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Generating Rock Volumes of Lower Radii (GRVLR) - Rock Crusher

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GENERATING ROCK VOLUMES OF LOWER RADII (GRVLR) - ROCK CRUSHER

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GENERATING ROCK VOLUMES OF LOWER RADII (GRVLR) - ROCK CRUSHER

By

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Abstract

The GRVLR team designed and constructed a human powered rock crusher intended to assist impoverished widows in Birendranagar, Nepal. These women crush rocks for a living as a result of intense gender discrimination which limits their access to better employment opportunities. The goal of this device was to provide an alternative method to this work that was superior under the criteria of efficiency, ergonomics, and safety. In order to inform the design of the machine, the GRVLR team used customer needs data to generate design requirements and success metrics, and finite element analysis (FEA) in order to evaluate and improve the strength of the system components. After several rounds of design iteration, the team produced a pedal operated rock crusher that uses a chain lift to hoist a heavy weight to drop onto the rocks below. The team is in the process of finalizing a working prototype to test its efficiency. Once this is completed next steps are to coordinate with the project's non-government organization contact in Nepal to see about introducing the device to the community and performing further design iterations based on firsthand customer feedback.

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1 Chapter 1: Introduction

Some widowed women in Birendranagar, Nepal face repressive gender discrimination leaving them with few economic prospects. Many are relegated to crushing rocks into gravel with a hammer for local construction companies for a living. This repetitive, high impact motion is highly damaging to their wrists, shoulders, and backs. They get little reward for their efforts, making at most $2.50 for a six hour work day. If that were not enough, having such a small daily income can require them to pull their children out of school to aid in the production effort, thereby keeping the family in a cycle of generational poverty.

The primary goal of this project is to manufacture a functioning prototype of a manual rock crushing machine that is more efficient, ergonomic, and safe than the women's current method. The secondary goal is to partner with a local non-profit organization to assist the team in communicating with the women and managing the maintenance of the device after it is introduced to the target community. Finally, the team plans to keep organized documentation so the project will be in the best position to continue on and be successfully implemented by another group next year. The hope is that the project will eventually help the women supplement their income enough to allow them to keep their children in school.

The GRVLR team is building off the Poverty Crusher project from 2014 initiated by Rob Golterman, Brian Hammond, Ryan Le, and Arvin Lie. Brian was informed by his cousin, Maggie Doyne, the head of a nonprofit in the area, that many of the impoverished women in the nearby village of Birendranagar were left no choice but to do the harmful, menial work described, and Brian was inspired. With Rob, Brian visited the community to gain more specific information about the nature of the work and the needs of the women. This information gathered was used by their team as well as the current team to inform their respective design choices.

The following thesis outlines the progress made by the GRVLR team over the course of the 2020-21 academic year. This progress was divided into four chapters: Project background, GRVLR design selection, Prototype construction, and Project summary and future plans.

In the second chapter, the background of the project brings into perspective the lives of some of the women in the Nepalese widowed community and justifies the need of a GRVLR device by showing alignment with their specific needs. The mission objectives are stated in the form of identified customer needs and project constraints, in terms of engineering standards and social considerations. To conclude this background chapter, there is a description of the technical research completed to accomplish the physical goals of the project, including research into other industrial and manual rock crushers, relevant patents as well as the fracture mechanics of rocks themselves.

Next, the third chapter, GRVLR design selection, discusses the system breakdown by defining the subsystems and presenting the design process based on the customer needs and market research. Along with the final design prototype description, there is a detailed explanation of the design comparisons, verifications and changes of overall design options, and specific final design components made based on hand calculations, finite element analysis, and other research. To conclude this detailed systems chapter, there is a summary of supporting analytical methods used before any prototype construction commenced and predictions for the GRVLR prototype results.

Following these predictions, the fourth chapter explains the in-person prototype construction of the GRVLR. The construction process includes an overview of the building of the wooden proof of concept model, manufacturing processes used for the final prototype in the Machine Shop, and materials procurement.

Lastly, the fifth chapter conveys the GRVLR project summary and future plans by evaluating the final design with the initial objectives set, describing the team's organization and management via their timeline and budget, and suggesting plans for the eventual implementation of the GRVLR prototype in Nepal. In specifying the plans for further development, there is a description of the Nepalese material sourcing and production cost estimation still needed as well as the planned continued involvement of the partnered non-government organization, the Himalayan Climate Initiative. In order for the GRVLR project to go into completion, another senior design team at Santa Clara University is required to continue developing the prototype with more accurate Nepalese rocks and user interaction data. The team also includes a self-reflection of the lessons learned within the project and wisdom to pass onto the next team so that they can successfully integrate the GRVLR into the target user community of impoverished widows in Birendranagar, Nepal.

2 Chapter 2: Project Background

In this chapter the GRVLR project background is discussed as it pertains to the reasoning behind the design and building of the device. Furthermore the mission objectives of the project are explained via customer needs, project constraints and technical background. The purpose of this chapter is to provide all the background information needed to understand the design criteria and goals set for the GRVLR machine.

2.1 GRVLR Justification

Embarking on this humanitarian engineering project, to serve a community abroad, in the time of the coronavirus outbreak, made it difficult for the team to connect with their users. In order to gain a better perspective on how to successfully complete a humanitarian project the team connected with a Santa Clara University Civil Engineering professor, Dr. Tonya Nilsson, who is experienced working with projects abroad. From her advice the team looked into the ethics and social responsibility that they will hold as humanitarian engineers in designing, building and implementing the GRVLR Rock Crusher. One concern to be wary of was to avoid falling into practices of Voluntourism in their intent and Neo-Colonialism in the way that they communicate and interact with their target consumers. Instead they must focus on how they can best serve their user[1].

Voluntourism is a form of global tourism where people from developed nations pay to go on a trip where they perform a survey for an impoverished community usually abroad. This sounds good in concept, but becomes harmful when the intent of the trip is more focused on the experience of the people performing the labor than the people receiving the service. This can lead to an exploitative relationship where poverty of some people can become commoditized, and rarely produces any greater impact than a simple donation of the money that was spent to go on the trip. In terms of this senior thesis, the main requirement is making sure that the project is always being directed on how to best assist the target consumer with a primary focus on their needs.

Neo-Colonialism, in the context of this project, is the practice of an economically dominant country imposing its economic agenda, culture, or cultural views onto another nondominant country using indirect means. One method of indirect control is to use foreign aid to create dependency on the resources of the larger nation. Another common pitfall in humanitarian engineering, as a result, is that the engineers become taken with an efficient and seemingly perfect solution to the problem without checking to see if it would fit with the user community's culture. Under the guidance of Dr. Nilsson the project has been operated with the needs and lifestyles of the Nepalese women community as an overarching guide to check the biases and differences of cultural context of the team and assist in providing independent economic benefits. These same checks are instituted to make sure that the project is communicated and eventually implemented in a manner that uplifts the individual dignity and agency of the women that are the target audience.

With this as a guide, the team sought to better understand the cultural barriers the Nepalese women are facing so as to affirm that the device would genuinely be providing assistance to the target audience. In addition, understanding the Nepalese culture would allow the team to meet the necessary manufacturability, sustainability, economic, social, and safety standards of a successful frugal humanitarian project. The following section is a summary of that background research into the position of widowed women in Nepal as well as the analysis of necessary standards and realistic constraints facing the project.

2.1.1 Nepalese Women Community

In the case of unmarried women, gender discrimination has a large impact on Nepalese women as well as their children. As declared in the Nepalese constitution, citizenship is granted through one Nepali parent, however without the Nepali father supporting the application, mothers can experience extreme hardship in obtaining said citizenship for their children whether or not the father is present in the family's life. This is despite the fact that a 2011 Supreme Court decision granted citizenship rights to children of

[1] Birzer, Cristian, and Jaimee Hamilton. "Humanitarian Engineering Education Fieldwork and the Risk of Doing More Harm than Good." Australasian Journal of Engineering Education 3 July 2019: 51–60. Web.

unknown or absent fathers through their mother. According to a 2018 human rights report by the U.S. State Department in Nepal, it is estimated that some 5.4 million Nepalese people, roughly 24% of the population aged sixteen and over, were without citizenship documentation. In Nepal, citizenship documents are issued at the age of sixteen, and without that documentation the stateless people cannot register to vote, register marriages or births, buy or sell land, sit for professional exams, open bank accounts, gain access to credit or receive state social benefits and experience discrimination in nearly all aspects of life. According to that same report, even women looking to obtain citizenship by descent for themselves cannot do so without an endorsement from her father, husband, or her husband's family if she is widowed that she is allowed to obtain it[2]. This heavily restricts the social mobility of children of unmarried mothers, the agency of the mothers themselves, and shows the favor shown and importance given to the role of men in the family.

When a woman marries, it is hopefully with the belief that they will live a contented or happy life with their partner and that their life might improve. In Nepal this is not a guarantee as married women are three times more likely to experience a major depressive disorder than single women according to research conducted by Professor of Sociology at the University of Michigan, William Axinn. This is not difficult to comprehend when one realizes what happens to these women. In rural Nepal the marriages are most often arranged, with the women having little to no say in who their partner will be[3]. Once they are married they lose their inheritance rights from their birth family as it is defined in the Muluki Ain, or the National Code of Nepal, that the head of the family, whether that be the father or husband, is only legally bound to care for his wife and sons when it comes to inheritance. There are laws that have been put in place to protect unmarried women's inheritance rights from her birth family and some to protect married women from their husband's family, but they go almost completely unenforced as cultural traditions still reign as king[4].

For example, Sadhana, whose name was changed for her safety, is a forty-nine year old Nepalese widow. At the age of eighteen she was informed by her parents that she would be married later that day. Sadhana had never met this man before and was forced to leave her family to go live with him with no prior notice. By the time she was twenty she had endured two years of forced hard labor and abuse from her mother in law and had given birth to no children. Without children, and in particular no sons, Sadhana had no standing within her husband's family, so when he died that year, in the eyes of their culture, she had no right to her inheritance from her husband that was legally owed to her. Sadhana's inlaws took it all and disowned her[5].

Conditions worsen significantly if the woman's husband passes as was depicted in the case of Sad-

[2] Bureau of Democracy, Human Rights and Labor, NEPAL 2018 HUMAN RIGHTS REPORT §. Accessed March 27, 2021. https://www.state.gov/wp-content/uploads/2019/03/NEPAL-2018.pdf.

[3] Axinn, William. Coronavirus, marriage and depression. Other, April 14, 2020.

[4] "Gender and Land Rights Database - Nepal." Food and Agriculture Organization of the United States. Accessed March 20, 2021. http://www.fao.org/.

[5] Ibrahim-Leathers, Heather, and Kayla Tsongas. "NEPALESE WIDOWS STRUGGLE FOR INHERITANCE RIGHTS." World Policy, July 9, 2012. http://worldpolicy.org/.

hana. But, even those who are not cast out of their husband's family are expected to follow many customs according to the Hindu religion. They cannot wear colored clothing to ensure they will not be unfaithful to their husband, they must assume a vegetarian diet, cannot remarry, and are excluded from religious ceremonies[6]. These rules they must follow portray them as others within their own communities through absolutely no fault of their own.

Taken together, women in Nepal, and particularly unmarried and widowed women, are in a very vulnerable position socially. They are often denied their inheritance rights, often have no choice in who they marry, are completely at the mercy of their natal or husband's family, cannot obtain citizenship for themselves and can often face hardships in obtaining it for their children. This obviously hinders their ability to break out of their prescribed social roles. This is no less the case of Ram Devi Tamang, who at the age of twenty-five was widowed and cast out of her husband's family and her village. Despite her hardship, before being cast out she had a tailoring business and was able to use those skills, as well as selling vegetables, to support herself and put her two daughters through school. She is now forty-seven and has served as a local mayor while advocating for the rights of widows. She stresses the importance of developing skills in the widows which can be transferred into employment opportunities as a way of breaking the social norms and cycle of poverty that widows face[7].

That cycle can be broken through skill training for the women themselves, but by gaining access to education for their children as well. According to a 2016 demographic and health survey 47.8% of girls from families in the lowest wealth quintile, which families of widowed mothers will often fall into, have had no education and 23.9% went to primary school for a time before dropping out[8]. Having impoverished families not afford to keep their children in school, places limitations on their future employment prospects and potential marketable skills knowledge, which perpetuates the cycle of poverty.

The ultimate goal of the GRVLR project, as a result, is to supplement the income of these unmarried and widowed women such that they can keep their children in school and hopefully gain enough time back in the day that they can seek out skill-training from resources like the women's center in Surkhet.

2.2 Mission Objectives

After justifying the existence of the GRVLR project, the team began looking into specific design constraints as they pertain to the direct needs of the target users, in this case impoverished widows in rural Nepal, and larger scale categories like manufacturability, sustainability, economic viability, social impact, and health and safety.

[6] Bader, Martin. "'They Called Me Husband-Eater': A Widow Fights Back Against Prejudice." The New Humanitarian, May 24, 2018. deeply.thenewhumanitarian.org/.

[7] Bader, Martin.

[8] Ministry of Health, Nepal; New ERA; and ICF. 2017. Nepal Demographic and Health Survey 2016. Kathmandu, Nepal: Ministry of Health, Nepal.

2.2.1 Customer Needs

Given that this project is international and the target users are difficult to communicate with directly, the team set about establishing contacts in Nepal to serve as an intermediary between the team and the users to collect customer needs data. The team started the year working off of interview data, displayed in Appendix 2, given to the previous team in 2014 while they were working to establish their own contacts. By December the team had made contact with the CEO of the Himalayan Climate Initiative, Shilshila Acharya. Rob Golterman, a member of the previous team, passed along the contact of Pawan Kumar Karki, a local engineer in Surkhet, the nearest city to the project's target community, who then introduced the team to Shilshila. Shilshila was based in Kathmandu, which is on the other side of the country from the target community and so she put the team in contact with Sunita Bhandari from the Kopila Valley Women's Center who was located in Surkhet.

The team gave her a series of questions to ask the target community to verify the data from the 2014 interviews. From the responses she provided the team established a list of customer needs that can be broken down into four main criteria: ergonomics, efficiency, safety, and cost-accessibility. Under each category there are a variety of different objectives that must be met in order for this project to be successful. The criteria for success and overall objectives for each category, along with some brief descriptions, are listed below.

Ergonomics is a very important standard to influence the project's design. Currently, the targeted users crouch or kneel on the ground to crush rocks with their hammers, which has shown to result in them developing neck and back problems. Additionally, the repetitive motion of swinging a hammer against a rock has shown to cause the woman's wrist and shoulder pain. From this, it is clear that harmful repetitive operation must be transitioned to a less damaging motion. Based on these identified ergonomic needs, the following two design objectives were outlined. The rock crusher machine must be operated via a sitting or standing position and have limited repetitive motion within a range of input force of 50-90N. If satisfied, the act of rock crushing should take a lesser toll on the bodies of the users.

Efficiency is the category that ought to have the most improvement. Their current method of rock crushing employs the use of a hammer, which requires a great deal of force, repetition, and time. Efficiency standards of the machine are measured by the final rock size of about 1.5 to 2.5 cm in diameter compared to the initial size of about 15 to 20 cm in diameter. Furthermore the crushing rate must be faster than the hammer, which is noted to be about 150 to 200 kg of crushed rock per day from the interview data collected by Ms. Bhandari in April 2021. Based on these identified efficiency needs, the following two design objectives were outlined. The rock crusher must be able to crush rocks to roughly 1.5 to 2.5 cm in diameter which will be determined with the help of a filter and be faster than 150 to 200 kg of crushed rocks per day. If satisfied, the team's device should increase the daily production volume and overall income of the Nepalese widows.

Given that the target community suffers greatly from poverty, the machine is only truly beneficial to them if it is cost-accessible. Cost standards of the machine are noted by the limited maintenance required, since it will be continuously operated for roughly six hours each day, and if any parts need to be replaced they must be commonly available in the area. In addition, if this machine is partnered with a non-government organization (NGO) the cost range of the machine can be higher than the initial maximum price of 25 dollars as women now have the possibility, if they so choose, to share the device. Based on these identified cost needs, the following three design objectives were outlined. The rock crusher must be durable, cost-accessible, require minimal maintenance, and use inexpensive, locally available materials. If satisfied, the machine should be readily available for more women and be used as a transition tool to help them out of poverty through parallel work with the NGO partner.

Last, the safety category concerns the user during the act of operation, maintenance and transportation. The final design needs to be safer than holding a rock and hitting it with a hammer. Safety standards for the user include a protected crushing area that is enclosed so that no rock shards fly towards the user at any point during operation. Additionally, any moving parts must be covered so that no gaps between the moving parts and the user are open to avoid opportunities for crushed fingers. Based on these identified safety needs, the following three design objectives were outlined. The rock crusher must have a protected crushing area, an indirect user feeder structure, and have no open gaps where a hand or other body part could easily get caught. Ear protection should also be provided to prevent hearing loss given that impact between metal, rock, and metal will likely cause sounds above the safe 20dB level and the machine will be operated for many hours daily. If satisfied, the team's device should provide the user with no bodily harm.

When looking at the system as a whole, the GRVLR was designed to be more ergonomic, efficient, safe and cost accessible. Below is a graphical representation of the primary and secondary needs that have been identified via our customer community in Nepal in relation to the team's four objectives (Table 2.1).

Table 2.1: Customer Needs Summary and Hierarchical Ranking

Ergonomics	Efficiency	Safety	Cost Accessibility
*** Eliminates damaging effects on these women's bodies from hammering rock ** Can be operated comfortably in sitting or standing position *** Is human powered (either foot or hand) ** Machine limits repetitive motion ** Lightweight (less than 25 lbs) for portability ** Machine requires less work from user than using hammer ** Machine is easy to operate	*** Can crush rocks down to desired size faster than using a hammer * Crushes a minimum of 200kg *** Crushes rocks to less than 1.5 to 2.5cm	*** Machine has properly secured all moving components to withstand multiple hours of continuous operation without dismantling ***Crushing area is completely enclosed to protect from flying rock shards ***Access to potential pinch points are minimized * Machine design and construction is understandable and easy to replicate ***Provide ear protection to operator	*** Affordable and as inexpensive as possible that balances with the increased efficiency ** Made from inexpensive and/or recycled materials available in the area ** Machine requires little to no maintenance

Importance rating for the secondary needs are indicated by the number of *'s

*** - High, ** - Middle, * - Low

Those outlined above are known crucial needs for a successful integration of the team's design with the target market of impoverished Nepalese widows. This is the known scope of the project thus far based on the interview data and is visually depicted in the Product Design Specifications Table (Table 2.2).

Table 2.2: GRVLR Product Design Specifications and Requirements Table

Requirements	Units	Datum	Target Range
Performance			
Crushed Rock Rate	Kilograms of Rocks / Minute	0.90	>0.90
Locally Available Device Materials	All / Some / None	All	All
Final Rock Size	Centimeter [cm]	NA	1.0-1.5
Device Weight	Kilograms [kg]	NA	< 20
Filtering for Size	Yes / No	No	Yes
Device Cost	American Dollars	10	25
Operation Position	Sitting / Standing / Squatting	Squatting	Sitting/Standing
Maintenance Easibility	Easy / Medium / Hard	N/A	Easy/Medium
Safety			
Indirect Feeder	Yes / No	No	Yes
Pinch Points	Unitless	1	0
Covered Crushing Area	Yes / No	No	Yes
Input Operating Force	Newton [N]	~ 150	20 - 50

Knowing all of this, and understanding that this product has the potential to help lessen the burden on these impoverished Nepalese women, the next step is to ask how best can this product idea be made a reality? And, important to consider, how best can it be made a reality while taking into account manufacturability, sustainability, economics, potential social consequences, and health and safety.

2.3 Technical Background

With the conclusion that there is a demonstrated need for a manual rock crusher amongst impoverished unmarried and widowed women in Nepal, research was conducted into current methods of rock crushing in industry and amongst hobbyists in the United States. Additional research was conducted into the fracture mechanics of rocks. The summary of such research is detailed below.

2.3.1 Market Research

Gravel production for construction purposes is often performed by large industrial machines. These designs do not scale down well to the manual rock crushing device the team was looking to make given the limitation of single-person input power. With that said, these crushing methods were used for general inspiration and were helpful in generating ideas. The most common rock crushers used in industry today are jaw crushers and stamp mills.

2.3.1.1 Relevant Patents

A jaw crusher, like that patented from Metso Minerals, Inc., crushes rocks by pinning them between one stationary plate and another oscillating plate. They employ a circular motion by moving an eccentric shaft that pushes the moving plate into the static plate. It is to be noted that this project is a continuation from a previous senior design team that designed a smaller scaled version of a jaw crusher, titled the Poverty Crusher. This original group's design had a shaft that slid along the back of the moving plate, causing the plate to rotate about its lower access (Figure 2.1).

Figure 2.1: Poverty Crusher Final Design (used with permission)

The previous senior design team faced issues employing the pure horizontal compression force from a jaw crusher, admittedly as a result of design mistakes. It is possible, though, that even had the team not made those mistakes, the pure horizontal compression force necessary could have been feasibly generated by human power alone as is the goal of this project. As such, in the Metso Minerals, Inc. patent and in some examples of other jaw crushers, the moving plate is not fixed on a stationary axle at the bottom, so the eccentric shaft creates a vertical movement as well as a radial movement. Additionally, the contact surfaces on most industrial jaw crushers have ridges aligned with the direction of movement in the crushing stroke. The original team's crushing plates did not include these ridges which may be one reason that their design was not highly effective. Based on the operating principles of a jaw crusher, bi-directional compression paired with a textured crushing surface seem to be two design elements that could aid in the transition to human power.

Another machine type that is commonly used in industry to crush rocks is the stamp mill. Stamp mills are crushing machines that use mechanical cam systems to raise and drop a weight (Figure 2.2). They crush rocks through a high impact force which repeatedly strikes the rock with the blunt crushing object which is always in continuous motion[9]. This was particularly intriguing to the team as it seemed to be the most simple method of crushing, by dropping a weight from a given height.

