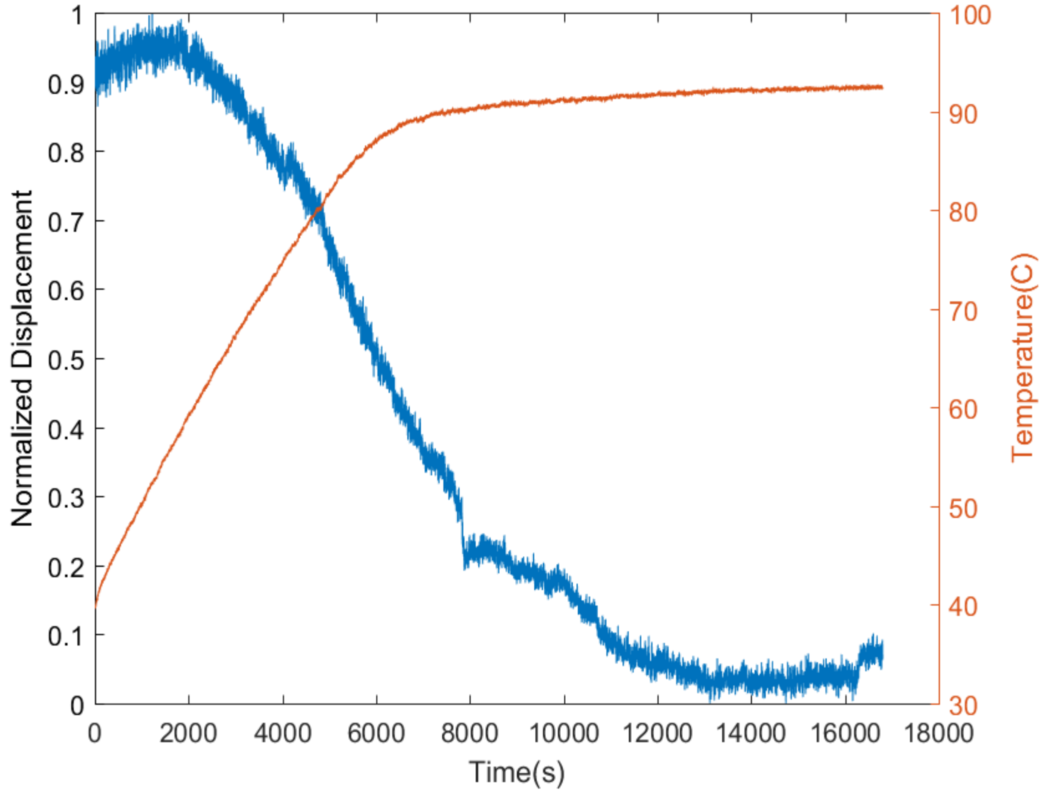

Figure 20: Sample 3, 227 grams of Tension

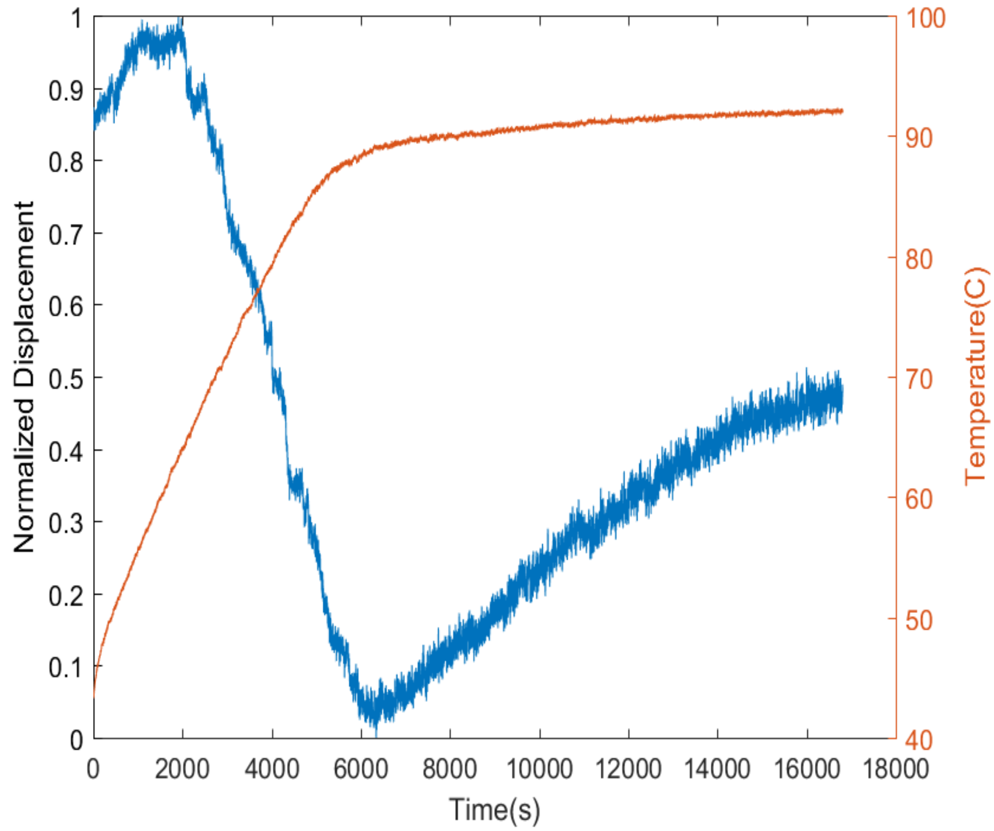

Figure 21: Sample 7, 227 grams of Tension

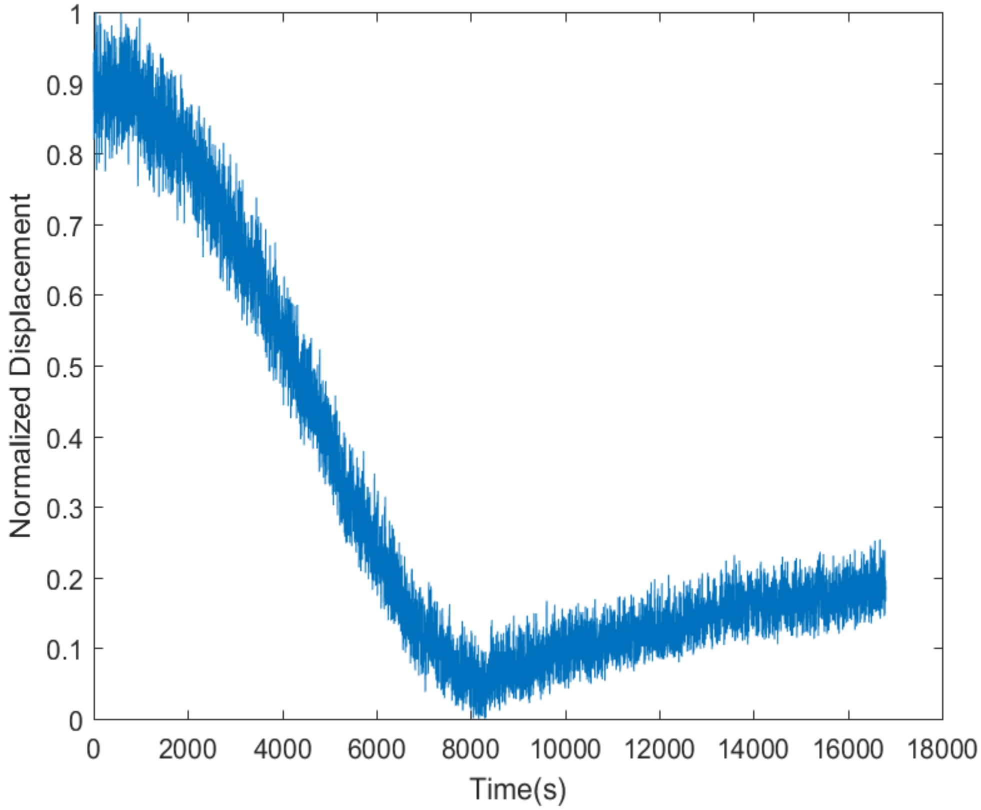

Figure 22: Sample 8, 227 grams of Tension

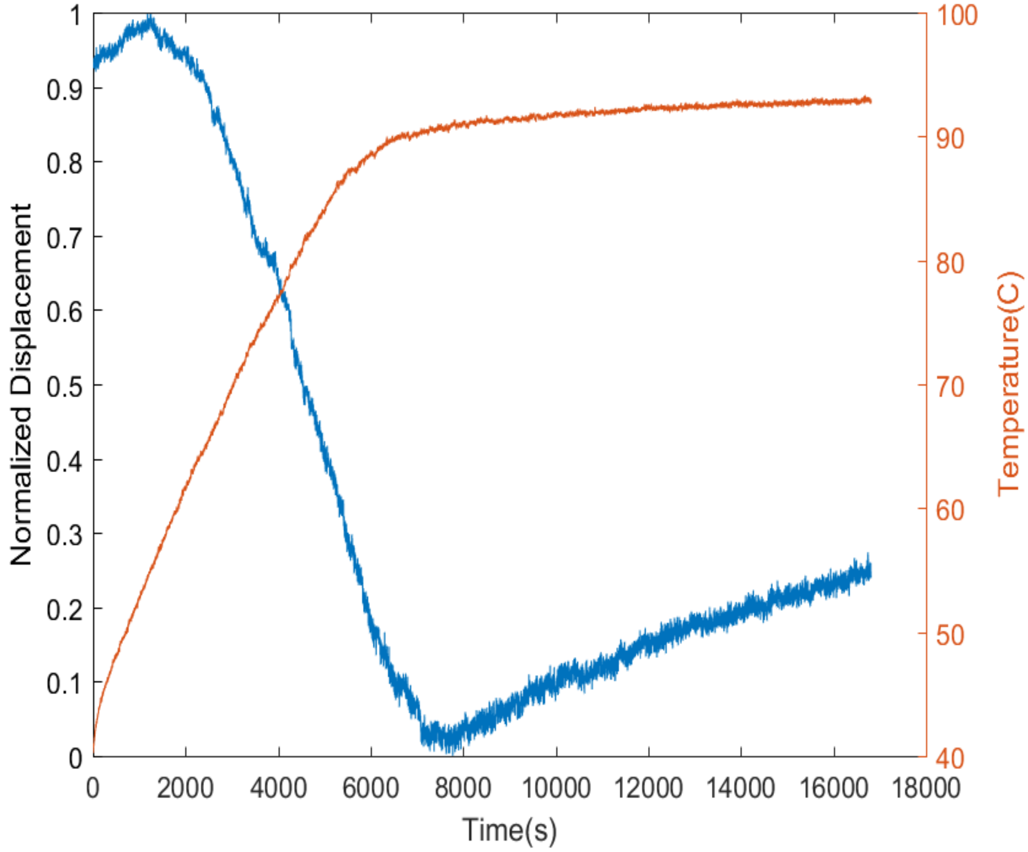

Figure 23: Sample 15, 300 grams of Tension

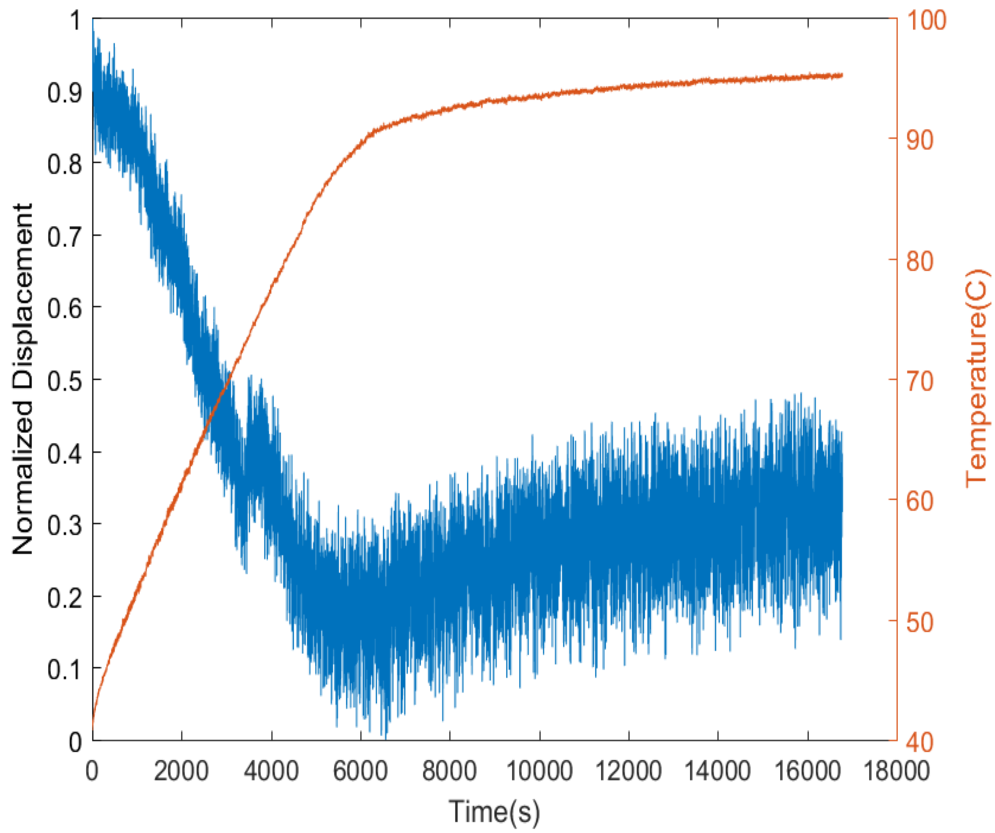

Figure 24: Sample 12, 300 grams of Tension

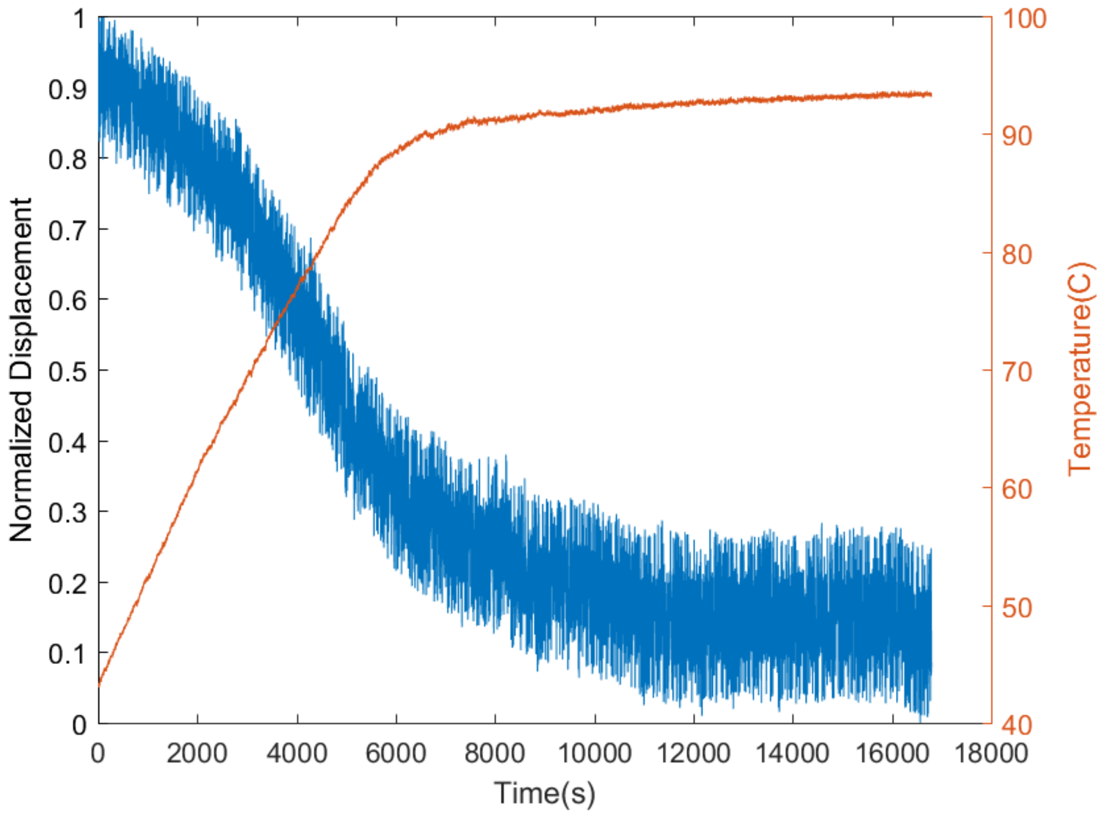

Figure 25: Sample 13, 300 grams of Tension

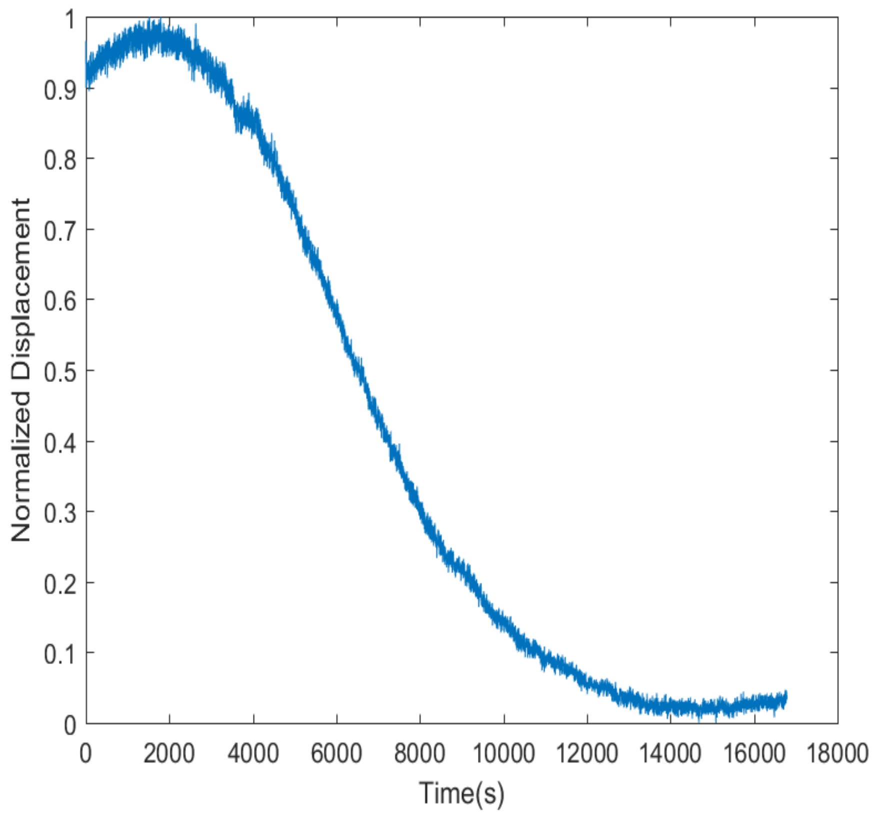

Figure 26: No Temperature, Sample 16 of Tension 300 grams

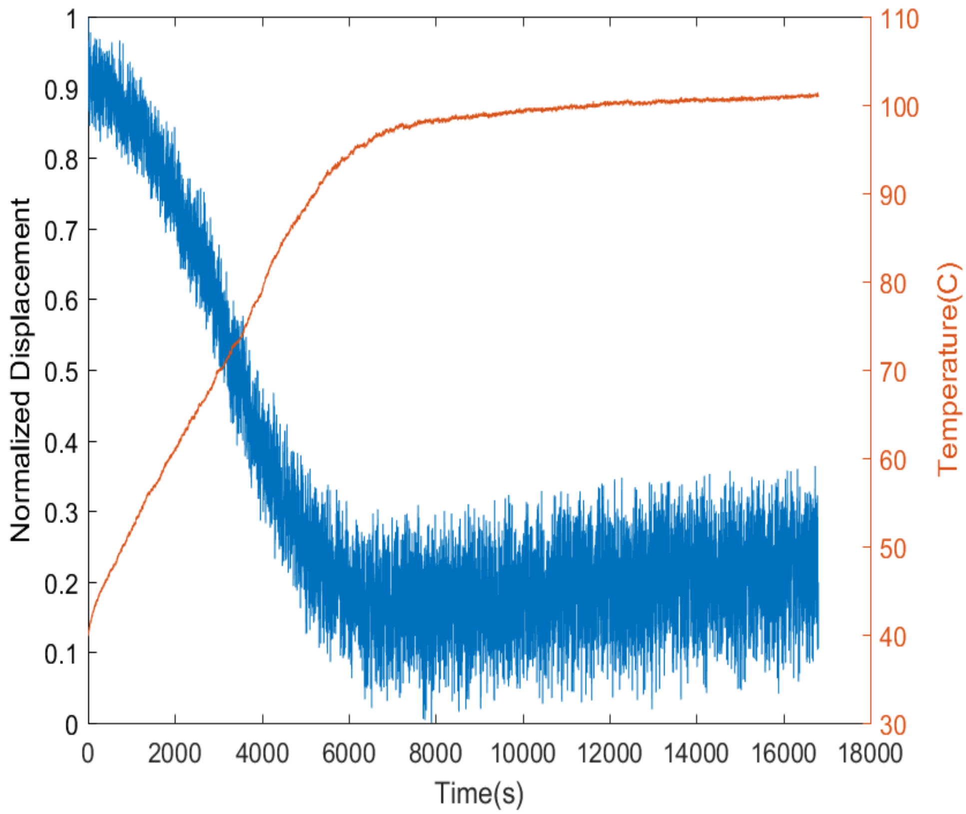

Figure 27: Sample 28, 400 grams of Tension

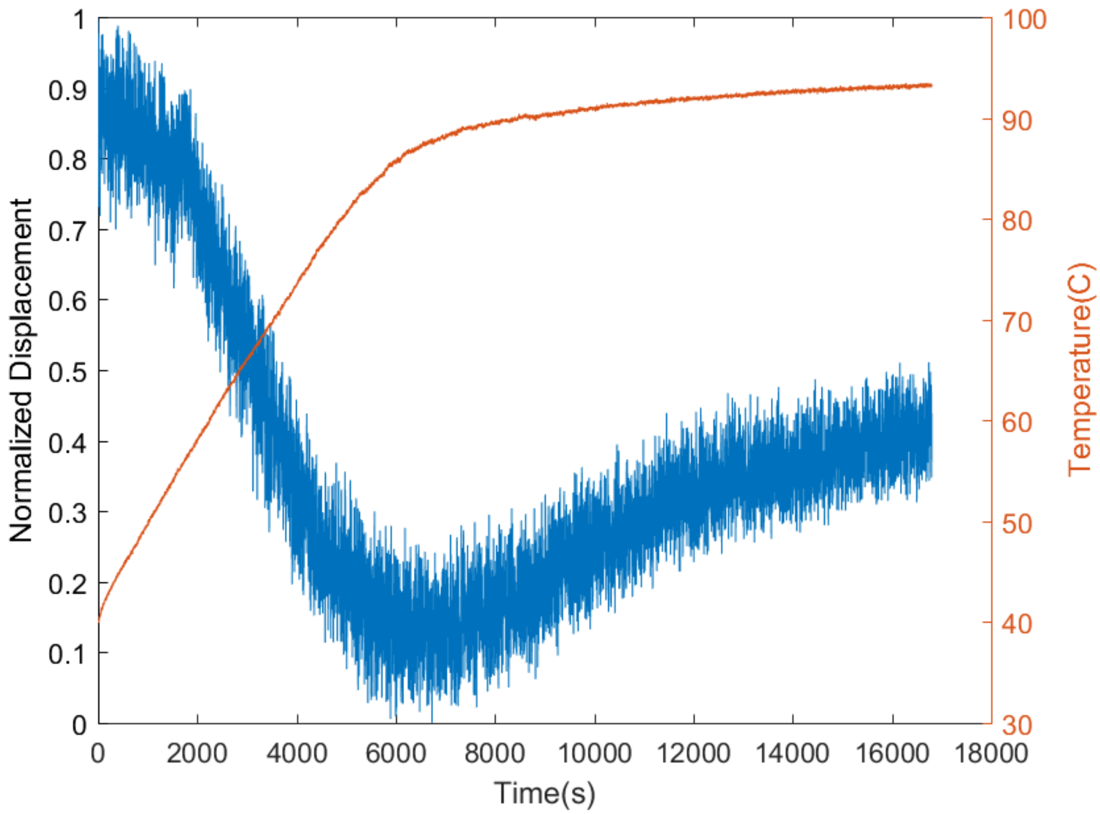

Figure 28: Sample 23, 400 grams of Tension

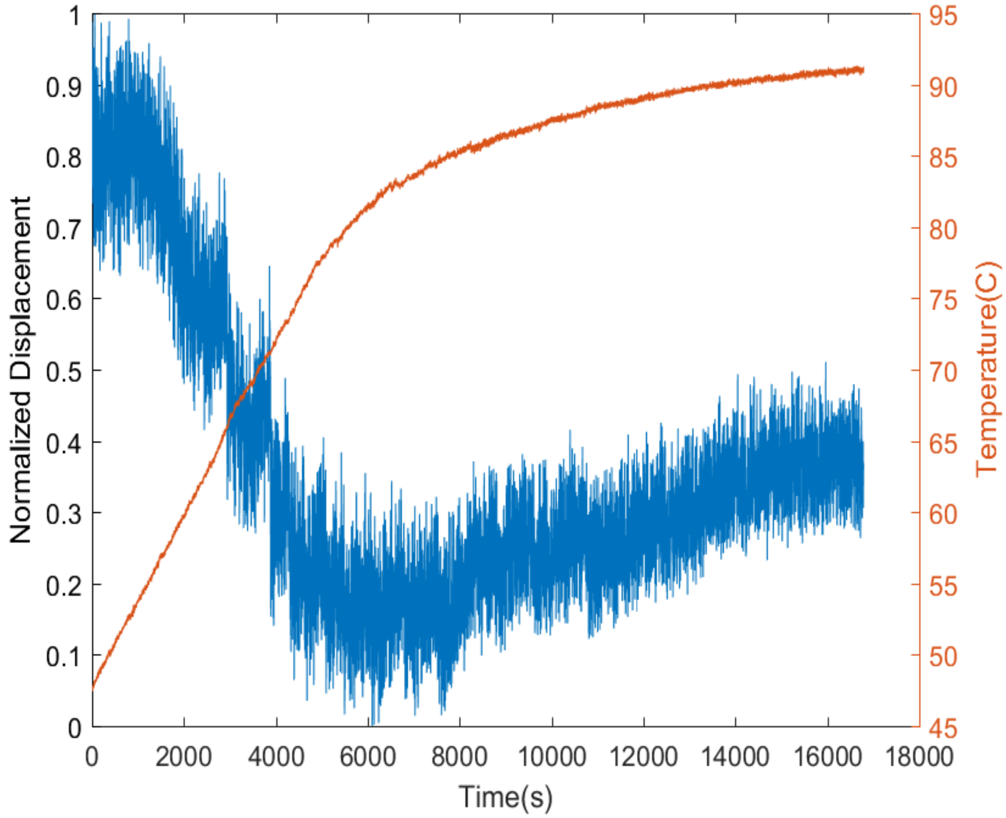

Figure 29: Sample 25, 400 grams of Tension

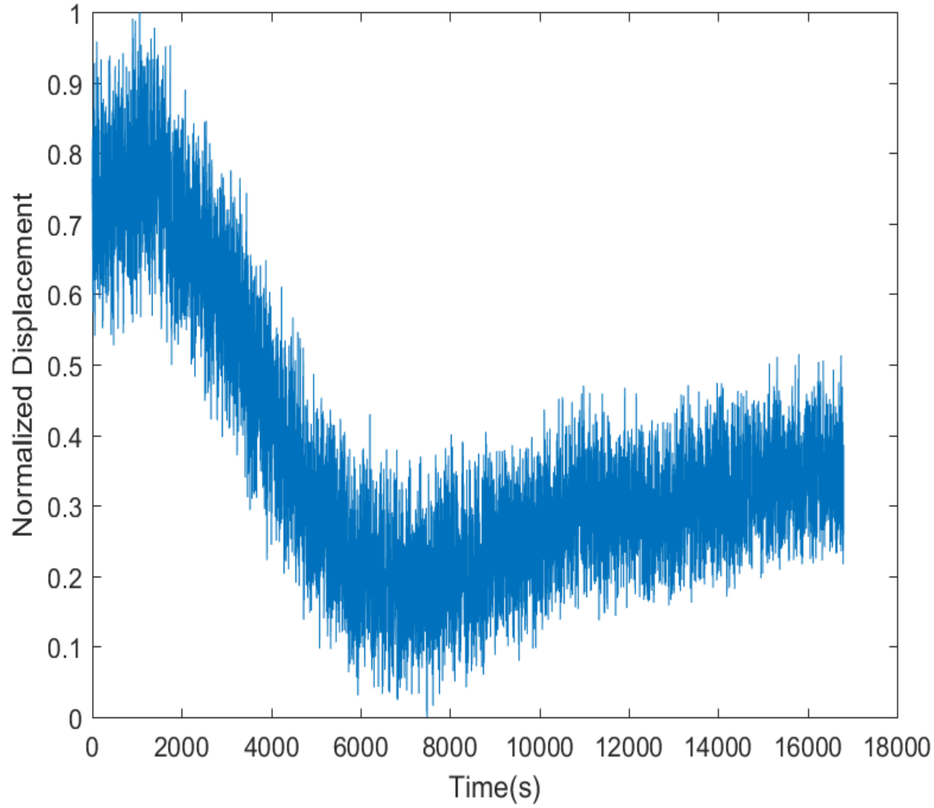

Figure 30: No Temperature, Sample 24, 400 grams of Tension

Conclusion/Final Statement

This experiment overall was believed to be successful with some minor drawbacks. On the one hand, the 30 samples of the TCPA fibers were fabricated and were interpreted to match the characteristics of the absolute curve in the LVDT sensor. Each step within the methodology was successful, and more TCPAs can be fabricated for future research. The calibration of the core was also successful. However, the team must record phase information in the future. The new conditioning board for the LVDT would eliminate most of the problems from the current experimental setup. There were some issues with the temperature sensor and placement of the sensor core. The team must develop an experimental methodology to ensure that the core of the LVDT is placed at an appropriate starting point. The proper placement of the core would ensure that no measurements are taken in the non-linear region of the LVDT.

