Design of a Tensile Tester to Test an Ant Neck Joint

THESIS

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Abstract

Insect body and limb segments are connected using internal, soft membranous and external hard materials of varying geometries to allow for motion whereas vertebrates employ internal stiff and soft components with physical constraints. Insect joints are therefore mechanically distinct from vertebrate joints. Ants, in particular, have a highly integrated system that is comprised of composite materials, internal muscle mechanisms, and material microstructure. As a result of their unique structure and material properties they are able to carry loads in excess of 1000 times their own weight, the load path of which passes through the neck joint. To study this joint, multiple experiments were conducted prior to this research project using a custom-built, open centrifuge following a method also used to investigate the attachment forces of arboreal ants. The current project builds on the results obtained from the previous project, including the development of a device for a neck joint tensile test. This improved design involves a load cell and a displacement sensor that record the load and displacement values when the neck is being loaded to the point of failure. These values are then used to determine the stress and strain values and compared to the values obtained in the previous research. The design of the tensile tester also includes the design of a fixture for holding the ant without compromising its internal structure and geometry.
This work is dedicated to my family
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Chapter 1 : Introduction

Insects bodies utilize a combination of novel material components and structures which make them capable of remarkable mechanical functionality. Ants, in particular, have evolved the ability to carry extremely heavy loads relative to their own mass (~1000 times). The neck joint is the singular part that withstands the full load carried by the ant. Previous mechanical testing results show that the combination of materials forming the neck joint of F.exsectoides (Allegheny mound ant) exhibits an elastic modulus of 230±140 Mpa and can withstand ~5000 times the ant's weight. In a previous study, live ant specimens were tested in a custom-built, open centrifuge, the minimum required speed of which was calculated using the following equation:

\[
\text{rps} = \frac{1}{2\pi} \sqrt{\frac{F \times \text{FoS}}{(r)(m)}}
\]

where F is the applied load in Newtons, r is the radial distance of the applied load in meters, m is the mass of the body in kilograms, rps is revolutions per second, and FoS is
the factor of safety, which determined how much the instrument exceeded the minimum performance requirement [1].

Problem Definition

Background on Ants Structure

Based on research conducted previously, it has been found that ants can lift weight that is up to 5000 times their own weight. The load follows a path from the jawbone through the neck and the body and to the legs. Since the neck joint is the smallest structure in this path of load transmission, it is important to understand the material properties and geometry in order to determine the design of this joint.

Ant exoskeletal systems are typically constructed of a tough polymer of chitin. An exoskeleton is a multi-layered structure with four functional regions: Epicuticle, procuticle, epidermis, and basement membrane. The neck is comprised of a soft membranous region bridging stiff exoskeleton of the head and thorax. In previous studies, multiple experiments were carried out using Formica Exsectoides with the purpose of modeling these joints. Formica Exsectoides, the scientific name for the Allegheny mound ant, was chosen because of its availability and size. The previous experiments comprised of testing these specimens in an open centrifuge by anesthetizing them first in a 30 degree F chamber. The 3D structure was then imaged using microCT with a focus on head, neck, and thorax at the same time to capture the internal and external features of the neck joint.
The data from prior experiments, and ones that will be performed in the future, will be used to test create a qualitative and quantitative model that will be used to model the neck joints. This model can also be used for material characterization, muscle forces, and kinematics.

Device Background

Prior work:
Material testing is the measurement of the characteristics and behavior of substances such as metals, ceramics, plastics etc. under various conditions. Mechanical testing, an important aspect of material testing, determines a material’s ductility and toughness along with other properties such as elasticity and strength. It is usually destructive and is done by clamping on the ends of the specimen. Where the material is soft, it’s very difficult to clamp the ends of the material without permanently deforming it. This, therefore, poses a challenge when testing biological specimens. Federle and Holldobler used a centrifuge setup to compare the feet attachment forces of arboreal ants on smooth surfaces [2]. Vienny Nguyen, a graduate student at The Ohio State University, used the centrifuge setup to better understand the design of the neck joint. She used a centrifuge, along with a strobe and camera for the experiments. The output of the centrifuge motor was attached to an open air drum and the speeds were varied from 0-6000 rpm. A high speed video camera captured images at 200 frames per second using a stroboscope at 200 Hz. The images captured were analyzed in Matlab to calculate the deformation of the neck joint. Using gray scale option for images in Matlab, the position of fiducial marks were
quantified along a line that crossed through the marks on the head and thorax. As these marks appear as peaks in the grayscale profile, the change in distance between the peak centers was used to quantify deformation of the neck.

Figure 1 General layout of the centrifuge setup [1]
The results obtained from Nguyen’s experiments were helped identify key material properties of the ant neck joint such as the elastic modulus.
As is expected from biological materials, the stress strain relationship was observed to be non-linear, with large displacements occurring at low loads and small displacements occurring at high loads. The data obtained from the experiments also allowed them to estimate the elastic modulus of the material in the neck joint to be 230±140 Mpa and the failure stress to be 37 Mpa.

These results were used to compare the ones obtained from a finite element model. The 3D model for the finite element analyses was created using the MicroCT scans of the ant specimens. The material properties for each element set in this model were based on experimental results or values from literature. A load was applied as a linear ramp over a time step of 1 second to a single node at the back vertex of the esophagus along a defined vector. The head was fixed by constraining the nodes on the front surface of the head and esophagus to zero displacement and rotation. The nodes on the back and bottom surfaces of the thorax and esophagus were rigidly tied to the displacement of the load node [1].
Using the FEA, it was determined that when a load was applied, the critical stress concentration was located between the soft membrane in the neck and the head exoskeleton.
This would normally be expected to be a weak region. But it was noticed that the neck is able to transfer surprisingly high tensile stresses without separating at this interface. Two material models were used for the FEA-linear and hyperelastic. When the results from both these models were compared to the ones obtained from the experiments, it was seen that the hyperelastic definition better approximated the behavior observed in the experiments and that the model behavior was dependent on the applied loading angle. As the loading angle was increased, the overall stiffness of the joint remained approximately constant at higher loads, while there was a marked decrease in stiffness at lower loads [1].

Figure 7 Load vs displacement for various loading angles [1]
Although the device used in Nguyen’s project provided a good set of results using a combination of experiments, images and modeling, it wasn’t an accurate method to determine the tensile loading behavior of the neck joint of an ant. The results here give only the ultimate tensile strength and also, the value obtained is an average value. The primary reason for this was the design of the experimental setup. The following aspects of the setup could give rise to an error in the results obtained:

1. Gluing the ant to the base: When gluing ant to the base, it is difficult to control the angle at which the neck joint is oriented.

2. Painting the body of the ant: Marking the body of the ant at predetermined points is subject to human error and hence this would carry over to the processing part of the images and ultimately give incorrect results.

3. It was observed that the internal contents of the ant body were evacuated during the mechanical test using a centrifuge, which could potentially lead to errors in the results due to changes in the ant mass.