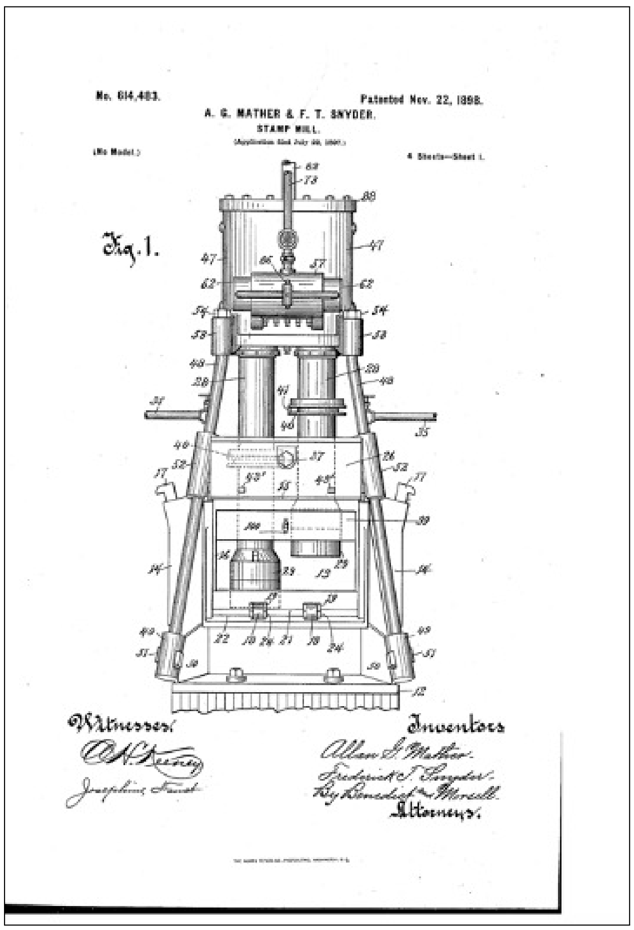


Figure 2.2: Stamp Mill Patented by Mather and Snyder in 1898 (used without permission)

While the industrial examples served as a kickstarter for ideation, for more specific ideas for manual

[9]Mather, A.G., and F.T. Snyder. Stamp Mill, issued November 22, 1898.

crushing devices in particular, the team looked to homemade rock crushers used by hobbyists or single person gold mining operations.

One such example is simply a long, hollow, square steel tube with a replaceable steel plate on the bottom. There are two cutouts, one to feed the rocks into and another to release the crushed gravel. A long solid square steel bar with two horizontal handles attached is placed inside to act as the weight (Figure 2.3). The bar is then lifted and dropped repeatedly until the rocks are crushed to the desired size[10]. The team did find some issues with the design though as the mass of the crushing weight and the aggressive repetitive motion needed for operation would cause harmful ergonomic effects and would not be operable consistently for six to seven hours each day. To try to reduce some of these negative ergonomic effects, the design would have to be converted from arm powered to some form of pedal power or hand crank.

Figure 2.3: Homemade Rock to Gravel Jaw Crusher (used without permission)

Another example was a cam operated rock crusher that was self-feeding and operated by a motor (Figure 2.4). It was built completely from scrap parts found at a junkyard[11] which piqued the team's attention. The largest issue with this design was the power source, given that one of the main objectives of the project was to create a manual rock crusher. Alternative methods considered by the team to produce power were pedal power and hand cranking. In transitioning to this new power source, calculations needed to be completed to confirm if bike pedals could deliver enough force to turn the shaft to raise the crushing

[10] Homemade Rock Crusher DIY Hand Powered, Crushes Gold Quartz Ore, Rock to Gravel Jaw Crusher. YouTube, 2018. www.youtube.com/watch?v=MOopvG6qio.

[11] HOMEMADE ROCK CRUSHER. YouTube, 2013. www.youtube.com/watch?v=yKnTT9XtkdM.

cylinder. In addition to the power source, another concern of the team was safety. As there are more exposed moving parts, there was an increased concern for fingers to get caught in the crushing chamber.

Figure 2.4: Homemade Rock Crusher (used without permission)

After exhausting research into existing devices that fit the project directly, other sub function related patents were researched to check if it would fit any of the necessary design criteria. In the case of the crushing interface, the team looked into a rock crusher incorporated into a tractor that picks up rocks, crushes them, and leaves them behind in order to create a better path[12]. The invention itself is not well suited to the team's needs, but the patent contains some information about using a chisel or other pointed tool to break rocks by causing a stress concentration (Figure 2.5). The application was for a very wide and uncontrolled area of rock crushing, but it is possible that decreasing the area over which rocks are being crushed and loading rocks more intentionally could have allowed the team to use the principles of this device to crush rocks more effectively.

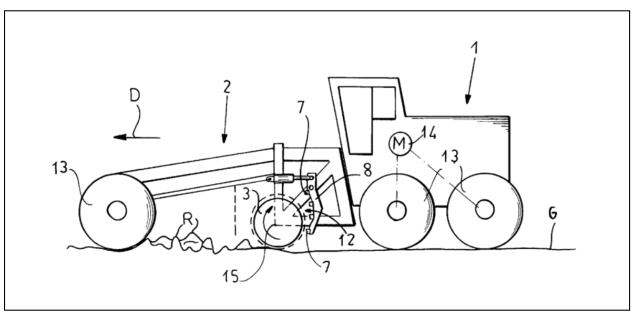


Figure 2.5: Traveling Rock Crusher Patented by Schmid in 1998 (used without permission)

Another method of crushing that fit many design criteria of the project was that of a chain lift design. With this, a lifting hook mechanism would need to be developed, so the team looked into the method of raising roller coaster cars up their lift hills. From this effort, the original design for this action, patented

[12]Schmid, J. (2002). U.S. Patent No. US5875980A. Washington, DC: U.S. Patent and Trademark Office.

by Philip Hinkle in 1884 was reviewed[13] (Figure 2.6). It functions by running a cable beneath the roller coaster track. Attached to the cable are hooks that grab the cars and pull them up the hill before releasing them at the peak and swinging back around to get the next car. The team could use this as inspiration for the chain mechanism, or even for the shape of the lifting hooks the device would require.

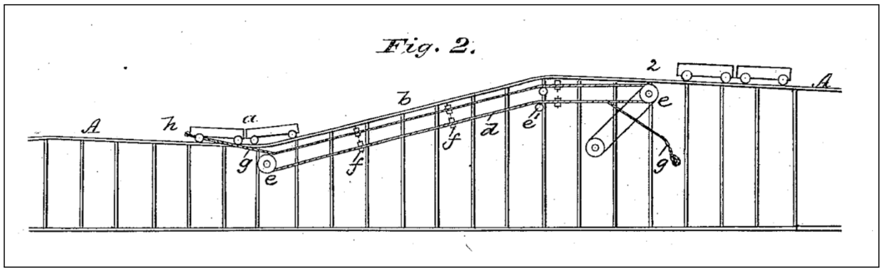


Figure 2.6: Lifting Mechanism Patented by Hinkle in 1884 (used without permission)

Finally, given that one of the main objectives of the GRVLR project is to design a more ergonomic method of crushing rocks than a hammer, one idea was to have it pedal operated so that the women could have their hands free to load more rocks while operating or to be operated in a recumbent position so that they can simultaneously hold a small child in needed. As such, the team found a pedal-operated threshing machine that processes grain by turning two different axles that are performing different processing tasks by connecting the different components by a belt run over corresponding gears[14] (Figure 2.7). This was a useful patent to be researched because it demonstrated how the bike pedals can be linked to the rest of a device and provided a helpful visualization as to how the gear and belt mechanism would run with the pedals.

[13] Hinkle, Philip. Gravity Pleasure Road, issued November 11, 1884.

[14] Moser, Tyler, James Wittel, Phyllis Schlafly, David Schmidt, Bethany Shotyk, Kenneth Shotyk, Marissa Scalzo, Gina Scalzo, and Adrianna Scalzo. Pedal-Operated Threshing Machine, issued November 25, 2010.

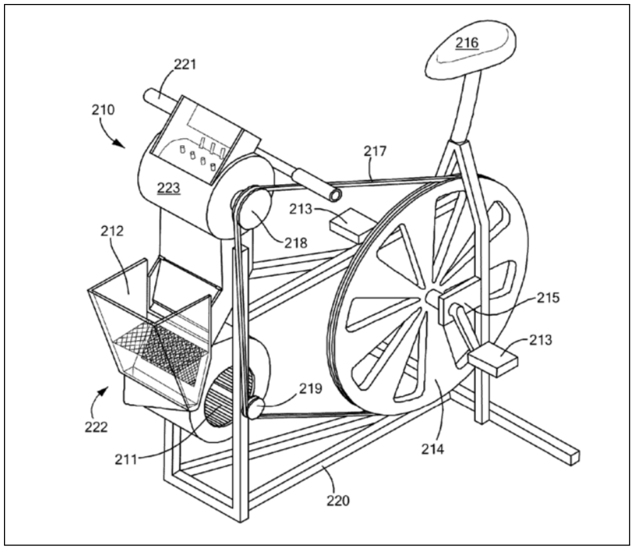


Figure 2.7: Pedal-Operated Threshing Machine Patented by Moser, et. al. in 2010 (used without permission)

2.3.2 Rock Fracture Mechanics Research

In addition to the research of potential design ideas, there was a significant effort spent into finding the most efficient methods for breaking rocks, and how to successfully manage a humanitarian project. In the former case, the research was aimed at understanding how cracks propagate within the rocks to best anticipate how they will fracture[15] given that we are looking to bring the fragments to a specific final size. It was also confirmed that the rocks that are available in the area are hard and brittle and thus particularly resistant to compression forces[16].

Depending on the crushing mechanism, adjusting the magnitude of the impact force to overcome this resistance might not be easily done, so the team also found in the research done that there is another method of crushing rocks. This is accomplished by decreasing the force delivered to the rock and increasing the application frequency of that force, or, simply put, by applying cyclic loading[17].

Unfortunately, the Santa Clara University campus was closed for the majority of the academic year, so the team did not have an opportunity to test their potential methods of crushing sandstone river rock as a method of selecting and refining their chosen design. As a result, efforts were redirected to research the fracture mechanics of rocks to see if that could provide justification for selecting a superior crushing mechanism.

[15] Wang, Fei. "Rock Dynamic Crack Propagation Under Different Loading Rates Using Improved Single Cleavage Semi-circle Specimen" Applied Sciences, Vol. 9 Issue 22.

[16] "Rock Mechanics, Rock" Encyclopedia Britannica Online. Accessed 10-20-20 www.britannica.com/science/rock-geology/Mechanical-properties

[17] Spagnoli, Andrea. "Experimental Investigation on the Fracture Behavior of Natural Stone Exposed to Monotonic and Cyclic Loading", Frattura e Integrità Strutturale, Issue 47.

By the time the research began the team was only looking into blunt impact forcing as the mode of rock crushing for their device, it was found that they were employing mode I loading . This is characterized by a load being applied normally to the plane of the crack, (Figure 2.8).

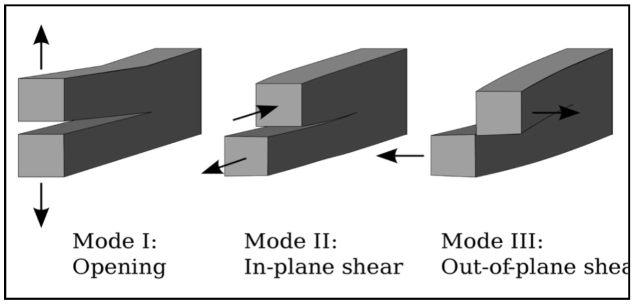


Figure 2.8: Modes of Failure (used without permission)

All materials have micro fractures or cracks within themselves. They vary in size, but are nonetheless always there. The downward force from impact begins to cleave these cracks, forcing the walls apart and causing the crack to grow and propagate through the whole of the material if the force is large enough and fact enough.

As the team was looking to induce fractures within the rocks, the corresponding material property that needed to be determined for the specific sandstone being crushed by the Nepalese women was its fracture toughness. Fracture toughness is the ability of a material to resist fast fracture, with the stress intensity factor, K_{IC}, representing the critical value by which the speed of the propagation of a sharp crack becomes rapid. The corresponding equation is displayed below, with σ_y representing the tensile stress at which the transition to fast fracture occurs and c representing the critical crack length that transitions from plastic deformation to fast fracture within the material.

$$K_{1C} = \sigma_y \sqrt{(\pi)(c_{crit})} \tag{2.1}$$

Equipped with this equation, the team sought to calculate the fracture stress and using the definition of stress (σ=Force/Area) determine the impact force necessary to break the sandstone given at the rock's assumed cross-sectional area. In order to determine the fracture stress, the team searched for the critical crack length for the specific sandstone type that is estimated as the rock, as well as the corresponding stress intensity factor for the specific type of sandstone. As such, the team then embarked on a search for the specific type of sandstone from that region in south western Nepal.

The team began by using a geological report drafted by the government of Nepal as well as two of its local universities. From this the team was able to determine that Birendranagar is located near the Bheri River and so the dry riverbed the women source their rocks from likely has the same geological composition.The geological areas in Nepal are divided based on proximity to the Himalayas. The area the team was looking into was designated as part of the middle Siwaliks B, characterized as being composed of coarse-grained, black and white colored sandstone[18]. However, looking at photos and videos taken of the women working, the rocks did not appear to be black and white (Figure 2.9. So, the team looked into the different types of sandstone and came across sandstone that is dominantly plagioclase[19], a group of feldspar minerals that form a solid solution series[20]. Feldspar is mined in Nepal[21], so it seemed, given that images of this sandstone composition appeared similar to that from the photos provided from the community, as reasonable an assumption as any that that is the type for which to look for the relevant material properties.

Figure 2.9: Sandstone Rocks from Birendranagar, Nepal (used with permission)

Now that the rock type has been estimated based on the Nepalese region, the team was able to resume the research effort to determine the fracture stress from the impact force equation above. In order to utilize the equation, the failure characteristics, c_{CRIT} and K_{1C}, of plagioclase sandstone were needed. In 2017 there was a study conducted by Baud, et al[22] which concluded that at ambient temperatures granite, which resembles the rock characteristics of plagioclase sandstone, has an average crack length of 56 micrometers. The team considered this value to be viable for the critical crack length in the impact force equation. In finding the stress intensity factor (K_{1C}), there was a study on plagioclase sandstone that was using impact forcing to determine the failure characteristics. This study concluded that plagioclase sandstone has a K_{1C} of 30 $^{0.5}$ (0.93 $^{0.5}$). Given these failure characteristics of plagioclase sandstone, the team was able to solve

[18]Kafle, Nirmal, Lelin Raj Dhungel, Kamala Kanta Acharya, and Megh Raj Dhital. "A BALANCED GEOLOGICAL CROSS-SECTION ALONG KOHALPUR – SURKHET AREA OF SUB-HIMALAYAN RANGE, MID-WESTERN NEPAL." Journal of the Japan Society of Civil Engineers 6 (April 8, 2019).

[19]Boggs, Sam (2006). Principles of sedimentology and stratigraphy(4th ed.). Upper Saddle River, N.J.: Pearson Prentice Hall. pp. 119–135. ISBN 0131547283.

[20]King, Hobart M. "Plagioclase." Geology.com. Accessed April 15, 2021. geology.com/.

[21]Sah, Ram Bahadur, and Kabi Raj Paudyal. "Geological Control of Mineral Deposits in Nepal." Journal of Nepal Geological Society 58, no. Special Issue (March 30, 2019): 189–97.

[22]Baud, P., Griffiths, L., Heap, M. J., & Schmittbuhl, J. (2017). Quantification of microcrack characteristics and implications for stiffness and strength of granite. International Journal of Rock Mechanics and Mining Sciences, 100, 138-150. doi.org/10.1016/j.ijrmms.2017.10.013

for the fracture stress using the impact force equation, which was calculated to be 70.1 MPa. To determine the impact force required to break the rock, the cross-sectional area of the rock needs to be multiplied by the fracture stress. Assuming the rock has a spherical shape and using a radius of 3 in (0.0762 m), the impact force required to crush the rock was estimated to be 1.279 MN. This impact force value was observed to be far too high to be realistically achievable. It was concluded that the error in this value can be attributed to the lack of accurate failure characteristics to the type of rocks in the area of Nepal in which this machine will operate.

Ultimately this rock fracture mechanics research proved to be a fruitless effort. Because impact testing was impossible at the time, there was no opportunity for the team to verify the numbers they arrived at. They could not confirm or scale the results in the case that there was a consistent and obvious scaled shift between the calculated values and the experimental data. Instead the team decided to move forward with the force value collected from a backyard impact test that had been conducted in September. The team, while utilizing appropriate protective equipment, took a sandstone rock, likely not the exact same material as in Birendranagar and smaller than the river rocks being used, placed it on a barbell weight, and dropped a twenty-five pound dumbbell on it from five feet up. This shattered the rock to shard sizes smaller than desired. However, given that the rocks were smaller than expected and that was the force to break one rock, the team continued with that number as the goal for force delivery.

There was some potentially useful information at the time that came from the research though. A paper from an issue of the journal *Geotechnical and Geological Engineering* conducted a study into the fracture toughness of sandstone samples from two different mines in India. The samples were cut into a semi-circle shape with notches cut perpendicular to the flat edge at their mid-point. Impact tests were conducted on these samples with varying notch lengths with the load applied to the top of the semi-circle opposite the flat edge. This was to determine the material fracture toughness and fracture energy of rock in Mode I failure. It was found that the fracture toughness of their sandstone samples decreases with an increase in notch length (Figure 2.10) as the applied load has less distance to travel to reach the tip of the notch[23]. This informed the team that as the internal cracks within the rocks get larger, less force is required to fracture it. Thus, when using impact forcing, it is possible that if the rock does not break on the first hit, if large enough cracks were initiated, a second hit of the same magnitude could break it.

[23]Sarkar, S., Kumar, R. & Murthy, V.M.S.R. Experimental and Numerical Simulation of Crack Propagation in Sandstone by Semi Circular Bend Test. Geotech Geol Eng 37, 3157–3169 (2019). doi-org.libproxy.scu.edu/10.1007/s10706-019-00833-0

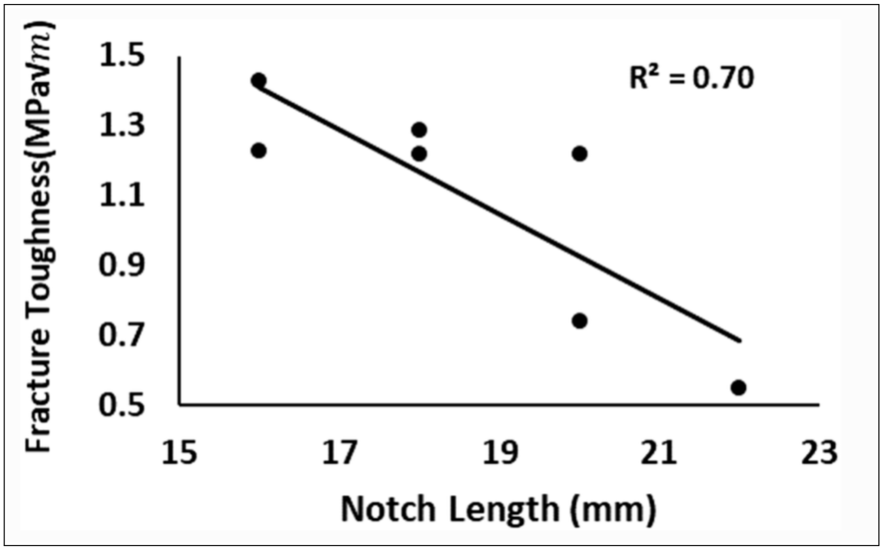


Figure 2.10: Relationship between fracture toughness and notch length from Sarkar's research (used without permission)

Another enlightening paper found was from the *Journal of Rock Mechanics and Geotechnical Engineering*. This paper covered crack propagation, specifically the conditions under which a crack is arrested. Crack arrest refers to when a crack stops propagating before reaching the outer surface of a sample. Impact tests were conducted to collect data, measuring the impact speed and speed of crack propagation. It was found that with the same mass of crushing weight, cracks are less likely to arrest when hit at a faster impact velocity[24] (Figure 2.11).

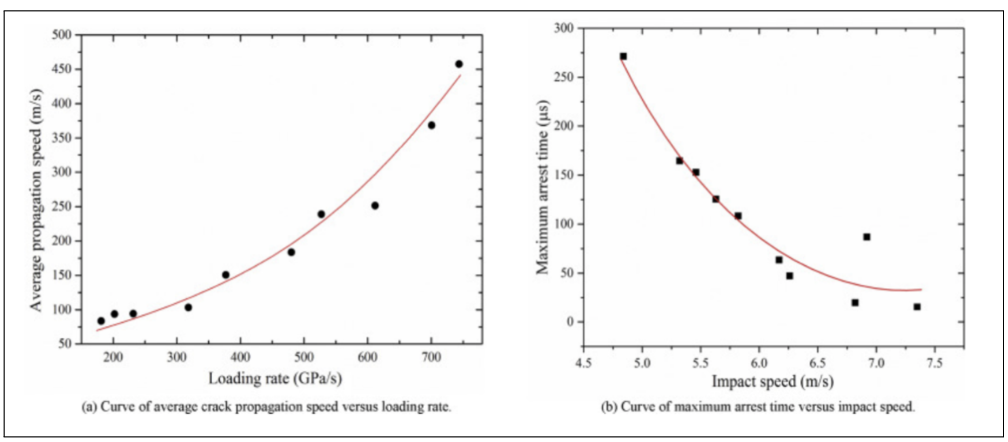


Figure 2.11: Relationship between impact speed and crack arrest from Yuqing's research (used without permission)

[24]Yuqing Dong, Zheming Zhu, Li Ren, Lei Zhou, Peng Ying, Meng Wang, Crack dynamic propagation properties and arrest mechanism under impact loading, Journal of Rock Mechanics and Geotechnical Engineering, Volume 12, Issue 6, 2020, Pages 1171-1184, doi.org/10.1016/j.jrmge.2020.01.008.

Given that the team was considering a cam design as a potential option, this was something to factor into deciding on the crushing mechanism. Cams have a limited stroke length, so gravity cannot be utilized in the same way as for a chain lift design and instead must rely on things like springs to be added to increase the force delivered without having to increase the mass of the crushing weight. Knowing that increasing the speed at impact could serve to balance out the advantages and disadvantages of each option is important to consider.

3 Chapter 3: GRVLR Design and Design Process

Given the need, goals, mission and design parameters of the GRVLR Rock Crusher, the following chapter discusses the next steps in the design process, prototyping. However, the team was restricted to on-campus machinery and lab equipment that were necessary to pursue this prototyping phase. In place of physical prototyping the team developed design ideas online using SolidWorks and conducted various simulations to test the durability of the designs theoretically, before finally being able to build in April 2021.

3.1 Rock Crusher Design Introduction

After analyzing the users needs and identifying criteria for the rock crusher, the design of the GRVLR was set in motion. The main considerations for the design were ensuring that it was efficient, ergonomic, and safe. Another aspect of the design was trying to include ways to reduce costs and maintenance of the machine without sacrificing other criteria. The first step was choosing to make the entirety of the machine out of steel since it is a durable metal that is easily accessible and relatively inexpensive.

