Mechanism Design for Avoiding Ice Deformation in Fixed Docks

A Major Qualifying Project
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Abstract

This project aimed to design and create an add-on mechanism that would be retrofitted onto fixed docks to avoid deformation and possibly failure in freezing temperatures. The mechanism allows a fixed dock to (1) have room to adapt to ice freeze by horizontal and lateral movement, and (2) serve as a truly fixed dock during the warmer months, with enough strength to dock a small boat. The project spanned C, D, and E terms in the 2022-2023 school year, with research completed in C, and prototyping and analysis in D term and E1 term. A final prototype has been developed using theoretical analysis and numerical simulations. The results confirm the design is significantly more tolerant to bending and deformation than conventional fixed docks. The provisional patent 63/460,831 - Water Dock Ice Tolerance for the mechanism has been submitted as the result of this project.

Acknowledgments

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Glossary

Deformation: The action or process of changing in shape or distorting, especially through the application of pressure

Epilimnion: Top layer of water in a stratified lake

Hull: The main body of a ship or vessel, including the bottom and sides

Hypolimnion: The lower layer of water in a stratified lake, is usually cooler than the water above

Marina: A dock or basin providing secure moorings for boats and offering supply, repair, and other facilities

Mooring: The ropes, chains, or anchors by which a boat, ship, or buoy is held

Piling: Stake or post installed to support the foundation of a structure

Thermocline: Steep temperature gradient in a body of water between the layer above and below

Waterbed: The floor of a body of water

1.0 Introduction

Docks are used universally around the world and there are a variety of options available to suit specific needs. In the United States alone there are over 3 million lakes, with the majority of them being in Alaska, Michigan, and Minnesota (*States with the Most Lakes 2022*, n.d.). The majority of the docks in the United States are in cold climates, creating a need for docks that can withstand ice freeze.

The common types of consumer docks are floating and fixed docks. Floating docks are ideal for deep water and locations where there may be large waves or water level rise; whereas fixed docks are ideal for small lakes or rivers where the water level is consistent. A major negative of having a floating dock is that it must be taken out of the water before the water freezes during colder seasons; then reinstalled after the ice melts in warmer seasons. This can be a strenuous and expensive task. Fixed docks are not suitable for deep water locations, as it is difficult and costly to construct a solid foundation in deep water. They also suffer deformation due to ice freeze as there is little to no movement in the joints; which causes binding or breaking in the pilings of the dock.

While there are sufficient solutions for floating docks, there is not an existing design that allows a fixed dock to remain in the water year-round while also avoiding the issue of deformation during ice freeze. Thus, the team began brainstorming ideas for a potential solution.

The ultimate goal of this project is to create a mechanism that allows a fixed dock to remain in the water year-round while suffering significantly less deformation than an average fixed dock, specifically due to ice freeze. To achieve this goal, the mechanism must allow the dock to move slightly in lateral directions to adjust to the ice freeze, while also maintaining sufficient strength to tie a small boat. This solution transforms a permanent dock such that it will be allowed to remain in the water year-round while suffering little to no deformation and hence does not require significant maintenance year after year. To prove that our solution works, the team conducted sufficient testing, including hand calculations, 3D modeling simulations, various experiments, and testing a prototype of the mechanism.

2.0 Background Information

2.1 Types of Docks

There are many types of docks, with the two main categories for consumer docks being floating or fixed. Floating docks float on top of the water, moving with the pond or lake. A fixed dock, also referred to as a stationary dock, is built above the waterline and has a permanent foundation (Williams, V. n.d.). Each dock has positive and negative aspects, and the decision to install each type of dock varies depending on the location and personal preference.

2.1.1 Floating Docks

As the name implies, floating docks sit on the surface of the water and are connected to the shoreline by a "gangway" or ramp that allows people to walk onto the dock from the shore. This can be seen in Figure 1, where there is a floating dock with a ramp attached to it. The ramp is typically attached via metal posts with joints buried in the shoreline, allowing for the dock to move up and down with the water.

Figure 1: Floating dock on a lake (Pirnie, K. C., n.d.)

The dock uses floats made from plastic, foam, or metal on the underside to act as the object with the buoyant force. Floating docks are a popular option for installation as they can be used in a wide variety of applications, and some of the most common reasons why they are installed are because the dock is not dependent on the depth of the water, and they change their height based on the level of the water (which can vary up to 10 ft in some bodies of water). As a floating dock does not require posts to support its structure, it is a much more cost-effective solution in deeper waters. This is appealing to owners as boats and jet skis can be attached to the dock without the obstacle of water level fluctuations.

Conversely, floating docks are not ideal for locations where the water level is shallow (about 5 ft deep), and where there is a lot of turbulent water (waves, wakes from boats, etc.). When the water level is too shallow for a floating dock, the underside of the dock can become damaged when it hits the floor of the water. It can also be dangerous for users if the dock does not rest level on the ground. Furthermore, turbulent water can also become dangerous to people on the dock and the dock itself, as well as for the vehicles (boats, jet skis, etc.) that are tied to the dock as storm surges can likely allow for the hulls of vehicles to hit other objects.

Another downfall of floating docks is the need to remove them in the winter. As floating docks sit on the surface of the water, they are susceptible to getting damaged when that water freezes over. The ice that forms throughout the winter is slowly moving with the currents and that can put a lot of stress on the supports of the dock. There is also the issue that while there may not be ice on the surface of the water, there is most likely still ice in the body of water (assuming that the climate is cold enough). "Heavy" ice as it is referred to often sits right below the surface of the water, also following the tides and the current, and is usually worse than surface ice as heavy ice can damage the dock with just one pass over it (*Lake and River Ice: Formation and Classification | Minnesota Sea Grant*, n.d.). In Figure 2, a floating dock is seen disassembled and out of the water for the winter. This particular dock consists of seven large pieces that need to be reinstalled when warmer weather allows. The process of taking a floating dock out and putting it back in can be costly if a consumer hires a group to do it and it is a dangerous process to do by themselves if the right equipment is not used as the dock is heavy and has several pieces that take up space and can become lost if not stored properly (see Figure 3). Individuals who own floating docks often hire companies to move and store their docks for the winter season, but this approach can become very costly. Finally, unless the owner also has steps that go into the water, the absence of a floating dock in the winter also makes it harder to do winter activities on the body of water, such as ice skating or using an ice boat on the water's surface.

Figure 2: Floating dock out of water for the winter in Westford, MA

Figure 3: A five-gallon bucket containing cotter pins, L-bars, etc. used to construct the dock shown in Figure 2

Figure 4: The eye bolts used to secure the floating dock to the shoreline in Westford, MA

2.1.2 Fixed Docks

Fixed docks are often used in shallow waters where there is little fluctuation in water level. Fixed docks are typically fixed at several points with pilings, including the shoreline, and locations throughout the dock. The amount and location throughout the dock will vary depending on the size, shape, weight, etc. of the dock. The foundations of the pilings below the waterline may include concrete, wood, or steel, depending on the environment. Figure 5 shows a fixed dock where the pilings are resting on top of concrete or large rocks. Figures 5 and 6 highlight the difference in pilings. The dock in Figure 5 has light-duty pilings that are used with no protectors while the dock in Figure 6 has heavy-duty pilings that are used with piling protectors. Piling protectors protect the piling from degradation because of the water, and are typically used in bodies of saltwater.

Figure 5: Fixed dock with light duty pilings in Westford, MA after the water was drawn down for the winter

Figure 6: Heavy-duty pilings with piling protectors around them (*Dock Repair. Piling Repair | Louisiana, Mississippi, Florida, Alabama, Texas*, n.d.)

Fixed docks are ideal for turbulent bodies of water (resulting from waves, or boating activities), shallow water, and for docking boats or jet skis. Fixed docks are typically easier to construct as well. Permanent pilings keep the dock in one position, allowing for no movement caused by the water. This also makes fixed docks ideal for docking boats and jet skis because the dock does not move, making it less likely to damage the vehicles. Furthermore, shorter pilings are cheaper in shallow water. Fixed docks also do not need to be taken out in the winter and reinstalled as it gets warmer. This means fixed docks can be used during the winter, making winter activities easier, such as ice skating, ice fishing, etc. While fixed docks can remain in the water during the winter, they are susceptible to deformation over time, making the dock dangerous as it is deformed.

With that said, deep water locations are not ideal as the water level may fluctuate substantially and submerge the dock making it difficult or impossible to use. Deepwater also creates the need for long pilings which increases the cost.

2.1.3 Consensus of Floating and Fixed Docks

Overall, fixed docks outclass floating docks when subjected to turbulent, shallow water, and warm and cold climates. Floating docks are ideal for deep water, warm climates, and water that fluctuates a sufficient amount. The two types of docks both have positives and negatives, unfortunately, the majority of both types will sustain deformation in their lifespan due to ice.

2.2 Ice Deformation in Docks

Ice freeze is a prominent factor in dock deformation during the winter months, as the ice may freeze in a multitude of ways forcing the dock to adapt. Most docks that remain in the winter are fixed docks, and the solid construction allows for little to no movement. The ice freeze requires the dock to adapt, but the solid construction of the dock attempts to hold it in one position, therefore forcing the dock to undergo deformation and decreasing its integrity greatly.

2.2.1 When and How Does Ice Freeze

Water freezes at 32 degrees Fahrenheit (0°C), however, large bodies of water do not freeze quickly at 32°F (0°C) because of water's high thermal capacity. In most cases, a below-freezing temperature that is held for a week or more is needed to freeze the top layer of the water. Water is unique in the sense that, in its solid form, is lighter than its liquid form, therefore ice floats at the top and does not sink. The density of ice is about 90% that of water, meaning that one-tenth of an ice cube or iceberg will float above the waterline.

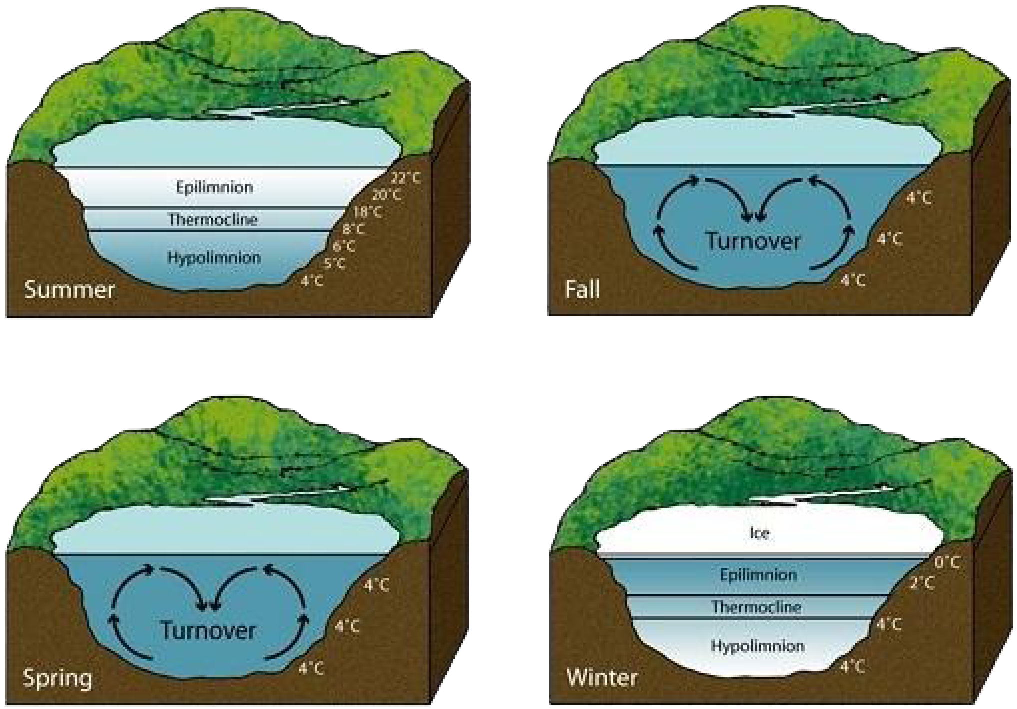


Figure 7: Diagram of the process of turnover typical for a lake (*A Look Under the Ice: Winter Lake Ecology | Ausable River Association*, n.d.)

2.2.2 Strength of Ice

Ice is the solid form of water, and when water freezes, the ice expands, taking up more space than the water. This causes the ice to exert a force on the material it is freezing against. Ice can exert an enormous amount of force such that most structures cannot withstand it and may succumb to deformation (Barbe, P., 2019, February 13).

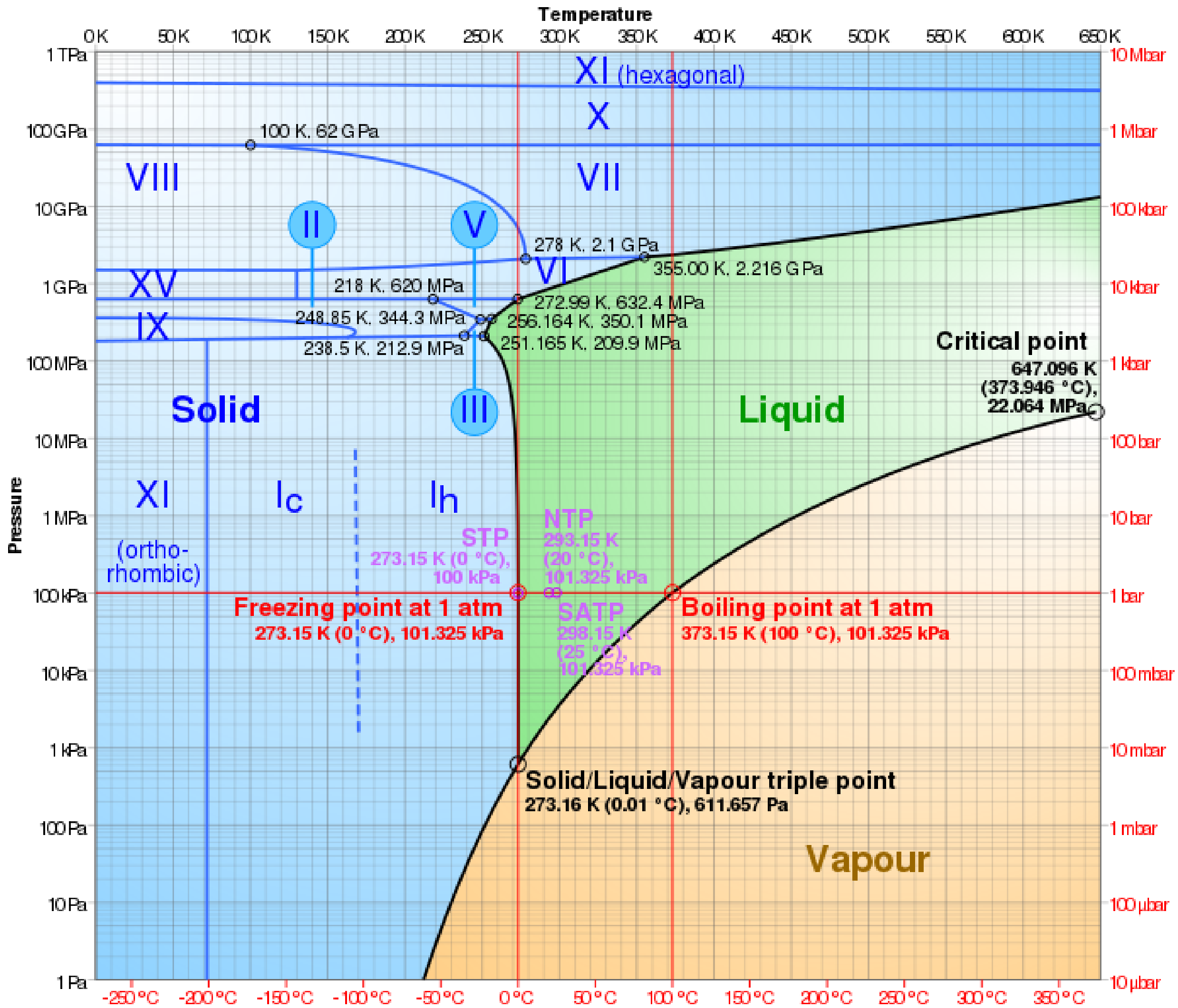


Figure 8: Phase diagram of water (*File:Phase diagram of water.svg - Wikimedia Commons*., n.d.)

2.2.3 Dock Deformation

There are many different contributors to dock deformation, including waves, wind, and recklessness, but one of the most common contributors is ice.

Deformation of Fixed Docks

Fixed docks will be forced to adapt to the ice. As there is no room for movement, the ice will cause deformation in the rigid construction. In Figure 9, the pilings are all crooked in one way or another, which is due to the deformation the dock has suffered over the years. The pilings are also not identical, showing that one or more may have been replaced over the dock's lifespan.

Figure 9: Fixed dock in Westford, Massachusetts

In Figures 10 and 11, the dock has completely fallen over, similar to the dock in Figure 9, where the dock has gone through deformation over its lifespan, in this case resulting in a catastrophic failure. In Figure 10, the pilings furthest from the water are seen on the waterbed, likely because the deformation from ice has contributed to pulling the dock from the shoreline. In Figure 11, a side view of the dock is shown where the pilings closer to the shoreline have also fallen toward the water. It should be mentioned that the dock in Figures 10 and 11 could have fallen over at any time, causing injury or even death.

Figure 10: Fallen fixed dock in Westford, Massachusetts

Figure 11: Fallen fixed dock in Westford, Massachusetts

Deformation of Floating Docks

Floating docks are typically not left in the water in the winter months as the ice would likely cause catastrophic deformation over time. However, if a floating dock were to remain in the water, the pressure from the ice would most likely cause costly damage to the floats (*How to Winterize Your Boat Dock*., 2022, February 2). Floating docks that use plastic material to float will be more susceptible to damage compared to a floating dock using a metal material to float as the metal is stronger.

2.2.4 Thermal Effects on Wood

Wood expands in warmer temperatures and shrinks in colder temperatures. Normally, gradual expansion and contraction due to weather do not severely harm the wood. However, it is when the temperature fluctuates that damage occurs. This fluctuation can cause torsional stress and strain within the wood, which results in warping and cracks. Humidity is a great contributing factor to fluctuations in weather as well. As far as seasons are concerned, during winter months atmospheric humidity at 76% is much higher than that of summer months at 66% (P, Walker, 2022, October 20).

2.2.5 Deterioration of Wood in Water

Waterlogged wooden architecture, such as dock pilings, are prone to damage and rapid decomposition over time. Put simply, due to the natural, organic contents of fresh and salt bodies of water, different factors can alter and waken the chemical structure of any long-term wooden material. Factors such as interfering biology, organic decay, natural weathering, temperature fluctuations, etc. (T. Lourençon, 2016, August 30) (J. Guo, 2019, November 16). Two of the most common types of wood used as a dock piling or deck material, pressure-treated pine, and cedar wood, require annual maintenance to avoid wood deterioration. A common way to maintain these woods is with a water sealer, which keeps water from saturating the wood. If maintenance is not done, then the wood will rot and become soft earlier than anticipated. Softwood brings further decay, mold, and algae growth (Advantage Lumber, 2019, April 11).

2.3 Existing Solutions

Existing solutions that solve the issue of dock deformation due to ice are not typically seen as often as one may think. There are not many options for consumers to choose from, especially when it comes to fixed docks, leaving an opening in the market.

2.3.1 Floating Docks

Floating docks have two main competitors that attempt to combat the issue of ice deformation, EZ Dock and Jet Docks.

EZ Dock

The EZ dock system is a system designed to stay in the water year-round, requiring only 1.5 in. of water to float and will pop up out of the water when it freezes (*Ice Friendly | No need to remove your EZ Docks in the winter*, 2021, June 29). An EZ Dock system typically costs about $3,000 to $30,000, depending on the size of the system purchased.

Figure 12: EZ Dock System (*EZ Plastic Floating Docks for Sale | Floating Boat Dock Kits & Systems*, 2022, October 19)

While the system does not need to be taken out of the water, it still suffers the deficiencies of a typical floating dock. Many lakes have the water drawn down a small amount in the winter, making it a possibility that the EZ Dock system will be damaged by coming into contact with the waterbed. During the warm seasons when boats are being docked, the EZ Dock will float up and down when waves come, whether they be from a boat or wind, and potentially damage a boat or jet ski. To combat this issue, EZ Dock sells a system called EZ Port, seen in Figure 13, where a user drives the jet skis up onto the actual system. EZ Port can potentially be dangerous for multiple reasons. Some users may lose control of the vehicle and move too fast, creating the possibility for someone to be hit, the jet ski could slide off if not secured properly and float away, and the system may cause damage to the hull of the vehicle. Due to the unstable nature of a floating dock moving with the water, it is more difficult to place chairs or even maintain balance on the dock to sit as it can be dangerous, especially for older adults and small children. Many consumers prefer being able to choose what material their dock is, whether that be a type of wood, composite material, or another material as opposed to choosing the tan plastic that the EZ Dock comes in.

Figure 13: EZ Port add-on (*EZ Dock EZ Port MAX 2i Makes PWC Docking Easy - boats.com*, n.d.)

Jet Docks

Jet Docks are similar to EZ Docks as they sell a floating dock that does not have to be taken out during the winter (*Winter Boat Dock | Discover Docks That Can Stay in Ice & Floating Cold Weather Boat Lifts for Winter - Jet Dock*, n.d.). Jet docks typically sell in the range of about $5,000 to $30,000 depending on the size of the dock and if purchased new or used. As a floating dock, Jet Docks suffer the same deficiencies as the EZ Dock system. These docks float up and down with the water causing potential damage to water vehicles, creating an unsteady platform making it hard for some people to use, and may not be suitable if the lake gets drained to where the dock will sit on the waterbed. In Figure 15, a Jet Dock is supporting a large boat in the same way an EZ port system does a jet ski. This also has potentially dangerous consequences as a driver may drive too fast up the dock, potentially hitting another person or damaging the boat itself. There is also only one set of ropes keeping the boat from slipping back into the water in the image, which creates a tripping hazard.

Figure 14: A Jet Dock surrounded with ice (*Winter Boat Dock | Discover Docks That Can Stay in Ice & Floating Cold Weather Boat Lifts for Winter - Jet Dock*, n.d.)

Figure 15: A Jet Dock supporting a large boat (*Great Lakes Jet Dock | Floating Boat Docks, Boat Lifts & Jet Ski Lifts – Jet Dock*, n.d.)

