

REBAR IMPALEMENT SAFETY

A Senior Project submitted to
the Faculty of California Polytechnic State University,
San Luis Obispo

In Partial Fulfillment
of the Requirements for the Degree of
Bachelor of Science in Industrial and Manufacturing Engineering

Report by
Steven Hoover
Spencer Nefores
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Abstract

This project is sponsored by Webcor with the purpose of finding a better solution to rebar impalement safety. The current rebar impalement safety caps being used by Webcor were found to frequently fall off after being installed. This results in workers being exposed to the hazard for longer than desired. The research that has been done by the team showed that rebar impalement is a serious hazard and results in injury or death every year. Site visits and interviews were performed to aid in understanding the problem and designing solutions. The customer needs, current state of the problem, existing solutions, historical data relevant to the project and the materials and methods of manufacturing were thoroughly researched and considered when designing potential solutions.

The team followed the Define, Measure, Analyze, Improve and control methodology when approaching the project. Once the current state was defined and measured through research and testing of the currently available caps, the team designed and tested a new prototype cap. The tests included vertical pull tests to determine how much force was required to remove a cap, a strike test to determine how well a given cap would withstand a sudden impact to the bar it is installed on, and a durability test to compare how well different materials withstood repeated installation. After comparing the results, it was found that the new prototype outperformed the current safety caps in all tests.

The two key factors of the new design that were found to be significant during testing were: the materials it was made of and the design of the interior of the cap where it's installed onto the bar. Using the results and experiences from the testing phase the team designed a improved version of the prototype, but were unable to produce or test it due to the time constraints of the project. Several considerations were taken when designing the final design: manufacturability, materials, sustainability and durability.

Table of Contents

Section 1: Introduction	5
<i>The Problem</i>	5
<i>Our Team</i>	5
<i>Our Sponsor</i>	5
Section 2: Background	6
<i>Customer Needs</i>	6
<i>Current State</i>	7
Literature Review	9
<i>Reinforcing Bar</i>	9
<i>Impalement History</i>	9
<i>Existing Rebar Safety Products</i>	9
<i>OSHA Regulations</i>	11
<i>Rebar Safety Drop Test</i>	11
<i>Materials and Methods of Manufacturing</i>	12
Section 3: Objectives	14
<i>Problem Statement</i>	14
<i>Problem Description</i>	14
<i>Design Specifications</i>	14
<i>Economic Evaluation</i>	15
Section 4: Solution Design	17
<i>Long Neck Prototype</i>	17
<i>Short Neck Prototype</i>	17
<i>Interior Configurations</i>	18
<i>Manufacturing Prototypes</i>	19
Section 5: Testing	20
<i>Vertical Pull Test</i>	20
<i>2.5in. Vs. 4in.</i>	24
<i>Kick Test</i>	27
<i>Durability Test</i>	28
Section 6: Final Design	30
<i>FEA</i>	31
<i>Injection Mold</i>	32

Material Selection	33
Section 7: Business Case	34
Section 8: Areas for Further Study	36
Section 9: Project Management and Analysis	37
<i>Design Process</i>	37
Key Activities	38
<i>Special Techniques</i>	38
<i>Key Deliverables</i>	38
<i>Overall Timeline</i>	38
Project Management Analysis	38
Client Communications Analysis	39
<i>Teamwork Analysis</i>	39
Section 10: Conclusion	40
References	41
Appendix A: Quality, Function, Deployment & House of Quality	44
Appendix B: Gantt Chart	45
Appendix C: Engineering drawings	46
Appendix D: DOE	49

Section 1: Introduction

The Problem

During construction, before the concrete foundation is poured, stage steel rebar is tied together and cast into the concrete foundation to provide added strength. Once the rebar is installed, there is usually a time frame when the rebar is left exposed before the concrete is poured. The exposed vertical rebar dowels present a substantial impalement risk to workers due to their sharp edges and rigidity. To combat this hazard, it is required that exposed vertical rebar that is less than six feet high be covered. This is usually accomplished by using OSHA-approved rebar safety caps. These are plastic caps with a steel plate embedded in their flat top. While the rebar safety caps offer effective impalement protection, they can fall off and re-expose the hazard. Our team has been tasked with finding a solution to better eliminate this hazard.

Our Team

Our team members have varied backgrounds and consists of three students from three different majors:

- Steven Hoover, Manufacturing Engineering
- Spencer Nefores, Industrial Engineering
- Brent Snyder, Construction Management

Our Sponsor

Webcor is a San Francisco-based construction company that focuses on building high quality, multi-floor buildings all over California. Our company sponsor is Galen Dougherty, a Project Engineer at Webcor and recent graduate of Cal Poly, SLO.

Section 2: Background

Customer Needs

To better understand our customer needs we interviewed our sponsor, Galen Dougherty, about his experiences regarding rebar safety.

According to Galen, Webcor Builders needs a better solution to prevent exposed vertical rebar. Currently, rebar caps are purchased from CMC Construction Services. A laborer working on the construction site places caps on exposed vertical rebar, but many of them fall off. This ultimately results in prolonged exposure of workers to the impalement hazard and requires the labor of capping the rebar to be done again; sometimes recapping must be done several times. Unfortunately, there is no available data on exactly how often the caps fall off because companies only require that workers fix any caps that have fallen off; they do not require that they report it for data recording. When asked to estimate how frequently he sees rebar safety caps that have fallen off, Galen replied “all the time”. He acknowledges that no data exists for the frequency that they fall off, but is confident that the problem is widespread and observed at every Webcor construction site that requires rebar installation.

While Webcor mostly uses OSHA approved rebar safety caps, Galen has mentioned that occasionally they also construct their own impalement safety measures using 2x4 pieces of wood fixed atop the vertical pieces of rebar. Our research into OSHA regulations shows that this practice can be effective, but to be OSHA approved it must be designed and drop tested. It was unclear from our interview if this is the case. The specifics of the OSHA regulations regarding rebar safety are covered in detail in the literature review section.

Galen and Webcor desire a better solution to rebar safety that will:

- a) Minimize employee exposure to the impalement hazard posed by vertical rebar
- b) Reduce the amount of work and re-work necessary to minimize the hazard.

In order to determine if the new designs are successful, the caps will be tested against current solutions with a series of mechanical pull tests and trials. These tests will be described in greater detail later in this report.

Galen has expressed interest in a new rebar cap design, but also acknowledges that if other processes/methods of design can eliminate the hazard, these types of solutions are also welcome.

Current State

To better understand the current state of the problem members of the team visited two Webcor construction sites just prior to the concrete pouring process. The first site was a 48 story building in San Francisco and the team got to observe as one of the last floors was getting ready to pour concrete. The team observed that much of the rebar for this site was not vertical and so did not require safety caps. Impalement hazards existed mostly in the form of steel stakes used to hold the concrete form boards in place and these were all capped. No caps had fallen off during the time of this visit, but the concrete pouring was about to commence which meant that large amounts of people were present and ensuring the caps were properly installed.

The most important thing learned at this site was that there were extreme tripping hazards everywhere. The floor that was being built was entirely covered in rebar that was raised about 12 inches off the ceiling of the floor below. This means that all of the workers have to balance and walk across half inch diameter bars. While the workers were adapted to this kind of hazard, the risk that any one of them could misstep or lose their balance is very real. Should they fall in the vicinity of an exposed impalement hazard, the results would be severe injury or death by impalement.



Fig 1: The first Webcor site visited by the team

The second site that the team visited was in the very early stages of construction. It was the foundation of a skyscraper that was several floors below street level. The foundation of such a

large building requires large amounts of concrete to be poured, and so there was a substantial amount of vertical rebar present. The team observed the first instance of a rebar safety cap that had fallen off while at this site.



Fig 2: The second Webcor site visited by the team

Several potential causes for rebar caps falling off were observed at the second site:

- The rebar sizes for foundations are much larger. Installing caps on larger rebar sizes damages the plastic fins that hold the cap to the bar.
- Damaged caps were frequently still being used and were occasionally taped onto the bar. If the tape wasn't used or failed, the cap was likely to fall off again.
- Long pieces of long rebar were stored horizontally at the base of vertically installed rebar (seen in the image above) that had caps installed. When the stored rebar was retrieved, it could strike the base of the vertical bars or knock the cap itself.

Overall, the site visit was extremely useful for the team to understand the process of installing rebar, why rebar safety caps are necessary and potential causes for them to fall off.

Literature Review

To further understand the problem and develop potential solutions, the team conducted extensive research into the topic of rebar, OSHA standards and injury data, impalement safety caps, and materials and methods of manufacturing safety caps.

Reinforcing Bar

The term rebar is short for “reinforcing bar”. The technique of using rebar to reinforce concrete was first developed in France around 1850 and became extremely common in the United States by the early 1920s. Adding rebar to concrete increases the load bearing ability, ductility and lifespan of the concrete. [19]

Impalement History

The Occupational Health and Safety Administration has online records of injury reports dating back to 1984. A search of rebar impalement resulted in 61 incidents. The key findings from the search of the OSHA data yielded the following:

- OSHA reported incidents involving rebar impalement result in death just over 26% of the time. 61 incidents, of which 16 were fatal.
- There is an average of 1.7 rebar impalement injuries reported to OSHA every year: 61 incidents over 36 years.

The data on the OSHA website only covers those incidents that were reported to, and recorded by, OSHA within the United States. [20]






It was also found on the OSHA website that 1 in 5 worker deaths in the United States in 2018 were construction related. The leading cause of death among construction workers were falls, which accounted for about 33% of their deaths. These deaths are not explicitly rebar impalement related, but show that falls are a commonly dangerous hazard on construction sites and that protection against impalement is necessary. [21]

Existing Rebar Safety Products

An important part of our research has been finding existing rebar safety cap products. This has informed and will continue to inform our understanding of the current situation and design decisions that we will make as the project progresses.

We found that there are two primary types of rebar safety caps: square and round flat topped caps made of plastic with steel plates embedded into the top. These types of caps are the most common impalement safety caps used in the United States. There are three other less common types, but not all are OSHA approved. Our findings are summarized in Table 1 below.

Table 1: Existing Rebar Safety Products

Product	Description	Picture
OSHA Orange Rebar Caps [9]	Fits #3 - #8 rebar sizes, California OSHA and Federal OSHA approved, patented design.	
Carnie Cap Rebar Protection Cap [11]	Only two required per 8ft of coverage. Holds a 2x4 over the tops of exposed rebar. OSHA approved. Fits #4 - #9 rebar.	
ERB ERB10 Safety Rebar Cap [13]	<i>Not OSHA approved</i> for impalement protection. Mostly for scratch/scrape protection. Fits size #3 - #8 rebar.	
NEVOSAFE Rebar Safety Strip [14]	<i>Not OSHA approved for impalement protection</i> , produced in Australia. Rated for 100 kg (~220 lbs) fall from 3 m (9.8 ft). Comes in 1 m strips.	
Dayton #9-#14 Suprotek Rebar Impalement Safety Cap [15]	OSHA approved, one size fits most, with steel plate.	