The research team has acquired a new conditioning board (NTC-6000) for the LVDT. The NTC-6000 will facilitate the initial setup of the experiment to ensure measurements are taken within the linear region of the LVDT. Currently, the team is working on a methodology to calibrate the NTC-6000 to our LVDT properly. Within the next couple of months, the team should have a calibration methodology, and the new conditioning board should be ready to be used. In the future, the research team should also consider trying other materials for the muscle fibers. The fishing line is cheap, durable, and convenient to use and acquire, but it would be interesting to observe the results from using yarn or some other polymers. A team led by Ray Baughman at the University of Texas Dallas has designed another type of fiber made from polymer yarns. They have shown that these fibers can generate 40 times more mechanical energy per second than human muscle and nine times more than the highest-power alternative electrochemical muscles made to date.

In the end, this research work has accomplished the following goals:

- ✓ Fabrication of different TCPs that would be used in future experiments.
- ✓ Calibration of the LVDT.
- ✓ A better understanding of the importance of adequately placing the core.
- ✓ Physical characteristics of each TCPA that were fabricated.

The results from this research work would help the team perform more accurate and significant experiments. It will allow them to gather better data that can be used to generate mathematical models using different techniques like genetic algorithms. The overall goal of this research has the potential to begin a new chapter in biomechanics like never before. There is still much work to be done, but with previous and future research, these minor setbacks will be the foundation to strengthen the TCPA fiber research.

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Appendix

ΔL .... Change in Coil Length

N .... Number of coils

I .... Length of the Filament

ΔT.. Change in filament twist

JMP .... Johns Macintosh Project

LVDT .... Linear Variable Differential Transformer

TCP .... Twisted Coiled Polymer

For the figures below, each TCPA fiber is categorized to their tested tension as well as the measurements that don't have temperature readings. A total of 29 TCPA fibers are listed below.

