Exploration Station KIDShake Table Design Report

Team Shake ‘n Break

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Thank you to everyone at the Exploration Station for giving us the chance to design and build the KIDShake Table Exhibit.
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Chapter 1: Introduction

Sponsor Background and Needs

The Exploration Station, located in Grover Beach, CA, is a non-profit children’s museum that educates young children of the Central Coast through science and technology. It hosts various science exhibits, interactive displays, and weekly activities in its main showroom. The showroom currently holds many exhibits where children can learn science and physical concepts through small interactive stations.

To contribute to their collection, the Exploration Station greatly desires a shake table exhibit that teaches children about earthquakes and their effects on the construction and destruction buildings. The exhibit consists of children building a structure out of building blocks and proceeding to test a structure they created by shaking the table at various speeds. They would like a hand-powered table that would be suitable to all children and adults but be designed for a target age of 10 years old. This table must safe for any user and be durable to withstand many years of use.

 Formal Problem Definition

The Exploration Station of Grover Beach, CA has requested that we completely design and build a mechanical shake table exhibit to put in their children’s museum. This shake table must be completely mechanical and the user must input the desired motion of the shake plate. The target age for this exhibit is 10 years old, although it should be simple enough to be used by younger children and entertaining enough to lure in older learners. The team is not only fully responsible for the design of the table but also the building blocks the user decides to knock down. The exhibit should display educational content and teach anyone using it about earthquakes and building structures. Specifically the table must demonstrate how differing building materials and building practices affect a structures ability to withstand an earthquake. Our team should concentrate our focus on safety, functionality, reliability, and durability. The table should be designed to last multiple years and withstand the abuse of young children and especially adults. The overall goal of this project is to have a fully functional exhibit by the end of May 2013 and deliver the table to the Exploration Station in June 2013.
Objective/Specification Development

1. Table should not cause harm to the user, possess no pinch points, exposed mechanisms, sharp edges, etc.
2. Table shall simulate real earthquake characteristics and kids should learn something about earthquakes from this exhibit.
3. Entire cost of table shall be under $3000.
4. Max table footprint is 4 ft. x 4 ft., max shake plate size is 3 ft. x 3 ft.
5. Max table height shall be 32 inches, focus on ergonomics for 10 year old age group but table must be usable for older age groups as well.
6. Limit weight so that the table can be moved by two men and a furniture dolly.
7. Plate motion shall consist of two axes of motion activated by two different hand controlled mechanisms.
8. Table shall require minimal maintenance and should last 10 years.
9. Appearance must be visually attractive, use of colorful tones and construction theme is recommended.
10. Must design the table with as many commercially available parts as possible.
11. Building blocks should cater to various age groups.
12. Mechanical components shall be visible to the user.
13. Include a storage area within the table design.

Table 1. KIDShake Project Table Formal Engineering Requirements

<table>
<thead>
<tr>
<th>Spec #</th>
<th>Parameter Description</th>
<th>Requirement or Target</th>
<th>Tolerance</th>
<th>Risk</th>
<th>Compliance</th>
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</thead>
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<tr>
<td>1</td>
<td>Table Size</td>
<td>3’ x 3’</td>
<td>Max.</td>
<td>H</td>
<td>I, A, S</td>
</tr>
<tr>
<td>2</td>
<td>Exhibit Size</td>
<td>4’ x 4’</td>
<td>Max</td>
<td>H</td>
<td>I</td>
</tr>
<tr>
<td>3</td>
<td>Power</td>
<td>“Kid” Power</td>
<td>1 child per axis</td>
<td>H</td>
<td>A, S, T</td>
</tr>
<tr>
<td>4</td>
<td>Height</td>
<td>30”</td>
<td>Max</td>
<td>H</td>
<td>I</td>
</tr>
<tr>
<td>5</td>
<td>Weight</td>
<td>100 lbs.</td>
<td>Max</td>
<td>M</td>
<td>T, A</td>
</tr>
<tr>
<td>6</td>
<td>Production Cost</td>
<td>$3000 ± $1000</td>
<td>L</td>
<td>A, S</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>User</td>
<td>10 yr olds</td>
<td>± 4 yrs</td>
<td>M</td>
<td>I</td>
</tr>
<tr>
<td>8</td>
<td>Noise</td>
<td>70 db</td>
<td>±10 db</td>
<td>L</td>
<td>I, T, A, S</td>
</tr>
<tr>
<td>9</td>
<td>Movability</td>
<td>2 People</td>
<td>± 1 Person</td>
<td>M</td>
<td>I, T</td>
</tr>
</tbody>
</table>

*H=high, M=medium, L=low
*A=Analysis, I=Inspection, S=Similarity to Existing Designs, T=Testing
Chapter 2: Background

Similar Existing Systems

We performed much background research on existing educational shake tables used in science museums and classrooms across the country. In each demonstration, children are instructed to build a structure out of items such as Legos, building blocks, and Lincoln Logs and then attempt to break the structure with a back and forth motion. Many different designs are utilized to obtain the motion needed to simulate an earthquake. Some designs involve electric motors while others use simple springs and linkages. Most systems we found were only capable of one direction of motion.

The San Luis Obispo Children’s Museum

The San Luis Obispo Children’s Museum houses a hand powered wooden shake table. In this exhibit, children build a structure out of plastic pieces and PVC piping and place it on the top plate of the shake table. The children are then instructed to turn a single hand crank, which moves the plate back and forth and causes the structure to fall. We were not able to see the mechanism used to obtain this motion, but assume it was some sort of simple linkage attached to the crank.

We made several observations about the exhibit, including things we would like to incorporate and things we would like to improve. An overall layout of the station can be seen in Figure 1 below. The first thing to note is the station took up a lot of space in the museum. The work table was very large and we would like to utilize a smaller size. We also thought the partition was unnecessary and actually inhibits children from being able to fully see the effects of the structure under the back and forth motion.

Figure 1. “Shake it Up” exhibit at the San Luis Obispo Children’s Museum
The building pieces consisted of plastic plates, plastic cross braces, and PVC piping. These pieces are shown in Figure 2 below. We liked the idea of the cross braces and how they add an element of structural support. We would like to incorporate some sort of magnet or connector to achieve similar support which enables the kids to learn more about structures than just simply piling blocks. However, we did find that the kids had trouble knocking down their structures because they were too structurally sound. Therefore, we would like to maintain a balance between the two extremes.

Figure 2. “Shake it Up” building structure materials

The table top of the shake table had many different features that we would like to consider incorporating into our design. The top plate is surrounded by space on all sides so it has ample space to move without pinching children’s fingers. Safety is a very big concern of ours and a “moat” design is a very good way of ensuring this. The plate also uses a rubber material that is used on playgrounds. We liked the idea of using such a material because it would provide a rougher surface for the building materials to rest on and is less noisy when pieces fall onto it. An overall view of the table top can be seen in Figure 3 below.

Figure 3. “Shake it Up” exhibit table top
OMSI

The Oregon Museum of Science and Industry, OMSI, is a science museum in Portland, Oregon and creates and produces many exhibits for other organizations across the country. They currently have an electric shake table exhibit where kids can build structures out of wooden logs or building blocks with and without cross bracing and then test them. The table is actuated with a simple button that causes a motor to power the back and forth motion. We believe this shake table also is only capable of one direction of motion. A picture of the exhibit is shown below in Figure 4.

![Figure 4. OMSI shake table exhibit](image)

Perot Museum of Nature and Science

The Perot Museum of Nature and Science in Dallas, Texas hosts many informational displays and interactive activities including a shake table exhibit. The exhibit consists of two electric shake tables that are controlled by a touch screen computer. Children build structures out of plastic rods and connectors and test them on the moving platform. While the structures sit on the platform, the children control the amplitude and frequency that it shakes. One of the exhibits aims is to show children how smaller and larger buildings respond based on their natural frequencies. The computer also had options for the children to choose real past earthquake waveforms. This added to the appeal of the exhibit from children and adults.

![Figure 5. Shake table exhibit at Perot](image)
The Randall Museum

The Randall Museum in San Francisco hosts an entire exhibit dedicated to earthquakes named “Living with a Restless Earth”. In one area kids can make their own earthquake by jumping on the floor which is connected to a seismometer that displays the intensity. In the basement is a second seismometer which registers real earthquakes for guests to view. The museum also has three shake tables where children can build structures out of Legos and test their ability to withstand different strength earthquakes. We could not obtain pictures or information regarding the specific designs of the shake table stations. An overall layout of the whole exhibit can be seen below in Figure 7. Further research is being conducted on the “Living with a Restless Earth” exhibit.
**Classroom Demonstrations**

Another part of our background research consisted of looking at classroom shake table demonstrations. These demonstrations tend to use very simple designs to acquire the desired back and forth motion. One simple design utilizes a wooden plate held in place by rubber bands attached to a wooden frame. This particular shake table allows motion in two directions; however, the user has little control over which way it moves. An example of this design is shown in Figure 8 below.

![Figure 8. Rubber band shake table](image)

Many classrooms perform these shake table demonstrations with designs that use hand drills to power the back and forth motion. The drill drives a rotating disk that is attached to a linkage. This linkage is also attached to the plate, which causes the plate to move. Some of the setups utilize tracks for the plate to translate on and some use springs to keep the plate in place. An example of a drill powered shake table can be seen below in **Figure 9**.

![Figure 9. Drill powered classroom shake table demonstration](image)
Chapter 3: Design Development

The design development that was implemented to tackle this project has followed the generic “design process.” We defined the problem, completed our initial ideation, and decided on concept ideas. Because of the scope of this project, the initial ideation was done for lower level systems rather than the full system design. The subsystems consist of movement mechanisms, plate suspension, exterior structure, and block design. Each of these subsystems were tackled individually, and subjected to its own design process. We mentally evaluated and set aside many solutions for each of the subsystems, then subjected the top ideas to decision matrices in order to select the final concept options.

Initial Ideation/Brainstorming

The initial ideation and brainstorming was broken down into five different categories. These categories included overall appearance, block design, actuation mechanisms, activation mechanisms, and plate material. A separate brainstorming session on a whiteboard was conducted for each of these categories and every idea that could possibly be thought of was written down without question. Once everyone on the team went through each category a couple of times, we went back and we reviewed all of our ideas. To document the ideas we had, photographs of the whiteboard were taken at various stages. Figure 10 is provided as an example but all photos can be found in Appendix A. The ideas that were highly impractical, dangerous, or unfeasible were eliminated first. After this first round of elimination more ideas than necessary were still present. In order to reduce the number of ideas a second round of elimination occurred. During this elimination session, thorough discussion among the team was done in order to make sure there was enough reason for eliminating certain ideas and for retaining others. Figure 11 shows the ideas that remained after the brainstorming and elimination session was concluded.
In order to further finalize our design concept, decision matrices were implored. A decision matrix was created for actuation mechanisms, activation mechanism, types of building blocks, and plate material. With the matrix, various important aspects were considered and a point system determined which options would be best for our needs. All decision matrices can be found in Appendix A.

The activation mechanism is the user interface with the earthquake plate movement. The top three options per our decision matrix were the pull and release rope, hand crank, and pull and release lever. Upon further discussion however, it was decided by the Shake n’ Break team that the pull and release lever would not be utilized and it would be replaced with an alternative. The pull and release lever is very similar to the pull and release rope and having a much different activation mechanism would be beneficial to keeping the children’s interest. The up and down movement was then considered to be either a jumping mechanism (Figure 14) or a hand pump mechanism (Figure 15). The hand pump idea was thought of after the decision matrix hence why it is not included.

**Concept Designs**
The hand crank is a simple activation mechanism that will allow the shake table to move in the axial direction. The hand crank is very easy to use and will pose no safety concerns for the user. The frequency of the plate in the axial direction will depend upon how fast the hand crank is spun by the user. The faster the crank is spun, the higher the frequency of the earthquake.

![Figure 13. Pull and release rope mechanism concept](image)

The pull and release rope mechanism will move the plate in the transverse direction. The spring will be located inside the housing of the shake table and the rope will be located on the outside for the user to pull. The user will pull this rope as hard and fast as they can in order to move the plate in an attempt to destroy the structure they have built. Once the rope is pulled, the spring will be compressed and want to return the rope to its original position. Differing strength pulls and how often the rope is pulled will cause the transverse direction of motion to occur at many different frequencies. This mechanism also does not pose a great safety risk.

![Figure 14. Jumping mechanism concept](image)
The jumping mechanism was decided upon as a concept idea because it would generate a lot of interest for the child user. The child would jump on the box mechanism shown in Figure 14 and this would in turn generate an up/down motion. Because this mechanism could pose a safety risk for the child, a bar would be attached to the outside of the table for the child to hold onto while jumping. The mechanism behind this up/down motion could pose some difficulty designing so it may not be the preferred method but a great concept idea nonetheless.

![Figure 15. Hand pump mechanism concept](image)

An alternative to the jumping mechanism for up/down motion is the hand pump mechanism. With the hand pump mechanism the user will push and pull on an accessible lever arm. This lever will be attached to another link which has a ramped cam on one end. As this cam link moves in and out, it will cause the table top to move up and down, providing the vertical motion desired. Constraining collars and shafts are not shown in Figure 15 but will be necessary for the mechanism to function properly. Note that all the activation mechanisms just presented, are concept ideas and not the final design.

The building blocks being made in conjunction with mechanical side of the shake table are just as important as the table itself. The motion of the table and the frequency at which it moves is strongly dependent upon how the blocks are designed to fall. All of the possible ideas for the blocks were discussed during brainstorming and the best options were put in a decision matrix. Upon reviewing the decision matrix, it was decided that the shake table would benefit from having different blocks available instead of having just one. Our concept allows for the user to choose from three different blocks in order to build their structure. The three types include blocks with pegs and magnets, blocks with magnets only, and plain blocks. The nominal size of each block is 3/4" x 6" x 3/4".