EZ Dock Vs. Jet Dock

While the EZ Dock system and the Jet Dock system are similar, they have their differences. Both systems are floating docks that can remain in the water year round with little to no maintenance required. The main difference between the two systems is that EZ Docks are aimed toward recreational usage while Jet docks are aimed at larger boats. This is because EZ Dock offers other systems, such as the EZ Port seen above, they typically have more space for seating as well. The Jet Dock system allows for the boat to essentially be parked on the dock as seen in Figure 15, which takes up space, limiting usage.

2.3.2 Fixed Docks

There are currently no mass-produced mechanisms that are aimed at creating a fixed dock that can avoid deformation due to ice freeze. Fixed docks are often thought of as being permanent, and while this is true in the sense that they stay in the water year-round, the issue of deformation that they face has not been solved. Fixed docks are simply repaired year after year because there are currently no mechanisms sold to solve the issue.

Dock bubblers are devices that are placed around or under a dock that causes the water around it to circulate, preventing ice freeze (Travel, n.d.). A typical dock bubbler costs about $500 to $3000, depending on the horsepower (HP) needed. Colder environments need higher HP while warmer environments need a lower HP dock bubbler (Travel, n.d.). Dock bubblers are often used at piers, marinas, and boathouses where many boats are docked but can also be used by consumers (Barbe, P., 2019, February 13). In Figure 16, it is seen that the water is circulating in the center, this is caused by a dock bubbler. However, dock bubblers can be unreliable in areas where power outages occur from snow storms and ice storms as most dock bubblers are powered via an extension cord. Dock bubblers are also not suitable for shallow water as the bubbler must be submerged to create circulation (Barbe, P., 2019, February 13).

Figure 16: A dock bubbler being used to prevent ice freeze at a boathouse (Barbe, P., 2019, February 13)

3.0 Design and Modeling

This research project aimed to design and create a solution to the issue of fixed docks suffering from ice deformation. The mechanism allows the joints and pilings of the fixed dock to move slightly during the winter, shifting with the ice, and preventing cracking or damage. The mechanism uses springs that allow movement in the cold months and keep the dock solid in the warmer months. Furthermore, the mechanism is designed in a manner where it can be retrofitted onto most existing fixed docks, avoiding the need to build a new dock that is compatible.

3.1 Preliminary Design

The goal of the mechanism was to create a product that consumers may buy and equip onto an existing stationary dock or incorporate into a dock currently being constructed. The current designs on the market do not solve the issue of a fixed dock suffering deformation as the current large-scale consumer options are strictly floating docks. Our mechanism combines the advantages of a fixed dock with the solution to deformation due to ice freeze.

Table 1: Design Matrix for Dock Solutions

	Weight	**Our Design**	EZ Dock	Jet Dock	Average Floating Dock	Average Fixed Dock
Able to Avoid Ice Deformation	25%	**X**	X	X		
Remains in Water Year-Round	20%	**X**	X	X		X
Suitable for Rough Water (Boats not damaged)	15%	**X**				X
Ease of Retrofitting	10%	**X**				
Solid Foundation (Stability During Usage)	10%	**X**				X
Low Cost	10%	**X**				
Suitable for Deep Water	5%		X	X	X	
Choice of Material	5%	**X**			X	X
Score	100%	**95**	50	50	10	50

Table 1 shows the important features taken into account when designing the mechanism. The features with higher percentages are of greater importance. These factors are based on the issue of deformation our product aims to solve and how a consumer would look at the product. Avoiding ice deformation (25%) and remaining in the water year-round (20%) are the most important features as our mechanism is designed to solve the issue of avoiding deformation. The next factors in order of importance are being suitable for rough water (15%), ease of retrofitting (10%), having a solid foundation (10%), and low cost (10%). These factors are important when looked at from a consumer perspective as the features increase the likelihood of a purchase. The last two features are the choice of material (5%) and being suitable for deep water (5%). Many consumers have a preference for what material they use, whether that be wood, plastic, metal, etc. The last feature is being suitable for deep water as some docks are in deep water environments. Our design received a score of 95/100, beating out each of the other dock systems by at least 45/100.

3.1.1 Design Strategy

The initial concept for this mechanism is not the same as the final design for several reasons. The initial concept consisted of simply adding two springs, each spring attaching to the piling and the frame of the dock, acting as a securement for the piling and the dock. The springs essentially take the place of screws that would typically be used to attach the piling to the dock. This is because research and observation show that the main point of failure on a dock is where the piling secures to the dock, meaning the screws or bolts are usually the first to fail. The idea behind the two springs was to allow for movement between the piling and the frame of the dock, the initial design concept was also not designed to be retrofitted to existing fixed docks. The two springs were to allow minimal movement between the piling and the dock frame to account for the forces felt during ice freeze and everyday use. The movement will lessen the forces felt on the piling as the piling will be able to adapt itself to the potential ice freeze.

The initial design was good in theory but it was determined that two springs would not be enough to sufficiently hold the piling in place. For example, the piling would be supported in the North and South direction but it would have too much movement in the East and West directions. To solve this issue, the new design involves four springs, one on each side of the piling, this accounts for movement in the North, South, East, and West directions, securing the piling in all four directions. The four springs chosen were short enough to not make the final mechanism too large while having a spring factor of 41.63 lbs./in., which based on initial calculations is an ideal spring factor for the forces the piling will be subjected to.

It was also determined that the mechanism should allow for an easy retrofit to existing fixed docks, this design flaw was changed with the consumer in mind, it would allow a consumer to purchase a mechanism for each piling on their dock as opposed to building a completely new dock which can be costly.

The final design also utilizes pressure-treated wood and outdoor screws and springs to give the mechanism a long life span. The usage of springs and a straightforward design also make the mechanism simple for upkeep for a consumer which enhances long term prospects for a consumer.

3.1.2 Final Design

The overall goal of the design was to create a mechanism that helps fixed docks avoid ice deformation. The final design was created in a way that would allow it to be retrofitted to existing docks or added to new docks as opposed to constructing a new dock that is compatible with the mechanism. As a result, the design was created as a 1-ft. by 1-ft. square, allowing it to be affixed to the corners or walls of existing fixed docks with screws or bolts.

The design began with using pieces of 2-in. x 6-in. pressure-treated lumber to create the 1-ft. by 1-ft. square. 2-in. x 6-in. pieces of lumber were chosen as they are stronger than 2-in. x 4-in. pieces and allow for more space within the square. Pressure-treated lumber was chosen as it is more resistant to degradation when exposed to water when compared to non-pressure-treated lumber (*5 Scenarios Where Pressure Treated Lumber is Beneficial*, 2016, September 20). Lumber is typically 0.5-in. smaller than the actual dimensions, meaning that a 2-in. x 4-in. measures 1.5-in. by 3.5-in. and a 2-in. x 6-in. measures 1.5-in. by 5.5-in. (*Lumber Sizes Explained | Howe Lumber | East Brookfield, MA*, (n.d.). This was taken into account when designing the mechanism as it affected how long the 2-in. x 6-in. pieces must be designed. The 2-in. x 6-in. pieces of lumber have predrilled holes in order to minimize the risk of splitting the wood during construction.

The next component is the Routing eyebolt for wood that connects the spring from the 1-ft. x 1-ft. square to the 4-in. x 4-in. piling. The eyebolt must be strong enough to withstand the tension of the spring and small enough to allow space for the spring to stretch. The overall length of the chosen eyebolt is 1.875-in. with 1.125-in. being the shank length. A zinc-plated steel material was chosen as the zinc coating allows the eyebolt to resist corrosion.

The next component is the corner brackets which are used to solidify the connection of the 2-in. x 6-in. pieces of lumber. The brackets chosen are a galvanized steel corner bracket that is 2.75-in. tall and 1.375-in. long on each wall, small enough to not create any conflicts and large enough to solidify the mechanism. To connect the corner brackets to the 2-in. x 6-in. pieces, screws and washers are used.

The fourth component is the spring which creates degrees of freedom for the dock to adapt to ice freeze. The spring must be strong enough to support the dock when in use during the warmer months and allow for enough movement to adapt to the ice in the colder months. The chosen spring was a 302 stainless steel corrosion-resistant extension spring with loop ends that are 1.5-in. long and 0.055-in. wire diameter. Extension springs were chosen for this application as the springs are installed at an extended length and the extension springs create a force trying to return to their original length (Collins, D.,2022, October 17). The force of four identical springs on each side holds the piling steadily in the center.

The next component is the 4-in. x 4-in. lumber piling, taking into account that the dimensions of the piling is 3.5-in. by 3.5-in.. The length of the piling varies depending on the depth where it is placed.

The next component was the 1-ft. x 1-ft. sheet metal covering at the top of the mechanism. This piece of sheet metal separates the existing dock from the installed mechanism. The sheet metal was designed with 8 holes in the top of it along the edges so it can be screwed into the 2-ft. x 6-ft. pieces of lumber.

3.2 CAD Model

SolidWorks 3D modeling software was used to construct our design mechanism assembly. The surrounding wood blocks, piling, and sheet metal barrier were modeled as separate parts and combined with the off-the-shelf parts to make the final design assembly. The off-the-shelf parts consist of the eyebolts, springs, corner brackets, screws, and washers. Figures 17 and 18 show views of the assembly and Figure 19 shows an exploded view of the assembly. Note that in Figures 17 and 18 the springs do not connect to both eye bolts as they are extended during the construction of the mechanism.

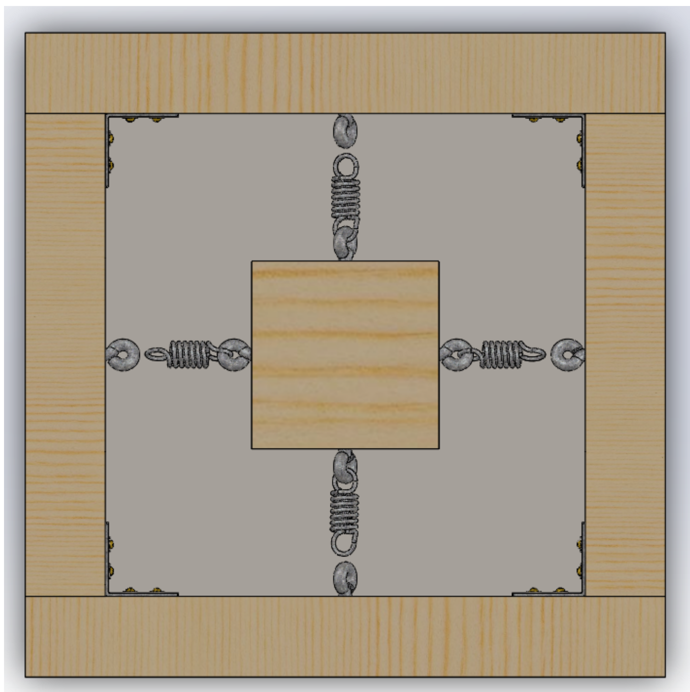


Figure 17: Bottom view of the proposed dock deformation mechanism assembly, outside of the 1 ft. x 1 ft. square enclosure is fixed to an existing fixed dock

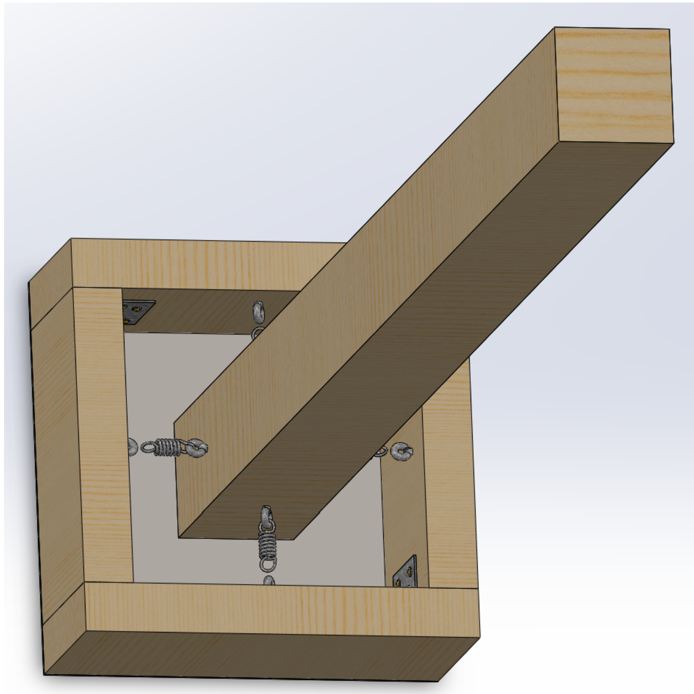


Figure 18: Angled view of the proposed dock deformation mechanism assembly

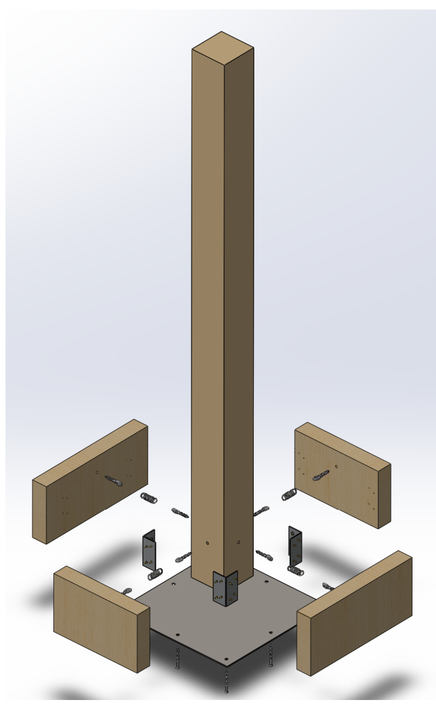


Figure 19: Exploded angled view of the proposed dock deformation mechanism assembly

3.2.1 Designed Parts

The walls, piling, and sheet metal pieces of the mechanism must be designed in order to create the base/surrounding of the system. These parts are combined with the off-the-shelf pieces to construct the mechanism.

Body

The square surrounding was designed first as it is the foundation of the mechanism. The square surrounding is made up of 2 different models, the 9-in. length wall and the 12-in. length wall. The 9-in. wall can be seen in Figure 20 while the 12-in. wall can be seen in Figure 21. These lengths were chosen as when combined as seen in Figure 17, it creates a 1-ft. by 1-ft. square. This is because the thickness of the lumber is 1.5-in., and the thickness of two walls are combined with the 9-in. wall to create a 12-in. total length. The square surrounding was designed to be 1-ft. by 1-ft. as it is small enough to be retrofitted to most existing docks but large enough to contain the mechanism.

Once the wall sizes were chosen, the other pieces of the mechanism were identified, specifically the eyebolt, corner bracket, sheet metal cover, and the respective screws that were used. Pre-drilled holes were then added to the model for these respective screws. The pre-drilled holes in the corner brackets were designed such that they allow the square surrounding to be constructed based on them. The corner brackets are attached via the holes and make the square surrounding complete. The hole(s) on the top of the 9-in. and 12-in. walls were added based on the holes on the sheet metal cover. Lastly, the hole for the eyebolt was placed in the center of the wall horizontally and 1.5-in. from the bottom. This allows the eyebolts to be centered on each wall, confirming the piling is centered in the mechanism. The dimensions for the 9-in. and 12-in. walls can be seen in Figures 20 and 21, respectively.

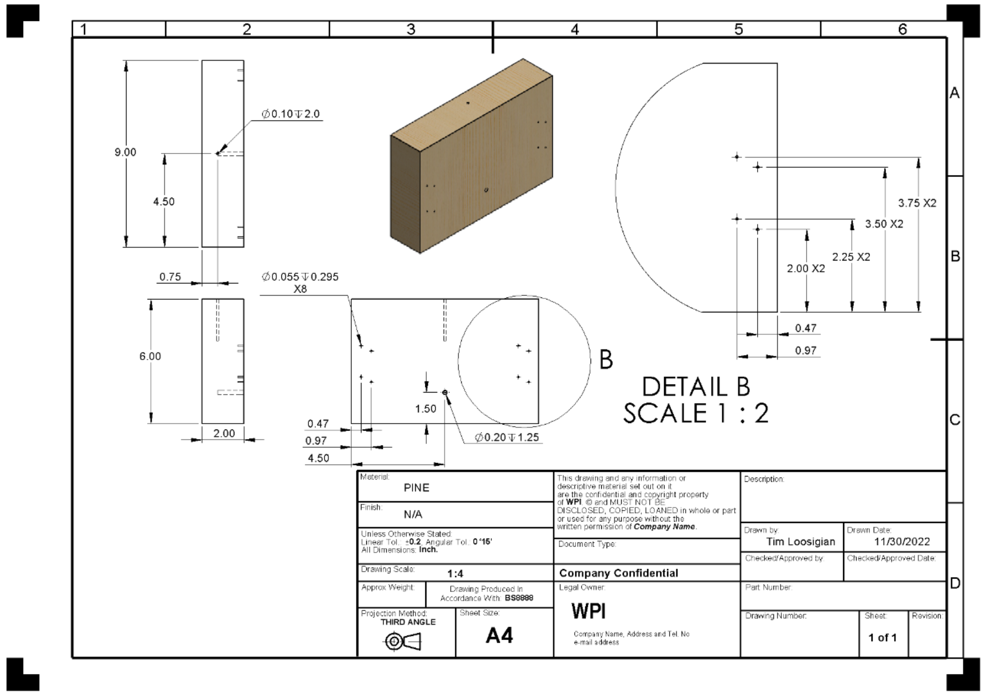


Figure 20: Technical drawing of 9-in. long 2-in. x 6-in. square surrounding wall with pre-drilled holes

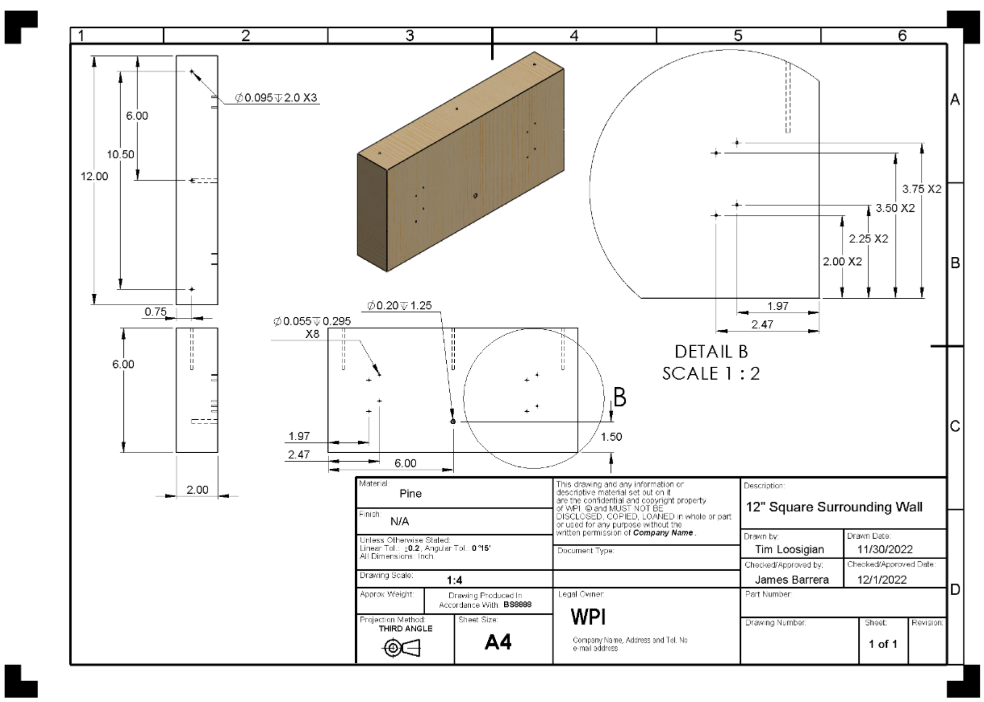


Figure 21: Technical drawing of 12-in. long 2-in. x 6-in. square surrounding wall with pre-drilled holes

Piling

The 4-in. x 4-in. piling was modeled as a 3.5-in. by 3.5-in. piling as lumber is typically 0.5-in. smaller than its listed size. The piling has 4 pre-drilled holes, one for each eyebolt, the holes were designed to be in line vertically and horizontally with the eyebolt holes on each wall. The holes are 4-in. from the top of the piling and centered horizontally. The dimensions can be seen in Figure 22, where it is worth noting that the length of the piling is not specified as it varies depending on the depth of the water.

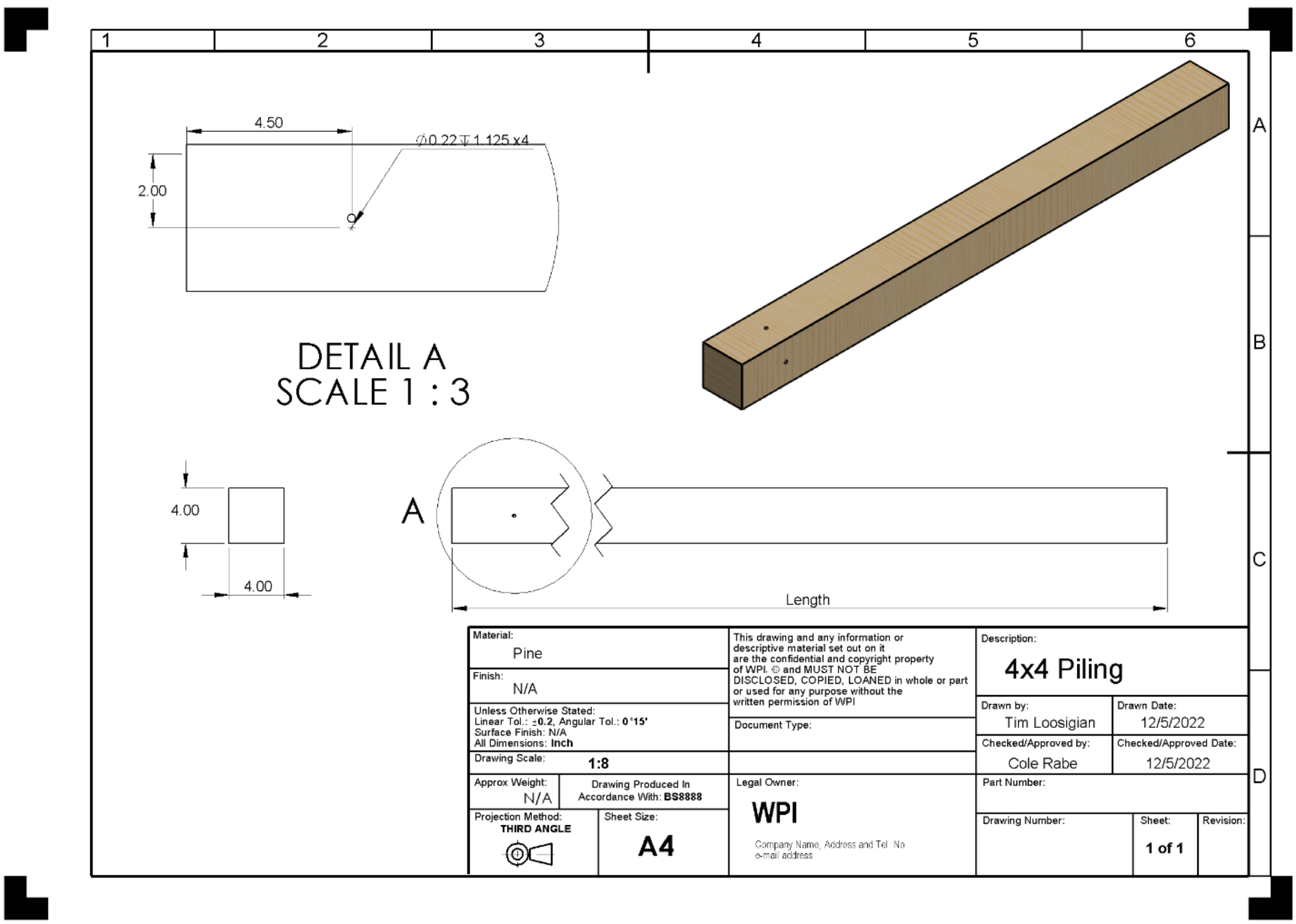


Figure 22: Technical drawing of the 3D modeled piling with predrilled holes

Sheet Metal Cover

The sheet metal cover, seen in Figure 23, is used to separate the piling from the deck of the dock. The sheet metal cover was designed as a 1-ft. by 1-ft. square as that is the size of the square surrounding. As seen in Figure 23, the holes in the sheet metal cover were placed 0.75-in.

from the edge as that allows the screws to be in the center of the 2-in. x 6-in. walls, ensuring the strongest point of contact.