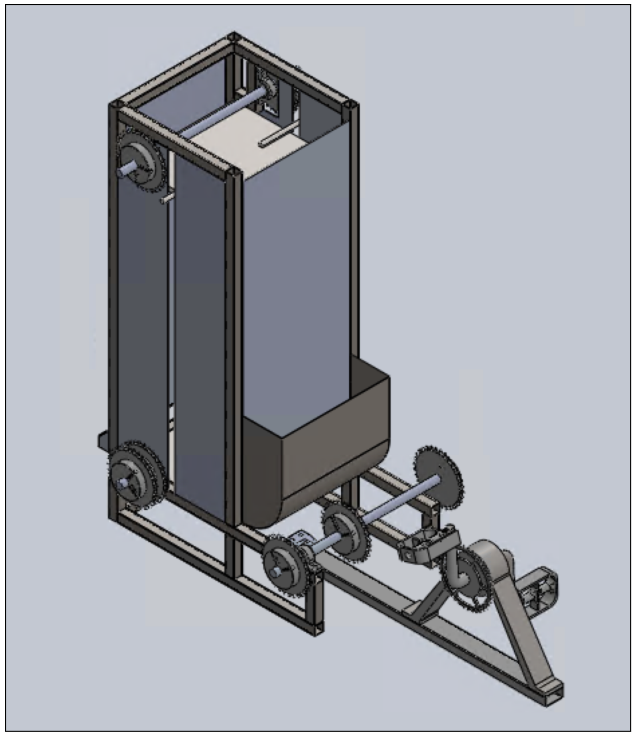


Figure 3.1: Computer Generated Model of GRVLR Rock Crusher

Within the overall design of the GRVLR rock crusher there are three subsystems. These were broken down based on functionality of separate components of the machine. Separating the rock crusher into three different subsystems was also decided upon in case a part were to break so that it could easily be identified and replaced individually. Each subsystem serves an individual function and they all interact with each other to crush rocks down to the desired final size.

3.2 Subsystem Definitions

The GRVLR machine was divided into three separate subsystems: crushing mechanism, power input and stationary support. The following sections will explain the material selection, design iterations and display the functionality virtually via the SolidWorks CAD.

3.2.1 GRVLR: Crushing Mechanism

The crushing mechanism is the subsystem of the machine which is responsible for crushing the rocks into gravel. Knowing that the current method of rock crushing is through high impact force it was thought that a similar method of rock crushing could be used for the crushing mechanism. After experimenting with different methods of crushing rocks it was concluded that dropping a weight onto a rock is an extremely effective method of crushing it. One thing to be calculated would be at what height the weight would need to fall from in order to generate enough impact force to break down the rock. Other considerations to be made are the weight and volumetric size and geometry of the weight.

After determining the method of how the crushing mechanism will function, the next step was to design it so that it crushes rocks more efficiently than the target users are currently able to. This means ensuring that the crushing mechanism is able to crush rocks down to the desired size at a faster rate and with less effort required than with a hammer. To do so the crushing mechanism must use some form of mechanical advantage to complete the crushing process for the user.

The crushing mechanism consists of three primary components: lifting chain drives, crushing weight, and crushing plate (Figure 3.2). The lifting chain drives are responsible for lifting and dropping the crushing weight, which is the part of the machine that is responsible for breaking down the rocks, onto the rocks which are resting on the crushing plate.

On both sides of the rock crusher there is a vertical chain drive. The lifting chain drives lift and drop the crushing weight from a height of 75cm. Each lifting chain drive consists of sprockets, axles, a chain, and a lifting hook. On each chain there is a lifting hook attached (Figure 3.3 below). Once the lifting chain drives are in motion the lifting hook goes around the chain and is able to latch onto the crushing weight and lift it. The lifting hook is able to catch onto the crushing weight because there is a piece of metal protruding from each side of the crushing weight which acts as a handle that the lifting hook can use to lift the weight.

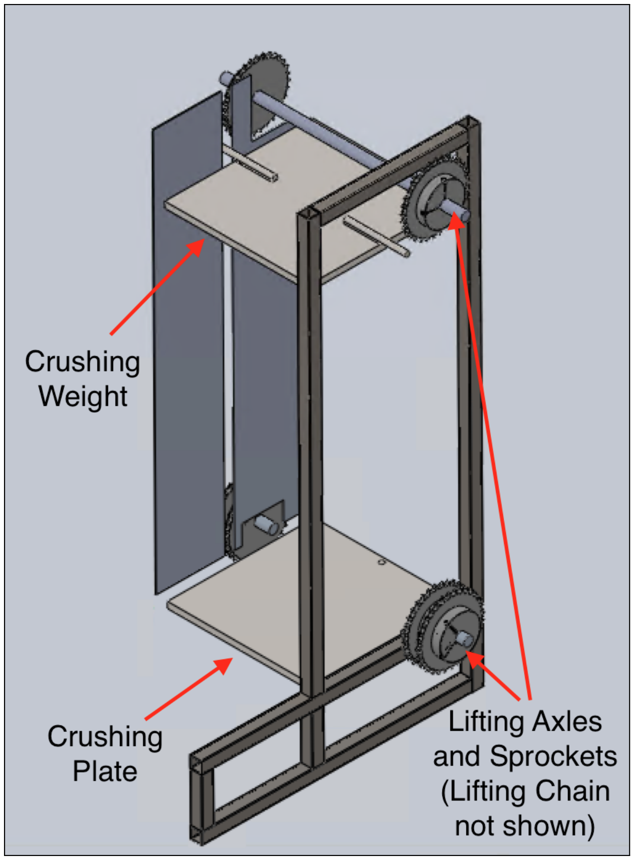


Figure 3.2: Labeled CAD of Crushing Mechanism Subsystem

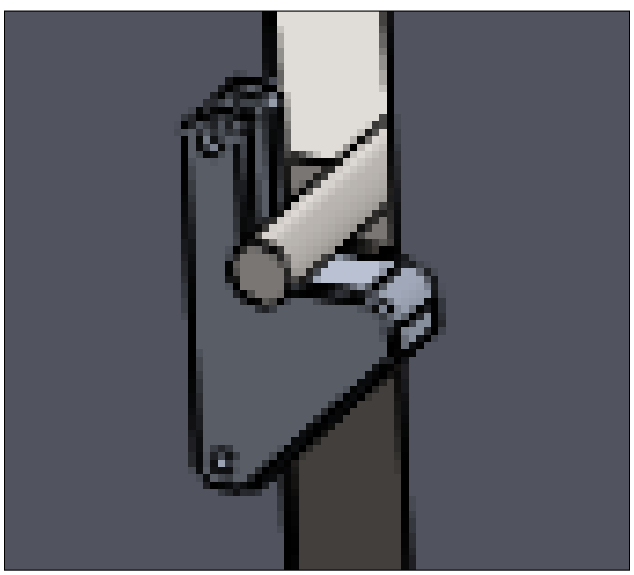


Figure 3.3: Lifting Hook

The crushing weight itself is made of a 30 cm by 30 cm square steel plate with a thickness of 1.5cm.

The handles on the crushing weight are round steel bars which are welded to the top of the steel plate.The round profile of the handle is intended to make the interface between the lifting hook and the handle transfer smoothly at the beginning and at the end of a stroke when the crushing weight is first lifted and then again when it is released from the lifting hooks. This design for the crushing mechanism allows the lifting system to self reset as the lifting hook goes around continuously, lifting and dropping the weight as it is operated.

At the lowest position of the crushing weight, to prevent rocks from leaving the feeder onto the top of it, there is also a piece of sheet metal on one side. This shield is a rectangular steel sheet perpendicular to the crushing weight, supported by a triangular sheet metal brace. When the crushing weight is at the bottom of a stroke, if the feeder currently has rocks in it, the metal sheet will prevent rocks from getting on top of the crushing weight which could disrupt the overall machine operation.

3.2.1.1 Design Selection Process

Before deciding on the chain lift design for the crushing mechanism subsystem, there were other design ideas that were considered as well. These designs also incorporated crushing a rock through the high impact force method and were named: the cam crusher and the pulley crusher (Figure 3.4 and 3.5 below) because of their use of the cam and pulley mechanisms respectively.

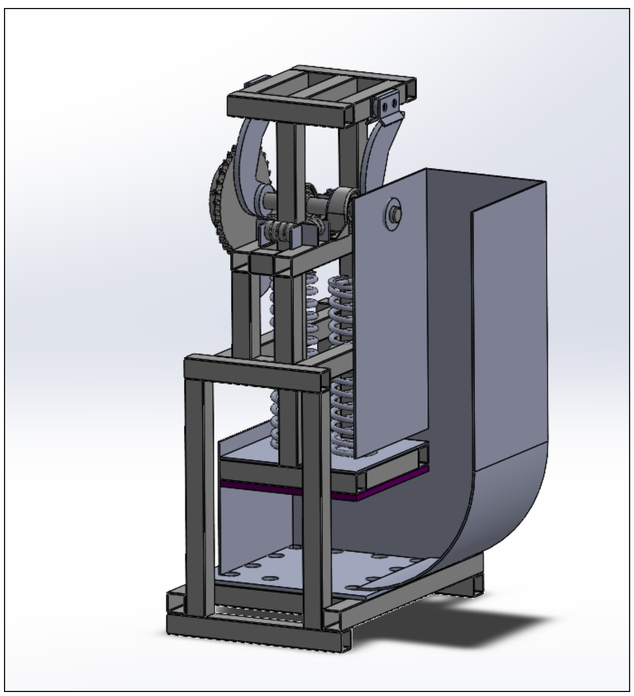


Figure 3.4: Cam Crusher

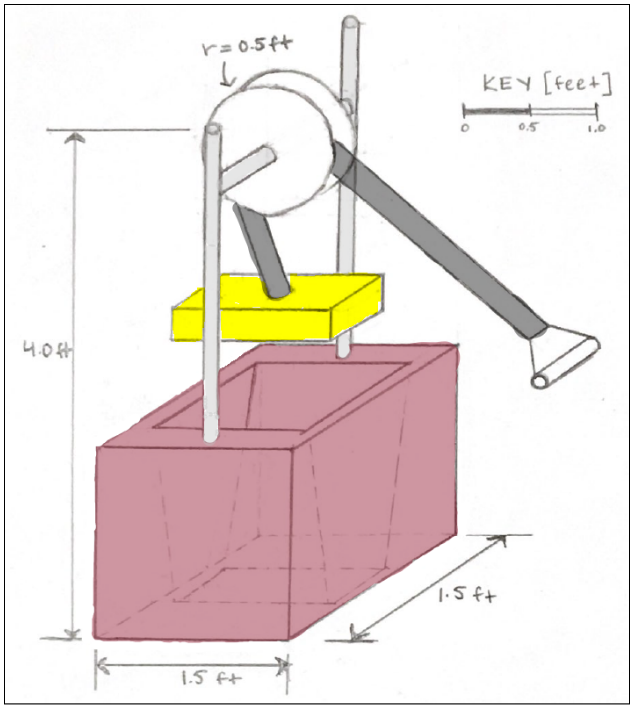


Figure 3.5: Pulley Crusher

The four main criteria that were used to determine which crushing mechanism would be the best for the purposes of this project were: stroke length, whether it could be operated continuously or not, the mechanical advantage, and how complex it would be to build (Table 3.1 below). After comparing the three design ideas for the crushing mechanism it was concluded that the chain lift was the best because it has an easily variable stroke length, can be operated continuously, uses the mechanical advantage of gear ratios and a chain drive for lifting, and is simple in design. Additionally, using parts such as sprockets and chains to facilitate crushing the rock is helpful in keeping cost low since recycled bike parts are easily accessible in Nepal.

Table 3.1: Crushing Mechanism Selection Matrix

Criteria	Cam	Pulley	Chain Lift
Stroke Length	Limited	Variable	Variable
Continuous?	Yes	No	Yes
Mechanical Advantage	Rotational Motion	None unless multiple pulleys	Gear Ratios/Chain Drive
Complexity	Complex	Simple	Simple

3.2.1.2 Crushing Weight and Plate: Material Selection

Because the crushing weight and plate are the two parts of the crushing mechanism, and of the entire rock crusher, that will experience the most wear from continuously crushing rocks, additional research was conducted to confirm which material would be best for these two components (Refer to "Appendix B: Material Selection" for more detail). The findings showed that ductile cast iron would be best for the crushing weight and plate as it was the least expensive material that met all requirements. The research also showed that other materials could be used as they also met the requirements of durability and hardness. One of these other possible materials was low alloy steel, which is the material that was used for the crushing plate and weight in the CAD model. This is because low alloy steel is the easiest material to access locally. However, for the actual GRVLR rock crusher that would be manufactured in Nepal, the crushing weight and plate should preferably be made from ductile cast iron, but low alloy steel would satisfy the necessary functions as well. This is also dependent on what is available in Nepal.

3.2.2 GRVLR: Power Input

The power input subsystem is the portion of the rock crusher that takes a user input and converts it to the rotational motion that is used by the crushing mechanism. The subsystem consists of two pedals on the same axle with a sprocket, a bike chain to transmit the motion between the pedals and the main axle, and the main axle with three sprockets (Figure 3.6 below).

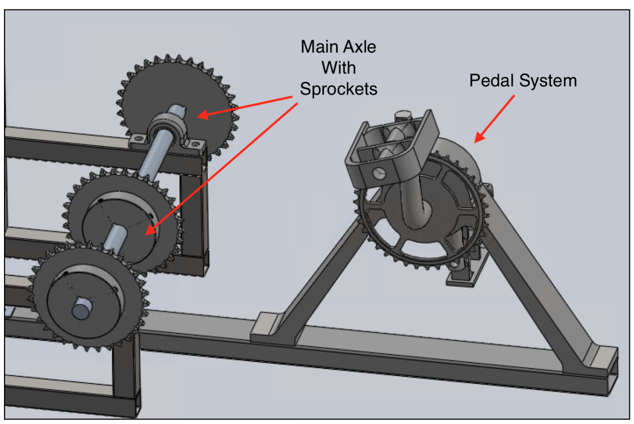


Figure 3.6: Power Input Subsystem

One of the goals of the GRVLR is to make the rock crushing process less stressful on the bodies of the women performing the work, so the power input designs were limited to methods that used relatively gentle and slow motions. Another goal is to achieve greater efficiency, so the team decided to weigh value on a system that took a continuous input where no part of the work and very little time was put towards resetting the system. While a hand crank, a ratcheting lever, and even a simple pulley were considered early on, a pedal input was ultimately chosen because it allows for a continuous, comfortable motion with a constant input of rotational energy. The design of the crushing mechanism had to be modified to accept a continuous rotational power input, however this did not prove to be a difficult task and was well worth the effort. Another advantage to the pedal system is that it can be manufactured using recycled bike parts which are widely available in the area.

The pedal system was designed to be high enough off the ground such that a person pedaling in a sitting position would not have to lift their knees too high above a sitting position therefore losing the full use of their legs to push in the pedaling action. The pedal system is attached with the pedal arm which is a 25mm x 50mm x 1mm square tube steel bar. This bar is secured with retaining pins which allow the pedal system to be removed for easier transportation and storage. The cadence that the system has been designed for is a pedaling cadence of approximately 60 RPM, which is a comfortable pace. At this rate gearing the force down to be an allowable amount of force to be applied with each pedal, the interval between each impact should be about 3 seconds. The average crushing time for the women with a hammer is approximately 14 seconds, so the GRVLR will be able to crush rocks more quickly than the women if it can crush a single rock in 4 or fewer impacts without even considering the fact that the GRVLR was meant to crush multiple rocks at once.

This subsystem can be constructed using recycled parts, up to a point. The pedals, the bearing that supports them, some of the sprockets, and even the pedal support legs can be taken from recycled bike parts. The axles, axle support bearings, sprockets of specific sizes, mounting hardware, and pedal arm can be found among recycled materials, but are not always easily available on bikes. Some elements have to be bought (Figure 3.7).

Figure 3.7: Pedal Assembly

3.2.2.1 Mechanical Advantage: Gear Ratios

Because In order to make the operation of the GRVLR machine comfortable, the gear ratio between the pedals and the main axle was calculated using an energy method based on a comfortable pedaling pace. Through some investigation using an exercise bike, the team found that a comfortable pedaling pace was 60 RPM or two pedals per second in order to maintain a pace for a long time. By finding the power output for a person of the average size of one of our target users while pedaling and knowing the energy required to lift the weight to its full height, the time required to comfortably lift the weight can be calculated. Once the time to raise the weights has been calculated, it can be used to find the rate of rotation required to drive the chain at that linear speed, and using the ratio between that rotational speed and the comfortable pedaling speed, the gear ratio between the pedal gear and the main axle can be calculated. The power output of a single woman can be expected to be approximately 75W based on their body weight and predicted general health [25]

$$\mathrm{P_{Woman}} = 75\ \mathrm{W} \tag{3.1}$$

$$\mathrm{E_{Mass}} = (9.81\frac{\mathrm{m}}{\mathrm{s}^2})(0.75\mathrm{m})(12\mathrm{kg}) = 88.2\ \mathrm{J} \tag{3.2}$$

$$\mathrm{f_e} \approx 0.5 \tag{3.3}$$

$$\mathrm{t} = \frac{88.2}{(0.5)(75)} = 2.35\,\mathrm{sec} \tag{3.4}$$

$$\text{Total Travel} = 35\ \text{in} \tag{3.5}$$

$$\text{Tooth Pitch} = .5\ \text{in} \tag{3.6}$$

$$\text{Driving Gear Number} = 38 \tag{3.7}$$

$$\text{Main Axle Gear Number} = 32 \tag{3.8}$$

$$\text{Pedaling Rate} = 1\ \frac{\text{Rev}}{\text{sec}} \tag{3.9}$$

$$\mathrm{R} = \frac{35}{(32)(0.5)} = 2.19\,\text{Rotations}, \frac{38}{2.19} \approx 18\,\text{teeth.} \tag{3.10}$$

[25] Science Learning Hub, Pedal Power, February 22, 2011 www.sciencelearn.org.nz/

$$\text{Period of Crushing Cycle} \approx 3\,\text{sec} \tag{3.11}$$

This gear ratio of 16:9 means that the crushing weight should fall about once every 4 seconds. The weight was set to crush a rock in a single fall, so depending on how the presence of multiple rocks affects the rate or crushing, the GRVLR could be 3x as efficient as the women or more. More testing is required to see exactly how quickly the crushing will be but based on the frequency of the weight falling it seems on track to meet the efficiency requirement.

3.2.3 GRVLR: Feeder, Filter, and Support

Currently the women are crushing rocks by gathering them in a pile then taking one at a time and crushing it with a hammer. There is no protection from the user hitting their hand with the hammer or from a rock shard flying off and striking them. In addition, this is by no means an efficient way of gathering rocks, loading them up to be crushed, and sorting through the gravel which is to size. The feeder, filter, and frame are the main parts of the rock crusher which help resolve these issues.

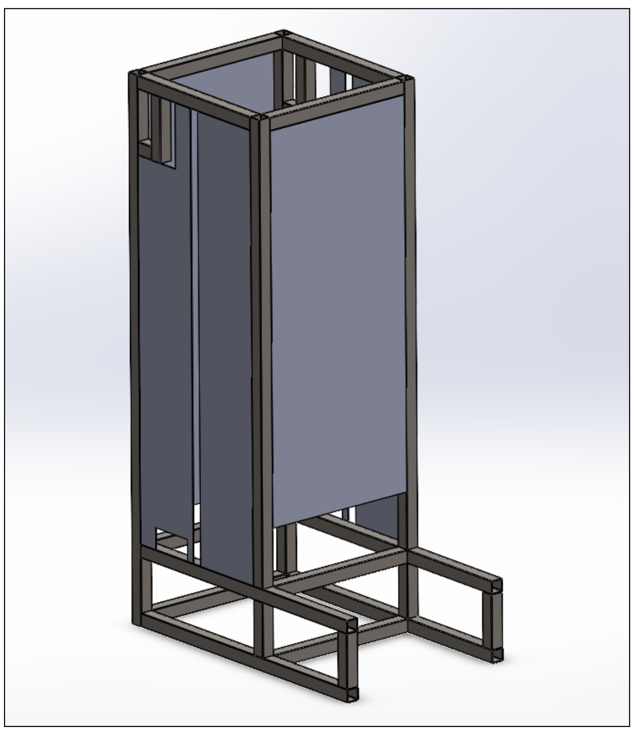


Figure 3.8: Computer Generated Model of Frame

These three components of the rock crusher are combined as a single support subsystem (Figure **??**) because they will all be stationary components with substantial structural considerations. The overall requirement of this subsystem is to be structurally sound and support all of the weight and motion required to crush the rocks. Although this is the main purpose of the subsystem, each individual component serves a specific function. The frame is the main structure of this subsystem and as a requirement must be extremely sturdy. This is because it must support the other subsystems which include moving parts, such as chains and axles, as well as a falling weight that crushes the rocks. The frame must also create an enclosure around the rocks that are being crushed within it. This is to prevent rock shards from shooting off and hitting the user. The frame is made of 1" by 1" steel square tubes with a thickness of 1/16" and 1/16" thick pieces of steel sheet metal. The square tubes are welded together to make up the outer skeleton of the frame, and the custom cut pieces of sheet metal are welded to together with the skeleton to fill the gaps in the frame (Figure **??** below).

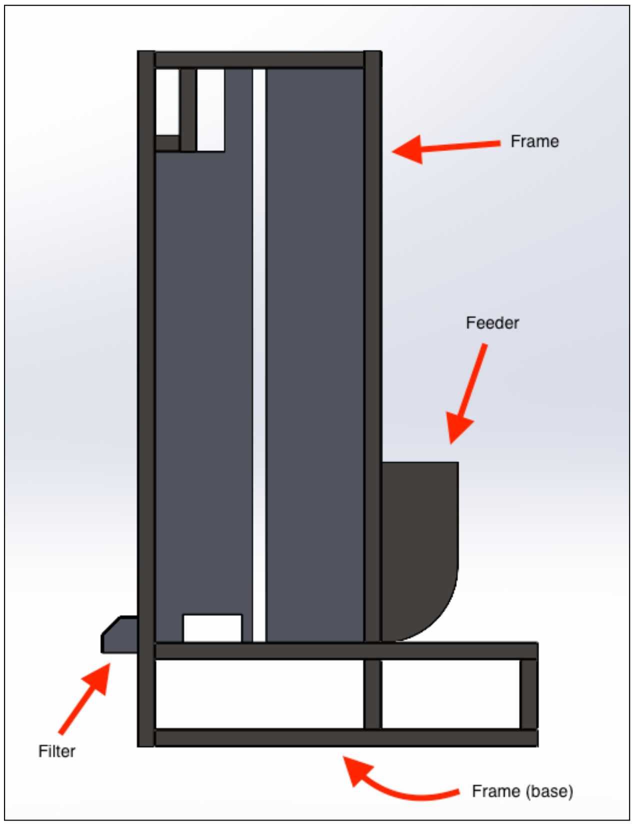


Figure 3.9: Labeled Computer Generated Model of Frame

The main function of the feeder is to allow the user to safely and efficiently load rocks into the rock crusher. To speed up the rock crushing process a main requirement of the feeder is to allow the user to load multiple rocks into the machine at once, as well as hold a large amount of rocks so that they can essentially be preloaded into the rock crusher. From there the rocks will be evenly distributed into the crushing chamber as the rocks are crushed by the crushing weight. The feeder chosen was a simple inclined slide made of sheet metal and covered on all sides. Additionally, the feeder is attached to the front of the frame to allow for easy access for loading rocks since that is where the pedals are and the user will be sitting.

The filter is just a simple hood welded onto the back of the frame so that the crushed rocks will form a pile on the opposite side of the rock crusher from the user. The gap in the hood is set to the desired final size of the crushed rock so that only rocks that have been crushed down enough can exit the crushing chamber of the frame. One concern with this filter concept is that because there is no actuating mechanism to push the rocks out of the hood some of the crushed rocks may remain in the crushing chamber and continue to be crushed down until they are no longer useful to the women. A next step for the next design team would be to implement some kind of actuation mechanism, or a different concept, so that the user can easily remove the rocks that are crushed to the proper size from the crushing chamber, instead of them just falling out of the back of the machine.