![Figure 16. Block with pegs and magnets](image)
The blocks with the pegs and magnets will resemble a building foundation. The pegs shown in Figure 16 will fit into the 1/4” peg board plate that is present on the actual shake table. When the earthquake motion begins, and the plate moves, the foundation blocks will stay in place and not slide around. In addition to the pegs on the bottom of the block, there will be small 1/4” diameter by 1/16” thick neodymium magnets on the top. These magnets will resemble strong building structure and will work in conjunction with the blocks that have only have magnets. A block with only magnets can be placed on top of the foundation blocks and the magnetic force between the two blocks will create a much stronger hold than if the magnets were not present. The last block choice is the plain blocks and this will resemble a weak building structure. The plain blocks can simply only be stacked upon one another and besides friction between blocks there will be nothing holding them together. The ultimate goal of having these varying blocks is to teach children the difference between having a weak or strong building structure and how an earthquake will affect it. Obviously will design the table so that the building that utilizes the foundation blocks and the blocks with the magnets; will not fall apart as easily as the other options. Any combination of blocks can be used to build a structure so it will be up to the user to choose how strong of a building is wanted.
In the above figure, our first overall shake table concept is presented. The only thing missing from this concept is the actual mechanisms within the table that cause motion in the plate. These mechanisms are still being designed and need to be integrated with our activation mechanisms. Changes decided upon but not yet corrected in our 3-D concept model are, the size of the polycarbonate sides and our third actuation mechanism. The polycarbonate sides are much larger than we will use in actuality. We plan to only have enough polycarbonate for the users to view the mechanical mechanisms inside the table and the rest of table side will be another material. We decided upon this change because large polycarbonate sheets are very expensive. The up/down actuation mechanism is the jumping actuation design presented in Figure 14. As explained earlier, this idea could cause possible safety hazards and would be difficult to design so we are shifting our focus to the hand pump mechanism as our up/down motion.
The second overall concept model fulfills many of our design specifications. The table has earthquake realism by having 3-axis of motion and each axis has its actuation mechanism. The mechanical mechanisms of the table will be visible with the use of some type of polycarbonate siding. The concept model fits the overall size criterion and the current dimensions are 4’ x 4’ and 30 inches high. Our buildings blocks will cater to various age groups and display the learning objective of strong building structure. Having three types of blocks allows any user, young or old, to have to think about how strong of a structure they wish to build. The concept has a specifically designed storage area on the bottom right hand side of the table that holds four storage bins. These bins are 14.5” x 10.5” x 6.25” and provide enough storage for all the building blocks. A backboard is also included in our shake table concept design. This backboard will allow for an exhibit description and we hope to fulfill some of the learning objectives with this space. So far we have researched as many commercially available parts as possible and the only decided upon part that is custom part are the building blocks themselves. Once we start to create final designs of the actuation and activation mechanism s research will have to be done to see if our ideas will have sufficient availability commercially. This could pose to be a difficult task later on but we will always ensure to try and make as many parts as possible commercially available. The one specification that we are finding difficult to maintain is the overall table weight. When analyzing weight versus durability, we have to side with durability as the most important factor. We plan on having the weight as low as possible but at this point it is unclear what the final weight will be. Currently our rough estimation is about one hundred twenty pounds but in the detailed design we will make every attempt to cut down on the weight.
Visual Concept

Overall Table Visual

Figure 20. Visual concept designs for overall table appearance and backboard logo
A proposed theme is to have the KIDShake table represent a construction site. This concept theme was chosen because our table emphasizes building construction practices and the effects of earthquakes. Also the construction color theme can be very appealing to children because of the bright colors and unique combination of colors. There are many possible ideas for this portion of the project but Figure 20 just emphasizes a few possible ideas that could be explored more. Ultimately the desire of the sponsor will have the most influence on the final look of the exhibit.

**Considerations for Outdoor Use**

Our sponsors initially had told us that the Shake Table was going to be used and stored outside most of the time. This gave us quite a challenge and a few solutions were found to partially solve the problem but not completely fix it. This prompted us to convince the sponsors to move the table inside. We had two major concerns, first, being in the sun will make the table top very hot and probably burn skin, two, Ultraviolet rays decimate almost any anti-corrosion coating we could possibly use. Ultraviolet damage reduced our material choice considerably since a plastic table top would warp and crack quickly, a wood top requires high surface finish maintenance, and composites would not endure it much better. This problem we thought could be solved fairly well just by covering the Shake Table exhibit with something opaque when not in use. The other option we thought of was buying a portable shelter (EZ-UP) or building a simple roof.

The first issue, solar heating, was an easily foreseen problem because metal was the only viable material, which gets rather hot in the sun. In order to confirm this and run parametric studies of our options, we created a simple heat transfer model in Microsoft Excel using transient lumped capacitance with solar radiation as the heat in and natural convection out. Since the table would heat up much faster than the air we used the hot plate facing up correlation (eqn 9.31) from Incropera &Dewitt *Introduction to Heat Transfer* (6th, 2011). We input data for dull and shiny (polished) 302 stainless steel, white reflective coating over 302 stainless-steel, and both dull and shiny (anodized) 2024 Aluminum. We tested several parameters including plate thickness (1/8" to ¼"), daily temperature high (70 to 110 0F), radiation absorptivity (.05 to .5), and the allowable table temperature. According to some quick research, skin burns fairly quickly at 140 0F and 120 0F is borderline safe for children. We found that no matter what we did the table either reached or went well beyond the safe temperature of 120 0F. In the worst case scenario, dull 302 Stainless Steel 1/8” thick, the table top could boil water. The white reflective coating was our best result but it barely did the job and the children would have needed something on the order of a shade 5 or better welding shield to even look at the table. This outcome left two options: either provide shade for the table or have it inside the building.
Chapter 4: Description of Final Design

Overall Description/Layout

Our final table design allows a child user to move the shake plate in two different coordinate axes while attempting to knock down their structure. One axis shall be controlled by a hand crank wheel and linkage system which will allow the user to control the frequency of the shake plate by how fast they can crank the hand wheel. The second axis shall be operated by a free oscillation mechanism using two springs and a pull rope. The user will pull the rope to deflect the plate (and springs) from equilibrium and once the rope is released the plate and springs will oscillate in a decaying under-damped 2nd order response. The plate is suspended on linear bearing guide rails which allow the two mechanisms to operate simultaneously or on an individual basis. The space where the mechanisms are housed shall be surrounded by transparent acrylic siding so anyone can see the inner-workings of the table. There are three different types of building blocks available to build with and each block has a unique design to help simulate different building practices. The table has built in storage underneath the main workings and locking cabinet doors for excess building blocks and spare parts. A backboard is attached to the table which will provide some general information on earthquakes and the capabilities of the shake table, along with building challenges.

Since the concept stage of design a few major changes have been made. The largest change is the removal of one axis of motion. Our original design had the ability to move in three directions. Due to its complexity and questionable reliability of the designs, the vertical motion was eliminated. Our team and our sponsors believed this decision would allow us to focus on the reliability and durability of the remaining axes to withstand the constant use of young children. In addition to this, the overall table dimensions were also decided. The table footprint will be 40” x 40”, the moat height will be 32”, and the plate height will be 30”. Other less critical decisions included adding a base plate at the bottom of the table and locking cabinet doors for storage. Also, the overall color scheme will follow a construction theme, have red colored sides, and the backboard visual will allow even non-reading children to understand how to use the table.

Detailed Design

Table Frame

For the frame we chose to fabricate an angle iron weldment. This was decided because we could have relatively high precision, reduced bulk, and higher strength compared to a wood frame. It also makes the table much safer: better earthquake resistance, stronger base to mount the exterior to, and perfectly safe to climb on. It is largely composed of 1” x 1” x 1/8” angle iron, which gave the best compromise between strength, weight, machinability, and cost. There is much less load on the horizontal members along the bottom edge so ½” x ½” x 1/8” angle iron is used to further reduce total weight. The frame will be done using MIG welding and finished by grinding flat. The horizontal squares shall be done first then add in the columns. The corner columns are two pieces so that the siding and windows have a flush surface to rest on to help prevent impact fracture. Also we chose to use the MIG welding process in order to greatly reduce the practice needed and cleaning up mistakes that TIG welding would inevitably incur. In order to mount all the parts to the frame there are some sixty holes.
all with weld-nuts on the opposing side since the frame thickness, 1/8” inch, is too thin to thread. For table leveling, a 5/16” stem adjustable rubber feet will be attached at the bottom. These soled table feet will reduce noise, wobbling, and strain on the frame.

![Figure 21. Render of table frame](image)

![Figure 22. Leveling feet from McMaster-Carr; A=2”, B=1.25”, C=3”](image)

**Motion Plate Mechanism (Rail and Pillowblock)**

The plate motion of the shake table had the most possibility for good solutions but also a large amount of impractical ideas. Right from initial ideation it seemed that using some sort of linear slider system was one of the better ideas. This is because a linear slider system has reliability, weight bearing
capabilities, and smoothness of operation. During the design stage, we evaluated pre-made linear sliders versus a shaft and linear bearing system that we would purchase and modify to our needs. Ultimately the shaft and linear bearing system was chosen for several reasons. These reasons included the motion in the two horizontal axes would be attained simply, the plate motion would be purely mechanical, the system could be modified to our needs easily, and it was one of the cheaper systems. The premade linear sliders were not chosen because too much modification was required and almost all the premade sliders are built with or require DC servomotors for operation and our table is to be hand powered. By using our own shaft and bearing design we avoided all of the negatives of the premade system and the mechanism looks better overall. Our thought was to purchase the shafts, linear bearings, compression coil springs, and clamping shaft mounts while fabricating our own special two bearing, two axis pillow blocks out of aluminum (Figure 22). These components would be assembled into a two axis motion system with the coil springs resting on the shafts where indicated. Our estimate of total possible motion was about two inches before it ran into a hard stop (maximum spring deflection) while our motion goal was about one inch of deflection based on rudimentary testing.

During our concept design presentation our sponsors suggested using rail-mounted shafts instead of end clamped shafts. We had initially disregarded this option since such rails are usually prohibitively expensive but we reconsidered them and through some research came across the VXB bearings, a relatively cheap online supplier. We decided this change was simple enough to make and benefitted the plate motion system. Modifications to the VXB rails and pillow blocks would be minimal as it only required us to drill a few extra holes versus making our own shafts and pillow blocks. One sacrifice to this system however is using metric size rails and bearings because the price was much lower compared to American Standard sized rails. Because of this we are using both metric and standard fasteners on our product but the metric bolts will likely never need to be replaced.
The two axes of motion are provided by mounting the second set of rails directly to the pillow blocks of the first set. The pillow blocks are prevented from running off the end of the rails by mounting pancake washers, rubber then steel, as soft stops. Also, the lower set of rails will be mounted to the plywood shelf beneath it to partially reduce the transmitted vibrations to the rest of the table. This way vibration will not greatly affect the table as a whole and only the motion plate will see any sort of shaking.
Direct Crank

The hand crank mechanism implemented in our design is most likely what comes to mind when one thinks of a hand-powered shake table. Since the beginning of the project, the hand crank had been in our design because of its simplicity, reliability and effectiveness to move the plate time and time again. This mechanism is the most intuitive way to let users provide variable speed motion input on the block buildings they wish to knock over. The crux of this design was finding pre-made, full-disk, hand-wheels that were both strong enough for the abuse and cheap enough to be considered. After much searching we found a polymer and metal hybrid hand-crank that we could modify slightly to rotate a shaft. Based upon this crank, we specified the remainder of linkage.

Figure 26. Assembly of pillow blocks, guide rails, and soft stops

Figure 27. Reid Supply 5.91 inch Diameter Dished Solid Hand Wheel with Revolving Handle
The hand-wheel is constructed of tough, reinforced plastic and its solid construction prevents injuries due to the hand getting caught in spokes. The overall diameter of the hand wheel is 5.91 inches and the handle height is 2.56 inches. Based on its build, this hand wheel can accommodate the hand size of many users. The shaft of the hand wheel attaches to a solid half inch steel shaft by a #10 machine screw through to the other side in addition to a #10 set screw to take up any play. This shaft rests on a SAE 841 Oilite flanged bronze sleeve bearing that provides alignment and resists the unwanted moments on the shaft. On the end of this shaft is a 1.5 inch steel crank arm with a 5/16 bolt in it as the crank journal. The bolt connects the crank to a 5/16” heim joint and an all-thread rod. The opposite side of the all thread rod has a clevis pinned end and it is it attached to a custom-made bar which in turn attaches to the slider mechanism assembly. This bar is made of ¼” steel flat bar which has endurance strength nearly an order of magnitude larger than the greatest anticipated stress. This should ensure that it will never suffer fatigue failure.

Rope and Spring Mechanism

The rope and spring mechanism has gone through several design iterations leading to our final design. We initially presented the idea of a mechanism consisting of a single compression spring with one end attached to the moving plate and the other end mounted at a fixed location. The rope would also be attached to the moving plate. The user would pull the rope and the plate would slide towards the user and compress the spring. This would provide the potential energy needed to allow the plate to freely oscillate once the user released the rope. We had some concerns about this design since the plate experiences a hard stop when the spring reached maximum compression. For this reason, we explored other design options that would eliminate such a collision.
To eliminate a hard stop of the table, we looked into a crank design incorporating a spring. This design consisted of two springs on either side of the plate and a cable that attached to both the moving plate and a hand crank. The cable would initially be slack and then be pulled in tension with the turn of the crank. This tension would displace one of the springs and upon release would push the plate back, displacing the other spring. This would result in cyclic back and forth motion and the table would oscillate freely until the plate came to rest due to frictional losses. Although this design eliminated the hard stops we were concerned about, there were some major drawbacks that we could not overlook. The intention of the mechanism is for the user to pull once and release to see the effects of free vibration; however, a hand crank implies continuous rotation. Continuous rotation would not cause any damage, but it would defeat the purpose of the mechanism. We want to provide two different types of responses and a continuous rotation would essentially be the same as our crank linkage mechanism. This resulted in a rethinking of the purpose of the spring mechanism and we decided to revisit our initial design.