**Devices on the market:**

As a result of the limitations with the prior testing, an improved method of testing the tensile behavior of the ant neck was designed. That objective is the focus of the work in this thesis. Initially a survey of currently available tensile testing devices was conducted. Some of the tensile testing devices that have been used previously for research are:
Honeywell

The Micro-Tensile Test System (MTTS) is designed to test materials that range from 0.002 inch to 0.030 inch and provides precision for testing very small samples.

The steel load frame of the MTTS makes it rigid, allowing axial loads of up to 250 pounds with minimal error in test results. In addition, the sample is aligned precisely to ensure even distribution of force during testing. The load/strain measurements of the MTTS have less than a 1% error rate due to these distinct features. It has PC-based software that facilitates data acquisition and evaluation of test results. There is also a stepper motor that provides constant displacement for tensile testing with speeds ranging from 0.0002 in/min to 0.25 in/min [3].
Deben-Mini tensile tester

These stages have been specifically designed to allow real time observation of the high stress region of a sample with an SEM, optical microscope, AFM or XRD system. With dual threaded lead screws, the center of the specimen stays centrally located. Load cells from 2N to 200N cover most applications, with extension rates from 0.1mm/min to 15mm/min.

![Deben-Mini Tensile Tester](image)

Figure 9 Deben-Mini Tensile Tester [4]

These come with sample clamps that are removable, allowing easy customization. This also allows for easy fitting of special clamps for different samples. They have fibre clamps, three and four point bending clamps and clamps to hold specifically shaped specimens. The stage can be supplied with temperature controllers and either heated or heated and cooled specimen clamps with a variable temperature range of -150C to 550C [4].

eXpert 4000 Micro Tester
The line of eXpert 4000 series MicroTest Systems are ideal for situations where one wants to measure very low forces and small displacements on samples that can often be difficult to hold. This is also useful for recording microscopic material behavior while the sample is under load [5].

![Figure 10 Micro Tester horizontal configuration [5]](image)

**Micro Autograph**

This device has a high-precision linear sensor that ensures high displacement measurement precision: displacement display resolution of 0.02 µm, and displacement measurement precision of ±0.2 µm up to 5 mm displacement. It also has a wide range of load cells from 0.5 N to 2 kN and assures a testing force measurement precision of ±1 % from a minimum load of 2 mN.
Highly reliable micro-displacement measurement can be performed because the frame has an extremely high rigidity of 45 kN/mm. Other options include as a heating plate, X-Y stage, stereo microscope allow for easy positioning and observation of micro samples [6].

**Kammrath Weiss**

This instrument is a sub-stage for the SEM specimen stage, which will also work under the light microscope. It is suitable for mechanical load experiments, such as static or oscillating tensile tests with extremely small solid bodies.
In unique cases it is quite difficult to clamp specimens, such as the neck joint in ants, in order to perform tensile or dynamic tests on them. These are so fine that it is difficult to operate on them manually. To get access to such dimensions, a piezo-controlled gripper mechanism was combined with crosstable mechanics of highest displacement resolution, and a load gauge that will do fractions of μN. A fatiguing platform allows carrying out dynamic experiments [7].

Even though there are capable devices on the market, the following issues meant that these couldn’t be used for testing our ant specimens:

1. Certain devices (such as the Honeywell MTTS) are operated exclusively by the U.S. Department of Energy and are hence not available commercially
2. The devices are bulky and take up a lot of space. They are also difficult to move from one location to another
3. The devices cannot be used to test ant specimens by keeping the neck at different angles.

4. These devices are expensive

**New Device**

The loading of the specimen should apply the desired range of forces to the specimen in a uniaxial manner while ensuring that a tensile stress is applied to the neck joint. The application of the force should be accompanied by mounting an ant specimen and holding it in a manner that does not affect the structural integrity of the neck joint, gripping its posterior end.

![Figure 13 Black Carpenter Ant](image)

Several approaches to gripping have been researched: electro-static clamping, application of adhesives and mechanically locking. These methods each have their advantages and
disadvantages, but a choice should be made taking into account the potential effect of gripping errors. These errors can lead to misalignment, resulting in undesired stresses in the specimen. Some forms of misalignment that can occur are i) force and specimen's longitudinal axis are parallel to one another, but not co-linear, ii) force and longitudinal axis are at an angle to one another. Therefore a precise mechanism is required to rotate the specimen and/or the gripper. The new device should have the ability to measure mechanical properties such as stiffness, deformation mechanisms (e.g. elastic, viscoelastic), and rupture strength of the neck joint in live specimens. Two other factors that should be evaluated are hysteresis and creep.
Chapter 2: Device Design

Engineering Functions

Functions of the tensile tester:

1. Fixture for holding the ant’s head and thorax to axially load the neck
2. A device to move the fixture axially to apply the appropriate load
3. Measure the displacement of the device to know how much the fixture has moved
4. Measure the load in order to determine the stresses at the rupture joint

1. Fixture for holding the ant

Since the purpose of this project is to determine the stress-strain behavior of the ant neck joint as well as the ultimate tensile strength of the neck joint, the ant has to be attached to a fixture which in turn can be moved to load the neck joint to failure. The ant would have to be fixed laterally on the fixture and pulled axially so as to determine the failure values in the axial direction. It is desirable for the design of the fixture to be adaptable in order to account for any design changes, such as adding or replacing a component, in the future.
2. A device to move the fixture axially

The fixture that has to be designed to hold the ant must allow axial movement of the neck joint in order to axially load it to failure. This is because the loading angle has an effect on the stiffness of the neck joint—as the loading angle increases, there is a marked decrease in stiffness at lower loads while it remains approximately constant at higher loads. Therefore, it has to be fixed to a device that can be moved axially and should have the capability to be moved in increments desired by the user. The device should also have a fixed base so that the movement of the fixture is not disrupted, otherwise this could potentially lead to the ant neck not failing axially, resulting in incorrect failure load values.

3. Measure the displacement of the device

The distance by which the device holding the fixture moves needs to be recorded. This is important because it will help in evaluating the point where the ant neck fails, and ultimately help in determining the strain values and the ultimate tensile strength of the joint. The upper limit of the range for this device can be set to a value that is significantly higher than the size of an ant neck. Therefore an approximate value of 25 mm can be used.
4. Measure the load

The load would have to be measured when it is being applied on the neck joint and hence there would have to be a device that can record this and output a value.

Based on these functions, the new device would have to have the following specifications:

1) Fixture with maximum dimensions of 8in x 5in (Length x Width). These dimensions were obtained from the base of a microscope upon which this fixture would be placed. The microscope would be used to observe and capture images when the ant neck is being loaded to failure.

2) Load Cell: to measure the load, with a range of 0.1N to 5N. The tensile failure load value obtained by Nguyen was 0.33N. Since there isn’t an exact range of known loads that would be output when testing the neck joint, a range of 0.1 N to 5N was picked as this contains the load value obtained by Nguyen and also encompasses significantly higher or lower values compared to this load.

