Variable Stiffness Beam

A Major Qualifying Project Report:

Submitted to the Faculty of the

WORCESTER POLYTECHNIC INSITITUTE

In partial fulfillment of the requirements for the

Degree of Bachelors of Science

By

Janelle Drake

Gerard Libby

Brian Silvia

Date: April 28th 2011

Approved:

Christopher A. Brown, Major Advisor

Contents

Table of Figures

Table of Tables

Table of Equations

Chapter 1: Introduction

1.1 Objective

The objective of this MQP was to research, design and create a mechanism which can be combined with a hockey stick in order to dynamically vary and control the flexibility. Ways in which the stiffness of a shaft can be varied via a mechanical means will be researched. Testing will be done on generic composite beams in the laboratory. A successful laboratory test will lead to the creation of a complete hockey stick prototype which should be fully functioning and able to be used in a competitive environment.

1.2 Rationale

The overall goal of the project is in creating a better composite hockey stick that the player can control the flexibility of. There are applications of this technology beyond hockey sticks. Other sports equipment, such as golf clubs or alpine skis could potentially benefit being able to change their flexibility "on the fly". Beyond sports, this technology could be applied to other areas such as building construction or vehicle suspension.

Specifically relating to hockey sticks, a variable stiffness shaft is desirable because it reduces the need to buy additional sticks. Currently, sticks are made with one level of flexibility or "flex", which cannot be changed. Different players require different flexes based on their skill, weight, level of play and personal preference. While a professional player may be able to afford purchasing a custom stick or a variety of sticks to find the best fit for him, this may be out of the range of a casual player. A variable stiffness stick would allow one stick to be purchased, and changed as necessary, such as when a young player begins to grow or change their equipment preference. Additionally, such a stick could be used as a training aid or to slowly rehabilitate an injured player.

Another advantage of this technology would be that the flexibility of the stick could be altered during the game. Typically, the harder a player flexes the stick, the faster the puck is shot when the energy is released. However, this means that the player has to put more time and effort into loading the stick. A player could make the stick more flexible, so that the shot could be released in less time, should it be necessary. Also, the player could stiffen the stick in order to make it more effective when attempting to tie-up opposing players sticks in order to regain the puck.

Finally, if the flexibility controlling mechanism were durable, it could possibly help alleviate another common problem in composite hockey sticks, frequent breakage. Currently, composite sticks are so prevalent because their enhanced flexibility over traditional wood sticks gives players a much harder shot. The down side is that they are more prone to breakage which is frequently seen at the NHL level and is also seen at lower levels of play. For example one article from the Boston Globe mentioned that University of North Dakota hockey players break 24-36 sticks per season per player. (Matson 2009) This results in monetary loss because the stick cannot be repaired, in addition the negative effects of this happening during a competition. Boston University coach Jack Parker said “They're so much more expensive and breaking often and at such inopportune times.” in regards to composite sticks. (Matson 2009). A stick that is as flexible as current composite sticks yet does not fail as easily would be a benefit to the sport as players could retain their hard shots without fear of breaking their stick.

Additionally, the economic elements of hockey sticks should be considered. A mass-produced composite stick could range from $150 to $300 for a stick reinforced with Titanium or other elements. This only represents the prices for mass produced sticks. Custom sticks, commonly used by higher level players, could potentially have an even greater cost. Such a mechanism to achieve these objectives could potentially offer a better priced option since one mechanism, and thus one stick, would appeal to many players. Players and coaches have noted that composite sticks do not show any signs of failure as traditional wooden sticks do. (Matson 2009) If this mechanism lessens the chance and/or degree of failure, it would reduce the consequences of having a stick fail during a game.

1.3 State of the Art

A variable flex hockey stick can be considered state of the art because no such product currently exists in the marketplace. The closest manufacturers have come to this technology is to structure the composite in such a way as to increase the stiffness of the shaft as the user flexes it more, but this is not the same as being able to predetermine a stiffness via a mechanical means. Two existing patents were found for similar technology.

The first was for a variable stiffness shaft which was noted that it could be applied to any type, including a hockey stick. The method for this was by running a cable along the inside of the shaft and tensioning it, which would put an initial tension on the shaft. (Brett P. Masters, 2002) Adjusting the input increases the amount of pre-tension thus decreasing the bending stiffness of the shaft.

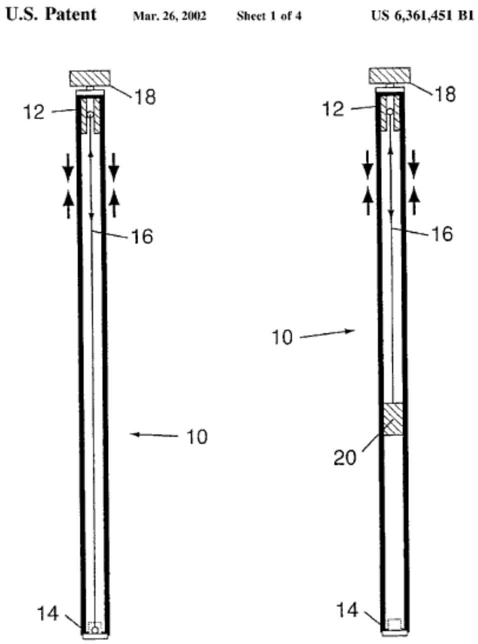


Figure 1: Cable Operated Variable Stiffness Shaft Patent

The second made use of an adjustable block within the hollow shaft of a hockey stick (Bird, 2000). By varying the location of the block, the point of flexure was adjusted, leading to a difference in flexibility.

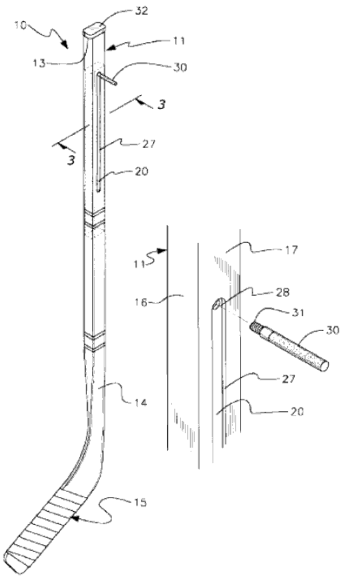


Figure 2: Adjustable Block Hockey Stick Patent

A study of a technology capable of implementing the desired functionality was also found. This made use of two composite tubes which had a working fluid in the gap between them (Li, 2008). By using valves to vary the flow of fluid into and out of the space, the flexibility could be adjusted. This technology was for use in building materials, however, and was not in any way associated with a variable flex hockey stick.

1.4 Approach

The project will design a system that can be used to vary the stiffness of the stick, based on user input, and will be self-contained within the stick, requiring no complex procedures or tools and will not affect the performance of the stick in game situations. This project will be accomplished by researching and developing methods of creating a variable stiffness beam. Developing a way to accomplish these objectives that have not been done before will be beneficial. It will allow for the creation of a hockey stick that is versatile and overcomes the limitations of current technology.

The proposed project would contribute to the state of the art because, while patents do exist for shafts with variable flexibility, they only represent two ways of accomplishing this particular task. They provide a basis for further designs, and they could be evaluated to see if they have any inherent advantages or disadvantages over the designs that will be created during the project. The patents themselves discuss the theory of operation but do not contain any information regarding their effectiveness. Our experimentation hopes to prove that there is a viable way to change the stiffness of a beam and that it will be useful for a hockey stick.

1.5 Method

The first step in creating these mechanisms will be to model a traditional composite hockey stick. This model will be used in FEA software to analyze typical forces on a hockey stick to understand how it operates and where points of failure exist. This will allow for an understanding of how a flexible beam will respond to changing its flexibility. It will also show how much force is imparted and in what locations so that we can ensure that the mechanism does not contribute to breakages.

The next step will be to design the necessary mechanisms. This will be done by first brainstorming ways in which the stiffness of a beam can be mechanically varied and in which breakages can be reduced. These initial ideas will be reduced down to the ways which seem most practical and capable of being created with the resources available. Using promising methods of both varying the flexibility and reducing breakage, approximately 2-3 designs of full mechanisms will be created. These mechanisms will be created through the use of axiomatic design. This will be done by maximizing the independence between functions of the flexibility mechanisms

The sub functions of the flexibility mechanism are:

1) A way for the user to select a flexibility
2) A way to change the flexibility of the shaft, such as altering the distance between the sides of the shaft
3) A way to ensure that the flexibility setting is not influence by anything other than the user input

These designs should be created in Solidworks and FEA analysis should be performed in ANSYS. The purpose of this is to ensure that the mechanisms will work, identify the benefits and drawbacks to each design, and determine how each can be created and implemented. Each design will be evaluated on the basis of: Cost, Simplicity, Effectiveness, and Durability.

The design which best satisfies all of these areas will be chosen as the design to prototype. The prototype will be created in the lab and implemented on a generic beam. It will be evaluated through the use of stress/strain gauges. It will be evaluated on whether or not the beam retains flexibility, has variable flexibility, and is durable. If the prototype fails any of these test criteria, the problem will be evaluated. If possible the design will be modified, or if necessary, a different design will be prototyped and tested.

If the prototype passes its tests it will be implemented into a hockey stick. This will either be an existing stick or one manufactured by the project team depending on which implementation would be easier. If a stick needs to be manufactured it will be made out of a common composite used for hockey sticks.

1.6 Design Introduction

It was decided that 3 separate designs would be created in order to achieve the goal of creating a variable flexibility hockey stick. These prototypes were designed to be incorporated with a composite shaft which would mimic the size and function of an actual hockey stick. This composite shaft was to be two feet long when constructed, compared with a production hockey stick which is traditionally 5-6 feet long. The reasoning in creating a shorter prototype was to save on the amount of material which would need to be purchased as well as to decrease the amount of manufacturing which would need to be done, in the interest of saving time. When using a hockey stick, based on the placement of the player’s lower hand, typically only a 2-3 foot section of the stick flexes, so we felt that our simplification would not greatly affect the validity of our results. In addition to standardizing the maximum length of each design to two feet, a coordinate system for the hockey stick was established. This is shown in the figure below:

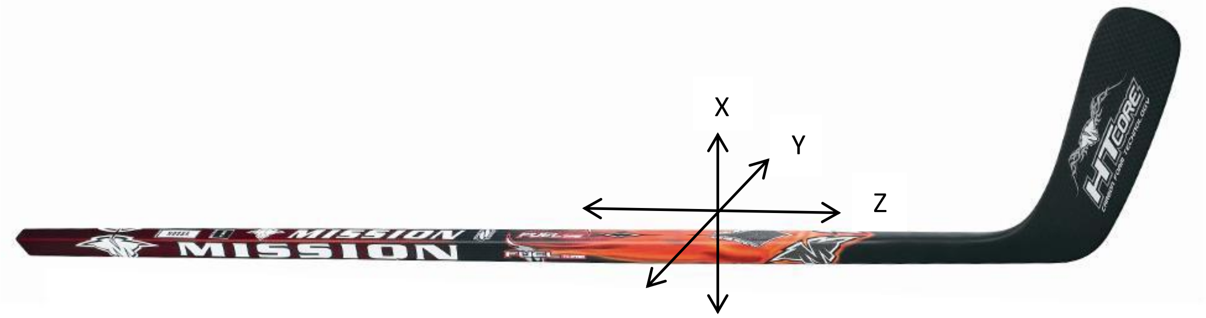


Figure 3: Hockey Stick Coordinate System

This system was chosen to eliminate possible confuse stemming from the orientation of the stick when playing hockey, versus the possible orientations when visualizing a mechanism to go inside of the hockey stick. The X axis is parallel to the longer cross-sectional dimension of the stick's shaft. The Y dimension is perpendicular to the longer cross-sectional dimension of the stick's shaft and the Z axis is parallel with the length of the hockey stick.

Chapter 2: Testing

2.1 Production of the Composite Shaft

Because these mechanisms were designed for use in a hockey stick, an approximation of a hockey shaft needed to be created. This shaft had to be able to hold all of the components as well as protect all components from harm. It also needed to maintain an initial flexibility that would hold the shaft rigid enough to support the mechanisms while flexible enough that it would not be detrimental to the testing of the mechanisms.

2.1.1 Initial Shaft

The initial prototype shaft was made from two layers of 1.25” diameter 12K heavy weight carbon fiber sleeve. A piece of foam was cut so that its dimensions were the same as the desired internal dimensions of the shaft. The foam was then wrapped in tape. The foam and tape were used as a mold that the carbon fiber sleeve was wrapped around. The tape was used to wrap the foam so that the epoxy used with the carbon fiber would not stick to the mold or melt the foam. Once the initial layer of carbon fiber was hardened, a second sleeve was wrapped around it. Epoxy was applied, and the shaft was allowed to set. When the carbon fiber was dry, the foam was dissolved with acetone and the tape was pulled out of the shaft. In order to achieve the desired length, the ends of the shaft were cut using a band saw.

This first attempt as making a shaft was not very successful. Using a foam mold did not work very well and allowed the carbon fiber to harden into a shaft that was not smooth, did not have straight edges, and did not have crisp internal angles. These visible defects made it very difficult for the mechanisms to fit in the shaft for testing and introduced forces that could not be accounted for. Another problem with this shaft was that it was extremely rigid. Having two layers of carbon fiber forming a box beam masked the contribution that the mechanisms made to the flexibility of the shaft. Overall, the testing done with the first shaft was not very conclusive and required a revision of the shaft.

2.1.2 Second Shaft

The second prototype shaft was very different from the initial shaft. To reduce the stiffness of the shaft, it was decided to use two flat strips of carbon fiber instead of a box beam to provide the structure for the shaft. These two strips were rigid enough to support the mechanism and protect it from external damage, but were flexible enough that they did not mask the effects of the mechanisms. To overcome the defects from using the foam mold, Lightweight 3K carbon fiber sheets were used to make the strips instead of the sleeves used previously. The sheets were flattened out on a plastic covered hard surface to ensure that they were smooth and straight. After they hardened, they were cut to the right size and shape. In order to hold the two strips together and make sure the mechanisms could fit, a carbon fiber sleeve was placed around the strips. The sleeve was not hardened. This allowed the shaft to retain its flexibility, expand or contract to hold differently dimensioned mechanisms, and hold the mechanism in the shaft. The second shaft was noticeably more flexible than the first shaft, due to the flexible sides and thinner top and bottom strips.

2.2 Testing Frame

In order to gather data on each design, it was necessary to fixture the beams so simply supported beam testing could occur. This was done via a testing frame adapted to the requirements of our MQP. It limited the effect of extraneous factors which could disturb results, so that consistency and repeatability of testing could be ensured.

2.2.1 Initial Frame

A frame needed to be constructed, so that the displacement tests could be performed on the mechanisms. A modular aluminum frame, previously used to test the bending of alpine skis, was available for use. After some re-configuration it was adapted for use with the beam mechanisms. The setup for testing is in the following figure.

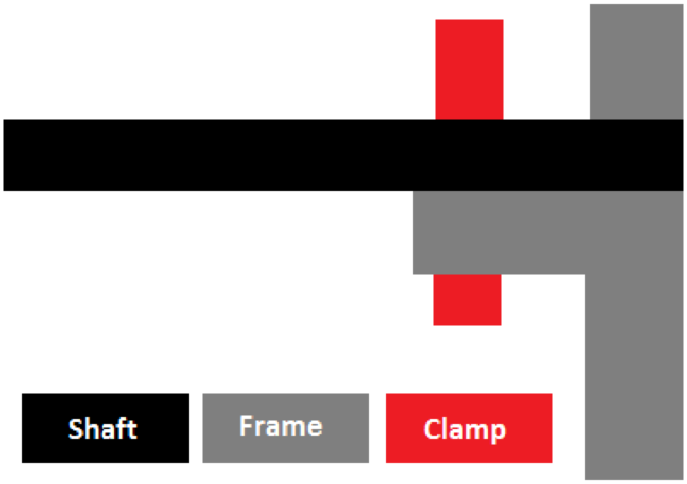


Figure 4: Initial Test Schematic

This figure shows an approximation of how the Veriner height gauge would have been used to measure the deflection.

Figure 5: Initial Test Photograph

This setup caused several problems with the testing. The sharp angle where the frame met the shaft caused forces unlikely to be expected by a hockey player by concentrating them along a single line. The clamp was used to stop the shaft from sliding off the support, but added external concentrated forces in a manner that was difficult to analyze and also unlikely to occur while being used by a hockey player. The frame also caused problems by having a portion of the shaft lie flat along it. All of these caused data acquisitions problems that would not be encountered in normal use.

2.2.2 Revised Frame

The revised frame took into account the problems with the initial frame and worked to correct them. A cantilever support system was decided on to improve the frame. To eliminate the concentration of forces at sharp edges, cylindrical rods were added to the frame so forces were coming from a rounded surface. This also eliminated the problem where the shaft was resting on a flat surface. To eliminate the need for the clamp, the cylindrical rods were made long enough that the shaft would not slide off of it. The resulting frame is shown in the following figure.

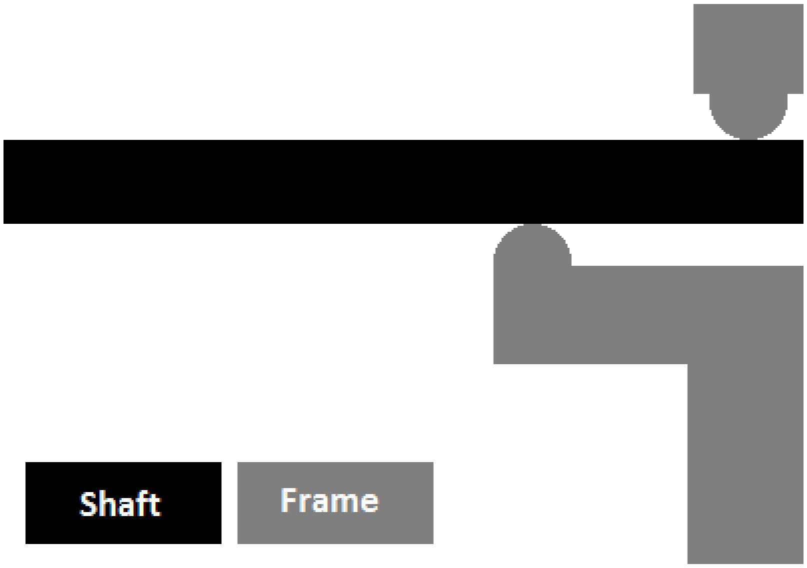


Figure 6: Revised Testing Schematic

The following figure shows a sample test set up.

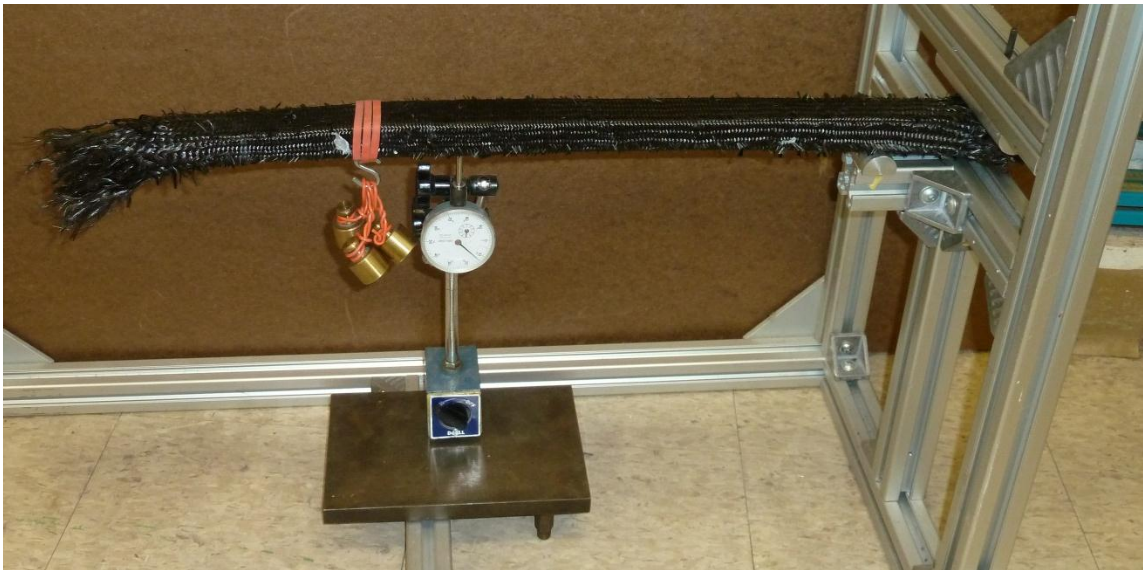


Figure 7: Revised Testing Photograph

2.3 Testing Process

To ensure that data was accurate, the testing process had to be done carefully. To determine the effects on the mechanisms under different stress loads, the mechanisms were tested under three different weights, of 20g, 40g, and 60g. To determine how much creep was experienced by each design, measurements were taken at three different time intervals.

2.3.1 Initial Process

The basic process for testing the mechanisms was kept consistent for all mechanisms. The mechanism was put into its more flexible setting. The height of the end of the shaft was measured, the lightest weight was added and the height was measured immediately, after fifteen seconds, and after thirty seconds. The weight was then removed. These steps were followed again, but using the middle and then heavy weights. After testing all weights, the mechanism was switched to its less flexible orientation and this process was repeated. Several sets of data were acquired for the shaft in its flexible and inflexible orientations for each mechanism.

A wire loop was wrapped around the end of the shaft. From this wire were hung the weights, using more wires. This probably introduced some errors into our data as the wire around the shaft could slide a little bit and the wires attached to the weights allowed for the weights to rock and provide inconsistent forces.

To measure the height, a Vernier height gauge was used. The base of the gauge was place on the floor and the gauge was placed above the shaft. A piece of paper was slid back and forth across the top of the shaft while the gauge was lowed onto the piece of paper. When the paper could not slide freely across the top of the shaft, the measurement was recorded. This process caused some problems. The floor of the workshop was not even and the base was not fixed, so when taking measurement, it is possible that the height was taken from different parts on the uneven floor. This would add uncertainty. Also, using the piece of paper was not accurate, as the longer the paper was used, the more worn it became. Additionally, the time required to adjust the height gauge was substantial and so getting the measurements at accurate time intervals was not possible.

2.3.2 Revised Process

The revised process eliminated these sources of error. To hang the weights, a rubber fastener was used at the end of the shaft instead of the wire. The fastener was tight enough that the friction prevented any accidental motion along the beam. Instead of using wires to hang the weights, S hooks were attached to the fastener so the weights were held securely. To counteract the inaccuracies of the height gauge, a dial indicator was used to obtain changes in height. The base of the dial indicator was an electro magnet that allowed the base to be fixed to a marked location for each test to ensure accuracy. The dial indicator provided constant accurate measurements of the height so that it was possible to obtain measurements at consistent time intervals. The dial indicator was also zeroed before each new weight was added or data set was started. This was something not done during the first round of testing and greatly increased the repeatability of the testing.

2.4 Testing Theory

The testing process was designed so that the various designs could be compared using quantitative data about their performance. This was done by testing the deflections of our prototypes under various loading conditions. The prototypes were tested in a cantilevered configuration because we felt this accurately represented the loading of the lower portion of a hockey stick in a game setting. This configuration is shown in the following figure.