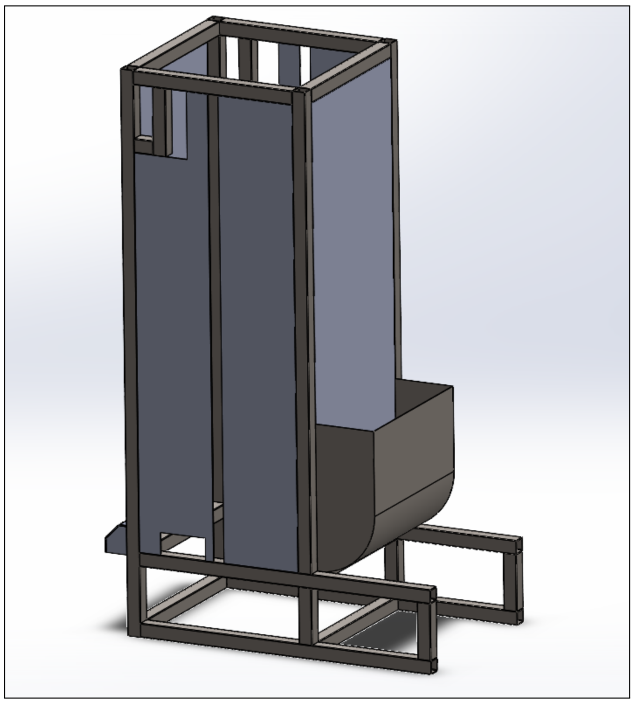


Figure 3.10: Dimetric View of Frame

3.3 FEA Design Evaluation

Finite element simulations were performed on models of prototype systems. This was done to test the viability of the prototypes in their initial stages of design, reveal points of high stress in the prototypes to advise the design process, and to provide a demonstration of the viability of the final design.

In the initial design stages, two design ideas, the cam crusher and the pulley crusher, were modeled using SolidWorks and were studied under simulated loads. The cam crusher FEA showed that the frame initially proposed was overly complicated and could be greatly simplified without sacrificing functionality. Additionally, based on the results of the initial tests, reinforcement was added in multiple areas to disperse the stress experienced over a larger area of the frame. The pulley crusher also showed that some parts would require reinforcement and overall showed that the original supporting mechanism was not robust enough and created stress concentrations on the sheet metal tube that supported the structure. These simulations also made it clear that the cam crusher would need to stand up to a lot more static load than the pulley crusher.

Subsequent simulations were performed on models of a revised pulley crusher design and the steel plates that would be delivering and receiving the impact of the crushing action in order to verify the robustness of the new design. The results were overwhelmingly positive, showing that the frame and plate were able to withstand many times the impact required. This result means that a prototype constructed in the way proposed would have the capability to be used with a highly increased crushing weight if testing were to show that to be required.

3.3.1 Early Prototyping

To improve the designs being considered at the time, finite element analysis (FEA) was performed on models of the two proposed designs using SolidWorks. The support structure subsystem consists of the stationary components that support the crushing mechanism. These systems must be stable and have the ability to support the force applied by the crushing weight or spring elements at maximum compression. Both designs were tested using the properties of 1010 hot rolled steel, which was chosen because of its ease of manufacturing, high yield strength, and common accessibility throughout the world. Each simulation was checked by hand calculations using assumptions to simplify the calculations required.

3.3.2 Design Review

3.3.2.1 Cam Crusher Design

The cam system was designed to operate on pedal power, using the circular motion produced by the user to turn the cam to lift the crushing weight and compress a spring (Figure 3.11). After half of a revolution the cam would release the crushing weight, using gravity and the potential energy built up by the compressed spring, to break the rocks sitting on the bottom plate of the machine. The support structure of the cam system would be required to withstand the impact from the crushing weight during repetitive rock crushing, as well as the alternating loading from the pedal system, and the spring support. The goal of the FEA is to verify that the system will not bend to the point of failure while the cam is being loaded and that the frame will not break under the crushing impact or deform enough to reduce the force of the crushing head below the critical force required to break the rocks.

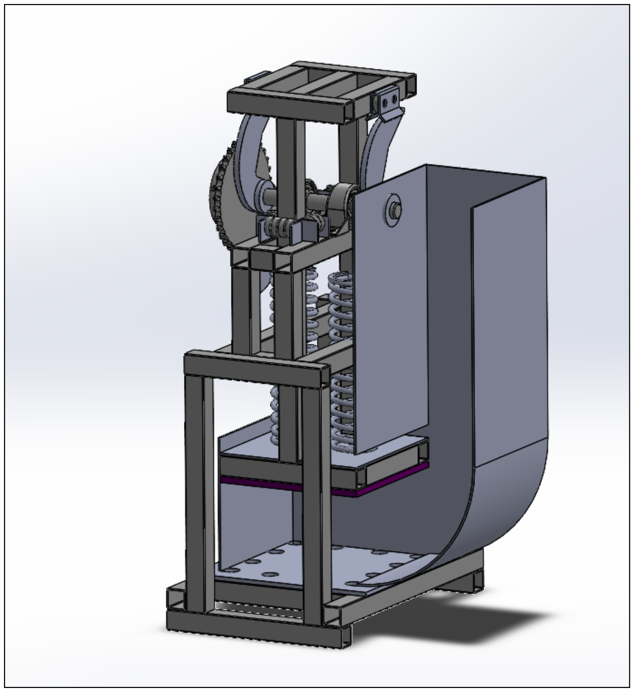


Figure 3.11: Cam Crusher Top Level

The support structure for the cam consists of 25 mm square tube 1010 hot rolled steel held together with fillet welds. Welding was chosen as the connection method because it forms strong connections and it reduces the need for drilled holes, brackets and mounting hardware.

3.3.2.2 Chain Lift Design

The support structure for the chain lift crusher design largely consists of a 915mm by 178mm 1060 aluminum sheet with 3.175mm thickness (Figure 3.12) formed into a tube. The aluminum sheet metal is the outer casing of the support structure for the crushing weight. There is another guard at the bottom of the machine to protect the user from rock shards during crushing and from injury caused by contact with the rotating sprocket at the bottom of the machine. The sprockets are supported by 1010 hot rolled steel square tubing attached to the side of the aluminum sheet metal support structure. There is a slit that runs up the side of the aluminum sheet that allows the chain to lift the crushing weight from inside the crushing chamber. The team determined that the four steel square tubes will be responsible for taking the load and supporting the chain and the lifting of the crushing weight; thus they should be the focus of FEA tests for the chain lift crusher.

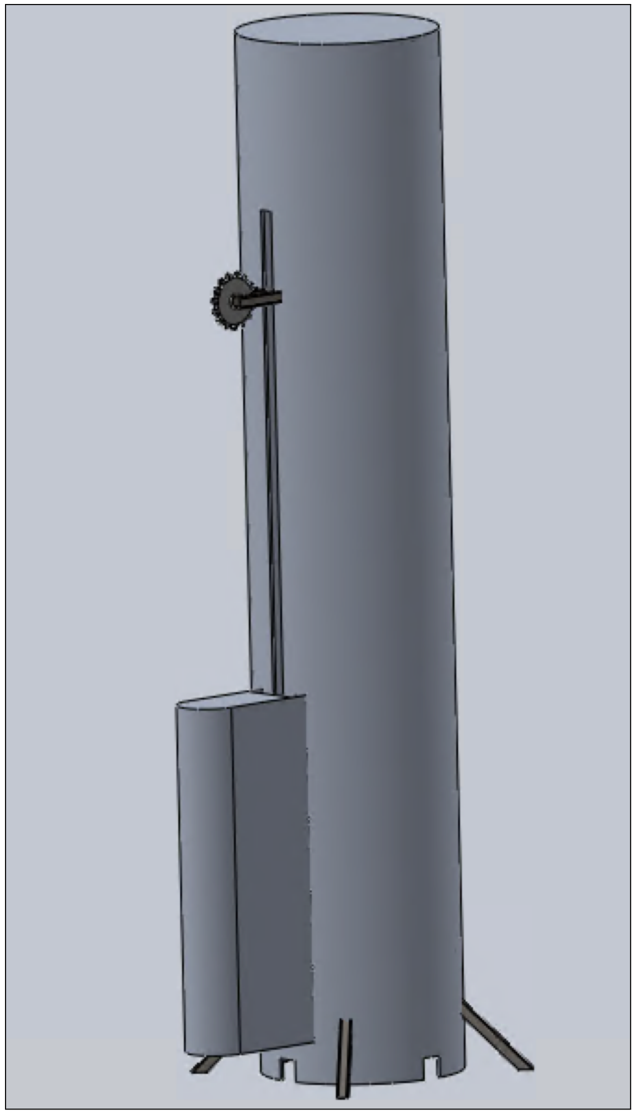


Figure 3.12: Chain Lift Without Brace

3.3.2.3 Assumptions

When modeling both designs, welded components were assumed to be completely unified. This assumption is somewhat reasonable because a well executed weld should fuse the two parts well. However, it does slightly underestimate the final dimensions, as the weld will add a fillet of metal that is not in the models. Another assumption made was that the act of modeling by mating the individual components together would be the equivalent of welding connections. When welding, the mechanical properties of the materials being joined changes, but for the sake of the FEA it was assumed that the material maintained their original properties. Lastly, it was assumed that all members under a given load were sharing it equally when in reality it is possible that some members will take more or less than others.

3.3.3 FEA Results

3.3.3.1 Cam Crusher FEA Results

The FEA for the cam operated system, performed using the 2020 SolidWorks student edition, was conducted on a newly designed and simplified frame (Figure 3.13). The loading on the frame was derived from the load that would be applied when the springs are in their fully compressed position. This load is applied as a distributed force over four bearings that support the axle, and also on the supports for the springs that would be loaded in compression. The model below was meshed fairly coarsely except for the area around two edges of each of the high stress components in order to provide high resolution stress data on a critical point for all members. The mesh, and plots of the stress are shown below.

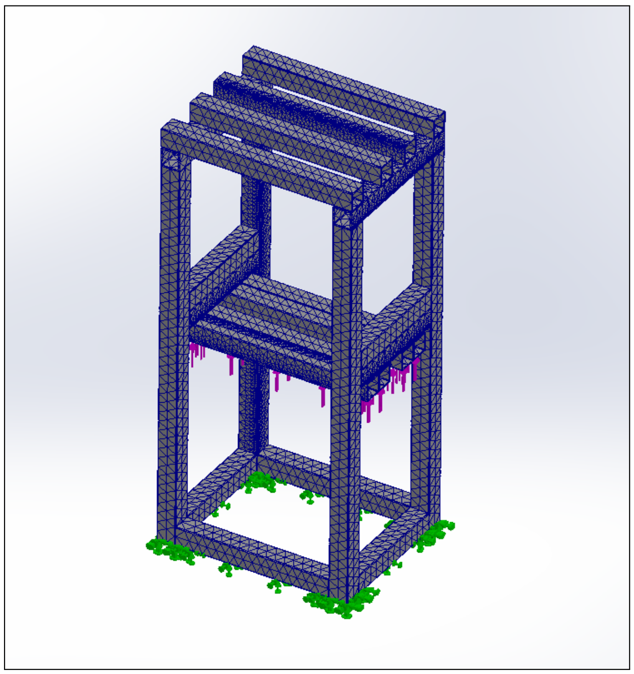


Figure 3.13: Cam Crusher Mesh

Plots of overall stress on the cam support structure were made using a predicted load of 3500 N (Figure 3.14 and 3.15). The left plot has the stress scale maximum set to the maximum stress experienced in order to show the areas of the frame under the most stress. The right plot has the maximum set to a value just above the yield strength of the material, this demonstrates that the frame is not close to yielding.

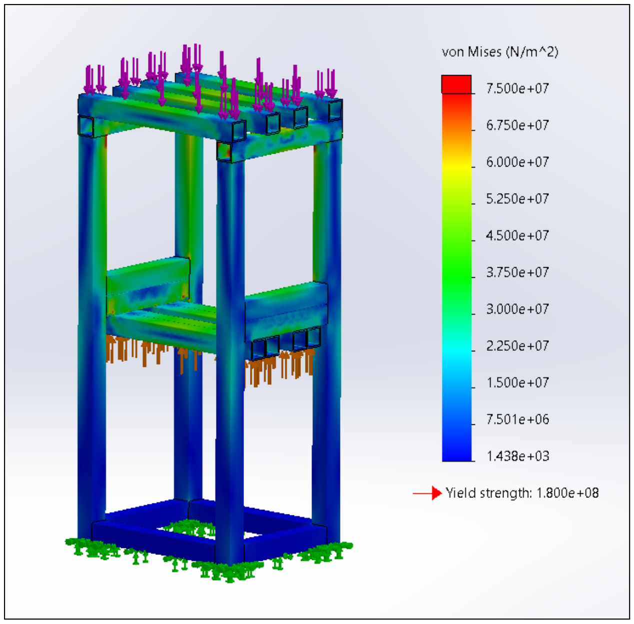


Figure 3.14: Cam Crusher Max Stress Scale

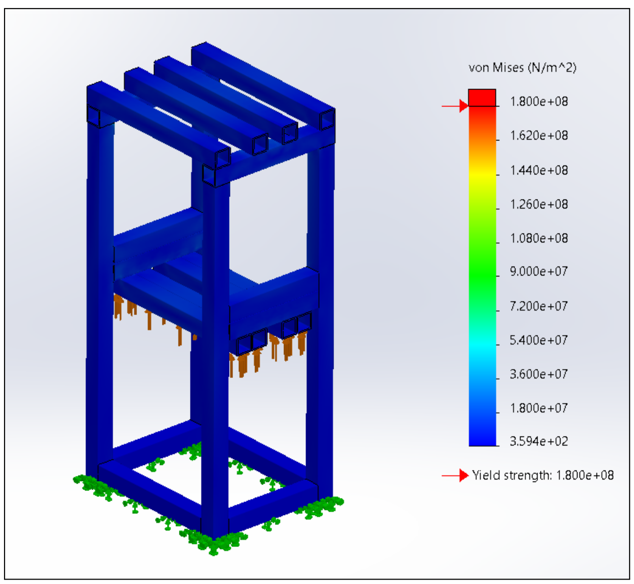


Figure 3.15: Cam Crusher Yeild Stress Scale

3.3.3.2 Chain Lift FEA Results

The FEA on the frame of the chain lift was focused on the steel square tubes which hold the chain and sprockets in place (Figures 3.16 and 3.17). This is because the square tubes take most of the load created by the vertical force required to lift the crushing weight and move the chain continuously. Additionally, out of all of the components in this design, the square tubes are the most likely to fail since they are attached to the side of the aluminum sheet frame without any additional support. This makes the steel square tubes susceptible to bending as they are essentially acting as a cantilever beam.

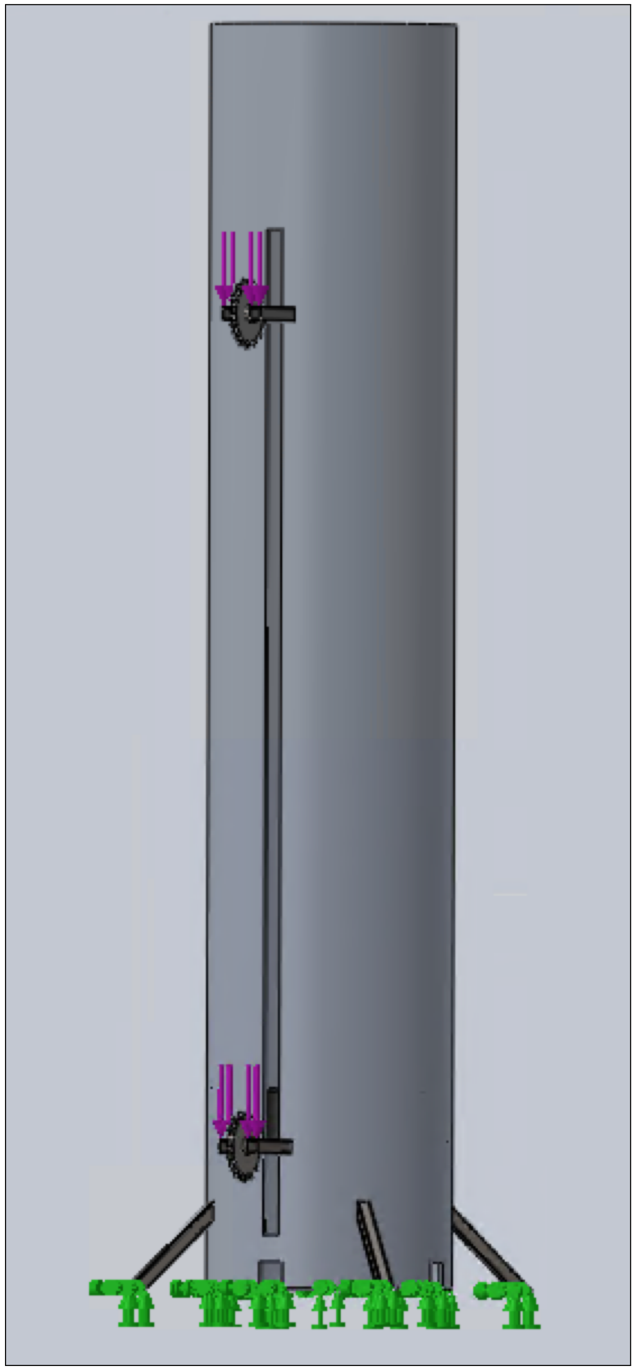


Figure 3.16: Chain Lift Fixtures and Forces

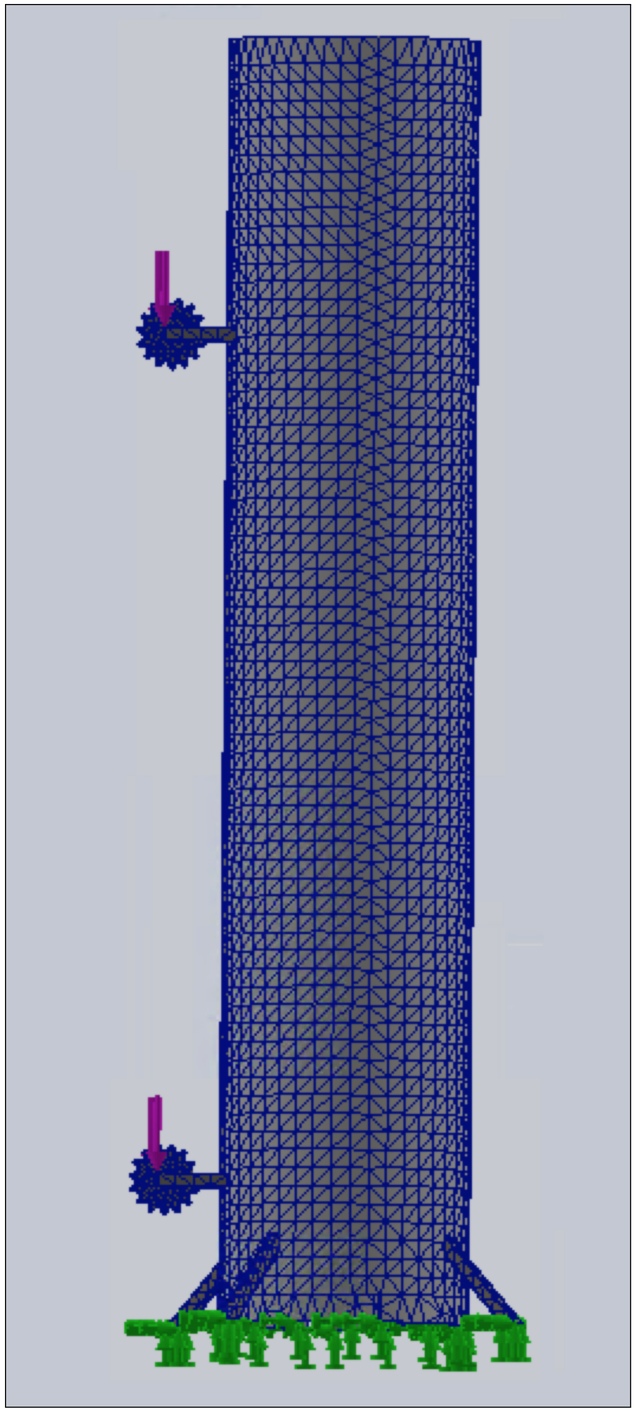


Figure 3.17: Chain Lift Mesh Macro

The FEA showed that the steel square tubes attached to the frame failed when a total of 4000N was applied to the system. Since it was assumed that the load would be distributed evenly, this meant that each beam took 1000N of force in the vertical direction. The resulting stress plot is shown below in Figure 3.18 and indicates where the critical stress points are, thus confirming that the beam experiences bending.

Additionally, the simulation study showed that the beam undergoes deflection and is displaced vertically from the horizontal axis (Figure 3.18).

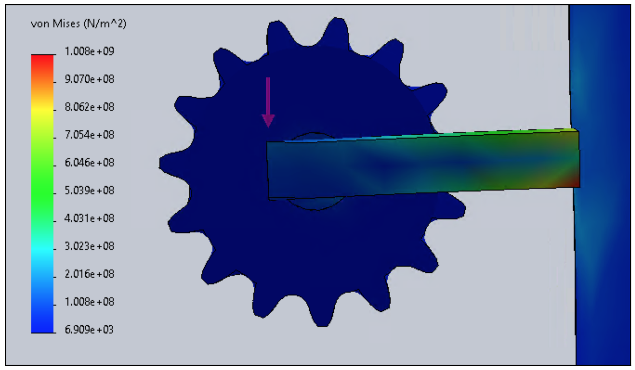


Figure 3.18: Chain Lift Stress View For 1000 N Load

3.3.4 Design Analysis and Comparison

The FEA conducted demonstrated the weakest aspects of the support structures of both the cam and chain lift design options. Initially, both designs were loaded to the maximum capacity that they could support to see where their most critical sections resided and then were modified accordingly to maximize the support.

3.3.4.1 Cam Crusher Analysis

In the case of the cam design, the most critical sections were at the corners where the cross beams join with the vertical supports, as can be seen in Figure 3.14. The initial load that was applied was 14 kN, roughly six times what is expected to be the necessary load. The initial design was not able to support this and so adjustments were made. Six additional pieces of tube steel were added to better support the critical sections resulting in the support structure shown. These additional pieces allowed the structure to withstand the 14 kN without yielding. The structure was then tested under 3.5 kN as displayed in the figures in the Cam FEA Results section above. Predictably the structure was able to withstand the load.

These results were verified by calculations done on the stresses of one of the top beams, shown in appendix C-2. At Point B there was only a 2.03% difference between the expected value by calculation and the resulting value from the FEA. At Point A there was a more significant difference of 9.61%. This difference could be attributed to the fact that for the calculations the beam was modeled as having a square cross-section, when in reality the corners are filleted. Additionally, the supports were modeled as points when in reality they have a width. Even still, the results are reassuring that the model is trustworthy. Finally, these differences could be attributed to the fact that shear stress was not taken into account. The shear stress is likely comparatively small to the bending stress, but the stresses by calculation are less than those from the FEA so it could be another factor.