3) Linear motion guide: for precise alignment of the ant without any distortion during gripping and tensile loading

4) Displacement sensor, from ±5 micrometers upto ± 25.4 millimeters. As the exact value at which the neck joint ruptures is not known, the upper range for the displacement sensor was set to a significantly higher number compared to the length of an ant’s neck.
In design and analysis, load-displacement and tensile stress-strain relationships are frequently needed as these relationships lead to an understanding of various mechanical properties such as the ultimate tensile and yield strengths, Young’s modulus, Poisson’s ratio, and the elongations and reductions in area. Also, the true stress-strain properties, strain hardening and tensile toughness can be calculated by means of conversion using special equations from the stress-strain curve. True stress and engineering stress differ negligibly from each other in the elastic region of a material. But since the neck joint comprises of biological materials which are not linear in nature, true stress and strain are considered instead of engineering stress and strain. True stress is the applied load divided by the cross sectional area (the changing area with respect to time) of the specimen at that load. True strain equals the natural log of the quotient of current length over the original length. Engineering stress, on the other hand, is the applied load divided by the original cross sectional area of a material. Engineering strain is the amount that a material deforms per unit length in a test [8].
To conduct a tensile test, it is first necessary to determine the appropriate testing equipment and specimens and then purchase or build the appropriate device. The most widely used tensile testing machines are screw-driven testing machines with a moving crosshead and a closed-loop servo-hydraulic testing machine with a hydraulic actuator [9] [10].

Figure 14 True stress and Engineering stress [8]
Figure 15 Screw driven testing machine [9]

Figure 16 Closed-loop servo hydraulic testing machine [10]
However, testing machines are relatively heavy and are typically installed in a laboratory. Conventional test methods for evaluating mechanical properties require a massive testing machine and relatively large material samples.

Miniature tensile testing techniques to obtain the mechanical properties of materials have been an interest of many researchers. One way of achieving this is a simple miniature disc-type tensile specimen and fixture to hold specimens with the help of a rigid pin to predict the mechanical properties of materials [11]. A miniforce tester driven by a DC-servomotor with a ball-screw guide-way was also developed for a solder ball joint shear test [9].

![Miniature disc type tensile specimen and fixture](image)

Figure 17 Miniature disc type tensile specimen and fixture [11]

A tensile device, that integrated a servo-motor and a three-stage reducer for a quasistatic loading module was also built for research purposes. It integrated a servo-motor and a three-stage reducer for a quasistatic loading mode with a loading speed of 10 nm/s [12].
A new uniaxial tensile testing system, consisting of a closed-loop piezo-electric (PZT) actuator, a load cell, and two grippers to hold the specimen was developed in order to investigate the mechanical behavior of thin films [12].

Figure 18 Schematic of the test system developed by Chen and Hou [12]

Figure 19 Schematic of the designed (a) tensile specimen (b) gripper [12]

However, these systems are complicated and/or much more expensive than conventional tensile testing methods.

Acquiring new instructional laboratory apparatuses and preparing samples are a challenge because of budgetary limitations. In addition, sophisticated skills are required to operate
the testing machine, especially the servo-hydraulic testing machine. Therefore, a new approach for an easy-to-handle and inexpensive tensile testing system is desired so that tensile tests can be conducted easily and economically.

For this project, a miniaturized tensile testing system to test the neck joints of ants is proposed. The system developed will be used to convert the rotation motion of a ball screw into the linear motion of grips that apply a tensile load on the specimen. The frame contains an aligned linear motion guide for the movement of the grips, ensuring collinearity of the travel axes. One side of the specimen is connected to a ball-screw block and the other side is connected to a load-cell to detect the load magnitude.

Design Concept

Tensile Tester

The machine will be designed to pull one end of the ant specimen, while it is attached to the load cell to monitor the applied load. The maximum tensile load to rupture the neck joint with a cross sectional area of $1.61 \times 10^{-2} \text{ mm}^2$ and an ultimate tensile strength of 233 MPa was determined to be 1.25 N. Thus, the maximum tensile force requirement of the machine was set to 5.0 N. The load is measured with load cells with 0.5% of the maximum rated load.

In order to pull the sample without torsion, a ball screw converts the stepping motor rotation into linear motion. A ball screw, positioned in line with the specimen, provides
the tensile force. A chain is used to couple the stepping motor to the ball screw because a collinear arrangement would make the system too long. A linear motion guide is adopted for precise alignment of the specimen without any distortion during gripping and tensile loading.

Figure 20 Tensile Tester Initial Concept Sketch (top view)

This concept is shown in Fig. 20.
The major aspect of this design was that it was modular. It subdivided the system into smaller parts (modules) which could be independently created and used in different systems/concepts. The advantage that this allowed were:

- Flexibility in design
- Augmentation—adding a new solution by merely plugging in a new module
- Cost reduction—due to less customization and shorter learning time
The Base

All of the modules would be attached to a fixed base. It was necessary to use a material that could be easy to work with to accommodate all these modules. This base would also need to be large enough to hold all the modules. One of the best options, therefore, was to use aluminum as it is easy to machine and is also cost effective.

Translation Base

Since the design involved pulling one end of the ant specimen, a moving mechanism had to be included in the design. For this, a modular base was required that would make it easy for a part to move on it. A guide rail with a sleeve bearing carriage was considered as one of the options for this modular base. This could be attached to the main base using bolts and is shown in the figure below. The idea behind this was that the moving part that would carry the ant could be fixed to the sleeve bearing carriage and could be moved linearly when performing the experiments.

For the initial prototype, the fixture onto which the ant would be placed was 3D printed. This 3D printed fixture was held on the sleeve bearing carriage, which in turn was placed on a guide rail. The sleeve bearing carriage along with the guide rail is shown in Fig. 22. Fig. 23 shows the front view of the carriage on the guide rail.
The Mover

The mover is the part that carries the ant fixture and in turn the ant. This consists of two parts—one to hold the ant’s head and the other to hold the ant’s body. The modular part that holds the ant’s head is fixed on the sleeve bearing carriage and the modular part holding the ant’s body is fixed to the main base.
The Moving Mechanism

In order to move the ant fixture on the mover, a lead screw mechanism was considered as one of the options. One end of the lead screw would go through the mover holding the ant’s head and the other end would be attached to a block using a bearing. This block
would in turn be fixed to the main base using bolts. There would be a sprocket attached to the lead screw end connected to the block fixed to the main base. There would be another sprocket attached to the shaft of a motor. These two sprocket would be connected with a chain. When the motor moves, the shaft would rotate and in turn rotate the chain and the lead screw. This would move the mover connected to the ant’s head and in the process, apply force to the neck joint till the head separates from the body.