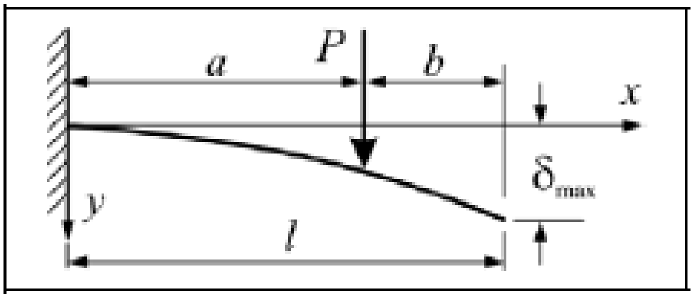


Figure 8: Cantilevered Beam Configuration

The deflection on a location at point X on a cantilevered beam subject to a point force is represented by the equation:

Equation 1: Deflection at X Position of Cantilevered Beam

$$\delta = \frac{Pa^3}{6EI}(3x - a)$$

Where "$\boldsymbol{\delta}$" equals the deflection, **"P"** represents the magnitude of the force, "**E"** the modulus of elasticity of the beam, **"I"** the moment of inertia, "**x"** the location at which the deflection is measured, and "**a"** the distance the load is from the fixed portion of the beam. For our testing, the masses of the weights were known, so **"P"** could be calculated by multiplying the mass by the acceleration due to gravity. The values for **"a"** and "**x"** were recorded during testing. These values represent the location of the hanging weights and the location of the dial indicator, respectively. Since "$\boldsymbol{\delta}$" was the value being measured by the dial indicator we could re-arrange the equation to solve for the quantity of **"EI"**. The "**E"** value is an inherent property of a material, and since our mechanisms were constructed of multiple materials, it would be difficult to get an equivalent value. The value of **"I"** is a function of the cross-sectional area of an element. Since our designs feature complex geometries and varying mechanisms, it was not practical to calculate this value. Calculating an equivalent **"EI"** value based on our experimental data will allow us to compare the operation of our various mechanisms. This data is located in the results section for each design.

2.5 Testing assessment

To ensure that our testing set-up was accurate, it was decided to test a beam made of a material with a known modulus of elasticity. By comparing our experimental results with the published values, we could determine if our testing method was valid. Aluminum was chosen for the test beam as its modulus of elasticity is known to be 68.9 GPa depending on the grade (Aerospace Specification Metals Inc., 2010). The revised testing frame and revised testing procedure were used to find the deflection of the aluminum beam. The aluminum beam had nominal dimensions of 2mm thick and 25mm wide and was 431.8 mm long. The beam was subject to a 20g mass since all heavier masses exceeded the measurement capabilities of the dial indicator. After collecting 25 sample data points measured at a length of 406mm, the average deflection was found to be 10.6mm. This meant that the experimental modulus of elasticity was found to be 42 GPa.

There is an obvious disparity between the experimental results and the accepted value for aluminum. However, this test was performed on a non-ideal sample using simple testing equipment. Our result is within the same order of magnitude as the published value, at is reasonably close to it. From this we can say that our testing method is sufficient for the data we will be collecting when analyzing our designs.

Chapter 3: Shear Friction Design

3.1 Shear Friction - Concept and Theory of Operation

One method which was discussed for varying the stiffness of a beam would be to vary the amount of friction between two surfaces located at the neutral axis of the beam. Since these two surfaces would be in shear as the beam was loaded, a change in friction between them would result in a change in the transmission of the shear force between them. It was hypothesized that by manipulating this shear friction, the beam could be made more or less flexible as the two surfaces were more easily able to “slip” past each other. This method would necessitate the creation of a solid boundary at the neutral axis of the beam, over which a mechanical device could act to change to friction. The term “neutral boundary” will be used to reference the solid surface located at the neutral axis of the hockey stick. Also, the mechanical device to increase the normal force is the device which is being designed as part of this MQP and will be referenced as “the mechanism”.

The first aspect of this design that had to be created was how a shear boundary would be created at the neutral axis of the beam. It was decided that providing a hollow space, which bordered on a thick bottom edge of the beam could create a boundary that existed at the neutral axis of the beam. A required thickness of 6.70 mm was calculated for the bottom portion of the stick.

A number of initial ideas were investigated as to how the force on the neutral surface could be increased and decreased on command. Linkages, cams, and sliding pins were all considered as possible solutions. Finally, it was decided that a helix shaped shaft would be used in order to progressively increase the force on different areas of the neutral boundary. By using a gradually spiraling helix, the friction could be incrementally increased, which would theoretically create different flexibility “settings”.

This helix shaft needed a surface upon which to act. A stiff plate, the width of the neutral boundary, would be used to distribute the normal force applied by the helix. This would ensure that the entire neutral boundary was engaged on each side. This plate would connect to a top plate via sliding pins. The purpose of the top plate is to hold the entire assembly to the inside of the beam, as well as to transmit the forces generated at the neutral boundary. A solid model of the final design is shown in the figure below.

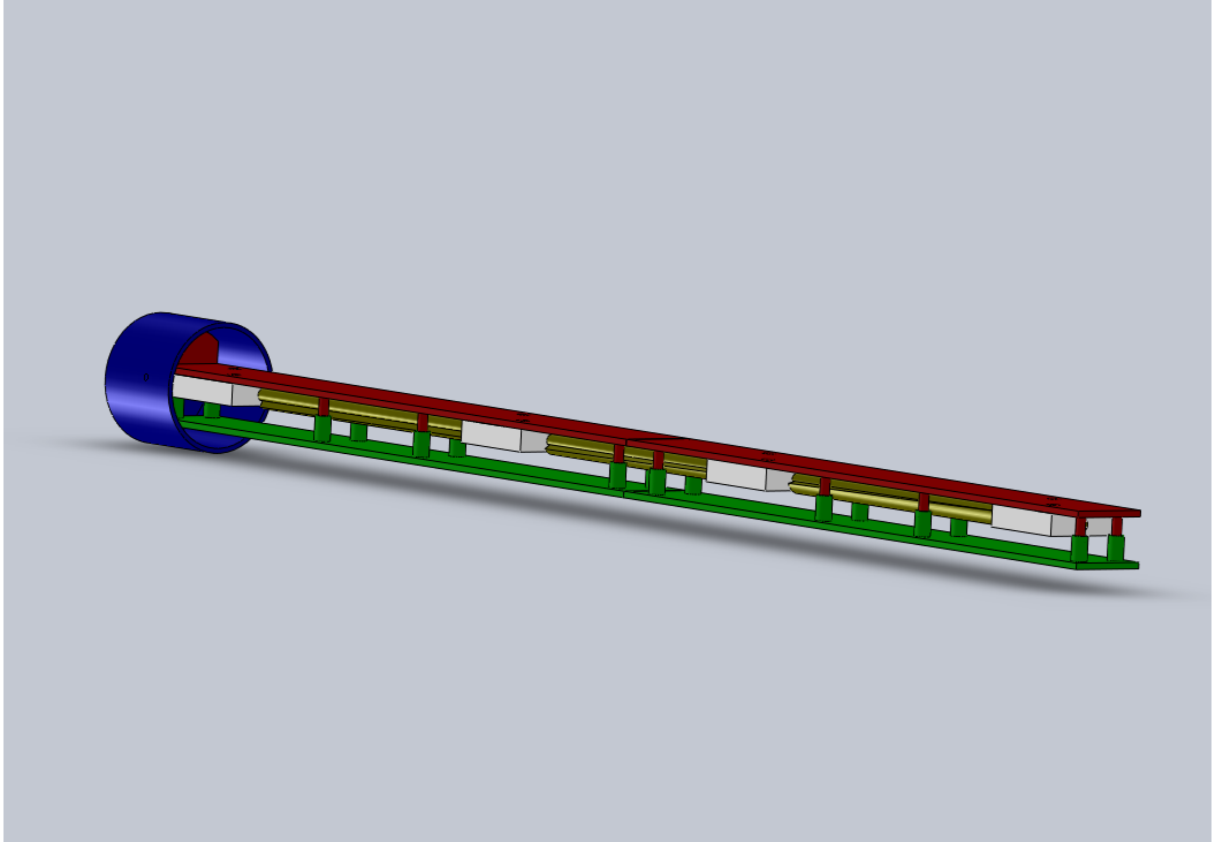


Figure 9: CAD model of Shear Friction Assembly

3.2 Shear Friction - Decomposition

3.2.1 Level One Decomposition

Table 1: Shear Friction Level 1 FRs and DPs

FR 1 – Provide Composite Shaft	DP 1- A graphite composite shaft which has a surface at the neutral axis and which protects the components contained within
FR 2- Increase normal force on surfaces in shear	DP 2 - A system to increase the normal force on the shear surface by increasing the force on moveable Plate B
FR 3- Control installation into composite shaft	DP 3 - An upper plate (Plate A) onto which all other components attach
FR 4 – Allow the user to control the normal force	DP 4 - A handle located at the top of the hockey stick which the user can rotate

This design involves an interaction at the neutral axis of the hockey stick. Theoretically, if two plates are stacked together and then flexed, there will be a sliding motion where those surfaces meet. The hypothesis was that, if the force on that location can be manipulated, then the flexibility could be changed.

The first level FRs and DPs are shown in the table above. In order for a variably flexible hockey stick to be useful, it needs to be similar to standard hockey sticks. This means it needs to have a shaft which has similar outer dimensions to traditional hockey sticks. For the purposes of this mechanism, it needs to have a surface at the neutral boundary for the interaction to occur. This is shown in FR1 and DP1. The multiple functions that the shaft needs to perform at outlined in DP 1. It needs to protect the components of the mechanism, and it needs to have a neutral boundary. Finally, it is specified as composite because the objective of the MQP is specifically to build mechanisms to vary the flexibility of composite hockey sticks.

In order to affect the flexibility of the entire hockey stick, the mechanism needs to increase the normal force on the surfaces in shear. This is necessary since an increased normal force will increase the transmission of the shear forces at the shear boundary. By increasing or decreasing the transmission of these forces, the flexibility can be varied. FR 2 is the requirement for the aspect of the design which will accomplish the change in normal force. In DP 2 it is shown that this will be done by a system which will increase the force on a moveable plate. This moveable plate will be the top part of the shear boundary. The lower part will be the boundary provided by the composite shaft, as outlined in FR 1.

The entire system described in FR 2 needs to be capable of being installed within the composite shaft. FR 3 describes the methods by which this will happen. As shown in DP3, a plate designated “Plate A”, will be the base to which all other components attach. This will allow a single assembly to be installed into the composite shaft. This will alleviate any difficulties which could arise from trying to install a complex mechanism into such a small space.

Finally, the system which increases the force on the surfaces in shear and needs to be controlled by the hockey player, as shown in FR 4. Since the mechanism is designed to be controlled by a hockey player, there needs to be a control system which they can operate. DP 4 shows a handle which the player will rotate in order to control the mechanism. This DP was chosen because it was believed that a rotational motion would be the easiest motion for the player to provide while holding the stick. The players hand will be located at the top of the stick regardless, and the stick is generally hollow, so this is a convenient location for the controls. It is easy to control the mechanism from that location, and it does not significantly alter the function of the stick, or how the player uses it.

3.2.2 Level 2 Decompositions

Table 2: Shear Friction Level 2 for FR and DP 1

FR 1.1 Protect internal components	DP 1.1 A void with such dimensions that that it does not affect the neutral boundary yet with enough room to fit interior components and with an impact resistant shell
FR 1.2 Control Initial flexibility	DP 1.2 Section modulus
FR 1.3 Control location of shear boundary	DP 1.3 A solid beam of such height that it forms at surface at the neutral axis of the entire composite shaft
FR 1.4 Control outer dimensions	DP 1.4 The shell should maintain dimensions similar to that of a normal hockey stick and be able to be comfortably used by a player

As shown in this table, the lower level FRs of FR 1 all deal with the various functions that the composite shaft itself will provide. Those functions are; protection, setting the initial level of flexibility and creating the neutral boundary.

Since hockey is a contact sport, and the stick itself is involved in high impact uses such as slap shots and stick checking, it is necessary that something protect the components used to activate the mechanisms. This is accomplished in DP 1.1. Hockey sticks are generally hollow. This fact means that we can use this internal space to house the components of the mechanism. Since the outside of the stick will be rigid carbon fiber, they will be able to protect the components within.

FR 1.2 is necessary because the shaft itself will have a great deal of rigidity itself, which must be controlled. The initial stiffness could potentially influence the effects of the mechanism. Thus, this initial flexibility needs to be controlled in order to produce a successful device. This is accomplished by controlling the initial dimensions of the stick’s cross section, as well as the material it is made out of. There is some difference in the material properties of different carbon fiber weaves, which could potentially be used to control the initial stiffness of the stick. In addition, different wall thicknesses, and different cross sectional areas can be used to control the initial stiffness.

The location of the shear boundary is critical as shown in FR 1.3. The stick must be designed in such a way that there is a physical surface located at the neutral axis of the stick. Care must be taken to design this surface such that it still provides a realistic amount of room inside of the shaft for the flexibility mechanism.

FR 1.4 is necessary because we don’t want the variably flexible hockey stick to be much different from what hockey players are used to. It is necessary to control the outer dimensions so players feel comfortable using it. If it was too large, players would not be able to handle it well or would feel it was hurting their game. If hockey players do not want to use this new type of stick then then there would not be any purpose in creating it.

A number of functions of a traditional composite hockey stick can satisfy the initial FRs for the composite shell, thus the shell for this design will closely mirror that of a traditional hockey stick. Since a hockey stick needs to be durable in order to withstand the abuse of the game, a shell made of the same material and in the same way will be able to protect the mechanism. By controlling the material the shell is made out of, and the moments of inertia, we will be able to control the section modulus and therefore establish our initial flexibility. The only difference between this composite shell and a traditional stick will be the build-up of material to create a surface at the neutral boundary. However, since traditional sticks are completely hollow, removing some of that space will not greatly influence the effectiveness of the hockey stick. It will add some weight but it is necessary for the operation of this mechanism.

Table 3: Shear Friction Level 2 of FR and DP 2

FR 2.1 Translate rotation into a force applied in the Y- direction increasing linearly along the length of the stick	DP 2.1 A system such that a rotation increases the force provided in the Y direction and such that a rotation increases the normal force at different locations moving linearly up the shaft
FR 2.2 Transmit normal forces to shear boundary	DP 2.2 A system (Plate B) such that the increase in normal force is transmitted to the entire shear boundary
FR 2.3 Restrict helix movement to rotation about Z-Axis	DP 2.3 A system which permits rotation of the helix yet does not allow any translation
FR 2.4 Attach user controls to helix	DP 2.4 A user input handle which has a hole into which the helix fits, and set screws to hold it in place

FR 2.1 shows that a system must be designed in order to allow the rotation of the controls to interact with the shear surface in the middle of the hockey stick. This necessitates the translation of a rotational movement into a lateral movement along the Y-axis, since that axis is perpendicular to the shear boundary. This increased force will increase the transmission of the shear forces and will allow them to be transmitted back to the hockey shaft. This will alter the flexibility as the shaft is loaded. DP 2.1 states that a system will be created in order to transform the rotational motion into an increased force in the Y direction. This system also needs to progressively increase this force at different locations along the X- direction of the stick. It was believed that by varying both the normal force and the number of locations where it is occurring, that a greater range of flexibilities could be achieved.

Since a player can easily rotate their hand located at the top of the hockey stick then actuating the mechanism using this motion would be preferable since it would not interfere with a player's regular movements during a game. Since the player would be provide a rotational motion, yet the normal force on the neutral boundary needed to act perpendicular, then the rotational motion would have to be converted to a translation in the Y-direction as defined by our coordinate system. A method of increasing this force via a sliding operation was also considered, however this would necessitate a slot being cut in the hockey stick which would weaken its structure and cause premature failure.

In addition, the normal force applied to the neutral boundary needed to be applied over the entire boundary, in order to effectively act upon it. FR 2.2 is necessary to create the method by which the normal force will be distributed. DP 2.2 states that a plate would be used to distribute the point load provided by the mechanism and increase the normal force. Early designs involved separate plates for each section of the neutral boundary; however FEA analysis determined that this would cause un-wanted flexibility in the surface applying the force so the plate was re-designed as a solid piece.

FR 2.3 is necessary so that the helix increasing the force is properly fixtured so as to not deflect when the force is increased. This would negate the effect it would have on the neutral boundary. DP 2.3 provides a system to restrict the motion of the helix to be only rotational motion.

Finally as shown in FR 2.4, this mechanism needed to be attached to the user controls. DP 2.4 states that this would be done via set screw. This solution was the cheapest and easiest to fabricate that also allowed the mechanism to be taken apart.

Table 4:Shear Friction Level 2 of FR and DP 3

FR 3.1 Permit installation of helix into bearing blocks	DP 3.1 A bearing block which splits into two halves
FR3.2 Attach bearing blocks	DP 3.2 A threaded hole in Plate A into which a screw can be inserted and tightened, through the two halves of the bearing block, tightening the whole assembly
FR 3.3 Attach to composite shaft	DP 3.3 Threaded holes in Plate A into which screws can be inserted and tightened from the outside of the hockey stick
FR 3.4 Attach Plate B	DP 3.4 A series of pins on Plate B which fit into hollow pins in Plate A. The height of the inside of the shaft holds the two plates together

The lower level functional requirements of FR 3 dictate how the mechanism needs to be packaged. Since this mechanism is being installed within a hollow shaft, it needs to be designed in such a way that the full mechanism can be installed into the shaft, since no further assembly will be possible once it is installed.

FR 3.1 is necessary because the assembly needed to be constructed in such a way that everything could be assembled prior to its installation into the stick. This was done by designing a two piece bearing block to hold the force increasing helix which is shown in the following figure.

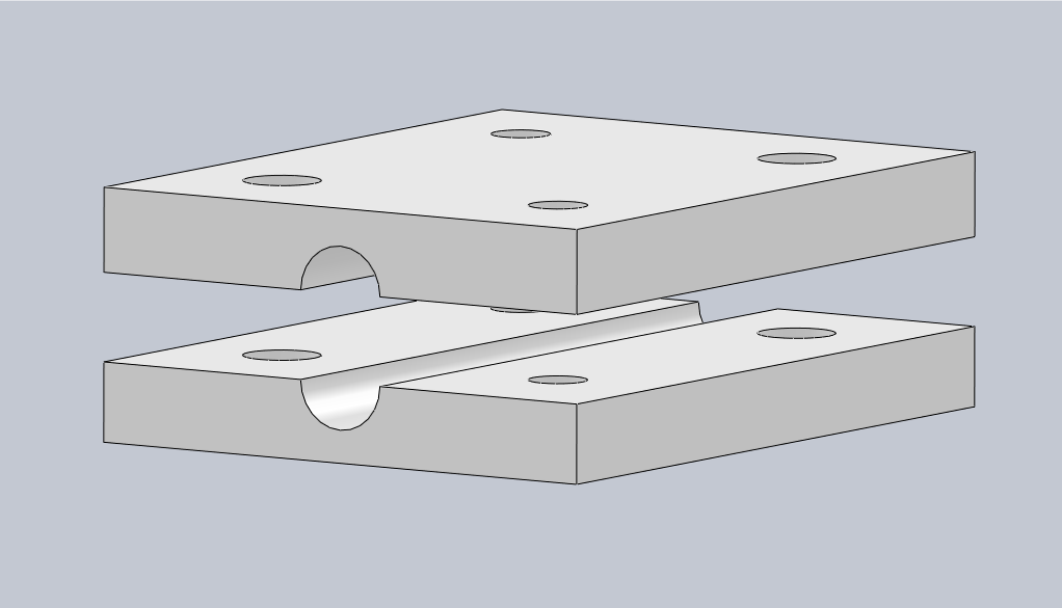


Figure 10: Two Piece Bearing Block

This allows it to support the thinner sections of the helix so that it can prevent un-wanted translation of the shaft. These bearing blocks, which support the entire helix, are attached to an upper plate, designated “Plate A”. This plate is discussed in DP 3. Plate A provides a stable platform to attach all other components to. The bearing blocks are threaded so that screws attach them to Plate A via threaded holes within the bearings as described in DP 3.2. “Plate B” which is the lower force distributing plate, is attached to Plate A using hollow tubes which slide around pins projecting off of plate A as described in DP 3.4. This allows Plate B to translate in the Y – direction while still transmitting the shear loads generated in the X direction. Finally, plate A is threaded so that machine screws can come through holes in the hockey shaft and thread into Plate A, holding it on the hockey stick. The holes in the top surface of the hockey stick will be relatively easy to line up with the holes in Plate A.

Table 5: Shear Friction Level 2 of FR and DP 4

FR 4.1 Match diameter of outer shell	DP 4.1 The handle should not be significantly different from the rest of the stick
FR 4.2 Create enough space for a player's hand	DP 4.2 The handle should be large enough that a players is easily able to grab it
FR 4.3 Select level of flexibility	DP 4.3 A ball spring, contained within the upper plate that interacts with one of six detents on the interior of the handle

These FRs shown in the table above, describe the functions the control system which set the level of flexibility for the stick. In order for the final design to be useful as a hockey stick, the controls must be ergonomic, or else players will be unwilling or unable to use it.

FR 4.1 ensures that the dimensions of the handle were not much larger than the traditional outside diameter of a hockey stick. This is because if the handle is too much larger than the outside of the stick, it will be uncomfortable for the player to hold, since their hand is kept at the top of the stick. FR 4.2 kept the total height of the handle small enough that it would not be un-wieldy, yet would still be able to be manipulated by the player. The controls also needed a definitive means of selecting the level of flexibility desired as shown in FR 4.3. The flexibility was set via a spring plunger, a pre-fabricated device available which requires a pre-determined amount of force to push a ball bearing out of a groove, which would then permit motion. The technical drawing of this device, provided by Mc-Master Carr, is shown below.

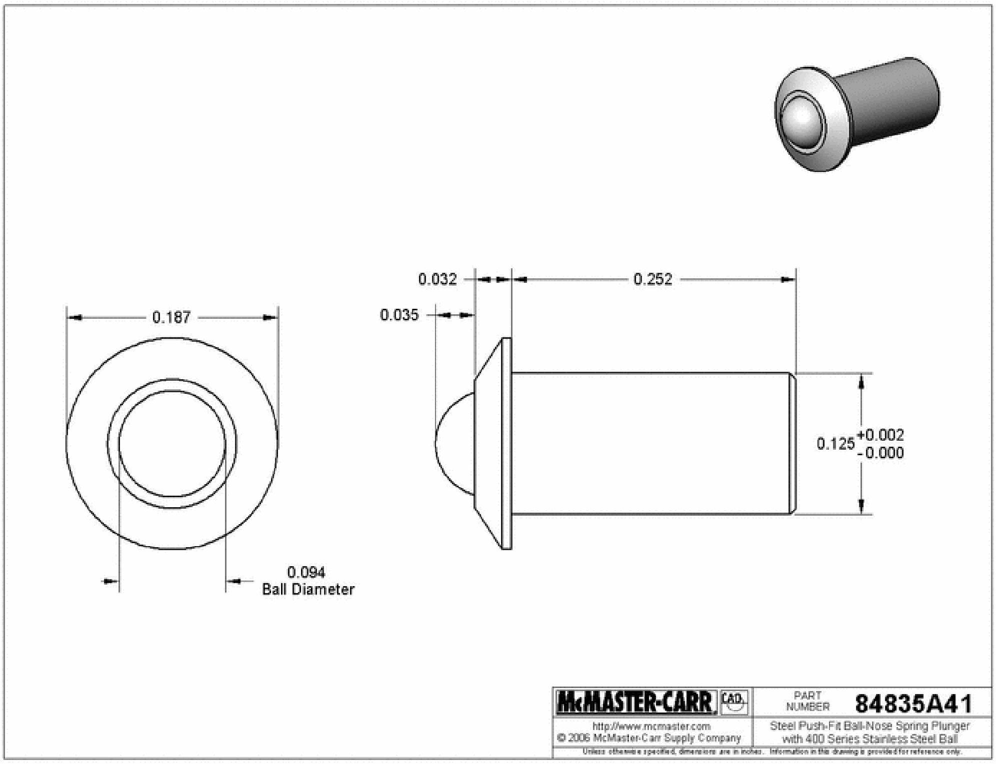


Figure 11: McMaster-Carr Spring Plunger

The handle of this design had 6 such grooves to correspond with 6 levels of flexibility. A spring plunger with a force of 2.3 pounds was used, as this would be easy for a player to over-come via rotation but enough that movement of the stick would not cause an accidental change in the level of flexibility. These spherical grooves are shown in the following figure.

