Development of Electrically Heated Polymer Artificial Muscles

By

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Declaration

I, Luke Harding, declare that this thesis is submitted in partial fulfilment of the requirements for the conferral of the degree Masters of Engineering - Research, from the University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualifications at any other academic institution.

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August 2017
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Abstract

Artificial muscles show great potential in several applications, particularly medical prosthetics and robotics. Thermally-activated stretched rubbers and thermally-activated twisted thermoplastic fibres have not received much attention in comparison to other polymers but show promise in these applications. The aim of this thesis was to address the lack of data on thermally driven polymer fibre actuators. Two types were considered: thermally-activated stretched rubbers and thermally-activated twisted thermoplastic fibres.

Spandex polyurethane was plied with steel, copper or carbon fibre and thermally actuated by passing electrical current through the conductor. The effect of the power input, temperature, stiffness and the force applied during sample manufacture and actuation were investigated. It was proven that as temperature increases the contraction of carbon fibre and polyurethane samples increases. This is consistent with the mathematically derived thermodynamics of heating rubber which state when rubber is strained and is then heated the rubber will contract in the direction of the loading. It was also shown that as the power through the conductive component of the sample increases, the temperature increases linearly. Therefore it can be concluded that as the input electrical power increases the contraction of the sample will increase. It was found that a sample manufactured with more weight applied during plying has significantly lower stiffness resulting in higher contractions compared to a sample manufactured with less weight, and that this relation holds across all actuation weights. The actuation of the spandex occurred by contraction of both the spandex and the carbon fibre coil wrapped around the spandex, and when the carbon fibre coil was stiffer the contraction of the spandex was reduced. The higher weight during manufacture decreases the bias angle during testing which increases the spring index of the carbon fibre coil resulting in decreased stiffness. Maximum contraction is achieved with minimum actuation weight. The maximum contraction observed was 10.2 %.

Overtwisted coiled nylon samples were produced by twisting nylon with carbon fibre until completely coiled. Mandrel wrapped samples were twisted nylon only and coiled around a rod, with heating applied via a furnace. Power input, temperature, temperature change, stress applied during manufacture and actuation, fibre diameter, sample length and coil pitch were investigated. The contraction of electrothermally heated overtwisted nylon samples increased linearly as the power through the conductor, and thus the heat generated, increased. For 0.45 mm diameter monofilament nylon, maximum contraction occurs when the weight on the
samples is somewhere around 100 g and 150 g. Maximum contractions occur in furnace heated mandrel wrapped nylon with maximum temperature changes. Maximum contractions also occur with minimum coil pitch and sample length. The largest contraction observed was 9.6%.

A variance in twist upon actuation was observed with shorter samples resulting in larger heat-induced untwist. This is unexplainable based on the current literature and future work should be carried out to investigate this. These experiments are unique in that they investigated larger coil pitches. This may fall outside of the coil contraction regime wherein untwist remains constant, or more likely the variation of twist with sample length is a result of variation in manufacture of samples. Contractions around 5% of the initial length were observed, with a maximum of 5.1%. This is less than other results using smaller pitch coils, however these results confirm that smaller pitch coils produce higher contractions.

The ability to store nylon samples is simpler than stretched rubber as nylon samples do not require constant application of force, allowing work to take place in stages rather than a continuous process. Although the manufacturing process for nylon samples takes much more time, it is evident that the results are repeatable and there are opportunities to investigate further to gain larger contractions. The contraction achieved for stretched polyurethane was larger than nylon; however work carried out by others has resulted in larger strains of 33% compared to 28.5% for latex. The simplicity of nylon actuator manufacture coupled with the low cost and high strains position nylon as a high potential material for commercial artificial muscle applications.
# Table of Contents

Declaration ............................................................................................................................................... i  
Acknowledgments ................................................................................................................................... ii  
Abstract .................................................................................................................................................. iii  
Table of Contents .................................................................................................................................... v  
List of Figures ....................................................................................................................................... vii  
List of Tables ......................................................................................................................................... ix  
Notation .................................................................................................................................................. x  

1 Chapter 1 Literature Review ........................................................................................................... 1  
   1.1 Introduction ..................................................................................................................................... 1  
   1.2 Drive for Artificial Muscles ............................................................................................................ 3  
   1.3 Artificial Muscle Alternatives ......................................................................................................... 3  
   1.4 Rubber as an Artificial Muscle ......................................................................................................... 4  
   1.5 Heating of Rubber ........................................................................................................................... 6  
   1.6 Electrical Heating ............................................................................................................................ 9  
   1.7 Heat Transfer ................................................................................................................................... 11  
   1.8 Spring and Polymer Actuation ........................................................................................................ 12  
   1.9 Twisted and Coiled Polymer Fibres .............................................................................................. 14  
   1.10 Problem Definition ....................................................................................................................... 21  
      1.10.1 Aim ....................................................................................................................................... 21  
      1.10.2 Objectives ............................................................................................................................. 21  

2 Chapter 2 Methodology ................................................................................................................ 22  
   2.1 Introduction ................................................................................................................................... 22  
   2.2 Electrothermally Heated Coiled Polyurethane ............................................................................. 22  
      2.2.1 Introduction ............................................................................................................................ 22  
      2.2.2 Methodology .......................................................................................................................... 22  
      2.2.2.1 Steel Wire Wrapped Polyurethane with Manual Manufacturing Method ......................... 22  
      2.2.2.2 Copper Wire Wrapped Polyurethane with Mechanised Manufacturing Method ............. 25  
      2.2.2.3 Carbon Fibre Wrapped Polyurethane ................................................................................ 29  
   2.3 Electrothermally Heated Overtwisted Nylon ............................................................................. 31  
      2.3.1 Introduction ............................................................................................................................. 31  
      2.3.2 Methodology .......................................................................................................................... 31  
   2.4 Furnace Heated Mandrel Wrapped Nylon ................................................................................... 32  
      2.4.1 Introduction ............................................................................................................................. 32  
      2.4.2 Method ................................................................................................................................... 33
List of Figures

Figure 1-1: Graph of actuator stroke vs stiffness ratio for actuators acting against a restoring spring, Y = actuator elastic modulus, Y' = actuator elastic modulus whilst voltage applied (Spinks & Truong 2005). .................................................................................................................................................... 14

Figure 1-2: Polymerisation of caprolactam to form nylon 6 (Wikimedia Commons). ............... 17

Figure 1-3: Structure of semi-crystalline polymer fibre after drawing showing: (A) amorphous tie chains, (B) crystalline bridges, and (C) connecting crystalline blocks aligned in the direction of the draw (Haines et al. 2014). ..................................................................................................................... 18

Figure 1-4: Hydrogen bonding between nylon 6,6 polymer chains (Young & Lovell 2011)......... 20

Figure 2-1: Plied sample made of 100 turns/m of A) Steel and B) Spandex under tension .......... 23

Figure 2-2: Schematic (i) and photograph (ii) of equipment set up for spandex and metal wire testing. Included is A) Power supply, B) Electrical connection, C) Clamp and stand D) Sample, E) Sample connection point, F) Force/distance transducer, G) Thermocouple, and H) Data logger ............... 24

Figure 2-3: Microphotograph of single spandex fibre ................................................................. 25

Figure 2-4: A) Microscope, B) End block, C) Ruler, D) Stopwatch and E) clamps necessary for automated manufacturing method ................................................................. 27

Figure 2-5: Schematic (i) and photograph (ii) of equipment set up for spandex and copper testing after automated manufacture including A) Thermouple, B) Sample, C) Motor, D) Force/distance transducer, E) Electrical connections, F) Data logger, and G) Power supply ................................................................. 28

Figure 2-6: Microphotograph of carbon fibre ................................................................. 30

Figure 2-7: Schematic (i) and photograph (ii) of laser measurement rig including A) Power supply including electrical connections, B) Stand and clamp, C) Laser distance measurement device, D) Sample, E) Thermocouple, F) Weight platform guide, G) Data logger, H) Suspended weight platform. ................................................................. 30

Figure 2-8: A) Motor and battery used for coiling samples (weight not pictured) and B) sample. ...... 32

Figure 2-9: Initial twisting of nylon (B) using a drill (A) and weights (C) ................................. 34

Figure 2-10: Nylon that has been twisted and is beginning to form coils ................................. 35

Figure 2-11: Twisted nylon (A) held via clamp (B) on ruler (C) to hold stresses during annealing 35

Figure 2-12: Completed sample prior to testing ................................................................. 36

Figure 2-13: Schematic (i) and photograph (ii) of the furnace used for actuation testing including A) Glass tube, B) Nichrome wire running to power supply, C) Stand and clamp, D) Copper wire attached to the sample, E) Sample, and F) Thermocouple ................................................................. 37

Figure 2-14: Schematic (i) and photograph (ii) of complete actuation testing set up including A) Power supply and electrical connections, B) Copper wire component of sample, C) Sample connection, D) Force/distance transducer, E) Thermocouple, F) Furnace, G) Stands and clamps, and H) Data logger ................................................................. 38

Figure 3-1: Sample made of spandex (A) and steel wire (B) demonstrating buckling after tension has been released ................................................................. 42

Figure 3-2: Graph of complete actuation cycle for sample manufactured with 50 g of weight. The sample had an unloaded length of 80 mm ................................................................. 43

Figure 3-3: Graph of actuation cycle for sample manufactured with 50 g weight being actuated under 150 g of weight from 3000 – 4000 seconds. The sample had an unloaded length of 80 mm at room temperature ................................................................. 44

Figure 3-4: Graph of sample length contraction versus temperature change at 150 g of weight for samples manufactured with 50 g and 150 g weight ................................................................. 46
Figure 3-5: Graph of temperature change versus power measured during testing of sample manufactured with 150 g of weight. .................................................................47
Figure 3-6: Contraction versus weight for sample manufactured with 200 g of weight. Data split into three distinct phases. .................................................................48
Figure 3-7: Contraction versus weight on sample for samples heated to 80 °C and made with a range of weights during manufacture. .................................................................48
Figure 3-8: Optical and thermal images (°C) of samples manufactured with 50 g, 150 g and 300 g weight respectively when actuated with 50 g of weight ...........................................52
Figure 3-9: Optical and thermal images (°C) of samples manufactured with 50 g, 150 g and 300 g weight respectively when actuated with 300 g of weight. ...........................................52
Figure 3-10: Thermal image (°C) of sample manufactured with 150 g of weight and actuated with 50 g of weight. A) shows the spandex fibres, B) shows the carbon fibre. .................................53
Figure 3-11: Stiffness of the samples manufactured with 50 g and 300 g weight calculated for all actuation weights at room temperature and at 80 °C. Both samples had an unloaded length of 85 mm. .................................................................................................................................54
Figure 3-12: Graph of contraction strain measured at a constant load of 3.08 MPa and with various electrical power applied to the conductor. ........................................................................56
Figure 3-13: Graph of contraction versus weight on sample. ........................................................................57
Figure 3-14: Modified graph of contraction versus weight on sample. .............................................................58
Figure 3-15: Twist insertion to complete coiling versus fibre diameter: data previously published (Haines 2014) is compared with Sample 2. .................................................................59
Figure 3-16: Temperature and displacement over time. ..................................................................................60
Figure 3-17: Temperature and displacement over time (scaled). .................................................................61
Figure 3-18: Sample displacement versus change in temperature experienced. ..................................................62
Figure 3-19: Contraction as a percentage of the initial sample length vs coil pitch. ........................................64
Figure 3-20: Contraction as a percentage of the initial sample length vs initial sample length. .......................65
Figure 3-21: Calculated fibre untwist vs initial sample length. ........................................................................68
**List of Tables**

Table 1-1: Comparison of properties of potential artificial muscle materials (Bar-Cohen 2001; Brochu and Pei 2010)........................................................................................................................................................................4
Table 2-1: Inserted twist and change in sample length over time.................................................................26
Table 3-1: Repeatability of contraction of sample manufactured with 50 g of weight being actuated under 250 g weight.........................................................................................................................................................................45
Table 3-2: Contraction of sample 2 under different variables. ...........................................................................55
Table 3-3: Repeatability of contraction with sample 1.5 from Set #1B.................................................................62
Table 3-4: Complete set of testing variables and results for section 3.4..........................................................63
Table 3-5: Nylon diameter, initial weight and stress for the three sets of samples...........................................66
Notation

$A_0$ Initial unloaded cross-sectional area of a rubber (m$^2$)

$A$ Surface area of a polymer that heat is being conducted through (m$^2$)

$C$ Spring index of a coil

$D$ Nominal coil diameter from a fibre centreline (m)

$d$ Diameter of a wire or fibre (m)

$d_o$ Fibre diameter before heating (m)

$d_F$ Fibre diameter after heating (m)

$dL$ Difference in length due to a uniaxial force (mm)

$dQ$ Heat exchanged between a system and its surroundings (J)

$dS$ Change in a systems entropy (J/K)

$dU$ Change in a systems internal energy (J/kg)

$dW$ Work exchanged between a system and its surroundings (J)

$E$ Modulus of elasticity (N/m$^2$)

$F$ Contractive tensile force (N)

$F_T$ Tensile force applied during twist insertion (N)

$f$ Force (N)

$f_U$ Uniaxial force (N)

$G$ Shear modulus (N/m$^2$)

$I$ Current flowing through a conductor (A)

$ID$ Individual sample’s reference number

$K_S$ Stiffness of a spring (N/m)

$K_R$ Stiffness of an actuator – e.g. a thermally actuated polymer (N/m)
\( K \)  
Stiffness modelled as a spring acting in parallel to an actuator (N/m)

\( k \)  
Boltzmann’s constant, \( 1.38 \times 10^{-23} \) (J/K)

\( L_0 \)  
Initial unloaded length (m)

\( L \)  
Length of a conductor (m)

\( \Delta L_f \)  
Theoretical actuator stroke of a spring and actuator in parallel (m)

\( \Delta L_R \)  
Theoretical stroke of an actuating material i.e. a polymer (m)

\( \Delta L \)  
Change in coiled length i.e. the contraction per coil (m),

\( l_0 \)  
Initial length (m)

\( l \)  
Final length (m)

\( l_s \)  
Fibre length in a coiled sample i.e. the helical length (m)

\( \Delta l \)  
Change in length (m)

\( \Delta l_{\%} \)  
Change in length as a percentage of initial length (%)

\( \Delta l_\lambda \)  
Change in length as a percentage of coil pitch (%)

\( N \)  
Number of chain segments

\( n \)  
Number of coil turns

\( P \)  
Power dissipated in a conductor per unit time (J/s = W)

\( Q \)  
Heat generated (J)

\( Q_T \)  
Heat transferred (J)

\( q_T \)  
Heat transferred per unit time, \( t \) (W)

\( R \)  
Resistance of a conductor (Ω)

\( r \)  
Ratio of a spring and actuator stiffness’s

\( T \)  
Temperature (K or °C as stated)
$T_o$ Initially inserted twist per fibre length (m$^{-1}$)

$T_c$ Critical twist to initiate coiling (m$^{-1}$)

$T_{hot}$ Temperature of an electrically conductive material (K)

$T_{cold}$ Temperature of a polymer (K)

$\delta T$ Temperature range a sample is exposed to (°C)

$\Delta T$ Fibre untwist i.e. the turns per initial fibre length (m$^{-1}$).