*The Ant Head Holder*

The ant head needs to be held straight with respect to the body without any significant angular movement, so the force can be applied axially. It is desirable to keep the angular movement to less than 8 degrees, as that would give us load values that are approximately 0.99 times the load values that would be obtained with zero angular movement.

![Figure 26 Ant head and body alignment (top view) [14]](image-url)
Therefore, a spring loaded holder was initially considered. The holder is circular in shape and has a cutout that would house a spring laterally. This would then be put in an aluminum block that has a cutout in the shape of this holder albeit a bit smaller in size. When the holder is put in the cutout in the aluminum block, it would be loaded in compression because of the smaller size of the cutout but wouldn’t completely close because of the spring. This would in turn help hold the ant in the cutout made in the holder.
Figure 28 Holder with spring (top view)

Figure 29 Block holding ant holder
The issues that came up with this concept were that the sleeve bearing carriage was too difficult to move on the guide rail because of the high amount of frictional resistance.

![Figure 30 Sleeve bearing carriage movement issue [13]](image)

The holder would also need to be modified in this design in order to allow its use for different ant sizes. Also, this holder could potentially put a not insignificant amount of force on the ant’s head to hold it, which would be confounded with the data. It could also affect the structural integrity of the ant exoskeleton. It could also be difficult to account for different ant sizes when using this holder as the size of the opening in the holder is not adjustable.


Since the carrier block has to go on a base that could move easily, translation stages and pneumatic slides were considered as potential solutions. Pneumatic slides, although inexpensive, are more complex as compared to translation stages and can therefore be difficult to adjust and/or repair. They also take up more space as the slides are usually long. It was therefore decided that a translation stage would work best for this project. This stage would in turn be attached to a micrometer that would push the stage when the micrometer is turned.
There would be a block on the translation stage attached with the help of bolts. This block would carry the load cell as well as be the datum for the displacement sensor. There would be grooves made on the block to accommodate for the sensors on the load cell.

*Carrier Block*

There would be a block on the translation stage attached with the help of bolts. This block would carry the load cell as well as be the datum for the displacement sensor. There would be grooves made on the block to accommodate for the sensors on the load cell.
New Ant Holder

The ant holder would be attached to the load cell which in turn is attached to the carrier block. There were multiple designs tested for this holder and these are listed below:

a) Design 1: A thin piece of aluminum that would be bent on the two ends. One end would be attached to the load cell while the second end would have a slit to put the ant’s head. There would be another piece of aluminum with a machined groove that would be put behind the slit to hold the ant’s body in place. These two would in turn be held on an aluminum block that would be placed next to the translation stage.
Figure 34 New Ant Holder Design 1

Figure 35 New Ant Holder Design 1 Body Holder

Figure 36 New Ant Holder Design 1 Aluminum Block
When this design was tested, it was realized that it was difficult to hold the ant in the groove behind the slit. This was because the groove was a U-shaped slot and whenever an ant’s head was pulled, the body would slide off the slot as there was no mechanism to hold it down in the slot. Therefore, this design had to be modified.

Design 2: This design builds off of design 1 and consists of a second holder (similar to the one holding the ant’s head) resting against the first holder. In order to hold the second aluminum piece in place, it would be attached to an aluminum block placed next to the translation stage and bolted down to the aluminum base. While one of these parts would be held in place and hold the ant’s body, the other part would move and pull on the ant’s head.

Figure 37 Holders against each other
When the fixture was first tested on an ant, the walls on the side of the slit bent when the load cell pulled on it and therefore did not actually rip the ant’s head off. This was
because the walls of the fixture were too thin (0.01 inches) and couldn’t withstand the load being put on them. Therefore, the design of the fixture had to be changed to account for this.

Design 3: The modified design has thicker walls which then taper inward to a thinner wall size. Fillets were also added to the side walls to strengthen the holder. This would provide rigidity to the model and also help put the ant in the U groove (‘slit’). The hole on the holder, which was used to bolt it to the load cell, was also made into a slot to increase the tolerance value and to account for any errors in measurements. An aluminum block to hold the displacement sensor was also included in this design.

Figure 40 Ant Holder Design 3
In order to record the displacement of the load cell, a displacement sensor would be placed in front of the translation stage. This displacement sensor, GT2-H12, was bought from Keyence and has a resolution of 0.5 μm.

For the prototype, most of the parts were machined out of aluminum (the drawings for these are included in the appendix). The translation stage was obtained from Newport (model number 9064-X) and this had a micrometer with 0.01 mm graduations. The load cell was obtained from the electronics lab at OSU and had the following specifications:

Rated Load: 1Kg
Rated Output: 1.0 ±0.15mV/V
Zero Output: ±0.1mV/V
Input End: Red+, Black-
Output End: Green+, White-
Maximum working voltage: 15V DC
Operating temperature range: -20~60°C
Company and model number: Qin Bo Electronics, 11404417

The final design is shown in the figure below.

Figure 42 Modular Tester

Figure 43 Modular Tester Final Design (CAD)
Controller

The next phase in the design process included the design of the controller. This controller would take the voltage values from the load cell and the displacement sensor and convert them to the respective load and displacement values. For the programming aspect, I decided to use Labview as this allows me to work with various signal properties and also works well with most acquisition devices. To record the signals, I used an acquisition device from National Instruments called the myDAQ.

Since the signals obtained from the load cell would be really small, using an instrument amplifier (INA 129) (Fig. 21) in this case would be ideal as it would provide a gain and amplify the signals.

The gain in this case would be calculated based on the following formula:

\[ G = 1 + \frac{49.4k\Omega}{R} \] [16]

The resistance here depends on the scenario and after testing various resistors, I decided to go with a 100Ω resistor.
$V_s$ = pins for the signals from the load cell

$V_{IA}$ = pins for the acquisition device

$V_{ex}$ = pins for the power supply

$R_G$ = R used in calculating the gain

The power for this would be supplied by a DC power supply that was obtained from the Instrumentation Lab at OSU.

The code for the LabVIEW program is provided in the appendix.
The next step was to calibrate the load cell and the displacement sensor. To do this, one end of the load cell was clamped to a table and weights were put on the other end and the respective voltage values were recorded. The following weights were put on the load cell: 1g, 2g, 5g, 10g and 20g. These weights were obtained from the electronics lab at OSU. An initial reading without any weight on the load cell was also taken. The voltage values obtained from the respective weights were then input into Matlab and a curve was fit to these values to get an equation to convert the voltage values to the load values.
Table 1: Load Calibration values

<table>
<thead>
<tr>
<th>LOAD (in grams)</th>
<th>VOLTAGE (in volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.13032</td>
</tr>
<tr>
<td>1</td>
<td>-0.13089</td>
</tr>
<tr>
<td>2</td>
<td>-0.13135</td>
</tr>
<tr>
<td>5</td>
<td>-0.13286</td>
</tr>
<tr>
<td>10</td>
<td>-0.13529</td>
</tr>
<tr>
<td>20</td>
<td>-0.14009</td>
</tr>
</tbody>
</table>