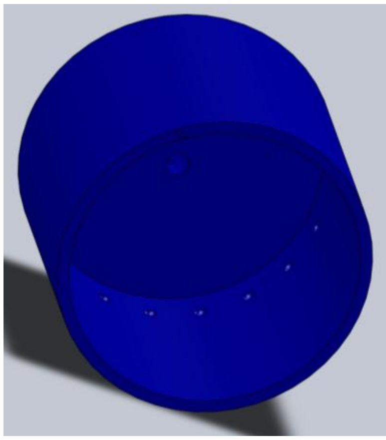


Figure 12: Shear Friction Handle

Initially the handle was designed as having a fixed spring which would always return the mechanism to its lowest setting. This would require the player to maintain a constant rotation of the handle in order to obtain the desired flexibility. This idea was dropped due to the extra effort needed by the player to maintain the level of flexibility and due to the fact that there would be no feedback regarding which level of flexibility was selected.

3.2.3 Level 3 Decompositions

Table 6: Shear Friction Level 3 of FR and DP 1.2

FR 1.2.1 Control Compression Strength	DP 1.2.1 A fiberglass composite in which the fibers are perpendicular to the direction of shear force
FR 1.2.2 Control Tension Strength	DP 1.2.2 A fiberglass composite in which the fibers run parallel to the normal force on the surface

These FRs shown above describe how the composite shell must be constructed in order to maximize the effect of the mechanism. When the stick is flexed it must be strong in tension so that it can distribute the force over the entire length of the beam, yet be weak enough in compression that the beam does not support itself and instead allows the flexibility changing mechanism to do its work. These needs are shown in FR 1.2.1 and FR 1.2.2.

Since we would be constructing the hockey stick which we would be using for our designs, we could manipulate the orientation of the fibers within the carbon fiber cloth to some degree. By manipulating the fibers such that they were parallel to the normal force yet perpendicular to the shear force, we could control how stiff the initial hockey stick would be. Since the carbon fibers are very strong we subject to tension, loading them in a direction perpendicular to their orientation would lead to a more flexible composite, when loaded in that direction. By constructing our hockey stick in this way, we would ensure that the initial flexibility of the stick was low enough that the mechanism would have an effect and manipulate the flexibility of the stick.

Table 7: Shear Friction Level 3 of FR and DP 2.1

FR 2.1.1 Translate and increase force	DP 2.1.1 A shaft profile shaped such that the profile gets larger as it is rotated, increasing the force in the plate below it
FR 2.1.2 Increase the force on a linear profile along the stick	DP 2.1.2 A series of different profiles forming a helix such that a rotation of the shaft causes more and more profiles to increase the normal force on the plates below them

These FRs describe how the system which increases the normal force, must operate. Since this design required that a rotation of a shaft would both increase the force acting in the Y-direction as well as increasing the number of locations at which this force increase was applied the further the shaft was rotated, a special geometry to accomplish this goal needed to be designed. The mechanism must translate the rotation the helical shaft provided by the player and transform it into a force in the Y direction so that there is a greater transmission of the shear forces. The increase in shear force was also designed to progress up the shaft of the hockey stick, allowing a greater range of flexibilities for the stick.

First, a profile was designed so that a portion of the profile could not reach Plate B from the center of the shaft, which was in-line with the bearings, as required in DP 2.1.1. The distance from the top of Plate B to the center of the shaft was determined, as this represented the largest diameter which the helix needed to be. A piece of metal of that size would press against Plate B and increase the transmission of shear forces.

DP 2.1.2 requires a number of different profiles so that as the shaft was rotated, the transmission of shear force would be increased at more locations along the length of the shaft. The following figure shows the different profiles of the helix along its length.

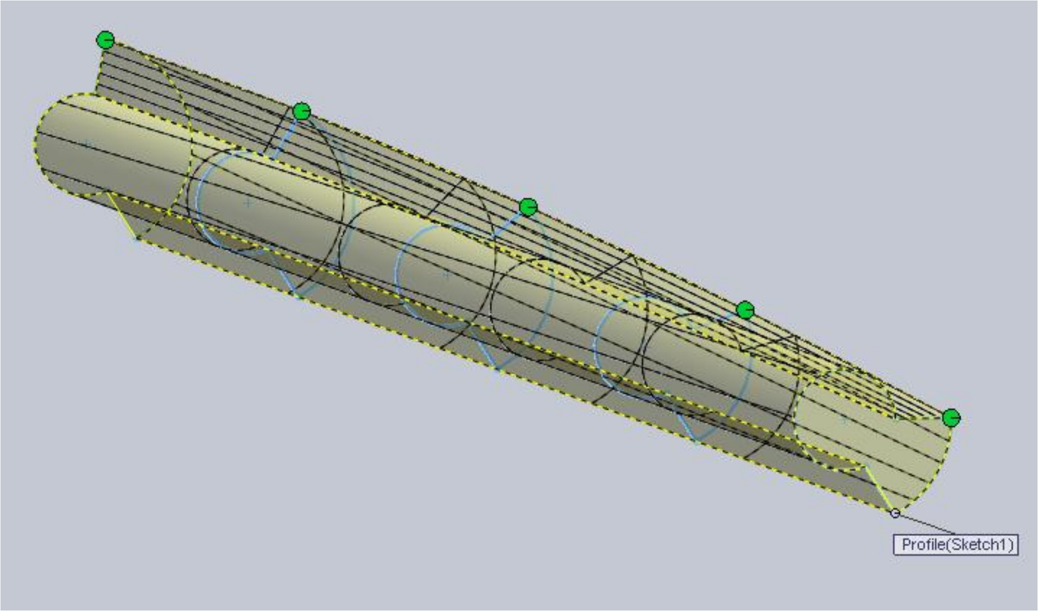


Figure 13: Shear Friction Helix

These different profiles meant that a further rotation of the shaft was needed to cause different sections of the neutral boundary to experience different amounts of shear transmission. This method was hypothesized to allow for a wide range of flexibilities since more of the stick would become rigid the more the helix was rotated.

Table 8: Shear Friction Level 3 of FR and DP 2.2

FR 2.2.1 Distribute Load	DP 2.2.1 A plate the same size as the shear surface which will distribute the point loads provided by the helix
FR 2.2.2 Limit movement to translation about Y-axis	DP 2.2.2 A tube on the plate into which pins from Plate A slide, preventing movement in all directions except for Y

FR 2.2.1 is necessary the neutral must be distributed over the entire neutral boundary, instead of just in one small area. This is because a distribution will ensure that any shear forces generated will be transmitted throughout the entire stick so the mechanism can alter the flexibility. DP 2.2.1 is necessary because a plate will be most effective at distributing this load because it can be the same size as the entire neutral boundary. It is necessary for Plate B to be the same size as the neutral boundary

surface upon which it acts, since a shear force will be generated along the entire neutral boundary when the stick is flexed. If it is stiff enough it will transmit the force provided by the small contact patch of the helical shaft over a large area.

FR 2.2.2 states that this plate must be restricted to moving the in Y axis so that it can allow for an increase and decrease in the normal force while still transmitting the forces generated at the shear boundary. The forces generated at the shear boundary will attempt to move Plate B when the stick is flexed. The plate must resist this motion by not translating in the X or Z directions. This is accomplished through the use of a pin and tube system shown in DP 2.2.2. This allows the tubes, located on Plate B, to slide on the pins located on Plate A, yet any other translation will cause interference, and will transmit the shear load. This system is simple and easy to implement, yet effective.

Table 9: Shear Friction Level 3 of FR and DP 2.3

FR 2.3.1 Prevent translation along X	DP 2.3.1 Bearing blocks which are attached to the shell of the hockey stick
FR 2.3.2 Prevent translation along Y	DP 2.3.2 Bearing blocks which are attached to the shell of the hockey stick
FR 2.3.3 Prevent translation along Z	DP 2.3.3 Sections of the helix on either side of the bearing which are too large to slide through the hole

In order for the helical shaft to perform its intended function it only needs to rotate about the Z-direction. Any other motion will not allow for an increase in normal force as needed. The system which holds the helical shaft must provide ways which limit the helix’s translational movement in the X, Y and Z directions.

The bearing blocks, which will attach to Plate A via machine screws, will prevent any translation of the helical shaft in the X or Y directions as required by DP 2.3.1 and DP 2.3.2.

The helical shaft has smaller sections in between the larger helical profiles discussed in DP 2.3.3. These thinner portions serve two roles. First, they ensure that the helix can be rotated smoothly in the bearings. These thinner sections are cylindrical, and rotate more smoothly in the bearings than a helix could. The grooves in the bearings on which the thinner part of the helix fit are precisely sized such that the shaft will fit into them, and provide a sliding fit without too much resistance to rotation, which could cause the mechanism to be hard to operation. In addition, the bearings are constructed out of nylon, which is a plastic known for its lubricity. The friction between the nylon and the steel shaft should be minimal, and eliminate any un-needed resistance to activating the mechanism. Also, the smaller portions of the helical shaft are surrounded by the large profiles of the helix. The helix sections are too large to fit into the bearings, and thus prevent the entire helical shaft from translating in the Z direction.

3.3 Shear Friction - Physical Integration

3.3.1 Finite Element Analysis

In order to test the hypotheses we had regarding this design, Finite Element Analysis was used to test the CAD model we created. Using the ANSYS 12 workbench software would allow us to visualize the deflections and stresses that the mechanism was subject to. It also allowed us to obtain approximate values for the stress and deflection.

A few simplifications were made during the FEA testing process. The first was that the mechanism would only be tested in the most rigid and least rigid positions. Since separate assembly files had to be imported for each test, two separate files were created. One file represented the helix being rotated out of the way, for the “flexible” position. The other assembly had the helix rotated to the fully “rigid” position. This allowed us to test the ranges of deflection we were likely to see. The second simplification was the used of solid bearing blocks. We felt that the relatively minor deflections caused by a two piece bearing block would not influence our results, by the addition of extra components would mean more processing time was required. The last simplification dealt with the carbon fiber shaft. Since carbon fiber can have different material properties based on the directions of the internal fibers, it is a hard material to simulate. Therefore, approximate values were used for the stick material in the analysis.

In the simulation, one end of the stick had a fixed support and one end was free, to simulate cantilevered bending. A remote force of 100N was placed on the end of the stick opposite the support. Simulations of the “rigid” and “flexible” orientations of the model were run to find the total deflection in each. The results are shown in the figures below.

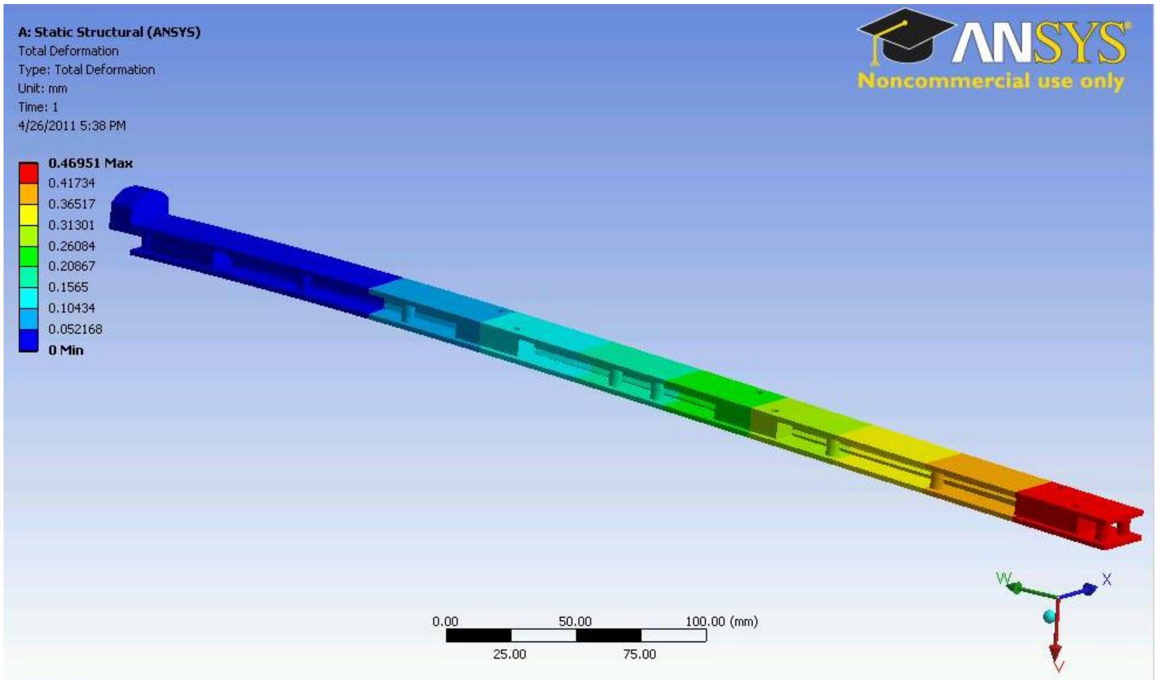


Figure 14: Shear Friction FEA of Rigid Beam

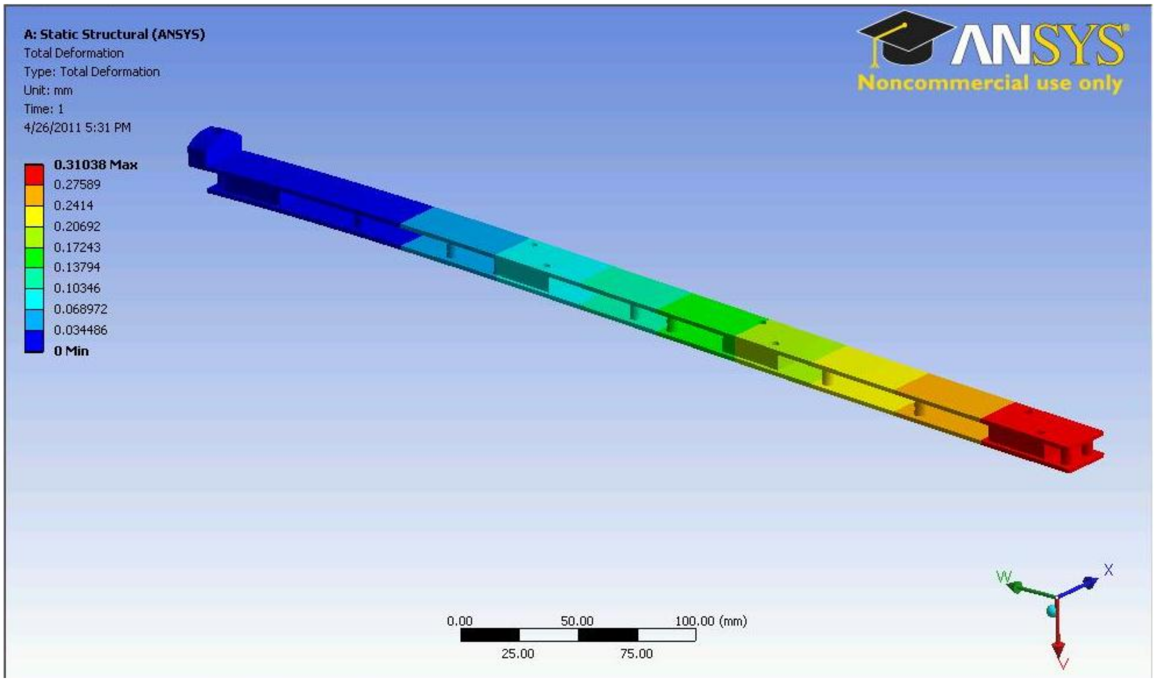


Figure 15: Shear Friction FEA of Flexible Beam

The results showed a 0.31038 mm deflection for the "flexible" setting and a 0.46951 mm deflection for the "rigid" setting. This is interesting since this is opposite our hypothesis on how the mechanism would work. It is interesting to note that there are different deflection values based on the orientation of the mechanism. It could be that our intuition about how the mechanism works is wrong, and that it actually operates the reverse of how we think it does. The other possibility is that the simulation is not properly analyzing the function of the mechanism. Possibly the interaction between Plate B and the helix, or Plate B and the hockey stick are not properly modeled. This could be due to a limitation of how the program performs its calculations.

This analysis is useful since it shows that this mechanism can alter its flexibility, even if it does work opposite of how we think it should. It is also worth noting the deflection values. It provides a basis for what our future physical measurements may be. The deflection values are great enough that would should be able to measure them with standard measuring equipment. The FEA analysis proves that the design shows promise and should be investigated.

3.3.2 Tolerancing

A number of the components manufactured for this design had specific tolerances which needed to be held. The bearing blocks needed to have a specific height so that they would not disrupt the interaction between Plate B and the helix. The bearing blocks also needed a close fit with the shaft of the helix so that there would not be unwanted movement, which would diminish the force increase that the helix could provide.

Since the original rigid shaft was to be constructed to match the diameter of a traditional hockey stick, this limited the amount of room which the mechanism had to fit into. The creation of the neutral surface further reduced the amount of room for this mechanism. The height of the space the mechanism was to be installed into was 0.46 inches. After the thickness of the top and bottom plates were taken into account, it was decided that the total height of the two bearing halves needed to be 0.27 inches in order to allow Plate B enough room to move in the Y - direction when the stick was flexed. The top half of the bearing had a height of 0.14" and the bottom half a height of 0.13". The maximum limit for the thickness of the bearing was 0.31" in which case it would be the same height as the helix. However, this represents a theoretical maximum; a standard tolerance of +/- .005" would be much more applicable. The table below shows the thicknesses of the manufactured bearing pieces.

Table 10: Shear Friction Bearing Thickness Tolerances

Piece	#1	#2	#3	Avg.
Top	0.195"	0.176"	0.196"	0.189"
Bottom	0.157"	0.167"	0.166"	0.163"
Total	0.352"	0.343"	0.362"	0.352"

Clearly these parts were manufactured well over their desired tolerance. While this is undesired, it was not unexpected. These oversized parts were the result of some problems encountered during manufacturing. The primary reason was that, due to the flexible plastic and small dimensions, the work piece had the tendency to flex during cutting. Due to this, there was a limit to how much material could be removed without completely destroying the part. Also, there was a concern regarding the amount of clamping force which could be exerted on such a small part. Due to this, the depth of cut was reduced so that sufficient clamping force could be provided while avoiding crashing the cutting tool into the vice.

Due to these factors it was decided that the parts would have to be manufactured as they were and that the outer diameter of the helix would have to be increased.

Another important tolerance was the relationship between the groove in the bearings in which the shaft portion of the helix sat. According to the Machinery handbook, an RC4 running fit best describes the type of fit needed between the shaft and the bearing, since the shaft needs to rotate yet have minimal play. According to the table, for a .157 nominal diameter the hole has a minimum tolerance of 0 and a maximum of +.0007”. The shaft has a tolerance of between -.0004” and -.0009” for a minimum clearance of .0004” and a maximum clearance of .0016”. The following table shows the diameter of the groove in each pair of bearing blocks.

Table 11: Shear Friction Bearing Groove Tolerance

Pair #1	Pair #2	Pair #3	Avg.
0.160”	0.162”	0.155”	0.159”

Our shaft, which was a nominal 4mm (0.157”) size, was measured to be exactly 0.157” in diameter. The data gathered on the diameter of the grooves within the bearing blocks show that it was not within an RC-4 class fit tolerance however, it is close to being the desired specification. When observing the relationship between the helical shaft and the bearings it is noted that the shaft turns freely within the bearing and that it has a minimal amount of excess play. The bearing blocks fulfill their intended function within the mechanism, even if they are outside of the tolerance. The likely cause of the parts being out of spec is that the bearings were designed to fit a 4mm (0.157”) diameter shaft. However, when the parts were manufactured, a 4mm ball end mill was not available, so a 1/8” ball end mill was used with a different cutting path. The in-accuracies from this cutting method most likely caused the bearings to be slightly out of specification.

3.3.3 Diagrams

The following figures match the Functional Requirements from the design decomposition with images, so that it is easier to understand how the mechanism operates.

FR 1 - Provide Composite Shaft

FR 1.3 - Control location of shear boundary

FR 1.4 - Control outer dimensions

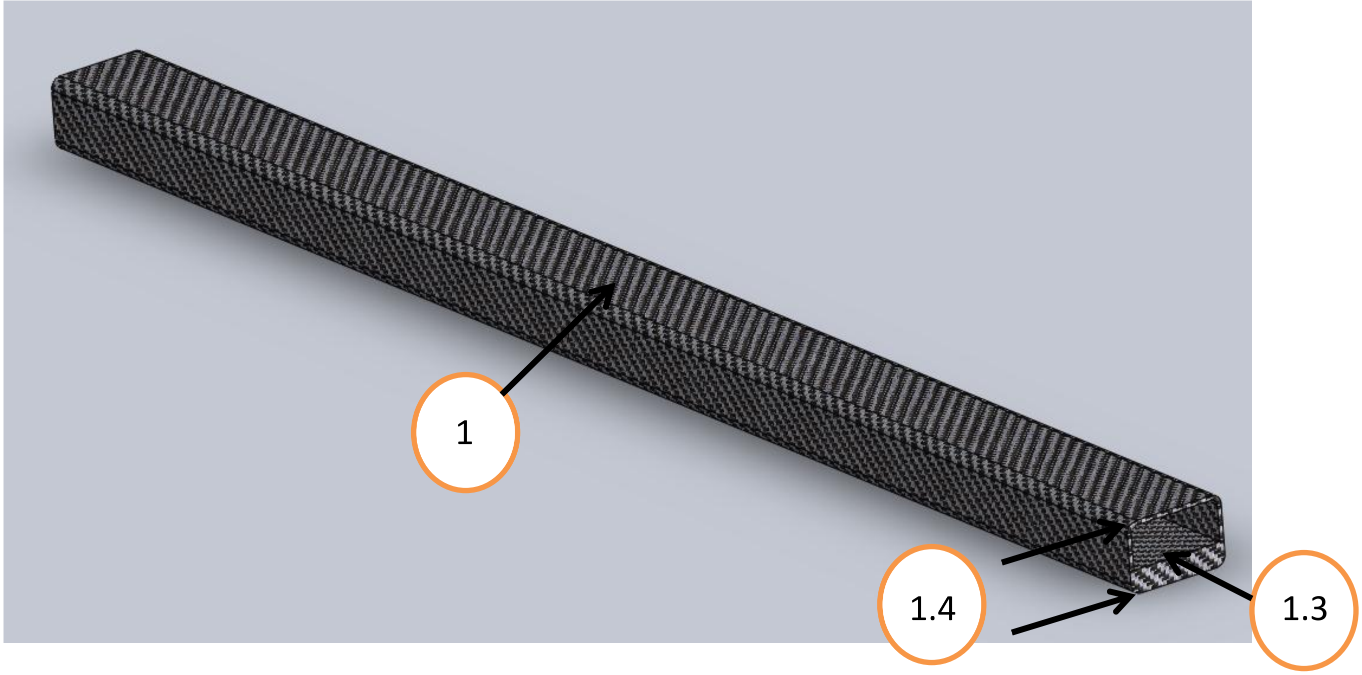


Figure 16: Shear Friction FR 1 Diagram

FR 2.1 - Translate rotation into a force applied in the Y- direction increasing linearly along the length of the stick