3.3.4.2 Chain Lift Analysis

In the case of the chain lift design, the most critical section was found to be the bars that support the sprockets, as can be seen in Figure 3.18. The initial load applied was 4 kN, roughly two times the expected necessary loads, also as shown in Figure 3.18. The bars were not able to support 4 kN without yielding and so bracers were added (Figure 3.19). This adjustment allowed the bars to successfully support the load.

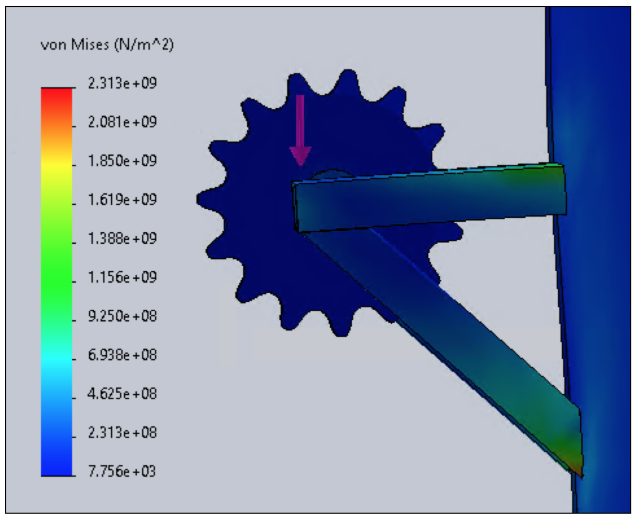


Figure 3.19: Chain Lift Stress With Brace

Calculations were performed by modeling the bars as cantilever beams with point loads on their ends. At Point B there was only a 2.17% difference in values and at Point A there was only a 3.53% difference. These small differences could be attributed to assuming the cross section was square in the calculations and thus not taking into account the fillets. Even so, the differences in stresses were small enough that the modeling was considered trustworthy.

3.3.4.3 Design Comparative Summary

In conclusion, the early FEA results were encouraging. They showed that the designs could successfully support more than twice the anticipated necessary load to crush the rocks. However, the state of the designs led the team to refine each design further and to decide on a single design.

In the case of the cam design, the FEA made it clearer that using springs to generate the crushing force means a much higher alternating load on the frame when compared to the relatively small loads involved in lifting the crushing weight in the chain lift design. This increased load leads to a bulkier frame and overall heavier and more expensive design. The circular frame of the chain lift design was also seen to be an issue, as cutting a slot in it removes a great deal of its structural integrity. The use of a tube also means that a prefabricated tube of the correct dimensions needs to be sourced or made, both of which can be very difficult to do. These considerations led to the conclusion that a chain lift design ought to be pursued and that a square frame should be used. After the redesign a new series of FEA simulations will be required in order to verify the new designs strength and performance.

3.3.5 FEA Design Verification

After conducting the FEA, the team was able to test the resilience of the cam design and chain lift design by simulating the approximate loading they would experience. After analyzing the results and discussing the advantages and disadvantages of both designs, the team decided to move forward with the chain lift design. The next steps were then to finalize the design so progress could be made towards manufacturing.

In order to accomplish this, the CAD of the power input mechanism was finished, the design of the support structure was revised, and any other necessary changes were integrated. Finite element analysis was then conducted on the crushing plate in order to reaffirm that it is capable of withstanding the stress caused by the worst case scenario of loading. Verification calculations on the lifting hooks used to raise the crushing weight were also completed to confirm that they could support their respective loads.

3.3.5.1 Crushing Plate FEA Result

Finite element analysis was conducted on the crushing plate using the assumed worst case scenario of loading. This was modeled as a point load near the welds on one of the edges (Figure 3.20). This simulates one rock present in the chamber such that all of the impact force from the crushing weight is translated to one point on the crushing plate. It is placed near the edge to test the strength of the welds, as they are the plate's weakest points. The material used was gray cast iron. It was selected as a result of the material selection analysis summarized in Appendix B.

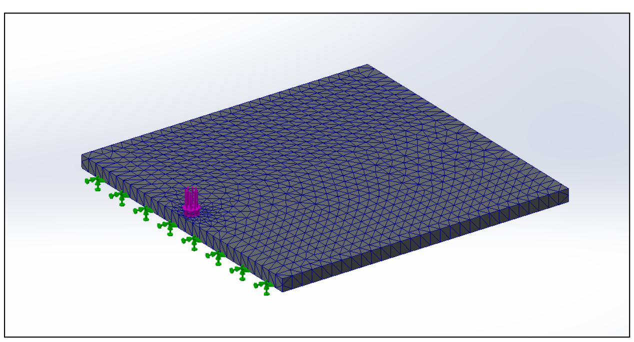


Figure 3.20: Crushing Plate Mesh

First, a point load of 1000N was applied 1.5cm from the edge. 1000N was found to be the expected force delivered to the smallest rock size and 1.5cm is the radius of the smallest rock size expected to be in the chamber. It was clear that there is no yielding occurring with the maximum Von Mises stress experienced somewhere around 30 MPa. The minimum yield strength of gray cast iron is 97.4 MPa, which leaves the crushing plate with a factor of safety against yielding of 3.3. After verifying the plate could support the applied load, it was tested until failure. It was found that yielding began when a load of 6000 N was applied (Figure 3.21). This is encouraging because if it is found from testing the prototype that the crushing weight designed is not successfully capable of crushing the rocks, the plate can support a crushing weight with a greater mass without needing to be redesigned.

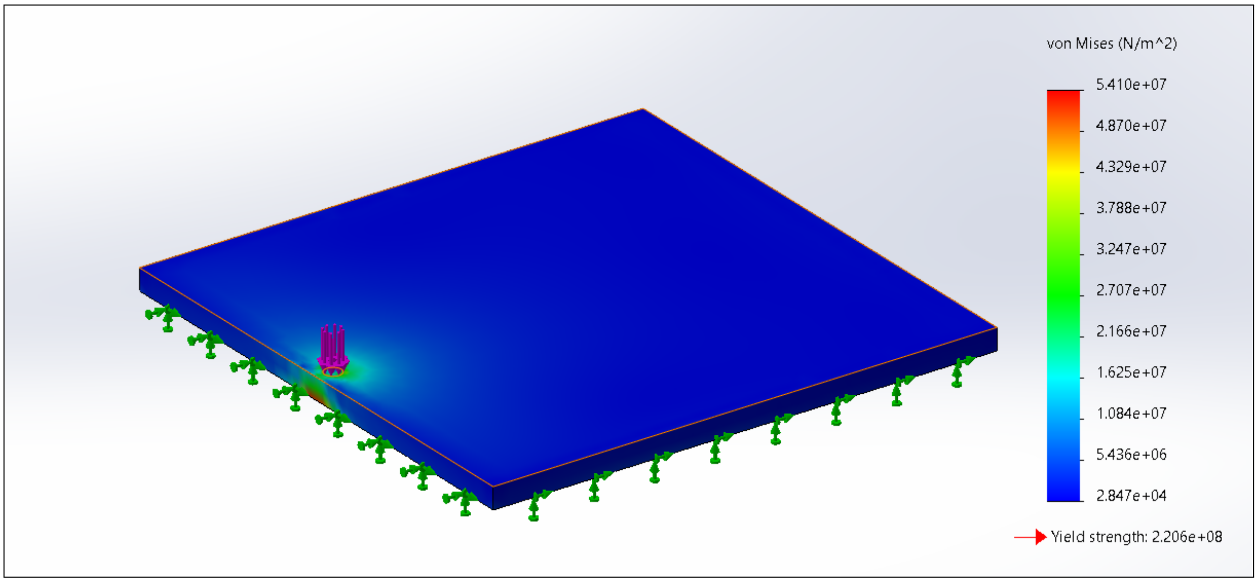


Figure 3.21: Crushing Plate Stress

3.3.5.2 Lifting Hook Stress Verification

Two lifting hooks are used concurrently to raise the crushing weight. They are joined to the chain via two pin connections. These are their most likely points of failure, so FEA modeling was conducted to verify that they are capable of withstanding the loading they are expected to be subjected to. The worst case scenario of loading was assumed to be at the point when all of the weight was applied to one point on the tip in the moment before the crushing weight is dropped off. A model of the primary design was made and revised based on the dimensions of common bike chain and FEA was performed. One change that seriously affected the design was the realization that in order to prevent interference between the teeth of the gears and the lifting hook the rear spine had to be hollowed out. This presented a more complicated part to create and overall meant that a more robust part would be required. Based on the first round of FEA it was found that the stress experienced was close to the yield stress of the material that had been selected for the part (1610 aluminum), and so the part was reinforced and new simulations were performed.

The finalised version is shown below (Figure 3.22).

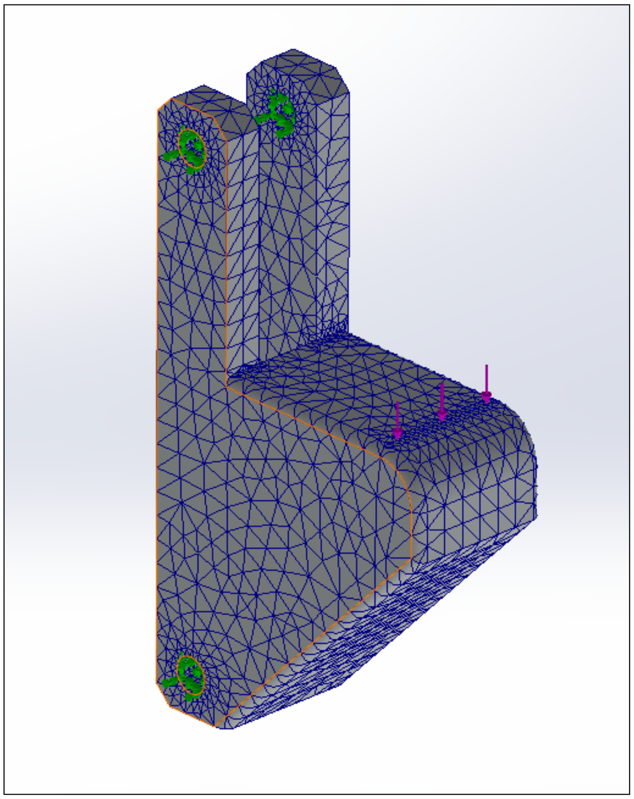


Figure 3.22: Lifting Hook Mesh

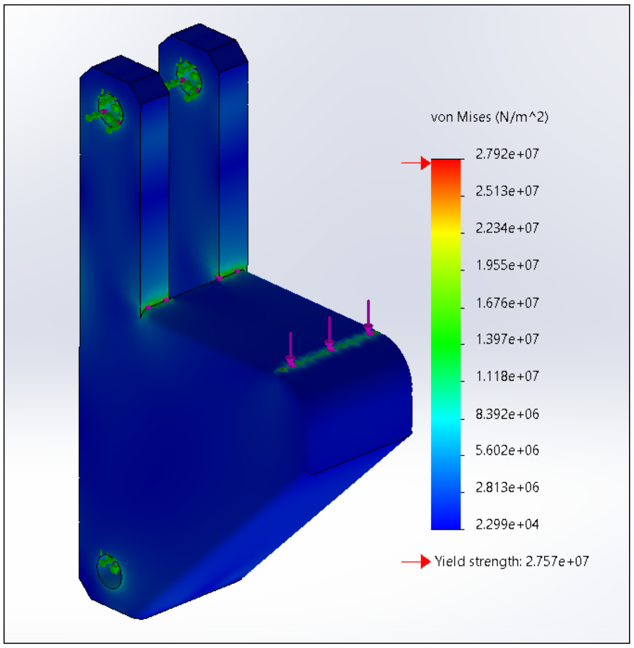


Figure 3.23: Lifting Hook Stress

3.3.6 Chain Lift Crusher Improvements

Since the previous iteration of the chain lift design many updates were made that were not accounted for in the FEA or the calculations performed. These updates consist of changes in the support structure, the lifting mechanism, and the inclusion of a power input subsystem and a feeder.

The structural support frame is now a 1m tall steel square structure with 35x35cm outer dimensions and 30x30cm inner dimensions. This frame is intended to be more sturdy than the cylindrical design and was increased in size so that it could fit more rocks in the crushing chamber at a given time.

As demonstrated above in the calculations, there will now be two lifting hooks to lift the crushing weight from both sides. This means that there will be two lifting chains, one on each side of the square frame. The lifting chains will be attached to sprockets at the top and bottom of the sides of the frame and the lifting hook will be attached to the chain. The lifting hook will lift the crushing weight which will have a hook on each side sticking out of the slits in the side of the frame. This will also ensure that the crushing weight is well guided as it falls and does not move around awkwardly in the crushing chamber.

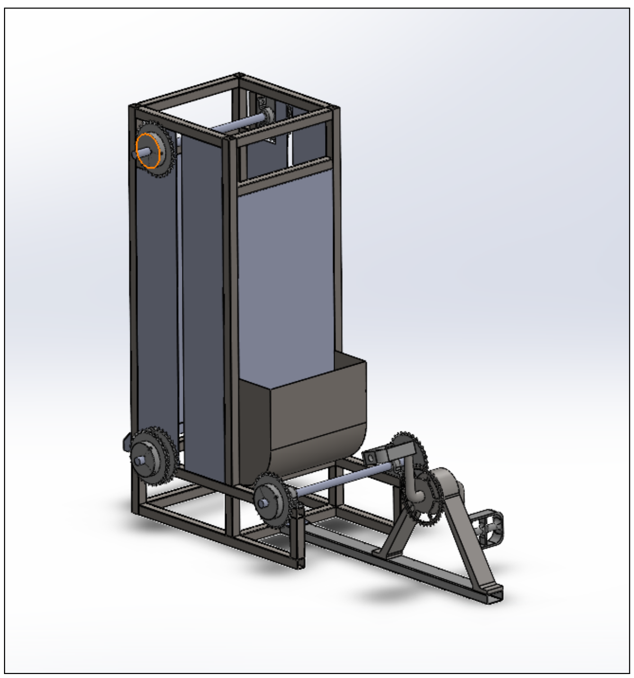


Figure 3.24: GRVLR Top Level Improved Chain Lift Design

Since there were now two lifting chains, it needed to be determined how they would be activated through a single pedal power input system. The solution was found to be adding a center rotating axle that is connected to the pedal system and two other activator chains. In order to make this design more complete, the power input subsystem was developed and integrated to the chain lift rock crusher. Due to the repetitive motion required by the user, it was concluded that leg power would be better than arm power to reduce the likelihood of early fatigue during operation. Thus, the pedal power system was created. For this pedal design a gear ratio of 38/14 was used, which is a medium sized gear ratio for bikes. Assuming that the user is spinning at a cadence of 60rpm, the average speed generated is 20 km/h, which can be used later to determine the average rate of rock crushing per day and in turn average earnings per day.

3.4 Design Impact

As a humanitarian engineering project there are many factors that need to be considered outside of the act of designing and building alone. Five of the most important constraints to the GRVLR project looked into by the team were manufacturability, sustainability, economic viability, social impact, and health and safety. The summary of these considerations are listed in the following sections.

3.4.1 Manufacturability

A major concern of the GRVLR project is keeping the unit cost low. Sunita Bhandari emphasized to the team the value in the women being able to pay for the device in some capacity. There is a certain sense of pride and enhanced responsibility that comes from being able to purchase things for oneself, as opposed to simply receiving it as charity. It was proposed to the team by a representative from the Himalayan Climate Initiative, Shilshila Acharya, that if the product proved beneficial to the target community it could be subsidized by the government. In this case, the government would pay for the construction of the device and then sell it to the women at a lower, more affordable price. The team has realized that it is impossible to build a rock crusher that is as inexpensive as using a hammer, because otherwise the women would already be employing that method.

Without having this as a guarantee, though, the team looked to reducing costs wherever possible. One idea presented itself in utilizing recycled materials. Given the high strength, abundance, and relatively low cost comparatively, steel was determined to be the best material. The team has been in contact with their Nepalese partner organization to determine the retail price of steel and see if there is easily accessible scrap steel available near to the community. Another way to reduce cost that was identified was to limit the amount of maintenance necessary.

3.4.2 Sustainability

The GRVLR rock crusher is designed with a focus on cost efficiency and durability. The rock crusher is designed to be operated for at least six hours a day continuously and so is made of highly robust parts. The crushing weight and plate are made of .5 inch thick low carbon steel. These parts will be sustaining the greatest impact. According to material analysis conducted using Granta EduPack (Appendix B), the hardness of the plates and the fact that contact between the plates and the rocks will be mainly straight on impact resulting in failure due to fast fracture and yielding, it is predicted that a long time will have passed before sufficient wear will have compromised the overall machine function. Due to COVID-19 setbacks there was not enough time to test this hypothesis, and as such confirmation will need to be achieved by the future team to take on this project.

The frame of the machine is steel tubing reinforced with steel sheet metal, this makes the machine robust enough to avoid warping during operation for optimal rock crushing, but also makes it strong enough to withstand years of use and misuse without failing. The bearings used are also sealed in order to prevent any outside material getting in and obstructing their movement. The only part that may require some maintenance would be the chain, which may need to be cleaned and lubricated. This maintenance is extremely cheap and can be performed very infrequently while still maintaining maximum productivity.

In terms of environmental sustainability, the rock crusher is made of metal which can have a high environmental impact, but it has no continuous emissions as a result of its use and is designed to make use of recycled materials wherever possible.

3.4.3 Economic Viability

The GRVLR rock crusher was created in order to improve the lives of impoverished women, in part, by increasing their income and overall economic position. When the first team attempted this project their initial business model was to have a woman save up the money to purchase a machine. Based on interviews with some women who were rock crushers, the maximum they could possibly invest in a device like this was \$25. As a result, the team tried to construct a rock crusher around this budget. It was nearly impossible to construct a machine any better than a hammer on that budget. This makes sense because if there was a better option that they could afford, why wouldn't they buy it?

The current plan is to try and have the machine subsidised by the government in order to lower the purchasing cost for the women, and for the women then to pay a portion of the cost of the machine over time in a leasing program. This idea was brought to the team's attention by Shilshila Acharya, the CEO of the team's NGO partner in Nepal, as she knew of other social works projects that the government had assisted in paying for in the past. Because at this stage the number of machines that would be made is relatively small, the initial investment would not be extremely large as it would only be for materials and the labor of those who would be constructing the machine.

The most important economic aspect is that the machine is able to significantly improve rock crushing efficiency and decrease the strain on the user's body compared to crushing rocks with a hammer. This will not only make it easier for the women to pay a lease on the device while still paying for their needs, but will also justify it as a program worthy of investment for HCI or the local government in Nepal to invest in.

3.4.4 Social Impact

The reasons that many women turn to rock crushing in order to make money are not purely economic, there are many social barriers to women that can prevent them from being able to find work that can provide for their own basic needs and the needs of their dependents. The social issues in Nepal regarding the rights of women are not something that can be addressed by this project, but the project can provide an improvement in quality of life for those experiencing discrimination right now and possibly provide avenues to education and job training for the women and their children. The hope is that if the women currently crushing rocks for a living are able to make more money in a smaller amount of time, they will be able to take some time off to attend training from groups like the Kopila Valley Women's Center who give free vocational training to women. Hopefully, they can also send their children to school in order to provide them with better future employment opportunities to break the cycle of poverty.

The women work for six to seven hours each day. In that time they crush 150 to 200kg of rock. For this work they receive $1.50 to $2.50 in compensation.The women use their own form of impact crushing through the employment of a hammer. The GRVLR device utilizes a similar method by dropping a weight on the rocks. However, the chamber of the GRVLR can hold four to six rocks at a time and crush them in the same time interval as it takes the women to crush one. From this it can be extrapolated that the GRVLR can quadruple to hextuple the women's daily earnings if it were to be operated in the same time frame. With this supplemented income the women could afford to keep their children in school, or they could choose to have a shorter work day and seek out the available vocational training that are available to them.

One potential concern the team has is that if the device makes the labor required to make the gravel too easy that companies would buy the machines for themselves and put the women out of work. This is not a particularly large concern as the device is completely manually operated and there are large industrial machines at their disposal that are already used by some companies.

3.4.5 Health and Safety

Another two important aspects to the GRVLR project are health and safety. In the context of this project, health mainly concerns ergonomics and ensuring that operating the machine does not cause any adverse health effects for the user. Safety, on the other hand, constitutes designing the rock crusher such that all possible safety risks are mitigated and ensuring that the machine follows relevant engineering safety standards.

The health of the user is a major concern since crushing rocks with a hammer is extremely damaging to joints and tendons of the target users and can cause them to develop musculoskeletal disorders (MSD). The Occupational Safety and Health Administration (OSHA) states that manual labor workers are more prone to developing MSD if they are performing actions that require excessive repetitive movements that irritate tendons and increase pressure on nerves. This includes, but is not limited to, motion that requires increased speed or acceleration while bending or twisting[26]. With this information in mind, a design goal for the rock crusher is to ensure that repetitive motion is eliminated and that the user does not need to exert as much energy and force to crush the rock as one would with a hammer. Additionally, designing the rock crusher so that it can be operated in a comfortable position should also be kept in consideration to avoid poor posturing while operating the machine.

The safety of the user is also important because crushing rocks can be quite dangerous and there is an increased possibility of serious injury if the machine is poorly designed. The major concerns with safety for a rock crusher have to do with rock shards flying off at impact and striking the user, or the crushing object landing on the user's hand or other body part. According to OSHA standard 1910.28, the area where the crushing occurs must be completely barricaded such that no projectiles or other related objects can harm the user or pedestrians while in operation[27]. This standard will be satisfied by ensuring in the design there are not any gaps or exposed openings where rock shards could shoot out or the user could get a body part stuck in and crushed. There is the possibility of injury due to pinching if the user were to put their hand into place where the chain and gears mesh, but the team elected not to put guards on our prototype under the reasoning that at the speeds that the women will be pedaling there is no more risk of injury due to pinching than there is on a bicycle, which are very safe to ride without guards over the chains or sprockets. If in testing it was found that the operation made the pinching more of a threat than originally perceived, then guards would be added, but at this time it seems like an unnecessary additional cost.

3.5 Summary of Design Methods

Based on the FEA performed, the crushing plate should be able to stand up to the force applied even in a worst case scenario, and the lifting mechanism should be able to withstand the force of lifting the weight up. These calculations and simulations provide enough verification that the team feels comfortable moving forward with the construction of a model to serve as a building platform for our mechanisms.

As was described earlier in the chapter, the team chose to organize the design into three subsystems and produced separate ideas for each one. The intention was to make the solutions modular so ideally any one power input idea could fit with a given crushing mechanism idea for example. The main objective for the final device is for it to be manual and more ergonomic, efficient, and safe than using a hammer. To accomplish this, each individual subsystem requires its own necessary design criteria that it must satisfy to create a successful design.

[26] "UNITED STATES DEPARTMENT OF LABOR." Ergonomics - Overview — Occupational Safety and Health Administration, www.osha.gov/.