We really wanted to incorporate the freely oscillating spring mechanism into our shake table design but our original concern of the hard stops still loomed over the design. After reconsidering this problem, we reasoned that the mechanism would only experience one hard stop during the initial pull. Since the system loses energy due to friction, the table will not collide with the end of the rails after the first pull. We justify this single hard stop by utilizing bumpers at the end of the rails that can withstand such a force.

After finalizing on the spring actuation, the next step was to decide what type of springs to use. We initially decided on the use of two compression springs that would be attached to the table. The table would be pulled and the springs would compress and upon release would allow the table to freely oscillate. We found that these compression springs would necessitate special mounting including cable clamps and brackets. As a result, we looked into extension springs since they come with loops at the ends which would simply allow the use of a bolt to fix the ends. In this design, two extension springs are mounted on opposite sides of one of the guide rails and secured to the plywood base beneath. When the user pulls the rope, the opposite spring will be placed in tension and upon release will return, while the other spring is pulled in tension. This will provide the desired free oscillation of the plate. In order to avoid spring buckling, the equilibrium position of the springs will be mounted partially stretched out so to give a preload. Spring clash, and also the hard stop, is avoided by placing a cable clamp on the rope, string this rope through an eye bolt in the base, and have thick rubber damper on the rope between these two. This design is presented in Figure 28 below.
For the actual rope we specified a lawn mower crank pull cord for three reasons: cheap to buy or replace, easy to find, and it is a thin rope designed for hard pulls. To guide the rope through the viewing window and inside the table we used a plastic nylon fairlead as seen on ships (Figure 30). The rope is then threaded through an eye-bolt mounted to the base shelf and is attached to the guide rail by a figure eight stopper knot.
Motion Plate and Building Blocks

The actual moving portion of the table is called the “plate” During our brainstorming phase we decided on a composite of sheet metal backed with wood and this eventually led to the final design of a 21.5” x 21.5” square steel pegboard backed with 3/4 inch plywood. The pegboard was chosen so that we could easily show how the foundation of a building is placed into the ground. The pegboard plate works in conjunction with the pegged building blocks. Having blocks with pegs built into them allows the child user to fix certain blocks into the plate and this is how the foundation is simulated. We decided on making the pegboard an earthy brown color so it ties in with our construction oriented theme and foundation simulation idea.

To go with the pegboard we designed several types of blocks: plain, magnetic, and pegged with magnets. The blocks are all made of maple and cut to ¾” x ¾” x 6” nominal size then planed down a bit for aesthetic purposes and smoothness. The plain blocks were left their original wood color to indicate that these were buildings made with wooden frames. As these block structures are only held together by friction, they represent the weak structure. The magnetic blocks were made by drilling two sets of opposing holes 3/16” deep into the blocks 1” away from each end. In each hole a 1/8” x 1/4” disk-shaped neodymium magnet was epoxied at the bottom. The foundation blocks have two pegs four inches apart on one side to tie the structure to the ground and magnets on the other side to tie to the magnetic building blocks. These three styles of blocks will allow the children to understand the effect of building materials, construction, and use of a foundation on a building’s ability to withstand an earthquake.
Storage Moat

One of the sponsor’s desires was to have the shake table mechanics be visible by the user. To this end the sides of the shake table have clear windows so the user or other children can see the moving parts in action. A problem that arose with this however is that because the windows were small in terms of height due to the linear mechanism assembly being short, not much light would be transmitted into the space below the plate. Without much light, the mechanism would hardly be seen and the sponsor’s goal would not be met. In order to remedy this problem a translucent material could be used for the moat. This would allow light to pass through the top of the table making the mechanism much more visible. The translucent plate will be constructed from acrylic but will not be completely clear. Instead the acrylic will be frosted for multiple reasons including: regular acrylic will scratch and wear over time and eventually become frosted anyway, abrasion resistant clear acrylic is prohibitively expensive, similar translucent materials such as glass are also extremely expensive) and would have to outsourced for fabrication.

We chose ½ inch thick acrylic because it allowed for a child to stand on it with relatively little deflection and a failure safety factor greater than two. We will have to machine this sheet of acrylic to
size and shape with the center cutout and edge slots. It is sized a nominal 1/16” smaller than the inside of the frame which will provide a close fit that can easily be sanded down as needed. The moat bed will be secured at the edges by flat head machine screws through the wooden edges to under the topmost frame member. Slots instead of holes at the edges were chosen since the wall thickness would be too weak to hold if the moat bed deflected. Also, the center cutout has rounded corners to relieve the stress concentrations there.

Between the moat and the motion plate we have as small a clearance as we could get away with: about 1/8”. With this design, even a child’s finger will have a difficult time getting under the shake plate. The moat edge is comprised of 2” x 2” birch with mitered corners and a slot along the full length of the bottom. The nominal length is slightly oversized to allow for minor fitting adjustments in the finished size of the frame weldment. The wood type was chosen to bring some natural qualities to the table and because it is an easily replaceable material. The slot along the bottom fits over the top edge of the frame and windows. This serves to protect the windows from fingers prying them away from the frame and possibly getting children’s fingers stuck in between. The bottom window edge is guarded by the thicker plywood siding immediately next to it.

Mechanism Viewing Windows

Our final window dimensions are 40” by 5.75” with two sets of ¼” clearance holes on each end spaced two inches apart. This window size is very long and thin; especially considering we initially sized the windows to be three feet long and one foot tall thinking that the motion mechanisms would take up much more space than they eventually did. The windows are made of 1/4” acrylic based on our failure analysis. We had initially specified polycarbonate but one of our technically oriented sponsors thought that the use of polycarbonate was unnecessary.
Siding and Doors

For the siding and doors we specified 1/2” ACX pine plywood since it offered the best combination of impact strength, stiffness, and decently lightweight. It also seemed to be the siding material preferred by our sponsors’ handyman that maintains all the exhibits. The siding measures 40” x 24” and has a set of three bolt holes, quarter inch, on each vertical side for mounting to the frame. The siding serves both as triangulation for the frame and is part of the exhibit’s aesthetic appeal.
Backboard

For ease of possible display redesign we made the backboard area above the table 30”x40” which fits several standard poster sizes with a 36” width. The backboard measures 40.25x60 inches and is made of 3/4” ACX pine plywood attached to the mounting holes made for the siding and windows. The poster on the backboard displays some information about earthquakes and the aspects we managed to model with the shake table. It also holds challenge cards for the more advanced users to apply their hand to. The poster design presented below is the one our team designed and presented at the Senior Project expo. Our sponsors wished to modify this design somewhat but were unable to finish their decision making before the printing deadline and so they decided to finish that aspect of the table themselves.

![Figure 38. Backboard poster design as presented in Senior Project Expo](image-url)
Aesthetics and Finishing Touches

We considered and rendered several versions of the table with different color schemes including blue and red, blue and brown, and cartoony versions with graphics on the sides. We wanted to avoid a childish looking exhibit which ruled out the first row pictures in Figure 40 below. We also wanted something that would stand out which the second row did not achieve.

The design we decided on was a blue and silver theme using flat-faced gray doors and siding with aluminum edging. The silver colored aluminum acccents the battleship gray siding and doors which keeps the bottom half from being boring but still clean and not detracting from the main focus of the table top. We still kept the black and yellow construction style border to tie in with the building theme of the table. This yellow and black banded theme we extended from the moat edges to around the backboard poster to keep a unified feel on the table-top.

The motion plate is painted brown to resemble the dirt of a construction site while the blocks are plain wooden tan or steel gray (magnetic blocks). These, along with the black and yellow banding around the perimeter, give the exhibit a construction oriented feel which will hopefully make the exhibit both self-explanatory to the illiterate and inspire creative constructive juices.
The challenge cards were created in order to provide extra educational material in the way of guided discovery. We made the cards with 67 lb cardstock which was then laminated for a highly durable but cheap to produce design. There are nine challenges including: vary building height, varying frequency, bridge building, using foundations, wall building, cumulative damage, changing materials (blocks), non-square buildings, and the safe distance between buildings should one collapse. Pictures using the actual blocks are featured on every card in order to facilitate understanding of the challenge independent of reading level. Additionally, each card has a bit of trivia at the bottom that usually pertains to the challenge.
Safety Considerations

As with any machine that has human operators nearby or using it, safety guides many of our choices. Foremost in our safety concerns was eliminating the possibility of injuries during normal operation. The motion plate rides less than a 1/8” above the surface of the moat so that fingers cannot readily become stuck in between. The pull rope passes through a hole smaller than over 95% of children’s fingers which we considered to be acceptable. The rope does present the possibility of minor rope burn but that heals quickly and is a lesson kids need to learn. The hand crank wheel was chosen to be solid (no spokes), since that could easily cause a great deal of pain with hands and limbs caught in it. Another worry was that the magnetic blocks might spontaneously connect themselves with enough force to hurt fingers. This was determined with actual testing of several different prototype blocks to find a good balance of safety and magnetic attraction. The windows were also a concern but this was addressed by hiding the upper edge in a slot, aluminum covers on the bolted ends, and a close fit to the plywood siding below.

Our second concern was whether the kids (and parents) could play with the table and not break it. To this end we decided to use a model of a 140 lb child moving at 10 mph running into the sides and windows. From this we confirmed that the ½” ACX siding and ¼” acrylic windows would be safe under all sorts of abuse. Also we modeled this child on top of the table to ensure the acrylic moat would not crack or break under load and again we found that using ½” acrylic was well within the material limits. Another concern was edging the plywood siding, backboard, and cabinet doors to keep the plywood from splintering and to reinforce the most abused point of the exterior components.

Our last concern was that the table be able to stand up to events not seen in proper use such as kids hanging on the backboard or standing on the table. For the backboard we did a static analysis to ensure that any force capable of overturning the table would not break the plywood. Once this analysis proved that ½” ACX was sufficient we went ahead and specified ¾” plywood for even more strength and a higher quality look. For standing on the table, we analyzed the frame buckling and stress on the moat bed. The frame was found to be well capable of supporting several hundred pounds on each leg so we aren’t worried about that. The acrylic moat bed warranted FEA analysis for which we confirmed that a 140 lb. child standing on one foot was safe situation. Detailed explanation of the FEA analysis is located in the Analysis of Exterior Components section.
Detailed Analysis

To ensure that many of the components of the KIDShake table can and will withstand the loading and use by multiple users, analysis was required. The analysis done has been broken down in five categories and multiple components within those categories were analyzed. The types of analyses that have been done include, statics, stress, buckling, fatigue, and finite element. For fatigue analysis the estimated worst case amount of cycles is 31 million. This value was calculated using the following criteria: 10 years at 52 weeks per year, 5 days per week, 1 hour per day, 200 rpm continuously for that hour. This cycle estimate gives a great over-estimation of the actual number of cycles the mechanisms will take. Pictures of our hand-written analysis and other analysis materials are located in Appendix E.

Analysis of Plate Motion Components

The manufacturer of the guide rail and linear bearing assembly (VXB) specified on its website that each pillow block could withstand a 115lb (510 N) dynamic load. This load represents an entire child weight on the mechanism and since our design has four pillow blocks, the rated load is well above a case that the table will actually experience.

Analysis of Hand Crank System

Crankshaft Arm Fatigue

The crankshaft lever arm is subjected to variable moment loading and near constant normal loading. Based upon a 30lb force being transmitted through the connecting rod, the expected moment on the crank arm is 1.56 ft-lbs. The expected stress from the bolt is 19.3 ksi and this is based upon 30 ft-lbs of bolt torque. The fully corrected endurance strength came to be 13.5 ksi under normal loading and 10.6 ksi under torsion. Using the modified von-Mises stresses for the multiple loading loads and the Soderberg fatigue criterion we found that 1/8” x 1” steel was woefully inadequate with a 0.35 safety factor. In order to improve the safety factor a lower bolt torque was analyzed with the 1/8’ x 1” crankshaft arm. This however was still inadequate as a safety factor of 0.81 was generated. The next step was to change the material thickness to ¼” and used the original bolt torque of 30 ft-lbs. With this case we calculated a safety factor of 2 and could last at least 10 years.
Connecting Rod Fatigue and Buckling

A concern of the 5/16” all-thread connecting rod was its buckling and fatigue failure. Treating the rod as an Euler column, we found that the critical load to cause buckling was 330lbs and since our expected load is 30lbs there is clearly no danger of buckling and very little out of plane deflection. For grade 2 all-thread, the most readily available, the fully corrected endurance strength was 17 ksi while the fluctuating load was positive and negative 0.76 ksi. This yielded a factor of safety of 22.4 which is very comforting. Both the tie rod end and clevis pin came with given load ratings well above the expected load, so we felt that crunching numbers for those parts would be superfluous.
Connecting Bracket Fatigue

Due to the connecting rod attaching to the connecting bracket approximately 1 inch below the top plane of the linear bearing blocks, torsional fatigue failure was a great concern. Assuming a 30lb input force, the torque acting on the bracket came to be 21.2 in-lbs. With steel as the material and a 1/8” x 1” cross section, the connecting bracket would see a stress of 4.38 ksi. For a ¼” x 1” cross-section the connecting bracket would see a 1.17 ksi stress. Fully corrected endurance strength for this situation is 9.2 ksi so both the 1/8” and ¼” thick bars are more than sufficient to resist failure. Ultimately, the ¼” thick bar was chosen since the deflection would be much less and ensure good response from the table.