FR 2.2 - Transmit normal forces to shear boundary

FR 2.3 - Restrict helix movement to rotation about Z – Axis

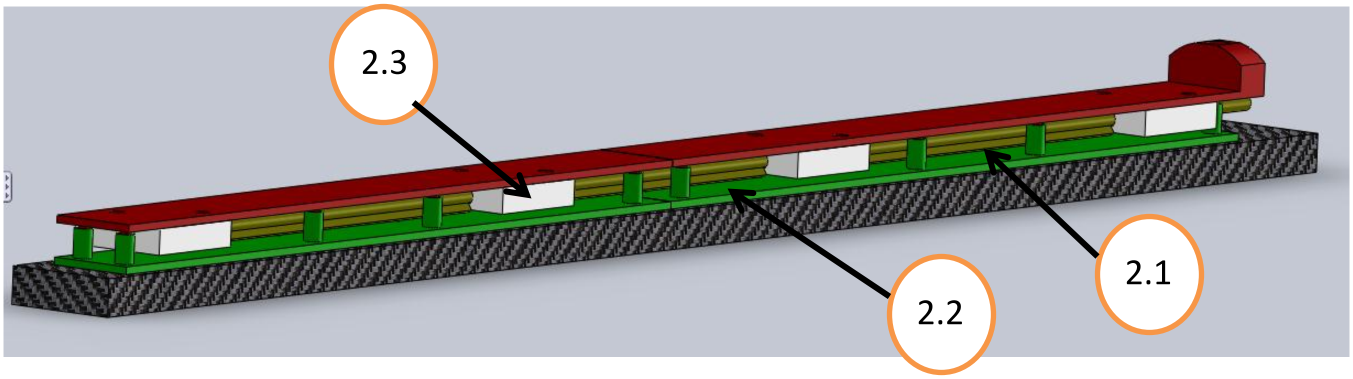


Figure 17: Shear Friction FR 2 Diagram

FR 3.1 - Permit installation of helix into bearing blocks

FR 3.2 - Attach bearing blocks

FR 3.3 - Attach to composite shaft

FR 3.4 - Attach Plate B

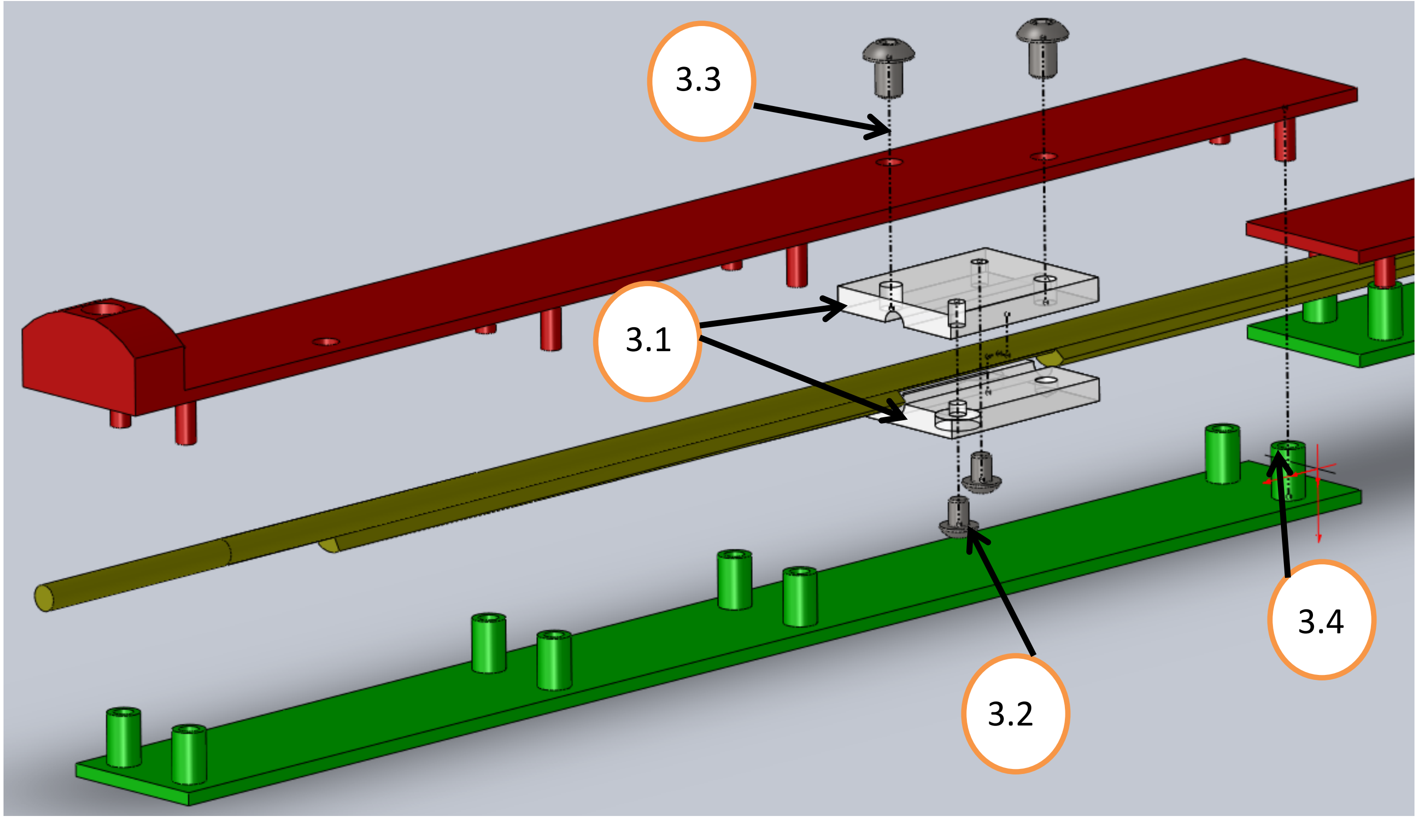


Figure 18: Shear Friction FR 3 Diagram

FR 4 - Allow the user to control the normal force

FR 4.3 - Select level of flexibility

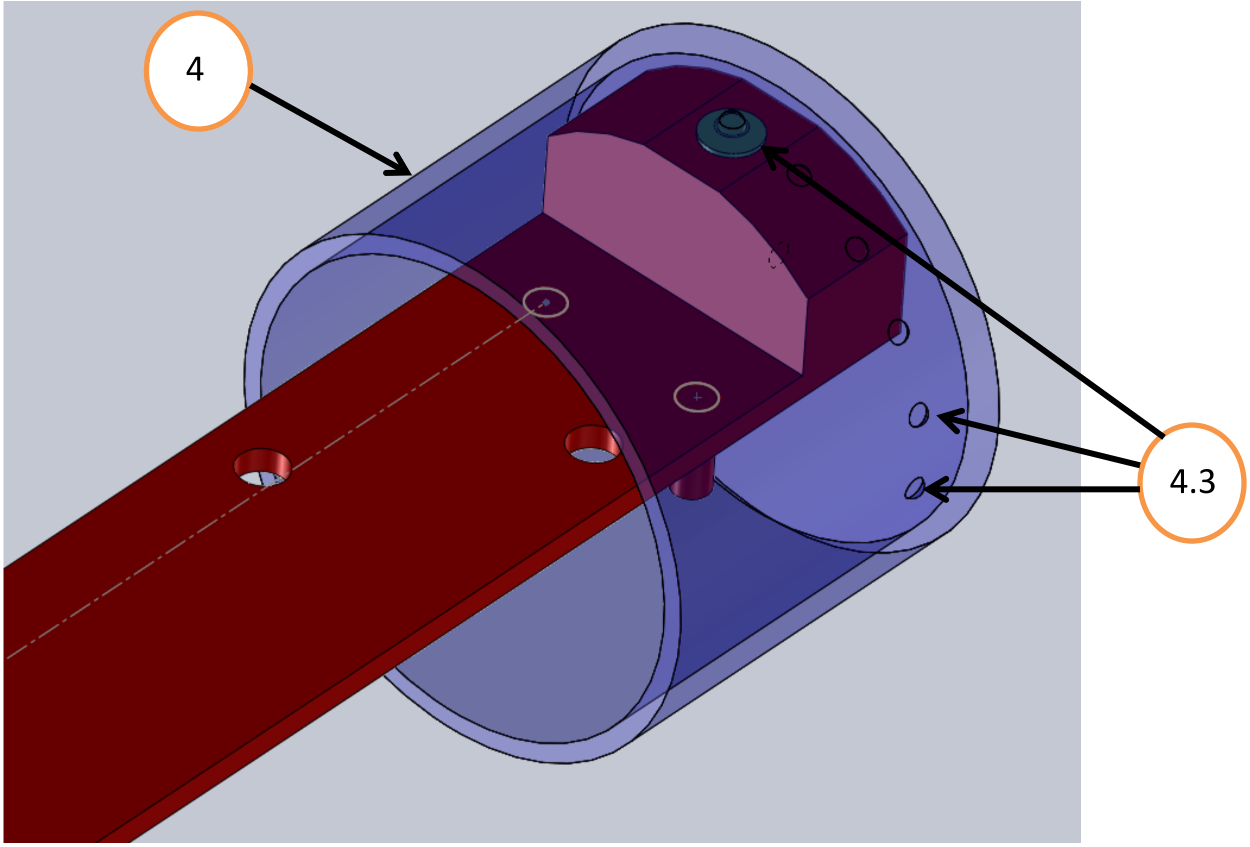


Figure 19: Shear Friction FR 4 Diagram

3.4 Shear Friction - Prototype Manufacturing

The creation of this design had many unique challenges when it came to producing a functioning prototype. The main difficulty which needed to be overcome was the small sizes of each of the parts. Since it was necessary that each part fit within a Carbon Fiber beam, of similar size to a hockey stick, the overall size of each part was very small. Further complicating matters was the fact that the creation of a surface at the neutral axis of the beam further reduced the available area.

For the creation of the bearing blocks, which would support the helical shaft and fix it to the upper rail, the material Nylon was chosen, as it was light and had a low coefficient of friction, which would allow the shaft to rotate easily within it. The bearing block needed to be split into two halves, which would allow it to be assembled around the thinner part of the helical shaft. This entailed creating two thin pieces, with a half circle trough running down the center. This trough was created through the use of a 1/8th diameter ball end mill, and the mold roughing and finishing operation available in Esprit. This ensured a smooth and uniform surface for the shaft to fit into.

Another major problem encountered during the creation of the bearing blocks, was the tendency for the machining vice to impart too much force when clamping the part. In order to create the blocks, the final shape was contoured out of an oversized stock piece. Then, the excess material by which the part had previously been clamped was to be milled away. However, the thin cross section of the finished block did not provide much surface area with which to clamp the part, and tightening the vice with the force necessary to prevent the part from being pulled out also caused the part to flex upwards as plastic was machined away. This caused a sloping cut on the back face of the bearing, which would cause it to not lay flat against the top rail. This problem was solved by re-orienting the bearing within the vice, so that the trough (which was where the material was at its thinnest) was perpendicular to the vice jaws instead of parallel to it, which did not cause a stress concentration. In addition, an aluminum backing plate was created at attached to the block using the threaded holes on them. This further stiffened the block and allowed it to be machined without damage.

Another part which had a difficult manufacturing process was the helical shaft, which is vital to the operation of this design. Due to the complex geometry of a shaft with a helix wrapping around it, the use of a 4 axis CNC machine was initially considered. However, there were a number of properties of the shaft that did not make this the optimal solution. As with the other parts, the small overall dimensions of the shaft (4mm at the thinnest section and 8mm at the largest) would have allowed for excessive deflection while machining. A fixturing device could have been made to support the back side of the shaft while it was being cut, but multiple set-ups would have been constructed to cut the full helix profile. Also taken into considering was how much time this process would have added to the overall machining requirements. It was finally decided to construct an approximation of this shaft via simpler means.

It was decided that by making a number of cylinders with an 8mm outer diameter, then shaping them into profiles similar to that on the designed helix, the intended function of the shaft could be met. By using the SL-10 CNC Lathe and drilling a center hole from either side of a steel cylinder, a 3 inch long cylinder was made to the correct outer diameter of the helix. Then, by using the Mini CNC Mill, different sections of the cylinder were cut away. These sections were then welded onto the 4mm rod in order to create an approximation of the helical shaft. By combining quarter and half sections of the cut cylinders, three distinct profiles were made.

The following figure shows the completed prototype.

Figure 20: Shear Friction Final Prototype Picture

3.5 Shear Friction - Results

The shear friction prototype was tested using the same methods as the other two designs. Due to the nature of the prototype, it was decided to only test the mechanism in the positions which theoretically yielded full flexibility and full rigidity. This was done to ensure that a discernable difference existed between the two settings, which would show how effective this design was at changing the flexibility of the stick. A diagram of the test set-up with location measurements is shown below.

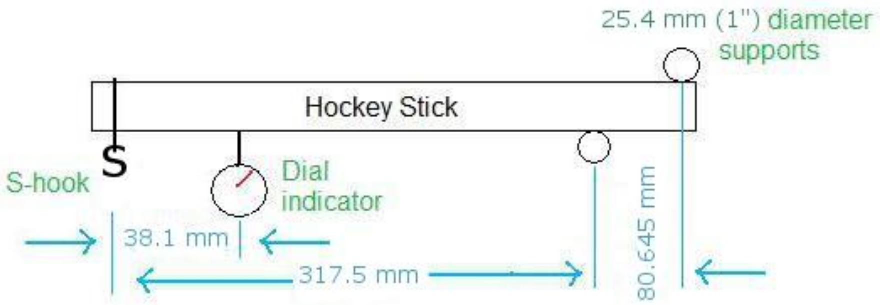


Figure 21: Shear Friction Initial Test Schematic

Since the change from the rigid, carbon fiber hockey stick to the upper and lower carbon fiber plates with fabric sides, some aspects of this design changed during testing. The upper plate, “Plate A” was still secured to the upper carbon fiber strip. However, the lower neutral surface was comprised of a properly sized piece of acrylic, which rested on top of the bottom strip of carbon fiber. The reasoning for this was that, after seeing how stiff the initial carbon fiber hockey stick was, it was believed that a hardened piece of carbon fiber which was the correct thickness would be too stiff and would diminish the effects of this mechanism. Thus, a properly sized piece of acrylic was substituted so that it would be more apparent if the mechanism was affecting the flexibility of the assembly. The results from testing are summarized in the table below. All tables show the deflection values in millimeters.

Table 12: Shear Friction Test 1 Results

		Test 1					
		Flexible			Rigid		
		20g	40g	60g	20g	40g	60g
1	0 Seconds	0.2032	0.762	2.032	0.6096	1.9304	3.556
	15 Seconds	0.2032	0.7874	2.0828	0.635	1.9812	3.6068
	30 Seconds	0.2032	0.8128	2.1336	0.635	1.9812	3.6068
2	0 Seconds	0.1524	0.8636	1.9812	1.2192	3.2004	4.6228
	15 Seconds	0.1524	0.9144	2.0066	1.27	3.2512	4.6736
	30 Seconds	0.1524	0.9144	2.0066	1.2954	3.2512	4.699
3	0 Seconds	0.0508	0.7366	1.8796	0.9398	2.5654	4.064
	15 Seconds	0.0508	0.7874	1.9304	0.9906	2.5908	4.1148
	30 Seconds	0.0508	0.7874	1.9558	1.016	2.6162	4.1402
4	0 Seconds	0.1524	0.889	1.8542	1.27	2.9972	4.4196
	15 Seconds	0.1524	0.9144	1.905	1.3208	2.9972	4.4704
	30 Seconds	0.1524	0.9144	1.9304	1.3208	3.0226	4.4704
5	0 Seconds	0.0508	0.7874	1.8288	1.397	2.8956	4.3942
	15 Seconds	0.0762	0.8128	1.8796	1.4478	2.9464	4.4196
	30 Seconds	0.0762	0.8128	1.9304	1.4478	2.9464	4.445
	Avg.	0.125307	0.83312	1.9558	1.120987	2.744893	4.24688

The results yielded data which directly opposed our anticipated results. The condition of the mechanism in which the helical shaft increased the force on the neutral boundary, which represented the mechanism being at it least flexible, showed much large deflections than when the mechanism was theoretically at its most flexible. Since this phenomenon occurred during all tests when the mechanism was in the "rigid" position, there is still a possibility that this mechanism is viable; it just does not operate how we anticipated.

Due to the reversed operation and the incredibly small deflections observed, a second round of testing was performed, using the same methods. The set-up diagram and results are shown below.

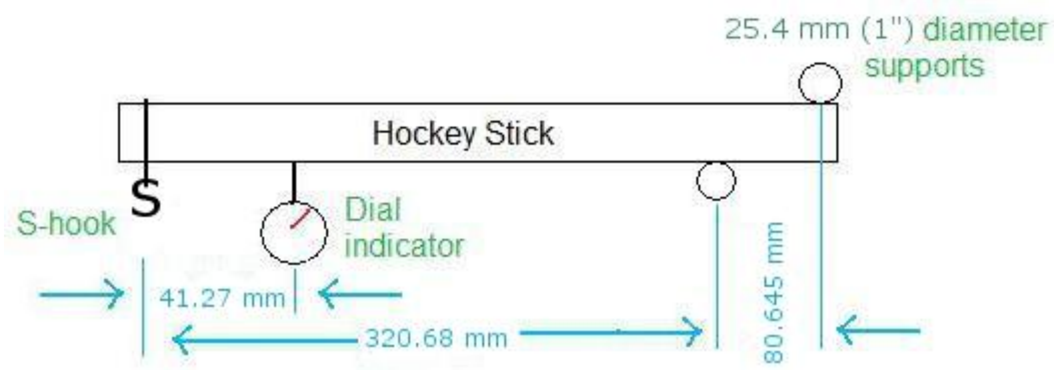


Figure 22: Shear Friction Revised Test Schematic

Table 13: Shear Friction Test 2 Results

		Test 2					
		Flexible			Rigid		
		20g	40g	60g	20g	40g	60g
1	0 Seconds	0.457	2.337	4.013	0.102	0.940	2.692
	15 Seconds	0.508	2.489	4.089	0.102	1.041	2.794
	30 Seconds	0.508	2.515	4.115	0.102	1.041	2.819
2	0 Seconds	0.711	2.692	4.724	0.229	1.803	3.658
	15 Seconds	0.813	2.794	4.826	0.330	1.930	3.734
	30 Seconds	0.838	2.819	4.851	0.356	1.956	3.759
3	0 Seconds	1.245	3.048	4.775	0.711	2.286	3.683
	15 Seconds	1.321	3.099	4.826	0.737	2.362	3.810
	30 Seconds	1.321	3.150	4.851	0.737	2.388	3.835
4	0 Seconds	1.372	3.251	4.877	0.838	2.413	3.785
	15 Seconds	1.422	3.302	4.953	0.889	2.515	3.861
	30 Seconds	1.422	3.327	4.978	0.914	2.515	3.886
5	0 Seconds	1.372	3.175	4.902	1.016	2.540	3.835
	15 Seconds	1.473	3.251	4.978	1.067	2.642	3.912
	30 Seconds	1.473	3.251	4.978	1.067	2.667	3.912
	Avg.	1.083733	2.96672	4.715933	0.612987	2.069253	3.598333

From this table we can see that the mechanism works as anticipated, larger deflections were recorded when the mechanism was in the “flexible” position. While performing these tests, the orientation of the helix was visually verified. Due to the results gathered in the second round of testing, it appears that there was an error when collecting the first set of data. The most likely explanation is that the helix was not rotated to the correct positions to be flexible and in-flexible. This would have been the result of miss-marking how the shaft had to be rotated in order to correctly align the helix. The second set of results fits the type of data we would expect. The amount of deflection relates to the position where it was hypothesized that the mechanism would be more or less flexibility. Also, the values of the deflections are consistent, and large enough that they seem logical. It was noted during the analysis of this data that there appeared to be an increasing trend of the deflection of the beam. By the end of testing, the “rigid” deflection was greater than the than the initial “flexible” deflection. While the mechanism was still operating as anticipated, this trend was cause for concern. It was not immediately clear why this trend existed. Upon further testing it was found that the beam which comprised the upper support of the cantilever was not fully tightened. This allowed the beam to shift slightly as the test shaft pressed upward on it. This error most likely caused the majority of the deflection trend, since it shifted over time. Once it was tightened, more consistent results were observed, as shown below.

Table 14: Shear Friction Test 3 Results

		Test 3					
		Flexible			Rigid		
		20g	40g	60g	20g	40g	60g
1	0 Seconds	0.432	1.778	3.175	0.203	1.168	2.413
	15 Seconds	0.457	1.803	3.226	0.229	1.219	2.438
	30 Seconds	0.457	1.829	3.251	0.229	1.245	2.438
2	0 Seconds	0.762	2.642	3.835	0.457	1.651	3.048
	15 Seconds	0.787	2.642	3.861	0.483	1.702	3.048
	30 Seconds	0.813	2.667	3.861	0.483	1.702	3.048
3	0 Seconds	1.118	3.048	4.318	0.965	2.413	3.632
	15 Seconds	1.168	3.200	4.470	0.991	2.413	3.658
	30 Seconds	1.194	3.251	4.470	0.991	2.413	3.658
4	0 Seconds	0.838	2.413	4.064	0.508	1.575	3.302
	15 Seconds	0.864	2.438	4.115	0.533	1.626	3.378
	30 Seconds	0.864	2.464	4.115	0.533	1.651	3.404
5	0 Seconds	0.965	2.845	4.369	0.965	2.032	3.480
	15 Seconds	1.067	2.896	4.470	0.991	2.083	3.531
	30 Seconds	1.067	2.921	4.496	0.991	2.108	3.556
	Avg.	0.856827	2.589107	4.006427	0.636693	1.800013	3.202093

Table 15: Shear Friction Test 4 Results

		Test 4					
		Flexible			Rigid		
		20g	40g	60g	20g	40g	60g
1	0 Seconds	0.864	2.464	4.191	0.229	1.067	2.210
	15 Seconds	0.889	2.540	4.216	0.229	1.092	2.261
	30 Seconds	0.914	2.565	4.216	0.254	1.092	2.286
2	0 Seconds	0.457	2.007	3.683	0.406	1.372	2.438
	15 Seconds	0.483	2.032	3.734	0.432	1.397	2.540
	30 Seconds	0.508	2.032	3.759	0.432	1.422	2.565
3	0 Seconds	1.016	2.794	4.521	0.508	1.397	2.515
	15 Seconds	1.092	2.845	4.572	0.533	1.397	2.515
	30 Seconds	1.118	2.845	4.597	0.533	1.448	2.565
4	0 Seconds	1.118	3.175	4.572	0.356	1.270	2.489
	15 Seconds	1.143	3.226	4.572	0.381	1.295	2.515
	30 Seconds	1.168	3.226	4.597	0.406	1.295	2.515
5	0 Seconds	0.965	2.819	4.318	0.203	0.965	2.413
	15 Seconds	1.016	3.023	4.369	0.203	0.965	2.489
	30 Seconds	1.041	3.023	4.394	0.229	0.965	2.489
	Avg	0.91948	2.70764	4.28752	0.3556	1.22936	2.45364

An additional variation in the deflections is most likely due to two factors. The first is the fact that the support points of the cantilever will settle into the parts of the beam which the support. As the beam is loaded, the initial components and materials can compress due to the pressure applied to them. This would cause the deflections to be greater over time. Additionally, the constant loading and unloading of the components can contribute to variations in deflections. Specifically the pins, which connect plate A and plate B, can shift due to the fact that they are only held in by a press fit. Tighter tolerances of these components would cause them to move less, and make the overall stiffness of the beam more stable.

The graphs below are plots of all the deflections for each mass amount across 3 sets of tests.