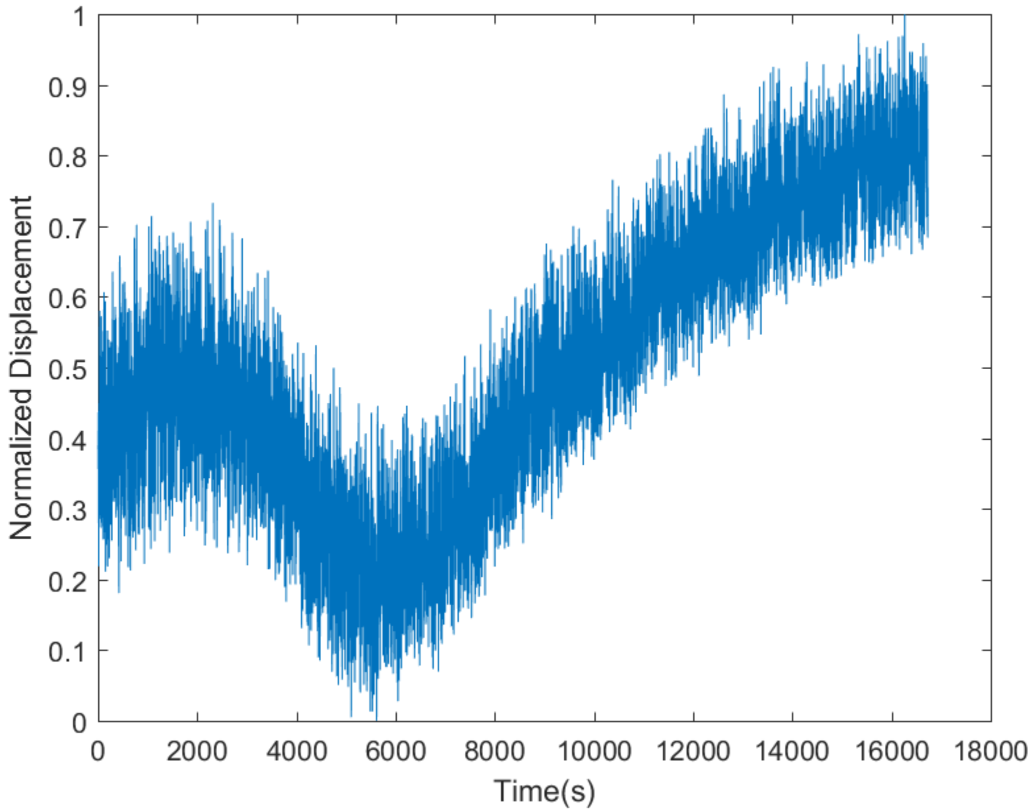

Figure 31: Sample 1, 227 grams of Tension

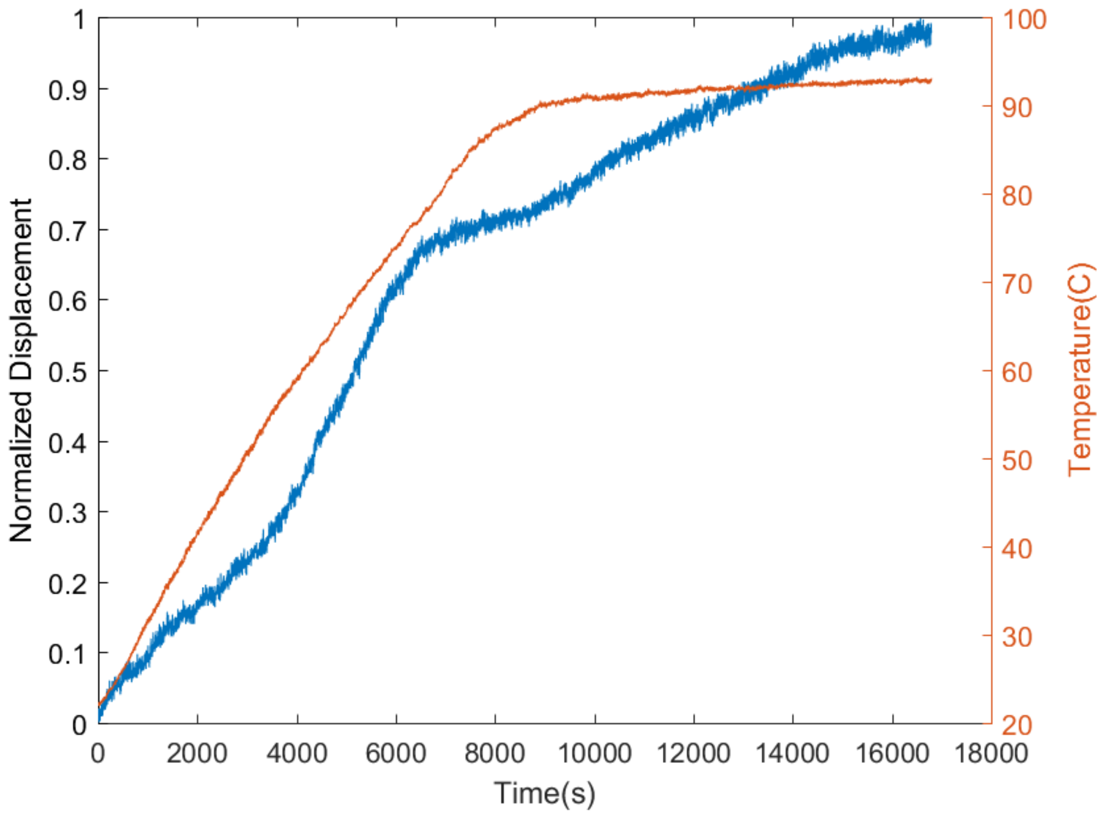

Figure 32: Sample 2, 227 grams of Tension

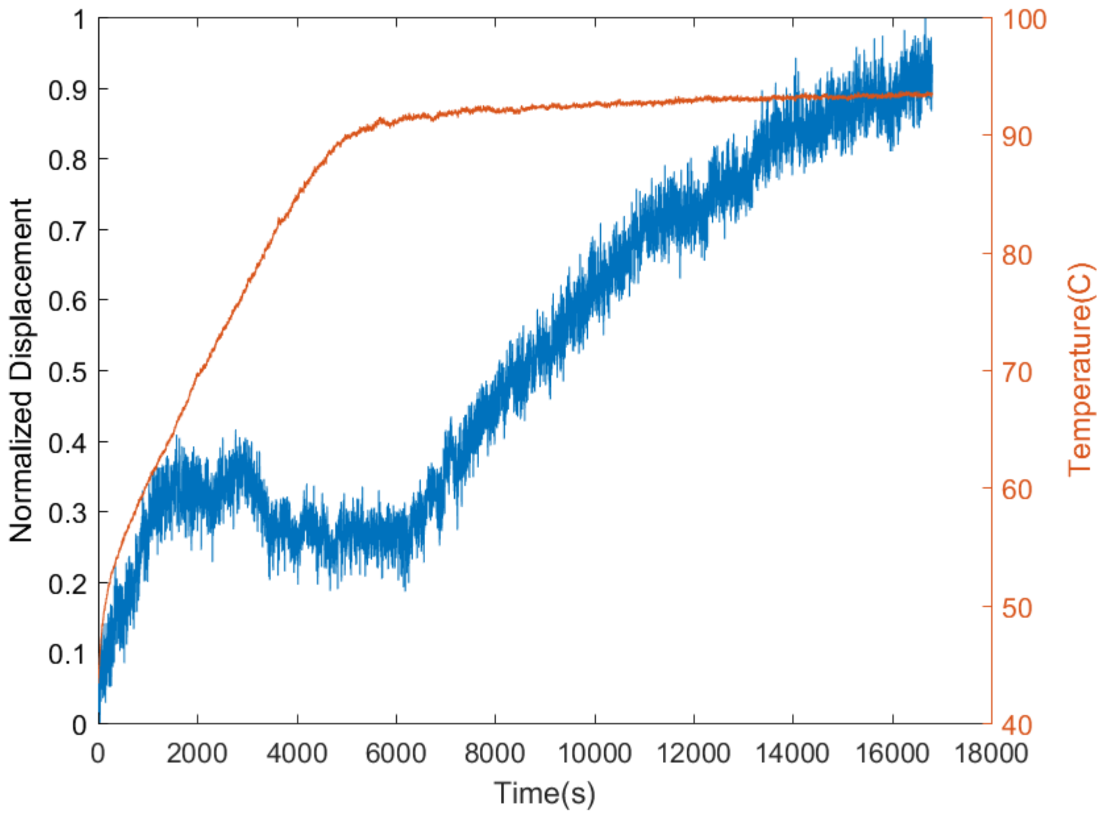

Figure 33: Sample 3, 227 grams of Tension

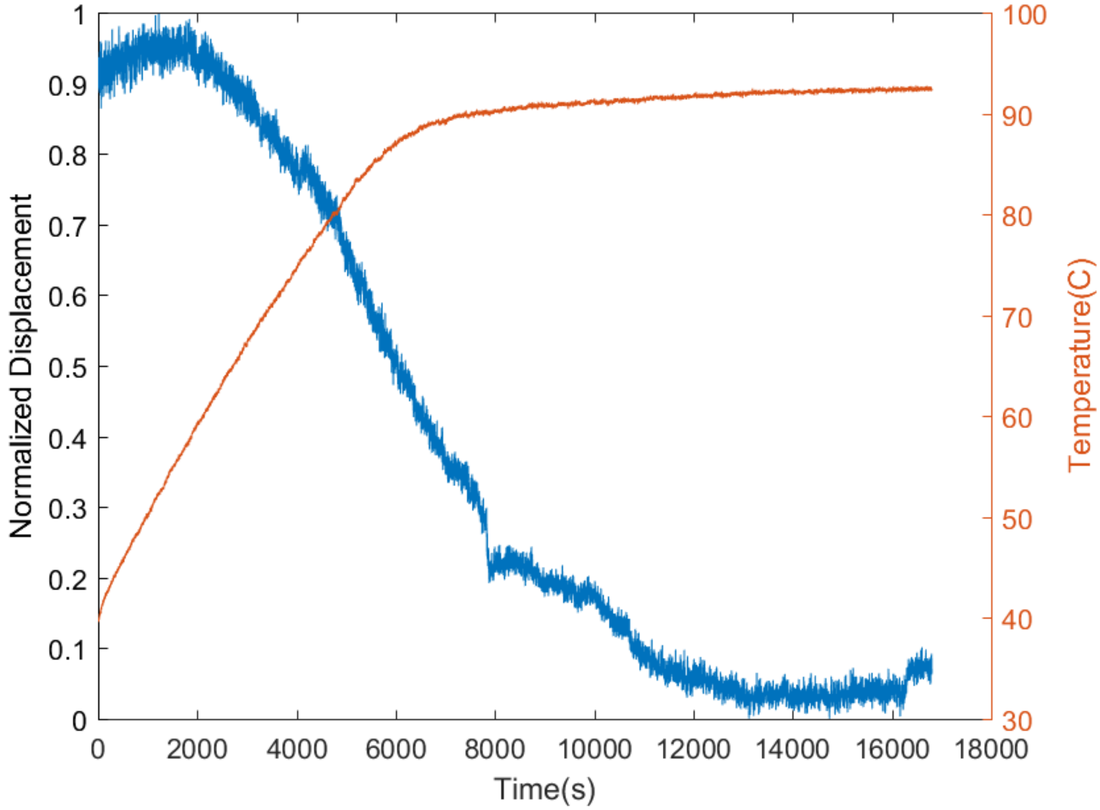

Figure 34: Sample 4, 227 grams of tension

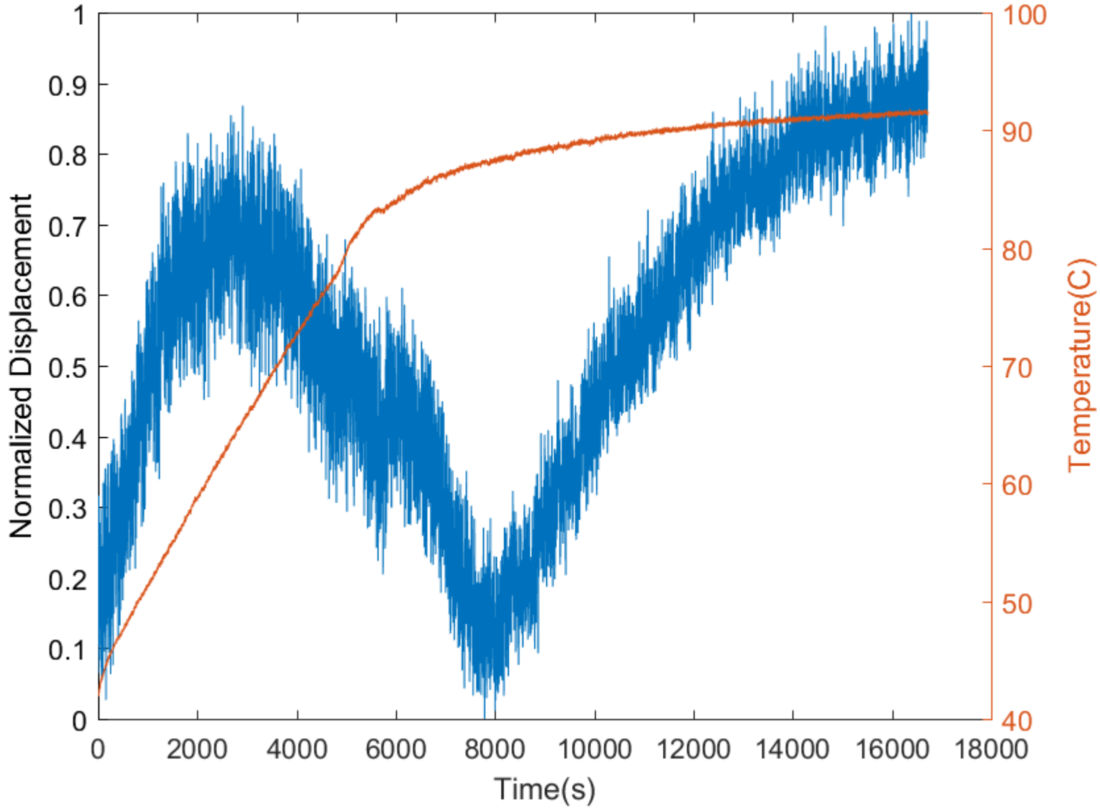

Figure 35: Sample 5, 227 grams of Tension

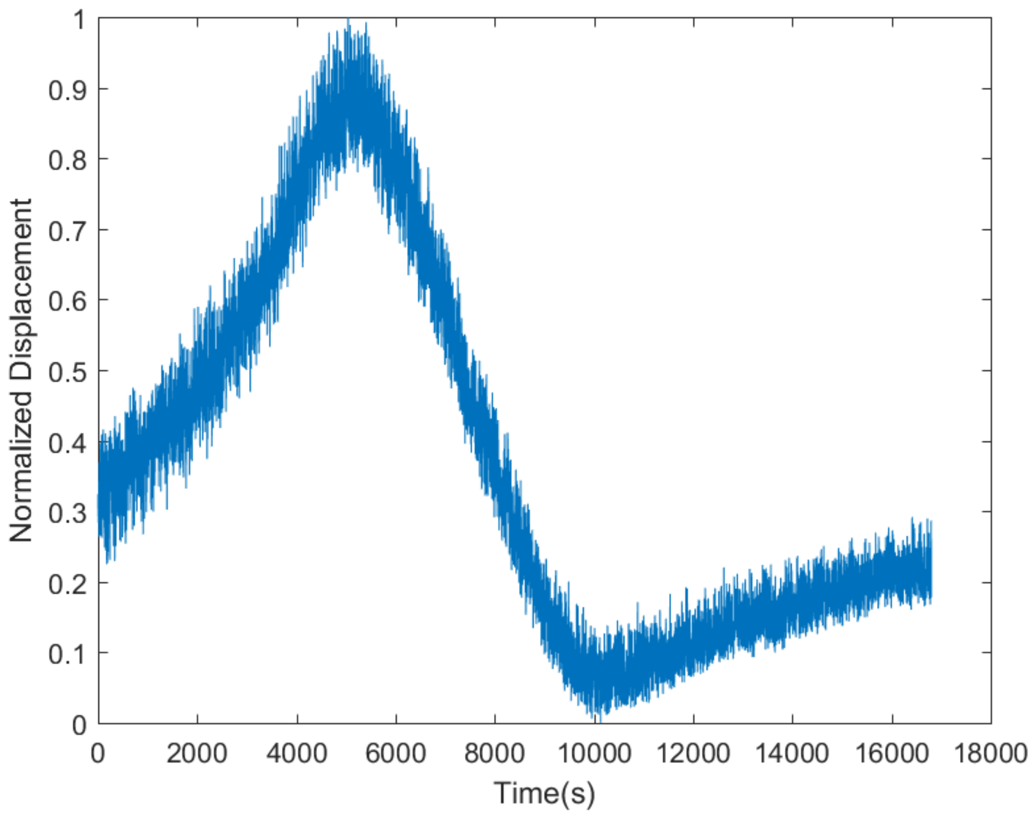

Figure 36: No Temperature, Sample 6 of 227 grams of Tension