Figure 45. Render of the connecting bracket

Figure 46. FBD of Connecting Bracket
Bronze Bearings Stress, Friction, and Wear

We specified SAE 841 oil impregnated bronze bearings to hold the crank shaft in place with an expected maximum speed of 200 rpm. This gave a pressure-velocity rating of 700 psi*fpm, where the limit is 50,000 psi*fpm. The expected friction force under estimated normal conditions is about 1.3 lbs. Also, using the analysis framework found in Shigley’s Mechanical Design, the maximum bearing wear is $2.55 \times 10^{-5}$ inches. The wear is considered negligible when compared to the worst case amount of use.

Figure 47. Flanged bronze self-lubricating bearing

Figure 48. Section view showing flanged bronze bearing in relation to shaft and hand wheel
Spring Pin Direct Shear Failure

A spring pin was initially specified in order to connect the hand wheel to the shaft that will ultimately cause one horizontal axis of motion for the plate. In the end we used a #10 machine screw which was close enough in size that we felt that doing the analysis over would be unnecessary. This spring pin shall be press fit into a hole through both the shaft and hand wheel. Using the maximum shear stress theory we calculated the maximum direct shear force the pin could experience. Two spring pin sizes were analyzed, a 3/32” diameter spring pin and a 3/16” diameter spring pin. An example of the spring pin cross section is displayed in Figure 35. For simplistic purposes the cross section of the pin was assumed to be a hollow shaft. The cross-sectional area used for calculation is slightly larger than in reality but this difference is negligible since the slot is very small.

Figure 49. Example of 3/16’ diameter spring pin from McMaster-Carr

Once manufacturing of the shake table began we ended up replacing the spring pin with a #10 machine screw. This decision was made because we felt it would be much easier take the bolt in and out if the table required maintenance. The hand crank has to be removed in order to remove the moat edging and the moat itself so if the spring pin ever got stuck or if it became too difficult to remove then this could pose problems in the future. This bolt has even more material than the spring pin so its likelihood to shear is non-existent for the loads generated on the hand crank.
Figure 50. Hand wheel, shaft, and machine screw assembly

Analysis of Rope and Spring System Components

A lawnmower starter pull cord was chosen for the rope mechanism because it is a thin rope with a handle attached that is already designed and rated for repeated yanking. The pulley is rated for far more load and cycles than the system will ever see in the planned ten year life. The polypropylene rope guide block is under very little load and it is unlikely that the rope will be pulled consistently enough to wear any type of groove. After selecting the rope type, an analysis of the springs that provide oscillatory motion was performed. The extension springs were selected based on two main parameters: the spring stiffness and the natural frequency corresponding to the stiffness. We set a maximum required force to compress the spring at 15 lb. Using Hooke’s Law, this equated to a spring stiffness of 30 lb/in for our desired 0.5 inch displacement. We initially selected springs with about the same spring stiffness but found that the calculated natural frequencies for springs in this range were much too high, about 4 Hz. In order to reduce this natural frequency to a more reasonable value, we looked at springs with a much lower stiffness. Our finalized springs have stiffness should be around 7-9lb/in and a natural frequency of 0.93 Hz. This is a much more reasonable natural frequency and we will not encounter any issues where children are not strong enough to move the table.

Table 2. Spring factors of safety

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Factor of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service Load</td>
<td>3.21</td>
</tr>
<tr>
<td>End Hook Bending</td>
<td>2.58</td>
</tr>
<tr>
<td>Coil Yielding</td>
<td>5.07</td>
</tr>
<tr>
<td>Body Coil Fatigue</td>
<td>5.23</td>
</tr>
<tr>
<td>End Hook Bending Fatigue</td>
<td>4.16</td>
</tr>
<tr>
<td>End Hook Torsional Fatigue</td>
<td>5.23</td>
</tr>
</tbody>
</table>
Based on the spring properties and our desired table response, a program in EES was written to calculate various factors of safety to ensure the spring can withstand the subjected loads. This program utilized equations from Shigley’s and is shown in Appendix E. The program calculates the stresses due to service loading, end hook bending; coil yielding and various fatigue possibilities. Factors of safety for each of these situations were calculated based on the stresses the springs can withstand compared to what they will actually encounter. All factors of safety were well within an adequate range and are shown in Table 3 below.

Analysis of Table Frame

Column Buckling

The main structural component of the frame consists of four 1” x 1” x 0.125” pieces of angle iron. One concern was how large of a load the angle iron could withstand before experiencing buckling failure. For the analysis, one piece was treated as an Euler column with fixed-fixed end conditions and no support from the table walls. Under these conditions the critical load for one column was 9377.5 pounds, which is far more than the table will ever experience. In the interest of saving weight and money, an analysis of wood 1” x 1” frame supports was performed using the same condition assumptions. This analysis ultimately led to a critical buckling load of 1612.53 pounds, which is a decent load carrying capability, but after looking more closely at the loading conditions caused by the plate’s oscillatory motion the wood columns were eliminated for potential fatigue concerns and the angle iron frame was selected.

Threads for Mounting

We hoped that we could save a fair amount of work and possible errors by simply making ¼-20 threads in the 1/8” thick material the frame is made of instead of welding on forty something nuts. Unfortunately we calculated that the minimum length of threads was 0.139 inches by machinist handbook standards and so we must use weld-nuts.

Analysis of Exterior Components

Finite Element Analysis on Moat Bed

A major objective given to us from our sponsor was that our KIDShake should withstand the wear and tear of children from a variety of ages. It is in the nature of young children to climb and jump atop various pieces of furniture or fixtures and our shake table is no exception to this. Due to this childhood nature our team believed that the acrylic moat atop the shake table would be a major weak point if children climbed atop the table and stood on it. If the moat could not withstand the weight of a child, it could potentially shatter or crack. This would cause a hazard for the user and the children standing in the vicinity of the table, plus the table would become unusable. So to ensure this problem would not happen we decided to focus on the stress the acrylic moat would experience for a couple different cases.
To analyze the stress of the moat it was decided that a finite element analysis (FEA) technique would be used because a hand calculation process could not be found. An FEA technique utilizes a displacement field assumption to determine the deformation of a part and then use that deformation to calculate stress. The problem parameters were determined and then a program called ABACUS was used to run the analysis. The moat was created in ABACUS using a shell element and the dimensions of the moat are 39.625” x 39.625” for the outside square and the inner cutout is 19.625” x 19.625”. The total surface area of the moat is 1185 in² and the thickness used for analysis was 0.5”. The material used was acrylic and this was modeled by inputting a Modulus of Elasticity (E) of 400 ksi and a Poisson’s ratio (v) of 0.4. The boundary condition of the moat consisted of fixing the moat in the x-y plane which is the top face of the moat. The moat was fixed in this direction because it will not be able to move in those directions when in the table itself. The last boundary condition was fixing all 4 sides of the moat in the z-direction. When the moat is placed in the table angle iron along with wood siding will fix the edges of the moat. The inner parts of the moat are still free to displace in the z-direction however, thus they were not fixed in the model. The last part of the model was to add a load. To ensure the moat could withstand the weight of a child, a conservative loading case was used. A 140 pound child standing on both one foot and two feet were analyzed. This load was applied to the plate using a pressure. We model the area of 10 year old foot as a 9.75” x 3.5” rectangle and applied a 2lb/in² pressure over that area on each side of the moat. This in turn yields a 70lb load on the foot area for each side to model the case of a child standing on two feet. To model the one foot case, a 140lb load was distributed over just one foot area.

Before running the analysis, the moat had to be broken up into many different elements in order to get an accurate result. This process is called meshing and the mesh size used for this analysis was a 0.5 in. The results of the FEA analysis were extremely promising. The ultimate stress of the acrylic is approximately 10,500 psi and the yield stress is approximately 8500 psi. The maximum stress and deflection came from one foot loading case. The 140lb child standing on foot caused a max stress of 1319 psi and a maximum displacement of 0.540 inches. This result is very acceptable in terms of how close the material is to both yield and failure. Because these results were acceptable, thicker material was not analyzed. In Figures 38 thru Figure 41, visualizations of the stress and displacement concentrations for both the one foot and two loading causes are displayed.
Figure 52. Mises Stress of the 0.5 inch thick acrylic moat for the two foot loading case

Figure 53. Z-displacement of the 0.5 inch thick acrylic moat for the two foot loading case
Figure 54. Mises Stress of the 0.5 inch thick acrylic moat for the one foot loading case

Figure 55. Downward displacement of the 0.5 inch thick acrylic moat for the one foot loading case
Table 3. Summary of FEA results for the one and two foot loading cases

<table>
<thead>
<tr>
<th>Loading Case</th>
<th>Stress (psi)</th>
<th>Displacement (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two Foot</td>
<td>704</td>
<td>0.392</td>
</tr>
<tr>
<td>One Foot</td>
<td>1319</td>
<td>0.540</td>
</tr>
</tbody>
</table>

**Backboard**

For the backboard we wanted to make sure that if someone was hanging on it the plywood would not break or significantly deflect. As such we calculated that the stress applied to the plywood from the bolts with enough force to lift the table off of its front feet. In this case the static yield stress using ¾” ACX pine was so far above the applied stress that we are not worried about it at all. Also the corresponding deflection was less than an inch which we felt was reasonable. We ended up using ¾” ACX because the cost was not that much more.

**Cost Analysis**

Per the specification, the entire cost of this project was to be under $3000. This specification has been met and our overall total cost is well below this figure. The entire cost of the project is estimated to be $1700. This cost includes all part costs, all shipping cost, and anything thing directly related or necessary to complete this project. Any items that were purchased fully belong to the Exploration Station of Grover Beach and any excess materials, unused parts, or spare parts will be included with the table delivery. Over the course of this project we tried to employ as many cost saving strategies as possible and we did our best to avoid unnecessary purchases. Our efforts paid off by not coming close to our budget cap. If another table were to be constructed, its estimated cost would be lower than the project cost the first time around. This was quite a learning process and money was spent on equipment or parts that ended up not being used. Excess material was purchased in many cases incase mistakes were made during manufacturing. If this table were to be professionally manufactured overall material cost would be much lower. In addition to these small mistakes there was cost incurred from purchasing items that were needed for our presentations and this cost will never be required again.
Table 4. Current cost breakdown by assembly

<table>
<thead>
<tr>
<th>ASSEMBLY</th>
<th>ITEM</th>
<th>QTY</th>
<th>Cost Each</th>
<th>Cost Total</th>
<th>Supplier</th>
</tr>
</thead>
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<td>$3.00</td>
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<td></td>
<td>fender washers</td>
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<td>$4.00</td>
<td>$4.00</td>
<td>Online</td>
</tr>
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<td>springs</td>
<td>4</td>
<td>$2.00</td>
<td>$8.00</td>
<td>McMaster-Carr</td>
</tr>
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Chapter 5: Product Realization

The manufacturing of the KIDShake table was done completely by our group, Team Shake ‘n Break. All parts were either manufactured in house or were purchased from outside vendors. All construction of the table and its components were done at the Aero Hangar and Mustang 60 machine shops located on campus.

Manufacturing Processes

The manufacturing process began with the construction of the table frame. This step had to be completed first since all other components were either attached to the frame or their dimensions depended upon the frame. All angle iron pieces were cut to length using an abrasive saw and had designated holes drilled into it using a hand drill. Once all the individual pieces of the table frame were cut to length and checked, the table was ready for welding. The pieces of the frame were welded in sections for easier assembly and cleaning with a wire brush and grinding was done in-between welds. The frame was welded using a MIG welder and once the frame was fully welded, the entire thing was grinded to ensure smoothness. To prevent any formation of rust on the bare steel, the frame was painted with grey Rust-Oleum.

Figure 56. Finished shake table frame

The next step was cutting out all the wood paneling for the table. This paneling included the two side panels, two front doors, back board, bottom shelf, and top mechanism shelves. These parts were cut using a table saw. Once cut, each wood panel was aligned with the frame so that we could ensure holes were aligned correctly and that the panels matched the frame geometry. Once the panels were fitted and attached, work on developing the plate motion mechanisms were the next focus. The rail-guides and pillow blocks are purchase components but before they were implemented into the table, modifications had to be completed first. Holes were drilled into them to attach the rail-guides to the
table and allow springs and a pull-rope to be attached to the rail-guides. These specifications are shown on our detailed engineering drawings located in Appendix B.

With the table mechanism shelves in place and the modifications complete on the rail-guide system, it was immediately placed in its proper location with spacer blocks. In order to get the hand crank mechanism and pull-rope mechanism fully operational, a lot of parts had to be manufactured first. With our focus on individual component manufacturing; the crank-shaft, connecting bar, moat edging, acrylic moat, spring brackets, plate spacer wood, and hand crank were made over the course of two weeks. Due to a large number of students using the machine shops on campus we employed a lot of manufacturing using hand tools and other smaller equipment instead of having to wait for precise equipment such as mills. These types of tools used to create our smaller components included a hand drill, drill press, bandsaw, hand router, circular saw, belt sander, hand sander, tap set, etc.