The purpose of the mechanism is to allow the piling to adapt to the ice that will surround it in the winter. This means that the piling must move slightly in whichever direction it is forced to move, a smooth surface is vital in allowing this to happen. The static friction coefficient of wood to metal is 0.3 (Kuwamura, H., 2011) while the static friction coefficient of wood on wood is 0.25-0.50 (*View of Static and kinetic friction coefficients of Scots pine (Pinus sylvestris L.), parallel and perpendicular to grain direction | Materiales de Construcción*., n.d.). The team used the static friction coefficient in this case as the static friction coefficient tells us how much force is needed to begin movement; the higher the number, the more difficult it is to move. This information tells us that the piling moves easier on sheet metal when compared to wood.

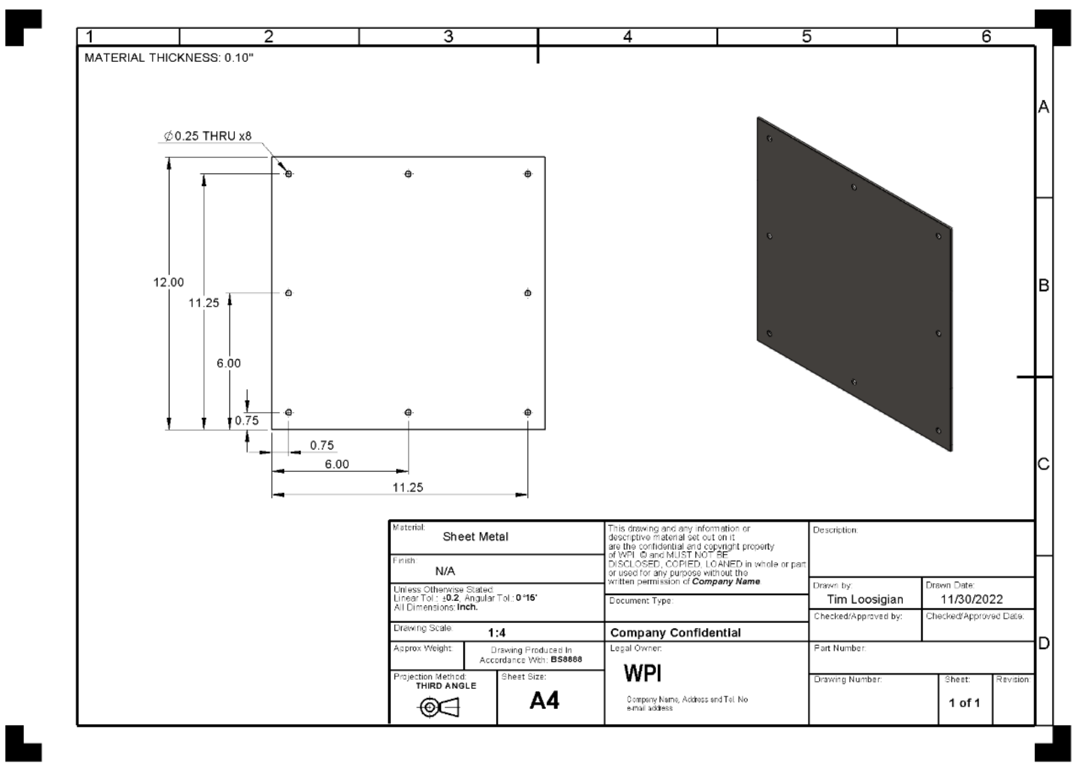


Figure 23: Technical Drawing of 12-in. x 12-in. Sheet Metal cover

3.2.2 Off-the-Shelf Parts

The off-the-shelf parts were chosen based on strength and size, taking the material into account as well. These aspects must be carefully chosen to give the highest functioning mechanism.

Eyebolts

The eye bolts are used as the points of contact for the springs, in this case, to connect the walls to the piling. These eye bolts were chosen as the zinc-plated steel material is able to resist corrosion and the eyebolts are strong enough for the mechanism while not being too large.

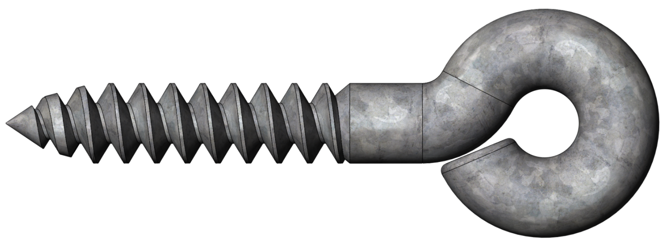


Figure 24: Routing eye bolt for wood

Extension Springs

The extension spring is used to connect the walls to the piling via the eyebolts. It has a spring constant of 41.63 lbs./in. This spring was chosen as the material is resistant to corrosion, the length and the spring constant are sufficient for the mechanism as the spring is stretched slightly, and the loop ends allow for an easy connection to the eyebolts.

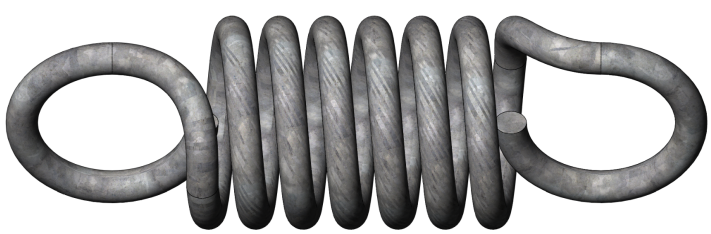


Figure 25: 302 stainless steel corrosion-resistant extension spring

Corner Brackets

The corner bracket was chosen as the material is resistant to corrosion and creates a strong foundation for the mechanism. The corner bracket was also chosen due to its low profile design, creating virtually no conflicts with the rest of the mechanism.

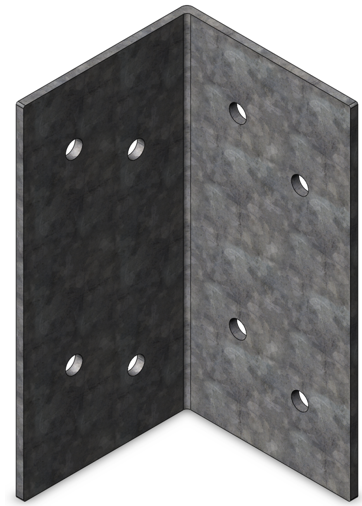


Figure 26: Galvanized steel corner bracket

Screws and Washers

The screws and washers were chosen due to their corrosion-resistant materials and due to their respective sizes. The screws for the sheet metal cover are 2-in. long and the corner bracket screws are ⅜-in. long. These lengths were chosen depending on which surface of the walls they were screwed into, the sheet metal cover screws have a longer distance while the corner bracket screws have only 1.5-in. to go through.

4.0 Calculations and Simulations

In order to gather a baseline that could be used to compare against the simulations and experiments, the team performed hand calculations for the fixed piling. The goal of completing hand calculations was to prove that the force on the screws used to retrofit the mechanism to the dock is less than that of the screws used to fix a normal piling to a dock in a traditional manner. These calculations proved that the mechanism has a true mechanical benefit when compared to a traditional fixed dock. Once the hand calculations were complete, the team initially conducted simulations to ensure that the hand calculations and simulations were comparable to each other, and then later performed further simulations of the mechanism.

4.1 Forces on Traditional Fixed Dock vs. Mechanism

Hand calculations were done to compare the forces and stresses on the screws used to fix the piling on a traditional fixed dock and that of our mechanism. As seen below, the forces and stresses on our mechanism were lower than that of the traditional fixed dock, proving that our mechanism reduces the deformation due to forces and stresses.

4.2 How Do the Springs Help

The implementation of the springs lessens the moment at the attachment of the piling to the dock as it lowers the distance from where the actual force from the moment occurs. For example, on a 36 in long piling, the moment on a traditional fixed dock will be from the location of the screws to the end of the piling. Contrast this to a piling of the same length but with our mechanism, the moment would be the distance between the top of the exterior box and the location of the screws, lowering the height where the force is felt to 4 in, decreasing the moment by a factor of 9. This factor varies depending on the length of the piling. The factor is greater for longer pilings and vice versa. The moment on a 5 ft (60 in) long piling decreases by a factor of 15, greatly reducing the chance of a catastrophic failure.

4.3 Proof of Concept Calculations and Simulations

4.3.1 Bending Analysis

In the real world, there are numerous factors that can cause bending forces and moments onto a dock piling. Some of the most important factors can be the strength of the current, collisions from a boat, and the main one that this project aimed to tackle ice deformation. When looking at the current of the water, wind and other objects such as movement from boats can induce currents in the water. These currents can build up over time and eventually get to a point where they can cause damage. Not only can the current be a serious factor, but the direct impact of boats and other water vehicles can cause irreversible damage to both the piling and the dock as a whole. Usually, individuals that can operate a boat are careful when docking boats, but there are times when there are external factors that complicate the process of docking a boat, or even cause issues once the boat is already tied up. Finally, ice deformation is a major concern, particularly in the regions where the freezing of bodies of water occurs, as the different depths of water freeze at different times. This variance in freezing can cause the piling to bend with the flow of the water, and allow for the piling to permanently deform.

Traditional Fixed Piling

The following figures show free body diagrams of the traditional fixed piling. The fixed piling can be modeled as a cantilever beam due to its nature, hence it is being analyzed as such.

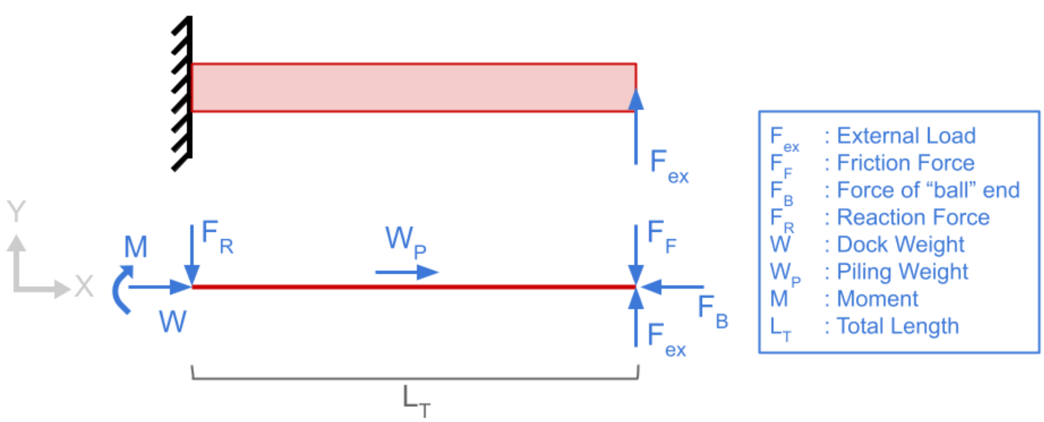


Figure 27: Traditional fixed piling FBD

The team assumed that the friction force was very minimal, at 0.4 lbf in the opposite direction of the external force. The interaction of the pilings with the ground was considered a ball connection, but for our analysis along the x-axis, this, along with the weight of the dock, can be neglected. "L_T" represents the total length of the beam (3ft). The following shows the numerical analysis of both the reaction force and reaction moment at the point of the fixed end when the external load is equal to 1000 lbf.

$\Sigma F_x = 0 = W + W_{post} = F_b$

$W >> W_{post} \qquad F_b \approx W$

$\Sigma F_y = 0 = F_{ex} - F_r - F_f$

$F_r = F_{ex} - F_f$

$F_r = 1000 \text{ lbf} - 0.4 \text{ lbf}$

$F_r = 999.6 \text{ lbf}$

$\Sigma M_{base} = 0 = (F_{ex} * L_T) - M - (F_f * L)$

$M = (F_{ex} - F_f) * L_T$

$M = 999.6 \text{ lbf} * 3 \text{ ft}$

$M = 2998.8 \text{ lbf*ft}$

This can be further demonstrated in the following CREO simulation, showing a bending moment resultant (ft*lbf), with the same setup. In CREO Simulate, an idealized beam was introduced with a fixed end (purple, left) and an applied load of 1000 lbf at the end, 36 in or 3 ft (yellow, right). There is also a friction force of 0.4 at the end of the piling in the negative direction.

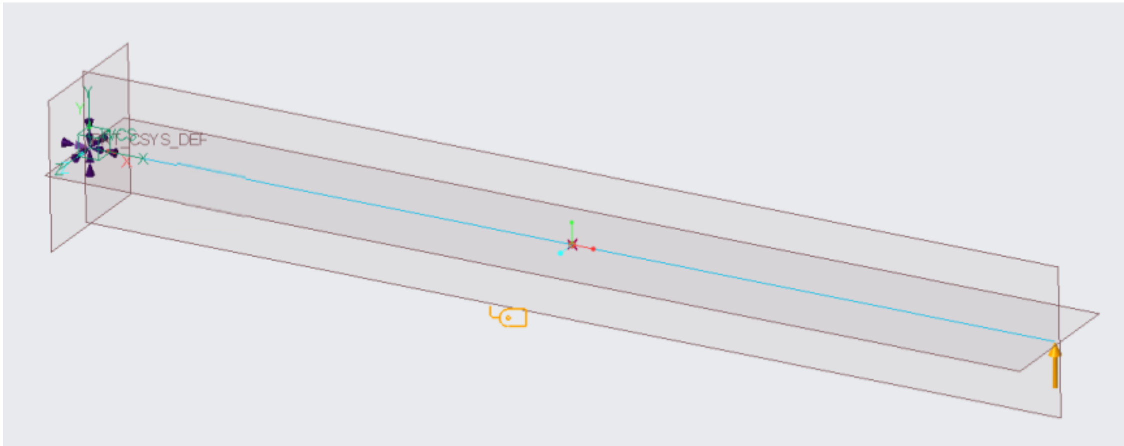


Figure 28: CREO Simulation Setup of Traditional Fixed Piling

Running this simulation for an applied load of 1000 lbf yields the following results:

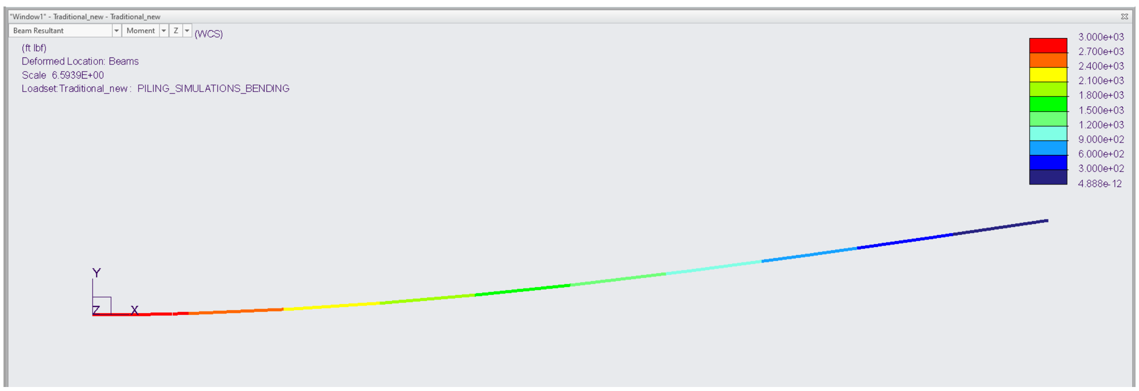


Figure 29: CREO Simulation of Traditional Fixed Piling (ft*lbf)

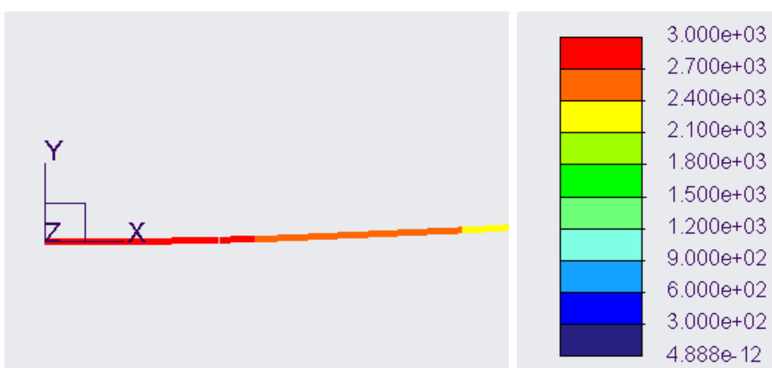


Figure 30: Magnified View of Figure 29 (above) (ft*lbf)

The bending moment resultant agrees with the hand calculation. The fixed end of the beam (left), being in the red, has an approximate bending moment of 3.000e+03 ft*lbf

Modified Spring Piling

Next, the following figures show the free body diagrams of the team's modified spring mechanism. The first FBD, in red, depicts the forces that act directly on the piling post. The interaction between the piling and the ground is considered a ball connection which will result in a moment to balance the FBD. The second FBD, in green, is the box surrounding the top portion of the piling that is fixed to the dock and houses the eyebolts and piling springs. This has a moment because it is directly fixed to the dock.

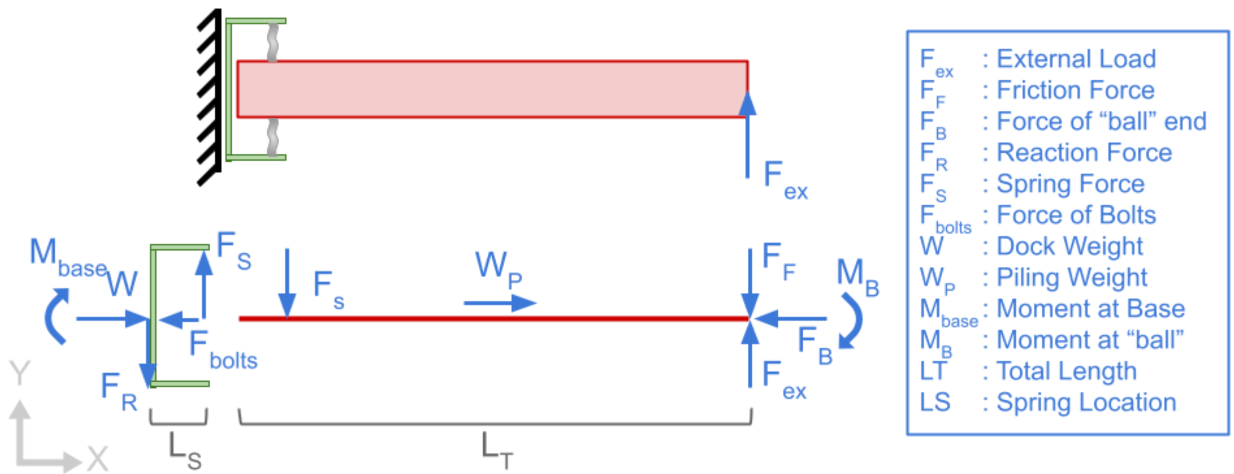


Figure 31: Modified Spring Piling FBDs

For FBD1:Piling (red), F_S is the equivalent force applied to the springs in response to the external load. This force is equal and opposite as the spring interacts with the fixed piling box, FBD2:Piling Box (green), thus resulting in F_R, the reaction force of the spring on the fixed box. This then causes a moment about the fixed point of the beam where the spring is located (L_S), 4 in. It is important to note for FBD1, the weight of the piling and the force of the ground "ball" connection are equal. Similarly, for FBD2, the weight of the dock and the weight dock and the force on the eye bolts are equal.

The following is the numerical analysis of the reaction force and reaction moment at the point of the fixed box (base) when the external load is equal to 1000 lbf. For this analysis, we are focused on the moment of FBD2: Piling Box.

FBD1: Piling (red)

$\Sigma F_x = 0 = W_{piling} - F_B \Rightarrow F_B = W_{piling}$

$\Sigma M_{base} = 0 = F_s (L_T - L_s) = M_b$

$\Sigma F_y = 0 = F_{ex} - F_s - F_f$

$F_s = F_{ex} - F_f$

$F_s = 1000 \text{ lbf} - 0.4 \text{ lbf}$

$F_s = 999.6 \text{ lbf}$

FBD2: Piling Box (green)

$\Sigma F_x = 0 = W - F_{bolts} \Rightarrow F_{bolts} = W$

$\Sigma F_y = 0 = F_s - F_r$

$F_r = F_s = 999.6 \text{ lbf}$

$\Sigma M_{base} = 0 = (F_s*L_s) - M$

$M = F_{ex}*L_s$

$M = 999.6 \text{ lbf} * 4/12 \text{ ft}$

$M = 333.2 \text{ lbf*ft}$

This can be further demonstrated in the following CREO simulation, showing the bending moment resultant (ft*lbf), with the same setup. In CREO Simulate, an idealized beam was introduced with a fixed end (purple, left) and an applied load of 1000 lbf at the location of the springs, 4 in from the left. (yellow, right). Similar to the previous FBD of the mechanism, in the real world, the beam is not fixed at the left end, instead, the load applied transfers through the springs onto the piling box. Thus, the setup of the simulation mimics this as seen in the following figure.