$t$ Time that current flows (s)

$V_0$ Initial unloaded volume of a rubber (m$^3$)

$V$ Voltage across a conductor (V)

$\Delta x$ Thickness of a region the heat is being conducted through (mm)

$Y$ Actuator elastic modulus (MPa)

$Y'$ Actuator elastic modulus whilst voltage applied (MPa)

$\delta$ Displacement produced by a force (mm)

$\varepsilon$ Extensional strain

$\kappa$ Thermal conductivity of a polymer (W/mK)

$\lambda$ Coil pitch, or gap between coils i.e. the length of a single coil (mm)

$\lambda_n$ Extension ratio in one of three spatial dimensions

$\phi_N$ Diameter of a fibre (mm)

$\rho$ Specific electrical resistivity (Ωm)

$\sigma$ Stress (N/mm$^2$ = MPa)

$\sigma_T$ Nominal tensile strength (N/m$^2$ = Pa)

$\tau_c$ Critical torque to initiate coiling (Nm)
1 Chapter 1 Literature Review

1.1 Introduction
Natural muscle has very good properties compared to currently known actuating materials. Such properties include, but are not limited to, capability of large strains of up to 40 % (Nordin & Frankel 1989), short response time, high life cycle, and sufficient stress generating capacity of 0.35 MPa (Baughman 2005). When compared to traditional actuating materials, it becomes evident that it is desirable to create a material that exhibits similar properties to natural muscle. Possible applications of artificial muscles include use in active clothing, artificial and damaged hearts and other organs, prosthetic limbs and robotics (Baughman 2005), and the fabrication of products such as robots with unmatched capabilities and dexterity (Bar-Cohen 2005). As artificial muscles are developed and refined further applications will undoubtedly be created. There are several different classes that fall under the broad category of artificial muscles. These include traditional technology such as combustion engines, electric motors, hydraulic systems, and pneumatic systems, as well as more modern technology such as Shape Memory Alloys (SMA), Electro Active Ceramics (EAC), and Electro Active Polymers (EAP). Numerous factors must be considered when determining which type of artificial muscle to use for a particular application. These factors can include the stress generated by the artificial muscle, the actuation strain that is required, the speed of the actuation, the size of the artificial muscle, the weight, the amount of noise generated, the life cycle of the artificial muscle, the power or energy required to actuate the artificial muscle and the resulting options for energy sources, and the efficiency (Biddiss & Chau 2008).

Previous research has provided evidence to suggest that rubber shows promise in artificial muscle applications (Wysocki 2010, Meldrum 2011, Harding 2012). Like most materials, rubber materials expand when heated, however, when pre-strained before heating the rubber will contract in the direction of the strain loading upon application of the heat (Pellicer et al 2001, Liff 2010). Contractions of up to 28 % have previously been recorded which is comparable to human muscle contractions of 40 % (Meldrum 2011). Rubber is also tough and resilient, elastic, has good fracture toughness and a high life cycle (Pusca et al 2010), and has been shown to be capable of low response times (Meldrum 2011). There are currently two different classes of rubber artificial muscle systems. The first kind involves heating and cooling the rubber indirectly using fluids including air and water. This process is inefficient
and requires a complicated set up to heat and cool the fluid as well as to ensure no leakage occurs during operation (Harding 2012). The second kind involves placing the rubber in contact with a material that has electricity passed through it. This material, for example copper wire, acts as a heating element with the internal resistance of the wire resulting in the generation of heat that can be transferred to the rubber. The conductor may be set into the material, or simply pressed against the material depending on the complexity and interfacial area desired. This system can provide quicker actuation due to increased surface area available for heat transfer, but as there is no forced cooling it takes more time to cool and as such more time for the artificial muscle to respond. When comparing indirect and directly heated rubber artificial muscle systems it has been found that directly heating is “less complicated, more compact, safer…and more efficient” (Harding 2012).

In addition to latex rubber, polyurethane spandex has also shown very positive results (Byrnes et al. 2013, Foroughi, 2016). The method of actuation utilised carbon nanotubes or steel and copper wires as the heating element twisted around spandex threads. The method of manufacturing the samples was also automated, with one study using a knitting machine to first wrap the spandex with conductor and then form a knitted fabric. The use of threads of spandex decreased the volume of actuating material required to heat up, resulting in the potential for both faster actuation and complete actuation cycles in comparison to results previously seen with this method. A negative of this method was that given the tight twists, the artificial muscle was required to remain in a stretched position or buckling of the heating element would occur on relaxation of the artificial muscle if the heating element was rigid e.g. steel wire.

Ordinary polymers fibres, such as nylon, have only recently come to light as a possible material for use as an artificial muscle. The method of manufacture involves twisting the fibre under tension until coiling occurs and annealing the fibre after twisting. The annealing permanently sets the coiled shape and twist inserted into the fibre. This is a huge benefit over rubber actuators to date, removing the effort required to keep the artificial muscle in a stretched state where it could actuate. Similar to rubber actuators, the coiled polymer fibres contracts upon heating, and then extends upon cooling. Nylon is significantly cheaper than other artificial muscle materials, and given the low annealing temperature it can be made into an actuator quite easily without any special equipment. It can be heated via both the fluid heat transfer method and the electrical heating method used for rubber artificial muscles.
1.2 Drive for Artificial Muscles
In 1999 Dr. Yoseph Bar-Cohen issued the challenge: “to develop a robotic arm that is actuated by artificial muscles to win an arm wrestling match with a human opponent” (Bar-Cohen 2001). This challenge was created with the aim of raising awareness, and encouraging advances, of electroactive polymers. Electroactive polymers were initially the only material that would be used to actuate the robotic arm. Electroactive polymers are defined as “materials that change shape and size when stimulated by an electric current or voltage” (Bar-Cohen 2005). The realisation of this goal was principally designed to be a stepping stone to creating medical prosthetics, as well as for use in robotics. As artificial muscles were further developed additional applications would be found as well.

In 2008 the rules were updated and explicitly stated the definition of an electroactive polymer (EAP). An exception of this definition was made, stating “An exception will be given to the use of polymers that are indirectly driven by electric current or field but they will need to be identified as being so. For example, thermally actuated polymer materials will be accepted if they use embedded electrical heating elements” (Bar-Cohen 2011). This enables heat actuated polymers including rubbers and nylon to qualify as electroactive polymers and enter the arm wrestling competition, dependent upon the heat being supplied electrically.

Bar-Cohen’s reason for choosing EAP for his challenge over the various other types of artificial muscles is due to “the fact that, with a very small difference between species, muscles are fundamentally driven by the same mechanisms in all animals suggests that they are highly optimized. Electroactive polymers…are human made actuators that most closely emulate muscles” (Bar-Cohen 2005).

1.3 Artificial Muscle Alternatives
Motors and engines have traditionally been used as actuating systems in robotics and other machines. Motors and engines offer several disadvantages such as their large size and weights, and their lack of flexibility. They often contain pressurised, explosive or otherwise dangerous fluids. These features have been some of the drivers for a new generation of artificial muscles, as well as reducing noise pollution, creating more fluid movements and increasing the force to mass ratio (Biddis & Chau 2008).

The new generation of artificial muscles contains several different types which are categorised based on both the material and how the force or torque is produced. The leading classes are electroactive polymers (EAP), shape memory alloys (SMA), electroactive
ceramics (EAC), and dielectric elastomers (DE). DE’s, whilst technically a subcategory of EAP, have undergone enough research and received enough attention to merit their own separate class. As mentioned, these classes are made up of various materials and work by several different mechanisms and as such they have various strengths and weaknesses in comparison to both each other, as well as human muscle, as seen in Table 1-1. In addition to the categories listed, there are several other variables to be considered including power density, cost, energy consumption and many more.

**Table 1-1: Comparison of properties of potential artificial muscle materials (Bar-Cohen 2001; Brochu and Pei 2010).**

<table>
<thead>
<tr>
<th>Property</th>
<th>EAP</th>
<th>SMA</th>
<th>EAC</th>
<th>DE</th>
<th>Human Muscle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain (%)</td>
<td>&gt;300</td>
<td>&lt;8</td>
<td>0.1-0.3</td>
<td>30-400</td>
<td>&gt;40</td>
</tr>
<tr>
<td>Stress (MPa)</td>
<td>0.1-25</td>
<td>700</td>
<td>30-40</td>
<td>1.2-7.8</td>
<td>0.35</td>
</tr>
<tr>
<td>Response Speed</td>
<td>μsec-min</td>
<td>msec-min</td>
<td>μsec-min</td>
<td>μsec-sec</td>
<td>msec</td>
</tr>
<tr>
<td>Drive Voltage (V)</td>
<td>&gt;1000</td>
<td>N/A</td>
<td>50-800</td>
<td>500-1000</td>
<td>N/A</td>
</tr>
<tr>
<td>Mechanical Behaviour</td>
<td>Resilient, elastic</td>
<td>Resilient, elastic</td>
<td>Fragile</td>
<td>Resilient, elastic</td>
<td>Resilient (self repairing)</td>
</tr>
<tr>
<td>Cycle Life</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Max Efficiency (%)</td>
<td>80</td>
<td>&lt;10</td>
<td>&gt;90</td>
<td>90</td>
<td>&gt;35</td>
</tr>
</tbody>
</table>

### 1.4 Rubber as an Artificial Muscle

One material for use as an actuator that has not received a great deal of attention is thermally actuated rubber. The Bar-Cohen arm wrestling challenge did not include polymer actuators indirectly driven by electric current or field for the first 9 years. This resulted in a focus on directly actuated polymers, however rubber displays many valuable properties including good fracture toughness, good strength, high cycle life, recovery from deformation, and elasticity. Rubber is capable of generating reasonable pressures up to 0.7 MPa which surpass human muscle at 0.35 MPa. Strains of up to 28.5 % have been observed and it has a relatively fast actuation speed (Meldrum 2011). The main limitations affecting the use of rubber as an
Actuator is the fact that the material must first be pre-stretched before actuation can occur, as well as the method by which the rubber is heated to cause actuation.

Actuation of rubber occurs due to a change in temperature of the material whilst stretched. This can be shown both in a thermodynamic study (refer Section 1.5) and in a simple experiment (Pellicer et al 2001, Liff 2010). The temperature driven mechanism means that actuation speed is restricted by the rate of temperature change. Temperature changes and thus actuation speeds for rubber have been increased by increasing the rate of flow of the fluid heating the rubber, changing the fluid used to transfer heat, and increasing the surface area of the rubber (Wysocki 2010; Meldrum 2011).

Electrical methods of heating rubber have been used which further increased the rate of contraction but the total actuation time was still restricted by the rate of cooling as there was no forced cooling (Harding 2012). Electrical heating of spandex fibre by a wrapped stainless steel wire has resulted in tensile contractions of up to 8% for plied samples, however reproducibility was found to be poor, in addition to multiple sample failures occurring (Byrnes et al 2014). Copper wire was also used as the electrical heating element. Byrnes et al suggested that heat distribution in samples with “thicker wires would be much more even” than thinner samples at the cost of increased stiffness resulting in the potential for poorer actuation. One recommendation for further work is the analysis of the heat distribution via thermal imaging to determine the effectiveness of the heating element.