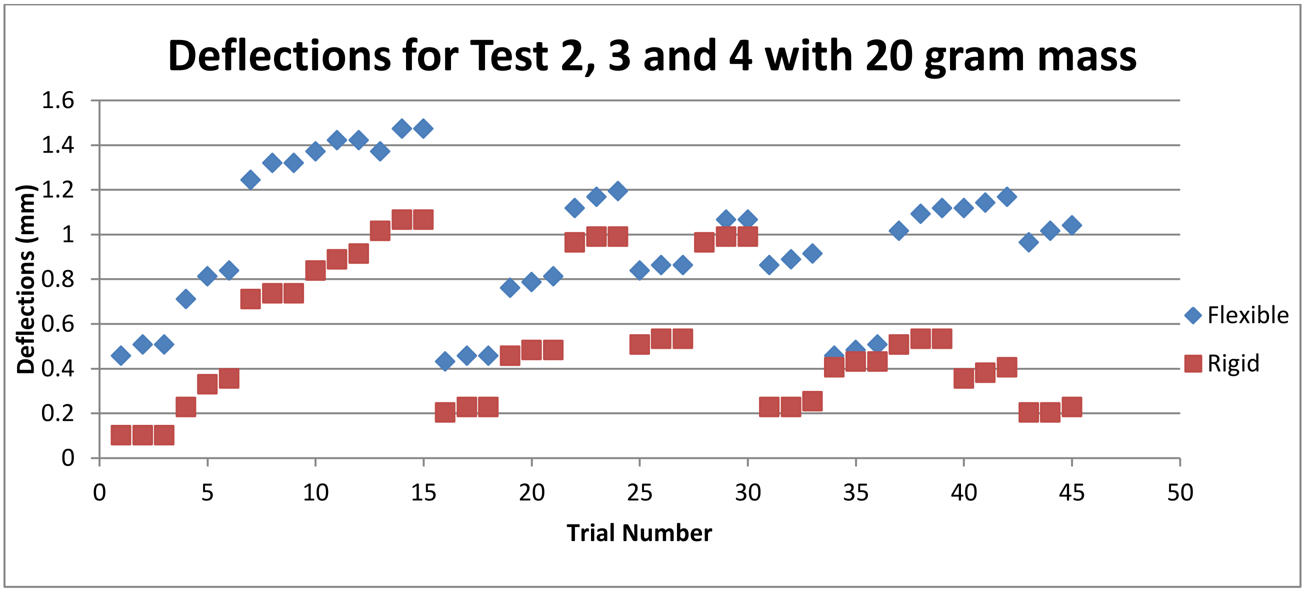


Figure 23: Shear Friction 20g Test Result Graph

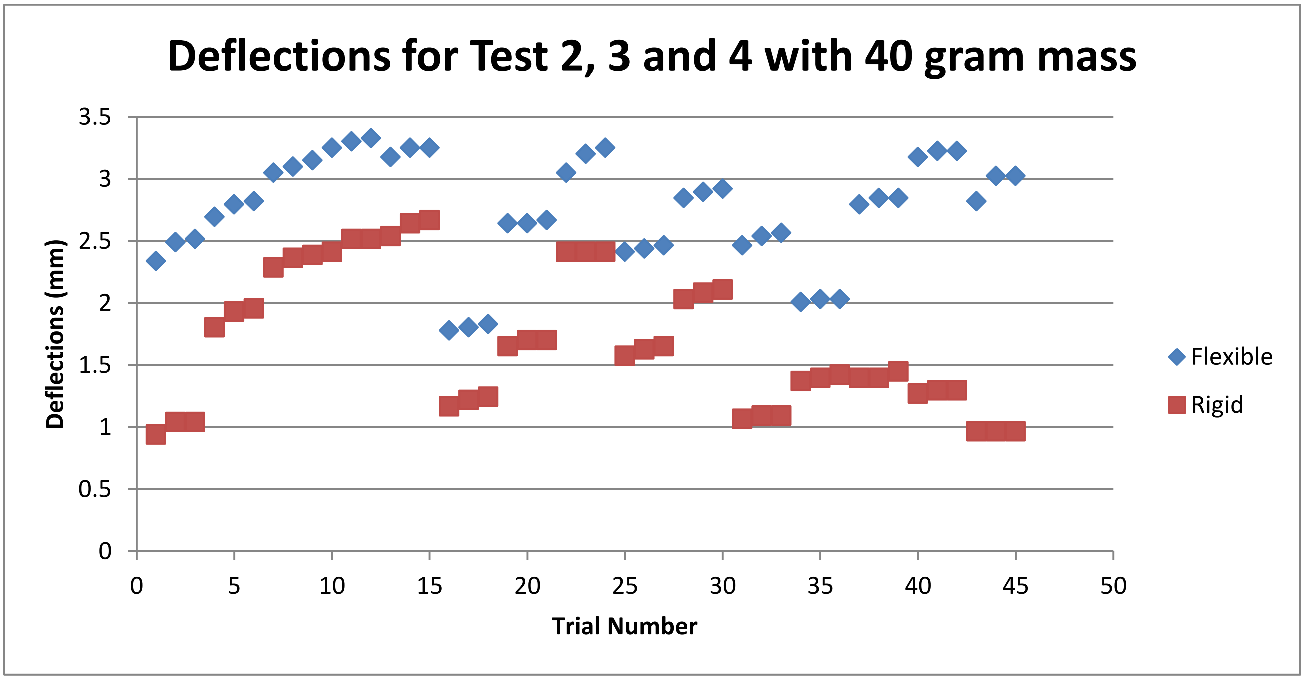


Figure 24: Shear Friction 40g Test Result Graph

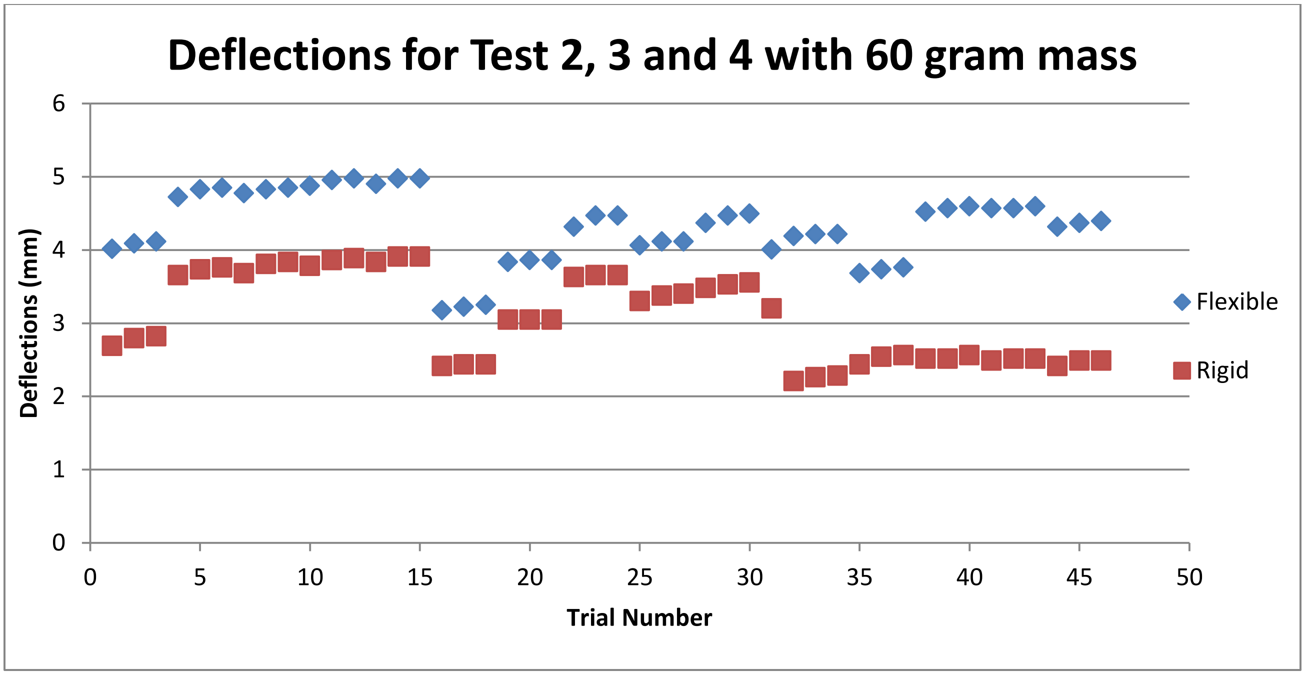


Figure 25: Shear Friction 60g Test Result Graph

As can be seen, the 60 gram tests were the most stable in their deflections, with less variation between trials. This is most likely due to the heavier amount of mass, smaller masses caused smaller overall deflections which meant that small variations would have big effects. As seen in the 60 gram graph, there is a jump at trial number 15, due to the tightening of the upper cantilever beam. As discussed earlier, results after this point are more consistent, although there were still a number out outlier points. Looking at the raw data, it can be seen that test 2 had a greater variation in the measured deflections, due to the creep caused by the loose beam.

The average flexural rigidity (EI) was calculated through the use of the cantilevered beam equation. The results are summarized in the table below.

Table 16: Shear Friction EI Results

Test Number	Average EI “Flexible” (Nm^2)	Average EI “Rigid” (Nm^2)
2	0.936	2.041
3	1.106	1.643
4	1.208	2.342

The data from test number one was not calculated, due to the error in the orientation of the mechanism. The third round of testing shows a Rigid “EI” value which is much lower than observed in test rounds two and four. This is due to some larger deflections during the “rigid” portion of testing. This may be due to the helix not being oriented in the same manner as it was in tests two and four. There is also the possibility that the mass and dial indicator were located in slightly different positions than was recorded for that test. Despite this, the trials within these testing rounds were generally consistent, as shown above. They did not exhibit the substantial creep as noticed in the second round of testing. In all cases, the rigid setting was significantly stiffer than the flexible setting, so we feel confident about these results, despite some fluctuation.

3.6 Shear Friction - Discussion

The results of the testing for this design indicate that this design may be viable in creating a variable stiffness beam. Despite the problems in the initial round of testing, the second, third and fourth rounds produced results which were consistent with our hypothesis on the operation of the mechanism. This conclusion does not ignore the results of test 1 however, as doing so would present doubt in the validity of our tests. The first round of testing did show a difference in the rigidity of the mechanism; however it operated in the reverse of how it was anticipated to. As mentioned earlier, this is most likely due to the helix being in a position different from what it was believed to be in. This would make sense because there were differing amounts of deflection. If the mechanism had shown equal deflection regardless of how the helix was oriented, that would cast much larger doubts over the validity of our results.

The other concern presented during testing was the logarithmic deflection increase observed during the second round of testing. As discussed earlier, during the third round of testing it was observed that the upper beam of the cantilever was not properly tightened. After it was tightened the results were much more consistent. There were some anomalies in the data, such as trials in which the deflection was significantly lower. Overall though, the results were consistent and proved the operation of the mechanism.

A number of the problems encountered while manufacturing this mechanism need to be overcome to truly evaluate its effectiveness. The primary difficult was the construction of the helix. Due to both the geometry and the size, the exact helix could not be created quickly, so a prototype was made. The profiles of the individual pieces could not be exactly aligned, and the welding process warped some of the pieces. Because of this, the helix does not rotate smoothly, and does not engage the bottom plate in the exact locations it should. Had the helix been machined from a solid piece of material, these alignment problems would have been overcome.

Also, the pieces which made up the outer diameter of the helix needed to be sized slightly larger than the initial helix design, due to the fact that the bearing blocks were oversized. This led to limitation on where the helix could have a large profile and not interfere with the upper plate. This limited the number of locations to which the helix increased the force. Had the full helix been created, the mechanism most likely would have been stiffer in the “fully engaged position”.

This mechanism was tested and shown to be successful while using the revised shaft. This is not the same as testing the mechanism with a rigid box beam. Since current hockey sticks are constructed as box beams, the difference needs to be considered when developing future versions of this design. Since the shear friction mechanism itself is rigid, there is no reason why a hockey stick could not be made with flexible side walls, provided this mechanism was located inside of them. However, this would be a radical shift from how hockey sticks are currently fabricated. Further research would need to be done to determine if this method will still allow the stick to function as hockey sticks do now. In addition, there needs to be a consideration for player’s reaction to a stick which has flexible sidewalls, as this may influence their playing style. Analysis and feedback from players would reveal if this mechanism has the possibility of being integrated in a commercial product.

4.7 Shear Locking Conclusion

The results of the testing performed on this design seem to indicate that it is viable and that further re-search and prototyping should be done. Due to the budgetary and time restraints imposed by this project, it was not possible to further improve the design. There were drawbacks to the mechanism which was tested due to complications introduced in the prototyping/manufacturing phase. However, the prototype served its purpose, by being manufactured quickly and within budget and by providing something which could be tested. Since these tests indicated that the design has potential, the prototype has succeeded in its function.

Chapter 4: Shear Locking Design

4.1 Shear Locking – Concept and Theory of Operation

One method reviewed for altering the stiffness of a box beam was to change the geometry of sections of the beam. Different geometric profiles have different bending stresses associated with them. It was hypothesized that by changing the geometry of one face of the beam, the beam could be made more or less flexible. This method would necessitate the creation of a mechanism that could change the effective geometry of a profile.

The first part of the design that needed to be made was a fixed geometric profile that could be easily controlled. It was decided that a toothed profile would create a flexible shape that could be manipulated to become a less flexible solid box. This would be done by inserting other teeth from another component into the slots created by the fixed profile.

Many ideas were considered to determine to how the profile geometry could be altered on command. Sliding mechanisms, rotating components, and hinged features were discussed as possible ways to solve the problem. Finally, it was decided that a rotating shaft with teeth on one half of the diameter and a flat surface on the other half would be used to instantly change the profile along the whole beam length. The teeth on the rotating shaft match the spaces between the teeth on the fixed surface so they can mesh together. By using a toothed shaft, the profile inside the beam would be quickly changed, which would theoretically create two distinct flexibility settings.

Once the design of the internal rotating shaft was created, the team developed ways to attach the shaft to the hockey stick. This problem was solved by designing bushing blocks that would assemble around the inner diameter of the shaft and be fixed to the inside of the hockey stick. The fixed toothed profile and these bushing were designed to be put on guide rails which would allow for pre-assembly and spacing of the components before sliding the whole assembly into the hockey stick. A solid model of the prototype is shown in the following figure.

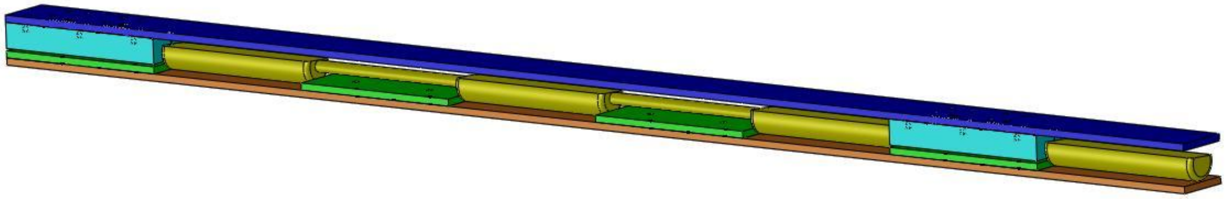


Figure 26: Shear Locking CAD Assembly

4.2 Shear Locking – Design Decomposition

4.2.1 Level One Decomposition

Table 17: Shear Locking Level 1 FRs and DPs

FR 1 – Provide components	DP 1 – Two components that interact to vary the flexibility
FR 2 – Lock and unlock the surfaces in shear	DP 2 – A system to vary the shear modulus on the locking surfaces by rotating Component B
FR 3 – Contain the system that increases shear modulus	DP 3 – A hollow fiberglass or carbon fiber composite shell which contains and protects the locking system
FR 4 – Allow the user to control the shear modulus	DP 4 – A handle located at the top of the hockey stick which the user can rotate

Two toothed surfaces, one rotating and one fixed, will be used in this design. Theoretically, if the two sets of teeth are locked together and then flexed, the sides of the teeth will push against each other and prevent further bending. The rotating shaft will provide the simplest method of ensuring that the force applied to the fixed surface will be spread through the entire shear boundary, and will not be concentrated in one place. Because of the interior dimensions of a hockey stick, the components of the device will be put together before inserting them down the length of the shaft. The user will be able to control the flexibility of the hockey stick through the use of a handle external to the rest of the design. Because of the usual grip of a hockey player, the best location for the handle is at the top of the hockey stick, where a hand is always located.

Because the different parts of the design work together to produce the final effect of altered flexibility, the system is collectively exhaustive. Because the parts of the system each control a different aspect of altering the flexibility, the design FRs are mutually exclusive.

4.2.2 Level 2 Decomposition

Table 18: Shear Locking Level 2 FRs and DPs

FR 1.1 – Provide static Component A	A component fixed along the z-axis with teeth that transmits loads to the outside shell of the stick
FR 1.2 – Provide moving Component B	A component parallel to Component A which rotates about the z-axis, with a locking surface and an unlocking surface, which transmits loads to the outside of the stick or the neutral axis
FR 2.1 – Rotate Component B to locked or unlocked position	An axle connecting the teeth of the locking surface to rotate the teeth of Component B
FR 2.2 – Connect to user input	A system to connect Component B to the user input
FR 3.1 – Control initial flexibility	A shell to be constructed such that it does not alter the desired lowest flexibility of the hockey stick
FR 3.2 – Control outer dimensions	Outside walls of the shell that do not exceed a dimension of 63 inches long
FR 3.3 – Attach to axle	Bushings fixed to the outer shell and around Component B
FR 4.1 – Provide a profile that is similar in size to the outer shell of the hockey stick	A handle of similar size to the rest of the hockey stick
FR 4.2 – Form the handle such that it is long enough for a player's hand	The length of the handle to closely match the width of a player's hand while in a hockey glove
FR 4.3 – Select level of flexibility	A system which allows the player to lock the components together or unlock them

The level 2 components of FR 1 deal with the various functions the device must satisfy, those being a fixed feature and a moving feature. The z-axis described is the length of the hockey stick, and is the axis to which the fixed component is bound. Component B rotates about its local z-axis, while Component A is fixed along the z-axis.

In order for the mechanism to work, one of the components must rotate to switch between the locked and unlocked positions. This will be accomplished by providing input from the user, so the device must have some way to be attached to this input.

The level 2 components of FR 3 discuss the method to hold the device in place while on the ice. The initial flexibility of the outside shaft must be controlled to allow the mechanism to work, as a standard box beam has high bending strength on its own. Controlling the outer dimensions of the shaft allow the players to easily use the new design, rather than forcing them to adapt to a new stick shape or size.

The shaft needs a way to attach to the axle of the rotating beam, so the forces applied to the beam can be evenly transmitted to the shell of the stick. This also helps keep the rotating component in place so it does not get misaligned from the fixed component.

Having the player be comfortable with the size of components in the design is important to allow for the most ease in using the device. It must be clear which flexibility setting the player chooses, as hockey is a fast-paced sport and choices must be made quickly to determine which flexibility to use and which is in use.

4.2.3 Level 3 Decomposition

Table 19: Shear Locking Level 3 FRs and DPs

FR 1.1.1 – Provide boundary with Component B near the stick's neutral axis	DP 1.1.1 – Solid sections that form the teeth, with the neutral axis of the stick in the middle of the teeth
FR 1.1.2 – Control initial flexibility	DP 1.1.2 – Component A to be constructed such that it does not alter the desired lowest flexibility of the hockey stick
FR 1.1.3 – Prevent movement in all directions	DP 1.1.3 – A fastening method that prevents movement in all directions
FR 1.2.1 – Provide locking surface	DP 1.2.1 – A surface on Component B with teeth that match with the teeth in Component A
FR 1.2.2 – Provide unlocking surface	DP 1.2.2 – A flat surface on Component B that does not interact with Component A
FR 1.2.3 – Provide boundary with Component A near the stick's neutral axis	DP 1.2.3 – A system which holds Component B in the locked position
FR 1.2.4 – Control initial flexibility	DP 1.2.4 – Component B to be constructed such that it does not alter the desired lowest flexibility of the hockey stick
FR 1.2.5 – Transmit loads at shear surface to outer shell	DP 1.2.5 – Bushings fixed to the outer shell and surrounding Component B which transmit forces
FR 1.2.6 – Restrict movement to z-axis	DP 1.2.6 – Component B should only rotate about the z-axis

FR 1.2.7 – Rotate Component B	DP 1.2.7 – An axle running through the locking teeth, controlled by the user, which positions Component B
FR 2.2.1 – Attach connection mechanism to Component B	DP 2.2.1 – A mechanism to connect to the axle of Component B
FR 2.2.2 – Attach connection mechanism to user input handle	DP 2.2.2 – A mechanism to connect to the user input

The level 3 components of FR 1.1 describe how the static Component A is to be constructed. It needs to have a surface that interacts with Component B near the middle of the shaft. Component A must have some degree of flexibility for the mechanism to work. Because this component is fixed, movement in all directions must be controlled. The initial flexibility of the components is important, as this plays a role in the accumulated flexibility of the sum of all components. The wording of DP 1.1.3 allows for different methods to fix Component A, such as screws or adhesive.

The components of FR 1.2 detail the roles that the moving part of the device must meet. The mechanism must translate the rotation of the shaft into a force on the sides of the teeth of Component A. There must be two profiles on the component to allow for the selection of flexibility. Component B must be kept in the unlocked or locked position to prevent an unwanted change in the flexibility.

To connect Component B to the user input, it is first specified that Component B be attached to an intermediate mechanism, then the intermediate mechanism connected to the user input handle. It was determined that the intermediate mechanism could occur in two ways. The intermediate mechanism could be a part of Component B if the length of the rotating shaft were extended past the edge of the hockey stick to go straight into the user input. The other option would be to have a linkage that connects Component B and the user input.

4.2.4 Level 4 Decomposition

Table 20: Shear Friction Level 4 FRs and DPs

FR 1.1.2.1 – Control shear strength	DP 1.1.2.1 – A fiberglass or carbon fiber composite in which the fibers are perpendicular to the direction of shear force
FR 1.1.2.2 – Control tension strength	DP 1.1.2.2 – A fiberglass or carbon fiber composite in which the fibers run parallel to the normal force on the surface
FR 1.2.4.1 – Control shear strength	DP 1.2.4.1 – A material strong in the direction of shear force
FR 1.2.4.2 – Control tension strength	DP 1.2.4.2 – A material strong in the direction of normal force
FR 1.2.6.1 – Restrict movement in x-axis	DP 1.2.6.1 – Bushings fixed to the outer shell and around the axle of Component B which restrict movement in x-axis
FR 1.2.6.2 – Restrict movement in y-axis	DP 1.2.6.2 – Bushings fixed to the outer shell and around the axle of Component B which restrict movement in y-axis
FR 1.2.6.3 – Restrict translational movement in z-axis	DP 1.2.6.3 – Bushings fixed to the outer shell and around the axle of Component B which restrict translational movement in z-axis

By controlling the shear and tension strengths of all components, the mechanism has a smaller chance of breaking while in use. If the fibers are parallel to the shear force, the material could tear when forces are applied. By putting the fibers perpendicular to the direction of shear, the component would be much stronger. By restricting the directions in which Component B can move, the teeth on this part are ensured to stay aligned with the teeth on Component A. The bushings in DPs 1.2.6.1, 1.2.6.3, and 1.2.6.3 are all the same components.