OSHA Regulations

Standard 29 CFR 1926.701(b), states: "all protruding reinforcing steel, onto and into which employees could fall, shall be guarded to eliminate the hazard of impalement" [3]. A 2014 OSHA letter interpreting this standard addresses possible solutions to rectify impalement hazards. While they neither advocate for nor ban any specific product, OSHA does say that protective devices that can withstand 250 pounds dropped from a 10-foot height fulfill the safety requirement in most cases [4].

Act of 1970 (General Duty Clause), requires employers to eliminate recognized hazards that may cause death or serious physical harm from job sites. This includes but is not limited to; Concrete Form Stakes, Exposed Bolts, and Steel Electrical Conduit. [13]

Rebar Safety Drop Test

Cal OSHA safety regulations mandate that manufactured safety caps for impalement risk must pass a drop test of a 250 pound dry (less than 10% moisture) sandbag from a height of 10 feet with no penetration of the safety cap. The sandbag should have a round shape with a circumference of 36 to 48 inches. [1]

The rebar used for the test shall be 6 inches long protruding vertically and be of size 4/8 inch diameter. Test stand can be seen below in figure 3.

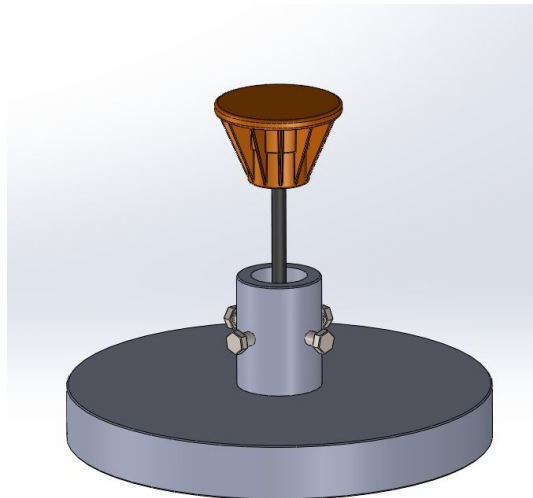


Figure 3. Rebar test stand design

For trough style safety systems, 3 pieces of 4/8 inch rebar are to be used with 12 inches between and on either end of the rebar. [1] A similar test stand may be used that will hold 3 pieces of rebar at the appropriate distances apart.

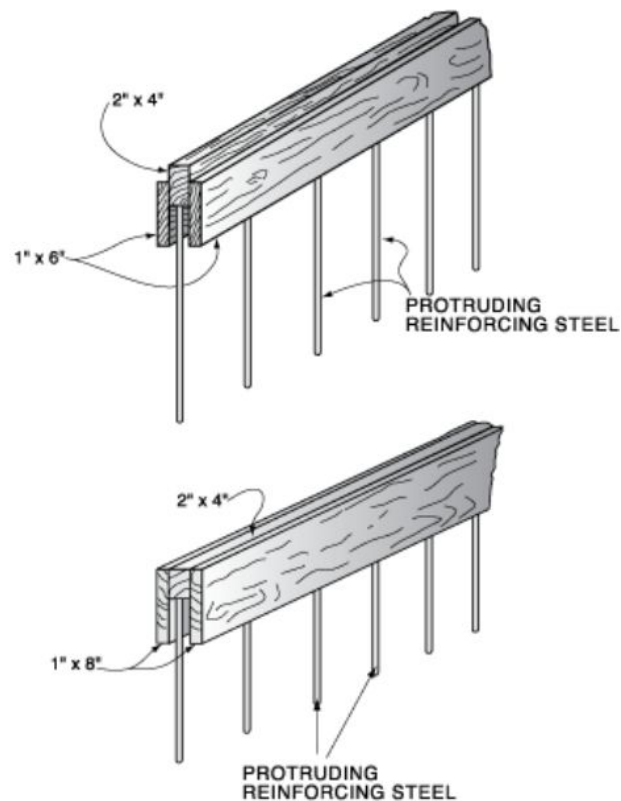


Figure 4. An example of a trough style rebar protection system [24]

Additionally, the safety cap must provide adequate surface area to prevent injury. Square top safety caps must be at least 4 inches by 4 inches, and round caps must have a minimum diameter of 4.5 inches. [1]

A registered engineer with appropriate competence must verify the test results. The test will be administered 3 times with separate caps. The first test shall be administered with the top flat and the subsequent 2 tests with the cap tilted at the maximum angle it can achieve while installed on the rebar. [1]

Materials and Methods of Manufacturing

The team searched through several patents, contacted manufacturers and reached out to materials engineers to try and determine exactly which materials were used, but could not find a definite

answer. The patents would only mention the material used was a high density polymer. This is likely referring to a trade secret blend of High Density Polyethylene (HDPE), a common plastic used in everything from hard hats, toys, automobiles and playground equipment. The popularity of HDPE stems from the fact that it has a high strength-to-density ratio, is relatively cheap and easy to mass produce. [22]

The most common method of mass producing HDPE products is injection molding. Injection molding is the process where a material is melted into a liquid state and then injected using pressure into a mold cavity holding the shape of the desired product.

Injection molding has several benefits and disadvantages. Two key benefits are the high-volume repeatability and low scrap rates. Simply put, once production has started it's easy to produce thousands or millions of the same product with a low rate of defects. There are two key disadvantages to injection molding: high tooling costs and the typical long lead times. Before the injection molding can take place, the mold that will hold the shape of the product must be designed from the design of the product itself. This often requires that the product design be altered so that the mold can actually be manufactured. It is common that a product be designed for injection molding without actually taking into consideration the limitations of manufacturing the mold for the part of how it will be removed from the mold. To properly design the part and the mold takes a significant amount of time and money that is directly related to the size and complexity of the desired product. [23]

Because rebar safety caps are needed in high volumes for the large types of construction taken on by Webcor, often in excess of 5,000 caps for on job, the team was confident that injection molding was the manufacturing method used for most caps. This was confirmed upon inspection of several safety caps and the discovery of ejector pin marks on each one. During the injection molding process, parts are removed from the mold with ejector pins that force the part out and leave recognisable marks.

Section 3: Objectives

Problem Statement

Exposed rebar is an impalement hazard for Webcor construction workers during the concrete pouring process and needs to be eliminated while minimizing labor and re-exposure.

Problem Description

There are two primary aspects of rebar safety that will be discussed in this section: the initial installation of rebar safety caps and the reinstallation of rebar safety caps that have fallen off.

Rebar is often left exposed for some period of time after it has been installed before workers can come through and install the safety caps. There is no standard amount of time that the rebar is left exposed and Webcor has expressed that they do their best to install the caps as soon as possible. It is generally the rebar subcontractor's job to install the caps, but this is not always the case, so Webcor considers it primarily their responsibility to buy, install and maintain rebar safety caps.

Due to the design of the current safety caps and the chaotic nature of most construction sites, the safety caps can fall off or be knocked off accidentally off at any time. There is no data available on how often the caps fall off, but it has been observed to happen and the risk is extremely dangerous because re-exposing the hazard leaves workers unprotected from possible impalement. Webcor has explicitly asked that this project examine ways to reduce this.

See Appendix A for a full list of customer needs and QFD.

Design Specifications

The specifications any proposed design must meet are: they must fit standard rebar sizes and must meet OSHA regulations. The OSHA regulations for rebar safety cap specifications are listed below.

OSHA Specifications

- Protective covers shall be made of wood, plastic, or other materials of equal or greater strength. [1]
- Square protective covers must have an impact surface of 4 inches x 4 inches or greater. [1]

- Circular protective covers must have a round impact surface with a diameter of 4.5 inches or greater. [1]
- Rebar safety caps must withstand a 250 pound impact from a height of 10 feet as specified in Title 8 section 344.90. [1]
- Caps must have a manufacturer's mark, model number or trademark, California approval number and size designation. [1] [2] [5]

Economic Evaluation

A major consideration for our project and any potential solution is that it must be economically viable. To determine this we must analyze and understand the current state of rebar safety economics.

The cost of buying or renting, installing and maintaining the rebar safety caps is substantial. The cost is different for every job, but Webcor provided an estimate of about \$27,000 for rebar safety for a 550,000 square foot/32 story building construction project. This includes the cost of all labor and materials related to rebar safety caps. This cost breaks down further into an estimated cost per square foot of \$0.05 for rebar safety. When the size and scope of larger construction companies is considered, with some skyscrapers like the Sears Tower enclosing over 4.5 million square feet, it can be understood that rebar safety costs are significant. Using Webcor's cost estimates, the cost for rebar safety for the Sears Tower would have been at least \$225,000.

Other Economic Considerations

Beyond the cost of materials and labor, there are other aspects to consider with regards to rebar safety. These aspects are more difficult to apply to our solution design for comparison, but must still be considered and serve as motivation for ensuring that this problem be properly addressed.

- OSHA Violations: \$13,260 per violation
 - Each uncapped piece of rebar reported by OSHA can cost the offending company the fine amount listed above. Repeat offenders can be fined in increasing amounts.

- Additional expenses:
 - Personal lawsuits: if an employer can be shown to be at fault, the injured worker can sue. These lawsuits are generally extremely expensive.
 - Cost of a high profile lawsuit involving a worker impaled by an uncapped rebar was \$ 22 million.
 - Workers' compensation: Workers injured on the job will generally be paid workers' compensation which can cost the employer hundreds of thousands, or millions, depending on the case.
 - Overtime for workers that need to cover shifts: If skilled workers get injured and cannot work, not only do employers have to pay the other costs listed above, they also will have to hire additional workers or pay for overtime to ensure that the job can continue on schedule.

Section 4: Solution Design

The senior project team decided to move forward with a cap style rebar safety device instead of the trough style cap in order to narrow the scope and allow for ease of prototyping and testing. For the exterior of the cap, they have developed two configurations for initial testing. The two configurations are a long and short necked variation. We chose to test these variations because we were unsure if the contact angle of the bar to the silicone core was significant. Appendix C shows the team's cap ideas, some of which were not made or tested.

Long Neck Prototype

The long neck variation has a 4in. Long neck with 12 fins. The team hypothesised that the longer neck will help the cap remain on the rebar when it is snagged by a piece of gear or hit on accident. The 12 fins will help the workers gear from getting stuck under the lip of the cap. Figure 5.