Knitted spandex and carbon nanotube composite yarns have achieved tensile contractions of up to 33%. Maximum specific work outputs of 1.28 kW/kg have been generated “which far exceeds that of mammalian skeletal muscle” (Foroughi et al. 2016). The manufacturing method used is highly scalable with the potential for producing industrial quantities of these composite yarns. Furthermore, the manufacturing method “operates at room temperature, requires no solvents, and does not compromise textile production speeds” as well as utilising less than 10% by weight of carbon nanotube resulting in relatively low material costs (Foroughi et al. 2016). In addition to their use as artificial muscles, the authors also demonstrated the use of the composite yarns as sensors capable of measuring length changes and movements via changes in electrical resistance of the carbon nanotube fibres. The electrical resistance changes were found to be “linear and largely hysteresis-free” between 0 and 80% strain.
1.5 Heating of Rubber
Upon heating rubber expands volumetrically like most materials, however when the rubber is strained and is then heated the rubber contracts in the direction of the loading. When at equilibrium, the properties of the rubber can be described by thermodynamics. The first law states that (Treloar 1975, p. 28):

\[ dU = dQ - dW \]  
\hspace{1cm} (1.1)

Where:

\( dU \) is the change in the systems internal energy (J/kg)

\( dQ \) is the heat exchanged between the system and the surroundings (J)

\( dW \) is the work exchanged between the system and the surroundings (J)

For uniaxial tension:

\[ dW = -f_U dL \]  
\hspace{1cm} (1.2)

Where:

\( f_U \) is the uniaxial force (N)

\( dL \) is the difference in length due to the uniaxial force (mm)

If the deformation process is reversible, then:

\[ dQ = T dS \]  
\hspace{1cm} (1.3)

Where:

\( T \) is the temperature (K)

\( dS \) is the change in the system entropy (J/K)

Substituting equations (1.2) and (1.3) into (1.1) gives:

\[ dU = T dS + f_U dL \]  
\hspace{1cm} (1.4)
From this the contractive tensile force can be found for a system in uniaxial tension with volume and temperature constant:

$$F = \left(\frac{dU}{dL}\right)_{T,V_0} - T \left(\frac{dS}{dL}\right)_{T,V_0} \tag{1.5}$$

The tensile force consists of two terms. The first term is $\left(\frac{dU}{dL}\right)_{T,V_0}$ which is the energy elasticity, or the energy contribution to the force. This contribution is due to the storage of energy that occurs from rotation about bonds and straining in bond angles and lengths from their equilibrium position. The second term is $T \left(\frac{dS}{dL}\right)_{T,V_0}$ which is the entropy elasticity, or the entropy contribution to the force. This is the decrease in entropy that occurs due to the uncoiling of molecular chains or segments of chains.

When rubber is strained, the majority of the change in length and energy comes from rotation of the bonds resulting in a change in conformation; the stretching of the bonds is negligible. Therefore at constant temperature the internal energy of the bonds is constant and it can be approximated that $dU = 0$. Therefore (1.5) becomes:

$$F = -T \left(\frac{dS}{dL}\right)_{T,V_0} \tag{1.6}$$

When stretched, the rubber moves from higher entropy state to a lower entropy state. This change in entropy is given by:

$$dS = -\frac{1}{2} N k (\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3) \tag{1.7}$$

Where:

$N$ is the number of chain segments

$k$ is Boltzmann’s constant, $1.38 \times 10^{-23} \text{ (J/K)}$
\( \lambda \) is the extension ratio in one of three spatial dimensions

The extension ratio is defined as:

\[
\lambda = \frac{l}{l_0}
\]  

(1.8)

Where:

- \( l \) is the final length (m)
- \( l_0 \) is the initial length (m)

When in uniaxial tension the extension ratios in the transverse directions must be equal, therefore \( \lambda_1 = \lambda_2 \) and as there is no volume change then \( \lambda_1 \lambda_2 \lambda_3 = 1 \). This means that:

\[
\lambda_1 = \lambda_2 = \frac{1}{\sqrt[3]{\lambda_3}}
\]  

(1.9)

Substituting (1.9) into (1.7) gives:

\[
dS = -\frac{1}{2} Nk \left( \frac{2}{\lambda_3} + \lambda_3^2 - 3 \right)
\]  

(1.10)

Combining (1.6) and (1.10) and rearranging results in:

\[
F = \frac{kTN}{L_0} \left( \lambda_3 - \frac{1}{\lambda_3^2} \right)
\]  

(1.11)

Where:

- \( L_0 \) is the initial unloaded length of the rubber (m)

(1.11) can then be used to find the nominal tensile stress:

\[
\sigma_T = \frac{F}{A_0} = \frac{kTN}{V_0} \left( \lambda_3 - \frac{1}{\lambda_3^2} \right)
\]  

(1.12)
Where:

\( \sigma_T \) is the nominal tensile stress applied in uniaxial tension (N/m\(^2\) = Pa)

\( A_0 \) is the initial unloaded cross-sectional area of the rubber (m\(^2\))

\( V_0 \) is the initial unloaded volume of the rubber (m\(^3\))

In (1.12) \( A_0, k, N \) and \( V_0 \) are all constants. This means if the rubber is experiencing constant force then the extension ratio is proportional to temperature, and as temperature increases the extension ratio decreases. This results in the rubber contracting when heated.

1.6 Electrical Heating

Electrical heating involves the conversion of energy from electrical to thermal. This has many applications in society including use for the heating of food, air and water. According to Joule’s Law of Heating, heat generated by the flow of current in a conductor can be given by (Tewari 2003):

\[
Q \propto I^2 R t
\]  

(1.13)

Where:

\( Q \) is the heat generated (J)

\( I \) is the current flowing through the conductor (A)

\( R \) is the resistance of the conductor (\( \Omega \))

\( t \) is the time that the current flows (s)

Given that (Petchers 2003):

\[
P = IV
\]  

(1.14)

Where:

\( P \) is the power dissipated in a conductor per unit time (J/s = W)
\( V \) is the voltage across the conductor (V)

And:

\[
V = IR \tag{1.15}
\]

Then (1.15) can be substituted into (1.14) to give:

\[
P = I^2R \tag{1.16}
\]

If (1.16) is then substituted into (1.13) it gives:

\[
Q \propto Pt \tag{1.17}
\]

Therefore heat generated is directly proportional to the power dissipated. This means that to maximise the heat generated without increasing the time, the power must be maximised.

Resistance of a conductor varies according to Pouillet’s Law:

\[
R = \frac{\rho L}{A} \tag{1.18}
\]

Where:

\( \rho \) is the specific electrical resistivity (Ωm)

\( L \) is the length of the conductor (m)

\( A \) is the cross sectional area of the conductor (m²)

When (1.18) is substituted into (1.16) it gives:

\[
P = \frac{I^2 \rho L}{A} \tag{1.19}
\]

Based on this, to maximise the power several different values must be optimised, such as:

- Increasing current flow, \( I \)
Increasing the voltage, $V$, which requires an increase in the resistance, $R$

- Increasing the length of the conductor, $L$

- Increasing the specific electrical resistivity of the conductor, $\rho$, i.e. using a more resistive material

- Decreasing the cross sectional area of the conductor, $A$

### 1.7 Heat Transfer

Actuation of thermally actuated polymers occurs with change in temperature, that is, for the actuator to contract and expand it must be heated and cooled respectively. To maximise efficiency of the actuator, as well as decrease actuation times, the heat transfer should be optimised. According to Fourier’s law heat flows from warmer objects to cooler objects. For electrical heating of thermally actuated polymers the heat transfer mechanism is conduction as it is the transfer of energy between solid objects that are in physical contact. In this case it would be the transfer of energy between the polymer and the electrically conductive material. For heat transfer between two planar surfaces the rate of conduction is (Rudramoorthy & Mayilsamy 2010):

$$ q_T = \frac{Q_T}{t} = -\kappa A (T_{hot} - T_{cold}) \frac{1}{\Delta x} $$(1.20)

Where:

- $q_T$ is the heat transferred per unit time, $t$ (W)
- $Q_T$ is the heat transferred (J)
- $\kappa$ is the thermal conductivity of the polymer (W/mK)
- $A$ is the surface area of the polymer that the heat is being conducted through (m$^2$)
- $T_{hot}$ is the temperature of the electrically conductive material (K)
- $T_{cold}$ is the temperature of the polymer (K)
- $\Delta x$ is the thickness of the region the heat is being conducted through (m)

It can be seen that there are several ways that heat transfer could be increased, and thus actuation times of the polymer could be decreased. These are:
- Increasing the surface area that the polymer is in contact with the electrically conductive material, such as by using smaller electrically conductive particles which would have larger specific surface areas, or by ‘wrapping’ the conductor around the polymer which increases the surface area of contact for the same length of polymer
- Increasing the temperature difference between the polymer and the electrically conductive material
- Decreasing the thickness of the region that the heat is being conducted through, such as by using multiple thinner polymer strips rather than one thick strip.

1.8 Spring and Polymer Actuation

A method of electrically heating a polymer could involve using a metal coiled around the polymer acting as a weak spring in contact with rubber. This would introduce mechanical resistance due to the metal spring acting in opposition to the polymer. This can be treated as an actuator acting against a restoring spring, which can be modelled as a spring acting in parallel to an actuator.

The actuator stiffness can be defined by (Ashby, Shercliff and Cebon 2007):

$$K = \frac{f}{\delta}$$  \hspace{1cm} (1.21)

Where:

- $f$ is the force (N)
- $\delta$ is the displacement produced by the force (mm)

For the restoring spring component, helical spring stiffness is given by (Drotsky 2013):

$$K_s = \frac{Gd^4}{8nD^3}$$  \hspace{1cm} (1.22)

Where:

- $G$ is the shear modulus (N/m$^2$)
- $d$ is the wire diameter (m)
\( n \) is the number of turns

\( D \) is the mean coil diameter (m)

The ratio of the stiffness’s is stated as:

\[
r = \frac{K_S}{K_R}
\]

Where:

\( K_S \) is the stiffness of the spring (N/m)

\( K_R \) is the stiffness of the actuator – i.e. the polymer (N/m)

The theoretical actuator stroke of a spring and actuator in parallel can be calculated by (Spinks & Truong 2005):

\[
\Delta d_f = \Delta d_R \left( \frac{1}{1 + r} \right)
\]

Where:

\( \Delta d_R \) is the theoretical stroke of the actuating material i.e. the polymer (m)

As the stiffness ratio increases, that is the spring stiffness increases relative to the actuator stiffness, actuator stroke decreases, as per Figure 1-1. Equation 1.24 can be further adapted to account for changes in the actuator stiffness that typically occurs when the actuator is activated. Figure 1-1 shows examples of the effect of changing actuator modulus from \( Y \) (unactivated) to \( Y' \) (activated) on the actuation stroke when operated against springs of varying stiffness.
1.9 Twisted and Coiled Polymer Fibres
In 2014, new materials came to light for use in artificial muscle applications. These materials included nylon 6 and nylon 6,6, polyethylene, Kevlar and polyvinylidene difluoride (PVDF). These materials required specific processing to enable contraction upon heating but offered several benefits over other artificial muscles, especially price and availability of materials. Fishing line tends to be manufactured from nylon 6, polyethylene and PVDF, while sewing thread tends to be made with nylon 6,6 and polyester. Both of these are very common and cheap materials.

Processing of the materials into artificial muscles, using nylon as an example, is detailed below. A nylon fibre is held at one end and twisted whilst under stress, often in the form of a load such as a weight on the end of the fibre. Once the inserted twist in the fibre is above a critical twist density coils spontaneously form. In monofilament precursor fibres the
nucleation tends to be at a single location from which more coils form from. In multifilament fibres there tends to be several coil nucleation sites along the fibre length. Once completely coiled the nylon is annealed which allows the fibre to hold the coiled structure. Upon heating and cooling the coiled fibre will contract and expand in length, which enables the fibre to do mechanical work. Several ‘training cycles’ are often required first to achieve reversible actuation that is stable and repeatable.

For calculations related to the experiments, loads are converted to nominal stress by using the precursor (i.e. untwisted) fibre diameter. Percent actuation stroke ($\epsilon$) was obtained by normalising the change in sample length during heating ($\Delta L$) to the low temperature length ($L$) of the coiled or non-coiled fibres under the given load. The spring index of the samples was also important, where the spring index of a coil is given by the following ratio (Bhandari 2010):

$$C = \frac{D}{d}$$  \hspace{1cm} (1.25)

Where:

$C$ is the spring index of the coil

$D$ is the nominal coil diameter from the fibre centreline (m)

$d$ is the fibre diameter (m)

Haines et al. investigated the main variables affecting the actuation behaviour of the twisted and coiled fibres. It was found that “stroke increases approximately linearly with temperature and depended little on the applied loads” that were used during the isotonic actuation tests. It has also been observed that “for coils with similar fibre twist, fibre length, and number of turns, the maximum percentage stroke increases with increasing spring index, but the stroke at high nominal stress decreases.” In addition to this, the “load lifting capability (of a coiled fibre) decreases with increasing spring index.”

The change in length of the coils was found to be driven directly by the torsional actuation occurring in the twisted fibre. Coils formed by first twisting the fibre and then forming a coil
by wrapping the twisted fibre around a mandrel could be made as either homochiral (fibre and coil with same twist direction) or heterochiral (opposite twist direction for the fibre and coil). The twisted fibres were shown to torsionally actuate when heated where some untwist occurred on heating and re-twist happened on cooling. The homochiral coils then contracted in length on heating while the heterochiral coils expanded. For coiled fibres it was found that the following formula gave a good approximation for coil deformation due to a change in fibre twist per initial fibre length (Haines et al. 2014):

\[
\frac{\Delta L}{L_0} = \frac{l_s^2 \Delta T}{L_0 n} \tag{1.26}
\]

Where:

\(n\) is the number of coil turns,

\(l_s\) is the fibre length in the coiled sample (m),

\(\Delta L\) is the change in coiled length i.e. the contraction per coil (m),

\(L_0\) is the initial unloaded coiled length (m), and

\(\Delta T\) is the fibre untwist i.e. the turns per initial fibre length (m\(^{-1}\)).