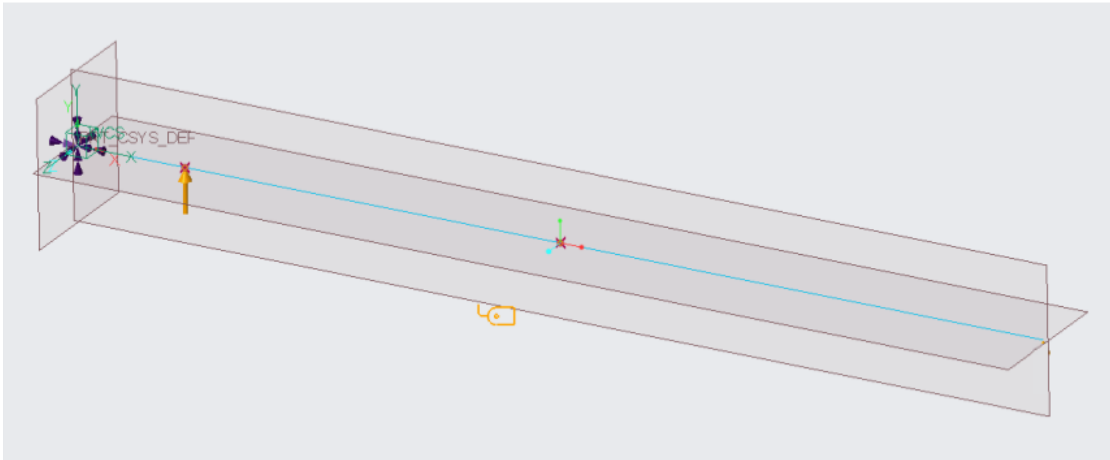


Figure 32: CREO Simulation Setup of Modified Spring Piling

Running this simulation for an applied load of 1000 lbf yields the following result:

Figure 33: CREO Simulation of Modified Spring Piling (ft*lbf)

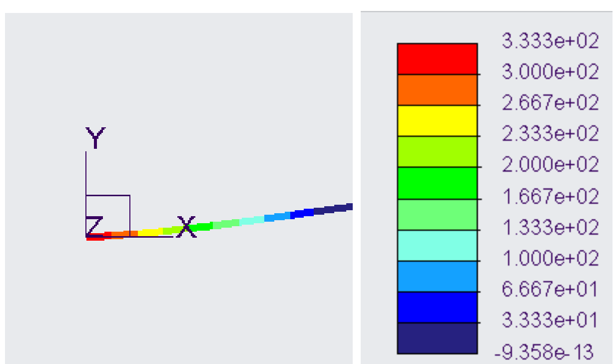


Figure 34: Magnified View of Figure 33 (above) (ft*lbf)

The resulting bending moment of the simulation agrees with the hand calculation. In this case, the fixed left end represents the fixed spring box, so being in the red gives an approximate 3.333e+02 ft*lbf.

Bending Evaluation

When comparing the bending moment of the traditional fixed piling to the modified spring version at the location of the fixed box, in both calculation and simulation, the modified spring piling bending moment results in 10% of the moment of the traditional piling. This is a substantial decrease in the theoretical moment that will be applied to the decking screw connection points.

Additionally, in the traditional piling setup, the maximum moment occurs at the top of the piling connection to the dock, which is tolerated by decking screws. Due to the moment, however, shear forces are experienced at the screws and can potentially lead to failure, causing ripping and deformation. In our modified piling, the maximum moment is shifted to the bottom of the post, which is supported by the water bed. As a result, the bolts that connect the piling springs to the fixed box experience tensile forces which are less prone to failure. The forces on the spring eye bolts would be less than a common shear force encounterd in metal bolt/wood connections, 75-125 pounds per screw (Backyard Sidekick, 2022). This analysis of the FBDs is expanded further in the Testing Report section with in-person experiments and observations.

In the long run, simulating incrementally larger loads being applied to the beam is done in MATLAB. The MATLAB code solves the analytical equation 10,000 times to see how, over time, the two types of piling differ. The code results in the following graph:

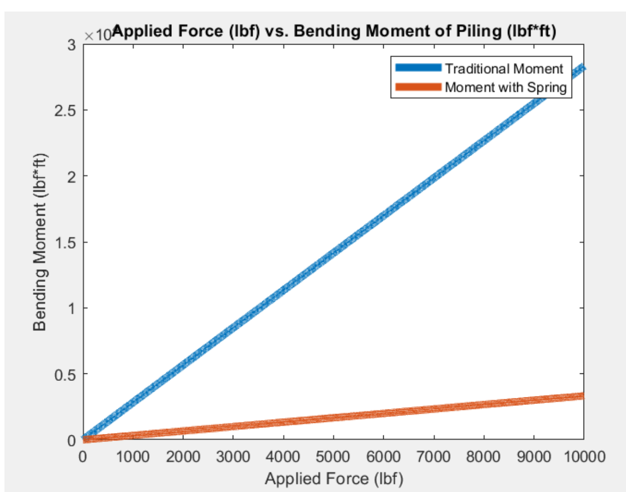


Figure 35: Applied Load (lbf) vs. Bending Moment of Piling (lbf*ft)

Notice how over many different loads, the bending moment of the modified spring piling is always lower than that of the traditional fixed.

4.3.2 Torsional Analysis

Real world applications that can cause torsional forces and moments onto a dock piling can be from the direction and strength of current, directional collisions, and, of course, ice deformation. Similar to bending forces, the impact of docking a boat or an already docked boat moving around with current can cause torsion forces.

Traditional Fixed Piling

The following FBD depicts torsion along a traditional fixed piling.

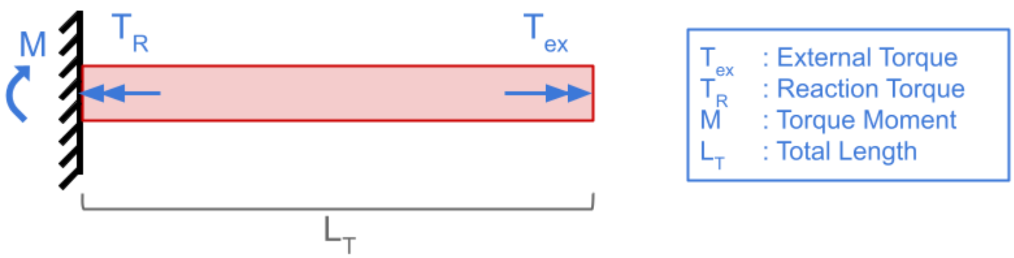


Figure 36: Torsion Along a Fixed Piling

If applying a torque of 300 lbf*ft at the end of the piling, the resulting torsional moment at the fixed position is as follows.

Torque = 300 lbf*ft

Torsional Moment = Torque * torque location

Torsional Moment = 300 lbf*ft * 3ft

Torsional Moment = 900 lbf*ft^2

This can be further demonstrated in a CREO Simulation which can show the torsional moment along the beam. In CREO Simulate, an idealized beam is created with a fixed end (purple, left) and an applied torsional load at the end, 3ft (yellow, right).

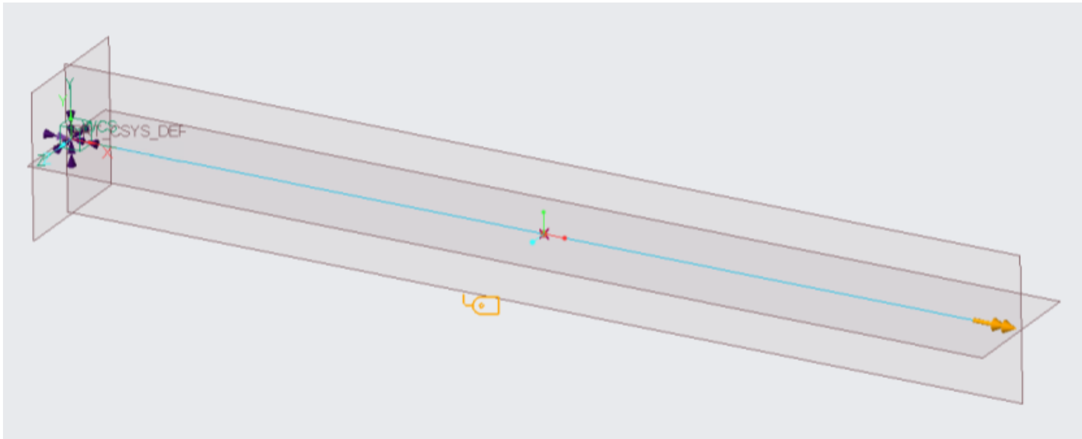


Figure 37: CREO Simulate Setup for Torsional Moment on Traditional Piling

Running this simulation for a torque of 300 lbf*ft yields the following figure:

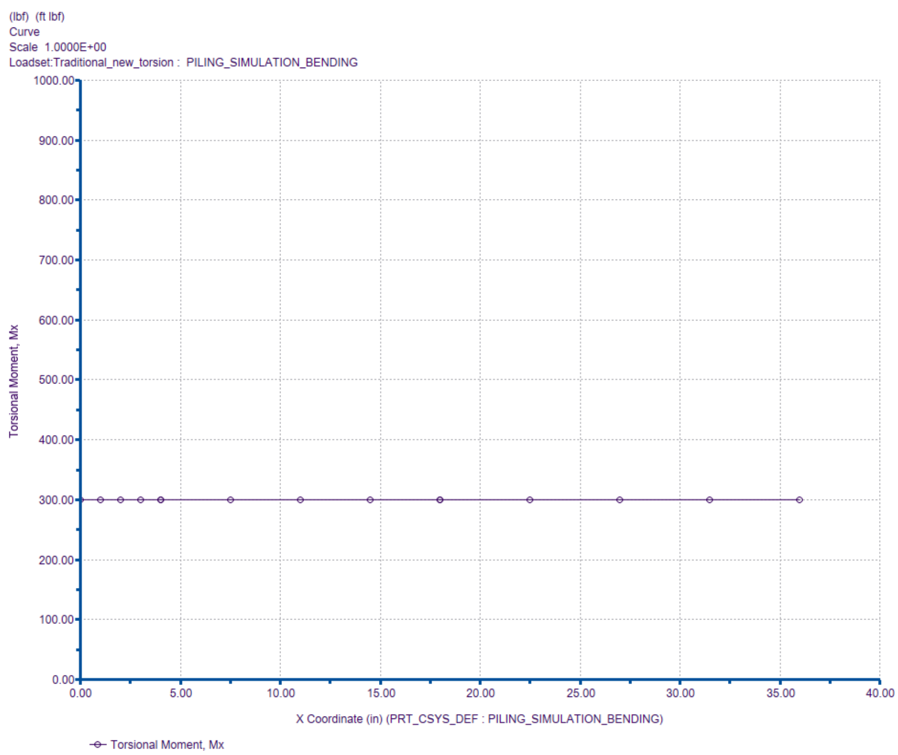


Figure 38: Torsional Moment Along Traditional Piling (lbf*ft^2)

The figure agrees with the hand calculation because the torsional moment at the location of the apple torque, 3ft, is equal to 900 lbf*ft^2. The figure also shows that with a torsional load at the end, the entire length of the beam is affected.

Modified Spring Piling

Additionally, the torsional moment around this fixed box position is also in consideration. The following FBD depicts a torsional force along the modified spring piling. The interaction between the piling and the ground is considered a ball connection which will result in a moment to balance the FBD.

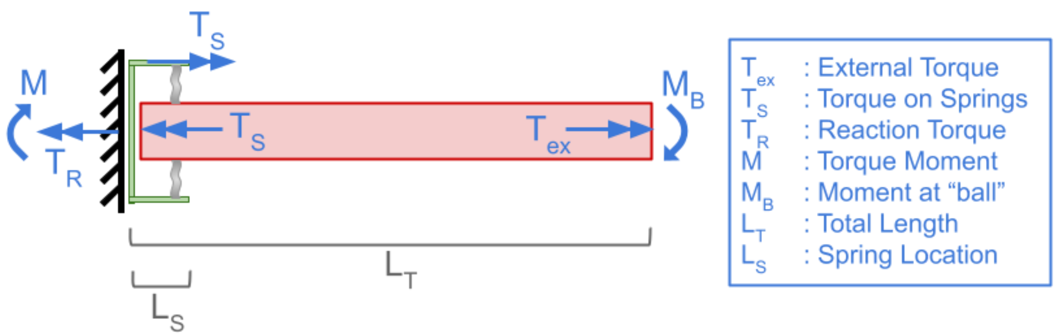


Figure 39: Torsion Along Modified Piling

If applying a torque of 300 lbf*ft at the piling, it has a similar effect to that of the bending. This is about equal to the reaction torque of the springs on the piling, as well as the reaction torque of the springs to the fixed box. The resulting torsional moment at the fixed position is now for the reaction torque at the location of the springs.

Torque = 300 lbf*ft

Torsional Moment = Torque * torque location

Torsional Moment = 300 lbf*ft * 4/12ft

Torsional Moment = 100 lbf*ft^2

This can be further demonstrated in a CREO Simulation which can show the torsional moment along the beam. In CREO Simulate, an idealized beam is created with a fixed end (purple, left) that represents the fixed position of the spring box. An applied torsional load is placed at the location of the springs, 4in from the left (yellow, right).

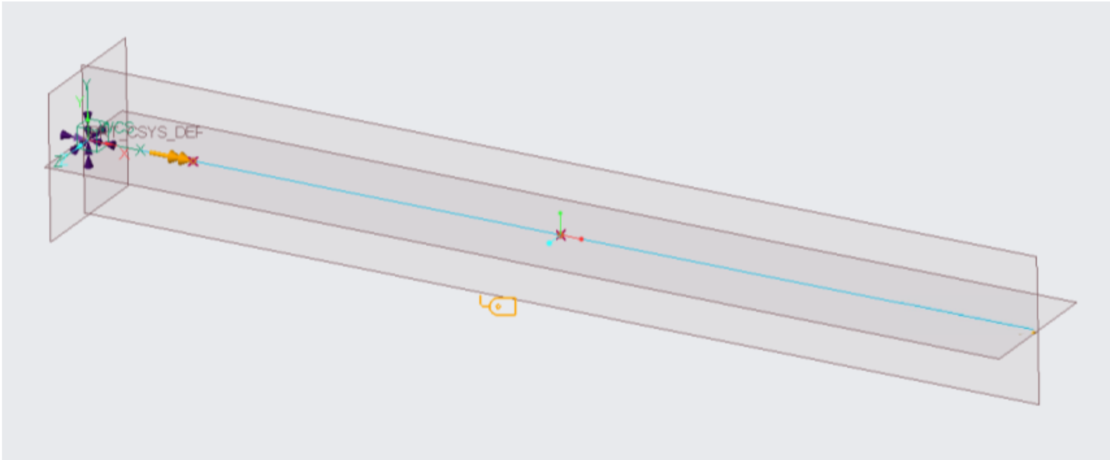


Figure 40: CREO Simulate Setup for Torsion on Traditional

Running this simulation for a torque of 300 lbf*ft yields the following figure:

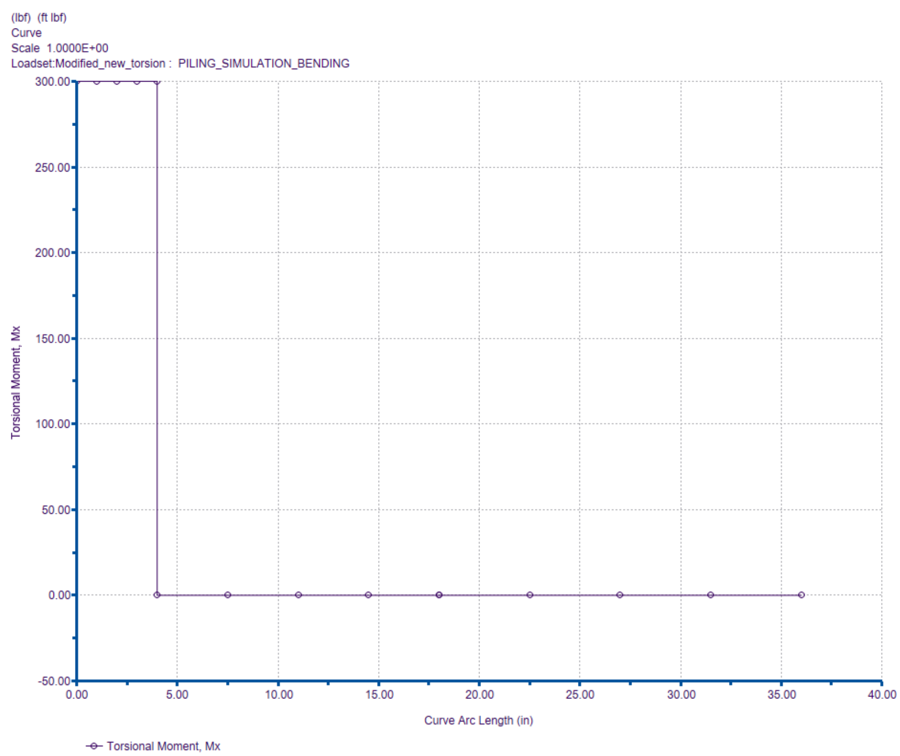


Figure 41: Torsional Moment Along Modified Piling(lbf*ft^2)

The figure agrees with the hand calculation because the torsional moment at the location of the applied torque, 4 in, is equal to 100 lbf*ft^2. The figure also shows that a torsional load applied to the beam does not affect the entire length of the beam because it is as if it were applied at the location of the springs, 4 in.

Torsion Evaluation

A comparison of the traditional fixed and modified spring systems show, both in calculation and simulation, that the modified spring mechanism provides a much less torsional bending moment about the location of the connection dock screws.

Simulating incrementally larger loads being applied to the beam is done in MATLAB. The MATLAB code solves the analytical equation 10,000 times to see how, over time, the two types of piling differ. The code results in the following graph:

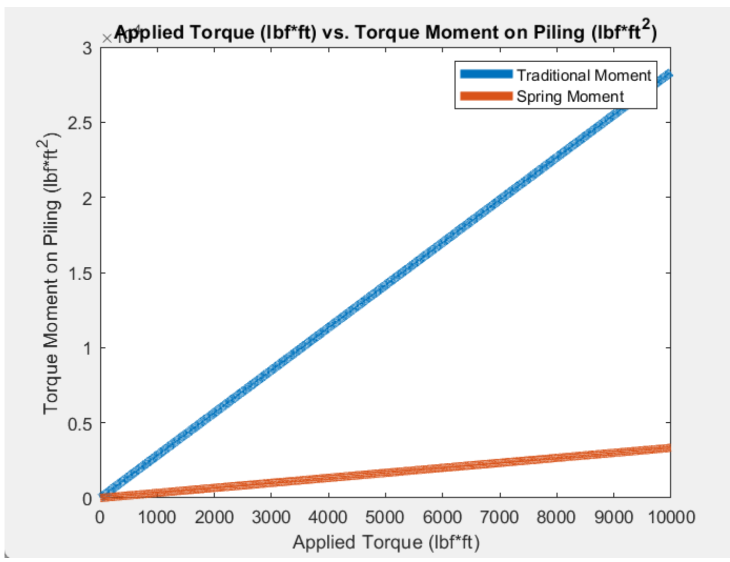


Figure 42: Applied Torque (lbf*ft) vs. Torsional Moment on Piling (lbf*ft^2)

The torsional moment of the modified spring mechanism always acts less than the traditional due to the reaction torque at that spring location on the fixed spring box.

4.3.3 Bending Deformation Analysis

The deflection of a cantilever beam at any ‘x’ location along it is calculated as sigma (σ) below. This gives a maximum deflection of a cantilever beam as sigma max (σ_{max}), below.

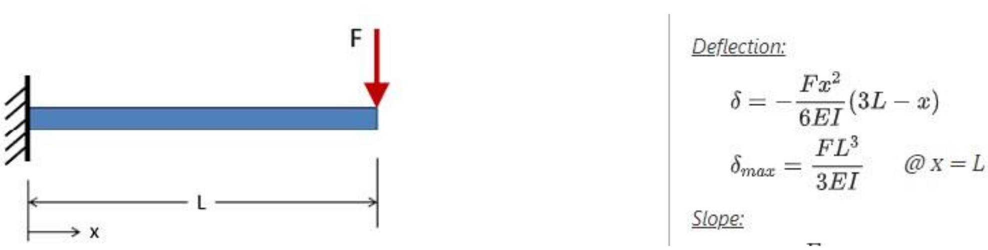


Figure 43: Diagram and Equation for Deformation Calculations (Beam Deflection Tables, n.d.)

Where:
F = Applied Load
L = Total Length
E = Elastic (Youngs) Modulus
I = Area moment of inertia ($I = (1/12)bh^3$), for a rectangular cross section

For these calculations, an E of 9.3GPa or 194234538.4 lbf/ft^2 is being used. This is CREO Simulate's E material property for softwood pine.

Traditional Deflection

Plugging variables into the deflection equation, for the case of the traditional fixed piling with a load of 1000 lbf at a location of 3 ft along the beam, the result is a sag deformation, δ = 0.045 ft or approximately 0.54 in.