4.3 Shear Locking – Physical Integration

4.3.1 Assembly

FR 1.1 – Provide static Component A

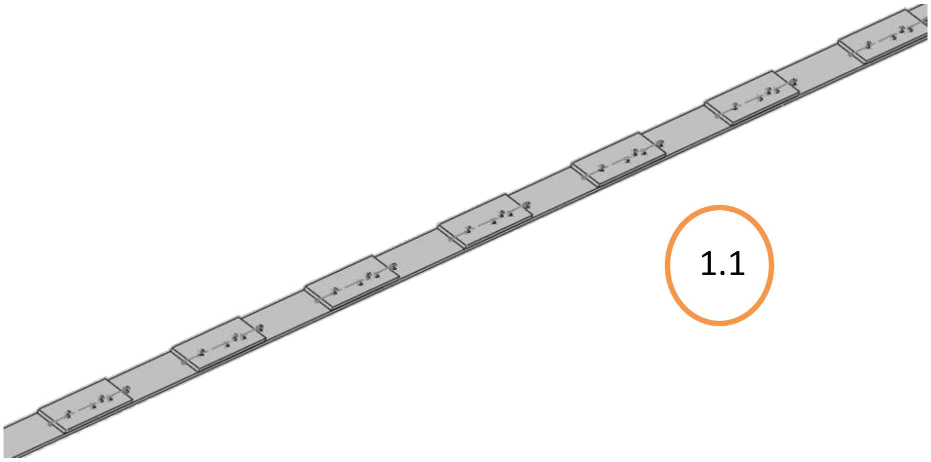


Figure 27: Shear Locking FR 1.1 Diagram

FR 1.2 – Provide moving Component B

FR 1.2.1 – Provide locking surface

FR 1.2.2 – Provide unlocking surface

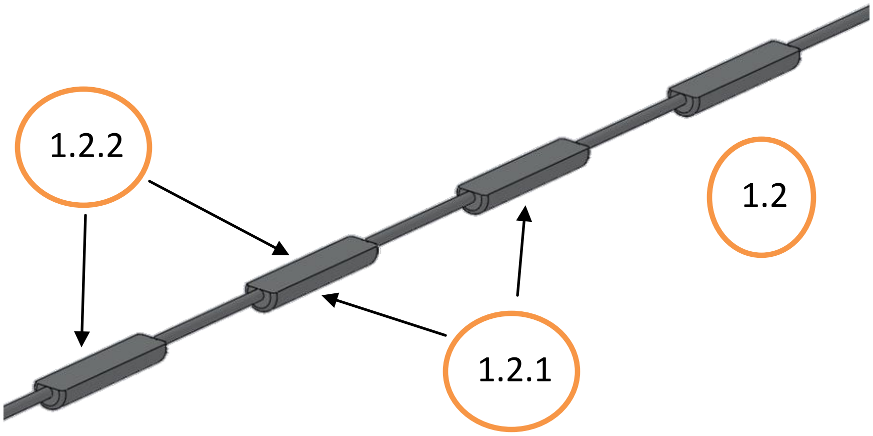


Figure 28: Shear Locking FR 1.2 Diagram

FR 1.2.6 – Restrict movement to z-axis

FR 2.2.1 – Attach connection mechanism to Component B

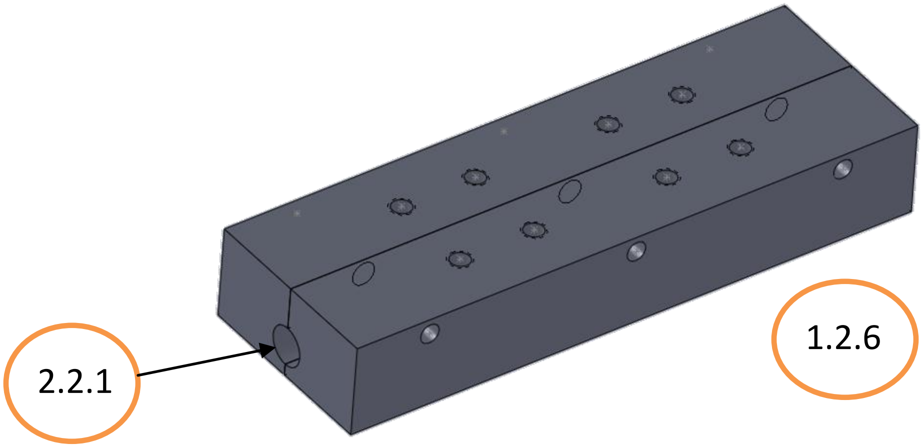


Figure 29: Shear Locking FR 1.2.6 Diagram

FR 2.2 – Connect to user input

FR 1.2.7 – Rotate Component B

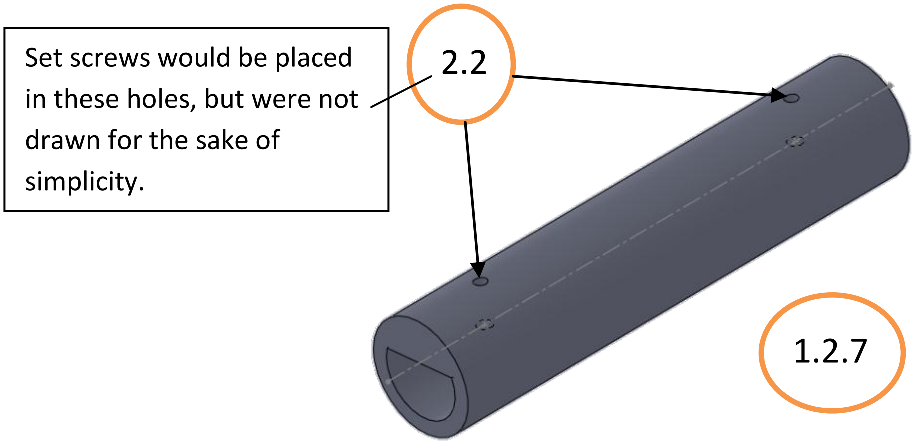

Set screws would be placed in these holes, but were not drawn for the sake of simplicity.

Figure 30: Shear Locking FR 1.2.7 Diagram

FR 3 – Contain the system that increases shear modulus

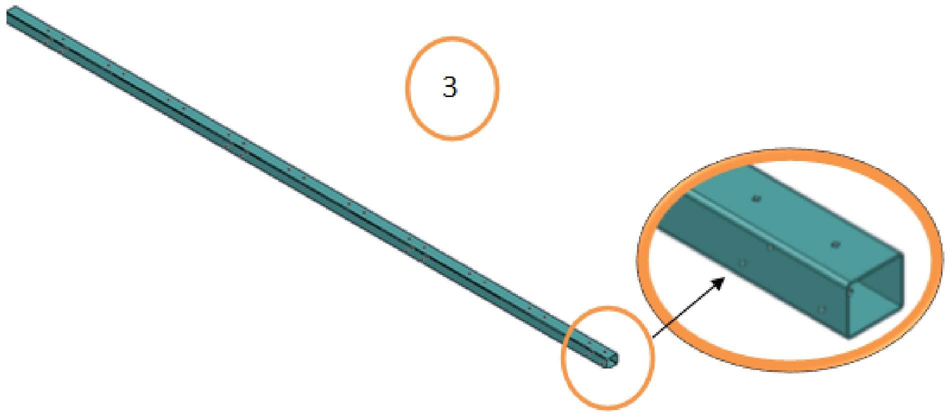


Figure 31: Shear Locking FR 3 Diagram

4.3.2 Tolerancing

All parts of this design had specific dimensions that needed to be adhered to for optimum use. The bushings needed proper height, width, and length to provide the proper fixture for the rotating shaft. The grooves in the bushings needed to be a specific distance from the wall of the block, to reduce interaction between the Component B and the guide rail for the bushings. The fixed teeth needed to have a tight tolerance to interact with the rotating teeth properly. While the widths of the guide rails and fixed teeth are important for maintaining the normal size of a hockey stick, these dimensions were the least important of the project.

Because all components needed to fit into a hockey stick, it was decided that the outer dimensions of the cross section were not to exceed 25 mm x 22 mm. Because of the assembly process, some parts did not fit together as well as they should have, so the largest actual width of the assembly is 26.93 mm. The height of the assembly is 21.60 mm, which is less than the desired outcome. The width of the assembly being over the desired outcome did not prove to be much of a problem, as two millimeters could be removed by making the guide rails thinner.

The bushings were designed to be 76 mm x 12.5 mm x 12 mm, with a tolerance of ±0.5 mm. The measured dimensions for all blocks are shown in the table below. The heights of all the bushings are less than the desired 12 mm due to the design and manufacturing process. The most probable reason for this is that in the original design the measurement was supposed to be 11 mm. When making the CNC code, the wrong CAD file was probably used due to similar labeling of files. Due to this, Component B interacted with the bushing guide rail and caused rotation from the user to be more difficult than expected. The guide rail flexed when hit by the rotating shaft, which created a curved profile rather than a straight one along that surface.

Table 21: Shear Locking Bearing Block Tolerances

Bushing block #	Desired length: 76 mm	Desired width: 12.5 mm	Desired height: 12 mm
1	74.67 mm	12.50 mm	10.96 mm
2	71.07 mm	12.69 mm	10.92 mm
3	75.93 mm	12.72 mm	11.09 mm
4	74.18 mm	12.60 mm	11.14 mm
5	71.10 mm	12.76 mm	11.16 mm
6	71.41 mm	12.85 mm	11.17 mm
7	74.45 mm	12.93 mm	11.33 mm
8	75.52 mm	13.01 mm	11.18 mm

The rotating teeth were designed to be 76 ± 0.5 mm long, with a 76 mm gap between them on the rotating shaft. The measured dimensions for these features are shown in the table below. The differences in lengths of the rotating teeth can most likely be attributed vibration of the CNC machine. The teeth gaps are all about the same size as expected, but the teeth slid while the epoxy was setting, causing the gaps to be larger.

Table 22: Shear Locking Rotating Tooth Tolerances

Rotating Teeth Feature #	Desired Length: 76 mm
Rotating Tooth 1	75.53 mm
Rotating Tooth 2	75.94 mm
Rotating Tooth 3	75.74 mm
Rotating Tooth 4	75.01 mm
Rotating Tooth Gap 1	76.71 mm
Rotating Tooth Gap 2	76.79 mm
Rotating Tooth Gap 3	76.95 mm

The fixed teeth were designed to be 76 mm x 25 mm, with a tolerance of ±0.5 mm. The measured dimensions for all fixed teeth are shown in the table below. The widths of all the fixed teeth are less than the desired 25 mm, due to inaccuracies of using the laser cutter to form these parts. Teeth 2 and 4 were cut after being fixed to the guide rail to accommodate for the rotating teeth which slid during the assembly process. This caused all gaps to be larger than expected.

Table 23: Shear Locking Fixed Tooth Tolerances

Fixed Teeth Feature #	Desired Length: 76 mm	Desired Width: 25 mm
Fixed Tooth 1	75.72 mm	24.64 mm
Fixed Tooth 2	73.03 mm	24.51 mm
Fixed Tooth 3	75.72 mm	24.49 mm
Fixed Tooth 4	73.37 mm	24.51 mm
Fixed Tooth Gap 1	77.85 mm	N/A
Fixed Tooth Gap 2	79.82 mm	N/A
Fixed Tooth Gap 3	76.66 mm	N/A

4.4 Shear Locking – Prototype Manufacturing

To create the rotating shaft, the group chose to use aluminum. This material was favored for its high strength and low weight. Originally, this part was to be made from one solid bar of aluminum, and have all features machined from it. The teeth were to be made in a lathe, and the flat face done in a milling machine. After reviewing the manufacturing procedure and the dimensions of the part, it was realized that the 5 mm center diameter of the shaft might be too small and would cause the part to break during the machining process.

This design setback was overcome by a new method of creating the shaft. Sections of 16 mm diameter aluminum were cut to the correct length of 76 mm in a band saw and 5mm holes were drilled through the centers of these sections on the lathe. After this, these tubes were put into a milling machine and the flat surface was machined with a facing operation. A 5 mm diameter rod was pushed through the holes in the tubes. The tubes were fixed in place at the correct distances from each other with the use of a two-part epoxy applied to the outside of the 5 mm rod. To align the flat faces of the teeth, each face was placed on a table while the epoxy was still wet. The shaft stayed in this position until the epoxy completely set.

The bushings were made of nylon blocks. This material was chosen because of its light weight and low coefficient of friction for easy rotation of the shaft within the bushings. The bushings were split in half to be assembled around the 5 mm diameter sections of the rotating shaft. The groove was made with a 5 mm ball end mill in the milling machine and was programmed with a contour path in Esprit. Holes were added to the bushings to be able to connect them together and attach them to the guide rail.

The guide rail for the bushings and the guide rail and teeth for the fixed profile were both made from a plastic called delrin. These parts were made in the laser cutter. The first time the group tried to make these parts, two passes with the laser cutter were made, and barely a dent was made in the delrin. After adjusting the settings, the group was finally able to cut all the way through the material for the outside profile. Because the through holes for screws in these parts were so small, the laser cutter was unable to get all the way through the delrin for these features. This was solved by punching the holes out of the parts with an awl after the laser cutting procedure was finished.

4.4.1 Component Models

The main component of this design, the rotating shaft, is shown in the figure below.

Figure 32: Shear Locking Rotating Shaft CAD Model

The fixed profile, with the teeth and guide rail for them, is shown in the next figure.

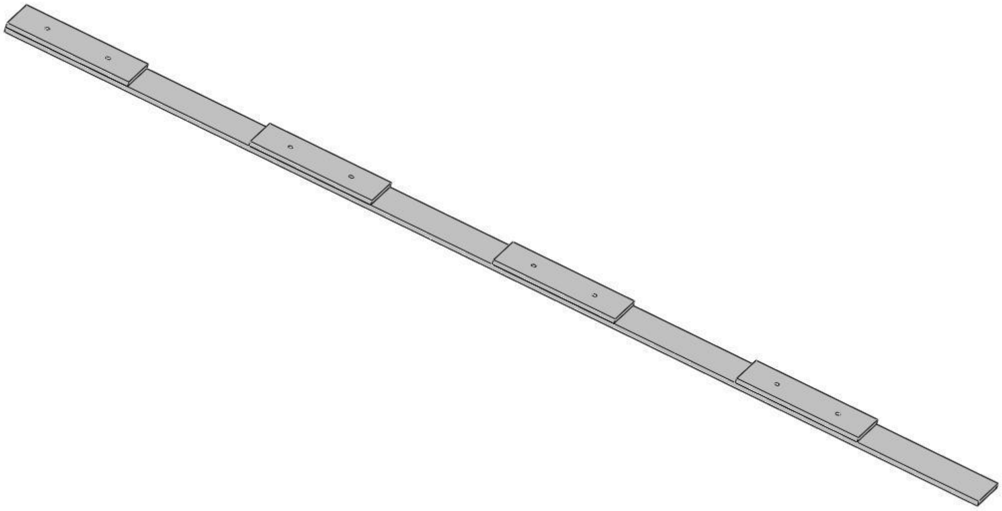


Figure 33: Shear Locking Fixed Profile CAD Model

The next part shown is a single bushing block. Two of these are attached together to hold a section of the shaft in place.

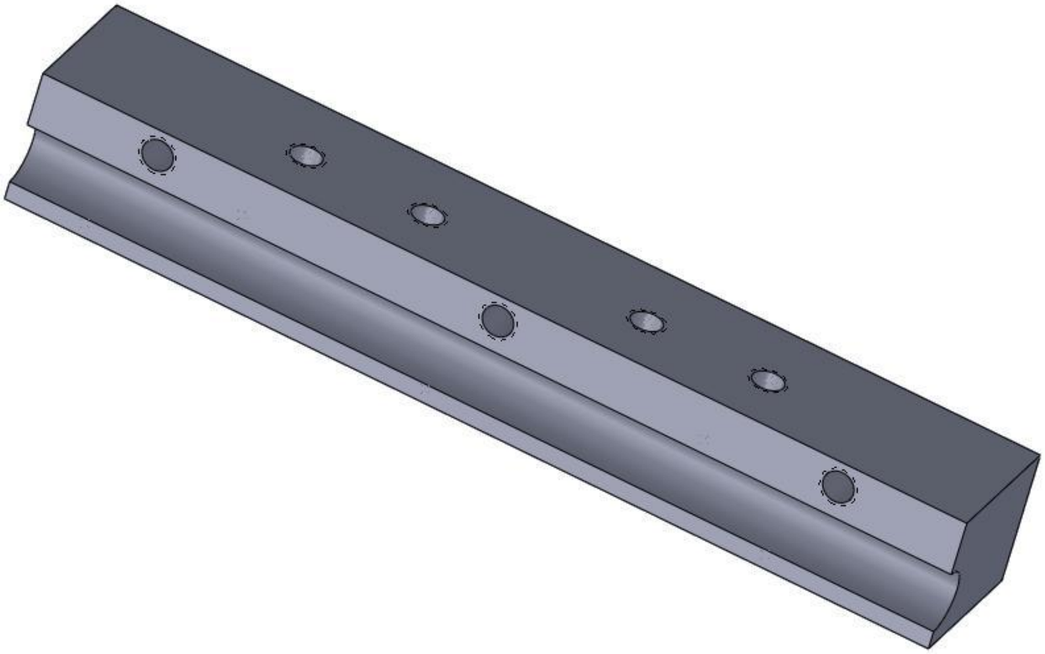


Figure 34: Shear Locking Bushing Block Model

The bushing guide rail is shown below. The bushings are attached to this to allow for easy assembly.

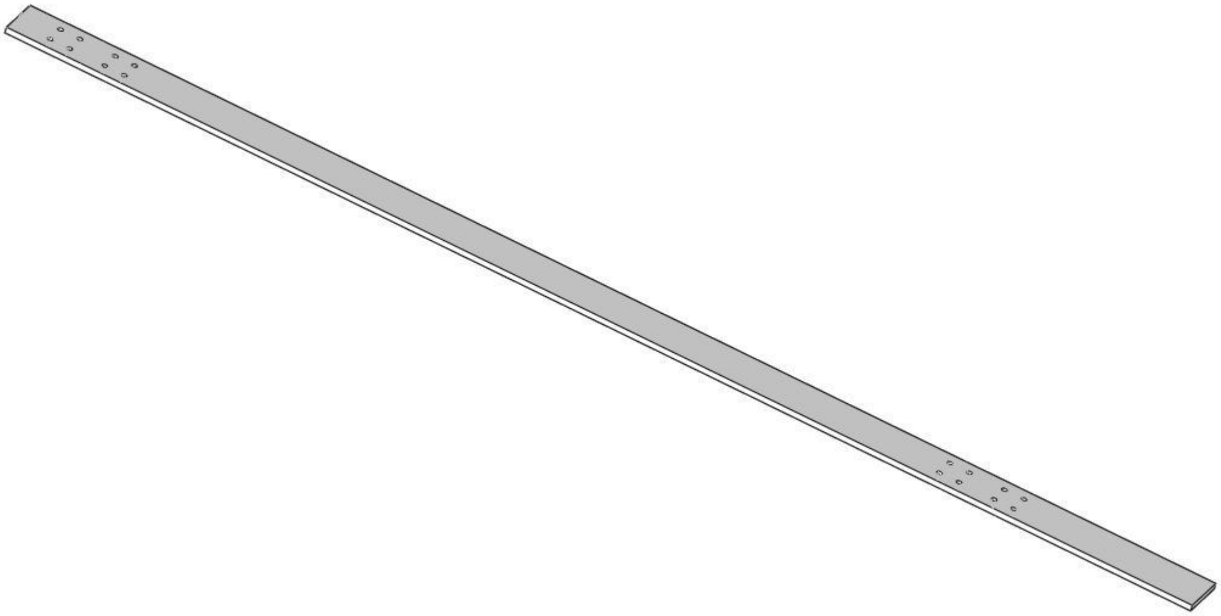


Figure 35: Shear Locking Bushing Guide Rail Model

The bushings and shaft are shown together in the figure below to show the assembly of these components.

Figure 36: Shear Locking Bushing and Shaft Assembly

4.5 Shear Locking – Results

The second method that the shear locking design was tested in was the same as the other two designs. The components of the design were as they were in the first test. The completed assembly was inserted into a three point bending fixture with circular supports, a dial indicator, and a singular S-hook to hang weights from. The layout was as seen in the figure below.

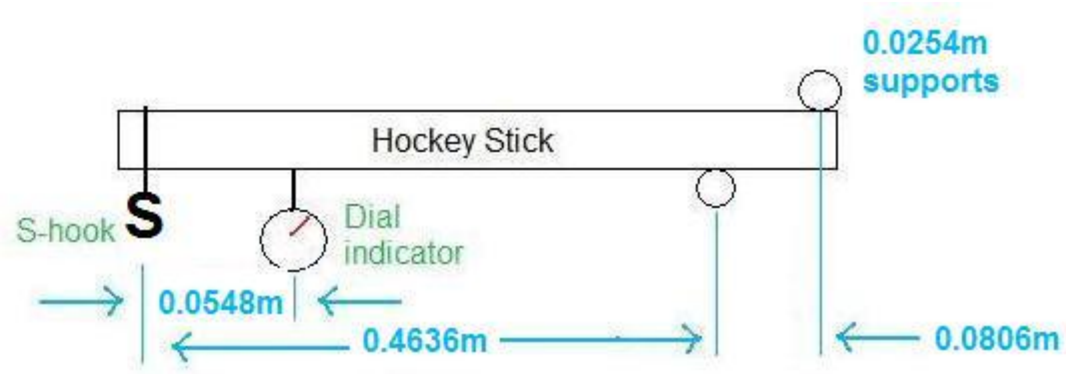


Figure 37: Shear Locking Testing Schematic

During testing of this design, some problems occurred. The teeth of the fixed profile were attached to the guide rail with the same epoxy used on the rotating shaft. While it bonded to aluminum well, the epoxy did not bond to the delrin as sufficiently as we would have liked. During testing with the first method, one of the fixed teeth broke off of the assembly. We continued testing with this missing tooth, which seemed to alter the flexibility a lot. After this round of testing all fixed teeth were removed and glued to the guide rail again with Gorilla Glue.

During testing using the second method, the Gorilla Glue started to make cracking noises. This occurred when testing the design in the unlocked position after 15 seconds with the 60 g mass hanging from the end. None of the teeth broke off during this test, and the cracking did not seem to affect the results of the test at all. Results from all trials using both testing methods are shown in the tables below.

Results from each trial, from both methods of testing, are shown in the tables that follow, with deflections in mm. Each blue or white section represents one set of trial runs. The yellow highlighted portions of data are test runs that support the group's hypotheses. The values listed are the deflections from the original position before the trial, in inches.

Based on the average deflections at the bottom of each column, as well as the data being inconsistent, it is difficult to say with any certainty that the design works as well as it should. Less than half of the data points support the hypothesis. In fact, based on the data, it could be suggested that the locking mechanism works in the opposite way we thought, where the "locked" position would be more flexible and the "unlocked" position would be less flexible.

Table 24: Shear Locking Initial Testing Results

Trials done using the vernier height gauge

		Flexible			Rigid		
		20g	40g	60g	20g	40g	60g
Trial 1	0 Seconds	2.921	9.042	12.217	0.838	2.515	4.953
	15 Seconds	2.921	9.144	12.319	0.965	2.616	5.207
	30 Seconds	4.928	9.144	12.675	1.067	2.769	5.639
Trial 2	0 Seconds	2.311	3.810	6.934	4.309	7.087	6.477
	15 Seconds	2.413	4.064	7.188	4.309	7.087	6.579
	30 Seconds	2.413	4.064	7.239	4.115	7.518	6.604
Trial 3	0 Seconds	1.956	6.071	15.723	5.486	8.719	17.399
	15 Seconds	1.956	6.071	16.891	5.588	8.433	17.780
	30 Seconds	2.311	6.325	17.018	5.867	8.738	18.542
	Average	2.692	6.426	12.014	3.556	6.096	9.906

Table 25: Shear Locking Revised Testing Results

Trials done using the dial indicator

		Flexible			Rigid		
		20g	40g	60g	20g	40g	60g
Trial 1	0 Seconds	3.277	8.890	16.764	4.089	8.611	13.157
	15 Seconds	3.404	9.042	16.891	4.115	8.636	13.208
	30 Seconds	3.454	9.093	16.967	4.115	8.636	13.411
Trial 2	0 Seconds	5.359	11.049	18.491	4.470	8.661	13.208
	15 Seconds	5.461	11.252	18.567	4.521	8.687	13.259
	30 Seconds	5.486	11.278	18.745	4.521	8.687	13.284
Trial 3	0 Seconds	5.512	11.252	18.771	4.470	8.915	13.945
	15 Seconds	5.588	11.303	18.898	4.496	8.915	13.945
	30 Seconds	5.613	11.328	18.923	4.496	8.915	13.945
Trial 4	0 Seconds	1.524	6.096	12.675	4.648	10.592	16.789
	15 Seconds	1.524	6.172	12.751	4.801	10.617	16.789
	30 Seconds	1.549	6.198	12.776	4.851	10.643	16.789
Trial 5	0 Seconds	74.193	7.087	11.887	5.207	10.922	16.688
	15 Seconds	2.972	7.137	12.802	5.258	11.024	16.739
	30 Seconds	2.997	7.163	12.802	5.309	11.049	16.764
Trial 6	0 Seconds	2.261	6.985	12.827	4.140	9.246	11.684
	15 Seconds	2.286	7.087	12.979	4.267	9.347	11.938
	30 Seconds	2.311	7.137	13.005	4.293	9.525	11.989
Trial 7	0 Seconds	2.972	4.902	14.529	5.080	7.315	11.532
	15 Seconds	3.073	4.953	14.605	5.207	7.366	11.557
	30 Seconds	3.607	5.004	14.605	5.207	7.391	11.582

Trial 8	0 Seconds	4.064	12.954	15.011	4.572	8.763	13.665
	15 Seconds	4.191	13.081	15.011	4.623	8.865	13.665
	30 Seconds	4.242	13.132	15.011	4.648	8.890	13.691
	Average	3.581	8.738	15.265	4.648	9.169	13.894

4.6 Shear Locking – Discussion

If more time were available, the group has changes to this design that we would try for improved results. First, the delrin used in the guide rails and fixed teeth was hard to work with while creating the parts. The group would try another plastic, such as acrylic or nylon, or a metal like aluminum to reduce manufacturing efforts and increase strength. The delrin cracked in a few places during the manufacturing procedure, so we fixed these cracks with epoxy.