The same method was used to calibrate the displacement sensor. The sensor head was moved a certain distance every time and the respective voltage values were recorded. Since the sensor head was moved using a micrometer, the actual distance moved was obtained from the reading on the micrometer. These values were then input into Matlab to get an equation to convert voltage values to displacement values.
**Table 2 Displacement Calibration values**

<table>
<thead>
<tr>
<th>DISPLACEMENT (in inches)</th>
<th>VOLTAGE (in volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.120832</td>
</tr>
<tr>
<td>0.01</td>
<td>0.131805</td>
</tr>
<tr>
<td>0.02</td>
<td>0.141499</td>
</tr>
<tr>
<td>0.05</td>
<td>0.172089</td>
</tr>
<tr>
<td>0.07</td>
<td>0.192799</td>
</tr>
<tr>
<td>0.1</td>
<td>0.223186</td>
</tr>
</tbody>
</table>
Chapter 3: Experimentation

Preparation

The ant specimens were obtained from George Keeney at The Ohio State University’s Aronoff Greenhouse/Insectary. There were various species of insects available there for entomological research. Therefore, it’s important to take care when visiting this site, in case any insects escape. Most of the insects there are non-poisonous but they do house some that are.

For the experiments, Camponotus Pennsylvanicus, also known as Black Carpenter ants, were obtained and placed in a transparent container. The top half of the container was lined with painted Insecti-slip (Fluon PTFE coating) to prevent the ants from escaping out the top of the contained. The container consisted of three glass test tubes with cotton balls in them. These tubes were covered with a tin foil and the ants mostly lived in these. The openings of the test tubes were wrapped with a tin foil and there was a hole made in each of these for the ants to come out. Dry sugar cubes were placed in the container and the ants were also fed Bhaktar’s agar regularly.
It would be difficult to put live ants in the tensile tester fixture as they would be moving and putting them in the holder this way would be a challenge. Therefore, to prepare them for the experiment, they either had to be immobilized or had to be euthanized. There were two methods to do this. The first one was to take the ants, put them in a jar and then place the jar with the ants in a freezer. This immobilizes the ants for a certain period of time, usually around 15-20 mins. But this method wasn’t really useful as the ants would wake up by the time they could be moved from the jar to the test setup. The second method involved placing the ants in a jar containing a paper towel soaked in acetone. The fumes from the chemical euthanize the ants, and then these ants could be placed in the tensile tester. The ant exoskeleton is a composite that consists mainly of chitin, which is insoluble in acetone [19]. Therefore, acetone would not affect the material properties.
Methodology

The ants were tested one at a time in the tensile tester. It was important to make sure that the ant was properly placed in the fixture, with it’s head in the mover attached to the load cell and the remaining part of the body in the second mover fixed to the base. The entire tester was placed under a microscope to record the experiment and the failure of the ant neck.

The next step involved turning on the DC power supplies. These provided power to the load cell, the displacement sensor, and the stepper motor. Then the programs to record the data and run the stepper motor were opened on a computer. LabView was used to record the load and displacement data while an Arduino program was used to run the stepper motor. When everything was setup properly, the Labview and the Arduino program were started. It was noticed in all the experiments that the ant’s neck failed with
a very faint cracking noise and after this, a membrane was the only thing holding the ant’s head to its body. Force was applied continuously until the membrane ruptured. As soon as this happened, the LabView and the Arduino program were stopped. This process was repeated with different ants 25 times, varying the speed at which the micrometer moved by using the stepper motor. The number of samples, along with the speed at which the micrometer moved are listed in the table below.

Table 3 Speed of micrometer along with number of samples tested

<table>
<thead>
<tr>
<th>Speed (in/s)</th>
<th>No. of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0044</td>
<td>10</td>
</tr>
<tr>
<td>0.0088</td>
<td>5</td>
</tr>
<tr>
<td>0.0056</td>
<td>5</td>
</tr>
<tr>
<td>Free hand</td>
<td>5</td>
</tr>
</tbody>
</table>

The recorded data was imported to an Excel file, which was then imported again into a Matlab file. This Matlab program converted the voltage values obtained from the load cell and the displacement sensor to load and displacement values respectively. This was done using the calibration parameters that were obtained from the calibration process.
Results

As mentioned above, the ant’s neck failed with a faint crack, after which there was a membrane that held the head to the body. This process is shown in the figures below:

Figure 48 Ant placed in tensile tester
The unfiltered data that was initially obtained from the tensile tester is displayed below in figure 51. As has been mentioned before, the load cell and the displacement sensor had an initial offset that had to be accounted for. To calculate the offset value, the power supplies were turned on and the Labview program that was created to record the data was run without any load being applied on the load cell. The mean of the values obtained
from the load cell in this configuration was then used as the initial offset. After this initial data offset was subtracted, the data that was obtained is shown in figure 52.

Figure 51 Initial Data obtained from the tensile tester
To filter the data that was obtained from the load cell and the displacement sensor, a number of filters were tested. These were:

1) Butterworth
2) Cascade
3) Bessel
4) Chebyshev

The data was obtained from each filter was then compared to the moving average of the unfiltered data. It was seen that the cascade filter gave the best results, and hence a transfer function was developed for this in Matlab:
\[
\frac{y}{x} = \frac{1}{\frac{x^2}{\omega^2} + \frac{2\xi\omega}{\omega} + 1} \tag{17}
\]

where \( \omega \) is the cutoff frequency and \( \xi \) is the damping factor. The cutoff frequency here is the frequency between the stop and pass bands. All of the signals with frequencies below \( \omega \) are transmitted and all other signals are stopped. It was seen that a cut off frequency of 0.003 gave results that were closest to the moving average. Hence this value was used for the transfer function. The damping factor here controls the resonant peak that develops in the vicinity of the cutoff frequency. The amplitude response for a filter varies for different values of this damping factor. But a value of 0.7071 gives the correct frequency response and this happens when the filter is critically damped. Therefore, the damping factor was set to 0.7071 in the transfer function.

The load-displacement data, after filtration, is shown in figure 53.
These values then had to be converted to the true stress-strain values. This is done because the neck joint is not linear and engineering stress strain values differ from the true stress strain values when the material is not linear, as was mentioned previously in the ‘Concept Selection’ section. The true strain values were calculated using the following equation:

$$\varepsilon = \ln\left(\frac{L_f}{L_i}\right)$$

where $L_f$ is the final length and $L_i$ is the initial length.

For true stress, the following equation was used:
\[ \sigma = \frac{F L_f}{A_i L_i} \]

where \( F \) is the load applied, \( A_i \) is the cross sectional area of the neck, \( L_f \) is the final length and \( L_i \) is the initial length.

In order to obtain the initial cross-sectional area, the SEM images for the neck region of an Allegheny Mound ant and a Black Carpenter ant were compared using the scale given on the images. The cross-sectional area of the neck of an Allegheny Mound ant was obtained from Vienny Nguyen’s thesis. Using this information and the ratio of the size of the necks obtained from the SEM images, the cross-sectional area of a Black Carpenter ant’s neck was approximated.