[27] "Occupational Safety and Health Standards." Duty to Have Fall Protection and Falling Object Protection. - 1910.28 — Occupational Safety and Health Administration, www.osha.gov/.

The power input subsystem requires ease of operation accomplished by some manner of a mechanical advantage and a working motion that is not taxing on the body. It also must not be costly to manufacture. The crushing mechanism, on the other hand, relies heavily on the ability to crush rocks efficiently and so having a mechanical advantage and running continuously are two desirable criteria. Lastly, the feeder, filter, and support subsystem deals with safety, efficiency, and resilience. Safety is important to avoid unnecessary harm from projectile rock shards or the crushing of body parts unintentionally. Efficiency is important because the machine ought to be able to run for hours on end without jamming before more rocks need to be fed in. It must be resilient to avoid compromising the system and ensuring a long life for the device. These women have no disposable income and so the machine must require little operating maintenance.

From these notable criteria the team was able to proceed with the design selection process and narrow down those that are worth pursuing next in the prototyping stage. In the case of the power input subsystem there were three options still to look into. The recumbent pedal power, crank, and simple pulley are all promising. The crank and simple pulley are attractive because of their simplicity and subsequent low manufacturing cost. Although, they do not utilize a continuous motion and are thus less ergonomic than pedal power. As such, pedal power was chosen as the better design. Some difficulties that were anticipated when selecting this design were its added design complexity and cost.

In the case of the crushing mechanism, the team had planned to proceed with the simple pulley and cam systems. Both utilize gravity to assist in creating a high impact force for the crushing. The team moved in this direction because it was found that crushing mechanisms in industry machines do not scale down well to a device that is human-powered. As such, the former is again attractive for its simplicity and also for its adjustable stroke length. This flexibility would allow us to potentially lower the crushing weight thereby making the device more portable. However, it does not run continuously, which significantly cuts into the device's potential efficiency. The cam system, on the other hand, while complex, and thus likely more expensive, does run continuously. And, while it does have a limited stroke length, in addition to gravity, the force delivered can be supplemented by adding springs. Because of this, while we are pursuing both options, our current favored design is the cam system.

For the last system of the feeder, filter, and structure, we are only still considering one option. A simple inclined feeder utilizes gravity and so is hands-free until more rocks need to be reloaded. It also helps protect against rock shards as the incoming rocks would block outgoing shards. A slotted impact surface filter allows shards of the correct size to fall out of the machine to avoid crushing to the point that the gravel is no longer useful as coarse aggregate for construction. This also adds to the safety of the device because a filter prevents the need for the user to put their hands in the crushing chamber. And, the support system will simply enclose the entire device to prevent rock shards from harming the user.

We are attempting to keep our options open because when speaking with members of the previous design team for this project, their most emphasized piece of advice to us was to keep our options open during the prototyping stage to avoid their mistake of developing tunnel vision and not realizing until too late that their selected design could not work.

Beyond designing and manufacturing a working device, we as a humanitarian project need to prioritize the user. We need to always be considering what is best for them, rather than assume what would be best for them. The best way forward, in our eyes then, is to partner with a local non-governmental organization. Not only will they be able to help us directly communicate with our user, but they will also be able to organize the women into a cooperative if possible and manage the use of the device after we leave the project.

3.5.1 Prototype Result Predictions

Finite element analysis is always a useful tool for any mechanical project, but particularly this year where it was often impossible for the team to perform physical testing or construct physical system level prototypes it served as method for design verification and iteration without being able to try anything real. The first round of FEA's brought the team to our final design and the second round verified elements of that design that had not yet been tested. Combined the two sets of simulations allowed the team to move forward into creating a physical prototype.

4 Chapter 4: Prototype Construction, Testing, and Results

4.1 Construction

After completing the various Finite Element Analysis simulations and reaching a final design, the team set about purchasing materials for a wooden proof of concept model and final prototype, then began the process of assembling.

4.1.1 Manufacturing

4.1.1.1 Proof of Concept Model

The decision to build a wooden model of the finalized design came from the advice of Rod broome, the Mechanical Engineering Machine shop manager who advised that having a proof of concept model would be useful to determine any last kinks in the design. Given that wood is vastly less expensive than steel, it is more cost effective for the team to test the design concept first and prove that the mechanisms work properly before constructing the final working prototype. The construction of the model was completed on campus in the Machine Shop, under the lab supervision of Rod Broome and all team members provided negative COVID-19 tests before meeting.

The first step to creating the proof of concept model was to build the frame out of wood shown below in Figure 4.1 While the 2x4 inch wooden pieces were provided to us, the other 2x2 inch wooden pieces were purchased from Home Depot. After gathering the wood materials, they were cut to size by a hand saw. The wooden frame was then assembled by drilling nails, starting with the bottom base and working upwards to form the square crushing chamber (Figure 4.1).

Figure 4.1: Proof of Concept Model Wooden Frame.

After forming the wooden frame, the axles, bearings, and pedal system were added to the model (Figure 4.2). First, the steel tube was cut to size as the length of the axles: two short and two long. Then, four of the bearings were placed in the relative location where they would be mounted on the final frame and the axles were positioned inside the bearings. Finally, the pedal mechanism was cut off of one of the donated bikes with a handsaw and was placed where it would be welded to a piece of scrap metal in the final assembly.

Figure 4.2: GRVLR Proof of Concept Model.

Ultimately, the model was able to give the team a sense of scale as to how large the device would actually be once constructed. It also allowed the team to see what it would like for a user to interact with the device (Figure 4.3). Beyond this, the team learned a valuable lesson in working with bicycles. It was found to be extremely difficult to disassemble bicycles without the proper tools. It took three hours to completely strip one bike of its sprockets and pedal assembly. As such, the team has to consider who will be assembling the final device and what tools they will have access to and if they will then be needed to be provided with any additional tools. The goal is to use recycled materials, but with that comes additional considerations that must be made that the next Senior Design team will need to look into when they source the materials in Nepal.

Figure 4.3: GRVLR Proof of Concept Model with Hailee for Scale.

4.1.1.2 Final Prototype

Once all materials were gathered, construction of the final prototype began. The square tube steel for the frame was initially tack welded together by Gary Sloan in the machine shop. A series of clamps and braces were used to keep the tubes at the desired right angles. Once the proper shape was secured the final welds were completed. A sander was then used to even out the edges and get rid of the excess welding material (Figure 4.4).

Figure 4.4: GRVLR Metal Frame Welding.

The axles were cut to size using the horizontal bandsaw. The top and rear axles were turned down using the lathe because they were welded seam pipes they were not perfectly round at the desired diameter. As a result, without being turned down on both ends to bring into round, they could not fit into the bearings that had been purchased.

Fittings were machined for the large set of bearings used to hold the front axle. To do this the team took a solid one inch diameter steel bar, the same dimension as the internal diameter of the bearings, cut off two pieces that were the same length as the bearing using the horizontal bandsaw. They then bored the pieces out using the lathe to the desired internal diameter of 0.75 inches. To avoid overheating the tools and the part, drill bits of increasing diameter were used to reach the final size. Once the hole was finished, a cut off tool was used to remove the fitting from the portion of the bar that was used by the lathe to grip the piece. The internal edges were then filed down to ease the joining of the fitting to the axle. Ultimately a hammer was used to bring the fitting into place.

The bearings were then mounted to the frame. One set used a welded plate with a machined groove that fits onto the frame material and two tapped holes to accommodate threaded rod stock. The other two sets are bolted on through holes in the frame (Figure 4.5).

Figure 4.5: Custom Bearing Mount.

In order to mount the pedal assembly it was first cut from one of the donated bicycles using a vice and a handsaw. Once it was detached a sander was used to remove all stickers and paint in order to prepare it for welding. It was then welded to the two inch wide bar by Gary Sloan.

All sheet metal pieces, to enclose the structure, form the feeder, and form the hood, were cut with the vertical bandsaw. Their edges were then filed down to avoid cutting injuries while being handled. A brake was used to bend the hood piece to its two 45° angles and a roller was used to mold the feeder to the six inch diameter quarter circle of its curved portion. To cut the sides for the feeder one side was cut and filed to fit the curve. To cut the other side the first was clamped to an uncut piece of sheet metal. The team applied a blue dye near where the piece would be cut. A scribe line was then drawn through the dye along the edge of the cut piece. This line was used to guide the cut of the second piece. Any section that had excess material was then sanded down to the scribe line. The side pieces for the feeder and hood were finally welded together by Gary Sloan.

The lifting hooks are two system critical components. Their function is to lift the crushing weight and so they have to be strong enough to lift that weight without their vertical arms breaking or bending or the pins shearing out of the part. The part also has to be small enough to wrap around the driving gear without significant deviation from the regular chain length. The length also has to be long enough to prevent rotation. They were manufactured from 6010 aluminum by cutting out the basic shape on a vertical band saw and then machining it to its final size and finish using the mill. The mill was also used to add holes to accommodate pins. The finished prototype pinned to a section of roller chain is shown below (Figure 4.6.

Figure 4.6: Lifting Hook with Attached Chain.

In order to attach the sprockets to the axles, hubs will be machined by the GRVLR team. The hubs will consist of a 3.5" diameter 1" thick disk of 6060 aluminum machined to have an internal diameter bore of $\frac{3}{4}$", space for two set screws 90 degrees apart from each other, and a centering ring sized to the internal diameter of the sprocket. Reducing the diameter to create the centering ring and location for the set screws as well as boring the through hole will be performed on a lathe. Drilling the 5 holes in the face for attaching the sprocket will be drilled using a program on the mill that will place them perfectly, in addition to drilling the holes for the set screws. All of the holes will be tapped so that bolts can be used without added nuts to attach to the hubs and axles.

The GRVLR requires a lot of chain in order to operate. The chain was purchased in incorrect lengths and so in order to get it to the correct lengths, we will combine two strands, measure the total length required under tension by placing it over the mounted sprockets, and then trim the strand to length. The tension on the chain is very important for the lifting hook functioning properly, and currently the GRVLR does not have a tensioner. So the chains have to be installed with a lot of tension on them initially

In order to mount the pedal arm, holes were drilled through the bottom of the pedal arm and the center of the frame's lower crossmember using a step drill bit. A large hole was added on the bottom and a smaller one on the top so that a bolt's head could fit through the bottom hole but would catch on the top. A nut was added in order to hold the bolt in place, then a sheet metal plate was added onto the exposed bolts and nuts were used to hold it down. This method means that the plate can be removed without removing the bolts and washers.

4.1.2 Material Procurement

One of the objectives of the GRVLR device is to minimize its cost to thereby maximize the profits of the target users. One way the team accomplished this was by designing the machine such that it required minimal maintenance, as described previously. The second method was selecting easily accessible materials world wide and utilizing scrap or recycled materials whenever possible.

Components like the rods used for the axles, bearing fittings, lifting hooks, hubs for the sprockets, arms for the crushing weight, and the shields for the crushing weight were all scavenged from the Machine Shop. None of these components faced significant loads. The highest were the two lifting hooks and two crushing weight arms that had to share a load of 20lbs. Because of this, the material selection process was not crucial to the successful operation of the device. This gave the team a large degree of latitude to utilize whatever they had access to, from hollow to solid steel rods, to scrap pieces of sheet metal, to scrap pieces of aluminum.

Additionally, Rod Broome, machine shop manager for the school of engineering, donated two bikes to the team and team member Sam Broyles donated an additional bike that were used to scavenge for usable parts. Ultimately, a pedal assembly was selected to be attached to the final prototype.

All remaining materials were purchased from either Amazon or Alan Steel & Supply Co. in Redwood City, CA. The square steel tubing and low alloy crushing plate and weight were purchased at Alan Steel and the sprockets, bike chain, and four of the bearings were purchased from Amazon. The itemized purchase list is displayed in Table 4.1 below.

Table 4.1: Final GRVLR Prototype Purchase List

EXPENSES				
Category	**Item**	**Item Price**	**Amount**	**Spent**
Experimental Prototyping	Steel Frame (square tube and sheet metal)	$352.03	1	$352.03
	Low Carbon Alloy 20 lb Weight	$43.90	2	$87.80
	32-tooth Motorcycle Sprockets	$24.04	7	$168.28
	32-tooth Bycycle Sprockets	$7.99	8	$63.92
	2-pack of Bearings	$20.35	1	$20.35
	Bike Chain	$15.88	5	$79.40
	Roller Chain Cutter	$14.45	1	$14.45
	18-tooth Bicycle Sprockets	$22.83	2	$45.66
	Aluminum Disks for Sprocket Hubs	$10.92	8	$87.36
	Aluminum Bar for Sprocket Hubs	$74.75	1	$74.75

The final cost for the prototype was $994.00. Obviously, this is grossly more expensive than could ever be justifiably marketed to the team's target users. The team would like to point out that it would take material sourcing in Nepal to know the true assembly cost. A more detailed description of budget is explained later in Chapter 5.

4.1.3 Safety Risks and Mitigations

There are several notable safety risks that will be generated in the construction, testing, and operation of our design. The main risks in the construction phase come from the machining process and the use of power tools. The machines can be dangerous and they can project metal shards that could damage the users eyes. The primary method of protection in this case is wearing the correct protective equipment, consisting of safety glasses, close-toed shoes, and no gloves or loose clothing. The rest of the safety practices for the manufacturing stage comes down to proper operation of the machines. All team members participating in the general manufacturing of the machines will have been trained in MECH 101L in the safe operation of all machines used. The remainder of the manufacturing conducted by team members will consist only of simple assembly with hand tools, requiring only safety glasses and proper street clothes in order to maintain safety.

In the testing phase there will be different risks based on the stage of testing. In the initial stages of testing, impact tests will be performed which will produce shards of rock which could be harmful. In order to remain safe during the tests all members will wear proper street clothes with the addition of safety glasses or face shields. Additionally, gloves will be worn and all appendages will be kept well away from the impact area so that no crushing will occur. During the post assembly testing, one major concern will be pinch and crush points in addition to the rock shards created by crushing. In order to keep ourselves safe from crush and pinch points, the operator of the machine and any other users will wear gloves and protective equipment. This is a precaution to keep the user safe, all pinch points like the chain-gear interface and the springs will be covered to protect the operator. Additionally, the chamber where rocks are crushed will be completely sealed off to protect the user. The goal is to make sure that during operation the user would be safe without any PPE, but our team will be wearing protective equipment and using safe practices during operation to ensure that no one is injured.

5 Chapter 5: Project Summary and Future Plans

While this marks the end of our team's progress up to May 28th 2021, we hope this is not the end of the GRVLR mission. With hindsight, the team has the ability to self-reflect on the challenges and opportunities that this project has brought and to set plans for the future success and continuation of the GRVLR project.

5.1 Final Design Evaluation

In comparing the final design to the initial goals and objectives set, in terms of ergonomics, efficiency, safety and cost accessibility, the team has fully designed the GRVLR machine and are in line to complete building by the start of June. The ergonomics of the machine was achieved by designing the power input to be dependent on pedal power limiting the harmful impact of repetitive motion. Efficiency was reached when the crushing chamber was designed to crush multiple rocks at once reducing the total amount of time spent crushing one rock. The safety of the machine was accomplished by completely enclosing the crushing area allowing for there to be little possibility of the user being struck by rock shards while being operated. The cost objective was delivered by having the machine be easily maintainable with common materials. While the GRVLR design is finalized to the best of the team's ability, given the extent of the virtual simulations, the team is still in the process of building and testing to confirm these results. Unfortunately the time management for team goals did not pan out as expected due to unforeseen setbacks such as monthly changing county-wide safety regulations which eliminated the opportunity to conduct testing off-campus and weekly monitoring of local COVID cases which restricted planning and access on-campus lab access.

5.2 Team Organization and Management

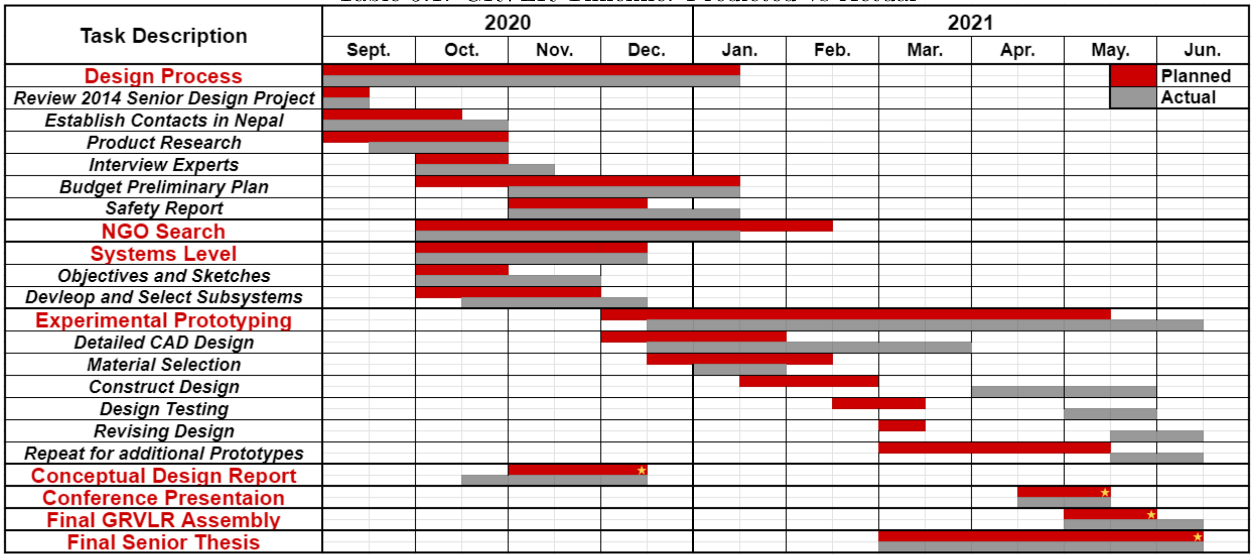
Throughout the course of the year, the team has worked tirelessly together and in this effort each team member has explored new positions that undertake different responsibilities. For the duration of each quarter, 11 weeks, the team divided the responsibilities of the GRVLR project into 4 positions: leader, scribe, facilitator and taskmaster. This team management approach has been beneficial in allowing the team to practice a variety of skills. By dividing tasks on the different assignments together and working on them independently, it gave the team a good balance of team interaction and individual task responsibility. As team leader, this person acts as the main point of contact with those outside of the team, sending emails to the school of engineering or to the Himalayan Climate Initiative (HCI) on behalf of the team. The scribe acts as team secretary, taking notes during all group, advisor and HCI meetings. Additionally, the facilitator's role consists of scheduling and setting the agenda for all meetings via zoom and google calendar. Lastly as the taskmaster, this person assists the leader in assigning roles to each member, enforcing deadlines and submitting team assignments.

Based on this team structure, it is crucial that each team member complete their own tasks for the whole team. Due to varying work speed and the comfortability between the team members, the team has run into some issues regarding meeting deadlines and properly structuring meetings to be as productive as possible, respectively. While this has been a dilemma that the team is still in the process of working on solidifying an efficient solution, one potential solution is to assign more permanent roles to each team member, such as through department heads of the subsystems, where the team members would be responsible for the same subsystem throughout the duration of the year. Each member would be held accountable for the progress of their subsystem as well as held responsible for speaking to the progress made in that area each week at team and advisor meetings. While this solution would ensure that each member takes more individual responsibility to work at their own speed, it would also allow for members to be pigeonholed into only having knowledge on how their subsystem interacts with the rest of the system. Another potential solution would be to increase the number of small deadlines for a given task, so if a team member falls short for one deadline it is not as disruptive to the overall team progress as it is happening farther away from the deadline.

5.2.1 Timeline

At the beginning of the year, the projected timeline was created for the GRVLR machine in the form of a Gantt chart (Table 5.1). Major deadlines for report submissions and the final assembly are represented as course milestones at the bottom. Testing and design process details are included as well and are organized in four categories: Design Process, NGO (non-government organization) Search, Systems Level and Experimental Prototyping.

Table 5.1: GRVLR Timeline: Predicted vs Actual



The design process is organized by tasks that indicate the steps taken before manufacturing and testing. The first task completed by all team members was to get familiarized with the 2014 Senior Design Project paper and resources. From reading their documentation and meeting with the previous team, contacts were shared and renewed in Nepal. Simultaneously, the current market of rock crushers was researched, interviews with professionals were conducted and customer needs were outlined. In addition, a preliminary budget was created, sent and approved by the School of Engineering at Santa Clara University. The safety report was also submitted to the School of Engineering and the team is awaiting confirmation before moving forward with manufacturing and experimental prototyping.

One of the main differences between this current project and the previous Senior Design Team is the planned partnership with an NGO. The NGO search is a task effort that is assisted by the Frugal Innovation Hub at Santa Clara University. While the team hopes to find an NGO Nepal, other countries that have a similar community of rock crushing women are also being explored, this includes additional countries in Africa. While the team has started this search, it is difficult committing to an NGO partnership and is anticipated to be completed by mid-January.

Systems level designing was organized in three stages. The first was creating design objectives as outlined in the customer needs and establishing system requirements. Second was the creation of design sketches. Last was the development of the system via subsystem selections. This process is the only task category completed to date.

After receiving confirmation that the safety report is approved, experimental prototyping can commence in person. Until then, the team plans on developing the detailed CAD design of the selected subsystem designs and starting the material selection process over winter break. Once the test materials and protective equipment necessary for prototyping have been ordered and received, prototypes can be constructed, tested and redesigned for an estimated loop of three times total. After completing the testing process to a successful point of maximum improvement, the final assembly of the GRVLR will take place. At this point, evaluations of budget and time resources still available will be made to see if more prototypes can be reproduced.

5.2.2 Budget

This project is currently being funded by the School of Engineering and the Frugal Innovation Hub via our income as depicted below (Table 5.2). The budget plan is organized into six main categories: experimental prototyping, final prototyping materials, outsourced prototype welding, test materials, protective equipment, translation of user manuals, and additional funds. This distribution between planned and ordered is also depicted in the table below as well as net reserved predicted and actual (Table 5.3). As can be seen in Table 5.3 the disparity between purchasing plans and what was purchased is quite large. Due to COVID-19 setbacks the team was not able to progress past the initial experimental prototyping phase. The details surrounding the plans for each purchasing category is detailed below.