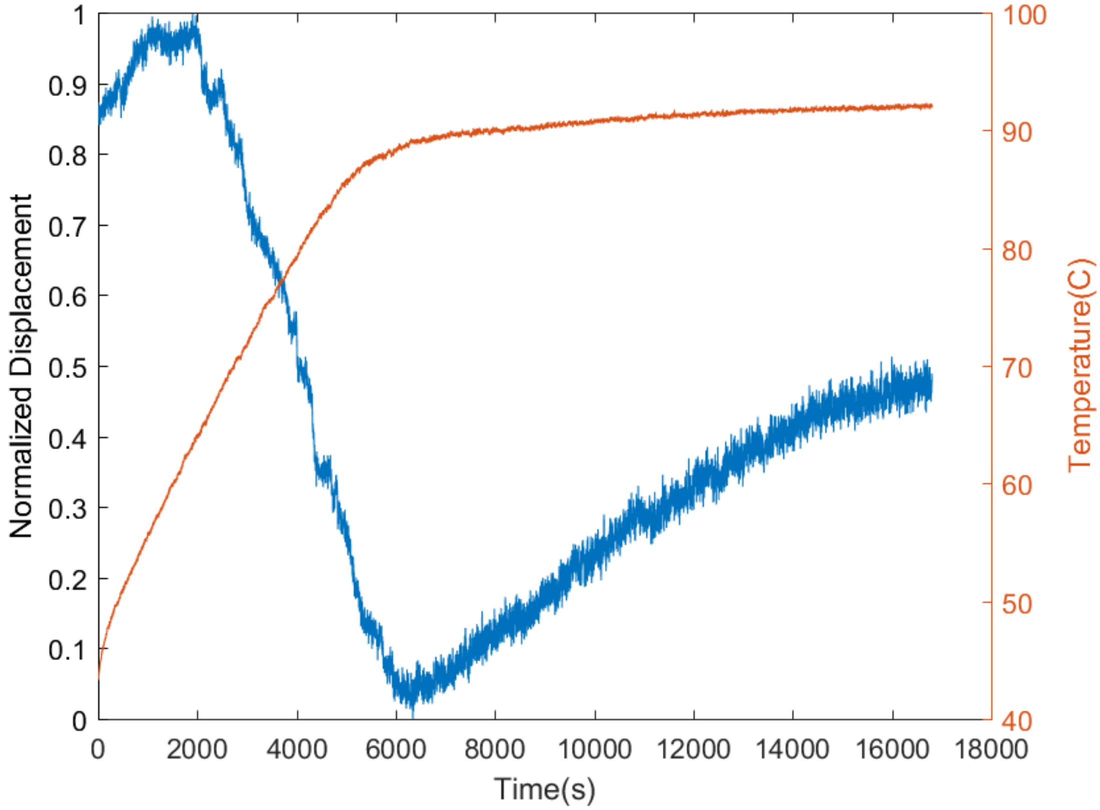

Figure 37: Sample 7, 227 grams of Tension

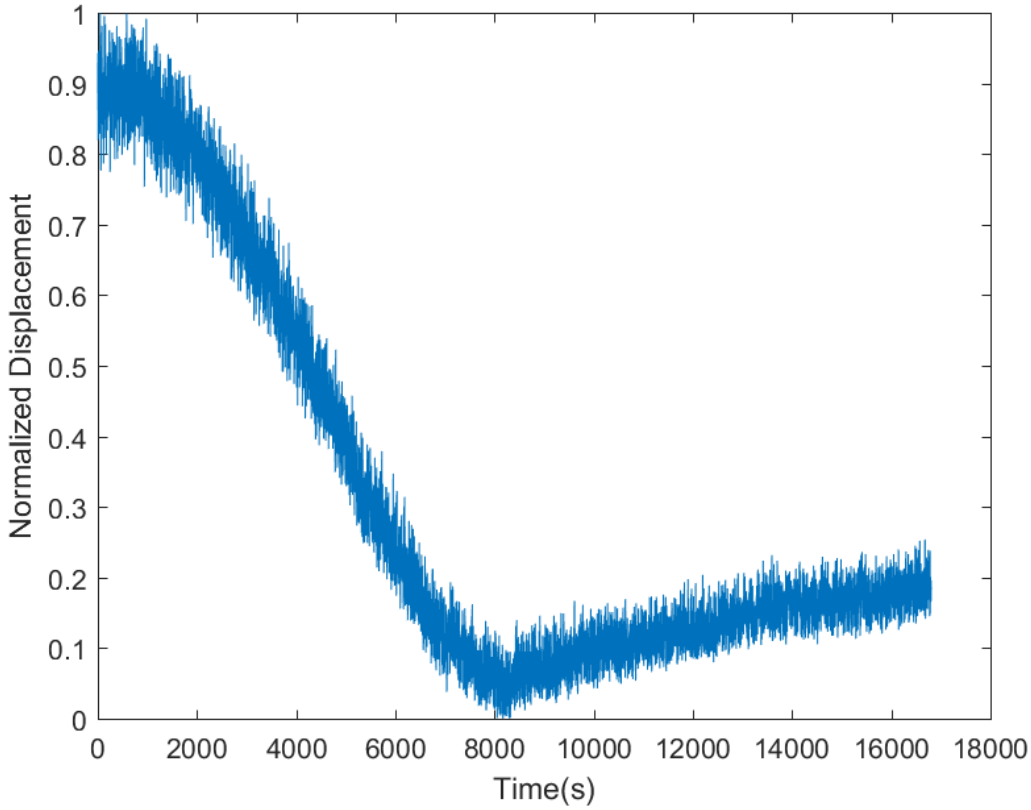

Figure 38: No Temperature, Sample 8 of 227 grams of Tension

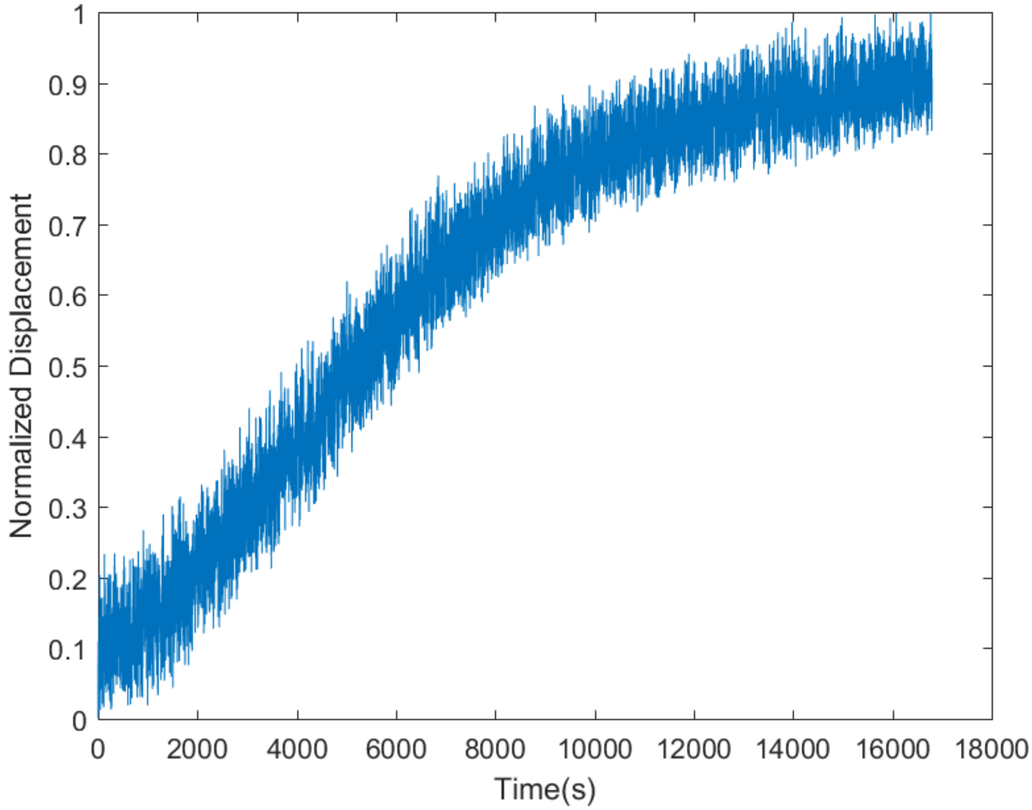

Figure 39: No Temperature, Sample 9 of 227 grams of Tension

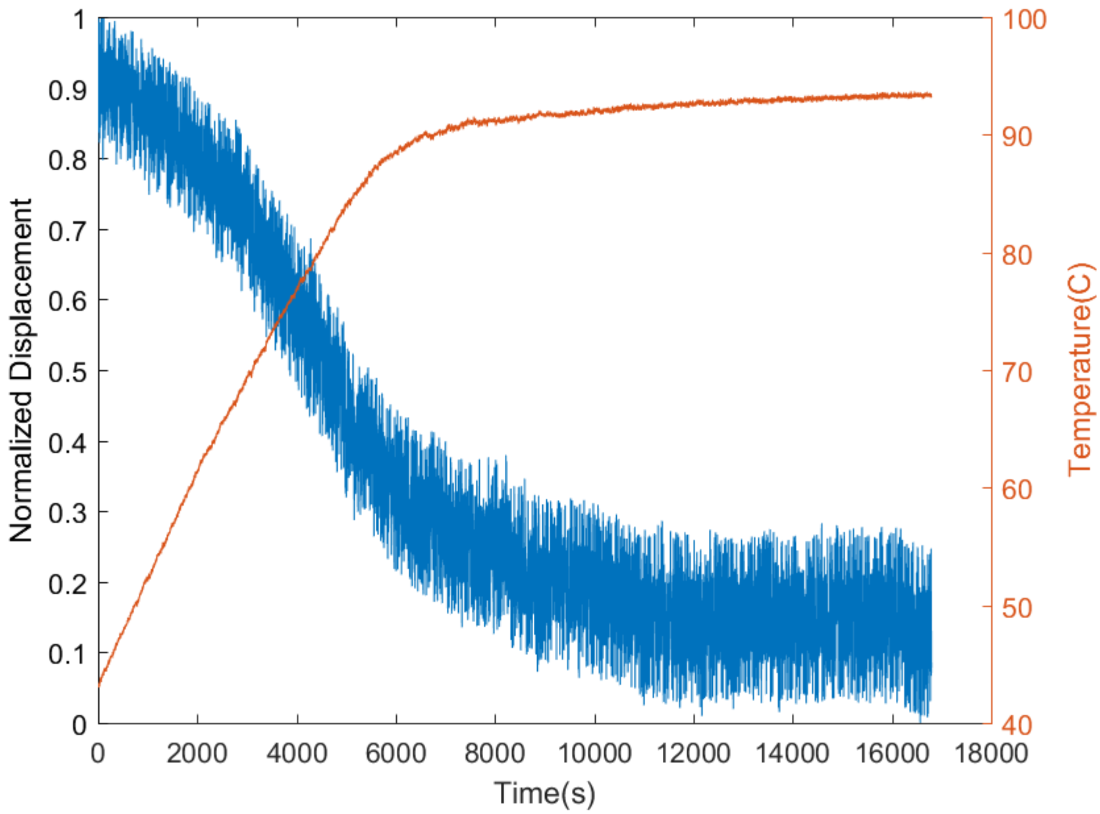

Figure 40: Sample 11, 300 grams of Tension

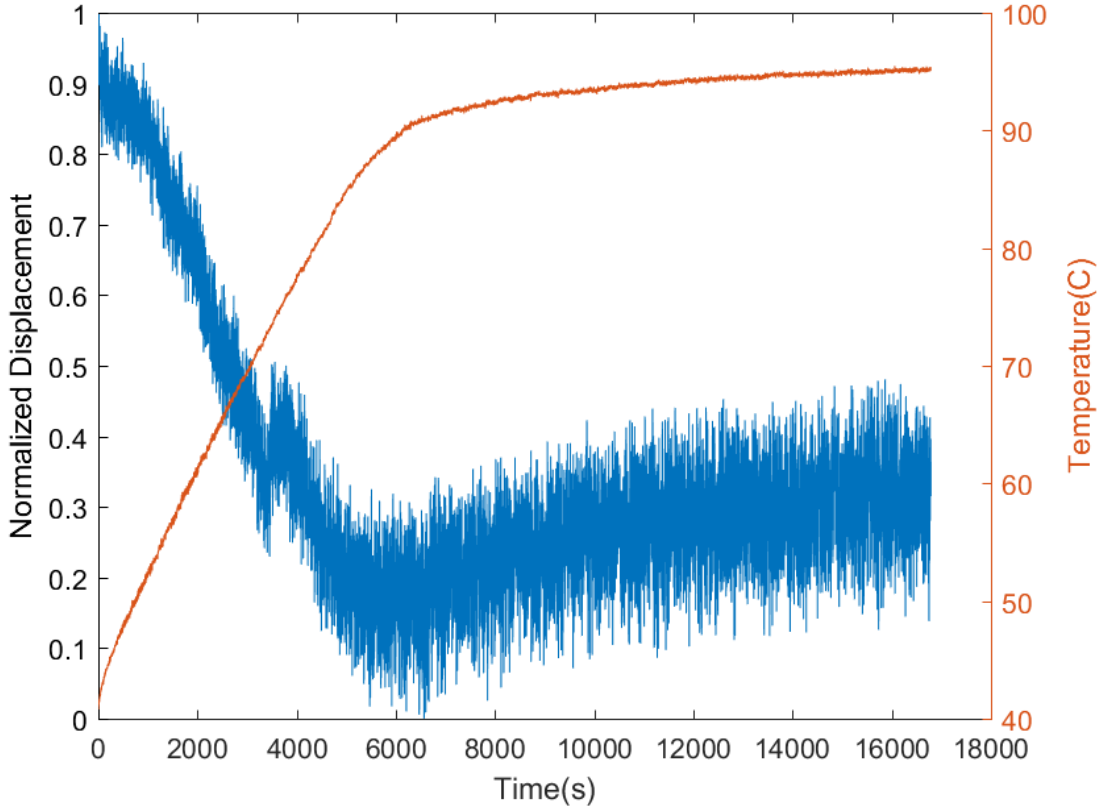

Figure 41: Sample 12, 300 grams of Tension

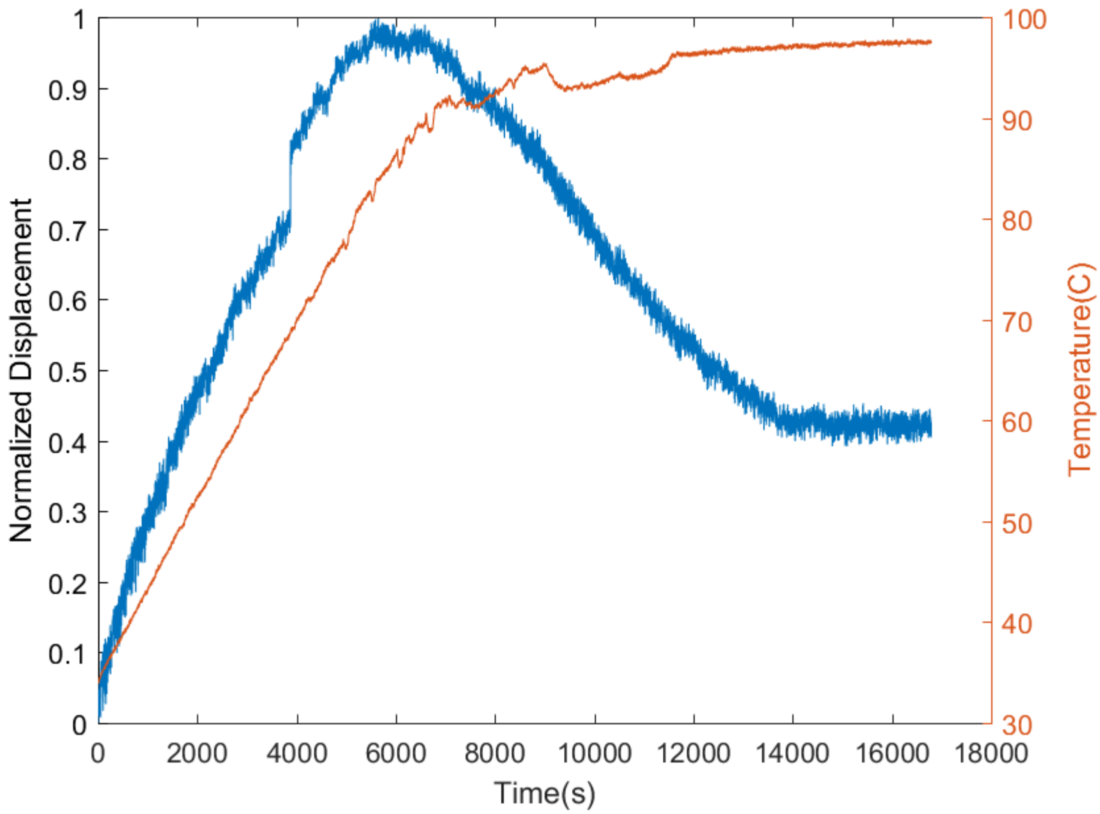

Figure 42: Sample 13, 300 grams of Tension