Approximate length of neck of an Allegheny Mound ant = 0.24 mm \[18\]

Approximate length of neck of a Black Carpenter ant = 0.37 mm \[18\]

Cross-sectional area of the neck of an Allegheny Mound ant = \(1.61 \times 10^{-2}\) mm\(^2\) \[1\]

Cross-sectional area of the neck of a Black Carpenter ant = \[
\frac{0.37}{0.24} \times 1.61 \times 10^{-2} \text{ mm}^2
\]

\[= 2.49 \times 10^{-2} \text{ mm}^2\]
Using this value and the values obtained for load and displacement, the stress-strain data (Fig. 56) was plotted for the load displacement data shown in Fig. 53.
Using the stress-strain data for n = 15 ants, the mean of the rupture stress, its standard deviation and standard error were calculated:

\[ \mu_{\text{sample}} = 33.75 \text{ Mpa} \]

\[ \sigma_{\text{sample}} = 16.06 \text{ Mpa} \]

\[ e = \frac{\sigma_{\text{sample}}}{\sqrt{n}} = 4.14 \text{ Mpa} \]
where \( \sigma_{\text{sample}} \) is the standard deviation and \( e \) is the standard error. In addition to calculating the above values, the confidence interval at a 95% level was also calculated, which provided an interval of (24.86 Mpa, 42.64 Mpa).

The shape of the curve for load-displacement and stress-strain was consistent among all the ants tested and it could be divided into two regimes - one with high loads and the other with low loads. The higher load regime was determined to be associated with the exoskeleton and the softer membrane comprising the neck joint while the lower load with the membrane holding the ant’s head to it’s body. This is because the exoskeleton has chitin as a major component which is tougher than the soft membrane that holds the ant’s head to it’s body.

For the higher load regime, the mean of the load and stress values were calculated along with the standard deviation and standard error. The elongation for this regime was also calculated.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
<th>Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress</td>
<td>14.74 Mpa</td>
<td>13.69 Mpa</td>
<td>3.53 Mpa</td>
<td>(22.32,7.16) Mpa</td>
</tr>
<tr>
<td>Load</td>
<td>0.0841 N</td>
<td>0.0745 N</td>
<td>0.0192 N</td>
<td>(0.1254, 0.0428) N</td>
</tr>
<tr>
<td>Displacement</td>
<td>0.0020 m</td>
<td>0.000777 m</td>
<td>0.000215 m</td>
<td>(0.0024, 0.0015)m</td>
</tr>
</tbody>
</table>
The design and implementation of a tensile tester allowed for the collection of load vs displacement data for the neck joint of a Camponotus Pennsylvanicus. These results were analyzed to determine the rupture load and stress as well as the elongation of the joint based on different regimes. It was also noticed that a change in the strain rates did not change the shape of the curve, nor did it affect the results noticeably.

The results obtained from the experiments would be used to analyze the structure of the ant body in the future by students of the HUCED lab to develop a finite element model.
Chapter 4: Discussion

Building a tensile tester that could apply load on the neck joint of an ant allows for the collection of data that can determine material properties, which can then be used to build an FEA model. The various concept and design phases to build a tester and holder that could hold an ant without disturbing its structural integrity showed the complexities of testing biological materials at the micro level. The results obtained from the experiments showed that the initial failure of the neck joint occurs in the exoskeleton, while internally there is a soft membrane that remains connecting the two segments to a level of much greater strain. A similar behavior was also noticed at different connecting joints between the segments of the ant body. These are discussed in the following sections.

To prepare the ants for the experiments, they were initially kept in a freezer where the cold would immobilize them. But this method was soon discarded as the ants would quickly mobilize again and this made it difficult to put them in the tensile tester. The ant exoskeleton is a composite that consists mainly of chitin, which is insoluble in acetone [19]. Therefore, these ants could be euthanized using the fumes from acetone, without damaging the exoskeletal structures.

The experiments performed on the ants showed that the initial failure of the exoskeleton comprising the neck joint is accompanied by a sharp increase in load, which then
decreases when the load is only being applied on the soft membrane holding the head to the body. The faint crack that is synonymous with the initial failure of the exoskeletal portion of the neck also suggests that the material is brittle. The soft membrane that holds the head to the body can be hypothesized to be the soft cuticle that is found between hard plates and body sections in arthropods. This soft cuticle allows for large deformations and stretching to accommodate motion and growth due to maturation and even abdominal expansion during eating or reproduction. In some cases, this membrane can be folded and laminated to provide a lower degree of extensibility but higher degree of strength [1]. The strength of an ant’s neck joint, which bears the full load when the ant is holding something, can be attributed to this.

When performing the experiments, the ants were placed on the fixture in such a way that the load would be applied on the head, while the body would in fixed in place. The results obtained from these experiments revealed an average rupture stress of 33.75 Mpa. This was similar to the result obtained by Nguyen (36.7 Mpa [1]) when she performed her experiments. In order to see if the segment to which the load was applied had any effect on this value or if it revealed any other phenomenon, testing was also performed with the ant’s orientation in the fixture reversed. This way, the load was applied on the neck joint via the ant’s body while the head was fixed in place. It was noticed that the average rupture stress in this case was 43.75 Mpa for n=4, which was close to the 95% confidence interval (42.64 Mpa) obtained when applying load via the head with the body fixed in place.
The soft membrane holding the head and the body also continued to stretch after the failure of the exoskeleton when the load was being applied in this manner. The mean of the maximum elongation (before which the soft membrane broke) in this case was $0.0165 \pm 1.6 \times 10^{-5}$ m, compared to the mean of $0.0066 \pm 5.15 \times 10^{-5}$ m when load was applied via the head with the body fixed in place. As mentioned earlier, this behavior can be attributed to high extensibility of the soft cuticle in different sections of the ant body when compared to the lower level of extensibility of the folded cuticle that provides more strength.