Table 5.2: GRVLR Project Budget: Income Received

INCOME				
Category	**Source**	**Sought**	**Committed**	**Pending**
Grant	Undergraduate School of Engingeering/Frugal Innovation Hub	$2,000.00	$2,000.00	$0.00
	TOTAL	**$2,000.00**	**$2,000.00**	**$0.00**

Table 5.3: GRVLR Project Budget: Expenses Spent

EXPENSES				
Category	**Item**	**Item Price**	**Amount**	**Spent**
Experimental Prototyping	Steel Frame (square tube and sheet metal)	$352.03	1	$352.03
	Low Carbon Alloy 20 lb Weight	$43.90	2	$87.80
	32-tooth Motorcycle Sprockets	$24.04	7	$168.28
	32-tooth Bycycle Sprockets	$7.99	8	$63.92
	2-pack of Bearings	$20.35	1	$20.35
	Bike Chain	$15.88	5	$79.40
	Roller Chain Cutter	$14.45	1	$14.45
	18-tooth Bicycle Sprockets	$22.83	2	$45.66
	Aluminum Disks for Sprocket Hubs	$10.92	8	$87.36
	Aluminum Bar for Sprocket Hubs	$74.75	1	$74.75
Final Prototype Materials	Replace any Broken Materials / Extra Materials for Design Iterations	$600.00		$0.00
Outsourced Prototype Welding	Expected Cost	$200.00		$0.00
Test Material	Quartzite Rocks	$150.00		$0.00
Protective Equipment	Face Shields	$28.88		$0.00
	Ear Plugs	$15.80		$0.00
	Safety Glasses	$29.98		$0.00
	Work Gloves	$51.62		$0.00
Translating Manual	Nepalese Translation	$100.00		$0.00
	TOTAL	**$2,170.28**		**$994.00**
	Net Reserve (Defecit)	**-$170.28**		**$1,006.00**

Experimental prototyping was planned to include the testing of several different contact surfaces and shapes, prototyping robust frames, and testing several power input mechanisms. The materials for this portion of the project will go into creating multiple prototypes of different mechanisms in order to choose the best mechanism most efficiently. Using the previous Senior Design Team's prototyping budget of $520 as a baseline, it was anticipated to cumulatively cost approximately $800. In actuality, due to the constant setback of building, the team was not able to start construction until April and thus only made it to this experimental prototyping phase. This means that the total amount spent was only used on securing the materials needed for this phase, which totals $996 and leaves the team with a net reserve of $1004. The increase in funds spent during this phase can be attributed to the offset in the mis-ordering of materials, specifically ordering the wrong sized sprockets. Given that the team was tight on building time, materials were purchased quickly and it was overlooked that the set of sprockets ordered were meant for motorcycles. As this project is meant to be manufactured out of recycled bicycle materials, another set of bicycle sprockets were double checked and ordered. This initial set of motorcycle sprockets were then donated to the School of Engineering at Santa Clara University for another project to hopefully use in the near future.

Final prototyping materials were anticipated to be about $600, which was approximated by basing the minimum cost of this prototype off of the previous Senior Design Team's but is increased due to their issues with the prototype's rigidity. This issue of rigidity was directly related to their design of a jaw crusher style, which is not directly correlated to this current chain lift design. In order to plan for avoiding this concern, more investments will be made into robust materials with higher than normal factors of safety (2 or 3).

Outsourced prototype welding was a predicted cost given that the design will likely require a very rigid metal frame, and while brackets or a prototyping system such as 8020 may be helpful in the early stages, using that material would be too expensive for the final product if it is expected to be purchsed, at least in part, by the target users themselves. For the construction of the GRVLR thus far, the team has been fortunate to have the assistance of Gary Sloan for the welding. However this assistance is not guaranteed for future prototypes. It was anticipated that there will be a need to pay a professional to weld together the final frame, since the team is untrained on how to safely weld with the right techniques and it was not a component of the Machine Shop training at Santa Clara University. This cost was estimated based on the area local to Santa Clara to be approximately $200.

Test materials consist of purchasing large volumes of rocks to crush in a variety of ways. The project predecessors spent a majority of their time in the development stage building a final cost and weight prototype that they believed would crush rocks. In designing this current product the team has intended to crush rocks continuously throughout the entire process guaranteeing that the device can perform the task without any issues. The team anticipates buying up to 23 kg of rocks for this testing, which should cost around $150.

Protective equipment included any necessary measures needed for the safety of the team or user during testing and the act of operating. Based on the conducted research and interviews, the best way to break rocks under human power is by a high impact force, which creates a lot of rock shards in the process. Additionally, some custom parts have been fabricated using hand tools, power tools, and machines which, when used on high-strength steel, can lead to dangerous shards and other hazards. When fabricating these components, the team worked only in the shop and abiding by these safety requirements were more easily adhered to given the nature and environment of working in the Machine Shop. During the act of testing, the team had planned to equip all members involved with face shields, gloves, and safety glasses as well as construct safety barriers in order to ensure that no one on-site is injured during the testing or manufacturing of the team's designs. Since safety is a high priority, it was anticipated to spend $150 to satisfy these safe standards.

After the device has been assembled, the translation of a user's manual is planned to be completed. Due to the international scope of this project, the device will most likely be manufactured and made in-country abroad, thus relying on a need for a translated users manual. While the team had planned to design a rock crusher that is relatively simple to operate and maintain, it was also aimed to provide instructions for properly building and maintaining the machine so that the users can learn to be more self-sufficient. None of the team members speak Nepali and so the team may require an expenditure of $100 to pay a third party to perform a coherent translation.

If, when finished, there exists extra funds, the team planned to make as many devices as possible or to send the current working device to the GRVLR target community. One of the main purposes of this project is to assemble a product for people who have a very low income, and while the women might need to pay for the device in some form, it will most likely be over a long period of time. Having as many devices ready at the time of initial delivery as possible will help them to be adopted more easily, as it can be proved to work faster and would encourage others to invest into the GRVLR device.

5.3 Further GRVLR Development

The team's progress this team has made consists of identifying a problem, coming up with solutions, designing and running FEA on a rocks crusher in SolidWorks, building a wooden proof of concept model, and then beginning construction of a working prototype that is near completion, as well as making numerous connections made with people who have helped contribute to this project. While the team is extremely proud of these accomplishments there are also some possible next steps which an upcoming senior design team could consider if they were to take on this project.

The first would obviously be testing the functionality, effectiveness, and efficiency of a working prototype. Currently only construction towards a functional prototype has been achieved, but the finished product will not be completed in time to allow for testing. For this reason testing needs to be conducted to obtain analysis on the prototype. This will help gauge not only how effective the GRVLR is at crushing rocks, but also if it truly is able to help these women crush rocks at a faster rate. Testing the rock crusher continuously, as the women would use it for hours each day, will confirm the ergonomics and ease of use of the rock crushers power input pedal system. Additionally, testing will prove the reliability and durability of the GRVLR to operate continuously without breaking.

Another possible next step would be to incorporate some sort of mechanism or design feature that improves the feeder by removing the crushed rocks from the crushing chamber. Currently the feeder is just a simple hood on the back of the frame which has a big enough opening to let out gravel of the desired size. However there is no actual way of removing the crushed rocks from the crushing chamber and the rocks just fall out of the hood as rocks continue to get crushed up. This is a problem because the crushing chamber could become blocked if too many rocks get crushed and not enough rocks exit out of the hood of the filter. A next step for the next design team would be to implement some kind of mechanism that removes rocks from the crushing chamber. This could be a sweeper type mechanism that is connected to the hood of the filter and allows the user to sweep gravel off the crushing plate and out the hood. Another possible idea would be building a mechanism that tilts the crushing plate so that the gravel falls off the plate and out the hood.

One last next step that has been considered is conducting Nepalese sourcing for local materials in Birendranagar, Nepal. This is a part of the project that was not able to be completed due to COVID-19 complications that made it difficult to communicate with connections in Nepal and get information about available materials in the area. This is something that the next senior design team would want to do since the machine will need to be made of parts available in Nepal as well as built and manufactured in Nepal. Once that is done an additional step would be to get in contact with a machinist or welder in Nepal in order to start thinking about a manufacturing plan.

5.3.1 Nepalese Cost Analysis

Because cost is a large consideration for building this rock crusher, all materials for the machine and manufacturing must be done locally in Nepal. As mentioned above, sourcing is something this team has been unable to do and is something the next senior design team should do to get a better idea of the cost to make the GRVLR in Nepal. One thing to reduce cost is to include recycled or scrap metal materials for the crushing weight and plate as well as the components of the support subsystem. Also, recycled or scrap bike parts for the pedal system and the chains and sprockets in the power input and crushing mechanism subsystems will also be used.

Among the progress and connections made by the team, one particular partner that has been extremely helpful is HCI. After talking to HCI, they believe that it would be best for the rock crusher to be introduced to the target user through a two-week timed trial of the GRVLR that they would monitor. This would convince the user that it is a worthwhile investment, and also prove that it is helpful and improves the efficiency of their ability to crush rocks. If all goes well HCI has offered to assist in getting the production cost of the GRVLR machine subsidized by the Nepalese government, which is something they have done before with other community based projects that require funding for impoverished communities. This would be a great option if everything were to work out, but otherwise manufacturing and production cost would need to be determined and likely the GRVLR would be leased to these women or some other way that makes it more cost accessible to them. Regardless, the next senior design team to take on this project would very much want to reach out to HCI to talk about getting the machines in Nepal subsidized by the Nepalese government.

5.4 Lessons Learned

Over the course of this year the team has had to adapt to many changing circumstances, change their working habits and learn some new tricks, this taught the team a lot of lessons, mostly in the areas of team and construction management. The team learned a great deal about how to crush rocks, as earlier described, but the additional advice that the team would like to pass onto the others or a team taking on this project is described below.

In the area of team management, the team learned a great deal from the specific circumstances of our project and from the things each team faces every year. The team learned a lot about the challenges of an international project. While it can be difficult to adjust to a different culture and schedule international calls, communication is the most difficult thing. In order to keep everyone on the same page there needs to be frequent, responsive, and scheduled communication, or there will be massive delays to your project based on waiting for communication or miscommunications. In addition to managing communication with partners abroad, the team had to manage itself, and its own goals. Three things that the team learned are first, having many small self imposed deadlines or check-ins to keep a constant healthy working pace rather than infrequent sprints. Second, even if team members are working on completely independent tasks, working in the same room or on a zoom together can help productivity and communication, especially in the midst of a pandemic where team members do not see each other for other purposes. Finally the team learned to be prepared to change plans at a moment's notice. Over the course of the year the team faced many sudden challenges and changes of scope and had to readjust goals and plans. If the team was not this flexible they would have not been able to move the project forward for months of the year.

There are also some things that the team learned from the intensive building that has been performed over the past quarter. The first thing is that there are no steps that can be saved for later. Eventually you have to drill holes and choose bolts and nuts for every part, if you save it for later it will only make things sloppy and difficult down the road so do it in the CAD stage. Another important lesson is that every single part needs a manufacturing plan and that manufacturing plan should be converted to a manufacturing task list so that you can perform manufacturing tasks in a timely manner. Many things that look beautiful in CAD are not easily manufactured or even manufacturable at all with the facilities on hand.

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A Customer and Professional Interview Data

A.1 Interview with Dr. Robert Marks concerning Methods for Breaking Brittle Materials

1. What type of force is best suited to rock breaking?

Rocks do quite well under a compressive force and very poorly under a tensive force. Breaking the rock over one raised point would be a way to force one side of the rock into tension. A shocking impact force likewise is a good way to break brittle materials.

2. What materials are best suited to rock breaking?

Brittle materials are better suited over ductile because you are looking for durable materials that are less likely to deform. Since you are likely to use some form of impact force with an impact surface that will be hit repeatedly, your contact surface should be resistant to denting.

3. Which brittle materials would you recommend?

Iron is a good alternative to steel given that it is both more brittle and less expensive.

4. Do you have any design ideas you think we would benefit from hearing?

Some form of jaw crusher with changing contact points would be a way to force the back side of the rock into tension. Another option would be dropping a weight onto the rock that is placed on a few contact points as another way to force part of the rock into tension while also using a sudden impact force.

A.2 Interviews Conducted With Women Who Crush Rocks Full Time

1. How long do you work each day? What hours do you work?

Woman 1, older: I start around 10 and finish around 4. Sometimes I start after lunch.

Woman 2, younger: I work every day of the week and do about 6 hours each day. From 10-4.

2. Are you tired after every day?

Woman 1: Yes, I'm exhausted.

Woman 2: Yes, I'm very tired.

3. Where are the rocks that you break actually from?

Woman 1 and 2: We go down into the river to collect these stones.

4. Who do you sell your rocks to? How much do you get per bag?

Woman 1: Sometimes we use these stones for our own house. I get 50 rupees for the bag when I sell them.

Woman 2: I sell my rocks to construction projects laying roads or making foundations. No company names. 50 rupees per bag.

Note: (My guess is that the bags weigh about 60-80 pounds each.)

5. How many bags are you able to fill each day?

Woman 1: A fast worker can do 10 or so. I fill about 4-5 bags each day.

Woman 2: I can do 31 in a day. [I'm assuming this is her record. She was cranking away while I was talking to her though, so I'd assume she averages 25 or something].

6. How far away do you live?

Woman 1: I live right here (points to house 10 feet away).

Woman 2: I live over there (points to her house 50 feet away across the river).

Note: [I then asked if all the women who work here live right near the river. Woman 2 said yes.]

7. If there were a machine to break rocks for you at a faster rate, would you want to use it?

Woman 1: This makes me so happy. I want to use it.

Woman 2: I would definitely use it; it would make my life much easier.

8. How would you want a machine like this to work? Would it need to be lightweight? Foot powered? Involve sitting? With wheels?

Woman 1: I'd like it to be foot powered and lightweight. [She was just agreeing with anything I said.]

Woman 2: It would be better if it were hand powered. I would want to be able to sit while using it.

9. If it could break four times as many rocks in a day, how much would it be worth to you?

Note: [This was a difficult question to ask without sounding like a salesman. I kind of suggested prices to gauge their reactions. I first asked if they'd buy it for 1000 Rupees or about ten dollars.

Woman 1: 1000 rupees is so expensive. I cannot afford that.

Woman 2: I would pay 180 Rupees for it.

A.3 Interview Conducted with Dr. Tanya Nillson Concerning Methods and Practices for Conducting a Humanitarian Engineering Project With a Partner Abroad

1. Do you have experience observing women break rocks for a living?

I do. While I was working on a project in Rwanda there was a group of women breaking rocks with a hammer and I went over and sat with them. Similarly, while I was in Nepal for a project I saw women breaking rocks.

2. As a person with extensive experience with humanitarian engineering projects what is the single most important thing for an overseas project?

You need to have a contact organization in-country, ideally an NGO (non-governmental organization), who can put you in contact with your target customer and oversee the project after you are done.

3. How would you recommend we go about communicating with this NGO?

Most countries do not operate with the same urgency when it comes to business as we do in the States. So, when communicating with them you need to add time constraints so they know how urgently you need the information. At the same time, you simply need to understand that communication will be slow.

4. What are some things we should ask of our contacts in Nepal?

A couple things I think would be important for your project would involve security and the demand for the gravel. For the first, where are the women going to store the machine? Is theft a problem in the area? And for the second, what is the demand volume for the gravel? You don't want to depreciate the price for the women who do not want to invest in the machine.

5. When we get the opportunity to communicate with our customers how do you recommend we go about asking them questions?

You will need to have well thought out questions. They have to be specific, but phrased in a way that will actually be useful. Instead of asking what they want out of a rock crushing machine, ask them what they do in a day or what they would do if they were given the opportunity.

6. Do you have any design ideas you think we would benefit from hearing?

You should think about weight. First, you find out about the terrain around the riverbed and how far the women would have to carry it. Then, you should not expect people to carry more than one quarter their body weight. In the case of these women, it should not be more than roughly 25 pounds per woman that is helping to move it. With that in mind, it might be a good idea to consider making it capable of disassembly.

7. We had the idea of seeing if the women would be willing to share a machine, do you have any ideas on how organizing this might work?

First, you have to make sure that they would be willing to do something like that before devoting any more time to the idea. If they are, I would recommend you consider organizing a cooperative. This is helpful for the women because there are then a set of predetermined rules on how the machine should be shared and the proceeds split. Oftentimes there is also a fee to join after the coop gets off the ground and that money can go towards purchasing and maintaining the machines.

8. Is there any more information or relevant contacts you have that you think might be helpful to us?

Yes, I will share with you guys some Nepalese steel prices we collected for a different project I worked on there.

B Material Selection

Final Project Report
MECH 163
Dr. Sepehrband
12/05/2020

Material Selection for a Rock Crushing Surface

Bryan Gilbertson & Hailee Silva

Introduction:

In Nepal, unmarried and widowed women face extreme gender discrimination, leaving them with few economic opportunities. In many instances, these women must resort to hard labor as their only financial option.

One such job is to produce gravel from larger rocks, but since no industrial machinery is available to them, they are forced to use a hammer to manually perform this task. The women then sell the gravel to local construction companies in exchange for a slim wage. This line of work has many adverse side effects including damage to their wrists, shoulders, and backs from the repeated motion of swinging a hammer. Additionally, the work barely satisfies their financial needs. At most, they are able to make $3 a day, or about $1,000 U.S. per year.

Between the adverse health effects and the extremely limited pay, hand crushing rocks leaves these women in extreme poverty, and their families are affected too. With such a small income, they pull their children out of school to help, which only solidifies the family's position in the cycle of poverty. The objective of the senior design project is to design and manufacture a manual rock crushing device for these women that is safer, more ergonomic, and more efficient than using a hammer. The reduced scope for this project is to select a material for the crushing surface that this device will use.

Problem Statement:

The goal for this project is to select a material for the crushing plate through a strength based design that will not fail by yielding or fast fracture.

The strength based analysis was chosen because the crusher depends less on its ability to resist possible deflection, and more on the durability, strength, and reliability of the chosen material. The yielding and fast fracture failure conditions were identified because of the machine's operating conditions. The device works by raising and dropping a weight, and because it is manually operated the machine is unlikely to fail by high cycle fatigue. Rather, it is more likely to experience forces that would permanently deform the plate or cause cracks to propagate through the material.

Other considerations that need to be taken into account are the environmental conditions and the type of rock being crushed. This device will operate in a relatively warm climate, 50℉ to 90℉, that receives an average amount of precipitation of 65 inches of rain per year. Since the device will not be near salt water, or other sources of extreme corrosion, it does not need a high corrosion resistance. However, corrosion should be a screening factor because the surface quality of the material, or rather damage to the surface, can affect its ability to resist yielding and fast fracture. Additionally, the material chosen must be harder than the rock itself, otherwise the rock will damage the surface with each cycle of the crushing machine. For our case, the vickers hardness of white sandstone is around 68.5[1]. This will be used to eliminate softer materials from our selection options even if they perform well under the strength and fracture criteria.

Assumptions:

For the actual project, the crushing surface will be an inclined plate where the rocks can excite the machine after crushing. Additionally, this device is intended to crush multiple rocks at a time, which is equivalent to a semi-distributed load. To simplify the problem, we have chosen to make a few assumptions to remove unnecessary complexity and account for the worst case scenario. Our first assumption is that the plate is equivalent to a horizontal beam undergoing three point bending. A diagram is shown in Figure 1.

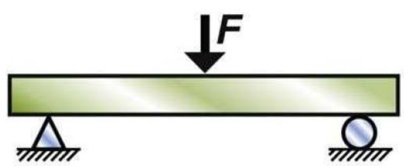


Figure 1: Diagram of Problem

This assumption allows us to assume that the stress generated in the beam is derived from the elastic bending equation

$$\sigma = My/I = M * (6t/Wt^3)$$

[1] Boutrid, A., Bensehamdi, S., & Chaib, R. (2013). Investigation into Brinell hardness test applied to rocks. *World Journal of Engineering, 10*(4), 367-380. doi:10.1260/1708-5284.10.4.367

Our second assumption is that the beam is unsupported under the span. This further aligns the problem towards the model in Figure 1. Supports under the span would make the beam take on more complicated bending. In addition, the unsupported case is also the worst case scenario the crushing plate would encounter in terms of bending. Another assumption is that the hardest stone being crushed is white sandstone, with a vickers hardness of 68.5. This will help to eliminate soft materials, however if harder stone is put into the machine the crushing plate may be damaged and surface cracks may be created . Our last assumption is that the common surface crack length (c) is 3 mm and the largest internal crack length (c/2) is 0.5 mm. The 3 mm measurement comes from the possibility of harder stone being placed in the machine and creating crack. The 0.5 mm measurement would come from typical manufacturing of the material from casting or rolling.

Translation:

Function	Objective	Constraints and Defined Factors	Free Variables
Crushing Plate	Minimize Cost	Vickers Hardness, 68.5 Durability: Rural Environments, Acceptable Plane Area of Plate, A Must not Yield Must not Fracture	Thickness, t Material Choice

Table 1: Translation of Problem Statement

Material Index Derivations:

To derive the material indices needed to select a material. We start off with the Objective equation where C_m is the cost per mass of material, and ρ is the Density of the material

$$C = C_m \rho A t$$

The next step is to eliminate thickness, t, from the cost equation because it is the free variable of the problem. To do this we take the strength provided by each failure constraint, insert it into the bending equation, and solve for t. From there we eliminate t from the objective equation and the material index can be identified from the new cost equation. This process is shown below for each constraint.

For the Fracture Resistance constraint, we find

$$t_1 = \sqrt{6M/W\sigma_f} = \sqrt{6M\sqrt{\pi c}/W} * 1/\sqrt{K_{1c}}$$
$$C_1 = C_m\rho At = A\sqrt{6M\sqrt{\pi c}/W} * [C_m\rho/\sqrt{K_{1c}}]$$

$$M_1 = C_m\rho/\sqrt{K_{1c}}$$

and for the Yielding constraint, we derive

$$t_2 = \sqrt{6M/W\sigma_y}$$
$$C_2 = C_m\rho At = A\sqrt{6M/W} * [C_m\rho/\sqrt{\sigma_y}]$$

$$M_2 = C_m\rho/\sqrt{\sigma_y}$$

Where M_1 and M_2 are the material indices that will be minimized in order to minimize the cost of the material.

Next, the material indices must be compared for each material. In the case where we have a shortlist of materials, the indices may simply be calculated and compared, but for the general case, the material index may be plotted against the other to form a coupling line that will compare all materials in the software. To do this we first set the cost equation for both constraints equal to each other and solve. This is shown below.

$$C_1 = C_2$$
$$A\sqrt{6M\sqrt{\pi c}/W} * [C_m\rho/\sqrt{K_{1c}}] = A\sqrt{6M/W} * [C_m\rho/\sqrt{\sigma_y}]$$

This yields an equation where one material index is equal to the other index multiplied by a constant dependent on crack length. .

$$(\pi c)^{0.25} M_1 = M_2$$

Because there is a wide range of index values, we take the log of each side to get the equation

$$Log(M_2) = Log(M_1) + 0.25 * Log(\pi c)$$

On a log scale, this line has a slope of one and a y-intercept that is dependent solely on the crack size. This is best highlighted in the next section, *Charts and Selection Method*, however this allows us to easily select regions on the chart that will give us the best materials for this application.

Chart and Selection Method:

Below, the material indices are plotted with the yield constraint (M_2) on the y axis and the fracture constraint (M_1) on the x axis. The objective is to minimize both material indices to ultimately minimize the cost of the raw material. To compare the two material indices, coupling lines are implemented to show where each index yields the same cost. The two coupling lines plotted below are defined by an assumed crack length of 3 mm and by an internal crack length of 1 mm. Any materials to the left of these lines are dominated by the yielding failure mode, whereas any materials to the right are dominated by the fast fracture failure mode. Selection boxes are utilized to easily select suitable materials. By positioning one corner on the origin and the opposite corner on a coupling line, we can compare materials based on their location relative to the box. Since we are looking to minimize each index, everything inside the box is more desirable, by both indices, than everything outside of it.