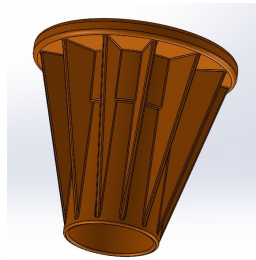


Figure 5. Long neck

Short Neck Prototype

The short neck is very similar to the 4in., with the only difference being that the neck is the standard 2.5in. length. The team will use this as a test comparison to see if the fin configurations and neck lengths are significant.

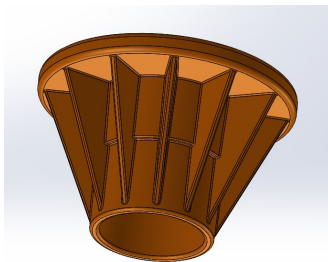


Figure 6. Short neck

Interior Configurations

The team believes that the fins located inside the neck of the cap that help it stay installed onto a piece of rebar could be better designed. After brainstorming possible solutions, the team selected a tapered interior cap design that can be seen below.

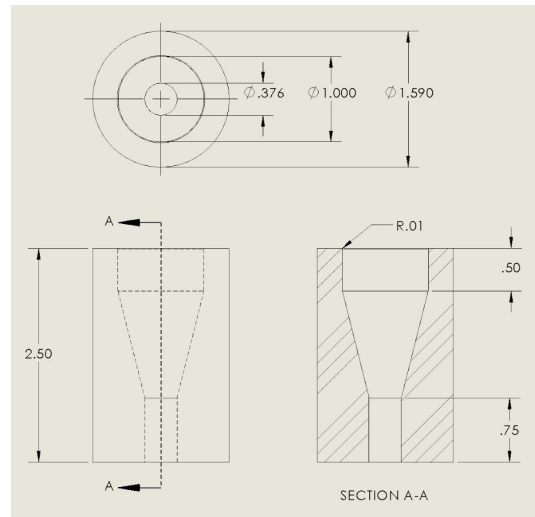


Figure 7: Tapered design

This tapered design was selected because of its potential durability. The fins in current safety caps seem to be the problem as they easily become damaged and lose their ability to effectively grip the bar. The tapered design has no fins and relies on surface area and surface texture between the cap and the bar to grip the bar. In designing this solution, the team had specific materials in mind to maximize its grip and durability.

The plastic used for the current caps is hard and slick. The team believes that a rubber or rubber-like material would be best as it would be durable and the surface texture would have more traction with the bar. The team did not have access to any methods or technology for fabricating a prototype out of the type of rubber that is used for more industrial purposes like tire rubber, but did have access to several different silicone and urethane rubber compounds.

Two silicone and one urethane material were selected to test how they interacted with the bar. These three silicone materials are:

- Mold Max 27T: A silicone rubber compound with shore hardness 27A.
- Mold Star 30: A platinum silicone rubber compound with shore hardness 30A.
- ReoFlex 60: A urethane rubber compound with shore hardness 60A.

Shore hardness is a measure of the resistance a material has to indentation and was a key property the team considered when selecting materials for prototyping. For reference, a rubber band is usually around 20A while a car tire is around 70A. Shore hardness reflects how much the material would flex out of the way of the bar during installation of the cap.

The three materials selected were available at hand and are created by mixing two component ingredients. The two components are mixed in specific ratios and then poured into a mold. Once poured, they are allowed to sit for a certain amount of time to cure. This process is relatively easy and not labor intensive, but it does take several hours to let the material cure.

Manufacturing Prototypes

To manufacture the prototypes of the selected design and material combinations, the team first 3D printed inserts of the shape of the interior taper. The inserts were fastened to 1.5in diameter PVC sleeves with metal tape to create the mold. Then the different silicone/urethane compounds were mixed and poured into the molds and allowed to cure. Once cured, the 3D printed inserts had to be removed with a press and were destroyed during the process because they bonded very strongly with the silicone material. These sleeved inserts were created to fit inside the existing 3D printed exterior caps that we prototyped. This was a cheap and efficient way for us to swap out materials and only use one body due to the extremely long build time and high cost of 3D printed material. The cores before silicone casting can be seen below in figure 8.



Figure 8. Core Prototyping

Section 5: Testing

In order to test different configurations and materials to evaluate what works best, the team came up with 3 tests.

Vertical Pull Test

In order to test how the materials compared to the current solution the team developed a test that measured vertical force to remove. This would show which material had the best retention on the bar and thus be less likely to fall or be knocked off.

For this test, a hook was fastened to the center of the top of each cap and a digital hanging scale was attached to the hook. A team member would install the cap being tested and pull straight up very slowly. The digital hanging scale was used to measure the force, in pounds, to remove each cap in the vertical direction. The test can be seen below in figure 9.



Figure 9. Pull Test

DOE for Vertical Pull Test

A full factorial design was developed with two factors. The first factor was material which consisted of four levels. The Silicone used in the test was 27T, 30, 60 and the standard cap. The second factor was the size of the bar used during the test. The levels for the bars were $\frac{3}{8}$, $\frac{1}{2}$, $\frac{5}{8}$. The test samples were tested for 3 replications in random order resulting in 36 treatments. The DOE run table can be seen in Appendix D. The test samples can be seen below in figure 10.



Figure 10. *Pull Test Samples*

Pull Test Results

The data was analyzed using JMP and did not reflect the constant variance assumption needed to conduct an ANOVA analysis. Because of this the data was transformed using a Logistic transformation. The data showed that the interaction between the bar and cap was insignificant so that term was dropped to further refine the model. An ANOVA table was then generated. The refinement of the model can be seen below in Appendix D.

The average force to remove for each material can be seen below in figure 11, where materials 1, 2, 3 and 4 are the 27A silicone, 30A silicone, 60A urethane and the current cap materials respectively. The average force to remove each cap, in pounds, is found under the mean column. As can be seen, the materials used in the prototypes outperformed the standard cap material by a significant margin, with the 60A urethane being the best performing material.

Least Squares Means Table			
Level	Least Sq Mean	Std Error	Mean
1	3.5000000	0.75202881	3.50000
2	3.0777778	0.75202881	3.07778
3	5.2000000	0.75202881	5.20000
4	0.6888889	0.75202881	0.68889

Figure 11. Average Force to Remove

It can be seen in figure 12 that material does have a statistically significant effect on the removal force of the cap. Additionally, the bar was not statistically significant.

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
bar	2	2	0.01822613	1.4200	0.2575
material	3	3	0.47304912	24.5702	<.0001*

Figure 12. Effects Test

The model can be seen below in figure 13. This shows that our model is statistically significant based on the low p-value. Additionally, the model is a proper fit for the data based on the R Squared value of .72.

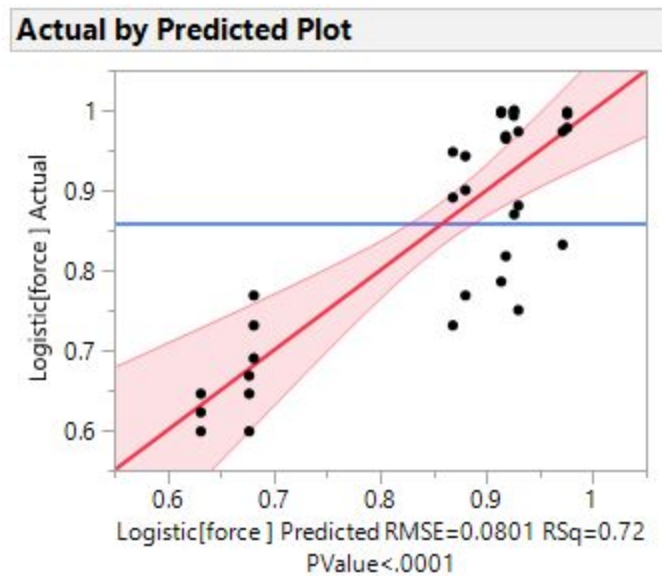


Figure 13. Model Fit & Significance

A Fisher LSD test was conducted on the data that shows the three silicone materials are statistically similar and differ from the standard cap. This can be seen below in figure 14. This test proved that all three silicones had the same gripping effect on the bar. Because of this, other criteria would need to be evaluated in the final selection of the material such as durability and cost.

Level		Least Sq Mean
3	A	0.95775352
1	A	0.91185660
2	A	0.90003425
4	B	0.66321032

Figure 14. Fisher LSD

Assumptions

Validation of the three ANOVA assumptions can be seen below in figures 15-17. These three assumptions allow the team to conduct the ANOVA tests seen above and are required in order to have meaningful and accurate data.

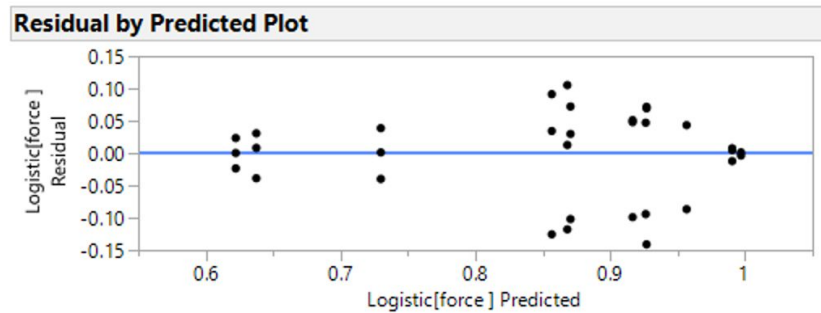


Figure 15. Check for Constant Variance

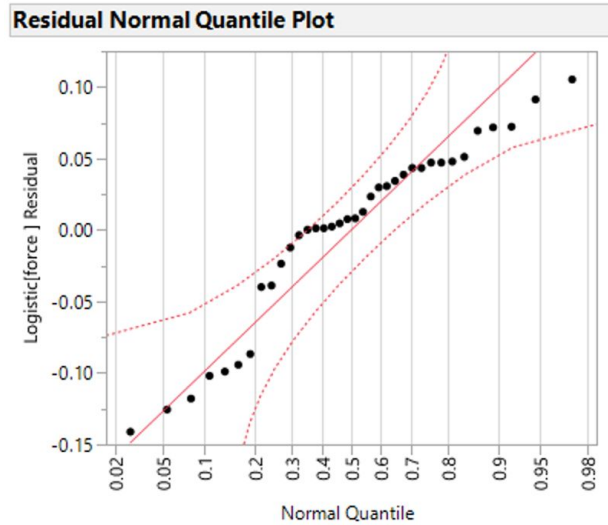


Figure 16. Check for Normality

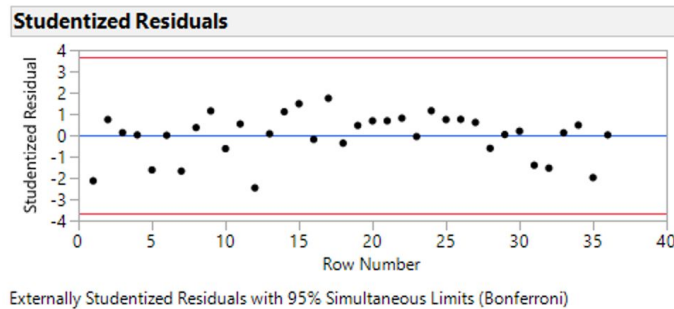


Figure 17. Check for Independence

2.5in. Vs. 4in.