While the initial design of the fixed profile called for a solid piece, the group instead made the profile by forming the teeth separately and using epoxy to fix them to the guide rail. The reason for this change was that the group thought there would be concentrations of stress in the corners of the profile when the part would be in a flexed position. This change to include the assembled profile caused alignment and manufacturing issues in the complete assembly of the hockey stick. For this reason, the group would revert to the original design of a solid piece. One option to use this solid design would be to add radii to the corners to remove the stress concentrators. Another option would be to calculate the stresses that would occur in those corners and if they are negligible, keep the profile as designed.

The testing shows that the mechanism is not consistent in the way it works. Some trials had very small deflections, while others with the same weight had much larger deflections. Some trials worked the way we hypothesized, with the “locked” setting being more rigid than the “unlocked” setting. Other trials did not work this way. One possible reason for the inconsistent data is the deviation from the tolerancing requirements during the manufacturing procedure. Another possible reason for the inconsistent data is the choice of materials used for the prototype. The plastics chosen might not have had the initial stiffness that was desired, or the plastics might lose stiffness over time. Further testing would need to be done with either or both of these suggestions to determine if these are the causes of failure for this design.

4.7 Shear Locking – Conclusions

After completing testing, it is apparent that this design does not work as well as we would have liked. In the 11 trials done with a mass of 60 g, three tests failed. With a 73% pass rate and inconsistency between trials, the design would need a lot more work before it could be implemented in any application. Parameters that could be tested to obtain improved results would be different materials, closer tolerances, and improved manufacturing, assembly, and testing procedures. The fact that most tests passed show us that this design could be feasible with more work.

Chapter 5: Variable Volume Design

5.1 Variable Volume - Concept and Theory of Operation

Another concept which was discussed for changing the flexibility of a box beam would be to use the properties of liquids. When a straight tube is bent, the volume inside the tube decreases. If the tube is not sealed, when it is bent, the decreasing volume would force the contents of the tube out through the opening. If the tube is sealed, then in order for it to bend, the contents of the tube would have to be compressed. Water requires such a large amount of force to be compressed, that it could be considered incompressible when the forces from playing hockey are exerted on it. If it is incompressible, then when trying to bend the tube, it should theoretically prevent that. In order to use this property to vary the flexibility, it would have to be possible to seal or unseal the tube.

A few different ideas were researched to determine the best way to use liquids to vary the flexibility. Initially it was thought that the flexibility could be varied by controlling the rate at which fluid could flow in and out of the tube. Another idea was using one way valves to control the flow of water. These would have been very useful designs because they would have allowed for continuously variable flexibility, but these ideas were thrown out because they would only change how quickly the beam could flex, but not how much it could flex. It was decided that using a single valve to control if water could flow in or out would work the best. The functionality was limited because it allowed for only two levels of flexibility.

To vary the flexibility, a tube would be contained inside the hockey stick. The tube would be filled with a liquid. The tube would be sealed on the bottom and be attached to a valve at the top. In order to make the stick rigid, the user would close the valve, sealing the liquid inside the tube. In order to make the stick more flexible, the user would open the valve to allow the liquid to flow out of the tube and into a second tube.

5.2 Variable Volume - Decomposition

5.2.1 Level One Decomposition

Table 26: Shear Friction Level 1 FRs and DPs

FR1 – Allow flexibility to vary	DP1 – A mechanism that uses fluid pressure to change the flexibility of a tube
FR2 – Control flexibility	DP2 – A mechanism that allows user input to control the flexibility
FR3 – Provide shaft	DP3 – A composite shaft that contains and protects the mechanisms
FR4 – Install mechanism into shaft	DP4 – A means of containing the mechanisms in the shaft

This design uses the properties of liquids to control the flexibility of the hockey stick. The volume of a fluid is dependent on the temperature and pressure of that fluid. Assuming the temperature of a fluid is not changing, then as the pressure on the fluid increases, the volume decreases. Fluids are very resistant to compression so that a lot of pressure is required to change the volume of a liquid. Theoretically, if a fluid is enclosed in and occupies the entierty of a container, then the pressure required to crush that container is very large. This design relies on this law to control the flexibility of the hockey stick.The shaft of the hockey stick, the mechanism that varies the flexibility, the mechanism that controls the flexibility and the means of holding the mechanisms in the shaft comprise the entire system and show that the method is collectively exhaustive. The disconnections between the roles and actions of the different parts show that these FRs are mutually exclusive.

5.2.2 Level Two Decomposition

Table 27: Variable Volume Level 2 for FR and DP 1

FR1.1 – Hold quantity of fluid constant	DP1.1 – A reservoir that contains the fluid to a single quantity
FR1.2 – Allow quantity of fluid to change	DP1.2 – A reservoir expansion that allows the fluid change quantity
FR1.3 – Control if quantity is constant or not	DP1.3 – A valve that controls if the fluid can flow from the reservoid to the expansion

The second level of decomposition for FR1 are all related to functions that the mechanism must be able to complete. For the concept behind this idea to work, the mechanism must be able to have two states, a state where the quantity of fluid is held constand and a state where the quantity of fluid can change. FR1.1 deals with holding the quantity constant while FR1.2 deals with the state where the quantity can change. FR1.3 is what controls which state the mechanism is in.

Table 28: Variable Volume Level 2 for FR and DP 2

FR2.1 – Allow user input	DP2.1 – A handle to allow the user control
FR2.2 – Control flexibility	DP2.2 – A mechanism connecting input handle to valve

The second level decomposition for FR2 all deal with the input from the user. FR2.1 is what allows the user to choose the flexibility based on their needs. FR2.2 is used to take the user's desired flexibility level and translate that to the mechanism controlling the flexibility, the valve between the controlled volume chamber and the expansion chamber.

Table 29: Variable Volume Level 2 for FR and DP 3

FR3.1 – Protect the mechanism	DP3.1 – Carbon fiber planks
FR3.2 – Control elastic modulus	DP3.2 – Fiber sheath
FR3.3 – Contain mechanism	DP3.3 – The shaft must have inner dimensions large enough to hold the mechanism

FR3 is the shaft of the hockey stick. The second level decomposition is made of the functions that the shaft must complete. FR3.1 and FR3.2 are related to the material composition of the shaft so that the shaft is flexible enough that the effects of the mechanism are not masked, while being rigid enough to protect the mechanism and give the shaft enough rigidity to be usable. The required dimensions of the shaft make up FR3.3 which must be large enough to contain the mechanism.

Table 30: Variable Volume Level 2 for FR and DP 4

FR4.1 – Prevent motion in the X direction	DP4.1 – Brackets
FR4.2 – Prevent motion in the Y direction	DP4.2 – Diameter of tube
FR4.3 – Prevent motion in the Z direction	DP4.3 – Fixed block

FR4 is composed of the different requirements for holding the mechanism inside the shaft. FR4.1 has to prevent the mechanism from moving around in the X-direction which is across the shaft and can be accomplished by using brackets to fill the gap between the tube of the mechanism and the wall of the shaft. FR4.2 has to prevent the tube from moving in the Y-direction. This was the easiest to solve by simply making the outer dimension of the tube the same as the internal Y-dimension of the shaft. FR4.3 has to prevent the mechanism from sliding up and down the shaft in the Z-direction. To do this, the tube was fixed to the bottom of the shaft with a threaded hole and rod.

5.2.3 Level Three Decomposition

Table 31: Variable Volume Level 3 for FR and DP 1.1

FR1.1.1 – Allow space for fluid	DP1.1.1 – A hollow tube to hold the fluid
FR1.1.2 – Contain fluid in chamber	DP1.1.2 – A block to prevent fluid from flowing out
FR1.1.3 – Prevent fluid from leaking	DP1.1.3 – Sealant to make chamber water tight

FR1.1 deals with all the functions required of the reservoir that holds fluid at a constant quantity. FR1.1.1 designates the fluid container as a hollow tube. FR1.1.2 is required so that the bottom end of the tube is blocked so that fluid cannot flow out of it. Sealant between the tube and block and valve make up requirement FR1.1.3 which has to stop any fluid from leaking.

Table 32: Variable Volume Level 3 for FR and DP 1.2

FR1.2.1 – Allow space for fluid to flow into	DP1.2.1 – A hollow tube for fluid to flow into
FR1.2.2 – Prevent fluid from spilling	DP1.2.2 – A rubber seal on the top of the tube

FR1.2 deals with all the functions required of the reservoir that allows the liquid to flow out of the constant quantity reservoir. FR1.2.1 is a hollow tube that fluid can flow in to. FR1.2.2 is a seal made of soft rubber that blocks the top end of the tube. This prevents fluid from spilling out of the system. Without this requirement, the user would have to frequently refill the stick.

5.3 Variable Volume - Physical Integration

5.3.1 Tolerancing

For this design, there were no strict tolerances. This design had only one moving part, the valve between the bottom tube and the top tube. This part was purchased pre built so the group did not have to determine tolerances for it. Another place where tolerances could make a difference was where the tubes connected to the valve. The tubes and valve were purchased from a single manufacturer with standard sizes so they would not leak. In order to ensure that there were no leaks, sealant was applied to these locations. These two reasons made tolerancing inconsequential.

The position of the tube inside the hockey stick was the only place where tolerancing was used, and even in this regard, it was barely used. For the tube to influence the flexibility of the hockey stick, it had to be touching both the front and back of the hockey stick. This did not require specifically measured tolerances, but merely checking for visual gaps between the tube and shaft. The tube also had to not be able to slide back and forth inside the shaft so the braces to prevent this motion were toleranced in the same manner as with checking to see if the tube was touching both sides of the stick, visually.

5.3.2 Diagram

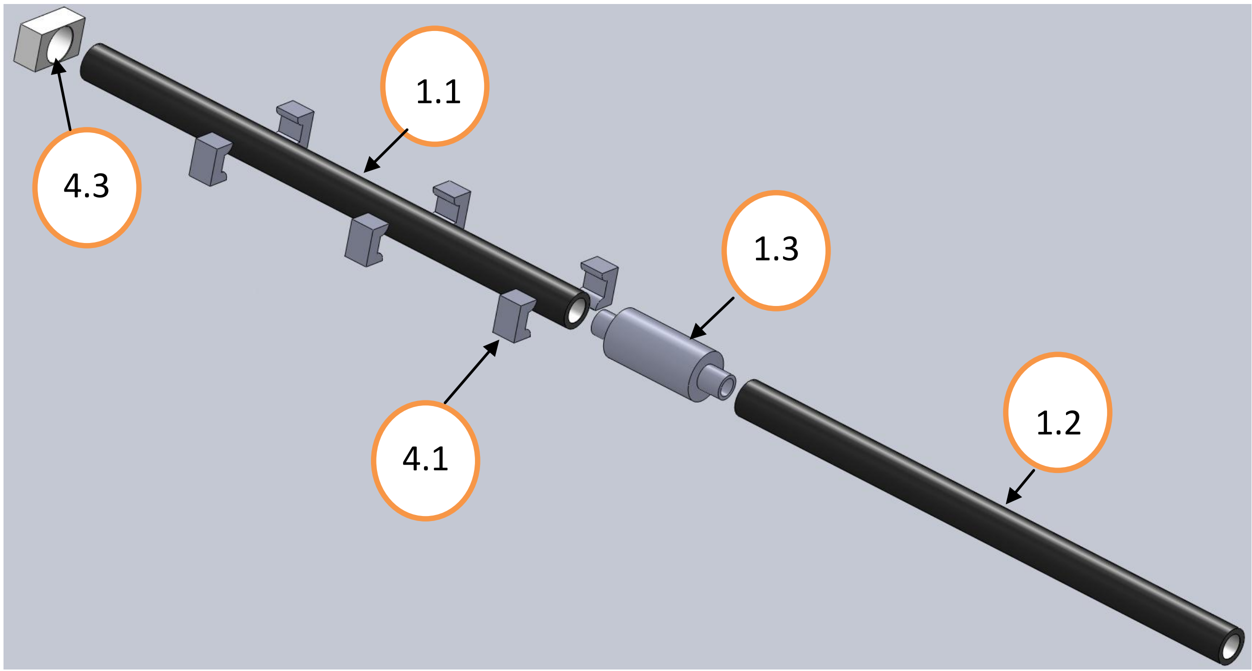


Figure 38: Variable Volume FR Diagram

FR1.1 – Hold quantity of fluid constant.

FR1.2 – Allow quantity of fluid to change.

FR1.3 – Control if quantity is constant or not.

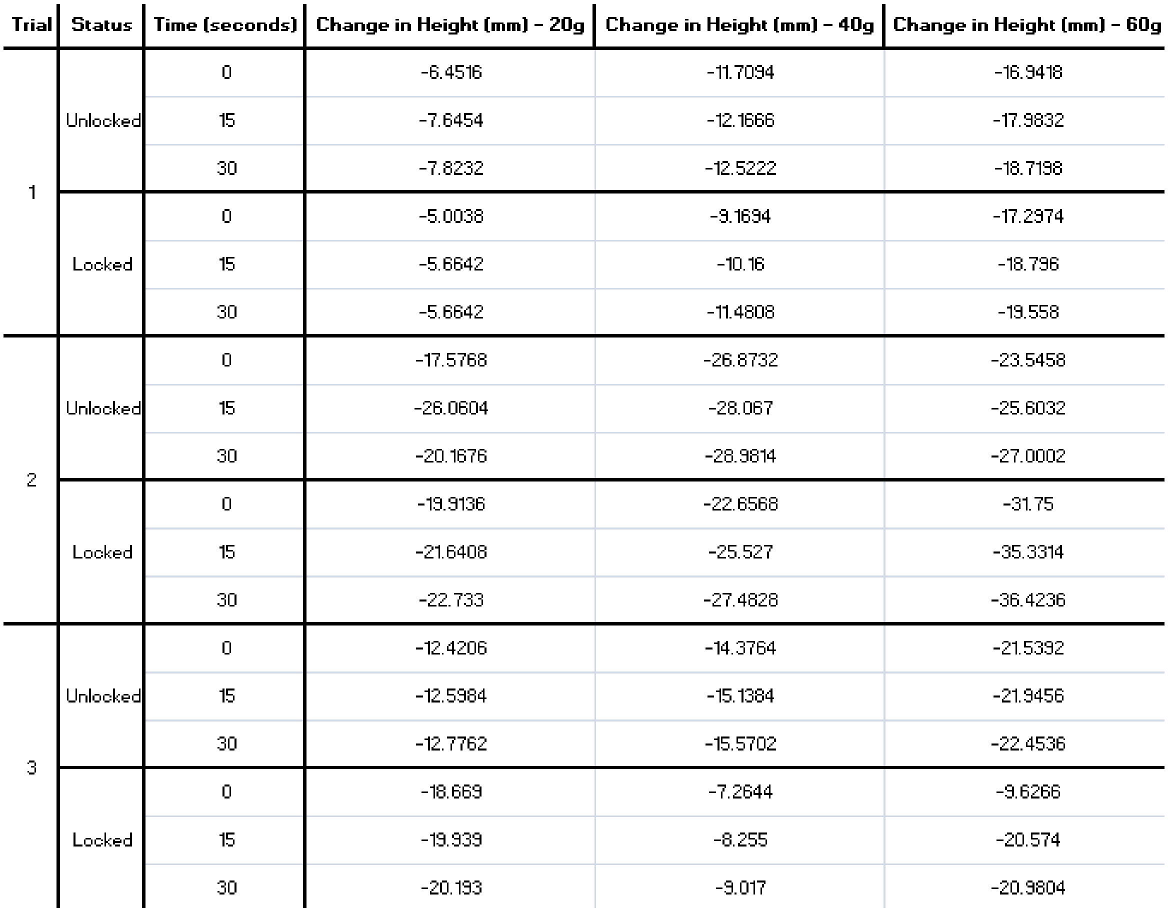
FR4.1 – Prevent motion in the X direction.

FR4.3 – Prevent motion in the Y direction.

5.4 Variable Volume - Results

The first set of data for the variable volume design presented some interesting results. Looking at the changes in height between data sets, it was apparent that this design did not produce consistent results, predictable patterns or complete the goal. Depending on which trial it was, if the time and weight were the same, the changes in height had huge variances even if the stick was kept in the same state of locked or unlocked. Also, on some of the trials, it showed that the unlocked state was more rigid than the locked state, which is the opposite of how it should theoretically be. During the acquisition of this data, the mechanism was leaking extensively and the tube had a very predominant bend to it. The collected data can be seen below.

Table 33: Variable Volume Results



Trial	Status	Time (seconds)	Change in Height (mm) - 20g	Change in Height (mm) - 40g	Change in Height (mm) - 60g
1	Unlocked	0	-6.4516	-11.7094	-16.9418
		15	-7.6454	-12.1666	-17.9832
		30	-7.8232	-12.5222	-18.7198
	Locked	0	-5.0038	-9.1694	-17.2974
		15	-5.6642	-10.16	-18.796
		30	-5.6642	-11.4808	-19.558
2	Unlocked	0	-17.5768	-26.8732	-23.5458
		15	-26.0604	-28.067	-25.6032
		30	-20.1676	-28.9814	-27.0002
	Locked	0	-19.9136	-22.6568	-31.75
		15	-21.6408	-25.527	-35.3314
		30	-22.733	-27.4828	-36.4236
3	Unlocked	0	-12.4206	-14.3764	-21.5392
		15	-12.5984	-15.1384	-21.9456
		30	-12.7762	-15.5702	-22.4536
	Locked	0	-18.669	-7.2644	-9.6266
		15	-19.939	-8.255	-20.574
		30	-20.193	-9.017	-20.9804

The second set of data produced much more stable results. For all trials, the unlocked state of the mechanism deflected more than the locked state. Also, the data showed a very consistent pattern. Every fifth data point had significantly lower deflection than the other data points. These data points coincided with when, during testing, the mechanism was turned over to bend in the opposite direction of the previous five points. Disregarding the fifth data point, all of the remaining points are very consistent, with little variance. While collecting this second set of data, the mechanism did not leak and the tube was much straighter than during the first set of data points. The second set of data contained more points that the first one and is summarized by the graph below.

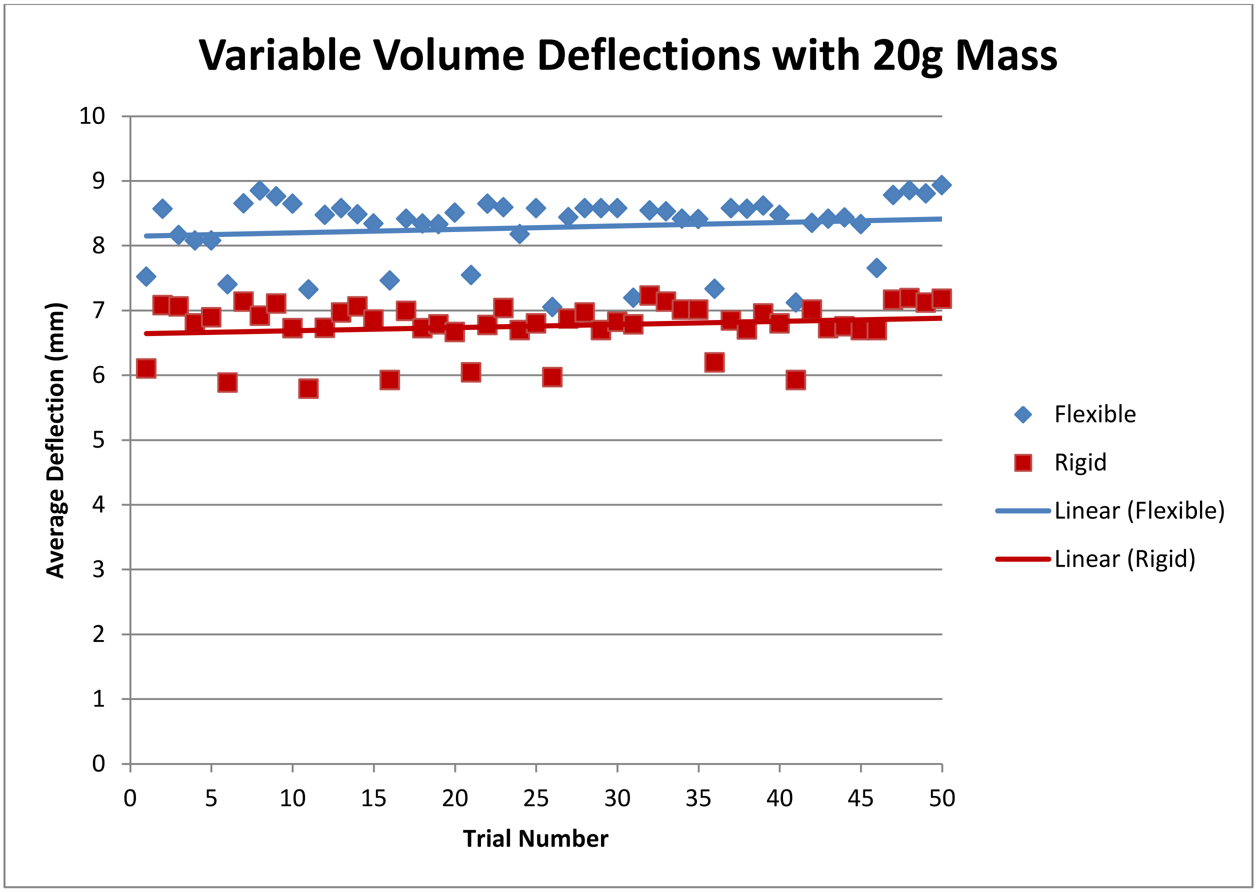


Figure 39: Variable Volume Deflections with 20g Graph

5.5 Variable Volume - Discussion

During testing a couple things were noticed about the variable volume design. The first thing noticed was that the mechanism leaked. During the first iteration of the mechanism, it would start leaking after a couple trials. The longer testing continued, the faster the mechanism started to leak. At the end of collecting a full set of data, the height of fluid left in the reservoir tube would have decreased several inches. After a sealant was applied to the connectors between the tubes, the leaking decreased drastically. The fabric would still be damp, but the mechanism would never drip, nor would the height of the fluid in the reservoir tube have visibly dropped. Given more time, future iterations of this design might try using seals and sealant to prevent leaks.

Another noticeable aspect of this design was that it had a significant amount of creep. Some of this creep was likely due to the leaking of the tubes, but changing the tubes might have helped reduce the creep. The tube that was used was a hard rubber hose covered in a fabric mesh. A more flexible material might allow the pressure of the fluid to exert more of an influence on maintaining the rigidity of the tube as opposed to relying on the tube itself. During the storage and shipping of the tube, it was coiled and retained a curve despite attempts to straighten it. The curved tube was exerting an additional force that could not be determined during testing. If the tube was more flexible, the tube would be less likely to retain its curve.

The last change that would be implemented if there was more time would be to keep the contents of the reservoir chamber under slight pressure. This would facilitate the flow of the liquid back into the main tube when the shaft straightened out after being bent. This would in turn increase the rate at which the shaft returned to its straight position.