Fibre length, also known as helical length, can be calculated for a single coil using the following formula (Isnard et al. 2009):

\[
l_s = \sqrt{(\lambda^2 + (\pi D)^2)} \tag{1.27}
\]

Where:

\(\lambda\) is the length of one turn in the coil (also known as the pitch length)

The total sample coil length is then equal to:

\[
L_0 = n\lambda \tag{1.28}
\]

Rearranging (1.28) and substituting into (1.26) gives:
\[
\Delta L / \bar{L}_0 = l_s^2 \Delta T / L_0^2 \lambda
\]  

(1.29)

Nylon is the most commonly used thermoplastic fibre for the study of twisted and coiled artificial muscles. Nylon is a polyamide that can be manufactured several different ways depending on the specific nylon polymer that is desired. Nylon 6 in particular is manufactured by way of ring opening polymerisation. Caprolactam is heated to 260 °C in a nitrogen atmosphere for several hours which breaks the ring open between the amide group and the carbonyl group. This can be seen diagrammatically below in Figure 1-2.

![Figure 1-2: Polymerisation of caprolactam to form nylon 6 (Wikimedia Commons).](image)

Nylon 6 has a melting point of 220 °C, a glass transition temperature of 45 °C, and a linear thermal expansion coefficient of \(8 \times 10^{-5}\) m/m.k. Due to the polar functional groups nylon 6 is hygroscopic and can absorb up to 11% of its weight in water. Water absorption alters the properties of nylon including decreasing the glass transition temperature (Olabisi 1997), increasing the physical dimensions of the nylon (Bunsell 2009), as well as decreasing the tensile strength and modulus whilst increasing toughness (NIIR Board 2004).

Nylon can be readily manufactured into highly oriented fibres that are highly anisotropic. The high degree of chain orientation provides large thermal expansion in the radial direction and thermal contraction in the fibre axis direction upon heating. The thermal expansion anisotropy is due to the structure of the nylon which comprises both crystalline and amorphous regions as seen in Figure 1-3.
Above the glass transition temperature of the nylon, the amorphous regions act in a similar manner to rubber where “when heated, the modulus of the amorphous tie molecules increases due to the thermodynamics of rubber elasticity and thereby further compresses the crystalline bridges (the modulus of the crystalline bridges does not change appreciably on heating). The result is thermal contraction in the draw direction” (Haines et al. 2014).

The increase in modulus with temperature is in contrast with the fact that many polymers undergo a decrease in modulus with increase in temperature. The modulus of rubbery polymers increases with temperature due to the fact that strain in rubbers is a mainly entropic effect and the energy of deformation is, therefore, directly coupled to temperature as explained in Section 1.5.

The thermal contraction of the heated nylon in the draw direction is much larger than the thermal expansion that results due to increasing temperature, thus resulting in an overall contraction of the nylon (Choy et al. 1981). The effects of this can be seen mathematically below.

The modulus is related to force by the following relationship (Lokensgard 2008):
\[ E = \frac{\sigma}{\varepsilon} \quad (1.30) \]

Where:

\( E \) is the modulus of elasticity \((\text{N/m}^2)\)

\( \sigma \) is the stress \((\text{MPa})\)

\( \varepsilon \) is the extensional strain

The extensional strain is defined by (Bolton 2015):

\[ \varepsilon = \frac{\Delta l}{l_0} \quad (1.31) \]

Where:

\( \Delta l \) is the change in length \((\text{m})\)

This can be rearranged to form the following:

\[ \frac{\Delta l}{l_0} = \frac{l - l_0}{l_0} = \frac{l}{l_0} - 1 \quad (1.32) \]

By substituting Equation (1.8) into Equation (1.32), and then Equation (1.32) into Equation (1.31), the extension ratio can be seen to be related to extensional strain by the following relationship:

\[ \varepsilon = \lambda - 1 \quad (1.33) \]

According to this relation, as the extension ratio increases, the extensional strain will also increase. Substituting Equation (1.33) into Equation (1.30) gives:

\[ E = \frac{\sigma}{\lambda - 1} \quad (1.34) \]

According to Equation (1.12), if the force on a rubber was constant and the temperature increased, then the extension ratio would increase. Assuming the amorphous tie molecules in
nylon act like a rubber, then under constant force and increasing temperature, the resulting increasing modulus in Equation (1.34) can be seen to be the cause of the decreasing extension ratio.

Chain packing of the polymer is controlled by hydrogen bonds between oxygen atoms and hydrogen atoms which results in “extended planar zig-zags joined together in hydrogen-bonded sheets” (Young & Lovell 2011). In crystalline regions each successive polymer in the sheet is one higher than the last due to the relative position of the oxygen and hydrogen atoms on each polymer which results in a monoclinic crystal structure. Due to nylon’s hydrogen bonding between molecules which favours a parallel molecule arrangement and its small functional groups it tends to have a high volume of crystalline regions. The higher the crystalline volume fraction the higher the tensile strength of the nylon, while increasing the amorphous volume fraction increases elasticity and fracture toughness. Extrusion and drawing tend to increase the crystalline fraction as more of the polymer chains become oriented in the drawing direction and align with each other, with the hydrogen bonds forming between the carbonyl oxygen atoms and the amide hydrogen atoms of separate chains, as seen in Figure 1-4.

![Figure 1-4: Hydrogen bonding between nylon 6,6 polymer chains (Young & Lovell 2011).](image)

Much of the research so far has focussed on coiled fibres as artificial muscles. This is partially due to the fact that only nylon and PVDF provided relatively large thermal contraction when non-coiled. Nylon 6 (and nylon 6,6) has a considerably larger negative thermal expansion coefficient at temperatures above its glass transition temperature. According to Haines et al. “with a melting point above 260 °C, over 4 % thermal contraction
can be generated by nylon 6,6 fibres when using room temperature as the lower temperature limit. By fully coiling...[this] can be increased to 50 %.”

1.10 Problem Definition

1.10.1 Aim
The aim of this thesis is to address the lack of data on thermally driven polymer fibre actuators. Two types have been considered: thermally-activated stretched rubbers and thermally-activated twisted thermoplastic fibres.

The effect of various parameters including temperature, filament diameter, annealing temperature and force will be tested to achieve optimum properties, i.e. maximum contraction for maximum efficiency.

1.10.2 Objectives
- Investigate practical means for electrically heating rubber
- Investigate how coil geometry affect the performance of twisted and coiled fibres
- Test the effect of different monofilament diameter, coil diameter, coil bias angle, twist inserted into filament, annealing temperature and time, and temperature range and force on nylon contraction
- Suggest possible future developments and areas of further research
Chapter 2  Methodology

2.1  Introduction
Several different experimental methods are utilised throughout this thesis, and with several different materials, both individually and in various combinations. This is done with the intention of creating a practical means for electrically heating rubber, determining how coil geometry affects the performance of twisted and coiled fibres, and determining the effect of different monofilament diameter, coil diameter, coil bias angle, twist inserted into filament, annealing temperature and time, and temperature range and force on nylon contraction.

2.2  Electrothermally Heated Coiled Polyurethane

2.2.1  Introduction
The initial testing carried out for this thesis was designed with the goal of understanding how to use the equipment that will be used throughout the thesis, developing a test method, and to address a lack of data on the behaviour of thermally activated stretched rubbers when heated via contact with an electrically conductive material. Due to positive results recently published (Byrnes et al 2013) and later (Foroughi et al 2016), as reviewed in Section 1.4, polyurethane is to be used for this initial testing.

2.2.2  Methodology

2.2.2.1  Steel Wire Wrapped Polyurethane with Manual Manufacturing Method
A commercially available polyurethane (spandex supplied by Spandex Co. Ltd. China) fibre was used as the contractile polymeric material in this work. To create the contraction and elongation the spandex was required to be stretched and then heated and cooled. Contraction occurs upon heating (refer to Section 1.5). The heat would be provided by passing electricity through a conductor in contact with the polymer. To get optimum heat transfer the spandex was twisted around a thin metal wire conductor to increase the surface area and thus available area for heat transfer (refer to Section 1.7). Multiple samples were made to test several variables including the electrically conductive heat source (steel vs copper wire), metal wire diameter, sample length and coil bias angle.

The initial samples were made by hand by wrapping the spandex around the conductor which was clamped at both ends. This was intended to simplify the process whilst gaining an understanding of the test method. Hand wrapping was carried out slowly and steadily to ensure consistency of bias angle and repeatability of the manufacture method. A 50 g weight (491 mN) was hung from the bottom of the spandex to ensure the spandex was pre-stretched
at a constant stress of 1.56 MPa. Without the pre-stretch the sample would not contract upon applying heat. The desired amount of twists of spandex was applied at the desired bias angle and then the spandex was attached to a frame to prevent the spandex releasing the ‘pre-stretch’. Figure 2-1 shows a stretched sample made of 0.018 mm diameter non-insulated steel wire with 4 ply polyurethane.

Figure 2-1: Plied sample made of 100 turns/m of A) Steel and B) Spandex under tension.

Actuation performance was determined using a tensile testing apparatus shown in Figure 2-2. The Aurora Scientific 305B tensile force and displacement measurement device was used to maintain the pre-stretch of the sample at a similar force as that used during manufacture of the plied spandex/steel samples. This force was kept constant during heating and cooling. Electricity was cycled through the metal wire to regulate temperature. As the temperature of the metal changed so did the temperature of the spandex. A thermocouple lightly touching the spandex was used to measure the temperature. The force was kept constant and is termed ‘isotonic’ testing. The sample temperature and length were recorded continuously throughout the experiment.
Figure 2-2: Schematic (i) and photograph (ii) of equipment set up for spandex and metal wire testing. Included is A) Power supply, B) Electrical connection, C) Clamp and stand D) Sample, E) Sample connection point, F) Force/distance transducer, G) Thermocouple, and H) Data logger.

Figure 2-2 shows the equipment set up used for the actuation testing. The sample was attached on the left side to a fixed clamp (C) attached to a retort stand. The sample (D) was
attached at the right (E) to the force/distance transducer (F) that allowed control and measurement of the force on the sample. The power supply is not photographed, nor are the electrical connections, thermocouple and data logger.

The sample was initially 100 mm long and was pre-stretched to a force of 400 mN. 4 ply spandex fibre was looped 10 times to create a parallel array of 40 ply sample. The electrical power to the metal wire was cycled on and off as the contraction and elongation of the sample plateaued and stabilised. Cycle times tended to be 70 seconds for heating and 70 seconds for cooling resulting in 140 seconds for a complete cycle, however it was observed that after 30 seconds of heating and 40 seconds of cooling the sample length changed very little. The additional time during both heating and cooling was to ensure the sample length was stable. The power was cycled several times to confirm that after the first two cycles the actuation strain was constant within experimental error. A potential difference of 2 V was used for copper as the conductor, and 15 V for steel as the conductor. The copper was 0.1 mm diameter insulated, while the steel was 0.018 mm diameter non-insulated. A spandex fibre was measured using optical microscopy and found to have a diameter of 0.10 mm unloaded as seen in Figure 2-3. Assuming the spandex was uniformly circular in cross-section, a 40 ply sample pre-stretched to a force of 400 mN would be under a tensile stress of 1.27 MPa.

![Microphotograph of single spandex fibre.](image)

**Figure 2-3: Microphotograph of single spandex fibre.**

2.2.2.2 *Copper Wire Wrapped Polyurethane with Mechanised Manufacturing Method*

A mechanised fabrication method was attempted to improve repeatability of test results and the speed of sample manufacture. The method was similar to that detailed in (Byrnes et al
A mechanical motor attached to a small battery as a power source was used to ply strands of spandex and a strand of an electrical conductor around each other. One end was clamped and the other end was connected to the mechanical motor. The sample length was decreased by moving the mechanical motor closer to the end block as time went on to release the tension on the sample that developed with increasing twist. A ruler on the desk underneath the sample allowed the change in length to be measured, and a microscope sitting over the sample gave the option to view the sample in much better detail. The motor turned at approximately 36 RPM, and by recording the time taken to make the sample the number of twists could be estimated. Samples followed the length changes observed in Table 2-1.

Table 2-1: Inserted twist and change in sample length over time.

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>Estimated Turns</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>60</td>
<td>36</td>
<td>50</td>
</tr>
<tr>
<td>90</td>
<td>54</td>
<td>40</td>
</tr>
<tr>
<td>150</td>
<td>90</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 2-4 shows the basic set up for some of the equipment required. The motor and a sample are not pictured, however they can be observed in Figure 2-5.
After inserting the desired twist, sample ends were clamped to keep tension on the sample and not allow the sample to untwist. The tensioned sample was then connected to the force/distance transducer and clamped at the other end to maintain tension and pre-stretch. Each end of the conductor ran to a transformer which was used to cycle the electrical power and thus control the heating and cooling cycle of the sample. Figure 2-5 shows the equipment set up for testing samples made using the automated manufacturing method. Not photographed are the thermocouple and data logger.

Due to failure of the steel wire during testing of the manual manufactured samples, for the mechanised manufactured samples it was decided to use copper as the heating element in the sample. It was also hoped that the larger diameter copper wire would be more resistant to the buckling of samples that was experienced upon relaxation of the forces on the manually manufactured samples.
Figure 2-5: Schematic (i) and photograph (ii) of equipment set up for spandex and copper testing after automated manufacture including A) Thermouple, B) Sample, C) Motor, D) Force/distance transducer, E) Electrical connections, F) Data logger, and G) Power supply.
2.2.2.3 Carbon Fibre Wrapped Polyurethane

A new experimental method was designed due to the repeated failure of samples regardless of the method of manufacture. For simplicity a manual method of wrapping was once again used to manufacture the samples. Carbon fibre strands were used for the electrical conductor. The bending flexibility and elasticity of the carbon fibre would allow better contact with the spandex which would result in more even heat transfer and a reduction in hot spots and the associated sample failures. It would also greatly reduce the buckling of samples that occurred with any relaxation in pre-stretch. The carbon fibre use was a readily available fibre that was measured using optical microscopy and found to have a diameter of 1.5 mm, although the fibres appeared to be packed loosely with some air gaps between individual strands as seen in Figure 2-6.