Figure 57. Table frame with bottom shelf, table mechanism shelves installed, and rail-guide system

Due to its simpler design, completing the hand crank mechanism was concentrated on first. Once all the parts required for this system were done, the hand crank mechanism was fitted and assembled to ensure it would work properly. The connecting bar and pillow spacer wood were attached first followed by the acrylic moat and moat edging. Once these parts were attached the shake plate was connected to the pillow block spacer wood. Next the self-lubricating bronze bearings were put into the designated holes in the moat edging and then the crank shaft was slid through. The hand crank was then attached to the crank shaft at one end to hold it in place. With these components fitted, the threaded rod, tie rod end, and clevis end connected the crank shaft to the connecting bar and resulted in table motion.
Once the hand crank mechanism was fitted and in working order, the pull-rope mechanism became the next focus. The only parts that had to be manufactured for this mechanism were two spring brackets. These brackets were built using 1/8 inch thick by 1 inch wide steel flat bar using a drill press and by hand bending the correct geometry. The springs were attached to one of the rail-guides using a pre-fabricated hole mentioned earlier and a bolt attached on the spring bracket. This is shown in Figure 31. With both springs and spring brackets in place a rope used for a lawnmower was tied to the other rail-guide at this level and fed through a cable clamp, rubber washer and eye hook, show in Figure 30. Finally the rope was tied to a wooden ball that acts as the pull handle to complete the mechanism.
With both mechanisms complete and fully operational, the aesthetics of the table were focused on. This is when all the wood panels on the table, two side panels, two cabinet doors, back board, and moat edging were painted their designed colors. The outside surfaces of the front cabinet doors and two side panels were painted red while the inside surfaces were painted white. The back portion of the backboard was painted all black white the front had to be painted very carefully. The bottom front half of the back board which would act as the back wall inside the table was painted white while the top front half was painted with caution stripes. The moat edging was also painted with caution stripes and this was accomplished by first painting that entire moat edge yellow and the using masking tape and black spray paint the stripes were created. The moat that separates the plate from the inner mechanism was designated to be frosting this way it was translucent enough to pass light through but also be more scratch resistant then plain acrylic. The frosting feature was completed by sandblasting the top surface of the acrylic. In addition to this, the acrylic windows were cut using a table saw and aluminum corners piece were made to hold the acrylic windows in place.
Differences from Planned Design

The overall finished table does not differ very much from our original planned design. The largest changes are related to the pull-rope mechanism. Other smaller differences are present in the building blocks and the overall table aesthetics. In the original plan for the pull-rope mechanism we had a pulley acting as an intermediate rope guide and a soft stop was originally going to be designed off this pulley to eliminate the hard stop on the rail-guide. The pulley we had purchased however was too large and hardly added any benefit to the pull-rope mechanism. Instead an eye-hook was added and a soft stop was designed on this using a rubber grommet and cable clamp. Also a rubber washer was placed on the acrylic window that the pull rope passes through in order to eliminate the rope from being rubbed on the acrylic edge. Other than other the difference just mentioned and other small dimensional differences the table as a whole is unchanged from our design.

The differences in the building blocks from the planned design are the material for the used for the pegs in the peg blocks and our overall color choices. In the initial table testing and usage we found that using roll pins for pegs damaged the brown paint on the plate surfaces. Since the roll pins are metal they easily scraped and chipped the paint on the plate. Although this problem wouldn’t affect the overall table performance it would cause aesthetic issues and potential hazards with paint chips. The pegs were then replaced by a nylon rod which do not damage the plate and still provide the same use. Also our original plan was to differentiate the differing styles of blocks with different colors to
demonstrate materials. Our sponsors ultimately decided however that they would prefer that the blocks not be painted at all and to let the child users figure out for themselves the differences in the blocks. Lastly, a couple small aesthetic differences are present in our table from the design presented at the critical design review. We had the idea to frost the table moat but it was unclear how we going to get it accomplished. We assumed that it could be hand sanded for convenience but we ultimately had it sand blasted by local company Full Spectrum free of charge. The sand-blasting frosted the acrylic perfectly and the moat is properly translucent and will show minimal scratches. The sides of the table were changed to a red color provided by ACE Hardware instead of the agreed upon grey color that went along with the construction theme. This change was asked for by our sponsor and the reasoning behind it was so that it would match other exhibits currently in place.

**Recommendations for Future Manufacturing**

If another table were to be manufactured from our specifications a few suggestions are offered. First off during the construction of the frame, hiring a professional welder who is certified would be recommended to ensure the welds are of high quality. The welds we performed are not perfect but are definitely at a level that will be suitable for this design. A professional welder however will have cleaner welds and will have to do much less clean up than what we had to perform. Also during the welding process, we recommend spending more time and effort into making sure the frame is as square as possible. The frame we constructed was not perfectly square and had a slight parallelogram shape to it in some spots. This distortion obviously did not affect the table functionality very much and it is not visible unless a square is placed at certain corners. With the table not being perfectly square some dimensions of certain parts had to be adjusted in order to ensure they fit properly. These changes were not included in our report or 3D solid model however because if the table is made square then these changes or problems would not arise.

Also due to the limited shop hours and the for the sake of convenience in some instances a lot of holes were completed using a hand drill. This is not the most ideal as some holes tended to be inaccurate and some holes needed to be re-drilled or made into an oval. We recommend that more precise measurements are to be taken and maybe using a drill press more often or even using a mill to ensure precision could be a viable option. The mill does have a limitation on the size of something we place on it so this option is more for smaller more important parts such as the rail-guides, and rail-sliders. Even though a lot of play was eliminated from the hand crank mechanism, some play still does exist. We recommend that this should be even more minimized and could be accomplished by focusing more on tolerance and alignment. The “play” currently present in the table does not pose any large risks in the overall function of the table.

Lastly a major recommendation would be to hire professionals for table construction. With hired workers more focus, time, and effort can be placed into the product and an even better performing shake table could become of this. That said, our group is fully happy with the current table and are completely confident in its ability to perform and last.
Chapter 6: Design Verification Plan

In order to verify our table design and its ability to handle vigorous use, testing protocols were designed and completed. We have developed tests to ensure that each one of our specifications were met properly, we tested individuals’ components to confirm designs, and we conducted a demonstration day for our sponsors. All of these tests have verified that our table meets expectations and outlined below are all the tests that were conducted.

Component Testing

Magnet Spacing Testing

In our original solid models the magnets were placed at a depth so that the top surface of the magnet was flush with the top surface of the wooden block. This nominal depth was chosen because the strength of the magnet was unknown. Upon completion of a few blocks with the magnets at this depth, it was concluded that this depth would not be suitable for our table because it would be too difficult to separate the blocks from each other when being shaken on the plate. Once this conclusion was reached we decided to test to more depths. The other two depths considered were placing the magnets 3/16” from the surface or at the center of the block (0.3125”). The magnets being used are neodymium and have a very strong magnetic force, so the surface level spacing had too much attraction for the purposes of this table. The block center depth ended up being too weak because magnet force is dependent upon distance squared and the attractive force was not enough to keep the blocks together. A happy medium was found with the 3/16” depth. The blocks have enough magnetic force between each other to stay together better than plain blocks and this simulates a stronger building structure which is the overall goal of including magnets on the blocks.

Spring Testing

Another component that required individual testing was the spring to be used for the pull-rope mechanism. It was unknown to us what spring constant would provide the best table motion during actual use so two different springs were tested. Both of the springs shown in Figure 64 were purchased from a local hardware and the spring constant was unknown. To find the spring constant of each spring, weight was attached to one end and the change in length of the spring was recorded. Once enough data was collected, these results were graphed and the slope of the force versus displacement graph yielded the spring constant.
The first spring that was tested was the larger one in size and had a spring constant of 8.24 lb/in. This spring provided very decent table motion and when the rope was pulled its entire distance and let go the shake plate traveled a total of 12 oscillations and took approximately 2.6 seconds to stop. While testing this spring, another use of the pull-rope mechanism was discovered. Our initial intention was to just use the pull-rope mechanism as a pull and release type mechanism but these springs also provided the option of back and forth pulling. If the user used the rope to pull the plate back and forth the springs would help counteract this movement and want to be pulled back into position. The back and forth motion also worked well while the crank was simultaneously moving as well. The smaller second spring with a spring constant of 2.86 lb/in proved to not be very successful. When the rope was pulled and released the plate hardly reacted at all and only oscillated a total of 2 times and stopped moving in approximately 2 seconds. With the performance of the first and it second use discovered it was the obvious choice for our table.
### Table 5. Results of spring testing for pull-rope mechanism

<table>
<thead>
<tr>
<th>Spring Constant (lb/in)</th>
<th>Trial</th>
<th># Oscillations</th>
<th>Time to Stop (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>11</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>12</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>12</td>
<td>2.7</td>
</tr>
<tr>
<td>K=2.86</td>
<td>1</td>
<td>2</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2</td>
<td>1.2</td>
</tr>
</tbody>
</table>

**Overall Table Testing**

To verify the overall design of our mechanical shake table a demonstration day was conducted and some basic verification testing was performed. Upon initial completion of the mechanical components a demonstration run was conducted with members from the Exploration Station and the child of one of our sponsors. At this demonstration run, both the hand crank and pull-rope mechanism were fully operational and our visitors/testers analyzed all aspects of the table. Each person constructed a building on the table and used one or both of mechanical mechanisms to knock it down. At one point we even told our child tester to use the table as hard as she could. The table performed wonderfully and no components showed signs of initial wear or damage. Although the demonstration went well it did yield some obvious problems with the current shake table. The biggest mechanical concern was not currently having a system in place to prevent the rail-slider mechanism from hitting a hard stop. The impact the hard stop created shook the table quite violently and also generated a loud noise. The other area of concern was the amount of slop in the hand crank mechanism. The slop was generated from the bolt that holds the hand crank onto the crankshaft being too small. This bolt replaced the original design of having a spring pin in that spot so the hand crank could be removed much easier.

![Figure 63. Soft stop for the pull rope mechanism](image-url)
To fix the concerns from the demonstration day, a new soft stop was designed for the pull rope mechanism. A picture of the system now currently in place is shown in Figure 65. This new design consists of an eye hook that replaces the original pulley, a cable clamp, and a thick rubber washer. When the rope is pulled the table travels approximately 1 inch in the transverse direction and then hits the soft stop. With the cable clamp in place it cannot pass through the eye hook causing the plate travel to stop. The rubber washer allows this stop to be “soft,” meaning it absorbs a lot of energy and provides a much quieter stop as well.

To remove the sloppiness in the hand crank a few options were considered. The first option was to find a larger bolt that fit the hole and simply replace the old bolt with it. This was tried first but the hole we drilled was slightly off center and no larger bolt size would fit in it at the current time. The next step was then to try and drill the hole slightly larger to match a bolt size. This was attempted but because a hand drill was used and not a drill press it only made the holes being off center worse. The next idea was to drill a completely new hole for the bolt. This idea was decided to be a worst case scenario to avoid having unused holes on the hand crank. Our final and best idea consisted of using a set screw to remove the slop. A small hole was drill perpendicular to the bolt holes and then it was threaded for a small set screw. With this set screw in place it pushes the crank shaft against the inner wall of the hand crank hole. This plan removed much of the slop but did not remove it completely. The remaining slop is due to the crank shaft diameter and sleeve bearings having a larger tolerance difference than expected. There is nothing we can do to remove the small bit of play remaining in the hand crank mechanism.

Once all the corrections found from the demonstration day were completed then basic verification testing was conducted using the hand crank mechanism. This testing included using the plain building blocks and constructing three different buildings at various heights. With each building size (small, medium, large) the hand crank mechanism was used and the number of cranks and time it took the blocks to fall were recorded. With this data, the frequency at which the hand crank was spun could be calculated and any relevant relationship could be seen by analyzing the data.
Table 6. Results of table verification testing

<table>
<thead>
<tr>
<th>Building Size</th>
<th># Blocks</th>
<th>Height (in)</th>
<th>Trial</th>
<th>Time to Fall (s)</th>
<th># Cranks</th>
<th>Frequency (rev/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small (12 blocks)</td>
<td>12</td>
<td>8.25</td>
<td>1</td>
<td>6.3</td>
<td>17</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>3</td>
<td>12.9</td>
<td>22</td>
<td>1.71</td>
</tr>
<tr>
<td>Medium (24 Blocks)</td>
<td>24</td>
<td>16.5</td>
<td>1</td>
<td>2.3</td>
<td>6</td>
<td>2.61</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>7.7</td>
<td>18</td>
<td>2.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>18.8</td>
<td>35</td>
<td>1.86</td>
</tr>
<tr>
<td>Large (36 Blocks)</td>
<td>36</td>
<td>24.75</td>
<td>1</td>
<td>4.9</td>
<td>16</td>
<td>3.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>7.7</td>
<td>16</td>
<td>2.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>11.6</td>
<td>22</td>
<td>1.90</td>
</tr>
</tbody>
</table>

Figure 65. Hand crank testing displaying the relevance between the frequency of the hand crank, building block height, and time to fall.

From the data provided above, it was determined that the faster the hand crank is spun, the quicker a given building will fall. At higher frequencies, the taller a building also increases its chances of falling much quicker than a shorter one. At low frequencies however taller buildings have a much greater chance of taking longer to fall than a shorter building. From observation it seems that this occurred because the friction between blocks for a larger building was greater due to the weight of more blocks being piled on. This added friction made the taller building stay up longer at lower frequencies.
Testing to Meet Objective Requirements

In order to properly confirm every specification had been properly met we performed the following
the tests on the table. The procedure that was used to inspect our table is provided below:

1. **Safety**: The table should be safe for children to use.

   To ensure the table is safe for children, upon completion it will undergo an extensive visual
   inspection. At least two team members will individually complete this inspection. If these
   members believe the table passes this inspection, it then must get approval from our project
   advisor Lee McFarland. A list of safety requirements are shown below and will be checked
   during the inspections. If the table does not meet any of these requirements, it will be modified
   and fixed. The inspections will be repeated until the table passes the safety requirements.
   a. The table does not possess any pinch points
   b. All mechanisms are fully enclosed
   c. Frame does not possess any sharp edges
   d. Moat is free from splinters, etc.
   e. All parts and accessories do not pose choking risk
   f. Cabinet doors can closed and remain locked
   g. No loose components

2. **Earthquake Realism**: The table should simulate characteristics of earthquakes for kids to learn.