This is further shown in a CREO simulation using the same setup in the Bending section of the traditional fixed. Running this simulation with a load of 1000 lbf at the end of the piling results in the following:

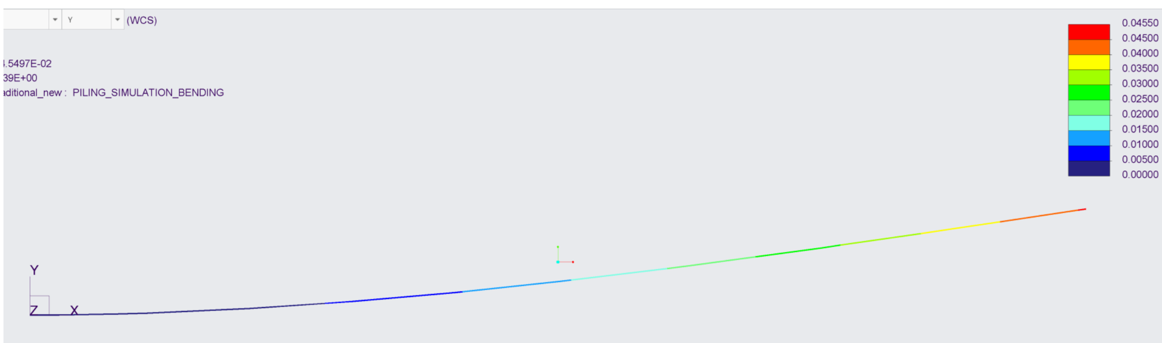


Figure 44: CREO Simulation for Traditional Bending Deflection (ft)

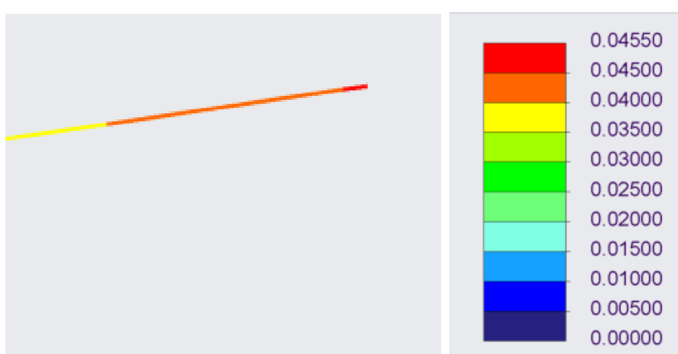


Figure 45: CREO Simulation for Traditional Bending Deflection Magnified (ft)

The result of this simulation shows a maximum deflection of 0.045 ft or 0.55 in at the location of the applied load. This agrees with the hand calculations. There is an approximate 1.02% error between the analytical calculation and the simulated result.

Modified Deflection

For the modified spring piling, since the applied load passes through the springs, the spring box is the component that needs to be analyzed for deflection. Plugging variables into that at the second deflection equation from Figure 43, with a load of 1000 lbf at the spring location, 4 in, the result is a sag deformation, $\delta = 1.24\text{x}10^{-4}$ft. or approximately 0.0015 in.

This is further shown in a CREO simulation using the same setup in the Bending section of the modified spring. Since the spring box is being analyzed, the beam length in this simulation is 4 in instead of 3 ft. Running this simulation with a load of 1000 lbf at the spring location results in the following:

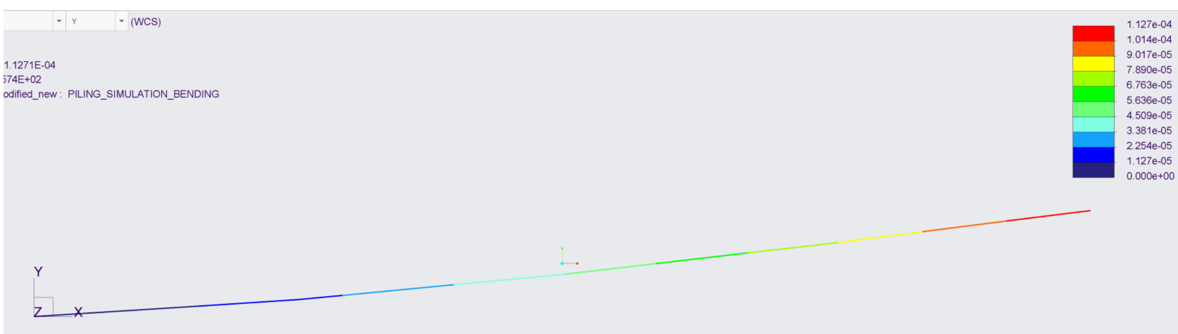


Figure 46: CREO Simulation for Modified Bending Deflection (ft)

Figure 47: CREO Simulation for Modified Bending Deflection Magnified (ft)

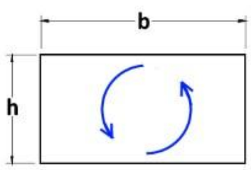
The result of this simulation shows a maximum deflection of 0.00011271 ft or 0.0014 in at the location of the applied load. This agrees with the hand calculations. There is an approximate 8.78% error between the analytical calculation and the simulated result.

Deflection Evaluation

When evaluating deflection between the traditional and modified pilings, both in calculation and simulation, the modified spring mechanism provides much less deformation at the location of the connection dock screws.

4.3.4 Twisting Deformation Analysis

The angle of twist, theta (θ), for a rectangular cross-section under torsional loading is seen in the following figure. Since the piling is a 4 in. x 4 in. piece of wood, the values for b and h in the following figure are equal. So the torsional parameter used is k_1.



$$\text{Ø} = \frac{TL}{k_1 b h^3 G}$$

Torsional Parameters for Rectangular Cross Sections											
b/h	1.0	1.5	1.75	2.0	2.5	3.0	4.0	6.0	8.0	10	∞
k_1	0.141	0.198	0.214	0.229	0.249	0.263	0.281	0.299	0.307	0.313	0.333
k_2	0.208	0.231	0.239	0.246	0.258	0.267	0.282	0.299	0.307	0.313	0.333

Figure 48: Diagram and Equation for Twisting Calculations (Rectangular Sectioning, n.d.)

Where:

T = Applied Torque

L = Length along beam

k = Torsional parameters, unitless

G = Shear modulus or modulus of rigidity

For this calculation, a G of 350MPa or 7309901.982 lbf/ft^2 is being used. This value was published in a creditable scientific journal at MDPI (Bilko, P, 2021). CREO Simulate does not have a set shear modulus property for softwood pine, nor can it be adjusted in the settings of the version the team is using.

Traditional Twisting

Plugging the variables for the case of the traditional fixed piling with a torque 300 lbf*ft at a location of 3ft along the beam, the resulting angle of twist is $\varphi = 0.07$ radians or 4.05°.

This is further shown in a CREO simulation of a twisting beam. In creo, a replica beam is modeled with a fixed surface (purple, left) and a surface applying a torsional load (orange, right). There is a point (red) on the edge of the load surface that measures its start and end position in a radial direction.

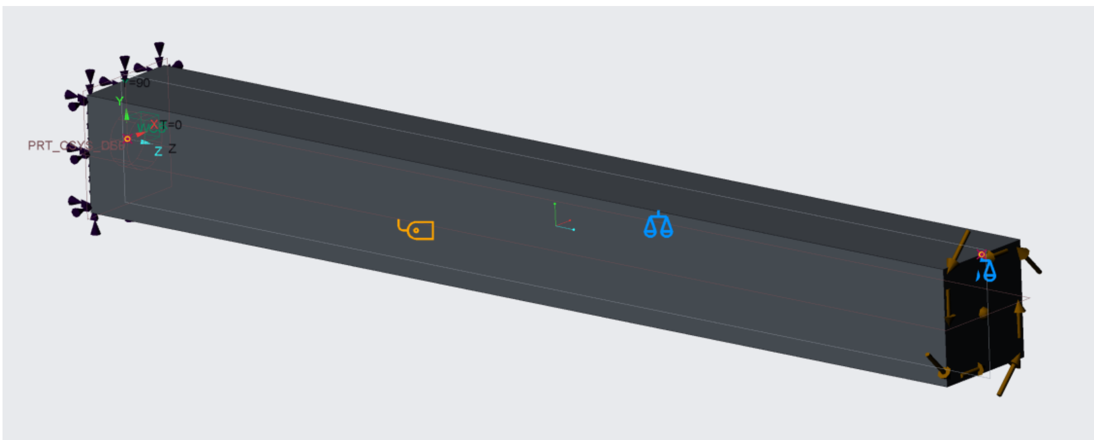


Figure 49: Simulation Setup of Traditional Twist

Running this simulation with a torque of 300 lbf*ft at the end of the beam results as follows:

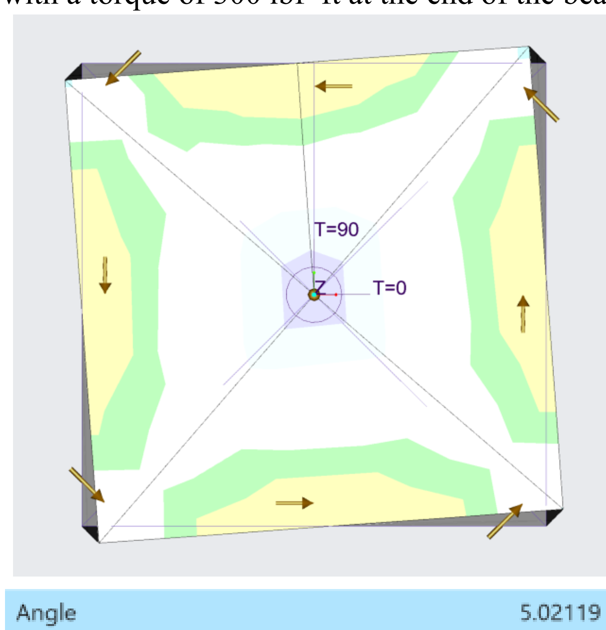


Figure 50: CREO Simulation for Traditional Twist (degrees)

In the figure, the gray surface represents the original position of the beam before torque is applied and the white surface represents the beam after twist. The result of this simulation shows a deflection of 5.02°, which has a 23.9% error between the analytical calculation and the simulated result. The high percent error could be due to the version of CREO potentially not accounting for the shear modulus value that the hand calculations did.

Modified Twisting

Plugging the same variables as used in the case of the traditional fixed piling with a torque 300 lbf*ft at a location of 3ft along the beam, the resulting angle of twist is $\varphi = 0.0079$ radians or 0.450°.

This is further shown in a CREO simulation of a twisting beam. Similar to the bending moment section, the spring transfers a torsional load to the spring box; which is fixed to the dock. Thus, it is acceptable to analyze this system as a torque at the location of the springs. In CREO, a replica beam the length of the spring box is modeled with a fixed surface (purple, left) and a surface applying a torsional load (orange, right). There is a point (right, red) on the load surface that measures its start and end position in a radial direction.

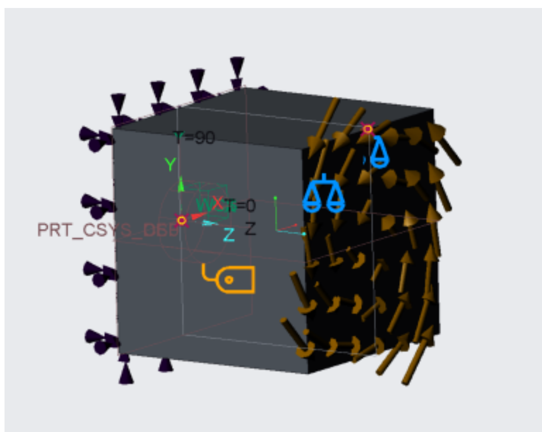


Figure 51: Simulation Setup of Modified Twist

Running this simulation with a torque of 300 lbf*ft at the spring location results in the following:

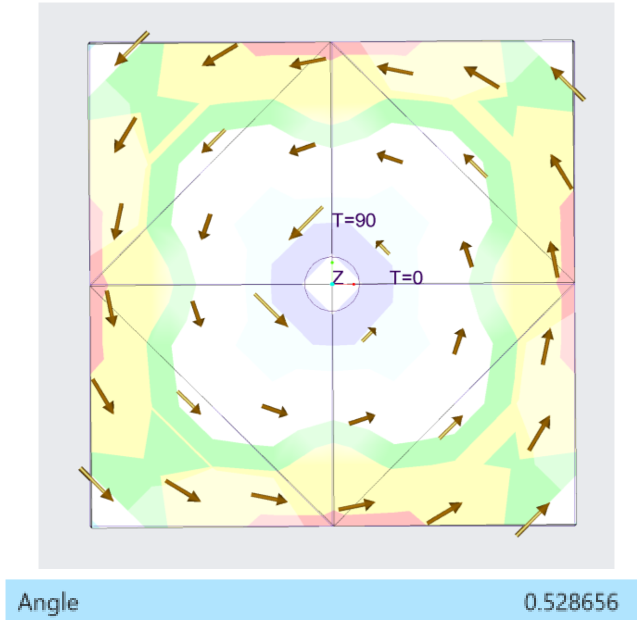


Figure 52: CREO Simulation for Bending Modified Twist (degrees)

In the figure, the gray surface represents the original position of the beam before torque is applied and the white surface represents the beam after twist. The result of this simulation shows a deflection of 0.528656 degrees, which has a 17.4% error between the analytical calculation and the simulated result. Again, this high error could be a result of CREO Simulate not accounting for the same shear modulus property the hand calculations did.

Twist Evaluation

When evaluating twists between the traditional and modified pilings, both in calculation and simulation, the modified spring mechanism exerts much less rotational deformation at the location.

5.0 Manufacturing

Initially, our mechanism was created as a 3D model, to manufacture the mechanism, several steps were taken. Each component of our mechanism had to be obtained before manufacturing was done. Once all components were obtained manufacturing could begin, this process is shown below.

5.1 Initial Spring Mechanism Prototype

Once the initial CAD model was complete, the team was able to begin manufacturing the initial prototype. The initial prototype was created to the same scale as the final design, keeping the initial prototype and final prototype as similar as possible. This also made our initial prototype testing more viable as there are fewer similarity parameters needed. The initial prototype was built using a chop saw to cut the walls of the mechanism casing and to cut the 4 in x 4 in piling. A drill and several drill bits were used to pre-drill the holes in the casing and the piling. Then the eye bolts were installed on the casing and the piling, followed by the construction of the casing using the corner brackets, washers, and screws. Then the springs were attached to the eyebolts on the casing and then attached to the piling. Lastly, the sheet metal cover was then cut to size using a metal saw, and the holes were made using several drill bits to create a smooth hole, and screws were used to fix it to the top of the casing. After this process the initial prototype was complete and it can be seen below.

Figure 53: View of the initial prototype from above

Figure 54: View of the underside of the initial prototype

5.1.1 Initial Prototype Testing

Once the initial prototype was complete, it was retrofitted to an existing fixed dock to see how it performs in the final environment. The mechanism was fixed to the dock using screws, the screws were 3 in long, allowing for a complete connection of the mechanism casing and the dock.

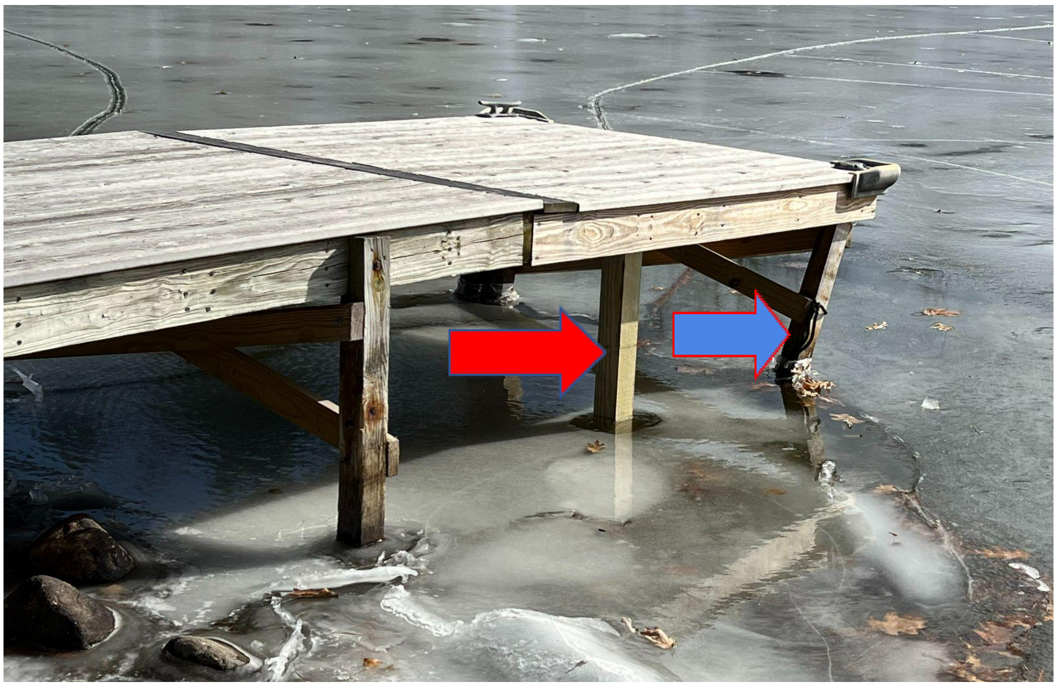


Figure 55: The initial prototype retrofitted to an existing dock

The image in Figure 55 was taken two weeks after the initial prototype was retrofitted to the dock, within those two weeks, the temperature went below freezing many times and reached sub-zero temperature as well. The initial prototype is highlighted by the red arrow, in the image it is evident that it is standing up vertically. On the other hand, highlighted by the blue arrow is a normal piling simply attached with screws, it is evident that the normal piling is significantly slanted. This shows that our design suffered less deformation visually when compared to the existing piling.

Figure 56: A stretched spring with horizontal movement on the initial prototype

In Figure 56 it is evident that the ice freeze caused movement of the springs in the mechanism. This is what the mechanism is designed to do, the springs lessen the force on the screws used to attach the mechanism to the dock. The spring moved to the side, demonstrating that a torque load was applied to the piling. In Figure 57 the spring was also stretched but has no horizontal movement, meaning no torque was applied in that direction. The spring was not subjected to any long-term deformation whereas in a normal fixed piling a screw likely would have.

Figure 57: A stretched spring on the initial prototype retrofitted to an existing dock

Figure 58: Underside of the initial prototype retrofitted to an existing dock

The underside of the initial prototype can be seen in Figure 58. The spring on the left is being compressed while the spring on the right is being extended and the spring on the top is subjected to lateral movement and extension. This means that the piling was subjected to lateral forces and torque, and the springs were subjected to these forces and torque, thus lessening the forces on the screws used for attachment.

Figure 59: Normally fixed dock piling suffering permanent deformation

A piling that suffered substantial deformation can be seen in Figure 59, the ice freeze can be seen towards the bottom of the image. The piling has tilted substantially, this may result in a catastrophic failure of the dock if this piling fails, resulting in a costly solution. A 2 in. x 4 in. beam can be seen in the image as well, this beam was added to create another point of contact between the piling and the dock, the tilt seen is evidence that the extra beam was not enough to solidify the piling.

5.1.2 Results From Initial Prototype Testing

Reinforcing the square casing of the mechanism

The square casing of the mechanism was held together by 4 brackets in the prototype, after initial testing it is evident that it would be beneficial to add reinforcement. This reinforcement is in the form of adding outdoor screws to the joints of the square casing. In Figure 54, the joints of the square casing are flush when compared to the joints after it was retrofitted to an existing dock. In Figures 57 and 58 it is seen that the joints have separated and are no longer as flush as they were initially. The installment of outdoor screws to the square casing would reinforce the square casing and prevent future separation in future design iterations.

5.2 Manufacturing Process - Final Prototype

After preliminary testing on the initial prototype, adjustments were implemented at this stage of the design. The majority of the design is constructed out of wood, specifically pine, and steel is the secondary material for the mechanism.

5.2.1 Mechanism Casing

The square casing provides the foundation of the mechanism, it is the part that is directly secured to a fixed dock with screws. This process began with cutting two 9 in wood 2 in. x 6 in. blocks along with two 12 in pieces. Then the eye screw hole was pre-drilled 4 in from the top of the wood block and in the horizontal center of the piece. Subsequently, the eye screw was screwed into each hole on each wood piece, this product can be seen in Figure 60 below.

Figure 60: 9 in. and 12 in. square casing 2 in. x 6 in. wood pieces

Then one side of a spring was added to each eye screw as seen in Figure 61. This process involved stretching the hook of the spring enough to fit over the eye screw and subsequently tightening the spring hook with pliers back to its original position.

Figure 61: The wood pieces from Figure 60 with the addition of the springs

After the springs were added, the next step was to measure where the bracket was going to be placed and then mark where to predrill each hole. Each wood piece will be predrilled and then the brackets were fixed to the 9 in long wood pieces as seen in Figure 62. During this step holes for the sheet metal cover were pre-drilled into the top of the wood pieces as seen in Figure 64.

Figure 62: A wood piece with the addition of the corner brackets

The final addition to the square casing was the screws that were added to the corners to solidify the mechanism shown in Figure 63. In the prototype, the wood pieces were separating from each other after the ice froze and subjected the square casing to a force. The screws were added to make the square casing stronger so there won't be any separation in the new prototype. The final square casing with the corner brackets is shown in Figure 64.

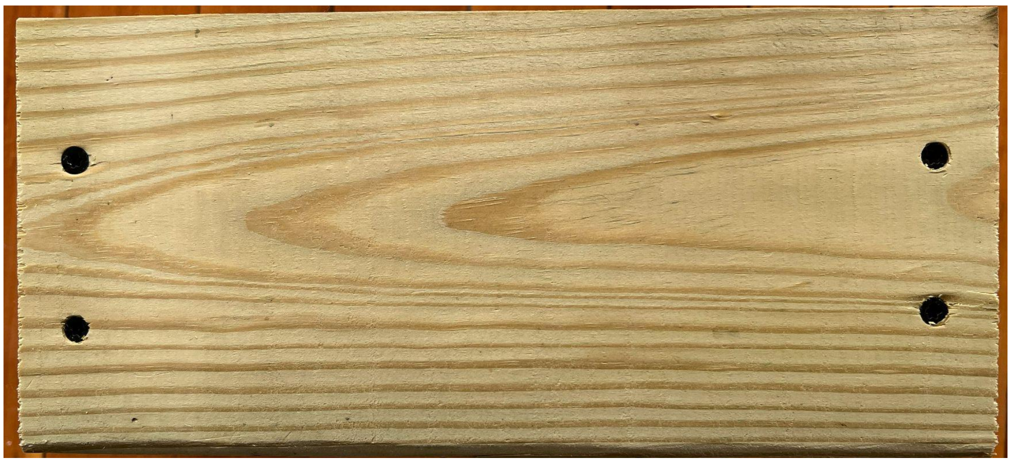


Figure 63: Square casing with the addition of screws to solidify the mechanisms foundation

Figure 64: Square casing with corner brackets

5.2.2 Piling

The fabrication of the piling subassembly is a similar process to that of the 4 wood pieces from the steps above. On each side of the piling, a hole was predrilled 4 in from the top and in the horizontal center and then an eye screw was screwed into each hole. The piling was then secured to the square casing by connecting the free end of the hook spring to the eye screws on the piling as shown in Figure 65.