![Figure 2-6: Microphotograph of carbon fibre.](image)

The samples were manufactured similar to those described in Section 2.2.2.1. Samples were made under load in increments of 50 g weight from 50 g to 300 g. Whilst the spandex was under load the carbon fibre was wrapped at a bias angle of approximately 60 ° from the spandex for all samples. The spandex was not twisted during the manufacturing process.

Once manufactured the sample was then placed in a newly designed test rig that used laser measurement of a moving platform on the rig to determine change in length of the sample as per Figure 2-7. Not photographed are the data logger and the power supply, however the electrical connections are visible. The sample was suspended vertically with a weight holder that was attached to a flat platform. The weights were used to control the force on the sample. The Micro-Epsilon optoNCDT laser measured the distance to the platform, and any change in this distance was due to sample contraction or elongation. Weights could be added...
to or removed from the weight holder to change the weight and thus change the force exerted on the sample, allowing the effects of these changes to be tested relatively quickly.

Figure 2-7: Schematic (i) and photograph (ii) of laser measurement rig including A) Power supply including electrical connections, B) Stand and clamp, C) Laser distance measurement device, D) Sample, E) Thermocouple, F) Weight platform guide, G) Data logger, H) Suspended weight platform.
2.3 Electrothermally Heated Overtwisted Nylon

2.3.1 Introduction
New results observed and published by a team of researchers including from the Intelligent Polymer Research Institute (Haines et al. 2014) showed promise with monofilament nylon, actuated in a similar method to the spandex samples described above. Positive results were also being seen with carbon fibre as the conductor to provide heat for the actuation to occur, similar to that described in Section 2.2.2.3. Preliminary tests were therefore planned using nylon as a thermally activated actuator and carbon fibre as the conductor to assess the feasibility of this system for further study.

2.3.2 Methodology
The initial test method was a modified version of the mechanised manufacturing method described in section 2.2.2.2. A mechanical motor attached to a small battery as a power source was used to twist a strand of 0.45 mm monofilament nylon and a strand of an electrical conductor around each other. The two strands were tied to a paper clip at either end. At the top the paper clip was connected via a hook to the motor. At the bottom a weight was hung from the second paper clip to keep the lengths of nylon and conductor straight and ensure the sample was as consistent as possible, refer Figure 2-8. The motor was turned on and the lower paperclip was loosely held flat to prevent it spinning, but to still allow it to rise up as the sample twisted and contracted. Once the desired amount of twists of nylon had been reached the motor was turned off. In this case the sample was twisted until it had completely coiled. The motor turned at approximately 36 RPM, and by recording the time taken to make the sample the number of twists could be calculated. The lower paperclip was then held to prevent the sample unravelling and a heat gun was used to anneal the monofilament nylon and heat-set the coiled shape.
The sample was then placed in a test rig that used laser measurement as described in Section 2.2.2.3. Initially the effect of power through the conductor on the contraction was investigated. Once this was carried out the optimum power was used for further testing with varying weights and thus force applied to the sample.

2.4 Furnace Heated Mandrel Wrapped Nylon

2.4.1 Introduction
In the previous results contractions of over 9 % were observed for coiled nylon heated to the maximum power available. The diameter of the nylon was kept constant for all tests. The contraction amount was found to depend on input electrical power and the amount of force...
applied to the actuator. Based on these successful results further work was planned to investigate several variables including amount of twist and forces present on the sample during manufacture.

Further work was planned to investigate the effect of the coil size, coil spacing and bias angle, as well as the initial nylon fibre diameter.

2.4.2 Method
A Dremel electrical drill holding a hook was used to manufacture samples. A length of the monofilament nylon to be actuated was tied off on a paper clip which was attached to the hook on the drill. A weight was then tied to the bottom of the length of nylon to create stress within the nylon as it was twisted. There was no conductor as part of this sample in contrast to previous samples. As the nylon was twisted the weights were attached to a flat piece of cardboard which was loosely held such that the weights could rise up as the nylon twisted and contracted, but would not allow the twists present in the nylon to unravel, refer Figure 2-9. The drill was turned on and the nylon was twisted until coils were just starting to form, then the drill was stopped, refer Figure 2-10. It was then clamped onto a metal ruler to stop the stresses being released (refer Figure 2-11) and placed into an oven at 60 °C for 1 hour to anneal the nylon. Cardboard was placed on the ends of the rule to prevent any damage to the nylon due to the sharp edges of the ruler.
Figure 2-9: Initial twisting of nylon (B) using a drill (A) and weights (C).
Figure 2-10: Nylon that has been twisted and is beginning to form coils.

Figure 2-11: Twisted nylon (A) held via clamp (B) on ruler (C) to hold stresses during annealing.
Once annealing was complete, the samples were cut to the desired length. Each sample was then attached to a length of 0.10 mm diameter insulated copper wire at each end to allow the sample to be held, and forces applied to the nylon. The copper wire was tied onto the end of the sample, and then a drop of UV curing resin (Dymax 3169-UR) was placed over the join before being cured with the Dymax BlueWave50 UV source. After the first annealing stage, the sample was placed on a bench to cool. Once cool, the clamps were released and it was then wrapped around a cylinder to form coils. In this case, a length of steel rod was used as a mandrel, giving an inner coil diameter of 2 mm. A second weight was hung from the bottom of the nylon parallel to the mandrel as it was wrapped to ensure tight wrapping of the fibre around the mandrel. Once coiled, the nylon was clamped at both ends and cut outside the clamps, and then annealed in an oven again at 60 °C for 1 hour. Samples had varied coil bias angles and as such different numbers of coils per length, or ‘coil pitch’ i.e. the distance between ‘peaks’ of a coil when viewed in two dimensions. The direction of the coiling of the samples was the same as the twist imparted into the nylon before the first annealing period. This is called homochiral coiling and is necessary to ensure contraction upon heating. If the coiling was carried out in the opposite direction it would be heterochiral coiling and would cause extension upon heating. Samples were attached to copper wire as per Figure 2-12 and then tested as described below.

![Completed sample prior to testing.](image)

Figure 2-12: Completed sample prior to testing.

When ready for testing, a sample was then placed inside a furnace and connected to a tensile machine on one side and a clamp on the other side via the lengths of copper wire. The furnace was a glass tube with nichrome heating wire coiled along the inside, refer Figure 2-13. Note that the thermocouple is incorrectly positioned in the photograph and should not be in contact with anything and positioned as central as possible. The Aurora Scientific 305B
tensile force and displacement measurement device was used to hold the sample directly in
the centre of the furnace. Electricity was cycled via a transformer through the heating wire in
the furnace to regulate the air temperature inside the tube furnace as necessary. A
thermocouple inside the furnace with the sample was used to accurately measure the
temperature. As the temperature inside the furnace and thus the temperature of the nylon
changed, the length of the sample changed and this was recorded by the tensile machine. The
force was kept constant. Refer to Figure 2-14 for a complete overview of the actuation
testing set up.

Figure 2-13: Schematic (i) and photograph (ii) of the furnace used for actuation testing
including A) Glass tube, B) Nichrome wire running to power supply, C) Stand and
clamp, D) Copper wire attached to the sample, E) Sample, and F) Thermocouple.
Figure 2-14: Schematic (i) and photograph (ii) of complete actuation testing set up including A) Power supply and electrical connections, B) Copper wire component of sample, C) Sample connection, D) Force/distance transducer, E) Thermocouple, F) Furnace, G) Stands and clamps, and H) Data logger.
The transformer was turned on and electrical current was passed through the heating wire until the temperature inside the furnace reached 80 °C. The power was then turned off and the furnace air cooled until the temperature was down to 30 °C. This point marked the end of one complete actuation cycle. This process was repeated for as many cycles as were desirable.

Set #1 samples were made using Jarvis Walker ‘Superior Quality Monofilament’ 25 lb (11.3 kg) line that was 0.45 mm diameter nylon-6. The weight used before the first anneal was 200 g, giving a stress of 12.3 MPa. For the second stage of sample manufacture the samples were split into two groups – Set #1A and Set #1B. Set #1A was made up of 4 samples that were coiled with 200 g weight on them again before the second anneal (12.3 MPa). Set #1B was made up of 3 samples that were made with 10 g weight when coiling the samples before the second anneal (0.6 MPa). The transformer was set up such that 14.5 V and 2.36 A passed through the nichrome wire in the furnace. This gives a power of 34.2 W and a final temperature of 80 °C was used. The tensile machine held the sample at a constant force of 300 mN (1.9 MPa).

Set #2 samples were also made from the same nylon-6 fishing line. The weight used before the first anneal was increased to 350 g (or a stress of 21.6 MPa). For the second stage of sample manufacture the samples were split into two groups – Set #2A and Set #2B. Set #2A was made up of 5 samples that were coiled with 200 g weight on them again before the second anneal. Set #2B was made up of 4 samples that were made with 10 g weight when coiling the samples before the second anneal. The transformer was again set up such that 14.5 V and 2.36 A passed through the nichrome wire in the furnace giving a power of 34.2 W, and a final temperature of 80 °C was used. The tensile machine held the sample at a constant force of 300 mN (1.9 MPa).

Set #3 samples were made using ‘Sport Fisher Monoline’ 50 lb (22.7 kg) line that was 0.70 mm diameter nylon-6. The larger diameter in comparison to Set 1 and Set 2 was due to a shortage of the 0.45 mm diameter monofilament nylon. The weight used before the first anneal was 100 g giving a stress of 2.5 MPa. For the second stage of sample manufacture the samples were split into two groups – Set #3A and Set #3B. Set #3A was made up of 4 samples that were coiled with 200 g weight on them before the second anneal (5.1 MPa). Set #3B was made up of 6 samples that were made with 10 g weight when coiling the samples...
before the second anneal (0.3 MPa). A different transformer was used during this set of testing. The transformer was set up such that 16.2 V and 2.30 A passed through the nichrome wire in the furnace. This gives a power of 37.3 W and a final temperature of 80 °C was used. The furnace also had an increased number of coils of nichrome wire on the inside. Given that the temperature was being monitored directly by a thermocouple, the change in furnace conditions was expected to lead to faster actuation, but not change the actuation results in any way. The tensile machine held the sample at a constant force of 300 mN (0.8 MPa).
3 Chapter 3 Results and Discussion

3.1 Introduction
The results for the testing of electrothermally heated coiled polyurethane, electrothermally heated overtwisted nylon, and furnace heated mandrel wrapped nylon can be found below, with further discussion of the results.

3.2 Electrothermally Heated Coiled Polyurethane

3.2.1 Results

3.2.1.1 Polyurethane Plied with Metal Wires
Both the manual and mechanised twisting methods created reasonable contact between the polyurethane and the electrical wire conductor. The manufacture of samples also appeared to be repeatable with even spacing between the coils of polyurethane.

The combination of the highly elastic polyurethane with the metal wires created problems that resulted in sample failure. Figure 3-1 shows a sample made of 0.018 mm diameter non-insulated steel wire with 4 ply polyurethane. The force on the sample which creates the pre-stretch had been released after twisting with the metal wire causing the sample to buckle and untwist. Due to the steel wire being strained less than the coiled spandex, when the tension on the sample was released and the polyurethane was able to contract, severe buckling of the sample occurred. When tension was reapplied the sample did not tend to return to its previous shape, with the polyurethane ‘clumping’ in some regions and leaving other parts of the sample unconnected to the steel wire. This issue required samples to be tested immediately after being manufactured, or to be stored whilst stretched which presented further difficulties.
Figure 3-1: Sample made of spandex (A) and steel wire (B) demonstrating buckling after tension has been released.

Another limitation was mechanical failure of either the metal wire or the polyurethane fibres. All samples made using the steel wire resulted in failure within minutes of electrothermal heating due to steel wire fracturing. The steel had a potential difference applied of 15 V to heat the stretched polyurethane with the goal of causing it to contract. The potential difference appears to have been too large and generated too much heat causing localised failure of the steel in both samples. It is unknown whether the failure was due to a combination of the temperature and the tension on the steel, or the temperature alone.

In the case of copper wire plied with the polyurethane, the polyurethane fibres failed. Three samples were manufactured from 0.1 mm diameter insulated copper and polyurethane. The copper had a potential difference of 2 V applied to heat the polyurethane. In all three of these samples one or more of the threads of polyurethane failed. It appears that the temperature of the copper was too high for the polyurethane which resulted in the failure.
3.2.1.2 Carbon Fibre Wrapped Polyurethane
Samples were prepared by twisting 4 plies of 0.1 mm diameter polyurethane with 1.5 mm diameter carbon fibre and with varying tension applied during twist insertion. Sample 1 was manufactured with 50 g weight (15.6 MPa), sample 2 was manufactured with 100 g weight (31.2 MPa) and so on until sample 6 which was manufactured with 300 g weight (93.7 MPa). Testing of each sample at varying isotonic loads starting with the load applied during twist insertion and increasing in 50 g increments to a maximum load of 300 g was applied. At each constant load, the sample was electrically heated and then cooled to observe any length change with the Micro-Epsilon optoNCDT laser. Several heat/cool cycles were performed at each load to evaluate the consistency of the actuation. Length measurements used were the single maximum and minimum of each actuation cycle. Further testing was conducted at decreasing increments of applied load from 300 g to the load applied during twist insertion.