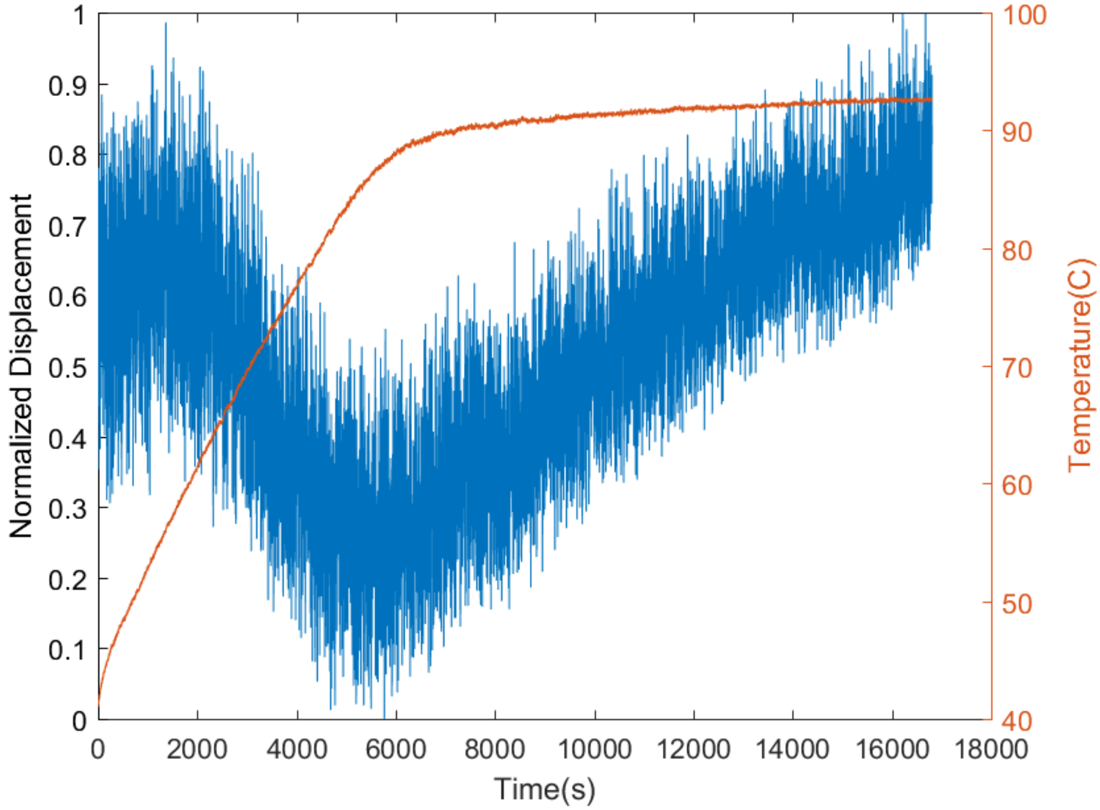

Figure 43: Sample 14, 300 grams of Tension

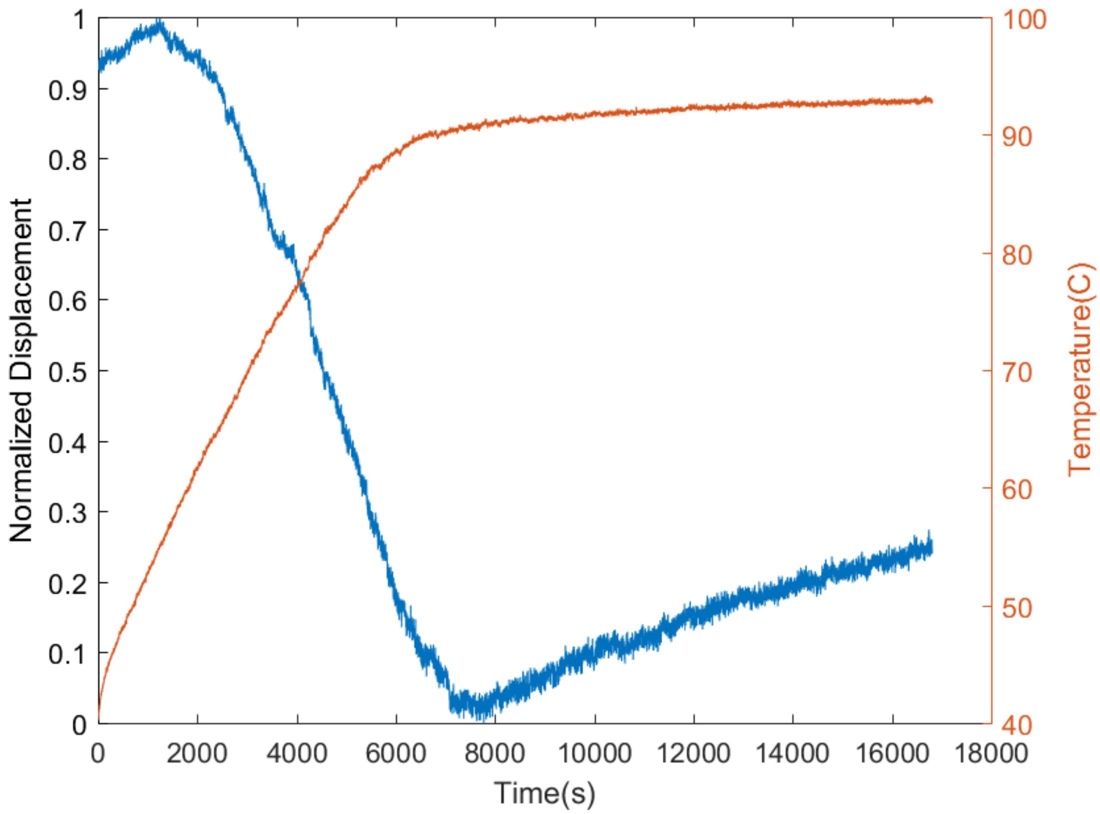

Figure 44: Sample 15, 300 grams of Tension

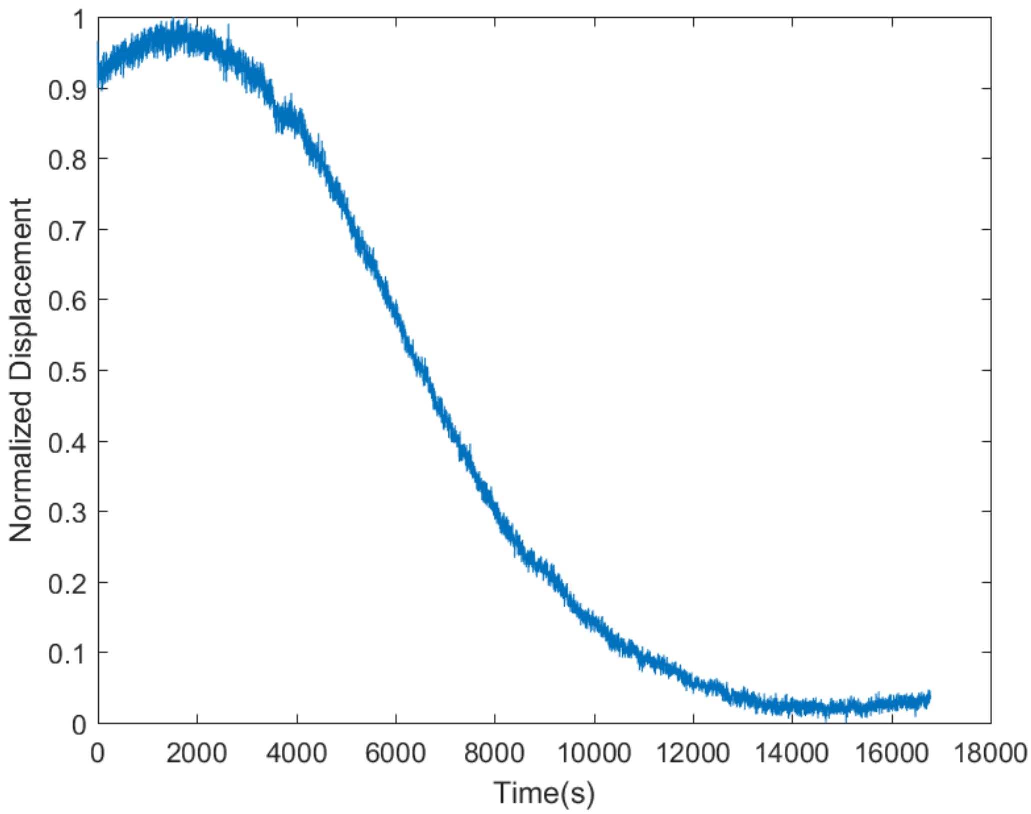

Figure 45: No Temperature, Sample 16 of 300 grams of Tension

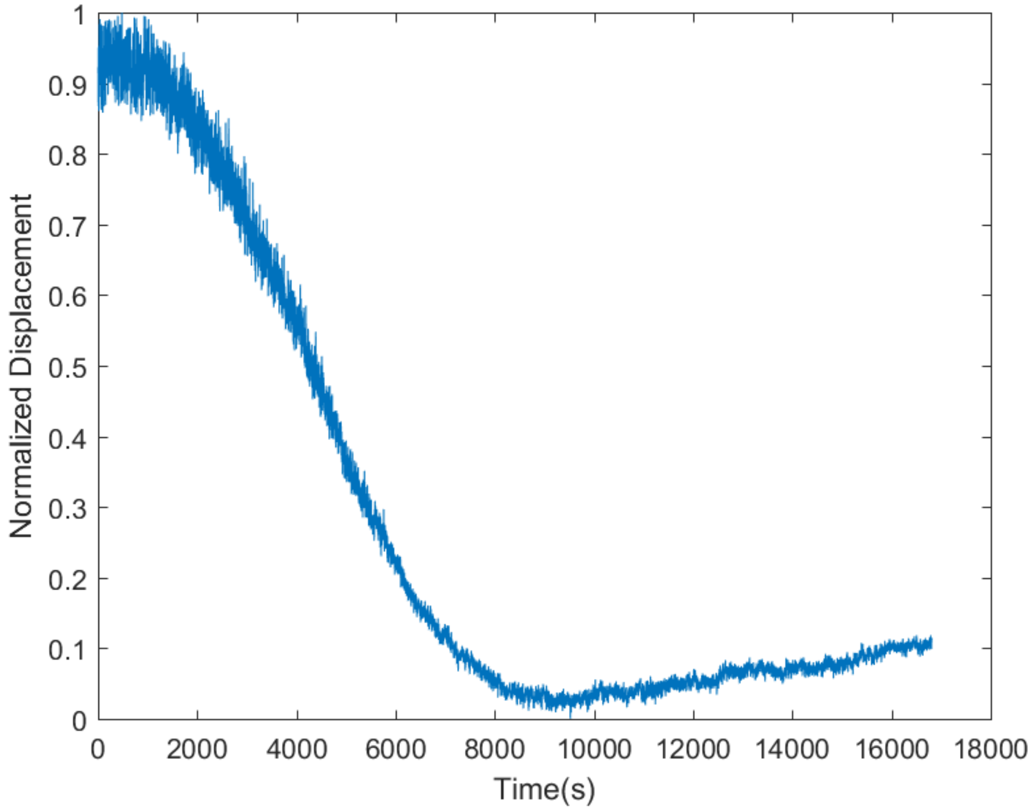

Figure 46: No Temperature, Sample 17 of 300 grams of Tension

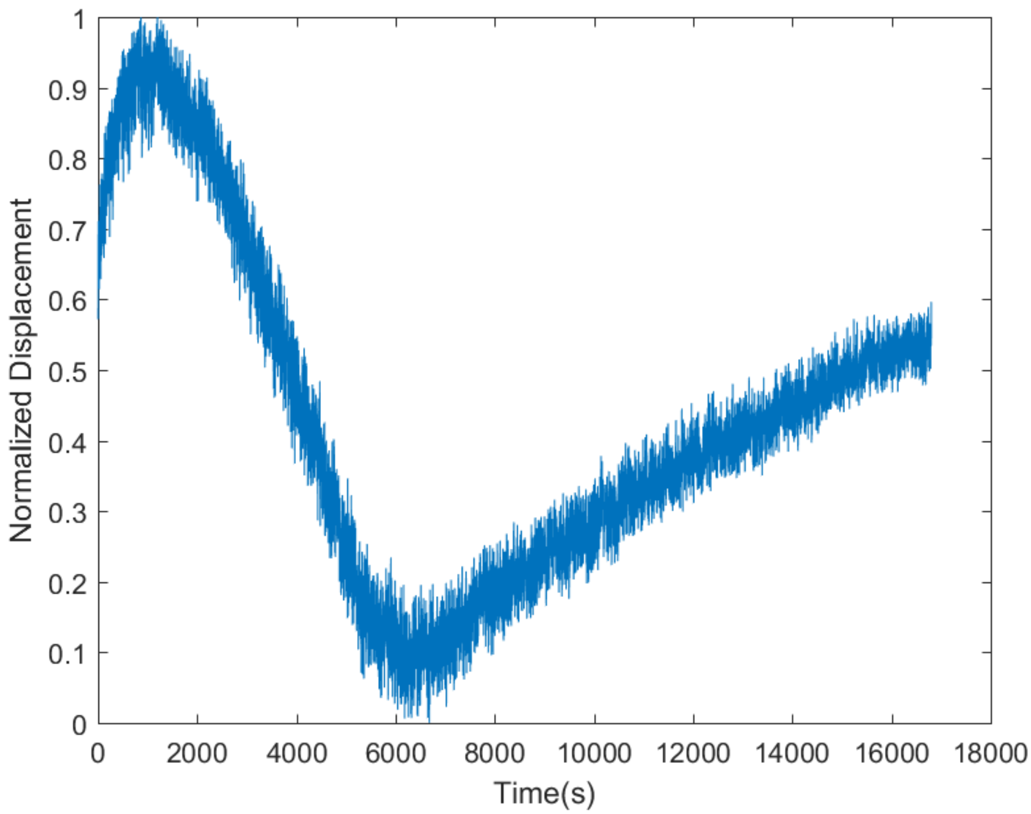

Figure 47: No Temperature, Sample 18 of 300 grams of Tension

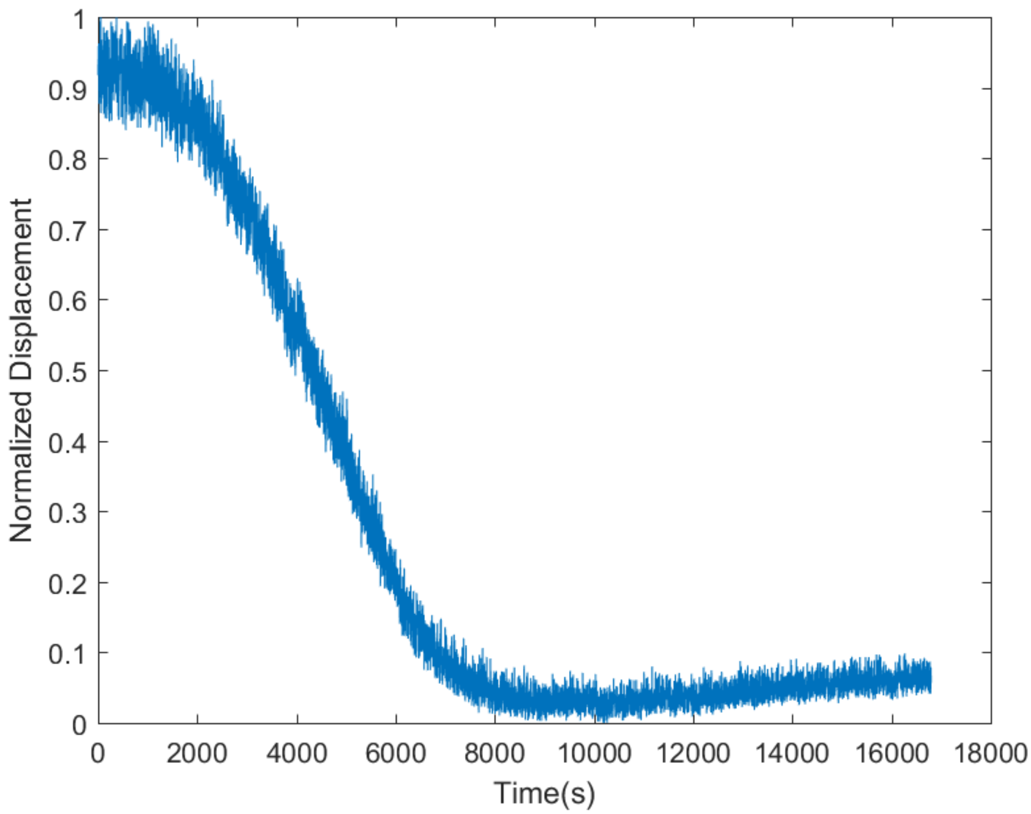