Figure 65: Square casing with the piling inserted

The last step of fabricating the prototype was to cut the sheet metal cover to a 12 in by 12 in square and drill holes around the edge to allow for a screw to be inserted through. The metal sheet was then placed on top of the mechanism and screwed into the predrilled holes with the screws. The final prototype is pictured in Figure 66.

Figure 66: Final assembly of the mechanism

5.2.3 Final Design Retrofitting

While this project planned on retrofitting the final design of the mechanism onto a dock and monitoring the behavior of the mechanism over the span of a couple of months. Due to the time limitation of the project, the team however was unable to retrofit the final design onto a dock, however the final prototype that was designed before the final design and is almost identical to the final design has been retrofitted onto an existing dock since February 2023 and has not shown any noticeable signs of wear and has functioned as expected.

5.3 Manufacturing Process - Baseline Testing Prototype

To compare the results of our spring mechanism with an existing dock a representation of a traditional fixed dock was necessary. The process of fabricating this mechanism was similar to that of our final spring mechanism prototype. Figure 67 shows the two variations side-by-side, on the left the spring mechanism is seen and on the right, the traditional representation is seen.

Figure 67: Final spring mechanism prototype (left) and the traditional fixed dock baseline testing representation (right)

The traditional fixed dock representation was fabricated using 2 in. x 4 in. pieces of pressure-treated wood for the square enclosure, a 4 in. x 4 in. pressure treated piling to simulate the piling, and 3 in. outdoor screws to secure each piece. The spring mechanism uses 2 in. x 6 in. pieces for extra strength while the traditional fixed dock representation uses 2 in. x 4 in. pieces as most traditional fixed docks. The square enclosure was designed with the same dimensions as the spring mechanism enclosure to keep the size constant to avoid any unwanted variants during testing. The square enclosure for the traditional dock was fabricated in the same way as the spring mechanism enclosure minus the inner brackets, using two 3 in. screws at each corner.

After the square enclosure for the mechanism was fabricated the piling was attached. The piling was placed in the corner of the square enclosure and then secured by drilling two 3 in.

screws through the square enclosure on each side of the piling. This means that the piling is secured to the square enclosure using four screws total.

The traditional fixed dock representation was designed based on average traditional fixed docks seen throughout our research and personal experience to ensure unbiased experimentation.

6.0 Testing

6.1 Experimental Setup

Once the mechanism was fabricated, the testing process began. A frame was constructed to encase the mechanism so that proper tests could be done as the mechanism casing must be fixed in place. The testing frame can be seen below in Figure 68. The testing frame was fixed to a wall, subsequently fixing the mechanism in place allowing for the mechanism to be subjected to forces and moments.

Equipment

- 2x 2 in x 4 in x 48 in wood
- 4x 2 in x 4 in x 33 in wood
- 2x 2 in x 4 in x 12 in wood
- 24x 2.5 in by #9 wood construction screws
- 4x 3 in by #10 exterior screws (for decking)

Constructing Procedure

1. Join two 48 in and two 33 in pieces of wood into a base frame using eight wood construction screws, two for each corner. Make sure the corners are square.
2. Attach the two remaining 33 in pieces perpendicular to the length of the frame; one at a location of 18 in from each end. Use two construction screws for each connection. Make sure they are square. The frame will now be in three sections with the center section being 12 in.
3. Add the two 12 in pieces into the center section perpendicular to the width of the frame; one at 11.5 in from each end of the length of the frame. Use two construction screws for each connection. There is now a 12 in x 12 in square section in the middle of the frame.
4. When it comes time to add the traditional or modified pilings, use the four exterior decking screws to secure the piling to the center square in the frame; one screw for each side.

Figure 68: The frame constructed for testing with the mechanism inside

The team further experimented with the modified mechanism with the springs as well as the traditional fixed dock. These experiments incorporated stress testing with a strain gauge for deformation and impact testing with load cells to measure dynamic forces and natural frequencies.

6.2 Natural Frequency

6.2.1 Goal of Finding Natural Frequency

Measuring natural frequency for a system can define its structural integrity. In the case of dock pilings, the goal of measuring natural frequency was to determine if the pilings could withstand certain external forces and vibrations without failure or permanent deformation. This was done by applying dynamic loads and analyzing oscillations. The results of this experiment further compared a traditional fixed piling to the modified spring mechanism.

The team used a Dytran 1051v4 IEPE Force Sensor which measures dynamic forces up to 5000 lbf with a sensitivity of 10 mV/lbf. This device eliminated the need for an external amplifier and allowed for accurate and reliable measurements of the applied forces on the pilings.

6.2.2 Dytran Force Sensor Calibration

The Dytran 1051v4 force sensor needs to be calibrated for this to ensure the device will work as desired. When a known weight is applied to the sensor, it will read a jump in voltage. This jump should correlate with the load that was applied. The team knows the device will work as desired when these variables are equal.

Additionally, the time constant of the sensor will be found. In certain dynamic systems that exhibit exponential decay or growth, such as ours, the time constant of the force sensor will be 63.2% of the start of decay from the peak value. The 63.2% corresponds to the mathematical constant e^(-1), which will theoretically show the time of substantial change in the system while minimizing bias (Storr, 2023).

Parts List

- 1x 1/8 in x 3.5 in by 5 in aluminum plate
- 1x 1/8 in x 3 in by 4 in aluminum plate
- 2x 1/4-28 in bolts
- 2x washers

Equipment

- 1x oscilloscope
- 1x Dytran 1051v4 Force Sensor
- 1x microdot 10-32 cable
- 1x Dytran 4114 Current Source Power Unit
- 1x screwdriver
- 1x vise or a flat stable surface
- known weight

Setup

The team first connects the force sensor to a Dytran 4114 Current Source Power Unit that allows the force sensor to be connected to an oscilloscope. In the experiments conducted by the team, a DSO6012A oscilloscope was used. From there, two 1/8" aluminum plates (3.5 in by 5 in and 3 in by 4 in) were attached to the force sensor using 1/4-28 threaded screws and flat washers. This assembly was clamped in between a vise. Clamping provides a stable environment for the sensor that will eliminate oscillation noise from any outside source. Next, a known weight was added on top of the sensor. The known weight for the team was a 1 lb weight. This step was needed to essentially remove the force sensor from the data, leaving only the forces onto the piling.

Once everything has been connected to the oscilloscope, center the voltage reading on the oscilloscope and modify the mv/div so the data fits perfectly inside of the window of the oscilloscope. From there, modify the s/div so that it is about 1 s/div. As there is most likely going to be noise in the system, average the data by two or four to remove the majority of that noise.

Procedure

1. Place the Dytran Force Sensor assembly onto a flat and rigid surface. The team used a vise.
2. Press the single button on the oscilloscope
3. Add a known weight onto the plate connected to the force sensor. The weight should be anywhere between 1 lb and 10 lb.
4. Allow for the oscilloscope to stop collecting data then import data to calculate lbs from the voltage change

Resulting Calibration Data

Table 2: Dytran Calibration Data Chart

Peek Volt (V)	Steady State Voltage (V)	Volt Jump (V)	63.2% of Peek Decay (V)	
1.13E-02	2.70E-04	1.10E-02	4.06E-03	
Time at Peek (s)			**Time at 63.2% (s)**	**Time Constant (s)**
-9.28E+00			-3.40E+00	5.88

The following figures depict this table in graphical form with an annotated explanation for understanding of the time constant.

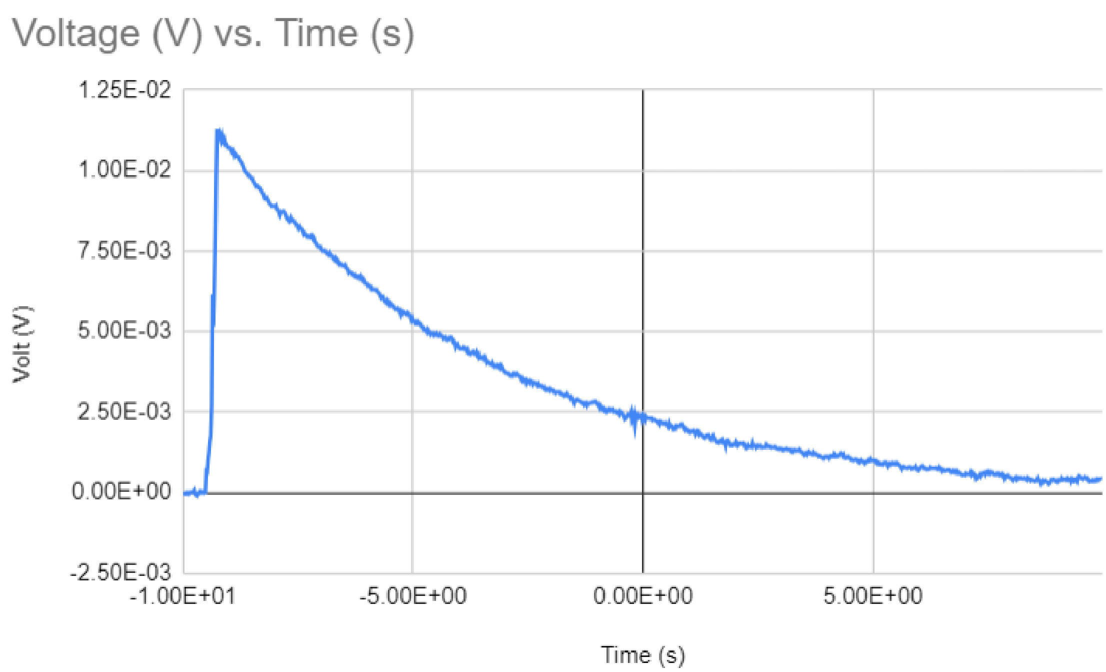


Figure 69: 1 lb weight being applied onto a Dytran 1051v4 Force Sensor

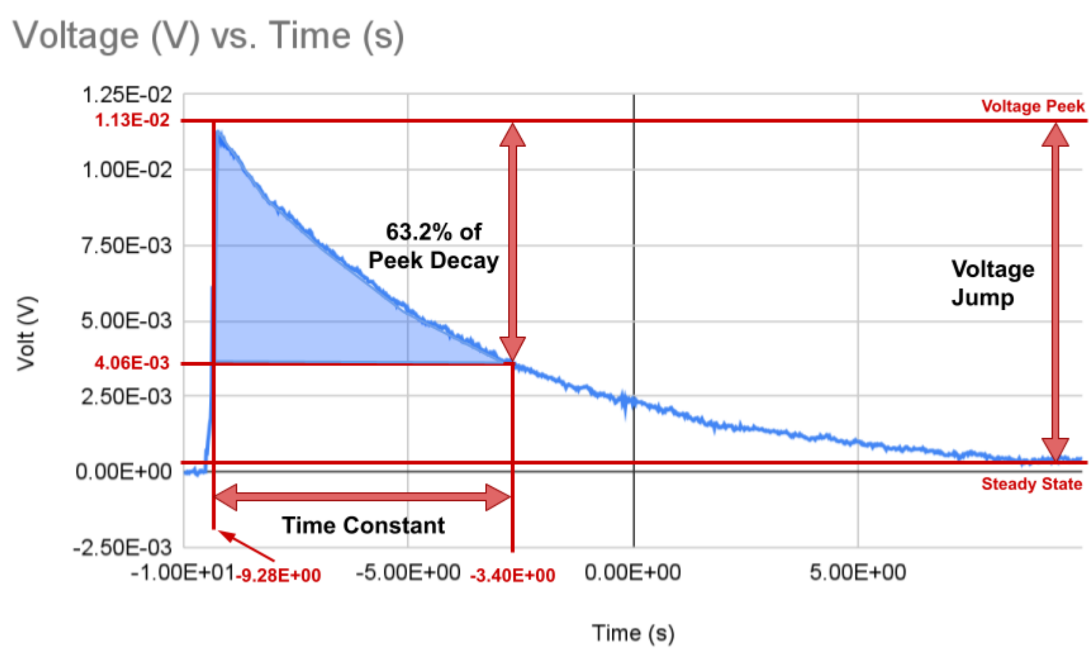


Figure 70: Figure 69 with annotations for understanding time constant

With a 1lb weight being gently placed onto the sensor, the Dytran sensor reads a voltage jump between the peak value and steady data of approximately 1.10E-02V or 11 millivolts.

Comparing this to the true sensitivity of the sensor, 10 mv/lbf, the calibration result shows a 10% error. With this result, the team knows that the sensor will work as desired.

This calibration data also gives a time constant of 5.88 seconds. This means, it will take approximately 5.88 seconds for the sensor's output to reach 63.2% of its final value. After that time, the output will gradually get closer to its steady state. Overall, the time constant of the force sensor represents the rate at which it responds to change in force.

6.2.3 Natural Frequency of Experimental Setups

Parts List

- Calibration Assembly
- Test Rig

Equipment

- 1x oscilloscope
- 1x Dytran 1051v4 Force Sensor
- 1x microdot 10-32 cable
- 1x Dytran 4114 Current Source Power Unit
- 1x screwdriver

Setup

The team connected the same metal plate assembly from calibration with the force sensor to the Dytran 4114 Current Source Power Unit. This allows the force sensor to be connected to a DSO6012A oscilloscope. One of the plates had two 3/16 in holes drilled into it so it can be attached to the end of the beam using two 2.5 in by #9 wood construction screws. One 31/64 in hole was drilled into each piling to allow for the head of the bolt connecting the force sensor to be recessed.

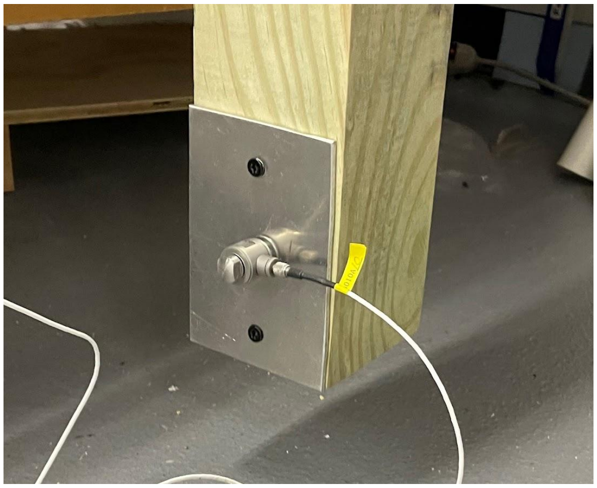
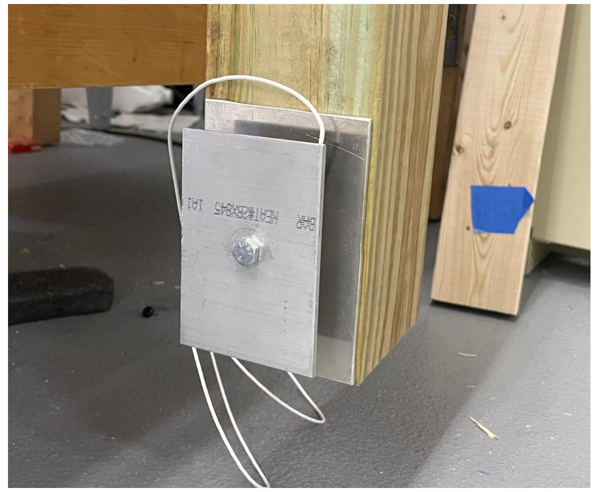



Figure 71a (left): Dytran Force Sensor Setup on Piling without top plate

Figure 71b (right): Dytran Force Sensor Setup on Piling with top plate

Once everything has been connected to the oscilloscope, center the voltage reading on the oscilloscope and modify the mv/div so the data fits perfectly inside of the window of the oscilloscope. From there, modify the s/div so that it is about 1s/div. As there is most likely going to be noise in the system, average the data by two or four to remove the majority of that noise.

Procedure

1. Press the single button on the oscilloscope
2. With a mallet, quickly tap on the center of the bolt going into the force sensor
3. Allow for the oscilloscope to stop collecting data

Results of Dytran Force Sensor on Traditional Fixed Piling

For this test, the traditional fixed piling was mounted to the experimental test rig using 4 decking screws, as explained in the experimental rig section. The piling was free floating so it did not make contact with the ground. The team assumed the piling to be a cantilever beam without friction on its free end.

Analytically, the first natural frequency of a cantilever beam is as follows:

$$\omega_{nf} = 1.875^2\sqrt{\frac{EI}{\rho A L^4}}$$ (Free Vibration, 2011)

Where:
- ω = first natural frequency

- E = Young's Modulus
- I = moment of inertia
- ρ = material density
- A = cross sectional area
- L = length of beam

For the 4 in. x 4 in. fixed piling, the base and height are 3.5 in. with E = 3171915283N/m^2 (finding this is explained in a further section where we calibrated a strain gauge to find E) and ρ = 537 kg/m^3 (Southern Pine Council, 2009). Plugging these values into the equation, the undamped first natural frequency of the piling is analytically calculated as 331.91 rad/sec or 52.83 hz.

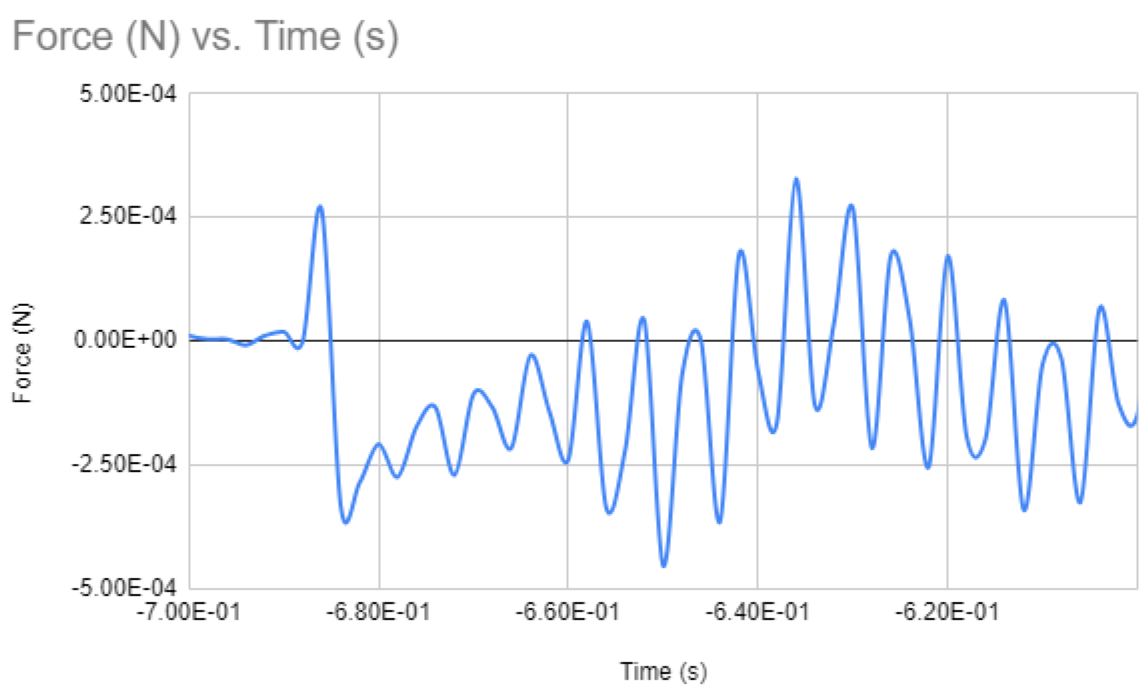


Figure 72: Voltage (V) vs. Time (s) of the fixed piling with Dytran 1051v4 Force Sensor

From this graph, it was calculated that the natural frequency of the fixed mechanism is about 981.74 rad/s or 156.25 Hz.

Results of Dytran Force Sensor on Modified Spring Piling

For testing the oscillations of modified spring piling, the team could not allow the piling to hang free in the testing rig. The weight of the piling would cause the springs to extend due to gravity. As a solution, the team created a false ground that emulated a friction force as the piling was impacted. This was made of thick brown packing paper that would allow the piling to slightly move on top of a secondary piece of wood.

Figure 73: Dytran Force Sensor Setup for Spring Piling

From here, the team recorded the data from the Dytran Force Sensor in order to calculate the natural frequency of the spring mechanism. The force was applied onto the piling using a rubber mallet to briefly strike the center of the Dytran Force Sensor. The following figure shows the primary natural frequency of the piling.

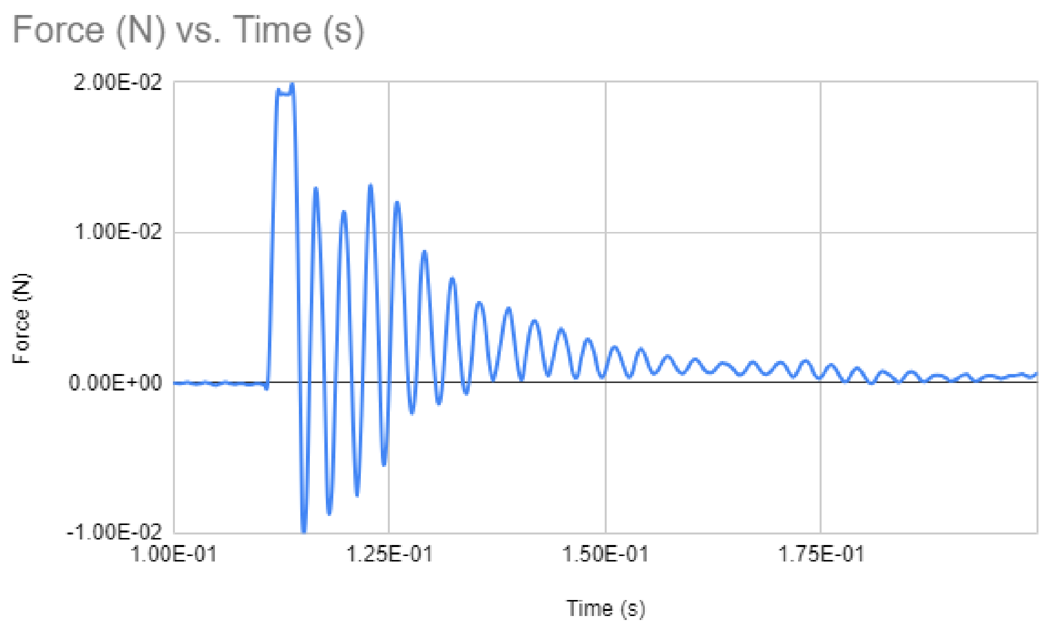


Figure 74: Force (N) vs. Time (s) of the spring mechanism with Dytran 1051v4 Force Sensor zoomed in

Once the piling was struck with the mallet, it was calculated that the natural frequency of the spring mechanism is about 1848.0 rad/s or 249.1 Hz.