The team wanted to evaluate whether there was a difference between the 2.5inch cap and the 4inch cap. The results of the Fisher LSD seen above in figure 14 showed that the three silicones were statistically similar. Silicone 60 was selected because it was about half the price of the other silicones. The same test as above was run using only cream 2inch and 4inch caps. This was silicone 60 which had the highest average force to remove and we suspected it was the most durable. We tested this suspicion later in the report. The 4inch test samples can be seen below in figure 18 but we only tested silicone 60 to limit the amount of treatments needed.



Figure 18. 4inch test samples

Our team designed a 2² factorial design using bars of size of $\frac{3}{8}$ and $\frac{5}{8}$, and cap size 2.5inch and 4inch. The data was coded and can be seen in appendix d. The data below in figure 19 shows that there is no significant difference between the 2.5inch cap and the 4inch cap thus the 2.5inch cap will be selected for use. The interaction was statistically significant but that was not the purpose of the test thus it was ignored. It is to note that this interaction did lead us down the path of the stair step design seen later in the report. We found that the more surface area on the bar helped retain the cap better than the portion with the taper.

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
bar	1	1	0.33333	0.0623	0.8092
cap	1	1	4.56333	0.8524	0.3829
bar*cap	1	1	128.05333	23.9203	0.0012*

Figure 19. Effects Test

Additionally, this is validated through the Fisher LSD test seen below in figure 20.

Level		Least Sq Mean
4in	A	9.9333333
2in	A	8.7000000

Figure 20. Fisher LSD

The model was shown to be statistically significant and have a good fit based on the p-value and R squared values below in figure 21.

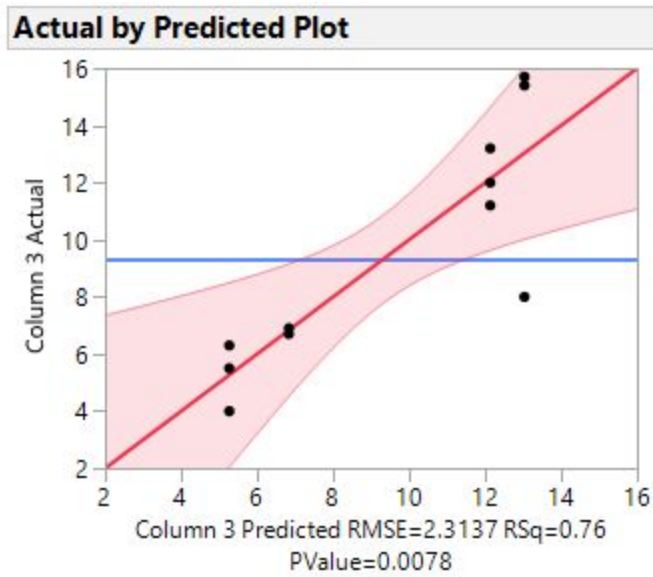


Figure 21. Model Fit & Significance

Assumptions

The ANOVA assumptions were validated and can be seen below in figure 22-24.

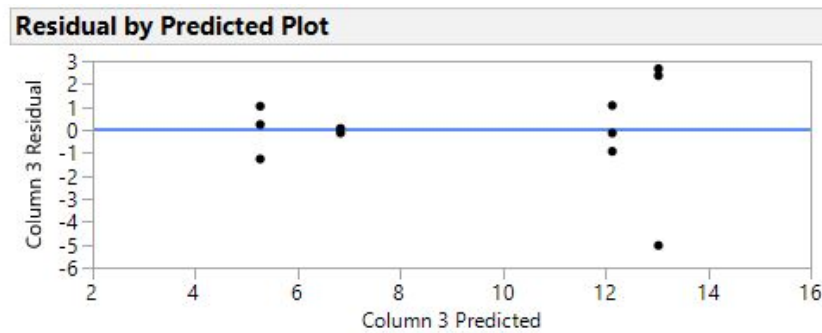


Figure 22. Check for Constant Variance

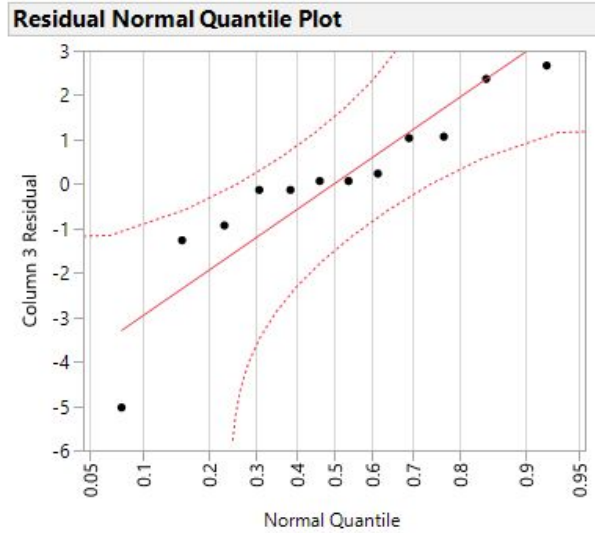


Figure 23. Check for Normality

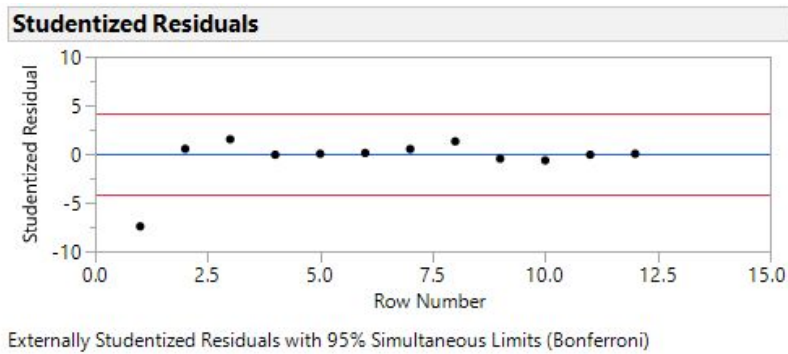


Figure 24. Check for Independence

Kick Test

Given what the team observed during their site visit and what Galen Dougherty has observed in his time working for Webcor, there was a desire to test how the caps do in relation to being struck and sustaining impacts. To accomplish this, a kicking apparatus was constructed to strike each bar and cap combination. The test was run with 3 replications for a total of 36 treatments similar to the first pull test. The test consisted of 3 bars with levels $\frac{3}{8}$, $\frac{1}{2}$, $\frac{5}{8}$, and with the 27A silicone, 30A silicone, 60A urethane, and the standard cap. The test setup can be seen below in figure 25. The run order can be seen in appendix d.



Figure 25. Strike Test

Because the data was binary the team conducted a proportion analysis and compared fall off rates. The current cap fell off 55.6% of the time whereas the silicone caps remained on the bar 100% of the time. The Mosaic plot in figure 26 is a graphical representation of the fall off rates of the caps. The raw data can be seen in appendix d. This test showed that the prototyped designs all held up very well when experiencing a strong impact, while the current cap was prone to falling off.

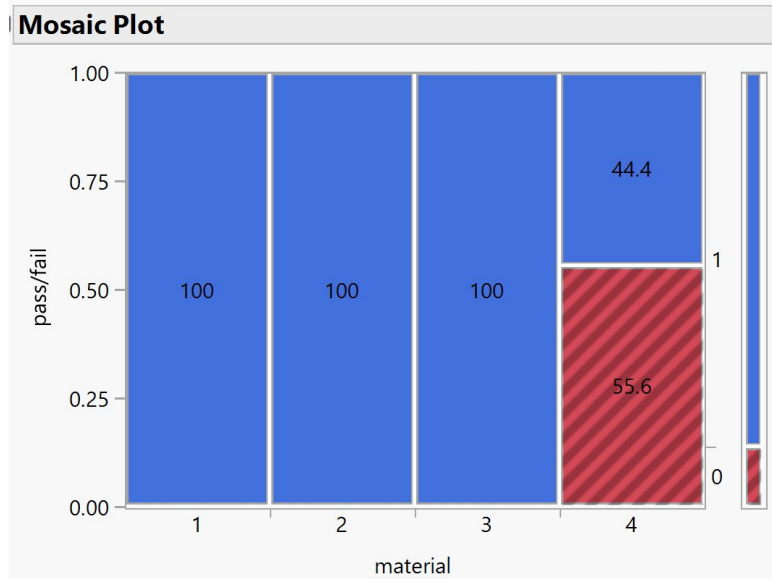


Figure 26. Mosaic Plot

Durability Test

The durability of the current solution was evaluated by placing the current rebar safety cap on a $\frac{5}{8}$ rebar dowel and removing it for 100 cycles. The results can be seen below in figure 27.

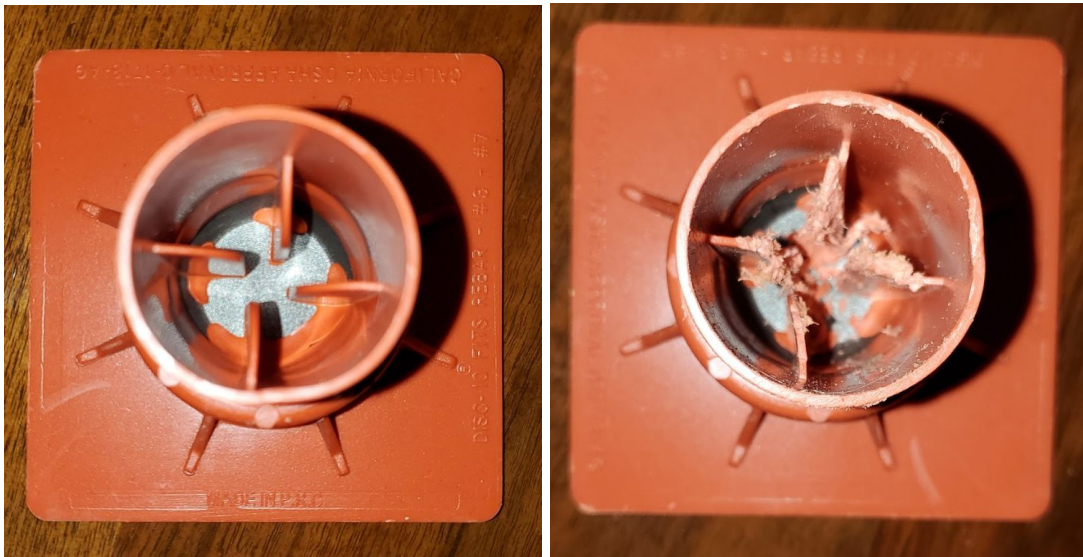


Figure 24. Standard cap before and after 100 cycles

The urethane 60A prototype was then tested for 300 cycles and the results can be seen below in figure 28. We chose to test the urethane much longer because there was almost no indication of wear after 100 cycles.