Figure 3-2 shows a full actuation testing protocol of a sample that is representative of all samples. The applied load was changed at the points indicated in the chart. Adjustments made to the laser distance meter after each load adjustment meant that the load-induced length changes were not accurately tracked. However, the length changes caused by heating and cooling at constant loads were measured without any adjustments to the laser meter and can be considered to be accurate. Temperature is varied and results in sample length changes. The various loads applied alter the size of the change in sample length with temperature.

![Figure 3-2: Graph of complete actuation cycle for sample manufactured with 50 g of weight. The sample had an unloaded length of 80 mm.](image)
An increase in sample temperature results in a decrease in the sample length, as shown in Figure 3-3 for the actuation cycle for a sample manufactured with 50 g of weight during the period 3000 – 4000 seconds when it was being tested under 150 g weight. Figure 3-3 also displays creep in the sample as the length at room temperature steadily increases over multiple heating and cooling cycles. This creep was observed in all samples for the first few cycles when subjected to a larger load. After the first few cycles of heating to ~80 °C and cooling to room temperature the length at room temperature appeared to stabilise.

Figure 3-3: Graph of actuation cycle for sample manufactured with 50 g weight being actuated under 150 g of weight from 3000 – 4000 seconds. The sample had an unloaded length of 80 mm at room temperature.

The sample contraction was calculated by taking the difference of the room temperature length and the high temperature length. The lengths used tended to be immediately before heating began and immediately before cooling began, as these were the most stable and often at the end of an extended plateau. The contraction was calculated as a percentage of the unloaded initial length at room temperature.

The repeatability of the contraction stroke was evaluated during multiple heat/cool cycles, as per Table 3-1. These tests were carried out with 250 g of weight on the sample manufactured with 50 g of weight. The contraction is calculated from the unloaded length of the sample which was 80 mm for this sample. The sample saw an increase then decrease in contraction amplitudes over multiple heating and cooling cycles whilst undergoing some creep. The standard deviation of the results is 13 % suggesting the results are reasonably repeatable.
Table 3-1: Repeatability of contraction of sample manufactured with 50 g of weight being actuated under 250 g weight.

<table>
<thead>
<tr>
<th>Initial Loaded Length at 30 °C (mm)</th>
<th>Final Loaded Length at 80 °C (mm)</th>
<th>Contraction (mm)</th>
<th>Contraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>89.41</td>
<td>88.96</td>
<td>0.45</td>
<td>0.56</td>
</tr>
<tr>
<td>90.13</td>
<td>89.63</td>
<td>0.5</td>
<td>0.63</td>
</tr>
<tr>
<td>90.89</td>
<td>90.34</td>
<td>0.55</td>
<td>0.69</td>
</tr>
<tr>
<td>91.18</td>
<td>90.62</td>
<td>0.56</td>
<td>0.70</td>
</tr>
<tr>
<td>91.95</td>
<td>91.35</td>
<td>0.6</td>
<td>0.75</td>
</tr>
<tr>
<td>92.46</td>
<td>92.07</td>
<td>0.39</td>
<td>0.49</td>
</tr>
<tr>
<td>93.14</td>
<td>92.71</td>
<td>0.43</td>
<td>0.54</td>
</tr>
<tr>
<td>95.26</td>
<td>94.78</td>
<td>0.48</td>
<td>0.60</td>
</tr>
<tr>
<td>95.49</td>
<td>95.03</td>
<td>0.46</td>
<td>0.58</td>
</tr>
<tr>
<td>95.64</td>
<td>95.21</td>
<td>0.43</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Ave: 0.61
Std Dev: 0.08
Std Dev %: 13%

Testing to determine any relation between temperature change and contraction was also carried out on sample 1 (prepared with 50 g weight) as per Figure 3-4. The sample temperature was controlled by adjusting the input electrical power, as shown in Figure 3-5. This testing was carried out with 150 g of weight on the sample. It can be seen that the contraction strain increases in magnitude as the temperature change increased from 10 °C to 35 °C and after approximately 35 °C temperature change the contraction appears to reach a maximum and plateau. The maximum achievable temperature change was approximately 55 °C (sample temperature of 80 °C) due to failures at localised hot spots in previous spandex based samples when heated with higher input electrical power. The lowest temperature was kept at 30 °C due to the long time needed in getting the samples to a room temperature ~ 25 °C). The speed of actuation took 47 seconds to achieve a sample temperature of 80 °C. Within the first 10 seconds of heating the sample increased in temperature 20 °C and 84 % of the total contraction had already occurred. The rate of contraction in this period was constant.

A sample with 150 g weight during manufacture was also tested for contraction at different temperature changes ($\delta T$) and with 150 g of weight on the sample (Figure 3-5). This sample also appears to reach a maximum contraction with increasing temperature (Figure 3-4),
however the relation appears to show a decrease in contraction at $\delta T = 61$ °C. This temperature change was larger than aimed for due to the speed of temperature increase being faster than anticipated. The contraction for the two samples shown in Figure 3-4 can be directly compared as these results are both from testing with 150 g of weight on the sample. It can be seen that the sample that had 150 g of weight during manufacture has higher contractions across all temperature changes than the sample that had 50 g of weight during manufacture.

![Figure 3-4: Graph of sample length contraction versus temperature change at 150 g of weight for samples manufactured with 50 g and 150 g weight.](image-url)
Figure 3-5: Graph of temperature change versus power measured during testing of sample manufactured with 150 g of weight.

Figure 3-6 shows an example of results obtained from a complete testing cycle and displayed as contraction strain versus weight applied during testing. The sample was manufactured with 200 g weight. As with all samples, weight was added in increments of 50 g from the manufacture weight up to 300 g. This is defined as the series ‘Increasing Weight’. After this series was complete, weight was removed from the sample 50 g at a time until there was only 50 g on the sample. This is defined as the series ‘Decreasing Weight’. The weight was then increased again in 50 g increments up to 300 g weight. This is defined as ‘Increasing Weight_2’. It can be seen that there is a tendency for the contraction to decrease slightly with each cycle as the ‘Decreasing Weight’ series has smaller contractions than the ‘Increasing Weight’ series, and the ‘Increasing Weight_2’ series has smaller contractions than the ‘Decreasing Weight’ series. This effect was present to varying degrees across all of the samples, with some samples only exhibiting minor or even negligible decreases in contraction size.
Figure 3-6: Contraction versus weight for sample manufactured with 200 g of weight. Data split into three distinct phases.

Figure 3-7: Contraction versus weight on sample for samples heated to 80 °C and made with a range of weights during manufacture.
It can be seen from Figure 3-7 that all samples showed a decrease in contraction strains when samples were heated to 80 °C and as the weight applied during actuation testing increased. It can also be seen that the weight applied during sample manufacture had a strong effect on the contraction strain. Higher contraction strains were observed for samples that were more stretched during twist insertion than those that were stretched less during the manufacturing process. This effect was most pronounced when the different samples were tested at low applied loads. At the highest loads applied during actuation testing, the effect of the weight applied during twisting was small as all samples showed very similar contraction strains. The largest contraction achieved was 10.2 %.

Samples manufactured at 150 g and 200 g both failed during testing. The samples both appeared to fail due to fracture of the spandex, most likely due to overheating from a localised hot spot in the sample.

### 3.2.2 Discussion

Three different combinations of fibre / wire conductor were twisted and plied with spandex polyurethane fibres and tested by stretching and electrically heating. Several samples failed during testing. It appears that localised heating of the polyurethane in contact with the metal wire or carbon fibre caused the failures, sometimes after repeated cycles. Failure either occurred in the spandex or in the wire. These failures of the samples could most likely be prevented by decreasing the potential difference across the conductor that was acting as the heat source for the spandex. Further work should be carried out to gain understanding of the failure mechanisms which could assist in achieving greater contractions of samples.

Most successful results were obtained using carbon fibre as conductor. In Table 3-1 it was shown that the contraction results for the carbon fibre and polyurethane samples were repeatable within a sample with 10 cycles giving a standard deviation of 13 % in the contraction strain. The variation between individual cycles may be due to slight differences between the maximum temperatures to which the samples were exposed. Errors in temperature measurement due to thermocouple movement, especially during sample contraction and expansion, could have resulted in some measurements being slightly closer to or even on the carbon fibre which would result in quicker maximum temperatures being reached. In this situation the whole of the spandex may not completely be at temperature and would result in smaller contractions being recorded. If the thermocouple was not in complete contact with the sample then the thermocouple may not have heated up as quickly which
would result in the sample being hotter than the thermocouple and higher contractions occurring due to the larger temperature difference on the sample.

Figure 3-4 shows that as temperature increases the contraction of the sample increases. Figure 3-5 shows that as the power through the conductive component of the sample increases, the temperature increases linearly. Therefore it can be concluded that as the input electrical power increases the contraction of the sample will increase. Figure 3-4 also shows that there is a critical temperature change between 35 and 60 °C above which the contraction plateaus or even decreases slightly. As such the polyurethane should not be heated to a differential greater than 35 °C as it appears to achieve nothing further and only increases the energy and time requirements for a complete actuation cycle, as well as increases the potential for sample failure due to localised hot spots. The relationship between temperature or power and sample contraction is well documented as per Equation (1.12), Byrnes et al and Foroughi et al. A possible explanation for the decrease in contraction with further increase in temperature change for the sample manufactured with 150 g of weight is that the quick rate of temperature change that was only observed for this temperature change value due to higher power requirements may have resulted in the spandex fibres not being heated completely through the cross section before the thermocouple reached the maximum temperature and the heating was turned off.

Figure 3-7 and Figure 3-6 show that as the applied load on the sample increases the contraction strain will decrease. In addition, Figure 3-7 shows that for the same amount of weight on each sample, the sample with the highest weight on it when it was manufactured will have the highest contraction.

One possible explanation for the effect of load during testing and the load applied during manufacture on the contraction strain relates to the temperature of the spandex during electrical heating through the carbon fibre. In particular, the heat transfer within the sample from the carbon fibre to the bulk of the polyurethane may be affected by the applied stresses. Given a non-equilibrium situation where areas closer to the carbon fibre heat up significantly faster than regions away from the carbon fibre, a smaller pitch of carbon fibre wrapped around the polyurethane fibres should result in more uniform heating of the polyurethane and contributes to a larger contraction strain. All samples were made with the same pitch of wrapped carbon fibre, however the additional stretching prior to actuation testing meant that
the carbon fibre strands will be further apart at larger test weights. In addition, when samples were tested at smaller weights than used during manufacture the carbon fibre wrap became loose with less direct contact with the polyurethane fibres. Both of these situations may result in reduced heat transfer from the carbon fibre to the polyurethane and thus reduced temperature change across the sample as a whole.

An infrared camera was used to view the heat distribution throughout the samples manufactured with 50 g, 150 g and 300 g of weight when each were actuated with 50 g, 150 g and 300 g of weight. Figure 3-8 shows the thermal and optical images of samples manufactured with 50 g, 150 g and 300 g weight when actuated with 50 g of weight and Figure 3-9 shows the equivalent for samples actuated with 300 g of weight. The spandex seems to be evenly heated in most samples. There are minor differences in the temperature profile along the sample length with the carbon fibre hotter than adjacent spandex, as illustrated in Figure 3-10. The biggest temperature variation was observed in the sample made with 50 g weight and actuated at this same weight. It is possible that the carbon fibre is not in such close contact with the spandex fibres. In general, however, the thermal imaging results suggest that temperature differences are not the root cause of the difference in actuation performance caused by increasing the load applied during the actuation test.
Figure 3-8: Optical and thermal images (°C) of samples manufactured with 50 g, 150 g and 300 g weight respectively when actuated with 50 g of weight.

Figure 3-9: Optical and thermal images (°C) of samples manufactured with 50 g, 150 g and 300 g weight respectively when actuated with 300 g of weight.
The optical images shown in Figure 3-8 and Figure 3-9 clearly show different tensions in the carbon fibre across the different samples. Releasing tension in the spandex between manufacture and testing causes the carbon fibre pitch to decrease and in many areas lose contact with the spandex as per Figure 3-10.

Figure 3-10: Thermal image (°C) of sample manufactured with 150 g of weight and actuated with 50 g of weight. A) shows the spandex fibres, B) shows the carbon fibre.

Samples that are more stretched before heating show carbon fibre wrapped at a lower bias angle (with respect to the long axis of the sample). All samples seem to generate small contraction strains when the bias angle of the carbon fibre is close to the axial direction of the spandex and perform better when the bias angle is further from the axial direction. One
reason for this is contribution of stiffness from the carbon fibre which will be larger when the carbon fibre is in the shape of a small diameter coil such as when fibre runs close to the axial direction. The stiffness is lower when the carbon fibre forms larger coils with higher bias angles such as after manufacturing a sample at 300 g then reducing the weight to 50 g.

The stiffness was calculated using the measured difference between the loaded length and the room temperature unloaded length. Stiffness was calculated for the samples manufactured with 50 g and 300 g of weight for all actuation weights, refer Figure 3-11.

![Figure 3-11: Stiffness of the samples manufactured with 50 g and 300 g weight calculated for all actuation weights at room temperature and at 80 °C. Both samples had an unloaded length of 85 mm.](image)

Figure 3-11 shows that the sample manufactured with 300 g of weight has significantly lower stiffness compared to the sample manufactured with 50 g of weight across all actuation weights. Given that the spandex should have been identical in each sample this suggests that the wrapped carbon fibre is indeed causing a difference between samples manufactured with different weights. The actuation of the spandex occurs by contraction of both the spandex and the carbon fibre coil wrapped around the spandex. If the carbon fibre coil is stiffer, then the contraction of the spandex is reduced. Samples manufactured with a higher weight when the carbon fibre coil is formed tend to have a lower stiffness and, therefore, allow higher actuation contraction strains.
It is suggested that for maximum contraction, samples should be manufactured with as high as weight as practical regardless of what forces the sample would be subjected to in service. Ideally the service forces would be as small as practical and the temperature difference 35 °C to achieve the largest possible contractions.