Because of higher extensibility when applying load via the ant’s body, the translation stage carrying the load cell would almost reach it’s travel limit. This could be rectified by moving the block holding the fixed part of the ant holder further down the base.
It was important to fix the ant properly in the ant holder. The following steps describe the process of loading an ant on the tensile tester:

a) The fixtures comprising the ant holder were placed next to each other, making sure there was no contact between them. If the fixtures touch each other, they would put a certain amount of load on the load cell and this would interfere with the load values we would get from the ant. To make sure they were not touching each other, a waveform graph was pulled up on LabView that would record the signals from the load cell. The reading on this would be a zero when there was no contact between the fixtures.

b) The ant’s head was then placed in the slot of the fixture that was attached to the load cell. This would put the ant neck in the middle of the two fixtures and the body in the slot of the fixture that was fixed relative to the base.
If it wasn’t fixed properly, it was noticed that the ant ruptured not at the neck, but at a point below the neck. This usually happened when the ant’s head was not entirely placed on the fixture connected to the load cell. This is shown in figure 60 below:
When the load vs displacement data was plotted for this ant, it was noticed that there were two peaks instead of one peak that was common with ants rupturing at the neck. The first peak was the incomplete rupture of the neck while the second peak was related to the ruptured of the ant at a point below the neck.
When the rupture took place at a point below the neck, it was seen that this point was usually one of the segments in the thorax. It can therefore be hypothesized that the load/strength requirements of the two regions are similar. This does not necessarily mean that the thorax region is as tough as the ant neck joint, and this can also be derived by looking at the dip in the peak value. As mentioned above, the main function of the soft cuticle here is to provide high extensibility whereas in the neck, it is to provide strength.
Chapter 5: Conclusion

The construction of a new micro tensile tester to test the neck joint of an ant along with the subsequent experiments provides an insight into the structure and material properties of the neck joint as well as its behavior under tensile loading conditions. The design phase involved taking into consideration the elaborate structure of the ant, the angular movement when applying load on the neck joint and finding a way to accommodate these. The experiments showed that the structure of the neck joint involves not just the exoskeleton but also a soft membrane. The failure values obtained in these experiments agreed well with the values obtained in previous research experiments conducted by a former Ohio State student, Vienny Nguyen. Although the new tensile tester provided a way to test the specimens at the micro level, improvements can be made to the tester that would help obtain data for future work on the project.

To begin with, a better load cell could be used for the experiments whose range can be drastically reduced from the one used in these experiments. The mean of the rupture load values obtained from the experiments was 0.19N, which corresponds to a value of 19.37g. Based on this value and to accommodate for any new phenomenon that might come up in future experiments, the upper limit for the load cell can be set to 50g. This range for the load cell would be expected to improve the signal to noise ratio. To improve the data acquisition process, signal conditioners can be used.
Signal conditioners manipulate signals to meet the requirements of the next stage of processing. The filters in these conditioners remove unwanted noise within a certain frequency range, such as using low-pass filters to block out high frequency noise in electrical measurements and also prevent aliasing from high-frequency signals [20]. Shielding agents, such as a faraday cage can also be used to improve this process. The effect of load angles on the neck joint of an ant can also be further studied by designing a fixture that could hold and load an ant at a specific angle. A potential design for this can be seen below:
An FEA model could be developed for an ant neck joint that would have different properties assigned to different regions of the neck joint. This could then be compared to the results obtained from the experiments. Another area that could be improved upon is the use of a better optical instrument to observe the loading behavior. For the experiments performed in this project, the microscope used couldn’t give an image with a sharp focus on the neck region of the ant when the load was being applied. A high powered microscope could be used instead in the future, or the setup of the device can be changed to get the microscope focused properly. These microscopes could be used to examine the point of failure.

The ant joint is a highly elaborate and complex system. Study of it’s structure and behavior could lead to the development of models which could be used in the design of devices to help human beings perform everyday tasks in a more optimized and efficient manner.
References


Appendix A: Matlab Programs
Load Displacement and Stress Strain

clc
clear all

dataset1 =
xlsread('Load_Displacement','Sheet1','A2:B10001'); % File containing load cell and displacement sensor values

V_L = dataset1(:,1);
V_D = dataset1(:,2);

L = 10.3.*(2.0538.*V_L + 0.2678)*0.0098;
D = (0.979.*V - 0.119)*0.0254;

% Transfer Function
os = 18.7*0.0098; % Offset value
L_m = L-os;
wn = 0.001;

z = 0.7;
s = tf('s');

G = 1/(s^2/(wn^2)+((2*z/wn)*s)+1);
t=0:length(L_m)-1;

% yL = lsim(G,L_m,t);

N = length(t);
dt = t(2)-t(1);

LL = [t' L_m];
sim('Fill_2')

yD = lsim(G,D,t);
% Stress Strain calculation

D_m_initial = 0.00944*0.0254 ; %initial length of neck

D_m_final = D_m + D_m_initial ; %final length of neck

strain = log (D_m_final./D_m_initial); %true strain

A_initial = 2.495*10^(-8); %initial cross sectional area of neck

stress = (y_L./A_initial).*(D_m_final./D_m_initial); %true stress

figure(1)
plot(yD,yL,'r')
xlabel('Displacement (m)')
ylabel('Load (N)')

figure(2)
pplot (strain,stress,'r')
xlabel('Strain');
ylabel('Stress');

function [X,f]=spectrum(t,x)
% find frequency content of signal

T=t(2)-t(1); % sample time, s
Fs=1/T; % sampling frequency, Hz
Fn=Fs/2; % Nyquist frequency, Hz (highest frequency can measure)
N=length(t); % number of samples

%NFFT = 2^nextpow2(L); % Next power of 2 from length of y
NFFT=N;
L=floor(NFFT/2);
% frequency resolution: \( df = \frac{fs}{N} = \frac{f_N}{N/2} \)

\( df = \frac{fs}{N} = \frac{f_N}{N/2} \)

\( f = 0 : df : f_N; \)

% frequency vector, Hz

\( XX = \frac{fft(x,NFFT)}{N}; \)

% complex amplitude (magnitude and phase)

\( X = 2*abs(XX(1:L+1)); \)

% magnitude of amplitude

### Peak Values

clc

clear all

%% Rupture Load

\( Rup\_load = ([0.1766\ 0.298\ 0.1468\ 0.1786\ 0.1321\ 0.2772 \ 0.0820\ 0.2307\ 0.1055\ 0.1671\ 0.2291\ 0.2539\ 0.1811\ 0.3182 \ 0.1546\ 0.3618\ 0.0562\ 0.2124\ 0.1527]); \)

\( m\_max\_load = mean(Rup\_load) \)

\( s\_max\_load = std(Rup\_load) \)

%% Rupture Stress

\( Rup\_stress = ([3.85*10^7\ 3.72*10^7\ 2.49*10^7\ 1.67*10^7 \ 4.60*10^7\ 1.93*10^7\ 6*10^7\ 1.43*10^7\ 4.54*10^7\ 4.70*10^7 \ 2.87*10^7\ 4.47*10^7\ 2.32*10^7\ 5.81*10^6\ 5.45*10^7]); \)

\( M\_rup\_stress = mean(Rup\_stress) \)

\( S\_rup\_stress = std(Rup\_stress) \)

\( n = length(Rup\_stress); \)

\( SEM\_Rup\_stress = std(Rup\_stress)/sqrt(n) \)

%standard error

\( ts = tinv(0.975,n-1); \)

\( CI\_1 = mean(Rup\_stress) + ts*SEM\_Rup\_stress \)

%confidence interval +95%
CI_2 = mean(Rup_stress) - ts*SEM_Rup_stress %confidence interval -95%