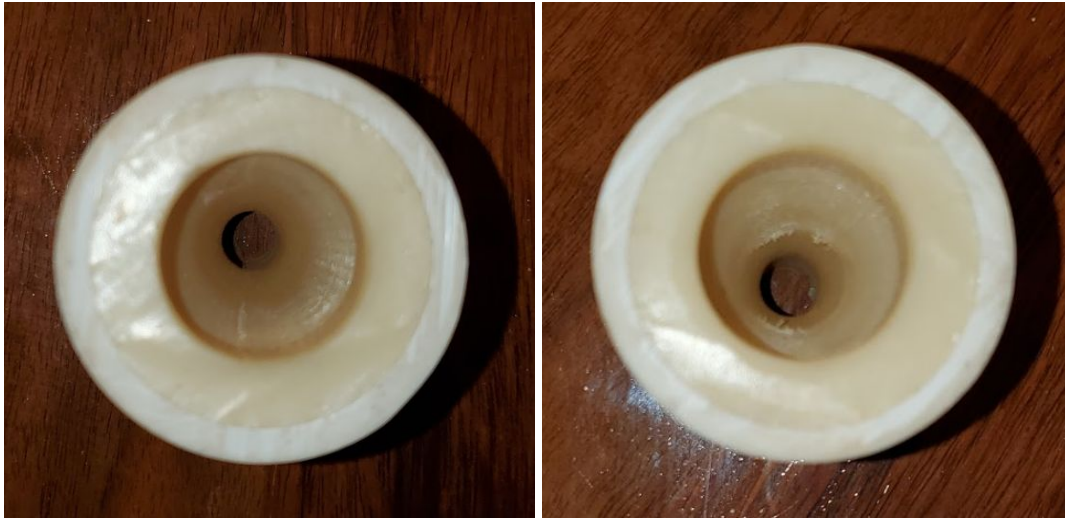


Figure 28. The urethane prototype before and after 300 cycles

An important thing to note when comparing these two results is that both designs are rated for the size of rebar they were tested on. Despite being rated for the bar, the standard cap deteriorated significantly faster than the urethane material. Even after being tested for over three times longer than the standard cap, the urethane material showed little signs of wear and tear. This is a promising result as damage to the fins in standard caps is suspected to be a major cause of their fall off frequency.

Section 6: Final Design

After testing the taper design, the team decided it could be improved by stair-stepping the taper in $\frac{1}{8}$ th increments to maximize the surface area on the bar. This is because after conducting testing they noticed that the $\frac{1}{4}$ rebar fit the best and had the best retention when the tapered design was installed. The $\frac{1}{4}$ is the only bar size that would fit into the straight section of the tapered design and the additional surface area is believed to be the cause of the better retention.

This design was not tested and will need further study. This design can be seen below in figure 29. A cross section of the design can be seen in Figure 30. An engineering drawing of the final cap can be seen in appendix c.

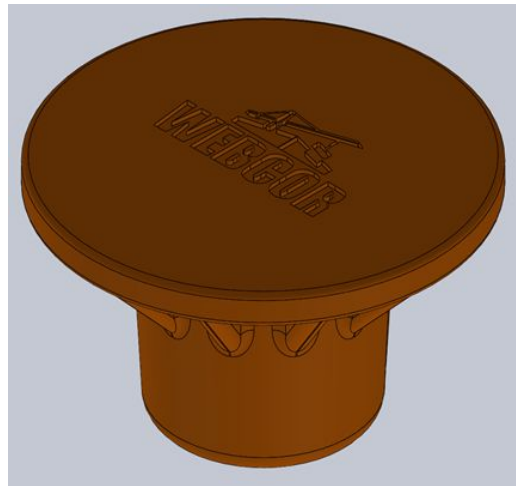


Figure 29. Final Design

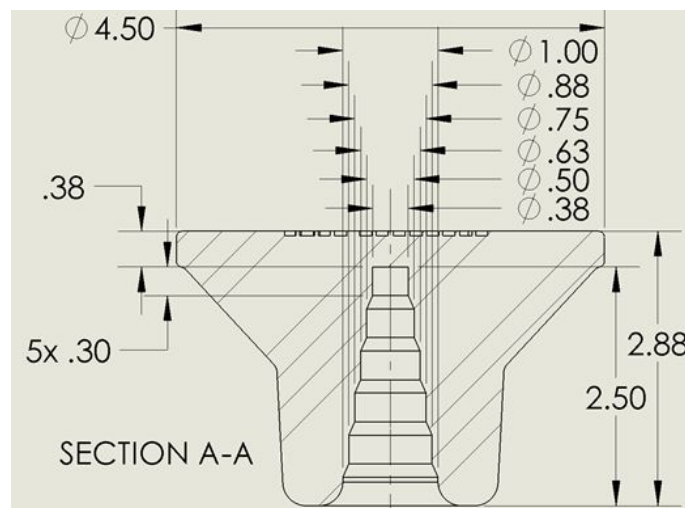


Figure 30. Cross section

FEA

It was suspected that the final cap may not need a steel reinforcing plate. This was never tested and is a topic for further evaluation in the future. A finite element analysis of the solution without a plate was conducted at various weights until the cap started to show failure. Figure 31 below shows a test with 2248lbs load applied to the cap. The test shows that the inner sleeve starts to fail but the rebar does not puncture the cap. The team is unsure if this is sufficient to pass a drop test and would need to be tested. If the test failed, the design would need to be altered to compensate or a steel plate would need to be added. The material properties can be seen in figure 32.

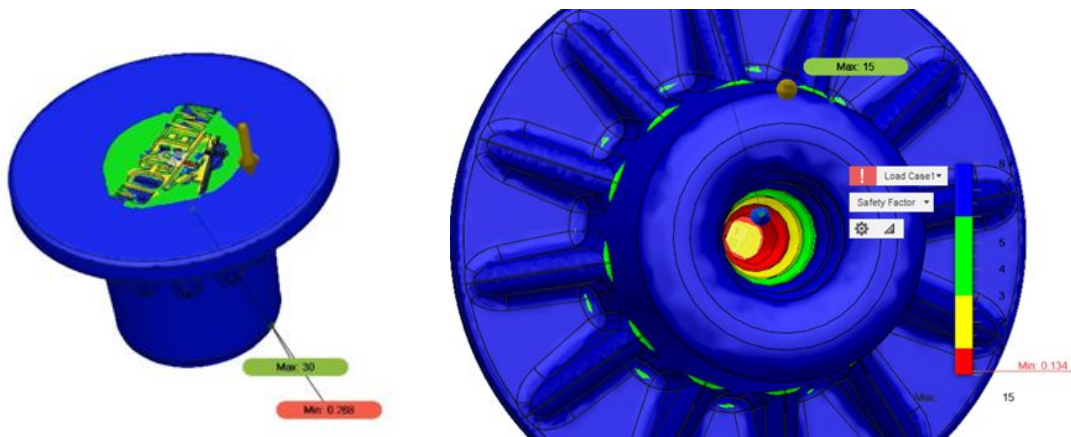


Figure 31. FEA Analysis

Material: Rubber, Silicone	
Density	1.25E-06 kg / mm ³
Young's Modulus	3 MPa
Poisson's Ratio	0.49
Yield Strength	10.34 MPa
Ultimate Tensile Strength	6.5 MPa
Thermal Conductivity	2.275E-04 W / (mm C)
Thermal Expansion Coefficient	8.1E-06 / C
Specific Heat	1880 J / (kg C)

Figure 32. Material Properties

Injection Mold

Webcor, and other construction companies, order thousands of rebar safety caps a year. To meet this high volume demand, injection molding was selected as the manufacturing method for the final design. This necessitated that a viable mold be designed.

The exterior of the cap was modified so that standard tools could be used in the machining of the mold cavity. The mold can be seen below in figure 33. Appropriate draft of 3 degrees was applied to vertical edges for ease of ejection from the mold seen in figure 34. Additionally, the parting line can be seen at the intersection of the red and green sections. Lastly, 4 ejector pins would eject the part from the mold.

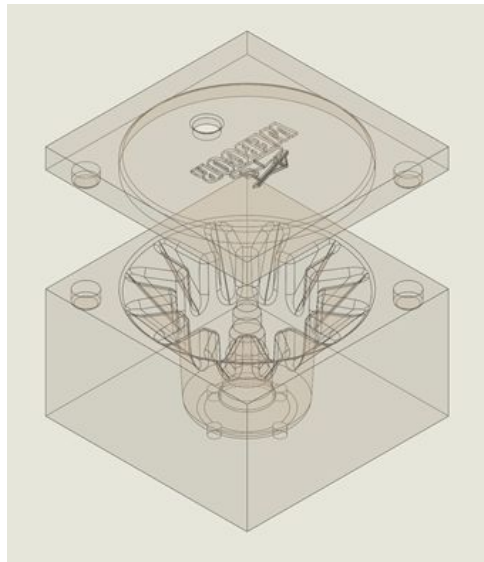


Figure 33. Injection Mold

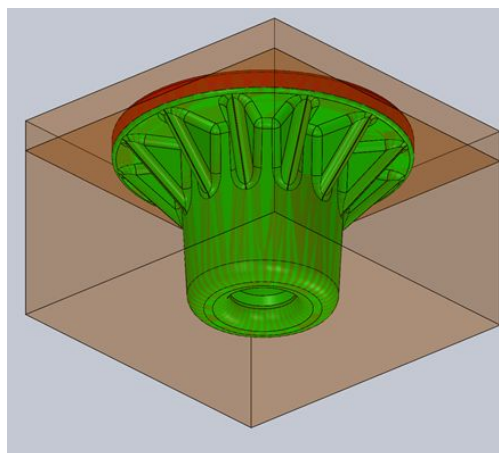


Figure 34. Draft Analysis

Material Selection

The specific rubber materials used to create the prototypes are not suitable for injection molding. The high temperatures and pressures would alter the properties of the material and result in lower quality products. This meant that the team had to find a material that could be manufactured using injection molding while retaining the properties that made it ideal as a solution.