3.3  Electrothermally Heated Overtwisted Nylon

3.3.1  Results
The initial experiments investigated the effect of electrical heating power and applied external load on the actuation of the coiled nylon fibres made by over-twisting. A sample was manufactured from 83 mm long, 0.45 mm diameter nylon-6 with a 50 g weight (3.08 MPa) used during twisting and coiling. The first coil in the sample occurred at approximately 470 turns/m, with the sample being entirely coiled at ~1080 turns/m. The sample was annealed for 20 seconds with a heat gun. Upon completion the sample length with no weight attached was 14 mm in length. The sample was then tested with varying power through the conductor and varying weights on the sample. Results are summarised in Table 3-2 and described below.

<table>
<thead>
<tr>
<th>Transformer Voltage</th>
<th>Current</th>
<th>Power</th>
<th>Contraction mm</th>
<th>%</th>
<th>Weight (g)</th>
<th>Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.83</td>
<td>0.33</td>
<td>0</td>
<td>0.0%</td>
<td>50</td>
<td>3.08</td>
</tr>
<tr>
<td>1.1</td>
<td>2.52</td>
<td>2.77</td>
<td>0.3</td>
<td>2.1%</td>
<td>50</td>
<td>3.08</td>
</tr>
<tr>
<td>1.36</td>
<td>3.14</td>
<td>4.27</td>
<td>0.75</td>
<td>5.4%</td>
<td>50</td>
<td>3.08</td>
</tr>
<tr>
<td>1.36</td>
<td>3.14</td>
<td>4.27</td>
<td>1.25</td>
<td>8.9%</td>
<td>100</td>
<td>6.16</td>
</tr>
<tr>
<td>1.36</td>
<td>3.14</td>
<td>4.27</td>
<td>1.2</td>
<td>8.6%</td>
<td>150</td>
<td>9.25</td>
</tr>
<tr>
<td>1.36</td>
<td>3.14</td>
<td>4.27</td>
<td>1.1</td>
<td>7.9%</td>
<td>200</td>
<td>12.34</td>
</tr>
<tr>
<td>1.36</td>
<td>3.14</td>
<td>4.27</td>
<td>1.05</td>
<td>7.5%</td>
<td>250</td>
<td>15.42</td>
</tr>
<tr>
<td>1.36</td>
<td>3.14</td>
<td>4.27</td>
<td>1.35</td>
<td>9.6%</td>
<td>100</td>
<td>6.17</td>
</tr>
<tr>
<td>1.36</td>
<td>3.14</td>
<td>4.27</td>
<td>0.75</td>
<td>5.4%</td>
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The results of varying the power and the effect on sample contraction can be seen graphically in Figure 3-12. The optimum power through the conductor can be seen to be as high as possible as the contraction appears to increase linearly with increasing power. The maximum
outputs the transformer was capable of was 1.36 V and 3.14 A, giving a maximum input electrical power of 4.27 W.

![Graph of contraction strain measured at a constant load of 3.08 MPa and with various electrical power applied to the conductor.]

The results of varying the weight and thus the force on the sample during actuation can be seen graphically in Figure 3-13. The electrical power was held constant at the maximum of 4.27 W for all tests. The magnitude of the contraction first increases and then decreases as the applied force increases. The maximum contraction occurs somewhere between the 50 g and 100 g weights. After testing the sample length at zero load had increased to 20 mm from 14 mm. This length increase is most likely due to creep and relaxation of the nylon during testing. This creep corresponds to a 43 % increase in length. The contraction values in Figure 3-12, Figure 3-13 and Table 3-2 were calculated using the initial unloaded length before testing of 14 mm.
Figure 3-13: Graph of contraction versus weight on sample.

When actuating carbon fibre and nylon it took 72 seconds for sample length to stop contracting and remain constant, with 92% of the total contraction occurring within 26 seconds. The rate of contraction in the first 26 seconds is constant before tapering off significantly.

3.3.2 Discussion
Problems with manufacturing samples were noted. While the motor made the twisting process faster, the samples falling off the hook on the motor introduced some inconsistencies in spacing and bias angle throughout the length of the sample as some loss of twist occurred. There were also significant inconsistencies with the annealing of samples, as the distance of the heat gun from the sample was not constant as the gun was held by hand. Any change in angle of the heat gun would also affect the temperature the sample reached during annealing.

Figure 3-12 shows that the largest contraction strain is achieved with maximum power possible from the available power supply. The contraction appears to increase linearly with increasing power, however it is unclear how much further the power could be increased before this linear relationship ends, such as due to degradation, melting or mechanical failure of the sample. As observed in Section 3.2, both failure of the polymer and the electrical conductor is possible.
The results appear to agree generally with past results such as those seen previously (Haines 2014, Harding 2012). The initial increase in contraction strain has been reported in these earlier studies. Coils coming into contact upon contracting has been suggested as the limiting factor for contraction in the lower weight range. Increasing the weight would force the coils further apart, and allow more contraction to occur. Haines and co-workers have also reported a decrease in contraction strain at higher applied loads, at least for coils made by over-twisting with low tension. This decline is likely due to a change in coil stiffness during the contraction.

It is highly likely that the creep in the sample affected the contraction values. The unloaded ‘true length’ of the sample for each test is not known, although it was noted that after all testing was complete, the sample had elongated by 43 %. The values in Table 3-2, Figure 3-12 and Figure 3-13 all assume an initial sample length of 14 mm for every test. Making an arbitrary linear adjustment to the initial sample length before each test to account for the creep gives the results shown in Figure 3-14. The contraction values are changed from the data given in Figure 3-13, but the overall trend in the results is the same. Due to uncertainty introduced in these results from the sample creep it was determined that samples should be measured before and after every test to ensure there are no significant changes occurring, especially for tests where the same sample is used multiple times.

Figure 3-14: Modified graph of contraction versus weight on sample.
A further interest is to compare the results with the previously published work by Haines et al. These researchers reported a maximum contraction strain in over-twisted nylon of 22%. This contraction is much larger than measured in the present study, however, the temperature of the electrically heated samples is unknown so direct comparisons are difficult. In terms of sample manufacture, it was reported by Haines et al that the twist insertion per length of fibre to initiate and complete coiling was inversely proportional to the precursor fibre diameter. The relation between twist insertion per length of fibre to completely coil the sample and the precursor fibre diameter is shown in Figure 3-15 for both Haines et al and the sample prepared in this study (Sample 2). It can be seen that the Sample 2 result fits reasonably well with the trends identified in the previously published results.

![Figure 3-15: Twist insertion to complete coiling versus fibre diameter: data previously published (Haines 2014) is compared with Sample 2.](image)

3.4 Furnace Heated Mandrel Wrapped Nylon

3.4.1 Results

3.4.1.1 Validation Experiments

Figure 3-16 shows a full actuation cycle of a sample that is representative of all samples. This particular sample was arbitrarily chosen, and was sample 1.5 from Set #1B.
Figure 3-16: Temperature and displacement over time.

The increase in displacement correlates to a decrease in the length of the sample, that is, a contraction. As can be seen, the contraction peaks are directly related to the temperature peaks. This is particularly evident in the two lower temperature cycles that were carried out between 3000 and 5000 seconds. It can also be seen that the first actuation cycle correlates to a relatively large change in displacement. Due to the large change in displacement of the first actuation cycle, many of the graphs are scaled such that the focus is on the following actuation cycles and may exclude some or all of the first cycle. An example of this can be seen below in Figure 3-17 which is the same data set as Figure 3-16 that has been scaled such that the relevant data can be seen more easily.
As can be seen in Figure 3-17, after the first cycle the displacements correlate closely with the temperature changes, cycling back and forth to approximately the same points. This drastic change in displacement on the first cycle is believed to be due to sample relaxation upon exposure to higher temperatures. As such, the first actuation cycle was ignored when considering the contraction of any particular sample. The remaining actuation cycles were averaged and this value was used as the actuation value in further analysis. The consistency of the strain of this sample as the temperature varied also confirms that after the first two cycles the actuation is constant, assuming the same temperature range. Given this, only three cycles would be necessary in future experiments. The first cycle allowed for sample relaxation and creep, while the second and third cycles were the ‘true’ actuation results, and assuming the results were similar, were valid.

Another trend that can be observed in Figure 3-17 is the effect of the temperature change on the sample contraction. This effect can be seen graphically in Figure 3-18. A linear relationship is evident, demonstrating that the temperature change experienced by the sample is directly related to the size of the contraction. The five cycles that experienced a 50 °C temperature change resulted in displacements as per Table 3-3. The standard deviation of the 5 cycles was found to be 8.1 %.
Figure 3-18: Sample displacement versus change in temperature experienced.

Table 3-3: Repeatability of contraction with sample 1.5 from Set #1B.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Contraction (mm)</th>
</tr>
</thead>
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<tr>
<td>1</td>
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<tr>
<td>2</td>
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</tr>
<tr>
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<td>4</td>
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<td>Average</td>
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</tr>
<tr>
<td>Standard Deviation (%)</td>
<td>8.1%</td>
</tr>
</tbody>
</table>

3.4.1.2 Further Testing
Once initial testing showed repeatability, more extensive testing took place. These tests covered variables both within sample sets, such as sample length and coil pitch, and variables between sample sets such as weight applied during manufacture, and nylon diameter. The complete set of results including those from Section 3.4.1.1 can be seen in Table 3-4.
Table 3-4: Complete set of testing variables and results for section 3.4.

<table>
<thead>
<tr>
<th>Set</th>
<th>ID</th>
<th>$\phi_N$ (mm)</th>
<th>1st Weight (g)</th>
<th>2nd Weight (g)</th>
<th>$\delta T$ (°C)</th>
<th>$\Delta L$ (mm)</th>
<th>$l_0$ (mm)</th>
<th>$l_S$ (mm)</th>
<th>$n$</th>
<th>$\lambda$ (mm)</th>
<th>$\Delta l_%$ (%$l_0$)</th>
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<td>1</td>
<td>14.0</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Where:

- Set refers to the group of samples manufactured together
- ID is the individual sample’s reference number
- $\phi_N$ is the diameter of the nylon
- 1st weight is the mass applied during the first stage of nylon twisting
- 2nd weight is the mass applied during mandrel wrapping
$\Delta T$ is the temperature range the sample is exposed to

$\Delta L$ is the change in length of the sample caused by temperature changes

$l_0$ is the initial coiled sample length

$l_s$ is the calculated initial twisted fibre length used to make the coils, refer equation (1.27)

$n$ is the number of coils within the sample length

$\lambda$ is the ‘coil pitch’ of the samples, i.e. the distance between coils

$\Delta l_{00}$ is the change in length as a percentage of the initial length

$\Delta l_{\lambda}$ is the change in length as a percentage of the coil pitch

Initial analysis was carried out comparing the three sample sets as a whole and not considering the separate ‘A’ and ‘B’ groups within each set.

Figure 3-19: Contraction as a percentage of the initial sample length vs coil pitch.

Figure 3-19 shows the relationship between the coil pitch and the contraction expressed as a percentage of the initial sample length. The data is separated into the three sets of samples. All three data sets show a trend of increasing contraction with decreasing coil pitch i.e. more coils per length of nylon. All data sets contain some scatter, but Set 1 in particular seems
particularly scattered. All three data sets sharply increase in contraction once coil pitch is
less than approximately 10 mm. Above 10 mm the contraction strains are less dependent on
coil pitch. Comparing the data sets, it can be seen that Set 3 has the lowest contraction above
10 mm, with the exception of two data points from Set 1 which appear to be data scatter.
Comparing between Set 1 and Set 2 above 10 mm coil pitch is difficult due to the scatter
present in Set 1.

Figure 3-20: Contraction as a percentage of the initial sample length vs initial sample
length.

Figure 3-20 shows the relationship between the initial sample length before testing and the
contraction expressed as a percentage of the initial sample length. The data is separated into
the three sets of data. All three data sets show a trend of increasing contraction with
decreasing initial sample length. Once again the scatter in Set 1 is evident, as well as Set 2
and Set 3 to a lesser degree. The scatter in Set 1 appears less obvious in comparison to
Figure 3-19. The relationships all appear relatively linear, although there is the possibility of
a plateau of the contraction occurring for samples initially 15 mm in length or longer.
Comparing between the data sets once again Set 3 has the lowest contraction with the
exception of a few data points from Set 1 that are expected to be outliers. Set 1 potentially
has higher contractions than Set 2, although it is difficult to be sure due to the scatter present
in the Set 1 data set.
3.4.2 Discussion
The results in Figure 3-18 agree closely with those seen in Figure 3-5 regarding the correlation between temperature and power, and Figure 3-12 regarding the correlation between power and contraction. The general observation of higher contraction strains when a higher power is applied to the conductors is due to the higher temperature that the sample experiences. The results of Figure 3-18 using furnace heating confirm the strong correlation between temperature and actuation. Figure 3-18 in particular demonstrates that to maximise sample contraction, the temperature change of the sample should be maximised to the limit of any sample degradation.

The value used for the displacement that occurred with a 50 °C temperature change in Figure 3-18 was the average of the five cycles, 0.418 mm. The contraction derived from temperature change was shown to be reasonably repeatable, with a standard deviation of 8.1%. This suggests that within any individual sample testing regime, the contraction values observed are valid.