5.6 Variable Volume – Conclusion

Based on the second set of data, this design is successful at varying the flexibility of a beam, however it is not applicable for use in a hockey stick. The second set of data shows that the flexibility of the beam is dependent not only on the state of the mechanism, but also on if the shaft has been bent already and in which way the shaft had been bent. Also, in hockey, the shaft must spring back into position quickly to allow the player to add additional force to their shots, but this design did not snap back to its neutral position quickly, which means that it would not work well in a fast paced environment such as hockey. It would be much more suited for applications where forces were applied and removed slowly or more consistently such as for structural building materials.

Chapter 6: Discussion

Out of the three prototypes tested, the Shear Friction design was the mechanism most ready to be implemented in a hockey stick. It always altered its flexibility by a consistent amount when tested. The shear locking mechanism was most likely inconsistent due to its manufacturing tolerances. It cannot yet be considered a failed design, and a re-manufactured prototype would most likely lead to more reliable testing. The variable volume design is not well suited to a hockey specific application because it did not “snap” back to the original position as expected. It may still be useful for a variable stiffness beam in other applications requiring lower return rates, such as building materials.

The project itself can be considered successful. One prototype was successful in the intended application, one was possibly useful for other applications, and the final prototype has possible reasons for being inconsistent. The testing method provided useful information that is similar to what we would expect these mechanisms to encounter when used in a hockey situation. It also provided questions which could be used for further research.

The project was successful in providing education in a number of areas important to engineering. Conceptual designs were created and refined using Axiomatic Design techniques. CAD models and assemblies were created so that the parts could be analyzed and eventually manufactured. Functional prototypes for all designs were created using a variety of computer controlled and manual machining methods. This highlighted the importance of part design, tolerancing, design for manufacturability, and practical machining skills. The designs for which this work was done were unique and beyond any technology which currently exists. Designing a product in this manner allowed the group to be creative in the design process, and to not be constrained by parameters of redesigning an existing product. An experiment was designed to the test the hypothesis relating to our project. This involved an analysis of the experimental data required, considerations regarding accuracy and repeatability, and an analysis of the final data. Should further development and research show these designs to be useful, a successful commercial product could be created.

Our mechanisms were not capable of altering the flexibility of the initial box beam. This opposed our hypothesis that a mechanism which could be integrated into current hockey sticks could be made.

For testing new mechanisms, or refined versions of the existing mechanisms, further development of the hockey stick itself should be done. The initial box beam was far too stiff to show the effects of the mechanisms, but the flexible-side beams we created are not similar to a production hockey stick. A thinner walled box beam may decrease some of the problems caused by our initial construction. Use of the vacuum bag method of carbon fiber lay ups may have helped the beam to have thinner walls and use less resin. This may increase the success of testing mechanisms within a box beam.

If creating a rigid box beam is not practical, further research should be done with regards to creating a beam with flexible sides. Despite the fact that current production hockey sticks do not exist in this configuration, the addition of an internal mechanism may mean that a stick with flexible sides is viable. Such an outer stick configuration may be vital to the operation of a particular type of mechanism. During our testing, we hypothesized that the best way to create a stick with flexible sides would be to create two rigid plates out of carbon fiber, slide the carbon fiber fabric shaft over these plates, and then use a thin strip of resin on the top and bottom to hold it in place. This was never tested, and experimentation may reveal a more suitable method of attaching fabric sides to rigid top and bottom plates. Additional, fabric materials other than uncured carbon fiber may prove more suitable for the construction.

Further testing is another recommendation related to this project. A relatively simple method was used for the prototypes created. Additional testing with other methods could reveal interesting information, such as a change in flexibility depending on how fast the shaft is loaded. Additional testing could be performed by actually having a player use a stick in a game situation. Analysis of the biomechanics of a player using the stick could reveal advantages or disadvantages to each design. This sort of testing would also reveal any improvements that would need to be made in order to make such a hockey stick a viable commercial product. Testing using electronic sensors would provide real time data regarding the stiffness of the stick and the effect of the mechanisms. This was not possible during this project, due to technical difficulties with the data acquisition system. Obtaining a working data acquisition system would lead to the use of strain gauges as well as electronic dial indicators. Use of these devices, especially by using multiple gauges at one time, would greatly enhance the quality of data regarding these mechanisms. Further testing in this way would be highly valuable to a future project.

Chapter 7: Conclusions

The final conclusions regarding the total project are as follows.

- The stiffness of a beam can be varied based on an internal mechanism
- The shear friction mechanism had different levels of flexibility based on its activation
- The shear locking mechanism was inconsistent, likely due to manufacturing tolerances
- The variable volume mechanism was not suited to a hockey stick application
- None of the mechanisms designed were found in patent research
- A functional hockey stick should be created to understand the effectiveness of the top designs

This project accomplished the majority of its intended goals. Not every design was proven to be successful, but the rationale for creating three prototypes was to see which design would be most successful, if any at all. All areas of the design process, from conception to testing, were accomplished to a sufficient degree. Ideally, a full prototype hockey stick would have been created because the application of the variable stiffness beam technology was chosen to be a hockey stick. Creating a working hockey stick would have shown if the technology was useful in this specific application. However, time constraints did not allow for a full prototype to be created. Everything else was accomplished and the core mechanism was created and tested. This provides a good basis for future research which will be able to expand upon groundwork laid out by this project. In essence, the concept has been proven, but further work needs to be done if this is to be developed into a viable commercial product.

Works Cited

Aerospace Specification Metals Inc. (2010). *ASM Material Data Sheet*. Retrieved April 20, 2011, from Aerospacemetals.com: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6

Bird, T. E. (2000). *Patent No. 6033327.* US.

Brett P. Masters, M. C. (2002). *Patent No. 6361451.* US.

Li, S. (2008). *A variable transverse stiffness sandwich structure using fluidic flexible matrix composite.* University Park : Pennsylvania State University.

Matson, B. (2009, January 29). Bit of a sticky situation: Composites often are at breaking point. *Boston Globe*.

Appendix

Aluminum Bar Data and Graph

Aluminum Bar Data – Revised Testing Frame and Procedure

Table 34: Aluminum Bar Raw Data

Trial	0 Seconds	15 Seconds	30 Seconds
1	10.897	10.922	10.922
2	10.617	10.643	10.668
3	10.693	10.719	10.744
4	10.465	10.465	10.490
5	10.643	10.643	10.668
6	10.643	10.668	10.668
7	10.668	10.668	10.668
8	10.566	10.617	10.617
9	10.465	10.465	10.465
10	10.668	10.668	10.668
11	10.719	10.795	10.820
12	10.846	10.846	10.871
13	10.490	10.541	10.541
14	10.566	10.592	10.617
15	10.693	10.719	10.744
16	10.643	10.693	10.719
17	10.744	10.744	10.744
18	10.770	10.770	10.770
19	10.439	10.439	10.439
20	10.795	10.820	10.820
21	10.414	10.439	10.439
22	10.846	10.871	10.871
23	10.719	10.719	10.719
24	10.693	10.693	10.719
25	10.744	10.744	10.770
Mean:	10.658	10.676	10.687

All measurements are from dial indicator in mm with 20 gram weight.

Aluminum Bar Graph – Revised Testing Frame and Procedure

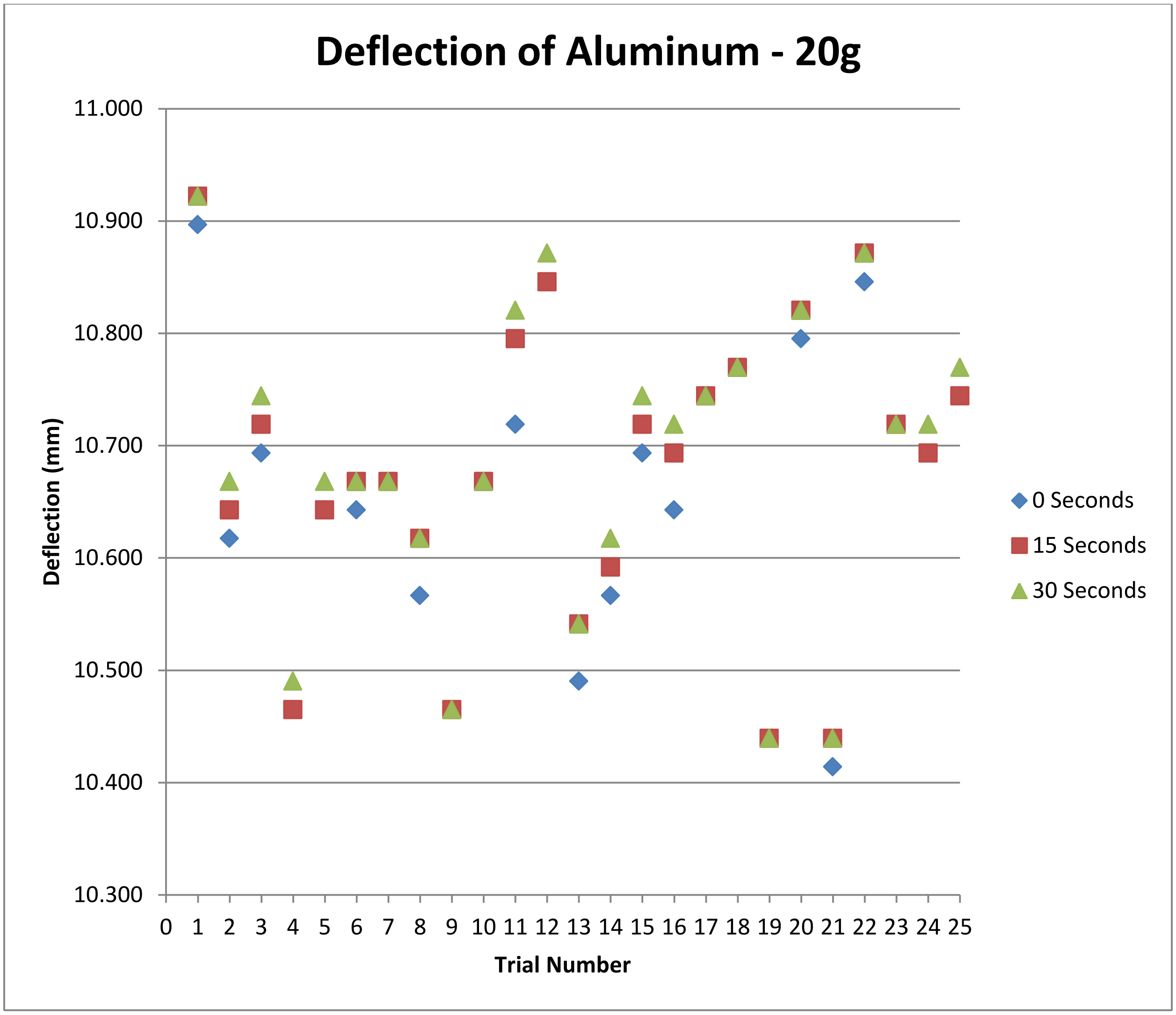
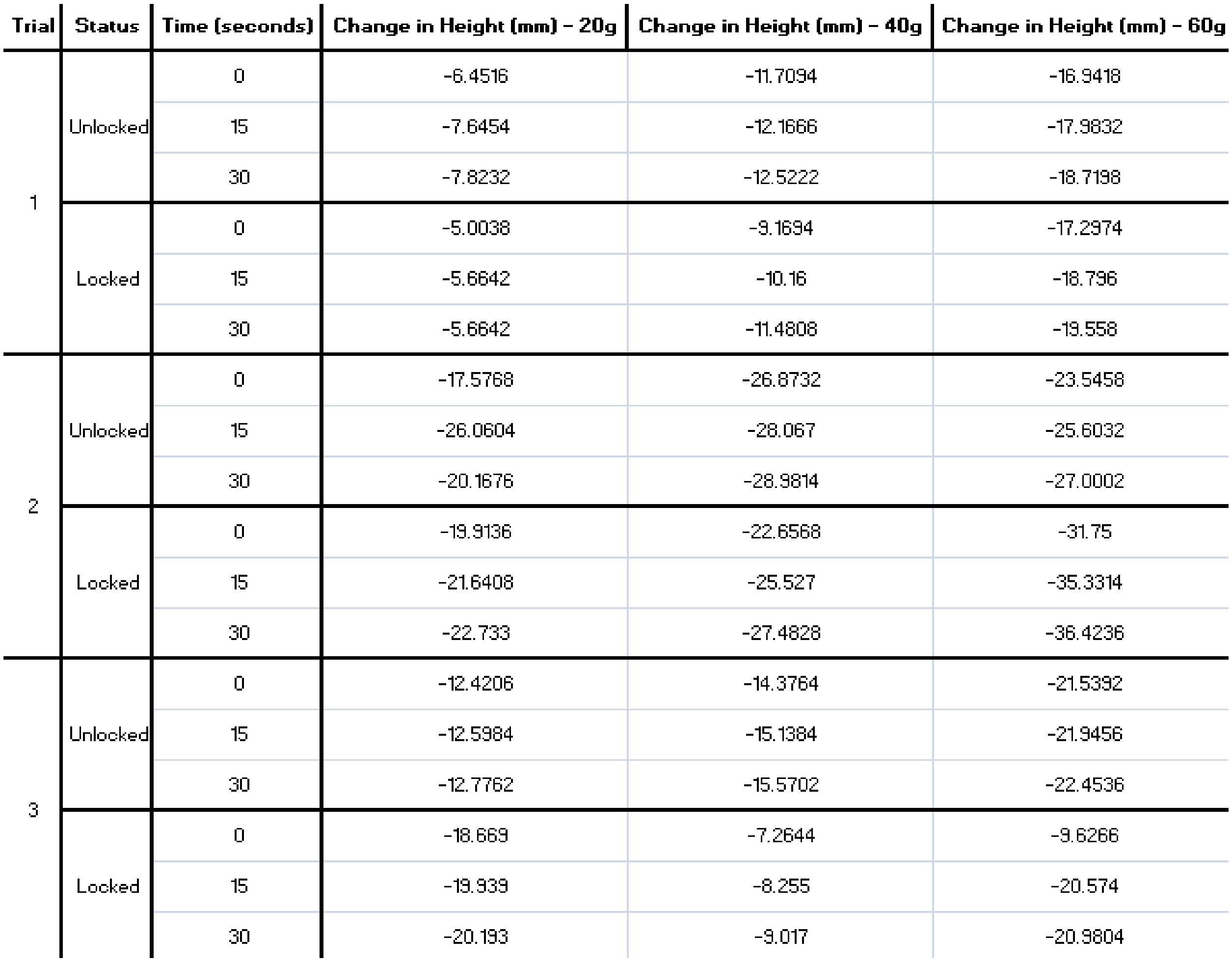


Figure 40: Aluminum Bar Data Graph

Variable Volume Data and Graphs

Variable Volume Data – Initial Testing Frame and Procedure

Table 35: Variable Volume Initial Testing Raw Data



Trial	Status	Time (seconds)	Change in Height (mm) – 20g	Change in Height (mm) – 40g	Change in Height (mm) – 60g
1	Unlocked	0	-6.4516	-11.7094	-16.9418
		15	-7.6454	-12.1666	-17.9832
		30	-7.8232	-12.5222	-18.7198
	Locked	0	-5.0038	-9.1694	-17.2974
		15	-5.6642	-10.16	-18.796
		30	-5.6642	-11.4808	-19.558
2	Unlocked	0	-17.5768	-26.8732	-23.5458
		15	-26.0604	-28.067	-25.6032
		30	-20.1676	-28.9814	-27.0002
	Locked	0	-19.9136	-22.6568	-31.75
		15	-21.6408	-25.527	-35.3314
		30	-22.733	-27.4828	-36.4236
3	Unlocked	0	-12.4206	-14.3764	-21.5392
		15	-12.5984	-15.1384	-21.9456
		30	-12.7762	-15.5702	-22.4536
	Locked	0	-18.669	-7.2644	-9.6266
		15	-19.939	-8.255	-20.574
		30	-20.193	-9.017	-20.9804

Variable Volume Data – Revised Testing Frame and Procedure

Table 36: Variable Volume Revised Testing Raw Data

	Locked				Unlocked			
TRIAL	0 seconds	15 seconds	30 seconds	Mean	0 seconds	15 seconds	30 seconds	Mean
1	5.994	6.121	6.198	6.104	7.493	7.518	7.544	7.518
2	7.010	7.087	7.137	7.078	8.560	8.560	8.585	8.568
3	6.985	7.087	7.112	7.061	8.153	8.153	8.179	8.162
4	6.731	6.807	6.858	6.799	8.077	8.077	8.077	8.077
5	6.782	6.909	6.985	6.892	8.052	8.077	8.103	8.077
6	5.791	5.893	5.969	5.884	7.366	7.417	7.417	7.400
7	7.061	7.137	7.214	7.137	8.636	8.661	8.661	8.653
8	6.807	6.934	7.010	6.917	8.839	8.839	8.865	8.848
9	7.010	7.137	7.163	7.104	8.712	8.788	8.788	8.763
10	6.655	6.706	6.807	6.723	8.611	8.661	8.661	8.644
11	5.690	5.817	5.867	5.791	7.290	7.315	7.366	7.324
12	6.629	6.756	6.807	6.731	8.458	8.484	8.484	8.475
13	6.909	6.985	7.010	6.968	8.534	8.585	8.611	8.577
14	6.985	7.087	7.112	7.061	8.407	8.509	8.534	8.484
15	6.782	6.883	6.909	6.858	8.331	8.331	8.357	8.340
16	5.817	5.969	5.994	5.927	7.442	7.468	7.468	7.459
17	6.909	7.010	7.061	6.993	8.407	8.407	8.433	8.416
18	6.629	6.731	6.807	6.723	8.306	8.357	8.357	8.340
19	6.706	6.782	6.858	6.782	8.331	8.331	8.331	8.331
20	6.579	6.680	6.731	6.663	8.484	8.509	8.534	8.509
21	5.969	6.071	6.096	6.045	7.544	7.544	7.544	7.544
22	6.680	6.807	6.833	6.773	8.611	8.661	8.661	8.644
23	6.985	7.036	7.087	7.036	8.585	8.585	8.611	8.594
24	6.629	6.706	6.756	6.697	8.153	8.153	8.230	8.179
25	6.706	6.807	6.883	6.799	8.560	8.585	8.585	8.577
26	5.867	5.994	6.045	5.969	7.036	7.036	7.087	7.053
27	6.807	6.883	6.934	6.875	8.433	8.433	8.458	8.441
28	6.883	6.985	7.036	6.968	8.560	8.560	8.611	8.577
29	6.629	6.706	6.756	6.697	8.560	8.560	8.611	8.577
30	6.782	6.833	6.858	6.824	8.534	8.585	8.611	8.577
31	6.680	6.807	6.858	6.782	7.188	7.188	7.214	7.197
32	7.188	7.239	7.264	7.231	8.484	8.560	8.585	8.543
33	7.061	7.137	7.214	7.137	8.509	8.534	8.534	8.526
34	6.934	7.010	7.087	7.010	8.382	8.433	8.433	8.416
35	6.960	6.985	7.087	7.010	8.407	8.407	8.407	8.407
36	6.096	6.223	6.274	6.198	7.315	7.341	7.341	7.332
37	6.756	6.833	6.934	6.841	8.534	8.585	8.611	8.577

38	6.629	6.731	6.756	6.706	8.560	8.560	8.585	8.568
39	6.883	6.960	7.010	6.951	8.611	8.611	8.636	8.619
40	6.731	6.807	6.858	6.799	8.433	8.484	8.509	8.475
41	5.842	5.944	5.994	5.927	7.087	7.112	7.163	7.120
42	6.960	7.010	7.061	7.010	8.331	8.357	8.357	8.348
43	6.629	6.731	6.807	6.723	8.382	8.407	8.458	8.416
44	6.680	6.782	6.807	6.756	8.433	8.433	8.433	8.433
45	6.655	6.706	6.731	6.697	8.306	8.306	8.382	8.331
46	6.629	6.706	6.756	6.697	7.645	7.645	7.671	7.654
47	7.087	7.188	7.214	7.163	8.763	8.788	8.788	8.780
48	7.137	7.188	7.239	7.188	8.839	8.865	8.865	8.856
49	7.036	7.112	7.214	7.120	8.788	8.814	8.814	8.805
50	7.112	7.188	7.239	7.180	8.915	8.941	8.941	8.932
Mean:	6.682	6.773	6.826	6.760	8.260	8.282	8.302	8.281

All measurements are from the dial indicator in mm with a 20 gram weight.

Variable Volume Graph – Revised Testing Frame and Procedure

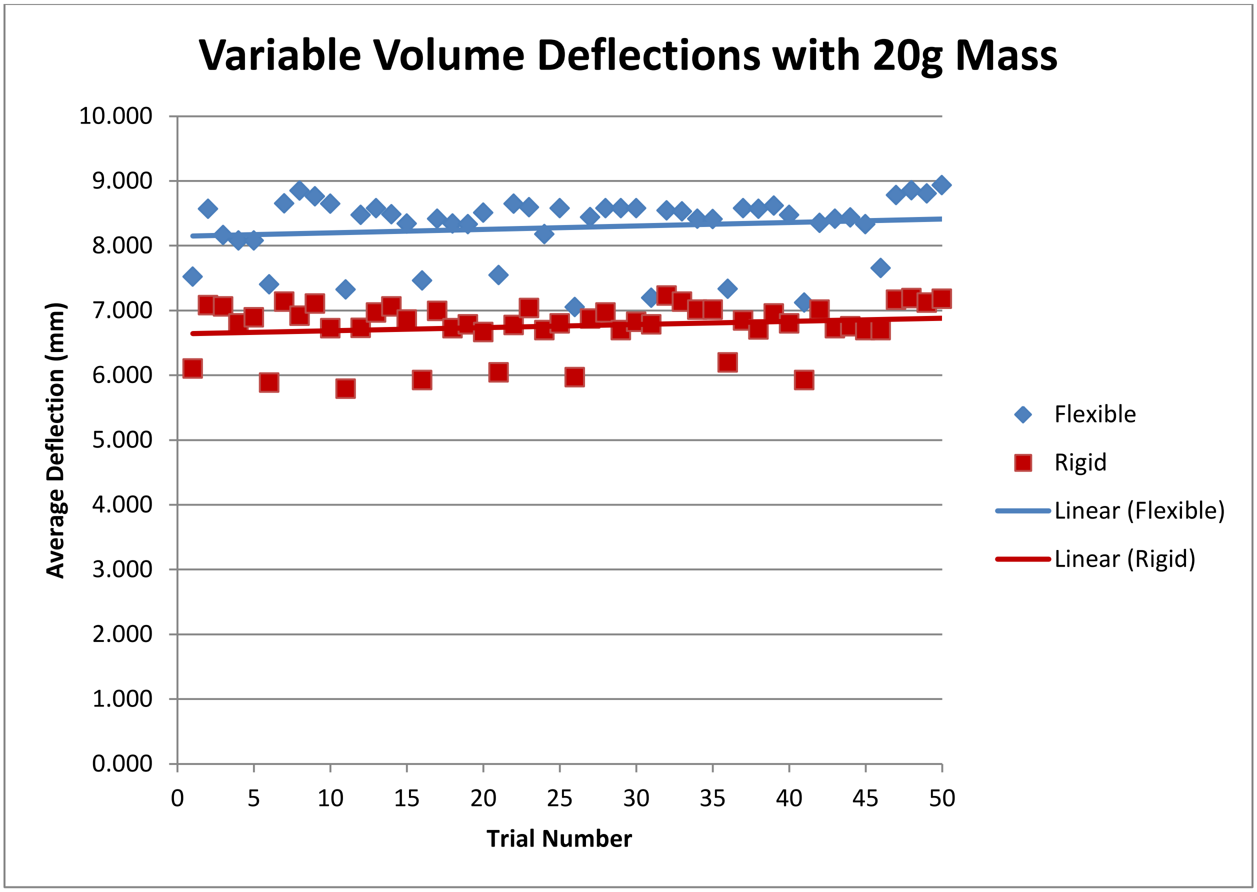


Figure 41: Variable Volume Revised Testing 20g Deflection Graph