The primary properties that made the prototypes successful were:

- Shore hardness of 60A: this allows the bar to push into the cap and increase surface area between the cap and the bar which results in better retention without causing damage.
- Durability: the caps are installed on steel bars with sharp edges several times per job. This is what caused damage to the current caps and resulted in their high fall off rate. Additionally, a higher durability cap means less purchasing of new caps and so a lower cost over time.

Other rubber compounds were researched to find a suitable replacement and the team found ethylene propylene diene monomer rubber, or EPDM. This rubber compound is suitable for injection molding and has the two key properties listed above. EPDM is commonly used in several vehicle components, seals, roofing materials, gaskets and several other areas due to its high durability, exception temperature operating ranges (-58 to 302 degrees fahrenheit) and high resistance to steam and water weathering. These properties make it an ideal candidate material for the final design solution proposed by the team.

The material was not available on campus and the time constraints of the project meant that the team was unable to request a prototype from a manufacturer before the project concluded, and so no testing has been done to ensure that EPDM yields the same results as the prototype materials. This will be a topic for further study.

Section 7: Business Case

Employee Safety and Wellbeing

The most important case that can be made for the new prototype is that it is much more likely to stay on the bar it is installed on. This means that, once installed, it is much less likely that a cap will fall off and expose workers to the impalement hazard. During the team's first meeting with Galen Dougherty, he said that his priority for the senior project was improving the safety of Webcor worksites. The team believes that their prototypes and proposed final design accomplish this.

The cap prototypes designed by this senior project team required several times the force to remove in the vertical pull test than the standard cap currently being used and did not fail a single strike test run while the current caps failed 55.6% of the time. This shows a dramatic increase in bar retention with the prototypes which would directly lead to an improvement of the safety of Webcor work sites.

Cost

To assess the financial viability for Webcor to adopt the final design proposed by this senior project team, several requests were made to manufacturing companies for production quotes. It is the understanding of the team, as confirmed by the sponsor, that Webcor has no intention of constructing a facility to produce the caps themselves. Their current supplier of rebar safety caps orders them from manufacturers in China, and so this was to be the basis for estimating costs. At the time this report was written, no company has replied to the request for a quote.

To establish a financial business case, despite the lack of production quotes, the team determined that the best method would be to use the durability testing to establish what the viable cost should be. This means using the cost information that Webcor supplied for the current state and a durability multiplier to determine what the maximum cost should be for the caps.

According to Webcor, they pay \$0.99 for a rebar safety cap. From the results of the durability testing, the team can say with confidence that their prototype cap will last at least 3 times longer than the standard safety cap. Given how little damage was observed on the prototype caps after the durability testing, it would be reasonable to assume they can last much longer than was tested for. This is an area for further study, but the team created a worst-to-best case comparison scenario.

- Worst case: the prototype designs only last 3 times longer than the standard caps.
 - This would put the competitive cost for the prototype cap at \$2.97 per cap
- Best case: the prototype design lasts 10 times longer than the current caps.
 - This would put the competitive cost for the prototype cap at \$9.90 per cap

This analysis provides an upper and lower range of the price that Webcor should expect to pay for the new caps. The lower end cost of \$2.97 is close to a general estimated cost for EPDM rubber custom injection molds provided by the company Brother Rubber. Brother Rubber provides a general price range for parts which is \$0.50 to \$1.99 per part. The parts from Brother Rubber range in size and complexity, some similar enough to the proposed cap design that it is not infeasible that the cost could be close to \$1.99, but a direct quote from them based upon the drawings provided would be required to say with certainty.

Another benefit of safety caps that last longer is that they will need to be reordered less frequently. This means less shipping, less reliance on global supply chains and a reduction in labor of receiving/distributing the new caps.

Sustainability

Another factor to consider is sustainability. The current caps are frequently thrown away when they become damaged, which means that they eventually end up in landfills. High density polymers are not biodegradable and are generally not recyclable or reusable. While rubbers are not biodegradable and are not directly recyclable, they can be repurposed. The EPDM rubber recommended by the team is frequently reused in the creation of non-slip coatings or as the safety surfacing under playgrounds. This means that any caps that do become damaged can potentially be sold or given to companies that make such products to avoid having them end up in landfills.

Section 8: Areas for Further Study

There are several areas of the project that would benefit from further study. The following items are those considered by the team necessary for the final design to be produced and implemented:

- Prototyping of cap in final design and material selections
 - The team did not have adequate time to obtain a prototype of the final design in the selected material.
- Drop testing the final design to ensure that it meets OSHA requirements
 - For any safety cap to be used on a work site it must be OSHA certified. This includes being drop tested.
- Testing of optimal material thickness
 - Given the exceptional strength properties of EPDM, there may be a thickness of material where a steel cap is not required. This could reduce costs.
- Testing of stair step design
 - Verify that the new design improves upon the previous one in cap retention tests
- Durability testing of selected material
 - The material would need to be tested until failure several times to discover its true durability and use lifespan. This would aid in the creation of a more adequate financial business case.
- Acquiring quotes from manufacturers for final cost
 - The team was unfortunately unable to get quotes despite making several requests to multiple companies. These quotes are critical to learning the actual cost of the final design.

Section 9: Project Management and Analysis

Design Process

For their project, this team has elected to use the DMAIC process to solve the rebar safety cap problem. The DMAIC process and the teams current progress is outlined below.



[5]

Define: Completed

Define customer needs and the current problem.

Measure: Completed

Visit Webcor worksites to gain understanding of the current state. Perform tests on the current rebar safety caps to measure relevant data for comparison to prototypes.

Analyze: Completed

Evaluate the collected data to identify the root cause of the problem. Compare results to the solution prototypes.

Improve: Complete

Using the data and experiences gained from testing to design solution prototypes. Create solution prototypes and conduct testing to compare to the current state.

Control: Complete

Evaluate solution prototypes with metrics used in the measure stage to determine if solution is successful. Improve design based upon the data and experiences.

Key Activities

- Visit active jobsite to assess the current state of the problem
- Visits of other (local) construction companies to gather more data/understanding
- Continuous literature review/research
- Updating of project Gantt chart to reflect progress
- Brainstorming and design reviews
- Project reports and presentations

Special Techniques

- Project management
- Design for manufacturing
- Computer Aided Drafting
- Design of Experiments
- Statistical analysis

Key Deliverables

- Literature Review
- Working prototype
- Final presentation of key findings
- Project technical report

Overall Timeline

The overall timeline for this project is dictated by the two quarter length of this Senior Project section. As such, the team had from the start of Fall quarter, 2019 until the end of Winter quarter, 2020 to complete their project.

The Gantt chart detailing tasks and task ownership can be found in Appendix B.

Project Management Analysis

The relatively small size of this team simplified the project management in many ways. With fewer people to delegate tasks to, it was easier to track who was responsible for what. The basic structure of the teams project management was based upon a schedule that was created at the beginning of every quarter. This schedule was then used to create a gantt chart. Weekly meetings were held to track the progress of tasks and the schedule was updated accordingly.

Team members were delegated tasks every week during team meetings. Any tasks that fell behind schedule were tracked and discussed. If needed, other team members would assist with a task or take over responsibility for the task to ensure that it was completed. This method of weekly meetings and task ownership was very successful as the team was ahead of schedule for much for the project

Client Communications Analysis

Maintaining client communication with the project sponsor, Galen Dougherty, was generally successful. Early in the project, the team had trouble maintaining contact with the sponsor, but a shift of the point of contact resulted in the team communicating via weekly phone calls and meetings with Galen. If a meeting needed to be canceled or moved it was clearly communicated with all members as soon as possible. After every meeting, a team member would email to the sponsor and all other team members the meeting minutes which detailed the subjects discussed as well as action items for both the sponsor and the team. This resulted in effective communication throughout the project.

Teamwork Analysis

Team communications were conducted using the GroupMe phone application to allow all members to observe any communications and stay informed of project progress. This was found to be an effective method.

Tasks were assigned at the beginning of every quarter so that each member was aware of their own responsibilities as well as the responsibilities of others. If a member was unable to fulfill their responsibilities by the dates scheduled, they would inform the other team members so that the proper actions could be taken.

Had a team member become delinquent with their tasks, neglected to effectively communicate with the team or had any other issues that prevented effective teamwork then the plan of action would have followed the following procedure: First, the other team members would have communicated with the member in question during a team meeting to determine the cause and a plan to correct the issue. If this was ineffective or the behavior continued, then the team would escalate the situation to the project advisor, Karen Bangs, and request a meeting with all members to resolve the issue. There was only one instance of this procedure needing to be implemented and it was early in the project's lifespan. The issue was resolved in the best way possible given the situation and the project was able to continue on schedule. No other instances occurred during the project that required this procedure to be enacted.

Section 10: Conclusion

The purpose of this report has been to document for both the project sponsor, Galen Dougherty, and the project advisor, Karen bangs, the research, testing and results of the rebar safety senior project. This conclusion will summarize the key findings and recommendations of the project team.

The research showed that rebar impalement is a serious hazard for construction workers. It was found that rebar impalement injuries occur at an average rate of nearly 2 per year and that at least 25% of rebar impalement injuries result in death. By visiting the site and interviewing the sponsor it was determined that the currency impalement safety caps are prone to falling off and re-exposing workers to the hazard. There are several varieties of rebar safety caps currently available on the market, but it was found that the most common solution is the standard orange safety cap design that uses plastic fins to retain the cap to the bar. This cap was found to be made of a high density polymer and produced using injection molding.

The testing and analysis of both the currently available rebar safety caps and the prototypes designed by the project team were conclusive. All prototypes designed by the team outperformed the current caps in all tests. Most notably, the prototypes had significantly better results in the vertical pull test, showing much improved retention, and the durability test which showed that the prototypes will last significantly longer without sustaining damage. The plastic fins that retain the currently used safety caps to the rebar were found to be a major cause of failure due to the fact that they quickly become damaged; even when installed on rebar sizes that they are rated for.

A final design was created using what was learned during the testing phase and a material that is suitable for mass production was also selected. This design is believed to further improve upon all aspects of the previous design, but was unable to be prototyped or tested due to time constraints.

There is still much that would need to be done for the project to result in actual production and implementation at a work site. The key items include further testing of the final design, obtaining quotes from manufactures and performing the OSHA required drop testing.

The team believes they have met the goals of the sponsor as detailed in the problem statement: the cap design proposed by the team would improve the safety of Webcor workers if properly vetted and implemented while not requiring any extra labor or training for Webcor workers.