Some general trends were observed in the data. Firstly, it is seen that in general the contraction decreased in the order of Set 1 > Set 2 > Set 3 for samples made to the same length. Secondly, the length of the coiled sample had a strong influence on the contraction for all three sets of samples.

The only difference between Set 1 and Set 2 is the initial weight used when manufacturing samples before the first stage of annealing. Set 1 used 200 g for the initial weight, whilst Set 2 used 350 g for the initial weight. Set 3 used 100 g but cannot be directly compared to Set 1 and Set 2 due to being made from a different diameter size of nylon due to a shortage of 0.45 mm diameter monofilament nylon. The stress applied during initial twisting of the fibres is given in Table 3-5.

<table>
<thead>
<tr>
<th>Set No.</th>
<th>Nylon Diameter (mm)</th>
<th>Area (mm²)</th>
<th>Initial Weight (g)</th>
<th>Stress (MPa)</th>
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</thead>
<tbody>
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<td>1</td>
<td>0.45</td>
<td>0.159</td>
<td>200</td>
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<tr>
<td>2</td>
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<td>3</td>
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</tr>
</tbody>
</table>

Table 3-5: Nylon diameter, initial weight and stress for the three sets of samples.
Equations (1.26) and (1.29) state that contraction of samples is dependent on the untwist of the fibre that occurs on heating. Aziz et al. (2016) have shown that the torsional actuation (untwist) occurring when twisted nylon fibres are heated is given by:

$$\Delta T = T_o \left(\frac{d_o}{d_F} - 1\right)$$  \hspace{1cm} (3.1)$$

Where $T_o$ is the initially inserted twist per fibre length and $d_o$ and $d_F$ are the fibre diameters before and after heating.

All samples were prepared by first twisting the fibres to the onset of coiling. The critical torque to initiate coiling ($\tau_c$) is given by Ross (1977) as:

$$\tau_c = \frac{2\pi E F_T d^4}{64 G^2}$$  \hspace{1cm} (3.2)$$

where $E$ is the fibre Young’s modulus and $F_T$ is the tensile force applied during twist insertion. The critical twist to initiate coiling is then:

$$T_c = \sqrt{\frac{32 E F}{\pi G^2 d^4}}$$  \hspace{1cm} (3.3)$$

Where $G$ is the fibre shear modulus. The critical twist inserted will then depend upon the tensile force applied and fibre diameter. From the data given in Table 3-5, the fibre untwist expected during heating of the coils would be expected to increase in the order Set 2 > Set 1 > Set 3. The data shown in Figure 3-20 suggests that the general order is, in fact, Set 1 > Set 2 > Set 3.

The strong relationship with the contraction as a percentage of the initial coiled length can be evaluated by calculating the fibre untwist occurring during coil heating and using equation 1.26. The calculated fibre untwist is shown in Figure 3-21 as a function of the initial coiled length. For all three sets of samples, the calculated fibre untwist decreases strongly as the initial coil lengthed increases. Since fibre untwist should be determined only by the twist inserted into the fibre before coil formation, it is expected that the fibre untwist would be independent of initial coiled length. As such these results are unexplainable based on the
current literature and understanding. It is possible these samples may fall outside of the coil contraction regime wherein untwist remains constant, or more likely the variation of twist with sample length is a result of variation in manufacture of samples such as annealing process.

![Figure 3-21: Calculated fibre untwist vs initial sample length.](image)

There are many possible sources of error in these experiments which could account for the scatter observed in the data and the unexpectedly strong influence of coil length on the coil contraction. The sample length was measured from the edge of the UV cured resin that was used to attach the copper wire to the nylon sample. Due to the small sample lengths, an error in the measurement of 1 mm is equivalent to 6.2 % of the sample length, using the average of all sample lengths, 16.1 mm, to illustrate the point. There is also the question of whether the measured sample length is the same as the ‘effective’ sample length, that is, does the strength and stiffness of the resin restrict contraction of the sample near the ends of the measured length resulting in a decreased sample length. Another source of error is the determination of the fibre length in the coils. This length was not directly measured before coil formation and instead was calculated from the coil length and coil diameter. It was assumed that the coil diameter was the same for all samples, since all samples were prepared by wrapping around the same mandrel. However, it is possible that the coil diameter may have changed after the
sample was removed from the mandrel. One other possibility is that UV exposure during resin curing was variable and may have had an affect on the nylon mechanical properties to varying degrees.

Another source of error is in the temperature measurement. Although a thermocouple was used with an accuracy of 0.1 °C, the location of the tip of the thermocouple may have resulted in errors in the temperature results. Given the ‘furnace’ was small, the sample was installed first, then the thermocouple was installed. The thermocouple had to sit in a location where it would not interfere with the sample, but also could not touch the nichrome wire that was acting as the heat source. Although best attempts were made at replicating the position of the thermocouple in every experiment, it is expected some deviation occurred. If the thermocouple was closer to the heat source in some experiments the thermocouple would heat up faster and the power to the heat source could have been switched off before the sample itself had reached the aim temperature, resulting in a false reading of a lower contraction. Conversely, if the thermocouple was further away from the heat source in some experiments the thermocouple would heat up more slowly and the power to the heat source could have been switched off after the temperature of the sample had already reached and exceeded the relevant aim temperature. As a result the sample experiences a higher temperature range resulting in false readings of larger contractions than expected. In a similar way, the sample placement is also a source of error. If the sample was closer to the heat source then the thermocouple, it would be experiencing higher temperatures then recorded which would result in larger contractions than expected. Conversely, if the sample was further away from the heat source than the thermocouple then the power to the heat source could have been switched off before the sample had reached the necessary temperature which would result in smaller than expected contractions due to the decrease in temperature range the sample is exposed to. Every sample was aligned in the centre of the furnace and directly in between the heating elements but it is highly likely some differences occurred in sample placement from sample to sample.

The above are all sources of error during testing. There are also several sources of error that could have occurred during the manufacture of the samples. During the initial twisting of the monofilament nylon, the process was stopped when the sample began to form coils. The number of twists per length of nylon was difficult to measure due to sample movement and the rapid speed at which the Dremel twisted the nylon. As the sample was twisted the weight
on the bottom steadily rose. It was kept from relaxing the increasing stress by a piece of cardboard which sat flat against a board and allowed the weight to rise but not untwist. It is possible that this caused some resistance and that the force calculated from the weights used are not representative of the actual forces on the sample.

Another source of error was after the initial annealing stage when the second set of weights was attached and samples were coiled. There was difficulty in maintaining the weight whilst coiling the samples with the desired coil bias angle, or the gap between the coils. As such the second weight values are a potential source of error.
4 Chapter 4 Conclusions and Future Work

4.1 General Conclusions
The aim of this thesis was to address the lack of data on thermally driven polymer fibre actuators. Two types were considered: thermally-activated stretched rubbers and thermally-activated twisted thermoplastic fibres.

The effect of various parameters including temperature, filament diameter, annealing temperature and force were tested to achieve optimum properties, i.e. maximum contraction for maximum efficiency.

4.2 Electrothermally Heated Coiled Polyurethane
Three different combinations of fibre / wire conductor were twisted and plied with spandex polyurethane fibres and tested by stretching and electrically heating. The conductors used were steel, copper and carbon fibre. Several samples failed during testing. It appears that localised heating of the polyurethane in contact with the metal wire or carbon fibre caused the failures, sometimes after repeated cycles. Failure either occurred in the polyurethane or in the wire.

Contraction results for the carbon fibre and polyurethane samples were repeatable within a sample with 10 cycles giving a standard deviation of 13 % in the contraction strain. The variation between individual cycles may be partially explainable due to slight differences between the maximum temperatures to which the samples were exposed. The maximum temperatures averaged 73 °C with a standard deviation of 6 %. Errors in temperature measurement due to thermocouple movement are also likely to be a factor.

It was proven that as temperature increases the contraction of the sample increases. It was also shown that as the power through the conductive component of the sample increases, the temperature increases linearly. Therefore it can be concluded that as the input electrical power increases the contraction of the sample will increase.

The speed of actuation took 47 seconds to achieve a sample temperature of 80 °C. Within the first 10 seconds of heating the sample increased in temperature 20 °C and 84 % of the total contraction had already occurred. The rate of contraction in this period was constant. Higher power inputs which heat the sample quicker could dramatically increase the speed of actuation at the risk of sample failure due to localised hotspots.
It was found that a sample manufactured with more weight has significantly lower stiffness compared to a sample manufactured with less weight, and that this relation holds across all actuation weights. Given that the polyurethane should have been identical in each sample, this suggests that the wrapped carbon fibre is causing a difference between samples manufactured with different weights. The actuation of the polyurethane occurs by contraction of both the polyurethane and the carbon fibre coil wrapped around the polyurethane. If the carbon fibre coil is stiffer, then the contraction of the polyurethane is reduced. Samples manufactured with a higher weight when the carbon fibre coil is formed tend to have a lower stiffness and, therefore, allow higher actuation contraction strains. It is not known what the maximum weight and as such minimum stiffness possible is.

It is suggested that for maximum contraction, samples should be manufactured with as high a weight as practical regardless of what forces the sample would be subjected to in service. Ideally the service forces would be as small as practical and the temperature difference 35 °C to achieve the largest possible contractions. The largest contraction achieved was 10.2 %.

A significant benefit of the copper or steel and polyurethane was that they were manufactured from readily available materials, but relaxation of the stretched samples resulted in severe buckling which effectively made the sample unusable. The carbon fibre and polyurethane samples were an improvement as the buckling was less of an issue due to the higher flexibility of the carbon fibre. Buckling still was an issue however and samples can’t be relaxed once manufactured. Overall there were multiple issues including time required to manufacture a single sample, inability to store samples and multiple failures of samples.

During the above experimental work monofilament nylon and carbon fibre samples were reported to be showing promise and offered a few immediate benefits. One such benefit was the ability to store samples without any special requirements such as pre-stretching making them much more versatile, and much less likely to lose their structure in general compared to polyurethane samples. The lack of pre-stretch also made scaling down and particularly scaling up an easier process as consideration would not have to be given to the forces required to stretch significant amounts of polyurethane. Given the promise shown by monofilament nylon, it was decided further work should be focussed on this material as opposed to polyurethane. This would eliminate the inability to store samples, and it was expected that a new test method should improve the time to manufacture samples and result in repeatable results.
4.3 **Electrothermally Heated Overtwisted Nylon**

Due to new results showing promise with monofilament nylon acting as the thermally activated actuator, testing moved away from the polyurethane used in section 2. This required development of a new test method which was developed and initial testing was carried out. The actuation measurement of the sample appeared to work well, however the method for the manufacture of samples needs to be improved and variables minimised.

The contraction of the sample increased linearly as the power through the conductor, and thus the heat generated, increased. For 0.45 mm diameter monofilament nylon, maximum contraction occurs when the weight on the samples is somewhere around 100 g and 150 g. When the weight is 50 g or below, or 200 g or above the contraction is much smaller.

When actuating carbon fibre and nylon it took 72 seconds for sample length to finish contracting and remain constant. 92% of the total contraction occurred within 26 seconds and the rate of contraction in the first 26 seconds is constant before tapering off significantly. As with carbon fibre and polyurethane samples, higher power inputs which heat the sample quicker could dramatically increase the speed of actuation at the risk of sample failure due to localised hotspots.

Creep of samples should be monitored more closely to allow more accurate relationships between variables to be observed. This can be carried out by simply measuring each sample before and after each test. The ability to store samples greatly simplifies the process, allowing work to take place in stages rather than more of a continuous unbroken process. Although the manufacturing process for nylon samples takes much more time, it is evident that the results are repeatable with contractions of up to 9.6 % of the initial length observed with the maximum power available. It is expected that more power would result in larger contractions.

4.4 **Furnace Heated Mandrel Wrapped Nylon**

The effect of the temperature change on the contraction was confirmed, and the repeatability of the contraction of a sample was proven with a standard deviation of 8.1 %. Maximum contractions occur when maximum temperature changes are used.

A clear relationship is evident between the coil pitch i.e. the gap between the coils, and the resultant contraction. Maximum contractions occur when minimum pitch between coils is used. A relationship was also observed between sample length and contraction with
minimum length resulting in maximum contraction. This implies variable untwist with change in initial coiled length and from the author’s understanding is unexplainable based on the current literature and understanding.

The maximum contraction observed was 5.1 % at the minimum coil pitch. This is less than other results using smaller pitch coils, however these results confirm that smaller pitch coils produce higher contractions.

4.5 Future Work
Several areas of future work exist across the various sample types.

Section 4.2 covered the lack of knowledge for the maximum weight and as such minimum stiffness possible of electrothermally heated polyurethane, and this could be an area of further work which would further improve contraction strains. Another area is to vary the diameter of the carbon fibre coil to determine the effect on both the stiffness and the heat distribution and how they affect the contraction.

Another opportunity is that investigation should be carried out to gain understanding of the failure mechanisms of the samples manufactured from steel or copper with polyurethane. This knowledge may be applicable to all combined conductor-polymer samples and could assist in achieving greater contractions.

Understanding the maximum power limits for electrothermally heated nylon would be beneficial, and would be expected to increase contraction.

Further work needs to be carried out investigating the effects of the diameter of nylon when mandrel wrapped as coils, and the weight and stress on the nylon during the first stage of manufacture, amongst other variables. Investigations and comparison of mandrel wrapped coils with various spring indexes would also be of interest.

Investigation into the relation between untwist and coil pitch would be beneficial to explain whether there is a limit where the existing literature no longer applies to the coils of high pitch.
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