   Various structures will be built and knocked down to test building characteristics. Two main
tests will be performed, one that tests the differing block types and another to test shaking
frequency at differing building heights.
   a. Block Test – Multiple trials will be conducted to test the both the times and frequencies to
   know down the plain blocks and the magnetic blocks. This test will be used to verify that
   the magnetic blocks are more difficult to knock down, simulating a more structurally sound
   building. If this is not verified, then new blocks should be designed and manufactured to
   simulate this concept.
   b. Frequency Test - Multiple trials will be conducted to test the breaking frequencies for
   various building heights. In particular, this test will be used to verify that larger structures
   can have a higher breaking frequency than smaller structures due to their natural
   frequencies. If this cannot be verified, then the instructional card should be removed or
   altered.

3. **Cost**: The total table cost will be under $3,000.

   Upon project completion, receipts will be gathered and project costs will be totaled. A final
   total project cost will be calculated and presented to our sponsor.

4. **Footprint**: The total exhibit footprint will be less than 4’x 4’ and table less than 3’x 3’.
Upon completion of construction, the table footprint will be measured. The total table footprint while users are at the table will also be measured to ensure that it fits within the 4’x4’ constraint.

5. **Height:** The height will not exceed 32” to accommodate target 10 year old.

   The height of the top edge of the moat and height of the plate from the ground will be measured. If these heights exceed the 30” maximum height, alterations will be made to meet this requirement.

6. **Portability:** The table will be moveable by 2 men and a dolly.

   To ensure the table can be easily moved, the table portability will be tested by two of the male team members. With all components in place, two male members will move the table at least 50 ft. with the assistance of a dolly. If this is accomplished, the sponsor should not have problems moving the table within the museum. If this is not accomplished, the team will provide an alternative solution to moving the table.

7. **Movement:** The table will have 3 axes of motion with 3 hand powered controls.

   Based on the sponsor’s instructions, the table will only have 2 axes of motion. The sponsor also specified that depending on the mechanism tests, only 1 axis may be requested for the final table. Upon completion of the two mechanisms, they will be tested and evaluated by the sponsor. Based on their approval, the second spring mechanism will remain or may be eliminated.

   The final mechanisms will also be thoroughly tested to ensure they work properly. During these tests the following will be looked at:
   a. The mechanisms move in a smooth, fluid motion
   b. There is not excessive friction in the linear bearings, hand crank, or spring mechanism
   c. The mechanisms are activated with little force

8. **Maintenance:** The table should require minimal maintenance.

   Upon completion, the mechanisms will undergo extended testing to observe how they perform after repeated use. The mechanisms will be activated for a set number of cycles. Several times throughout this testing, the mechanisms will be visually inspected to ensure no parts become loose. After the table is put through the total amount of cycles, the mechanisms will be thoroughly inspected by at least two team members to evaluate what sort of maintenance would be required.

9. **Appearance:** The table should be visually attractive.

   Once the team finishes the final painting of the table and printing of the backboard, sponsor approval will be required. After the team is given approval, the backboard will be attached and final paintings will be done. The team will seek approval in one of two ways:
   a. The sponsor will come and see the table and give the team the final approval.
b. Pictures will be sent by email and the sponsor will respond with the final approval.

10. **Parts**: Use as many commercially available parts as possible.

   After completion, at least two members will look through all table parts and components. Each part will be checked to ensure the sponsor will have sufficient information to make or replace the part in case it breaks or get lost in the future. At least one of the following must be provided for each part:
   a. Part name, number, and where to vendor information
   b. Manufacturer drawing
   c. Drawing made by team with manufacturing instructions

11. **Blocks**: Building blocks should cater to various age groups.

   A test run of the table will be performed with various age groups. The age groups will consist of 5 to 8 year olds, 9 to 12 year olds, and young teenagers to adults. At least two members will be present to observe what blocks are used by each age group and if they cater to each of these age groups. If the team believes a greater variety should be available, different blocks will be made to accommodate this need.

12. **Mechanisms**: The table mechanisms and linkages should be visible.

   Once all parts and side panels are installed, the table will undergo a visual inspection to ensure the mechanisms are easily visible to users.

13. **Storage**: Should include storage bins for excess blocks, etc.

   After all blocks and excess parts are manufactured, storage bins will be bought to allow for organized storage within the cabinets.

   Per this procedure we have concluded that our table meets all the design specifications and that the table is ready for use by the Exploration Station of Grover Beach.
Chapter 7: Conclusions and Recommendations

At this time, a complete working table is ready to be handed off to the Exploration Station. We are very pleased with the final outcome of the table and are confident it will provide visiting children a very educational and fun experience. We will soon deliver the table to the museum and hope everyone there will be excited to incorporate it into the showroom. The only further addition or modification to the table will be made by the board of the Exploration Station. This will entail creating and printing an educational back poster for users to read and gather information.

Based on our experience with this project and previously speaking with the Exploration Station board of directors, we suggest they approach the Cal Poly Mechanical Engineering Senior Project again. This exhibit greatly benefited both parties. The museum was able to work with our team to produce a custom made exhibit that fulfilled their specific needs within a very minimal budget. This project also benefited us by allowing us to work with a sponsor while completing a design from beginning ideation to final manufacturing. This has been a great experience and hopefully the Exploration Station and Cal Poly can maintain a relationship and produce more great exhibits in the future.

Figure 66: Team Shake ‘n Break at Senior Project Expo: (from left) Philip Hopkins, Jeremy Duhe, Matthew Ostiguy, Samantha Weiner
References

San Luis Obispo Children’s Museum
1010 Nipomo Street San Luis Obispo, CA 93401
(805) 545-5874

OMSI
1945 SE Water Ave. Portland, OR 97214
(800) 955-6674

Randall Museum
199 Museum Way San Francisco, CA 94114. San Francisco, CA
(415) 554-9600


Appendix A – Ideation Process and Decision Matrices

Figure A1

Figure A2
Figure A5

- Moat and Plate
  - 3' - 5'' retaining wall
  - Nothing

- Wall or net
  - Wood
  - Steel
  - Aluminum
  - Polymer
  - Coating?
  - Epoxy
  - Rhino liner
  - None
  - Treated material
  - Peg board

Figure A6

- Appearance
  - Earthy
  - Wood
  - Construction - yellow, orange
  - Cracked street
  - Plate below

- Have one side w/ just pic

- Scenarios
  - Vary building height
  - Foundation w or w/o
drift shaking
  - Be the designer
  - Picture instructions
**Figure A7. Decision matrix for activation mechanisms**

<table>
<thead>
<tr>
<th></th>
<th>Weight Factor</th>
<th>Jumping</th>
<th>Foam Hammer</th>
<th>Potential Energy Weight</th>
<th>Pull Release Lever</th>
<th>Ratchet Lever</th>
<th>Rope</th>
<th>Helm Wheel</th>
<th>Hand Crank</th>
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<td>7</td>
<td>8</td>
<td>9</td>
<td>9</td>
<td>9</td>
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<td>8</td>
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<tr>
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<td>7</td>
<td>4</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>8</td>
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<td>4</td>
<td>7</td>
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**Figure A8. Decision matrix for actuation mechanisms**

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<th></th>
<th>Weight Factor</th>
<th>Piston System</th>
<th>Lever (seasaw)</th>
<th>Linkage</th>
<th>Direct with Spring Assistance</th>
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<td>Assorted Blocks</td>
<td>Blocks/ Magnets</td>
<td>Lincoln Logs</td>
<td>Blocks w/ Pegs &amp; Holes</td>
<td>Magna-Tiles</td>
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Figure A9. Decision matrix for building blocks

<table>
<thead>
<tr>
<th>Weight Factor</th>
<th>Plate on Balls</th>
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</table>

Figure A10. Decision matrix for plate material
Appendix B – Drawing Packet

*All drawings are provided in this document but digital PDF versions and the original Solidworks drawing documents will also be given electronically.
SPACING ON 2 HOLE PATTERN ON EACH END IS IMPORTANT
RELATION TO CENTER WHOLE NOT CRITICAL
MADE FROM 2 LAMINATED 1X4's
MADE FROM 2 BIRCH 1x4's LAMINATED
MIRROR FOR PART 75302L
LENGTH DIMENSIONS INTENTIONALLY FAT FOR FITTING

TOLERANCE: ±.0625 UNITS: IN MATERIAL: BIRCH
NEXT ASSY: 75300 SCALE: 1:6 TITLE: RIGHT EDGE
DWG #: 75302R DATE: 3-3-2013 GROUP: SHAKE N BREAK
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<td>71606</td>
<td>SHORT COLUMN</td>
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<td>THIN SQUARE</td>
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<td>2</td>
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<td>VERTICAL MEMBER</td>
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**TOLERANCE:** ± .125  **UNITS:** IN  **MATERIAL:** 1018 STEEL

**NEXT ASSY:** 70500  **SCALE:** 1:12  **TITLE:** SHAKE TABLE FRAME

**DWG #:** 71600  **DATE:** 2-9-2013  **GROUP:** SHAKE N BREAK
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<td>LEFT EDGE</td>
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**Additional Information**

- **DRAWN BY:** JEREMY DUHE
- **INIT:**
- **CKD BY:**
- **INIT:**

- **TOLERANCE:**
- **UNITS:**
- **MATERIAL:**

- **NEXT ASY:** 70300
- **SCALE:** 1:8
- **TITLE:** TABLE MOAT

- **DWG #:** 75300
- **DATE:** 1-21-2013
- **GROUP:** SHAKE N BREAK

---

88
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<th>CKD BY:</th>
<th>INIT:</th>
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<td>DATE:</td>
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Fabricated from 1X1X1/8 angle iron. All holes are 1/4” clearance. Grind parts to match lengths.
#10-32 Tapped Hole

ALL HOLES ARE 4.5 MM
THE FOUR BOLT PATTERN ON THE ENDS
MUST BE MACHINED

MADE FROM VXB PART NO KH8512

TOLERANCE: ±.5 MM
UNITS: MM
MATERIAL: ALUMINUM

NEXT ASSY: 72400
SCALE: 1:2
TITLE: REWORKED RAIL BASE

DWG #: 72601
DATE: 2-9-2013
GROUP: SHAKE N BREAK
HOLE LOCATIONS ARE APPROXIMATE: USE ACTUALL RAIL HOLES

PLANING THIS PART IS LIKELY NECESSARY TO CLOSE GAP BETWEEN MOTION PLATE AND MOAT

---

**Mechanical Engineering**

**SolidWorks Student License Academic Use Only**

<table>
<thead>
<tr>
<th>DRAWN BY: JEREMY DUHE</th>
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<th>CKD BY:</th>
<th>INIT:</th>
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<tbody>
<tr>
<td>TOLERANCE: ±.125</td>
<td>UNITS: IN</td>
<td>MATERIAL: BIRCH</td>
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CONFIRM EACH PART IS SAME LENGTH WITHIN TOLERANCE
ALL RIGHT ANGLES

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DRAWN BY: JEREMY DUHE
INIT:
CKD BY:
INIT:

TOLERANCE: ±.0625
UNITS: IN
MATERIAL:

NEXT ASSY: 71600
SCALE: 1:8
TITLE: BOTTOM SQUARE

DWG #: 71605
DATE: 2-9-2013
GROUP: SHAKE N BREAK
ALL HOLES ARE 1/4" CLEARANCE
GRIND PIECES TO MATCH LENGTHS
ALL 1/4" CLEARANCE THRU HOLES

FABRICATED FROM 1X1X1/8 ANGLE IRON
GRIND PIECES TO MATCH LENGTHS

DRAWN BY: JEREMY DUHE
INIT: 
CKD BY: 

TOLERANCE: ±.0625  UNITS: IN  MATERIAL: 1018 STEEL
NEXT ASSY: 71600  SCALE: 1:5  TITLE: VERTICAL FRAME MEMBER
DWG #: 71603  DATE: 1-19-2013  GROUP: SHAKE N BREAK
### Appendix C – List of Vendors, Contact Information, and Pricing

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<tr>
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</tr>
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<td>Barrel Bolt</td>
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<td>Paint Solvent</td>
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<td>1/4&quot; x 1/16&quot; Disc Magnet</td>
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<td>800-379-6818</td>
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<td>2' x 2' Galvanized Steel Pegboard</td>
<td>$44.00</td>
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<td>diamondLife</td>
<td>(888)-983-4327</td>
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<tr>
<td>1/4&quot; Flat Bar Steel</td>
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<td>(805) 596-0857</td>
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<td>10-24 Screws/Nuts</td>
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<td>McMaster-Carr</td>
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<tr>
<td>Foam Board and Adhesive Spray</td>
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<td>Michaels</td>
<td>(562) 692-5919</td>
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<td>Reid Supply</td>
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<td>Solter Plastics</td>
<td>(562) 692-5921</td>
</tr>
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<td>9</td>
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<td>VXB Bearings</td>
<td>(800)-928-4430</td>
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<td>12 mm 60° Rail Guideway System Linear Motion</td>
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<td>Fairlead (rope guide)</td>
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<td>West Marine</td>
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Appendix D – Vendor supplied Component Specifications and Data Sheets

KHL-22 5.91 Inch Diameter Dished Solid Hand Wheel with Revolving Handle

Product Spec Sheet

<table>
<thead>
<tr>
<th>Item No: KHL-22</th>
<th>Price: $43.11 (ea)</th>
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</thead>
<tbody>
<tr>
<td>Quantity:</td>
<td>$47.75  $42.35  $44.33  $43.47  $42.95  $42.40</td>
</tr>
</tbody>
</table>

KHL-22 5.91 Inch Diameter Dished Solid Hand Wheel with Revolving Handle

Description:
- Solid Dished Hand Wheel
- With or Without Revolving Handle
- Inch

Construction:
- Constructed of tough, reinforced plastic
- Solid construction prevents injury due to getting hand caught in spokes
- Steel hub molded in
- Available with or without through bore