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Appendix A: Quality, Function, Deployment & House of Quality

Customer Needs	Importance (1-5)
Protects workers from impalement (reliable)	5
Inexpensive	4
Can be scaled to different sized jobs	2
Shortens capping time	3
Eliminates re-exposure risk (doesn't fall off)	5
Reusable	3

House of Quality

This is an assessment of the potential solution of a cap redesign. The engineering specifications were combined with the customer needs and then compared against two current designs: the OSHA Orange Cap and the Carnie Rebar Protection Cap.

Project:	Rebar Safety Cap
Date:	10/26/2019

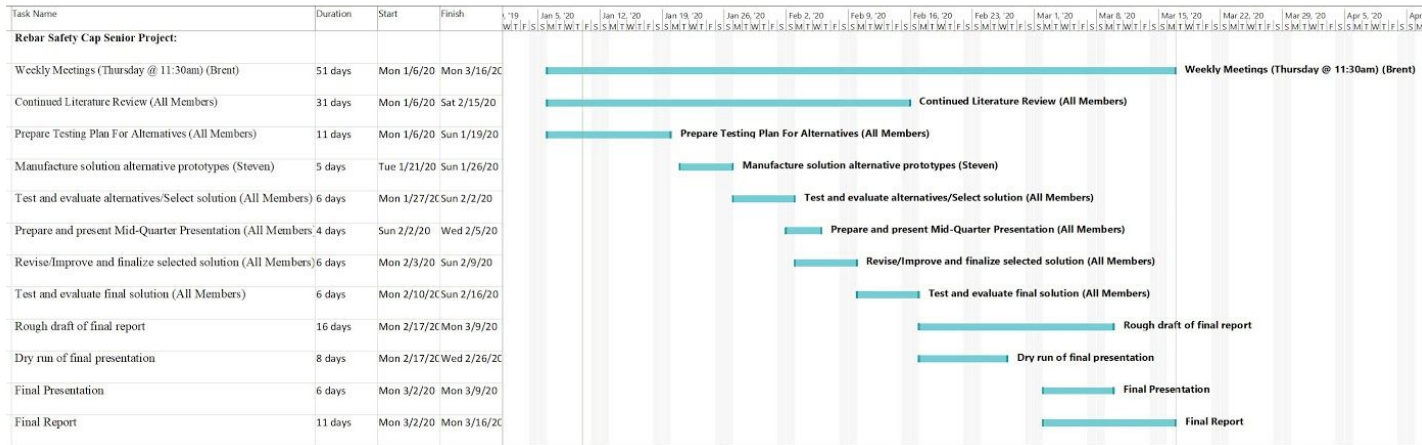
Relative Weight	Customer Importance	Customer Requirements	Functional Requirements					Customer Competitive Assessment		
			▲	□	□	▲	□	Our Product	OSHA Orange Square Rebar Cap	Carnie Cap (folds 2x4)
19%	5	Reliable (protects workers from impalement)	▽	○	●	●	●	5	5	5
19%	5	Inexpensive	●	○	○	○	○	4	5	2
15%	4	Scalability	▽	●	▽	▽	○	5	5	5
19%	5	Short Installation Time	○	○	▽	▽	▽	4	4	3
19%	5	Doesn't Fall Off	●	○	○	●	○	5	1	4
11%	3	Reusable	○	▽	▽	▽	●	5	3	5
Importance Rating Sum (Importance x Relationship)			455.5555556	366.6666667	322.2222222	433.3333333	551.8518519			
Relative Weight			21%	17%	15%	20%	26%			
Our Product			5	3	5	5	5			
OSHA Orange Rebar Cap			4	4	5	1	4			
Carnie Cap			3	3	5	4	5			
Technical Competitive Assessment										

-		+	
+		+	

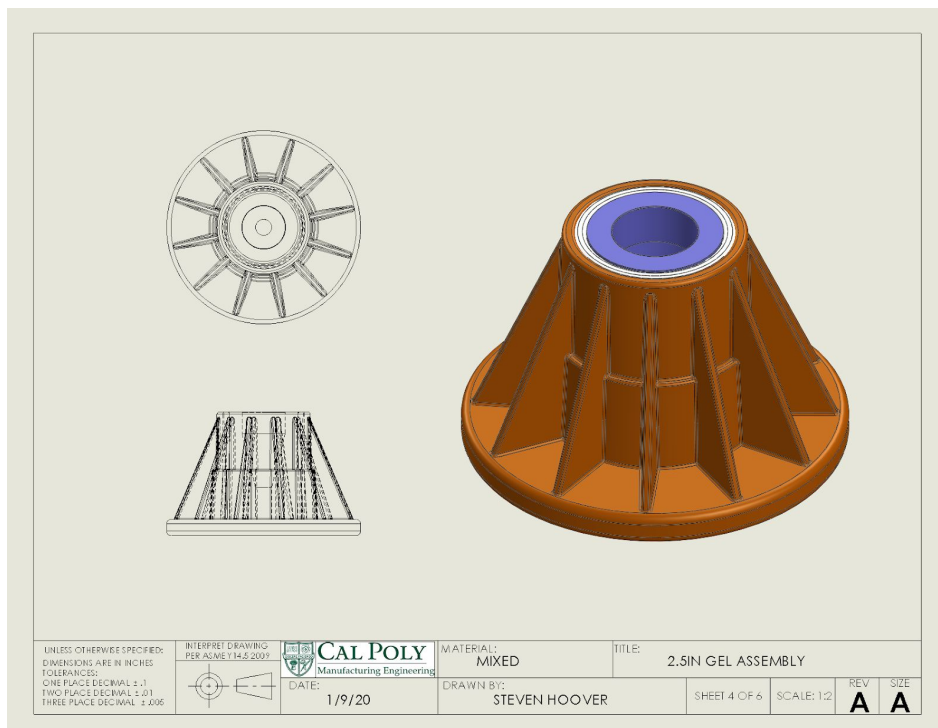
Correlations	
Positive	+
Negative	-
No Correlation	