%% Max Elongation

max_elong = ([0.0066 0.0103 0.0065 0.0046 0.0032 0.0049 0.0045 0.0049 0.0060 0.0060 0.0076 0.0086 0.0083 0.0073 0.0093]);

M_max_elong = mean(max_elong)

S_max_elong = std(max_elong)

initial_length = 0.00944*0.0254;

M_percent_elong = ((M_max_elong - initial_length)./(initial_length))*100

S_percent_elong = ((S_max_elong - initial_length)./(initial_length))*100

%% Max Elongation Regime 1

Reg_1_max_disp = ([0.0034 0.0014 0.0029 0.0020 0.0013 0.0015 9.3770e-04 7.5828e-04 0.0022 0.0026 0.0022 0.0025 0.0018]);

M_reg_1_max_disp = mean(Reg_1_max_disp)

S_reg_1_max_disp = std(Reg_1_max_disp)

n = length(Reg_1_max_disp);

SEM_max_elongation = std(Reg_1_max Disp)/sqrt(n);

initial_length = 0.00944*0.0254;

M_percent_elong = ((M_reg_1_max_disp - initial_length)./(initial_length))*100

S_percent_elong = ((S_reg_1_max Disp - initial_length)./(initial_length))*100

ts = tinv(0.975,n-1); %confidence interval, _+95%
\[ \text{CI}_1 = \text{mean}(\text{Reg}_1_{\text{max\_disp}}) + \text{ts} \times \text{SEM}_{\text{max\_elongation}} \]
\[ \text{confidence interval} + 95\% \]
\[ \text{CI}_2 = \text{mean}(\text{Reg}_1_{\text{max\_disp}}) - \text{ts} \times \text{SEM}_{\text{max\_elongation}} \]
\[ \text{confidence interval} - 95\% \]

%% Confidence Interval

\[ n = \text{length}(\text{Rup\_load}); \]
\[ \text{SEM}_{\text{Rup\_load}} = \text{std}(\text{Rup\_load})/\sqrt{n}; \]
\[ \text{ts} = \text{tinv}(0.975, n-1); \]
\[ \text{confidence interval, } +, 95\% \]
\[ \text{CI}_1 = \text{mean}(\text{Rup\_load}) + \text{ts} \times \text{SEM}_{\text{Rup\_load}} \]
\[ \text{confidence interval} + 95\% \]
\[ \text{CI}_2 = \text{mean}(\text{Rup\_load}) - \text{ts} \times \text{SEM}_{\text{Rup\_load}} \]
\[ \text{confidence interval} - 95\% \]

Moving Average

clc
clear all

dataset1 = xlsread('Load_Dispacement_3_14_2017_Ant2','Sheet1','A2:B17001'); % File containing load cell and displacement sensor values

\[ V_L = \text{dataset1}(:,1); \]
\[ V_D = \text{dataset1}(:,2); \]

\[ L = 10^3 \times (2.0538 \times V_L + 0.2678) \times 0.0098; \]
\[ D = (0.979 \times V - 0.119) \times 0.0254; \]

%%

% Moving average

\[ M_L = \text{conv}(L, \text{ones}(1001,1)/1001, \text{'}same\text{'}); \]
\[ M_L_{\text{off}} = M_L - 18.7 \times 0.0098; \]
\[ M_D = \text{conv}(D, \text{ones}(1001,1)/1001, \text{'}same\text{'}); \]

% Transfer Function
os = 18.7*0.0098; %Offset value
L_m = L-os;
wn = 0.001;
z = 0.7;
s = tf('s');
G = 1/(s^2/(wn^2)+((2*z/wn)*s)+1);
t=0:length(L_m)-1;
%yL = lsim(G,L_m,t);
N = length(t);
dt = t(2)-t(1);
LL = [t' L_m];
sim('Fill_2')
yD = lsim(G,D,t);

figure(1)
plot(yD,yL,'r')
xlabel('Displacement (m)')
ylabel('Load (N)')

figure(2)
plot(M_D,M_L_off,yD,yL,'r')
Appendix B: Simulink Program
Figure 64 Simulink program to make the filtered data start at the initial point
Appendix C: Arduino Code
**Stepper motor**

```c
int smDirectionPin = 2; //Direction pin
int smStepPin = 3; //Stepper pin
int num = 0;
int k = 0;
double distance = 0.001; //DISTANCE YOU WANT TO TRAVEL (INCHES)
int steps = distance/0.0000123;

void setup() {
    /*Sets all pin to output; the microcontroller will send them(the pins) bits, it will not
    expect to receive any bits from thiese pins.*/
    pinMode(smDirectionPin, OUTPUT);
    pinMode(smStepPin, OUTPUT);
    Serial.begin(9600);
    Serial.println("Enter 1 to start the motor, enter 0 to stop the motor, enter 9 to reverse
    back to starting position.");
    //Serial.println(steps);
}

void loop() {
    digitalWrite(smDirectionPin, LOW); //Writes the direction to the EasyDriver DIR pin.
    //HIGH is clockwise.
    /*Slowly turns the motor 1600 steps*/
```
while (Serial.available()) {
    num = Serial.read();
    num = num - '0';
    Serial.println(num);
}

if (num == 1) {
    for (int i = 0; i < steps; i++) {
        int delayvalue = 700; // speed control
        digitalWrite(smStepPin, HIGH);
        delayMicroseconds(delayvalue); // -> these delays control speed
        digitalWrite(smStepPin, LOW);
        delayMicroseconds(delayvalue); // -> these delays control speed
        k++;
    }
    delay(0); // Controls Delay between spurts -> delay(0) makes continuous
}

else if (num == 0) {
}

else if (num == 9) {
    digitalWrite(smDirectionPin, HIGH);
    for (int i = 0; i < steps; i++) {
        digitalWrite(smStepPin, HIGH);
    }

    digitalWrite(smDirectionPin, LOW);
    for (int i = 0; i < steps; i++) {
        digitalWrite(smStepPin, LOW);
    }
}

delayMicroseconds(600);
digitalWrite(smStepPin, LOW);
delayMicroseconds(600);
k--;
if (k == 0) {
    num = 0;
    break;
}
}
Appendix D: LabView Program
Load Cell and Displacement Sensor Signal Capture

Figure 65 LabView Signal Capture
Appendix E: Load Displacement plots
Figure 66 Load vs Displacement

Figure 67 Load vs Displacement
Figure 68 Load vs Displacement

Figure 69 Load vs Displacement
Figure 70 Load vs Displacement

Figure 71 Load vs Displacement
Figure 72 Load vs Displacement

Figure 73 Load vs Displacement
Figure 74 Load vs Displacement

Figure 75 Load vs Displacement
**Ant 11**

Figure 76 Load vs Displacement

**Ant 12**

Figure 77 Load vs Displacement
Ant 13

Figure 78 Load vs Displacement

Ant 14

Figure 79 Load vs Displacement
Figure 80 Load vs Displacement

Figure 81 Load vs Displacement, Body pull