6.3 Strain Testing

6.3.1 Purpose of finding strain and expected results

Testing for strain on a beam helps analyze the stress distribution and deformation under various loads and conditions. The data collected from testing with the strain gauges can calculate the bending moment at a fixed position.

The team is utilizing a strain gauge from Culler that was purchased from Amazon. This gauge has a sensitive grid of 10 mm x 2 mm and a base is 14.5 mm x 4.5 mm. The resistance of the device is 120 Ohm with a gauge factor of 2.08 (Culler, n.d.). For the gauge to be most effective, it was mounted to a location just before the fixed connection point. This is where it will experience the most amount of strain.

The team also used a Zemic H3-C3-200kg-3B Load Cell to obtain accurate measurements of the loads that are applied. This load cell works by applying a load onto the cell which is read as an electrical signal. This signal then gets converted by the computer to an accurate force measurement.

This gauge is connected to a full Wheatstone bridge which reads the output resistance from the gauge when it experiences a load or deformation. Being a “full” bridge, the strain is highly amplified. A diagram of a full bridge is as follows:

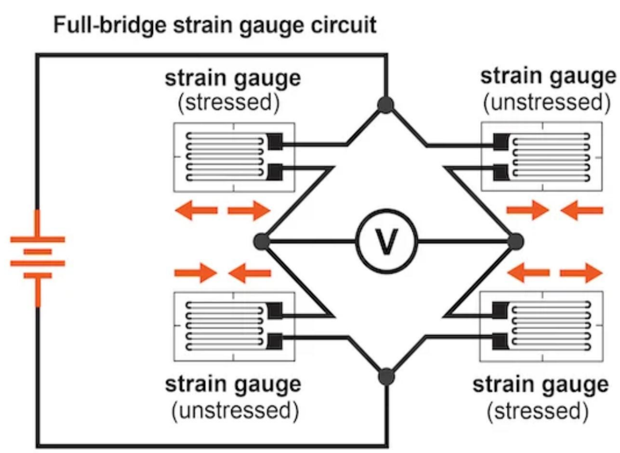


Figure 75: Full Wheatstone Bridge Diagram (Strain Gauges, n.d.)

The Wheatstone Bridge is connected to a National Instruments NI USB-6229 BNC Multifunction I/O DAQ unit with an integrated external power supply that provides +5V to power the bridge. This device also reads the voltage offset of the bridge and relays that information into a program called LabVIEW. LabVIEW is a graphical programming language that is used to measure the strain experienced by the strain gauge given a known gauge factor and impedance. The code that is used in the program to acquire this data was created by past WPI Faculty for the use of experiments in a class**.** Once the circuit is complete, the Wheatstone bridge needs to be balanced within LabVIEW.

The full electrical setup of the bridge, as well as a diagram, can be seen in the following figures. In the diagram, R represents a strain gauge. The strain gauge is connected to the connector in the bottom right of the in-person picture.

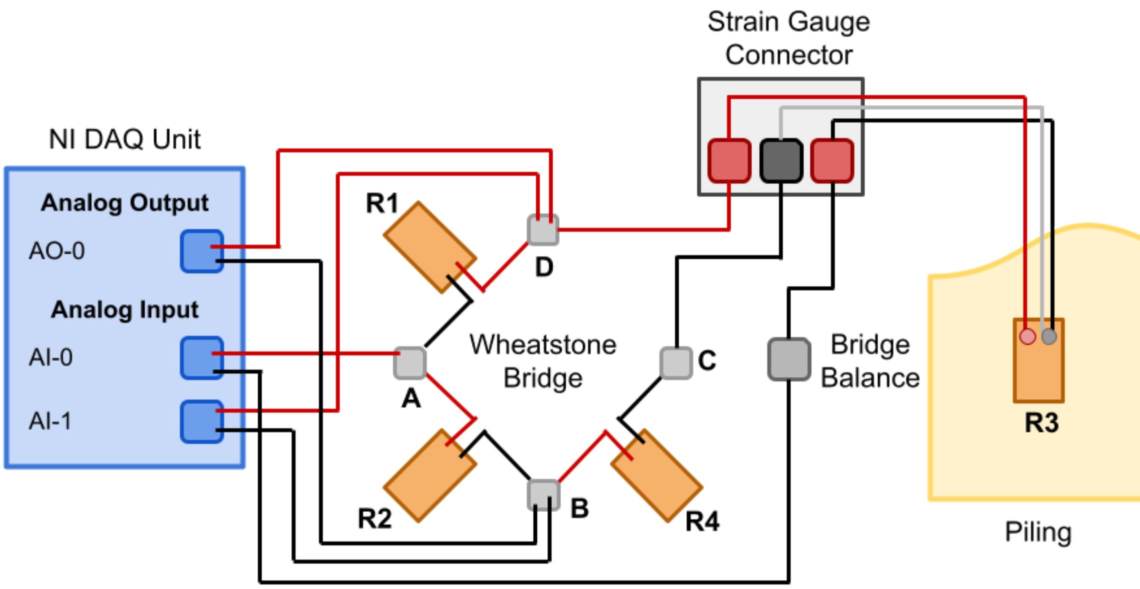


Figure 76: Wheatstone Bridge Set Up Diagram

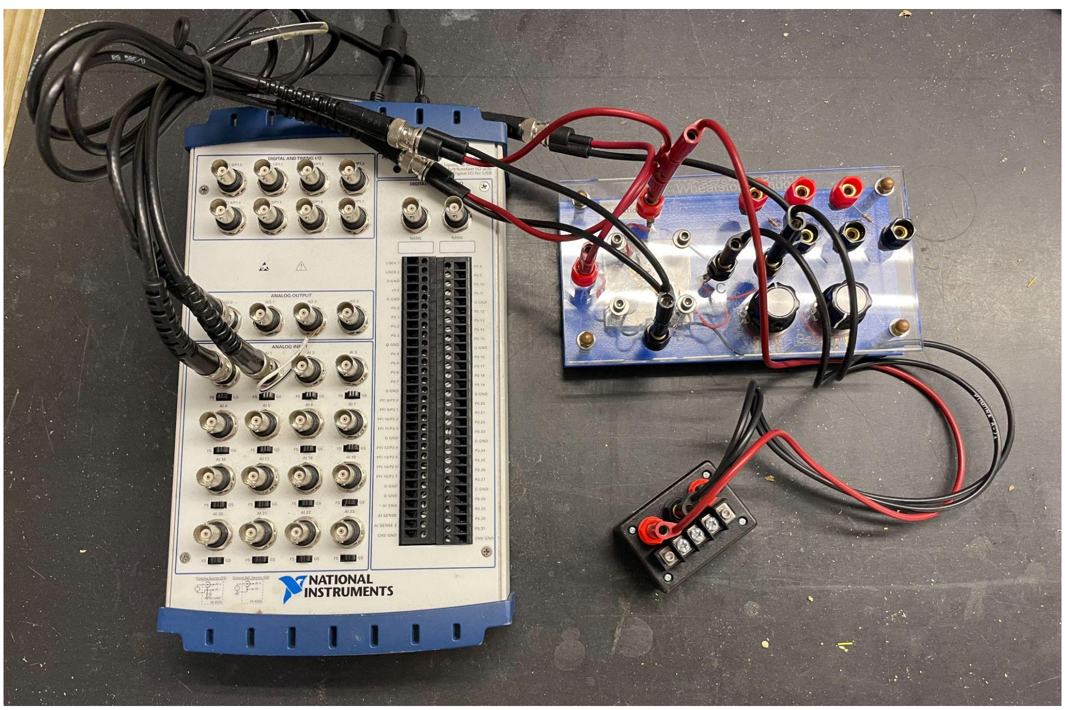


Figure 77: Wheatstone Bridge Set Up In Person

6.3.2 Strain Calibration on Fixed Beam

For calibration, the team took an experimental measured strain and compared it to a theoretical strain of the system to verify that the results from the experiment are accurate. This involves analyzing strain data and calculating Young's Modulus, E, of the wood used in the tests. The equation for theoretical strain is below:

$$\varepsilon_{Theoretical} = \frac{6*L_b}{(W_b*H_b^2*E)*F}$$

Where:
- L_b is the length of the piling
- W_b is the width of the piling
- H_b is the height of the piling
- E is the Young's Modulus
- F is the applied load on the piling

Parts List

- 1x 4 in x 4 in x 36 in pressure-treated pine wood
- 1x strain gauge

Equipment

- 1x load cell
- 1x Wheatstone bridge
- 1x NI USB-6229 BNC DAQ
- 1x ratchet strap
- 1x vise
- 1x paracord
- 1x secure location to mount ratchet strap

The piling is mounted inside of a vise on a rigid, heavy table to make sure it is secure when applying loads. The strain gauge is placed just above the jaws of the vice at the center of the beam's width. A ratchet strap is secured to a door parallel to the piling on one end, and to one end of the load cell on the other end. This system allows there to be a perpendicularly applied static load that can be adjusted and read with a load cell. The other end of the load cell is connected to a paracord that is looped around the end of the piling so that the force is both perpendicular to the length of the piling and at the point where the largest moment would be experienced. The following images show the physical setup of the calibration test:

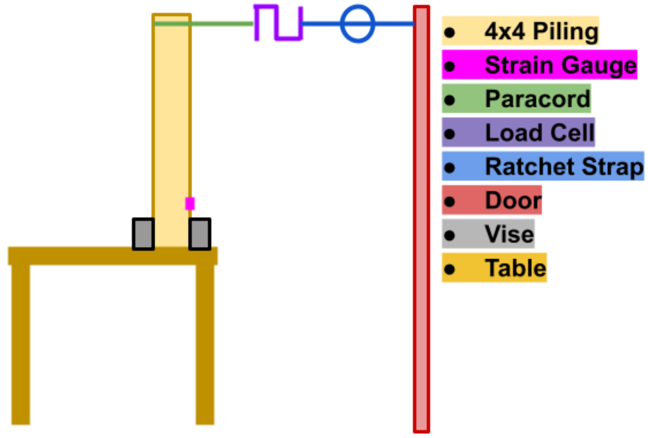


Figure 78: Experimental Setup Diagram

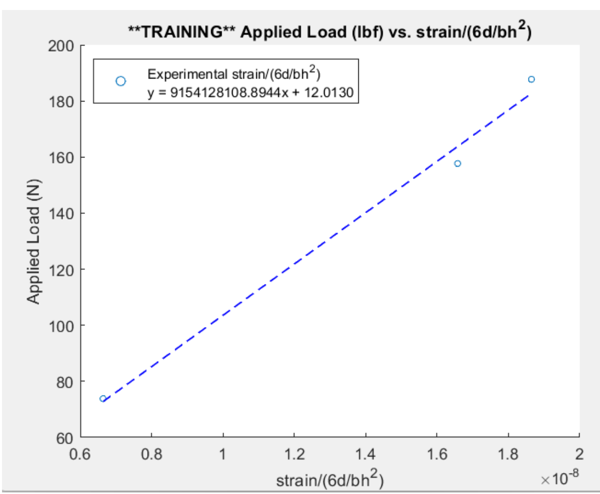
Figure 79: Strain Calibration Experiential Setup in Person

Procedure

1. Zero the load cell on a flat surface, by itself, with nothing attached. Ensure the load cell is set to read Newtons.
2. Using the WPI provided LabView program, balance the bridge using the "Start Bridge Balance" button, and wait for “Bridge Balance Complete” to be solid green. Press the "Start Bridge Balance" button once more to prevent the program from continuing to auto-balance.
3. Attach one end of the load cell to the end of the piling and the other to the ratchet strap.

4. Tighten the ratchet strap until the reading on the load cell is a desired load. Make sure not to touch the equipment or surface the piling is attached to once the desired load is reached.
5. Once the system is at an approximate equilibrium, record the microStrain output in LabView and the applied load from the load cell
6. Repeat steps 1 through 6 for a few times (3-4) with a large increment load so that a trend line can be acquired using the Matlab program. This is the “training data” to find E, the elastic modulus, of the wood.
7. Insert the dimensions of the beam (width, height, and length) as well as the training data into the array training data in the format training data = [Input Load 1, Output Strain 1; Input Load 2, Output Strain 2;...].
8. Repeat steps 1 through 6 multiple times.
9. Insert these values into the array strainpoints in the format strainpoints = [Input Load 1, Output Strain 1; Input Load 2, Output Strain 2;...].
10. Run the Matlab code. The program will calculate an E for the experimental data using the training data, and then apply that E to the theoretical strain on the beam to show how close the experimental data is to the theoretical data.

Results



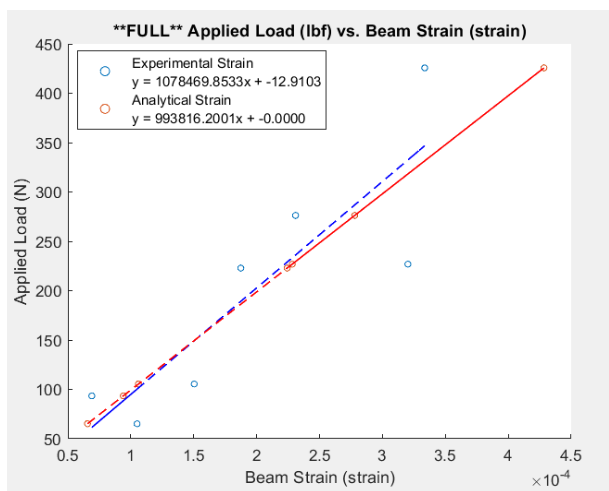


Figure 80a (left): Training data to calculate Young's Modulus of a 4x4 pressure-treated piece of wood

Figure 80b (right): Graph of the experimental strain of a pressure treated 4x4 (blue) with analytical strain (red)

This experiment consisted of two main parts, the training phase and the testing phase. The primary reason for the training phase is to calculate the Young's Modulus for the 4 x 4 piece of wood (see Figure 80a), as well as to confirm that the strain gauges were capable of measuring the strain on the wood. For this training phase, the x-axis is normalized using the equation $\frac{\varepsilon}{6d/(W_b * H_b^2)}$ in order to make the slope of the graph the Young's Modulus of the piling. This test yielded a Young's Modulus of 9154128109 n/m^2 which is approximately 9154.128 MPa, and is inside the range of acceptable values for a Young's Modulus of Southern Yellow Pine Wood. From here, the Young's Modulus is taken from the first phase and used in the training phase to calculate the analytical strain on the piling $\varepsilon_{Theoretical} = \frac{6 * L_b}{(W_b * H_b^2 * E) * F}$. Once the analytical strain is calculated, it is compared against the experimental strain of the piling to ensure that the data is correct, which can be seen in Figure 80b. This figure shows the analytical strain in red and the experimental strain in blue. Both trend lines overlap with each other for a large portion of the sample, but the experimental line trends away from the analytical line towards the end, most likely due to non-ideal conditions with the testing setup and wood.

6.3.3 Strain Testing of Experimental Setups

Traditional Fixed Piling

The traditional fixed piling was mounted to the experimental test rig using 4 decking screws on each of its 4 sides. For both static and dynamic tests, the piling was free floating and not making contact with the ground, the same as the natural frequency testing. For these tests, the strain gauge on the piling was placed at the location just before its fixed position. Theoretically, this is where the piling, also a cantilever beam, will experience the most amount of strain.

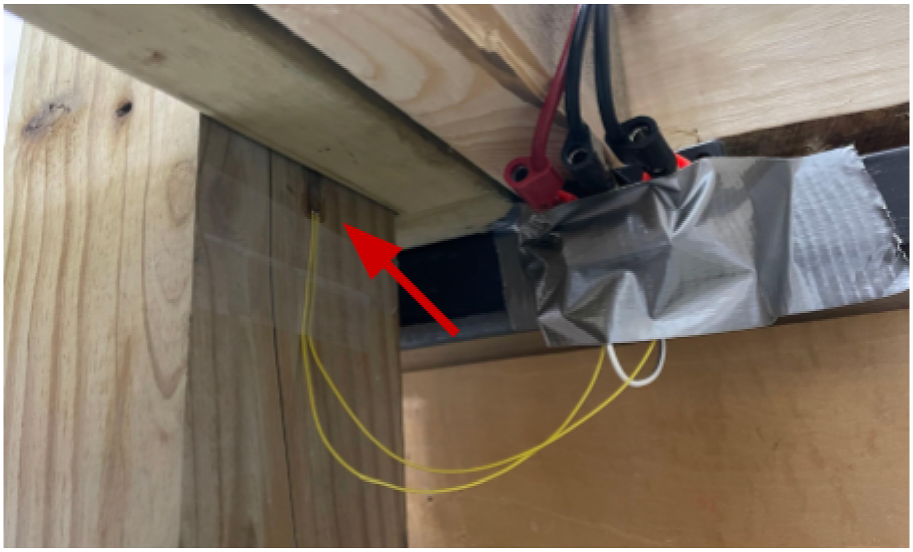


Figure 81: Traditional Fixed Piling Strain Gauge Location

Static Strain

Similar to the strain calibration, a ratchet strap was used to apply a static load. However, since the fixed piling is hanging down, the strap was attached to the leg of the table to connect the load cell to the piling. There is a slight angle between the location of the ratchet strap and the piling, however, this small angle can be negligible.

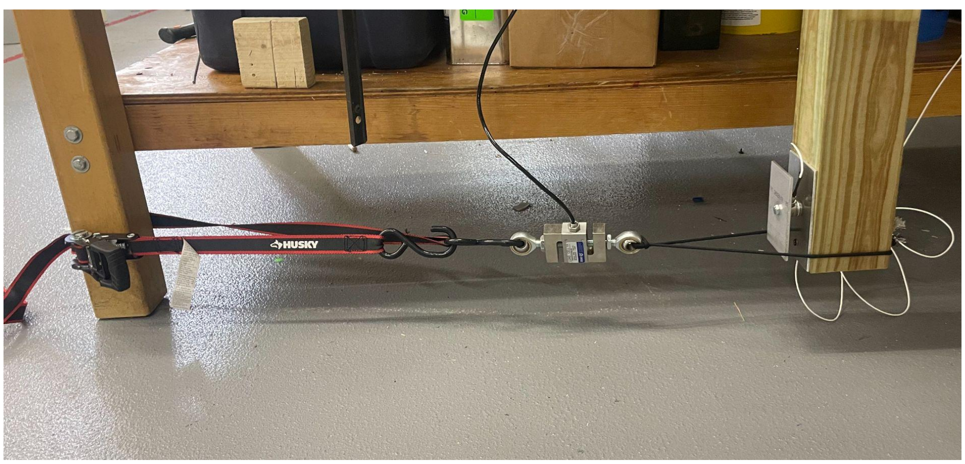


Figure 82: Traditional Fixed Piling Static Strain Setup

Three data points were collected with this setup. The goal was to get a variety of points, however, the ratchet strap method can be unforgiving. One extra click on the ratchet strap could result in a much larger applied load. Despite that, the following table is the strain results of the input load using the calibrated Young's Modulus, followed by graphical representations.

Table 3: Strain and Bending Moment Data for Fixed Piling

Input Load (N)	Strain (microstrain)	Beam Width (m)	Beam Height (m)	Beam Length (m)	Young's Modulus (N/m^2)	Load (N)	Bending Moment (Nm)	Bending Moment (lbf*ft)
104.2	342.55	0.0889	0.0889	0.8128	9154128109	451.7636623	367.1935047	270.8280305
196.4	610.14	0.0889	0.0889	0.8128	9154128109	804.6681678	654.0342868	482.3909343
187.4	584.36	0.0889	0.0889	0.8128	9154128109	770.6688474	626.3996392	462.0086642

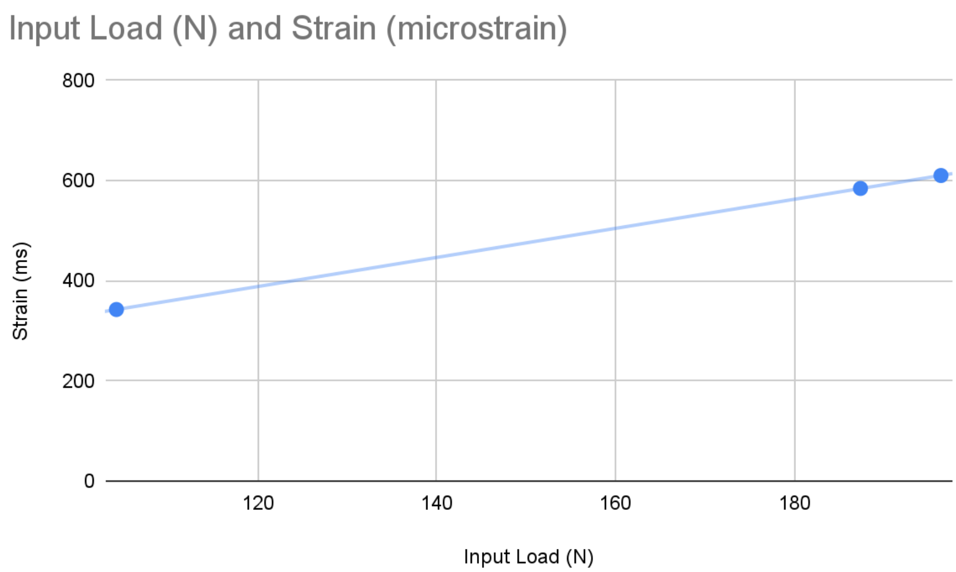


Figure 83: Applied load (N) vs. Strain (microstrain) graph for the fixed piling

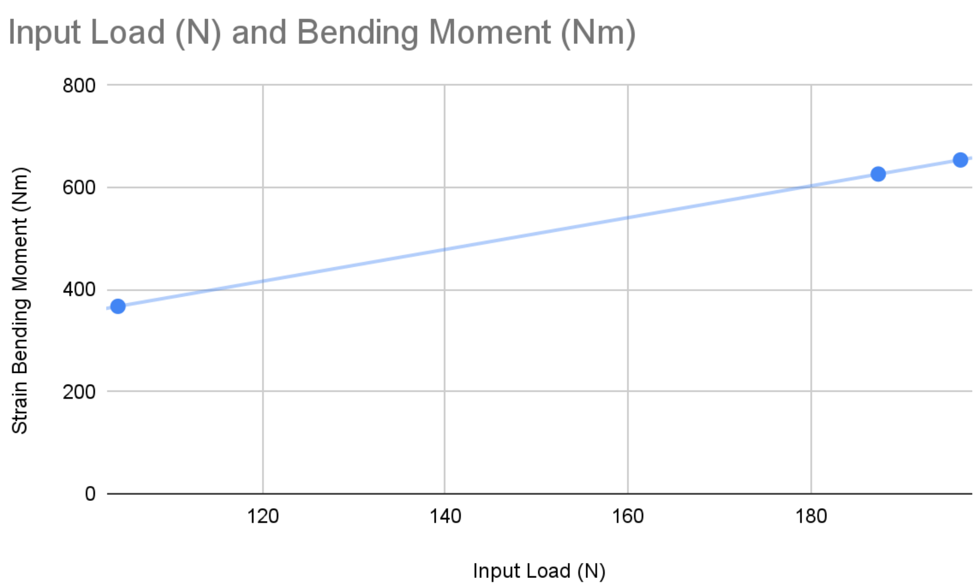


Figure 84: Applied load (N) vs. Bending Moment (Nm) graph for the fixed piling

Dynamic Strain

For dynamic strain, the piling was hit with a mallet similar to the natural frequency tests. In addition to reading the oscillation, the strain gauge is also recorded in this test to understand the relationship between strain and oscillation from an impact force on the system. Unfortunately, due to the response time of our LabVIEW script, we were unable to capture the impacts felt by the strain gauge. However, we were able to capture data from the force sensor as the piling was being impacted, and use the equation $\varepsilon_{Beam} = \frac{F*d}{(\frac{1}{6}bh^2)*E}$ to calculate the strain experienced at the screw end of the piling, which can be seen in Figure 85. In this equation, F is the force noticed at the force sensor, d is the distance from the sensor to the screw, b and h are respectively the base and height of the piling, and E is the Young's Modulus of the piling. One item to notice is the moments where the mallet struck the piling, which is circled in red on the figure.