Specifications:
- **Base Diameter**: 1.36 inch
- **Base Height**: 0.70 inch
- **Handle Height**: 2.59 inch
- **Handle Type**: Revolving
- **Height (Hub Base to Wheel Top)**: 1.89 inch
- **Hole Size**: 0.06 inch
- **Hole Type**: Core
- **Hub Diameter**: 1.73 inch
- **Hub Height**: 1.03 inch
- **Insert Diameter**: 0.44 inch
- **Measurement System**: Inch
- **Metal Inner Wheel Diameter**: 2.75 inch
- **Wheel Diameter**: 5.00 inch
- **Wheel Style**: Solid
- **Wheel Thickness**: .71 inch

Manufacturer Part Number: KHL-22

Drawing:

<table>
<thead>
<tr>
<th>Drawing Info</th>
</tr>
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<tbody>
<tr>
<td>A: 0.91 inch</td>
</tr>
<tr>
<td>B: 0.54 inch</td>
</tr>
<tr>
<td>C: 1.73 inch</td>
</tr>
<tr>
<td>D: 1.20 inch</td>
</tr>
<tr>
<td>E: 2.75 inch</td>
</tr>
<tr>
<td>F: 0.71 inch</td>
</tr>
<tr>
<td>G: 2.55 inch</td>
</tr>
<tr>
<td>H: 1.05 inch</td>
</tr>
<tr>
<td>I: 1.60 inch</td>
</tr>
<tr>
<td>J: 0.59 inch</td>
</tr>
</tbody>
</table>
Recommended 0.187" to 0.192" Diameter Hole Size
Notes:
Zinc-Plated Steel Housing
Chrome-Plated Steel Ball and Oil-Impregnated Bronze Insert

5/16"-24 Thread

11/16" Thread Length

1 3/8"

1 13/16"

7/8"

1/2"

7/16"

11/32"

5/16"

5/8"

14° Max. Ball Swivel

115
### 12mm CNC Bushing Linear Bearing Block Open Linear Motion (VBX.com)

<table>
<thead>
<tr>
<th>Designation</th>
<th>Main dimension</th>
<th>Slide bush</th>
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<tbody>
<tr>
<td>SC12UUOP</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>h</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>27</td>
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</table>
### 12mm 60" Rail Guideway System Linear Motion (VBX.com)

<table>
<thead>
<tr>
<th>Shaft (mm)</th>
<th>Dimensions (mm)</th>
<th>Mounting Dimensions (mm)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>H</td>
<td>E</td>
</tr>
<tr>
<td>12</td>
<td>12.46</td>
<td>17</td>
</tr>
</tbody>
</table>
Appendix E – Detailed Supporting Analysis

Analysis of Spring Pin in Direct Shear:

\[ \tau_{\text{max}} = \frac{S_y}{2} \quad (\text{Maximum Shear Stress Theory}) \]

\[ \tau_{\text{max}} = \frac{190 \text{ ksi}}{2} = 95 \text{ ksi} \]

\[ A_1 = 5.322E^{-3} \text{ in}^2 \quad A_2 = 1.935E^{-2} \text{ in}^2 \]

\[ \tau_{\text{max}} = \frac{V}{A} \]

\[ V_1 = \tau_{\text{max}} * A_1 = 95000 \text{ psi} * 5.322E^{-3} \text{ in}^2 \]

\[ V_1 = 506 \text{ lb} \]

\[ V_2 = \tau_{\text{max}} * A_2 = 95000 \text{ psi} * 1.935E^{-2} \text{ in}^2 \]

\[ V_2 = 1838 \text{ lb} \]

L-Bracket Buckling:

1018 Steel 1x1x0.125 L Bracket

\[ E = 30 \text{ Mpsi}, \]

Critical buckling assuming “long column” (eqn 4-43 Shigleys)

\[ P_{\text{cr}} = \frac{C \pi^2 E I}{L^2}, \quad I = 0.021 \text{ in}^2, \quad A = 0.234 \text{ in}^2 \quad C = 1 \text{ (fixed fixed)} \]

\[ P_{\text{cr}} = \frac{1 \pi^2 \cdot 30 \cdot 10^6 \text{ psi} \cdot 0.021 \text{ in}^4}{(25.75\text{in})^2} \]

\[ P_{\text{cr}} = 9377.5 \text{ lb} \]

1” x 1” corner support buckling

2in X 2in X 25.75in Wood

\[ E = 1.3\text{Mpsi (along grain)}, \quad h = b = 1\text{in}, \quad L = 25.75\text{in} \]

Critical buckling assuming “long column” (eqn 4-43 Shigleys)

\[ P_{\text{cr}} = \frac{C \pi^2 E I}{L^2}, \quad I = \frac{b h^3}{12}, \quad C = 1 \text{ (fixed fixed)} \]
\[ P_{cr} = \frac{1 \times \pi^2 \times 1.3 \times 10^6 \text{psi} \times \frac{1 \text{in}(1 \text{in})^3}{12}}{(25.75 \text{in})^2} \]

\[ P_{cr} = 1612.53 \text{ lb} \]
$F_0 = 30 \text{ lbs}$ treat 2" ends as fixed (well clamped)

**Case A:** Fatigue @ 0

$A_0 = 0.375(1/4) = 0.0938 \text{ in}^2$

$\sigma_x = \frac{F_0}{A_0} = \frac{30}{0.0938} = 320 \text{ psi}$

Well below $S_e$, NO problem

**Case B:** Fatigue @ P

Assume $\sigma_x$ negligible compared to $T_{\text{max}}$

$T_{\text{shear}} = \frac{3F_0}{2A_0} = \frac{3(30)}{2(0.0938)} = 180 \text{ psi}$ also negligible

$T_{\text{hoop}} = \frac{T}{bc} \left(3 + \frac{1.5c}{b}\right) = \frac{21.2}{1.25} \left(3 + \frac{1.5(0.25)}{1.25}\right)$

$T = 62 = 30(0.707) = 21.2 \text{ in lbs}$

$T_{\text{hoop}} = 1.17 \text{ kips}$ (seems low) check 1/8" thick $T_{1/8} = 4.38 \text{ kpsi}$

$S_{\theta} = 21.8 \text{ kpsi}$

$K_u = 0.14 \times 39,19 (49.5)^{1.915} = 0.622$

$K_b = 0.871(0.25)^{1.07} = 1.02$

$K_c = 0.51$

$K_e = 0.783 \text{ 99.97% Noble}$

$S_e = 9.24 \text{ kpsi}$

$\Rightarrow T = 1.17 \text{ kpsi}$

no fatigue failure

$S_{4/8} = 9.96 \text{ kpsi}$

$\Rightarrow T_{4/8} = 4.38 \text{ kpsi}$

no fatigue failure

**Conclusion:** 1/8" bar is fine but use 1/4" bar for kicks
Detailed Column analysis: C=1 pln-3in Connection

Try diam = 5/16" all thread d = .256" A_0 = .052111 ft^2

I = \pi d^4 = 2.07E-11 ft^4 I = A_k^2 K = .0844 in \frac{\pi}{\sqrt{I}} = \left(\frac{2(0.052111)^{1/2}}{0.052111}\right)^{1/2} = 10.19

\frac{P_{cr}}{A} = \frac{\pi^2 E}{(\pi/2)^2} \frac{P_{cr}}{A_0} = \frac{\pi^2 E}{(\pi/2)^2} P_{cr} = 328 lb \quad \frac{1}{K} = 2.174 \text{ Euler}

expected load = 32 lbs \quad \boxed{\text{no problem in buckling}}

Fatigue analysis

σ_0 = 0.55σ_{u4} = 0.55(67 ksi) = 28.5 ksi

K_p = 1.02 K_c = .85 axial K_f = 0.783 99.9% reliable

σ_f = 17.1 ksi

σ_{max} = A_0 = 0.052111 \quad \sigma_{min} = -\sigma_{max}

\sigma_m = \frac{\sigma_{max} - \sigma_{min}}{2} = 763 psi \quad \sigma = \frac{\sigma_{max} - (-\sigma_{max})}{2} = 763 psi

Soderberg \quad \frac{\sigma_f + \sigma_m}{\sigma_y} = \frac{1}{\eta} = \frac{763 psi + 0}{17.1 ksi} = \frac{1}{\eta}

n = 22.4, \text{ wow}

Threads in 1/8" thick steel to hold up siding
From FED-STD-123b, 1991 and Machinery's Handbook

length of threads (engaged)

L_e = \frac{2 \times A_t}{n} \quad \frac{K_{max}}{K_{min} - E_{min} - K_{max}}

K_{max} = \text{max minor D of int thread} \quad E_{min} = \text{minimum pitch D of ext thread}

n = \text{tpi}

L_e |_{1/4-20} = \frac{2 \times 0.0308}{.22 \pi \left(\frac{1}{2} + .87735(20)(.234 - .22)\right)}

= 0.139 \text{ inch} > 0.125 \quad \text{1/4-20 is go}

L_e |_{1/4-28} = \frac{2 \times 0.0304}{.23 \pi \left(\frac{1}{2} + .87735(28)(.238 - .23)\right)}

= 0.160" > 0.125" \quad \text{1/4-28 is go}

[Conclusion: must use 1/4-20 weld nuts on frame]
Design Calculations Continued

- Crank shaft cam tab

\[ T = \frac{F_a \cdot l}{2} \]

Assuming no deflection of bolts/nuts (joint stiffness >> load)

\[ T = \frac{F_a \cdot l}{2} \]

\[ F_a = 4700 \text{ lbs} \]

\[ \sigma_y = \frac{F_a}{A} = \frac{4700 \text{ lbs}}{\pi (0.05 \text{ in})^2} = 19.3 \text{ Kpsi} \]

1018 steel, \( S_{yt} = 49.8 \text{ Kpsi} \)

\[ S_e = 10.5 \text{ tons} \]

\[ K_a = 0.05 \text{ yield} \]

\[ K_b = 1.5 \text{ tensile} \]

\[ K_r = 0.75 \text{ stress} \]

Endurance strength

\[ q = 0.8 \]

\[ K_p = 1 + 0.33 (H_y - 1) = 1.5 (1.4 - 1) = 1.2 \]

\[ q = 0.75 \]

\[ K_p = 1 + 0.33 (H_y - 1) = 1.5 (1.4 - 1) = 1.34 \]

\[ \sigma_{a'} = \sqrt{(1.02 \cdot 19.3 \text{ Kpsi})^2 + 1.3 (1.34 \cdot 49.8 \text{ Kpsi})^2} \approx 112 \text{ Kpsi} \]

\[ \sigma_{a'} \approx \frac{0.17}{\sigma_y} = \frac{1}{n} 
\]

Soderberg's rule

\[ \frac{1}{n} = 0.35 \text{ highly conservative} \]

\[ n = 0.43 \text{ ASME elliptic} \]

Change bolt torque to 10 ft-lb \( \Rightarrow F_i = 1300 \text{ lb} \Rightarrow \sigma_y = 6.44 \text{ Kpsi} \)

\[ \sigma_{a'} = 13.4 \text{ Kpsi} \]

\[ \sigma_{m} = 12.3 \text{ Kpsi} \]

\[ n = 0.81 \text{ highly conservative} \]

\[ \nu_{ue} = 0.98 \text{ ASME elliptic} \]

Conclusion: Use flat bar thicker than 1/8 with bolt torque 10 lb-ft

1/4" thick available $9/4$ or use 1/8 x 3/16 iron scrap
Backboard strength and deflection

Beam theory:

\[ E = 10.3 \times 10^6 \text{ psi} \]

\[ f_0 = 5000 \text{ psi} \]

\[ A = 7 \times 10^3 \text{ in}^3 \]

\[ I = 0.077 \text{ in}^4 \]

\[ I_{em} = 0.009 \text{ in}^4 \]

\[ d = 28' \]

Calc for \( P \) to tip

\[ 31' \leq L_b \]

\[ 0 = 190'(20') - P(3'1''+28') \]

\[ P = 49.1 \text{ lb} \]

Deflection:

\[ \delta = \frac{F L^2}{3EI} = \frac{49.1 \times 10^3 \times (28/2)^3}{3 \times (10^3 \times 10^6 \times 9) \times (10^3 \times 10^6 \times 9)} \]

\[ = 0.0089'' \text{ negligible} \]

Shear stress @ bolt line #1:

\[ A_s = t \times w = (4.25'')(40') = 17.0 \text{ in}^2 \]

\[ \tau = \frac{49.1 \times 10^3}{17 \times 10^3} = 2.88 \text{ psi} \]

Normal Stress (Bending):

\[ \sigma_{max} = \frac{Mc}{I} = \frac{(49.1 \times 10^3 \times (28/2))}{(3 \times 10^3 \times 10^6 \times 9)} = 141 \text{ psi} \]

Von Mises:

\[ \sigma' = \left( \sigma_x^2 + \sigma_y^2 + \sigma_z^2 + 2\tau_{xy}^2 \right)^{1/2} \]

\[ \sigma_y = 0 \]

Brittle Coulomb Mohr:

\[ \sigma' = \frac{\sigma_x}{\sigma_y} = 812 \text{ psi} \]

Check bolt pullout: 2 top ones only for whole load, assume 3/4'' washers

\[ \sigma_x = \frac{49.1 \times 10^3}{2 \times 1.5''} = 558.6 \text{ psi} \text{ no problem} \]

Spring Calibration
Datum/Date: 2-3-13  Sammy Red

Design Comparison between 40" square and 38" square nominal

40" square 1st Order Analysis 38" square

Weight:
- Frame: 33.16 lb
- Moat: 25.5 lb
- Siding: 19.4 lb
- Shelf: 14.6 lb

all else (fasteners, windows, feet, mechanisms) either stays same or negligible

short total: 92.9 lb 86.9 lb

* a glass moat would add 23 lbs (and $300)
Only 6 lbs saved in 38" design

* The 38" design will waste much less 1x1/4 angle iron since comes 30'

- Based on 75x75x6 blocks (nominal dimensions)