Relationships	Weight
Strong	●
Medium	○
Weak	▽

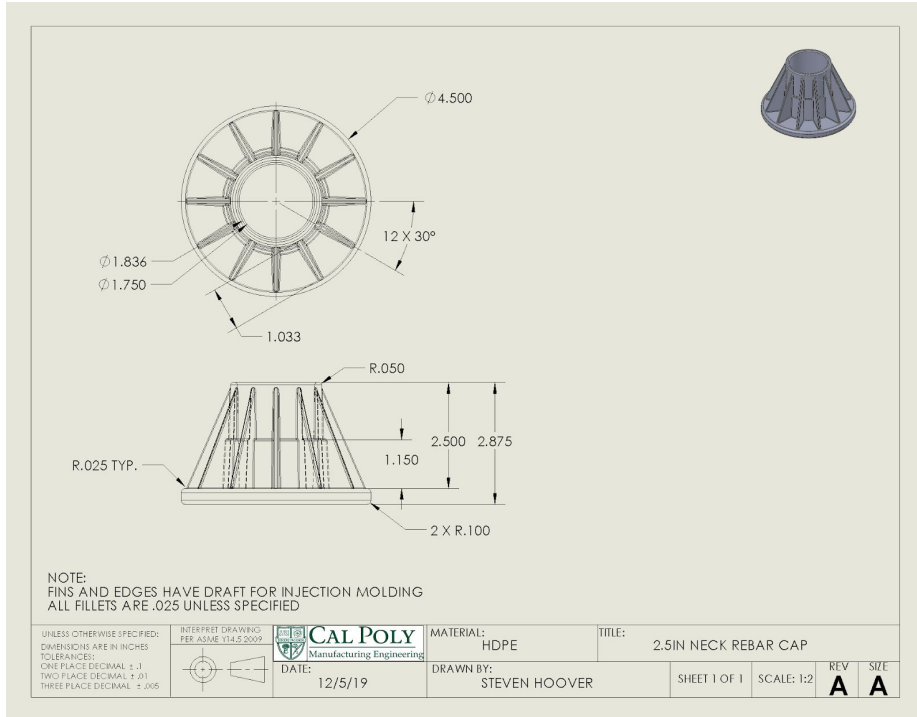
Appendix B: Gantt Chart



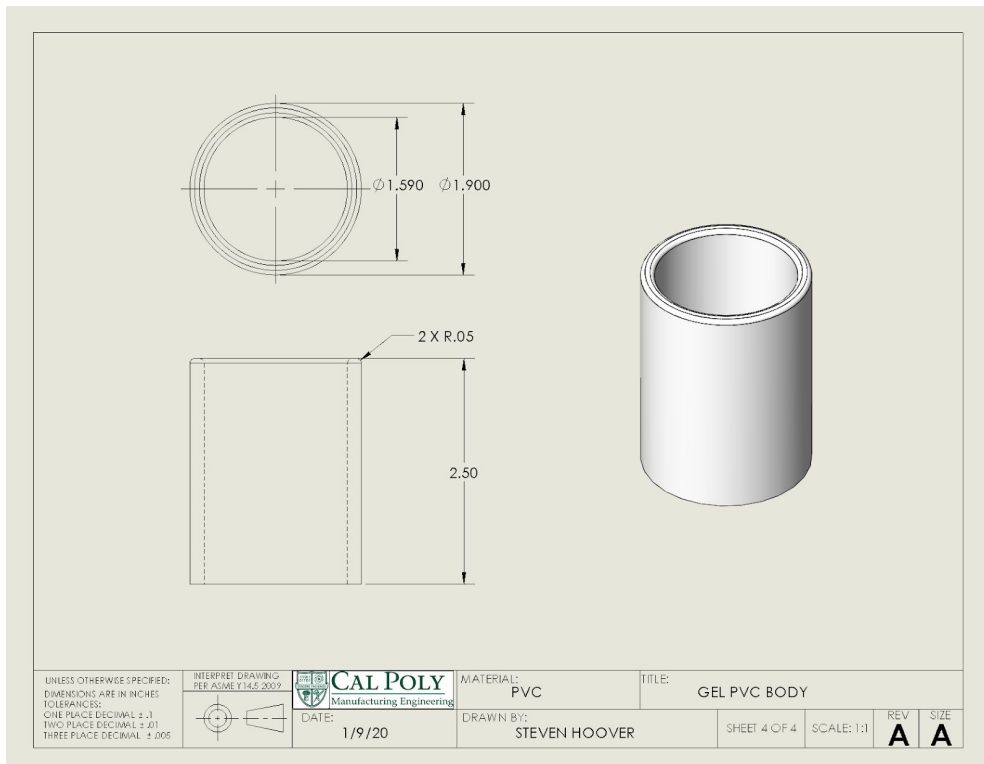
Appendix C: Engineering drawings



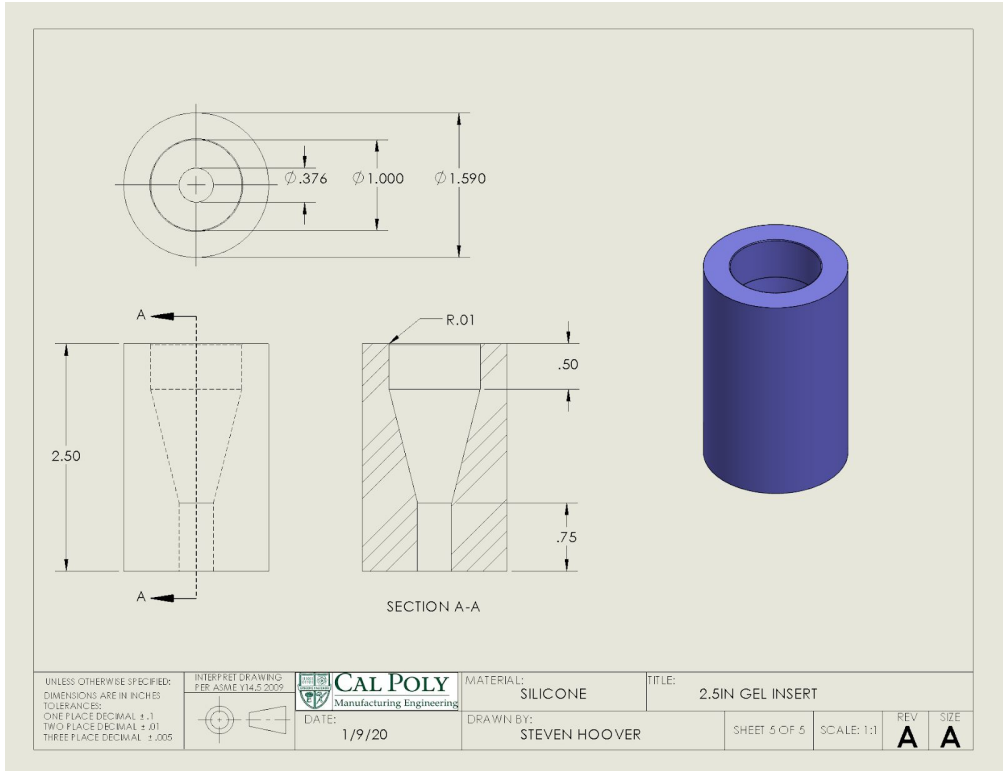
Safety cap and insert assembly drawing



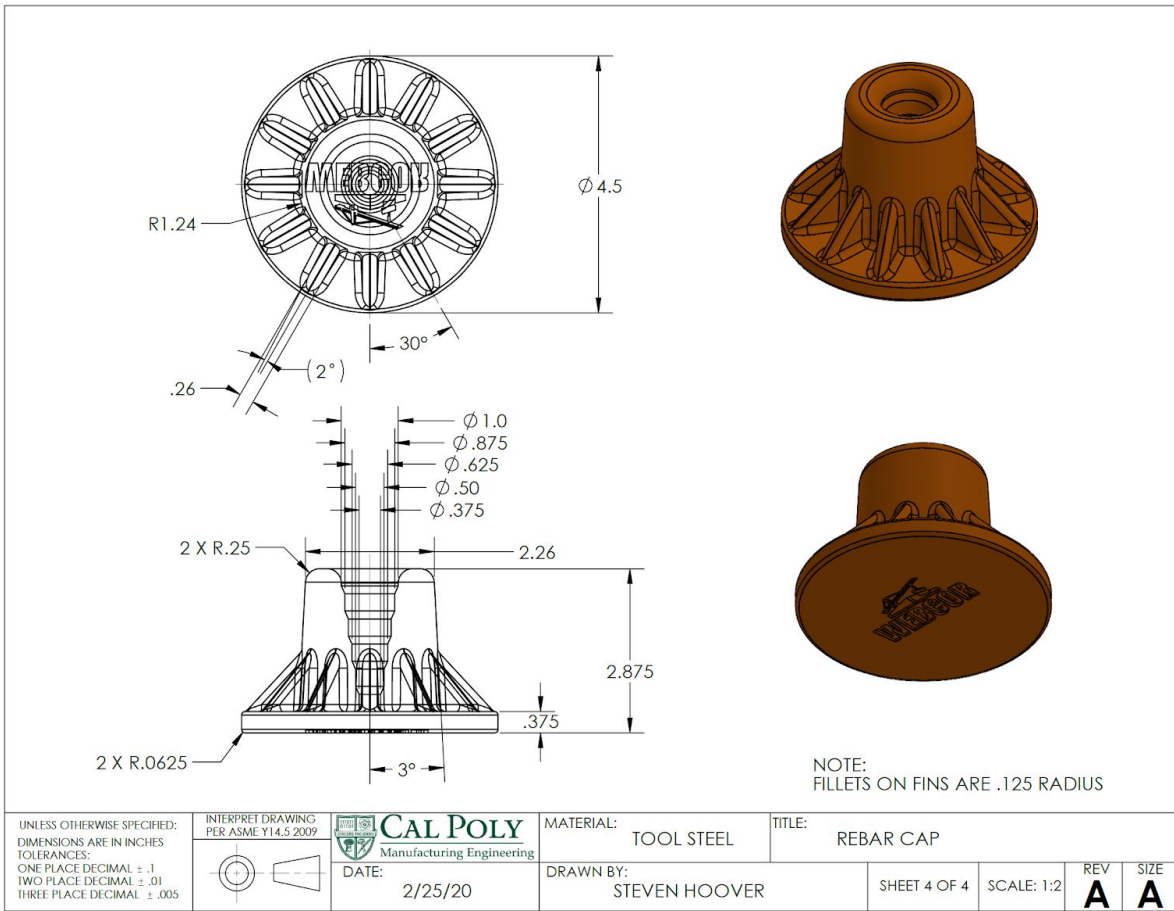
Safety cap exterior drawing



Pvc Body for inserts



Silicone Insert



SOLIDWORKS Educational Product. For Instructional Use Only.

Final Cap Design

Appendix D: DOE

Run Table

Statistical testing of materials:

Screening Design

Responses

Add Response ▼ Remove Number of Responses...

Response Name	Goal	Lower Limit	Upper Limit	Importance
Y	Maximize	.	.	.

Factors

Continuous Discrete Numeric ▼ Categorical ▼ Remove Add N Factors

Name	Role	Values			
material	Discrete Numeric	1	2	3	4
bar	Discrete Numeric	1	2	3	

DOE

Bar:

$\frac{3}{8} = 1$

$\frac{1}{2} = 2$

$\frac{5}{8} = 3$

Material:

White= 1

Blue = 2

Cream= 3

Plastic=4

Each cap and bar was installed per the run order. The test was initiated at 2:39 on 2/1/20.

Pull test:

Weight of control = .4

Screening Design		
Design		
Run	bar	material
1	1	2
2	2	3
3	2	4
4	2	1
5	3	2
6	1	4
7	1	1
8	1	4
9	2	2
10	3	4
11	1	2
12	2	2
13	3	3
14	2	2
15	1	2
16	3	3
17	3	1
18	1	4
19	1	1
20	1	3
21	1	3
22	3	2
23	2	1
24	1	1
25	2	3
26	3	2
27	3	4
28	2	4
29	2	1
30	3	1
31	1	3
32	2	3
33	3	3
34	2	4
35	3	1
36	3	4

Pull test run order

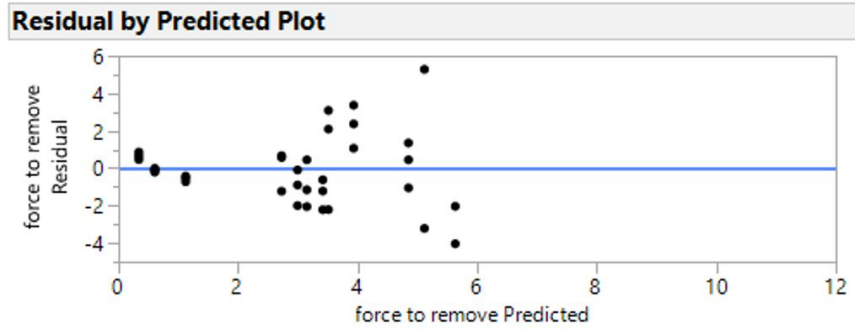
Initial Model

The model showed that the interaction between bar and material was insignificant and was dropped in the refined model. The p-values can be seen below:

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
bar	2	2	0.01822613	1.5292	0.2371
material	3	3	0.47304912	26.4598	<.0001*
bar*material	6	6	0.04950552	1.3845	0.2611

Assumptions

The initial data showed that the constant variance assumption was violated and thus needed to be transformed. Figure X shows the original data before transformation.



Check for Constant Variance

2.5in Vs. 4in Cream Cap

DOE Run Order

- Bar (1): $\frac{3}{8}$ inch bar
- Bar (2): $\frac{5}{8}$ inch bar
- Cap (1): 4 inch cap
- Cap (2): 2.5 inch cap

	Bar	Cap	Column 3
1	1	1	8
2	-1	-1	13.2
3	1	1	15.7
4	-1	-1	12
5	-1	1	6.9
6	1	-1	5.5
7	1	-1	6.3
8	1	1	15.4
9	-1	-1	11.2
10	1	-1	4
11	-1	1	6.7
12	-1	1	6.9

Screening Design		
Factors		
Design		
Run	material	bar
1	1	1
2	1	3
3	4	2
4	3	1
5	2	1
6	1	2
7	3	2
8	1	2
9	4	3
10	4	2
11	1	1
12	3	1
13	4	1
14	4	2
15	4	3
16	2	3
17	2	2
18	1	3
19	3	2
20	3	2
21	4	3
22	1	3
23	3	3
24	2	1
25	2	3
26	1	2
27	2	1
28	3	3
29	4	1
30	2	2
31	4	1
32	3	3
33	1	1
34	2	2
35	3	1
36	2	3

Kick test run order

bar=1

		pass/fail		
Count	0	1	Total	
material	1	0	3	3
	2	0	3	3
	3	0	3	3
	4	1	2	3
	Total	1	11	12

bar=2

		pass/fail		
Count	0	1	Total	
material	1	0	3	3
	2	0	3	3
	3	0	3	3
	4	3	0	3
	Total	3	9	12

bar=3

		pass/fail		
Count	0	1	Total	
material	1	0	3	3
	2	0	3	3
	3	0	3	3
	4	1	2	3
	Total	1	11	12

Kick Test Results