Figure 48: No Temperature, Sample 19 of 300 grams of Tension

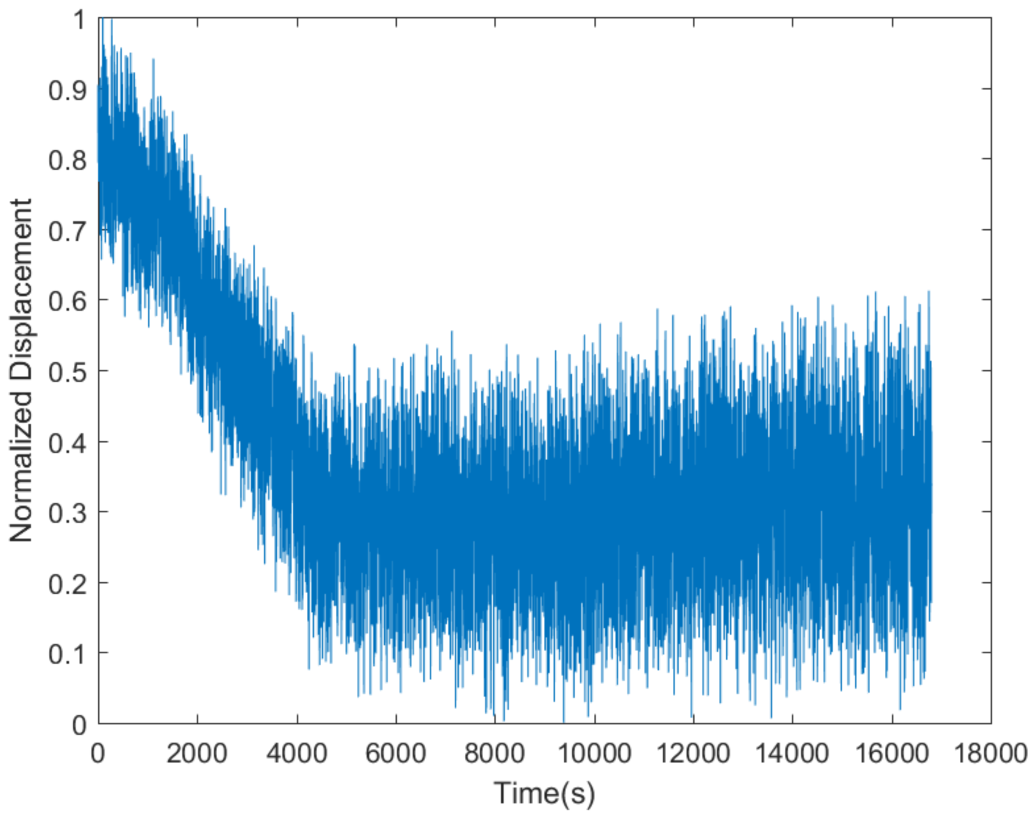

Figure 49: No Temperature, Sample 21, 400 grams of Tension

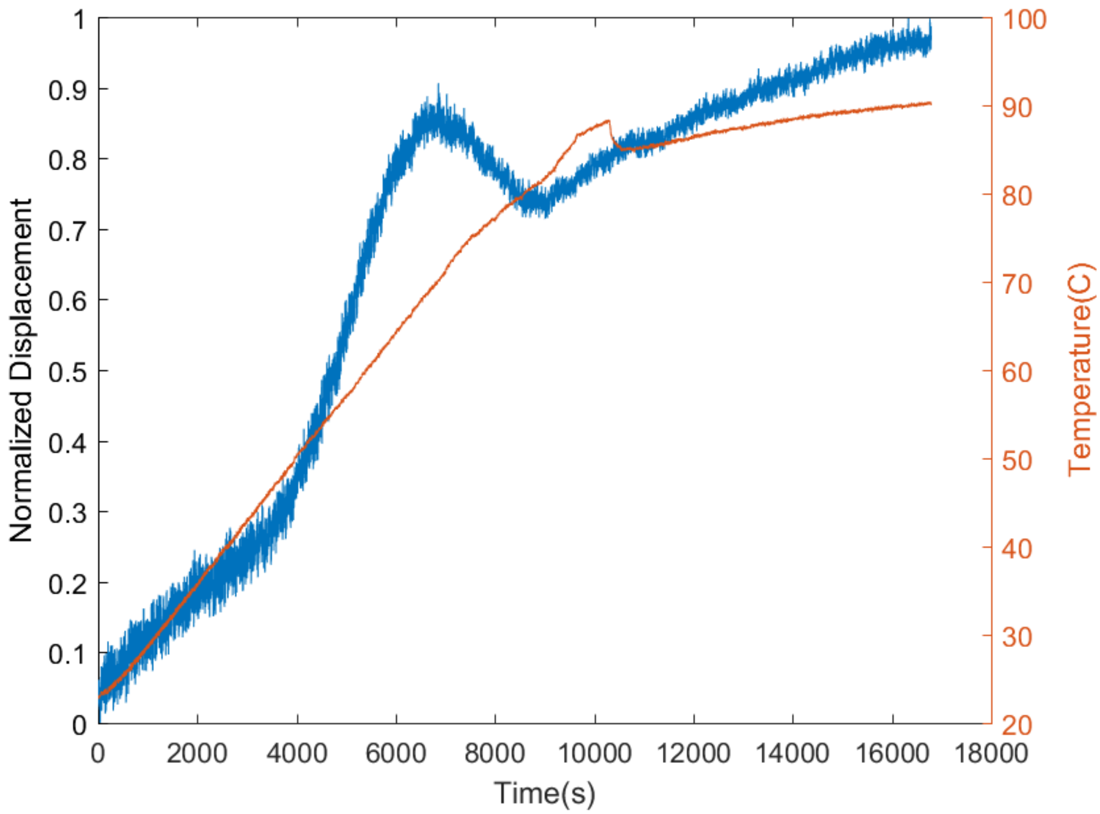

Figure 50: Sample 22, 400 grams of Tension

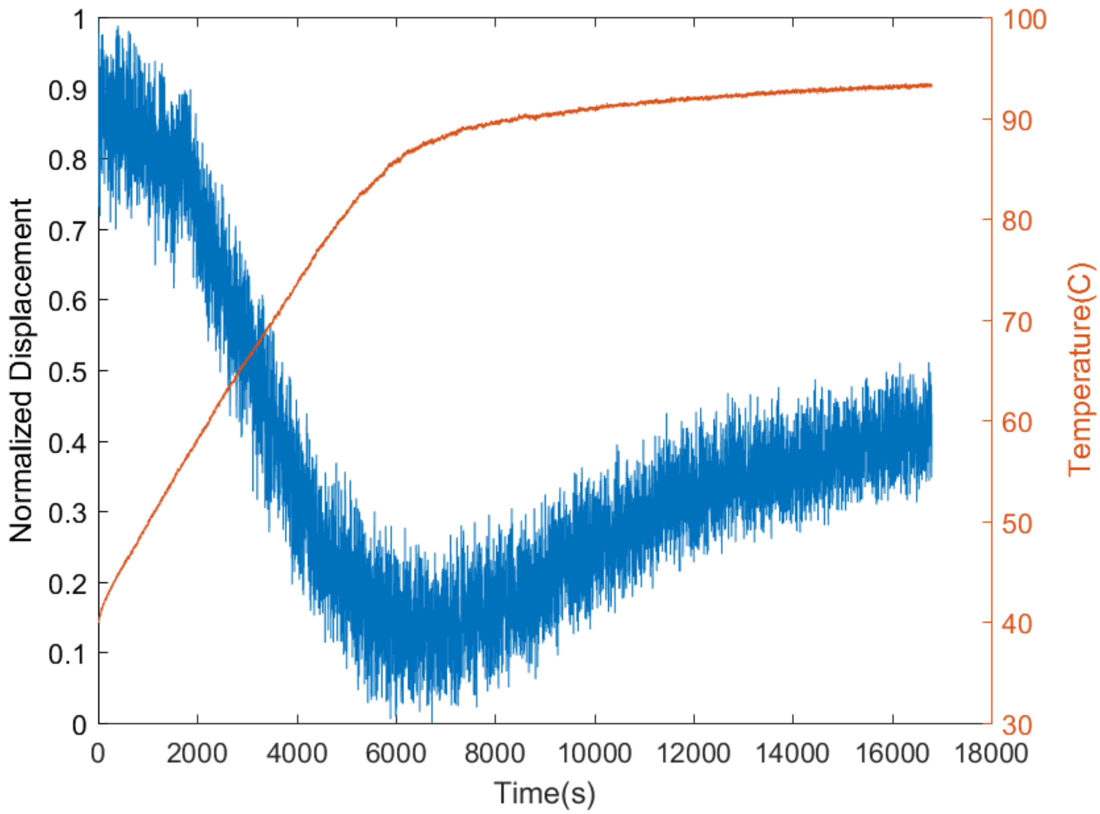

Figure 51: Sample 23, 400 grams of Tension

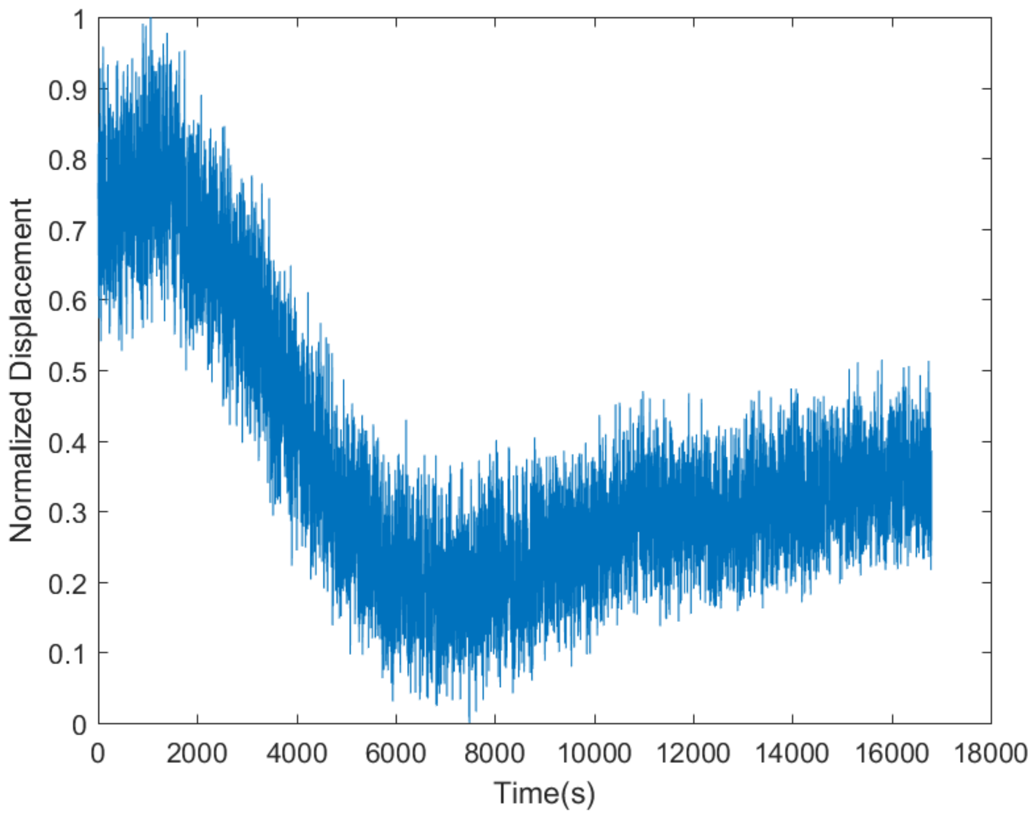

Figure 52: No Temperature, Sample 24, 400 grams of Tension

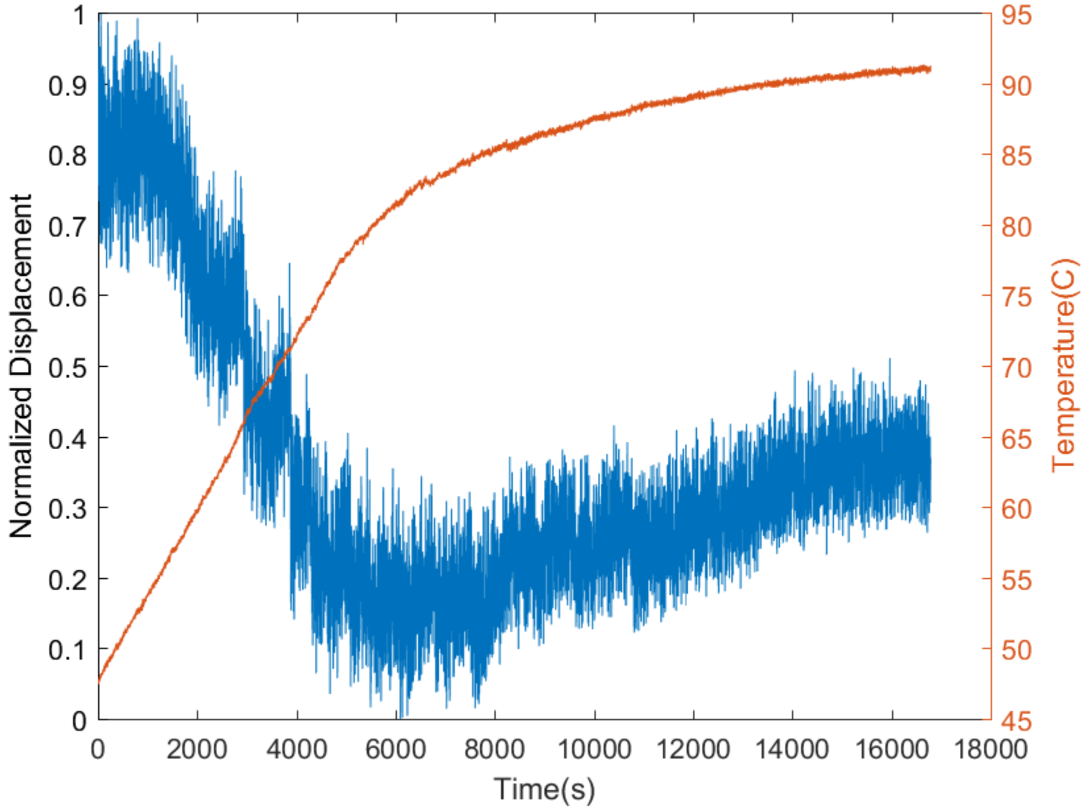

Figure 53: Sample 25, 400 grams of Tension

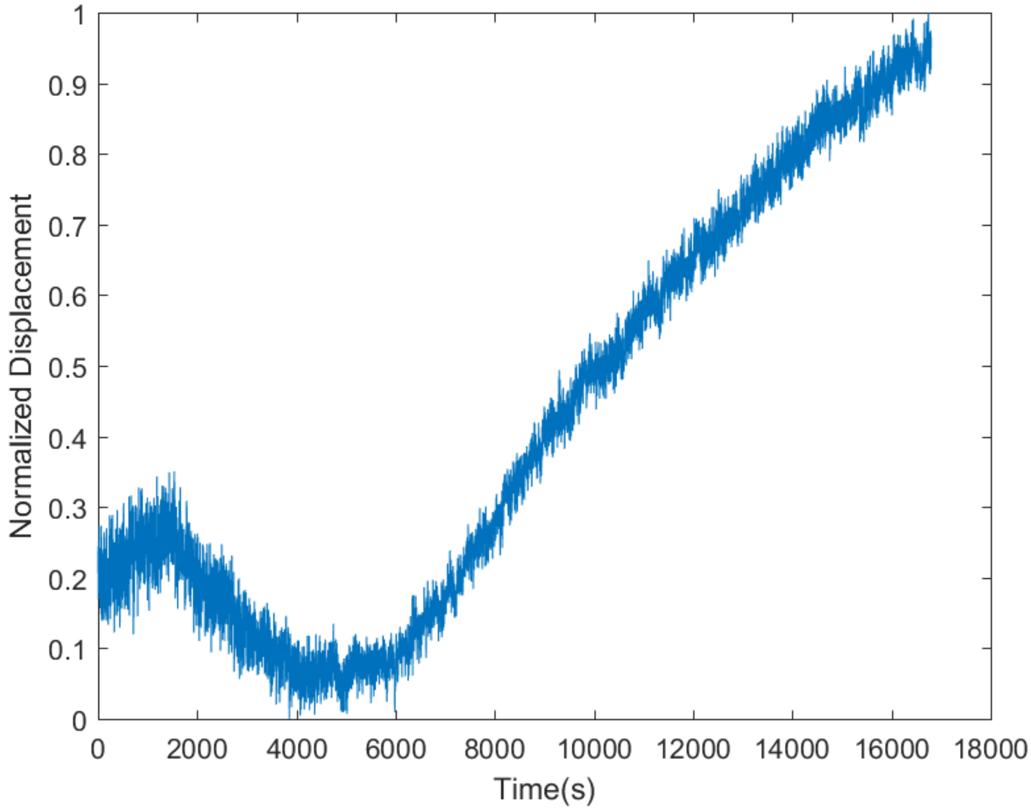