Area: \( 2(40) \times 2(189) = 1,198 \text{ in}^2 \)

Ideal # blocks: \( 2(\frac{75}{3}) + 2(\frac{28}{2}) = 208 \text{ blocks} \)

With mess \( \times \frac{1}{2} \) (ideal) \( \approx 104 \text{ blocks} \)

Good roughly 50 of plain, 50 of magnetic; 100 total
Spring Mechanism Program

Team Shake 'n Break

Hooke's Law

\[ x = 0.5 \text{ [in]} \quad \text{Desired Table Displacement/Spring Compression} \]

\[ F_{\text{user}} = 15 \text{ [lb]} \quad \text{Desired User Force to Compress Springs} \]

\[ F_{\text{spring}} = F_{\text{user}} \quad \text{Force on Each Spring to Compress to Table Displacement} \]

\[ k_{\text{max}} = \frac{F_{\text{spring}}}{x} \quad \text{Spring Constant Based on Desired Displacement and Forces} \]

Spring Properties from McMaster

\[ k_{\text{act}} = 1.57 \quad \text{Actual k Selected} \]

\[ F_{\text{spring,act}} = k_{\text{act}} \cdot x \quad \text{Actual Force on Spring} \]

\[ D_D = 0.75 \text{ [in]} \quad \text{Spring Outer Diameter} \]

\[ d = 0.062 \text{ [in]} \quad \text{Wire Diameter} \]

\[ L_0 = 3.5 \text{ [in]} \quad \text{Free Length} \]

\[ L_{\text{ext}} = 6.506 \text{ [in]} \quad \text{Compressed Length} \]

\[ L_{\text{load, max}} = 6.26 \text{ [lb]} \quad \text{Maximum Load Spring Can Handle} \]

\[ L_{\text{load, min}} = k_{\text{act}} \cdot x + F_i + 0.25 \text{ [in]} \quad \text{Minimum Load on Spring} \]

\[ F_i = 1.54 \text{ [lb]} \quad \text{Initial Tension That Must be Exceeded Before Deflection} \]

\[ F_{\text{max}} = L_{\text{load, min}} + k_{\text{act}} \cdot x \quad \text{Maximum Load on Spring} \]

Table Components and Weights

\[ W_{\text{peg}} = 4 \text{ [lb]} \quad \text{Weight of Pegboard} \]

\[ W_{\text{plywood}} = 8 \text{ [lb]} \quad \text{Weight of Plywood} \]

\[ W_{\text{pillow}} = 1.5 \text{ [lb]} \quad \text{Weight of Pillowblocks} \]

\[ W_{\text{rail}} = 3.2 \text{ [lb]} \quad \text{Weight of Rails} \]

\[ W_{\text{block}} = 1 \text{ [lb]} \quad \text{Weight of Block} \]

\[ W_{\text{total}} = W_{\text{peg}} + W_{\text{plywood}} + W_{\text{pillow}} + W_{\text{rail}} + W_{\text{block}} \quad \text{Total Weight to Move} \]

Natural Frequency

\[ m_{\text{total}} = W_{\text{total}} \cdot \frac{1}{32.2 \frac{\text{lbm}}{\text{slug}}} \quad \text{Total Mass to Move in Slugs} \]

\[ f_n = \frac{1}{2} \cdot \pi \cdot \left[ k_{\text{act}} \cdot 1 \frac{\text{slug} \cdot \text{ft}^2}{\text{lb}} \cdot \frac{12 \text{ [in]} \cdot \text{ft}}{\text{slug} \cdot \text{sec}^2} \right]^{0.5} \quad \text{Natural Frequency of Table, (Logbook Calculation)} \]
Calculated Spring Parameters

\( d_{\text{mean}} = OD - d \)  Mean Spring Diameter

\[ C = \frac{d_{\text{mean}}}{d} \]  Spring Index, (Equation 10-1)

\[ K_B = \frac{4 \cdot C + 2}{4 \cdot C - 3} \]  Bergstrasser Factor, (Equation 10-6)

Service Load Factor of Safety

\( m = 0.146 \)  Constant \( m \), (Table 10-4)

\( A = 169 \cdot 10^3 \)  Constant \( A \), (Table 10-4)

\[ S_{\text{ut}} = \frac{A}{\pi d^2} \]  Minimum Tensile Strength, (10-14)

\[ S_{\text{ty}} = 0.35 \cdot S_{\text{ut}} \]  Torsional Shear in Main Body, (Table 10-7)

\[ \tau_{\text{max}} = 8 \cdot K_B \cdot F_{\text{max}} \cdot \frac{d_{\text{mean}}}{\pi \cdot C^2} \]  Shear Stress Under Service Load, (Example 10-6c)

\[ n = \frac{S_{\text{ty}}}{\tau_{\text{max}}} \]  Factor of Safety, (Example 10-6c)

End Hook Bending

\[ K_A = \frac{4 \cdot C^2 - C - 1}{4 \cdot C \cdot (C - 1)} \]  Bending Stress Correction Factor for Curvature, (Equation 10-35)

\[ \sigma_{\text{t}} = F_{\text{max}} \cdot \left[ K_A \cdot 16 \cdot \frac{d_{\text{mean}}}{\pi \cdot C^2} + \frac{4}{\pi \cdot C^2} \right] \]  Maximum Tensile Stress on Hook due to Bending and Axial, (Equation 10-34)

\[ S_{\text{y}} = 0.55 \cdot S_{\text{ut}} \]  Yield Strength, (Table 10-7)

\[ n_{\text{AH}} = \frac{S_{\text{y}}}{\sigma_{\text{t}}} \]  Factor of Safety for End Hook Bending

Fatigue Parameters

\[ F_A = \frac{F_{\text{max}} - F_{\text{load min}}}{2} \]  Alternating Load, (Equation 10-31a)

\[ F_m = \frac{F_{\text{max}} + F_{\text{load min}}}{2} \]  Midrange Load, (Equation 10-31b)

\[ S_{\text{tu}} = 0.67 \cdot S_{\text{ut}} \]  Ultimate Shear Strength, (Equation 10-30)
Fatigue Parameters

\[ F_a = \frac{F_{max} - Load_{min}}{2} \quad \text{Alternating Load, (Equation 10.31a)} \]

\[ F_m = \frac{F_{max} + Load_{min}}{2} \quad \text{Midrange Load, (Equation 10.31b)} \]

\[ S_{Su} = 0.67 \cdot S_{u} \quad \text{Ultimate Shear Strength, (Equation 10.30)} \]

Body Cell Fatigue

\[ \tau_{02} = 8 \cdot K_B \cdot F_a \cdot \frac{D_{mean}}{2} \cdot d^2 \quad \text{Alternating Shear Stress, (Equation 10.32)} \]

\[ \tau_{0m} = \frac{F_m}{F_a} \cdot \tau_{02} \quad \text{Midrange Shear Stress, (Equation 10.33)} \]

\[ S_{se} = 35 \cdot 10^2 \quad \text{Unpeened Alternating Endurance Strength, (Equation 10.26)} \]

\[ S_{un} = 55 \cdot 10^3 \quad \text{Unpeened Midrange Endurance Strength, (Equation 10.26)} \]

\[ S_{se} = \frac{S_{ca}}{1 - \left( \frac{S_{cm}}{S_{ca}} \right)^2} \quad \text{Gerber Ordinale Intercept for Zimmerii, (Equation 6.42)} \]

\[ \eta_{body} = 0.5 \cdot \left( \frac{S_{Su}}{1500} \right)^2 \cdot \tau_{02} \cdot \frac{S_{ca}}{S_{ce}} \cdot \left[ -1 + \sqrt{1 + \left( 2 \cdot \tau_{0m} \cdot \frac{S_{ce}}{S_{Su} - \tau_{0a}} \right)^2} \right] \quad \text{Gerber Fatigue Criterion, (Table 6.7)} \]

Coil Yielding

\[ \tau_{0y} = \frac{F_y}{F_a} \cdot \tau_{02} \quad \text{Initial Shear Stress, (Example 10.7a)} \]

\[ r = \frac{\tau_{0y}}{\tau_{0m} - \tau_{0y}} \quad \text{Slope of Load Line for Coil Body, (Example 10.7b)} \]

\[ S_{zy} = \left[ \frac{r}{r + 1} \right] \left( S_{zy} - \tau_{0y} \right) \quad \text{Intersection with Yield Line, (Example 10.7b)} \]

\[ \eta_{body} = \frac{S_{zy}}{\tau_{02}} \quad \text{Coil Yielding Factor of Safety, (Example 10.7c)} \]

End Hook Bending Fatigue

\[ \sigma_{static} = F_a \cdot \left[ K_a \cdot 15 \cdot \frac{D_{mean}}{x \cdot d^2} + \frac{4}{x \cdot d^2} \right] \quad \text{Alternating Tensile Stress on Hook for Fatigue, (Equation 10.34)} \]

\[ \sigma_m = \frac{F_m}{F_a} \cdot \sigma_{static} \quad \text{Midrange Tensile Stress on Hook for Fatigue, (Equation 10.35)} \]

\[ S_e = \frac{S_{ce}}{0.577} \quad \text{Tensile Endurance Limit Using Distortion Energy Theory, (Example 10.7c)} \]

\[ \eta_{tens} = 0.5 \cdot \left( \frac{S_{Su}}{S_{m}} \right)^2 \cdot \sigma_{static} \cdot \frac{S_{ca}}{S_e} \cdot \left[ -1 + \sqrt{1 + \left( 2 \cdot \sigma_m \cdot \frac{S_e}{S_{ca} \cdot \sigma_{static}} \right)^2} \right] \quad \text{Gerber Criterion for Tension, (Example 10.7c)} \]

End Hook Torsional Fatigue

\[ \tau_{0ab} = K_B \cdot 8 \cdot F_a \cdot \frac{D_{mean}}{x \cdot d^2} \quad \text{Maximum Alternating Torsional Stress, (Equation 10.36)} \]

\[ \tau_{0mb} = \frac{F_m}{F_a} \cdot \tau_{0ab} \quad \text{Maximum Midrange Torsional Stress, (Equation 10.36)} \]

\[ \eta_{tens} = 0.5 \cdot \left( \frac{S_{Su}}{1500} \right)^2 \cdot \tau_{0ab} \cdot \frac{S_{ca}}{S_{ce}} \cdot \left[ -1 + \sqrt{1 + \left( 2 \cdot \tau_{0mb} \cdot \frac{S_{ce}}{S_{Su} - \tau_{0a}} \right)^2} \right] \]
## Appendix F – Gantt Chart

<table>
<thead>
<tr>
<th>Task Name</th>
<th>Duration</th>
<th>Start</th>
<th>Finish</th>
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<tbody>
<tr>
<td>Initial Contact Sponsor</td>
<td>9 days</td>
<td>Thu 9/27/12</td>
<td>Tue 10/9/12</td>
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<tr>
<td>Make requirements, constraints</td>
<td>8 days</td>
<td>Mon 10/1/12</td>
<td>Wed 10/10/12</td>
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<tr>
<td>Research/test necessary deflection and acc</td>
<td>2 wks</td>
<td>Thu 9/27/12</td>
<td>Wed 10/10/12</td>
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<tr>
<td>Project Proposal Writeup</td>
<td>5 days</td>
<td>Fri 10/12/12</td>
<td>Thu 10/18/12</td>
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<tr>
<td>Refine constraints, requirements</td>
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<td>Thu 10/11/12</td>
<td>Fri 10/26/12</td>
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<tr>
<td>Find/test force data for children under 12</td>
<td>2.2 wks</td>
<td>Thu 9/27/12</td>
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<tr>
<td>Brainstorming</td>
<td>7 days</td>
<td>Fri 10/12/12</td>
<td>Mon 10/22/12</td>
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<tr>
<td>Work on conceptual Mechanism</td>
<td>1.65 mons</td>
<td>Fri 10/12/12</td>
<td>Tue 11/27/12</td>
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<td>Research possible materials</td>
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<td>Thu 9/27/12</td>
<td>Mon 11/12/12</td>
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<tr>
<td>Begin Drawings, Detailed Concept</td>
<td>25 days</td>
<td>Tue 10/23/12</td>
<td>Mon 11/26/12</td>
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<tr>
<td>Conceptual Model due</td>
<td>1 day</td>
<td>Mon 11/5/12</td>
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<tr>
<td>Conceptual Design report</td>
<td>1 day</td>
<td>Thu 11/29/12</td>
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<tr>
<td>Building block design: size, variation</td>
<td>6 wks</td>
<td>Fri 10/12/12</td>
<td>Thu 11/22/12</td>
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<tr>
<td>Research premade parts</td>
<td>6 wks</td>
<td>Thu 10/11/12</td>
<td>Wed 11/21/12</td>
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<tr>
<td>Preliminary Stress/Fatigue analysis</td>
<td>5 wks</td>
<td>Tue 10/23/12</td>
<td>Mon 11/26/12</td>
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<tr>
<td>CDR Report</td>
<td>3 wks</td>
<td>Wed 1/30/13</td>
<td>Tue 2/19/13</td>
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<td>CDR Presentation</td>
<td>1 day</td>
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<td>Build Blocks</td>
<td>69 days</td>
<td>Mon 2/4/13</td>
<td>Thu 5/9/13</td>
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<td>Purchase components</td>
<td>26 days</td>
<td>Thu 2/21/13</td>
<td>Thu 3/28/13</td>
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<td>Assemble table</td>
<td>31 days</td>
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<td>Test Table</td>
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<td>Thu 4/4/13</td>
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<td>Aesthetic Design/Implementation</td>
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<td>Educational Material</td>
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<td>Thu 5/2/13</td>
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<td>Expo Prep (Poster)</td>
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<td>Senior Expo</td>
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<td>2 days</td>
<td>Sat 6/1/13</td>
<td>Mon 6/3/13</td>
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