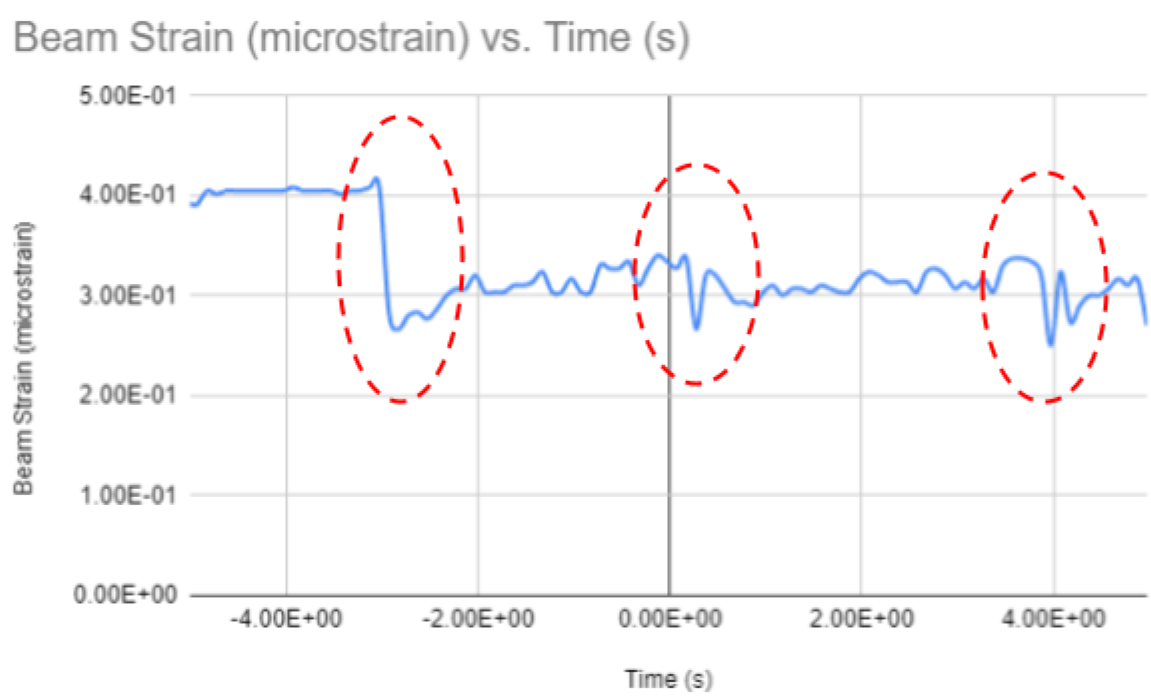


Figure 85: Beam Strain (microstrain) vs. Time (s) graph for the dynamic test on the fixed piling

This data shows that when the fixed piling is struck towards the bottom of the piling at a dynamic rate, there is a noticeable increase in the strain felt by the piling. While this graph only shows a change in strain of about 0.142 microstrain, the strain experienced by the piling will be much greater with stronger impacts. This dynamic strain test reveals how the traditional fixed piling will perform in a real scenario. In the graph, one can notice that the oscillations/vibrations between each impact do not show substantial damping or energy dissipation. This means that the fixed piling does not indicate proper energy absorption. However, with the modified spring piling, being that it is composed of springs, it will have superior energy absorption capabilities compared to a solid mass connection. The elastic nature of a spring allows it to store and release energy efficiently. Thus, in a real scenario of dynamic loading, the modified piling will perform better because the fixed piling does not dissipate enough energy after impact.

Modified Spring Piling

The setup for this test was the same as the natural frequency tests; with the piece of wood and packing paper to resemble ground friction. To measure strain, the team at first began a similar strategy to that of the fixed piling. A strain gauge was attached to the piling next to one of the eye bolts that attaches the piling to the spring box.

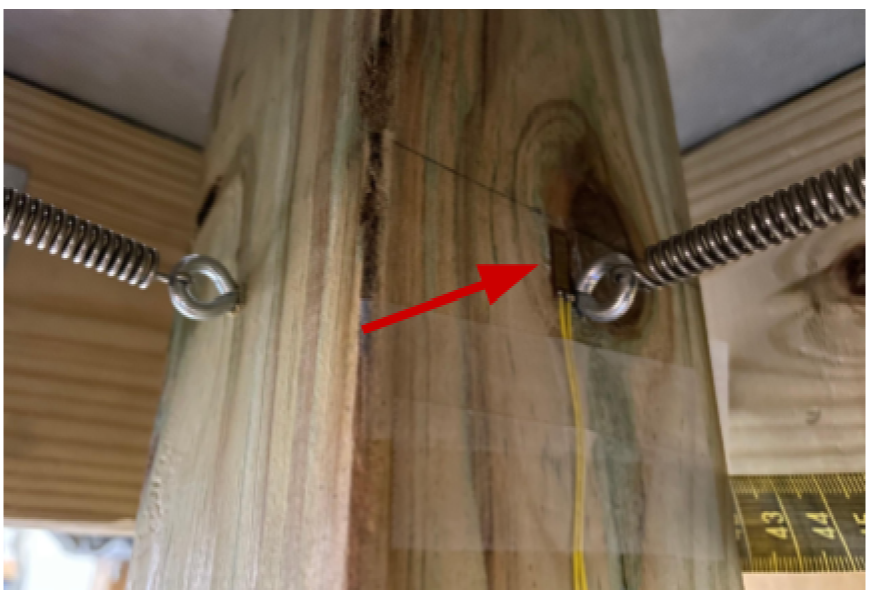


Figure 86: Modified Spring Piling Strain Gauge Location

However, due to the nature of the system and setup, an applied force at the end of the piling would not experience a substantial amount of strain for the gauge to see a change in resistance. The main component that would experience this strain is the eye bolt screw on the spring box. With this, the team decided to measure the force exerted on the eyebolt based on the stretch of the spring.

When adding a load to the piling, the spring expands a certain amount, so the team mounted a soft tape measure along the piling's direction of movement to see the displacement of the spring. With the displacement and the known spring constant of the spring, a force is calculated using Hooke's Law, $F_s = k * x$; where F_s is the force of the spring, k is the spring constant, and x is the displacement of the spring. The following figures demonstrate the system before and after an impact on the piling. This impact was created by hitting the end of the piling by a mallet.

Figure 87a (left): Spring Displacement Before Impact (33cm)

Figure 87b (right): Spring Displacement After Impact (33.4cm)

This test results in a displacement of 0.4 cm or 0.004 m. The spring constant of the extension spring we are using is 41.63 lbs/in which equates to 7290.53 N/m. Putting these values into Hooke's Law gives a force of 29.16 N or 6.6 lbs being applied to the eyebolt by the spring. Due to the spring's movement, it is observed that this force is normal to the eyebolt. This test and observation give an insight into why the modified spring version is a more optimal choice; which was originally mentioned in the Bending Analysis section of the Modified Spring Piling.

In the traditional fixed piling, a force introduced will generate a moment at the screw locations. This moment will impact the screws holding the piling with a normal force perpendicular to the screw's cross-section and a shear force occurring parallel to the screw's cross-section. Traditionally, it is the shear force that is applied onto the screws that are the leading cause for the piling to rip from the deck and deform.

However, in the spring version, a force on the piling will only exert a push or pull force onto the spring; which will result in just a normal force onto the eye bolt connection. The modified setup will not apply a shear force onto the screws/eye bolts. This system will ensure the connecting eyebolts will experience fewer forces than the traditional screws and will show more tolerance to shearing, and therefore, deformation.

6.4 Underlying Argument for Modified Spring Setup

As explored in the previous section, in the modified piling, the screws that connect the springs to the piling will not experience a shear force. These screws will theoretically only experience a normal force as a result of the piling not creating a moment at this location. Continuing, the team conducted research on axial and lateral force limits of the screws.

When a load is applied to the end of a traditional piling that resembles a cantilever beam, it will experience bending stresses that increase towards the fixed end. The load applied to the piling will create a bending moment, or rotation, around the fixed end. For the piling, the fixed end is secured by decking screws. The moment will cause the piling to experience deflection, resulting in a change in the angle of the force transferred to the screws. The magnitude of the applied load will influence the magnitude of deformation and, consequently, the pulling angle of the force on the screw. This following figure visualizes a small and large bending moment which result in a small and large pull angle, respectively.

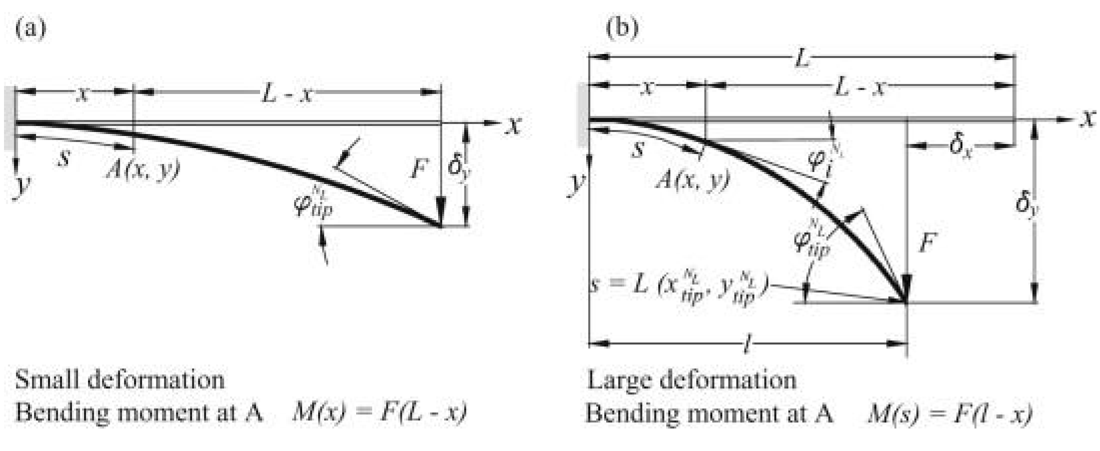


Figure 88: Comparing magnitude of bending moment and deflection angle (Saha & Ghuku, 2015)

Understanding the impact of the pulling angle on a screw's shear strength capacity is vital in our case because our cantilever beam piling undergoes constant static and dynamic loads (ice deformation, docking a boat, current). For pull angle, greater the angle, the more force is being applied to the fastener, and the closer the fastener is towards its shear strength limit; which can relate to its load capacity. Load capacity is measured by how much a fastener can support when the load is in the normal/axial direction, 0 degrees. For angles below 5 degrees, the load capacity remains unchanged. However, a pull angle of 15°, 30°, or 45° can reduce this weight capacity by 20%, 35%, and 70%, respectively (Admin, 2020). For instance, a 1/4 inch eye bolt with a straight pull capacity of 600 pounds would have a reduced capacity of 480 pounds at a 15-degree angle.

The team manufactured the traditional piling using #10 3” exterior decking screws, which members of the team can attest is common practice with their personal experience. Generally, these screws can support 75-125 lb per screw before they begin to fail due to shearing loads (Backyard Sidekick, 2022). However, with the pull angle concept in mind, this load capacity limits to 60-120 lb per screw at a pull angle of 15%.

As explored in this report, in the modified piling, there is no bending moment at the location of the springs along the piling itself. This means that there will be no deflection or resulting pill angle associated with the moment, because it theoretically does not exist. Due to this, when a load is applied to the piling, the screws will only experience a normal force and no shear force; which was confirmed in our testing experiments. Since the load applied to the screws is normal, it is being applied at a pull angle of 0 degrees. As a result, no matter the size of the applied load, there will theoretically be no decrease in the decking screws load capacity due to any unexpected load angle.

Comparing the effect on the screws with and without a shear force can be seen in the diagram below.

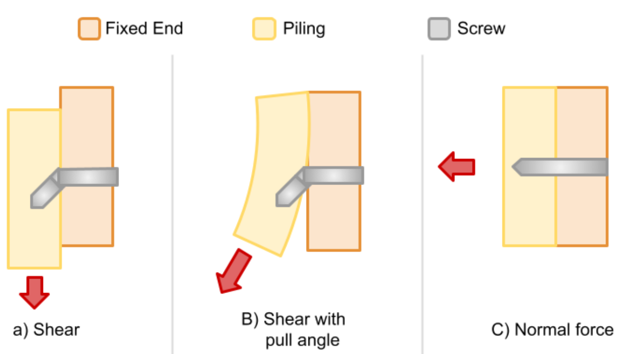


Figure 89: Comparing forces on the screws

7.0 Concluding Remarks

This project ended up being successful in achieving nearly all of the goals that were stated in the design process, and in some aspects went above what was expected in the time that was used. Furthermore, the mechanism was retrofitted onto an existing dock in the water that received use from the owners with no noticeable issues. While the period that the mechanism was tested in was not freezing conditions, the real-world test did prove that at a minimum this solution would not be worse than the current solution during the warmer months of the year (the period outside of which the mechanism was being tested for). Overall, the project followed the expected path set out in the early stages, except for a couple of small areas that were scrapped due to time and equipment constraints.

7.1 Recommendations

As a whole, our mechanism performed very well as it substantially lessened the forces subjected to a traditional piling. Even though our mechanism performed well, there are always improvements that could be implemented. There were several limiting factors in our project, including, cost, testing conditions, time, etc.

Due to cost constraints, we were unable to purchase any competing products to our mechanism such as an EZ-Dock system, Jet Dock system, or a water bubbler. While this allowed us to focus on strictly testing our mechanism, we were unable to directly compare it to competitors. The team was able to find information about the competitors by doing research but we were not able to do any testing on the competitors due to cost constraints. In the future, it would be ideal to have at least one of the competitors to our mechanism in order to do testing which would allow for a direct comparison between existing solutions and our proposed mechanism.

The testing conditions were not ideal because the lake where our initial outdoor testing was done only froze once during the project timeframe. While we were able to retrofit our prototype to the dock before the water froze and gather qualitative information, it would have been beneficial to conduct more testing in the real-world environment of the mechanism. One recommendation is to conduct more testing in an environment where the lake water will freeze and allow for qualitative and quantitative data to be gathered. The majority of testing was done indoors, but testing outdoors introduces testing factors that would be beneficial for our mechanism.

Time was a major limiting factor as one of the premises of our mechanism is that it is a long-term solution to a problem. Due to time constraints in the project timeline, we were unable to do any long-term experiments to see if any degradation occurs in the materials over time. One recommendation for this is to perform long-term testing in air, water, as well as freezing conditions on the materials chosen for the mechanism as there is potential for degradation. Long-term testing would also be beneficial to the mechanism itself because, as stated previously, the mechanism is a long-term solution to an ongoing problem.

Along with this recommendation, we would also recommend that more time is spent looking into the strength and integrity of the wood that is used after being submerged for extended periods of time. This mechanism uses pressure-treated southern yellow pine wood, which is somewhat common when building fixed docks. Looking at alternative materials to this wood to compare its strength over time could increase the longevity and performance of the mechanism.

Lastly, we recommend looking into implementing an enclosure to the spring encasement as it would allow for protection from the outside environment. While leaving the springs open provides ease of access to the mechanism in the case where any adjustments need to be made, it could be beneficial if the mechanism was protected from the outside environment. In the case where the mechanism were to have a full enclosure, the enclosure should act as a door or be easily removed so that it still allows for ease of access as it is important to be able to view the inside of the mechanism for a variety of reasons.

7.2 Conclusion

Throughout this project, the entire design process was implemented. We found an existing problem, brainstormed solutions, designed a mechanism, and then tested the mechanism. When designing the mechanism, we modeled a prototype in CREO, allowing for simulations to be performed on the modeled prototype. We performed hand calculations while doing these simulations to confirm the validity of the simulations as well. As simulations were done a 1:1 prototype was constructed of the mechanism, and a 1:1 model of a traditional piling was also constructed so that testing could be performed on both models for a direct comparison. At the conclusion of the testing, modifications were implemented and recommendations were made.

The final mechanism prototype was a success in that it substantially reduced the forces and moments that a traditional piling was subjected to. Due to constraints, long-term testing was unable to be performed but through testing, the mechanism performed very well. The final prototype mechanism was a success because no corners were cut in the design and testing of our mechanism.

This project acted as our final senior project and major qualifying project and we used what we learned as students at WPI to succeed. We used many different resources WPI offered and were able to learn more about the engineering design process.

7.3 Economic Factors

Our product is a beneficial financial investment as it increases the lifespan of modern fixed docks. Traditional fixed docks have a tendency to gradually suffer deformation over time due to environmental tendencies whether that be ice freeze, turbulent water, or human usage. With the addition of our product fixed docks will have an increased lifespan and lessen the burden on the homeowner when it comes to costly repairs year after year. Our mechanism also allows fixed docks to remain in the water year round suffering substantially less deformation. This means the user will not need to remove the dock at any point, which can be a costly endeavor.

7.4 Patent

The testing and preliminary implementation of this mechanism was noticed by Worcester Polytechnic Institute as a potential solution towards ice deformation in structures and recognized the potential for patenting this mechanism. WPI has helped our team in the process of acquiring a provisional patent, 63/460,831 - Water Dock Ice Tolerance, for which they will also help find a market our work can be applied to. The cost-effective nature of our mechanism makes it an attractive proposition to many different markets, including the consumers that own fixed docks and are unable to remove them each year. Through our diligent utilization of the resources provided by WPI, as well as our comprehensive understanding of the engineering design process, we have developed a solution that performs well against the current market. Our mechanism has the potential to be developed further and could see a utility patent in the near future.

7.5 Engineering Ethics

Throughout the design of this mechanism the Mechanical Engineering Code of Ethics was followed to ensure the mechanism was designed as effectively as possible. Our team has been honest and impartial in the design process to allow for an unbiased design and to allow a clear vision of any potential pitfalls with the design. As a team, we also strived to increase the competence and prestige of the engineering profession by finalizing a complete and effective design.

7.6 Codes and Standards

In the development of the mechanism, the team recognizes the significance of adhering to the Code of Ethics of Engineers as outlined by ASME. Throughout the design and testing processes, the team's focus was on enhancing the welfare of other humans. While this mechanism is not without flaws, the work that was completed with this mechanism used the combined knowledge of WPI students and faculty to test the effectiveness of the modified piling against the traditional method of attaching a piling to a dock. This report is a reflection of the work that has been completed over the span of three terms and includes both the success and failures of the engineering design process of developing a mechanism that can reduce the deformation caused by ice freezing in the winter.

7.7 Societal and Global Impact

The goal of this project did not aim to impact groups in the areas of health, safety, or culture but instead try to better the wellbeing of individuals who would otherwise have to resort to sometimes expensive processes companies provide for removing a dock in the winter, remove the dock themselves, or just leave the dock to become damaged. This project does pose both intended and unintended consequences, mainly involving the mechanism once it has been applied onto a dock.

For intended consequences, the modified mechanism provides enhanced stability and durability, absorption of shock and vibrations, and improved safety. In terms of stability and durability, the springs in the mechanism provide flexibility and allow the dock to better adapt to the changing water conditions. This idea can be further iterated on when talking about durability, where the freedom allowed by the springs helps distribute the dynamic loads that are applied by waves, boats, and other watercrafts. Not only does the mechanism improve stability and durability, but it also allows for better absorption of shock and vibrations. Again, as the springs allow for some movement in the dock, the springs can act as shock absorbers, reducing the dynamic loads that are applied to the dock and minimizing the potential damage to the dock and anything that is attached to it. All of these consequences help improve the safety of the dock for both the dock as well as the person on the dock.

As with almost all products, with intended consequences comes unintended consequences. As the pilings are connected to the dock with springs, there could be a decrease in the structural rigidity of the overall dock, which may lead to excessive movement during less than ideal weather conditions and potentially impact the usability and safety of the dock. Furthermore, while the components for the mechanism were chosen to resist corrosion, if the components are not checked every so often, there is a potential that the metal components can rust and fail. These failures can result in a dock that is not structurally sound, and if it is unknown to the user that the part did in fact fail, there could be potential injury for the user.

7.8 Environmental Impact

The designed mechanism increases sustainability when it pertains to the environment and sustaining the fixed docks' lifecycle. A direct competitor to our design is that of metal fixed docks, metal, as a material is not as sustainable for the environment as wood, a natural material is. It is ideal to put natural materials, such as wood, into environments such as a lake as it is more beneficial to wildlife as well. While the mechanism does utilize certain metal components such as the screws, brackets, and springs, it does not compare to an entire dock created out of metal and/or plastic.

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