Figure 54: No Temperature, Sample 26, 400 grams of Tension

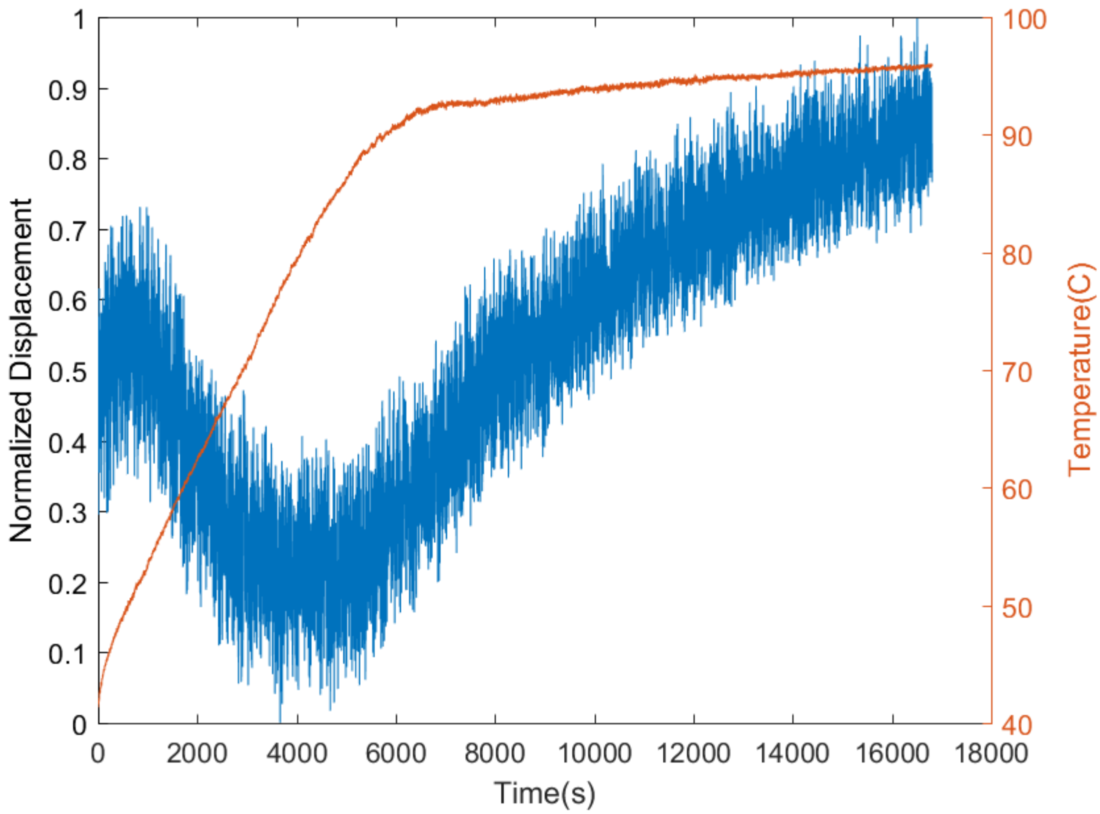

Figure 55: Sample 27, 400 grams of Tension

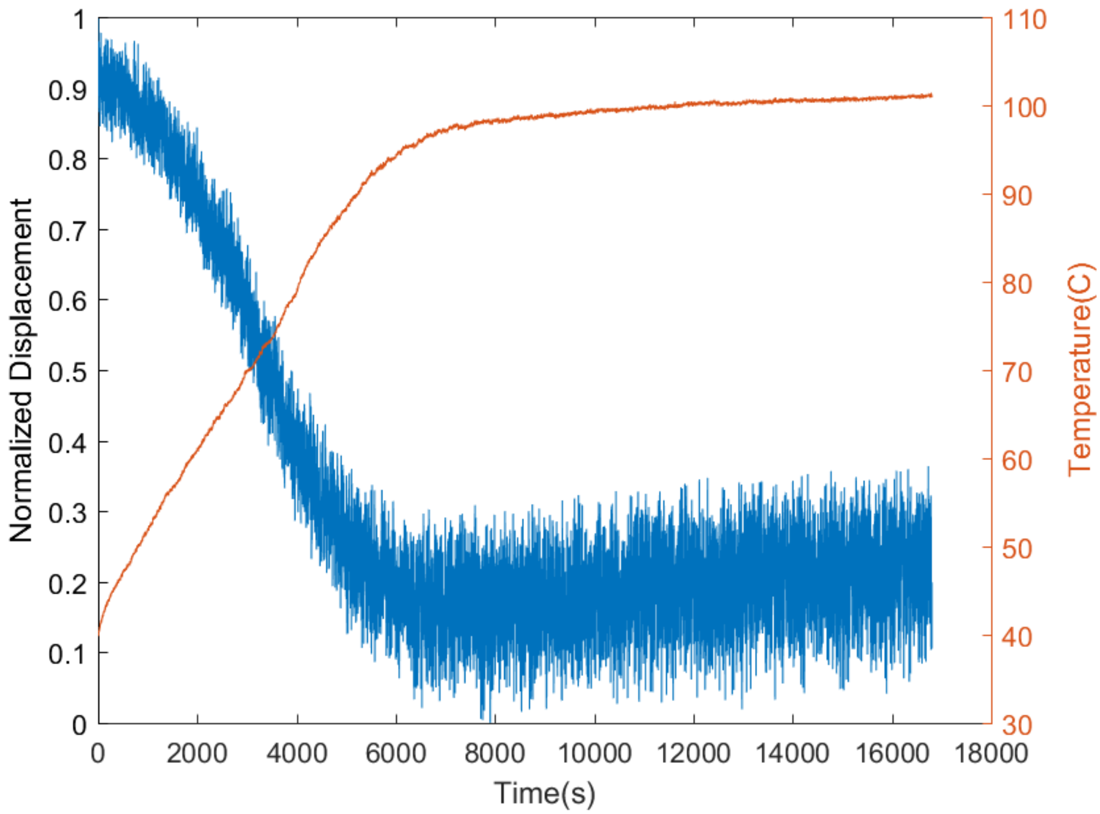

Figure 56: Sample 28, 400 grams of Tension

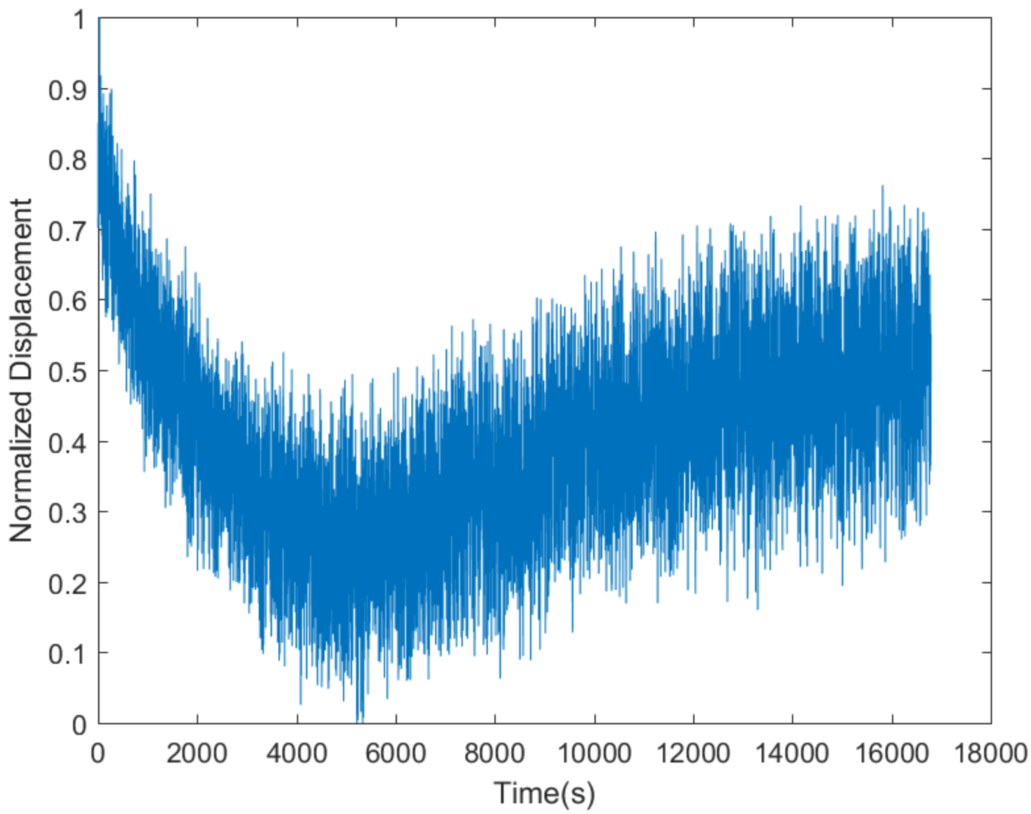

Figure 57: No Temperature, Sample 29, 400 grams of Tension

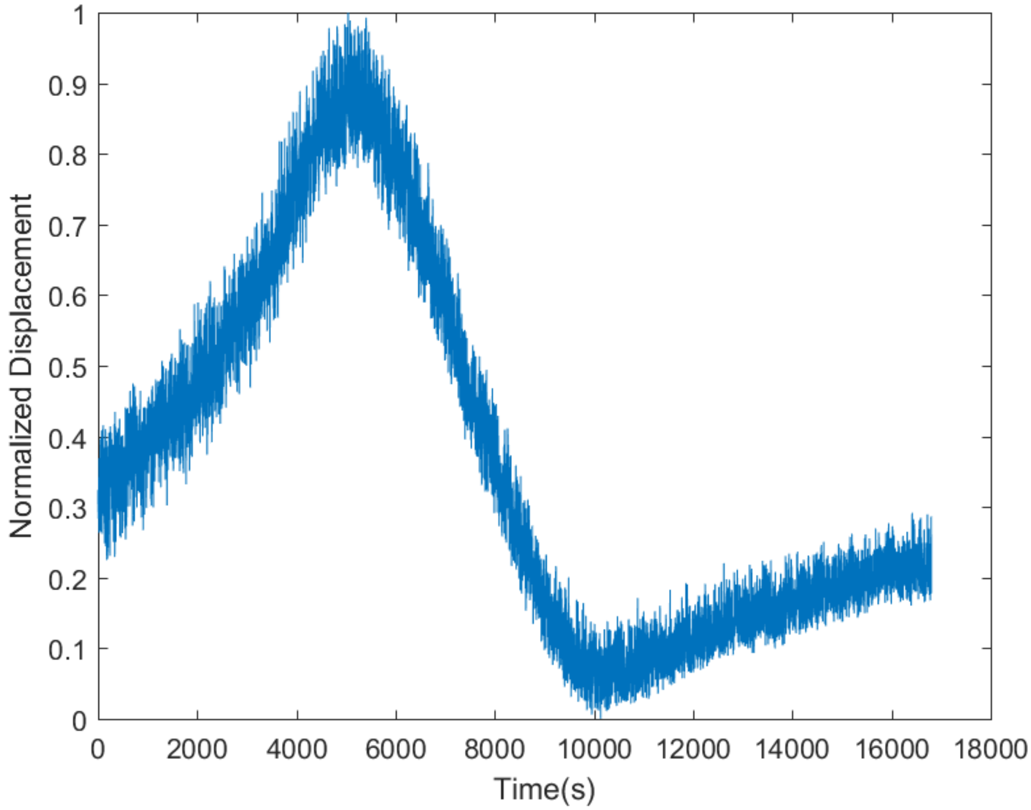

Figure 58: No Temperature, Sample 30, 400 grams of Tension

Vita

After completing his work at Baytown Christian Academy, Houston, Texas, in 2015, Ryan Ronquillo entered Stephen F. Austin State University at Nacogdoches, Texas. He received the degree of Bachelor of Science in Engineering Physics from Stephen F. Austin State University in December 2020. During the following two years, he was employed as a grad teaching assistant at Stephen F. Austin State University, where he enrolled to continue his education for his Masters's degree on January 2020. After two years, he received the degree of Masters in Natural Science of Physics in 2023

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