For the case below, boxes are minimized to the bottom left corner because we are looking to minimize both of the material indices in pursuit of the cheapest suitable material. Materials inside of the smaller box must be used because it will satisfy the conditions for both crack lengths.

Level 2 was selected for this project because the figure is less busy and easier to read compared to a chart in Level 3. Level 2 provided a good degree of specificity that would point us in the right direction of more specific materials.

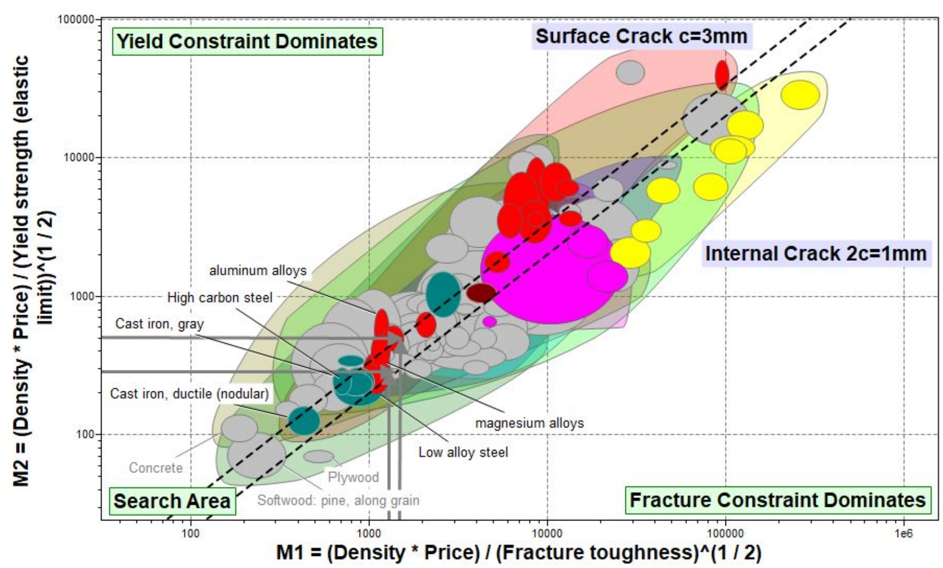


Figure 2: Chart comparing each material index

It can be seen in Figure 2 above that all materials perform roughly the same in resisting the different failure modes. How they can then be judged is their ability to pass the screening factors and how expensive they are. All of the materials passed the necessary adequate durability in rural environments, however all of the gray bubbles represent materials that failed the minimum Vickers hardness required to break white sandstone.

Results and Considerations:

From the chart it is clear that ductile cast iron is best suited for our application because it is by far the cheapest and satisfies all other requirements. Additionally, cast iron can easily be found locally which satisfies a goal of the senior design project and helps reduce cost. With the 3 mm crack length, cast iron performs equally well in both constraints, however for the 0.5mm crack it is better suited to resist fast fracture than yielding. The main downside to using ductile cast iron is that it has lower corrosion resistance in rural environments than many of the other materials included in the chart. However, it should perform well enough to serve the needs of the part. Other materials that could satisfy the needs of the project would be low alloy steel, gray cast iron, and high carbon steel, all of which can also be found locally, but are generally more expensive. Magnesium alloys and aluminum alloys fall into the same category of performing well with the failure modes, but are too expensive and thus lie outside our limiting selection box.

It can be seen on the chart that without the hardness screening factor softwood pine performs the best in terms of both constraints. Concrete and plywood would also do well. However, all three of these materials fail the hardness screen, and thus would be incapable of breaking the rock without damaging itself in the process. This highlights how important additional screening factors are when choosing a material.

C Hand Calculations

C.1 Cam Crusher Hand Calculations

Calculations were completed to support the validity of the model. One of the top cross beams was modeled as a beam under an equally distributed load of 3500 N/m and supported by two fixed points (Figure C.1). Stresses were calculated at the inner (Point A) and outer (Point B) in the top left hand corners when looking down the beam from the left hand side. Point B was found to experience 16.7 MPa according to the calculations and 17.1 MPa according to the FEA. Point A was found to experience 14.1 MPa according to the calculations and 15.4 MPa according to the FEA. Since the FEA stresses resulted in similar stress when calculated by hand, it is concluded that the FEA is valid for the cam design.

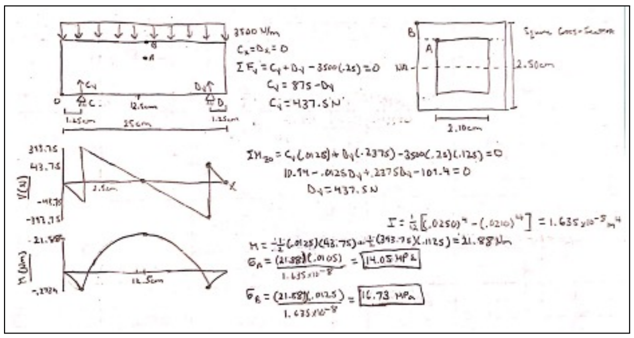


Figure C.1: Distributed Loaded Beam to Model Cam FEA Component Calculations

The FEA conducted showed that the proposed design was experiencing approximately one quarter of the stress that would cause yielding under the standard load. Additionally the areas that would experience yielding are very localised. As such, in the next design iteration in order to minimize weight, some redundant supports will be removed and replaced with smaller lighter plates that target specific areas of concern. The part that proved to be most likely to yield was the vertical support. A plot of the stress along the inner edge of the part is shown below (Figure C.2).

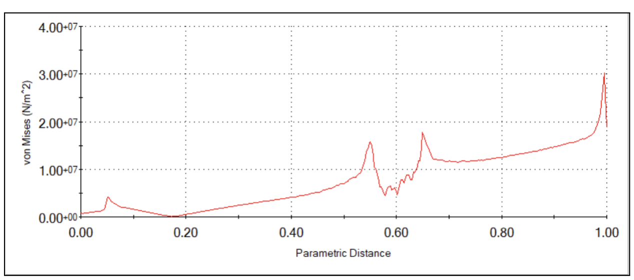


Figure C.2: Plot Of Stress Along Vertical Support Members

There is a sharp increase in the stress at the very end of the member, which is the location of the highest stress in the assembly. This is where extra support will be added in order to ensure safe long term operation. Similar plots were taken on edges of interest on one of each type of member in the system.

The mesh was generated more densely in those areas in order to produce more accurate results. Now that the model has been shown to be accurate, the design process will move forward with material selection and weight optimization in order to produce the lightest and most effective machine possible.

Approximated Necessary Force

The first calculation is to determine an approximate necessary force to bring the rocks to our desired final size. Equation (1) below is that for an impact force, with F as the impact force, mg the force caused by gravity, h the height from which the weight was dropped, and d the distance over which the rock was impacted, or the thickness of the rock. The data used for this calculation comes from preliminary testing conducted by our team.

$$F = \frac{mgh}{d} \tag{C.1}$$

$$\frac{(11.5kg)(9.81m/s^2)(1.5m)}{.08m} = 2115\ N \tag{C.2}$$

Approximated Production Rate of the Women

The second calculation is to determine an approximate production rate benchmark we need to exceed to make our machine cost effective for the women. The data used for this calculation comes from the interviews conducted in 2014 by the previous Senior Design Team.

$$Rate = (10bags)\frac{32.4kg}{1bag}\frac{1}{6hrs}\frac{1hr}{60min} = .9\ kg/min \tag{C.3}$$

C.2 Chain Lift Hand Calculations

To validate the analysis completed above, calculations were completed (Figure C.3). The component supporting the sprockets was modeled as a cantilever beam with a point load on its end. Stresses were calculated at the inner (Point A) and outer (Point B) top left hand corners when looking down the beam from the exposed end. The shear stress was calculated for one of the two but was found to not match between the two. Point B was found to experience 470.4 MPa according to the calculations and 460.2 MPa according to the FEA. Point A was found to experience 382.6 MPa according to the calculations and 369.1 MPa according to the FEA.

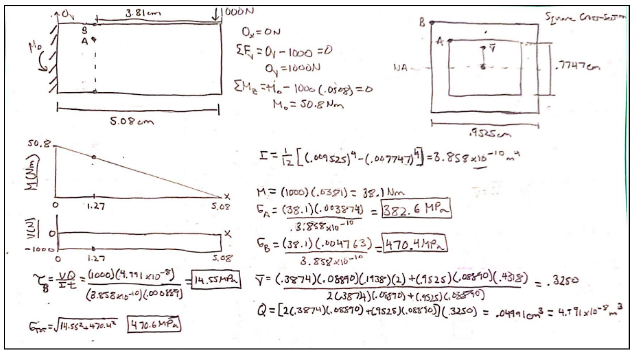


Figure C.3: Cantilever Beam to Model Chain Lift FEA Component Calculations

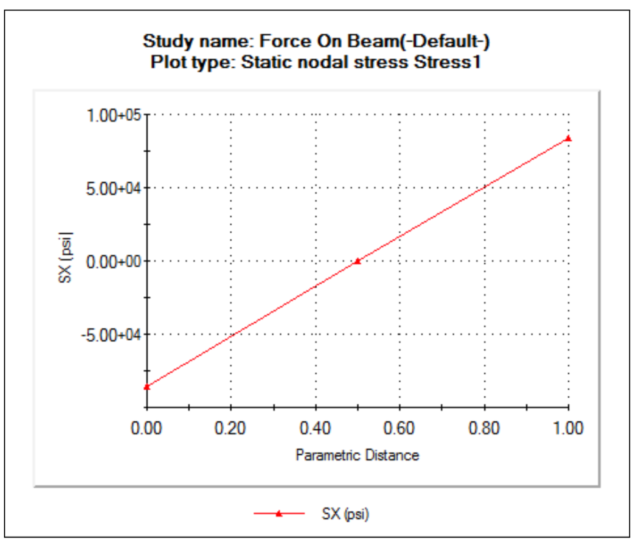


Figure C.4: Plot of Stress along outside of Beam at 1.27cm from end with 1000N of Applied Force

The plot in Figure C.5 was taken from the FEA results and further confirms the calculations of the stress on the outside of the beam. This plot represents the stress along the outside of the beam along the cross sectional plane that contains the same point as in the calculations. Because the results of the

FEA showed the beam failed due to bending, it seemed clear that additional support was required. After discussing possibilities, a 45° steel square tube bracer was determined to be the best option, due to the fact that it would not require any additional materials to be located and should provide vertical support and bracing against bending. A simulation of the same model but including the brace with the same loads (Figure C.5).

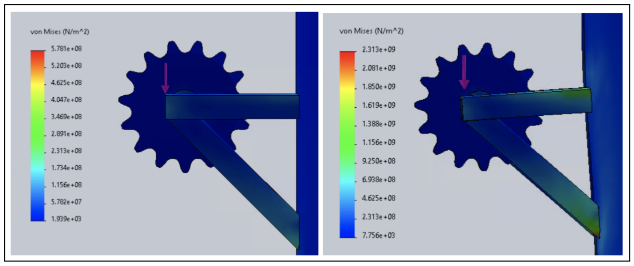


Figure C.5: 1000N and 4000N Force on Beam with Bracers

After running multiple tests, the results of the FEA showed that with the addition of the bracer the beam was now able to support a load of 1000N, shown in Figure C.5 on the left. In fact, the bracers increased the maximum force the beam could take four times from the initial test, shown in Figure C.5 on the right, resulting in the beam being able to handle 4000N of force in the vertical direction.

C.3 Lifting Hook Verification

They are joined to the chain via two pin connections. These are their most likely points of failure, so calculations were conducted to verify that they are capable of withstanding the loading they are expected to be subjected to (Figure **??**). The worst case scenario of loading was assumed to be at the point when all of the weight was applied to one point on the tip in the moment before the crushing weight is dropped off. The respective shear stresses experienced by the top and bottom pins were found to be 1.5 and 0.95 MPa, which are both significantly lower than the yield strength of 580 MPa of their material, 1050 steel. This supports that the lifting hooks are more than capable of serving their function in this design.

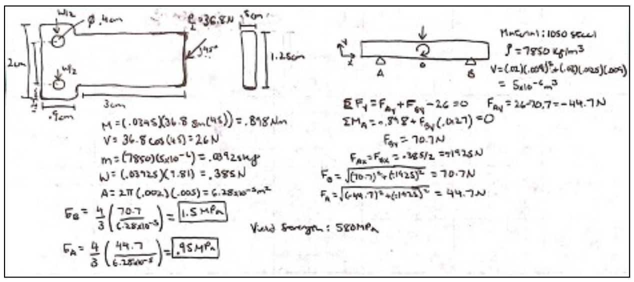
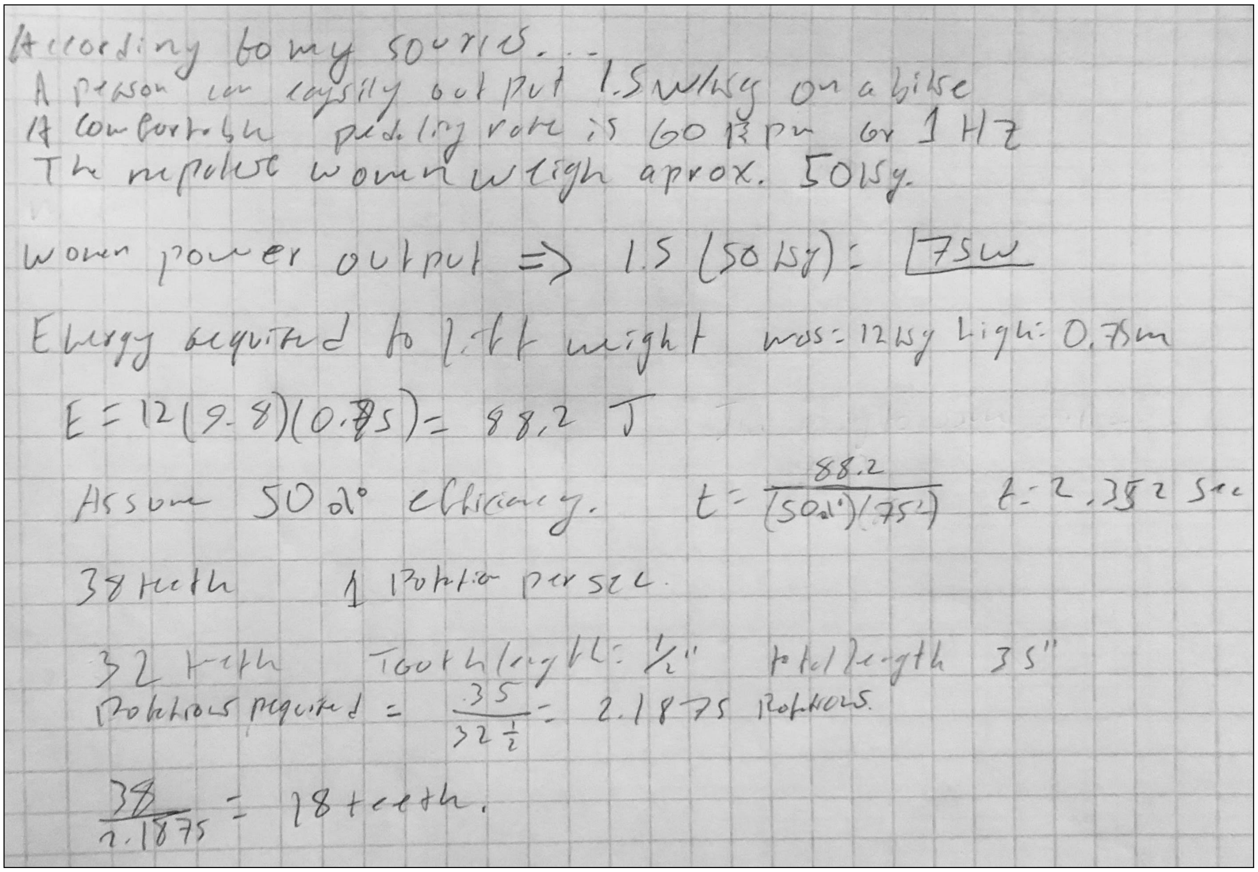


Figure C.6: Lifting Hook Verification Calculations

C.4 Gear Ration Hand Calculations

Below describes the calculations used to determine the necessary gear ratio required for the GRVLR ideal mechanical advantage (Figure C.7).



According to my sources...
A person can easily output 1.5 w/kg on a bike
A comfortable pedaling rate is 60 RPM or 1 Hz
The Nepalese woman weigh aprox. 50 kg.

Woman power output ⇒ 1.5 (50 kg) = 75W

Energy required to lift weight mass = 12 kg height = 0.75m

$E = 12(9.8)(0.75) = 88.2$ J

Assume 50% efficiency. $t = \frac{88.2}{(50\%)(75)}$ $t = 2.352$ sec

38 teeth 1 Rotation per sec.

32 teeth Tooth length = ½" total length 35"

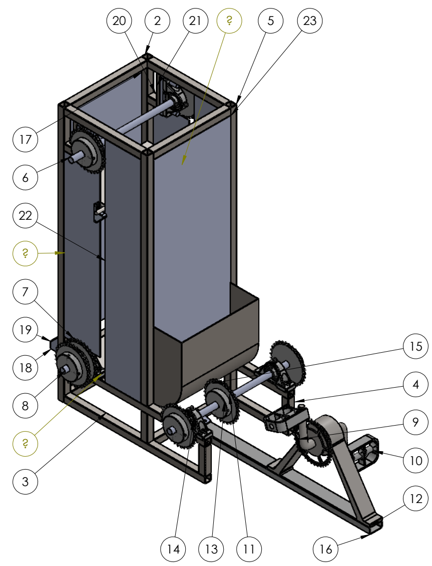
Rotations required = $\frac{35}{32 \cdot \frac{1}{2}} = 2.1875$ Rotations

$\frac{38}{2.1875} = 18$ teeth.

Figure C.7: GRVLR Mechanical Advantage: Gear Ratio Hand Calculation

D Drawing Packet

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	6527K726	25MM HIGHT 2MM THICKNESS 300MM LENGTH SQUARE TUBE STEEL	7
2	6527K726	25MM HIGHT 2MM THIKHNESS 1000MM LENGTH SQUARE TUBE STEEL	2
3	6527K726	25MM HIGHT 2MM THICKNESS 550MM LENGTH SQUARE TUBE STEEL	2
4	6527K726	25MM HIGHT 2MM THICKNESS 100MM LENGTH SQUARE TUBE STEEL	4
5	6527K726	25MM HIGHT 2MM THICKNESS 850MM LENGTH SQUARE TUBE STEEL	2
6	500mm .75D axl	500MM LENGTH 19MM D STEEL AXIL	2
7	6236K166		9
8	75mm .75D axl	75MM LENGTH 19MM DIAMETER STEEL AXLE	2
9	PedalSystem_Sproket With Padel Link		1
10	PedalSystem_Foot Pedal		2
11	PedalSystem_Inner Chain		1
12	PedalSystem_GroundSupport		1
13	PedalSystem_RearGear		1
14	Pedal support plate		1
15	Feeder		1
16	6527K736	25MM HIGHT 50MM WIDTH 2MM THICKNESS 600MM LENGTH RECRANGULAR TUBE STEEL	1
17	Back Plate	300MM X 790MM X 2MM 1010 SHEET STEEL	2
18	Hood side plate		4
19	Hood		2
20	6527K726	25MM HIGHT 2MM THICKNESS 35MM LENGTH SQUARE TUBE STEEL	2
21	6527K726	25MM HIGHT 2MM THICKNESS 120MM LENGTH SQUARE TUBE STEEL	2
22	Side wall	140MM X 825MM X 2MM 1010 SHEET METAL	2
23	Front Wall	720MM X 300MM X 2MM 1010 SHEET STEEL	1
24	Part1^Frame Assemblie 3		1
25	Crushing Plate		2
26	Crushing plate sheild		1
27	Crushing plate sheild brace		2
28	lifting arm		2



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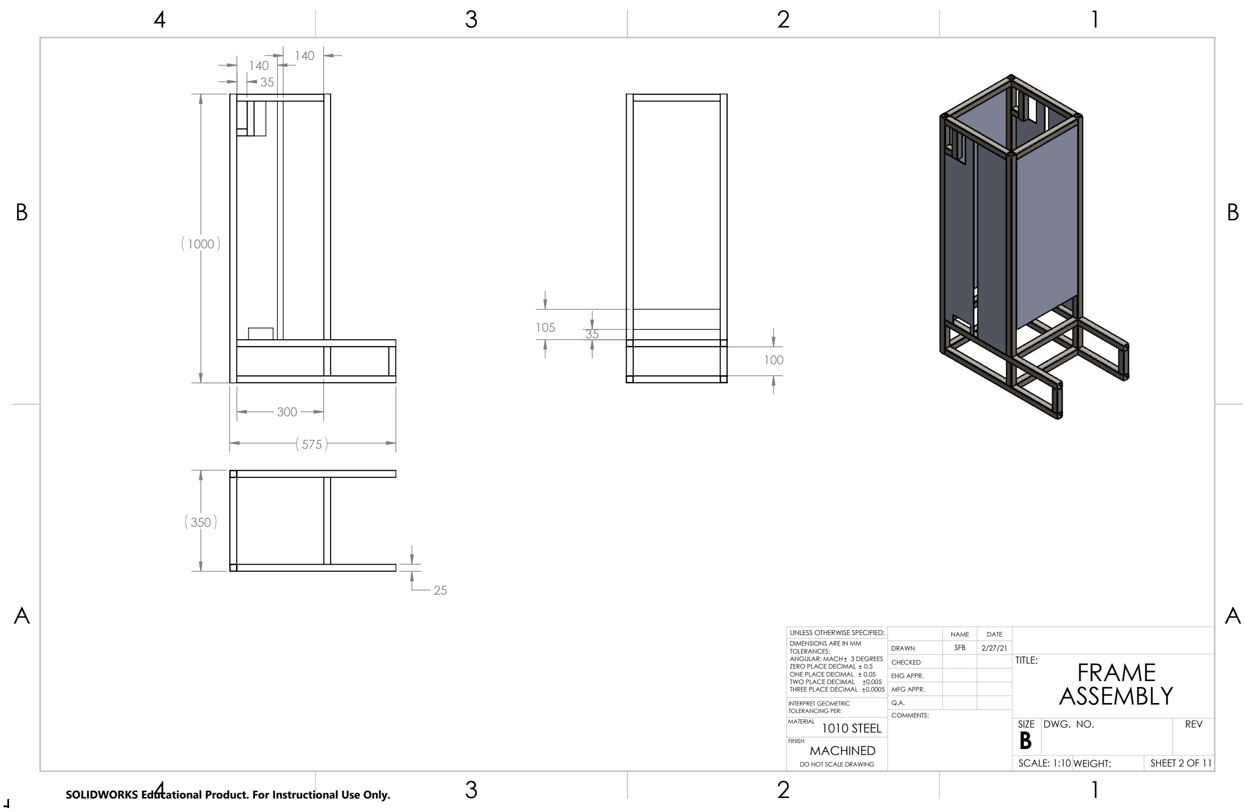
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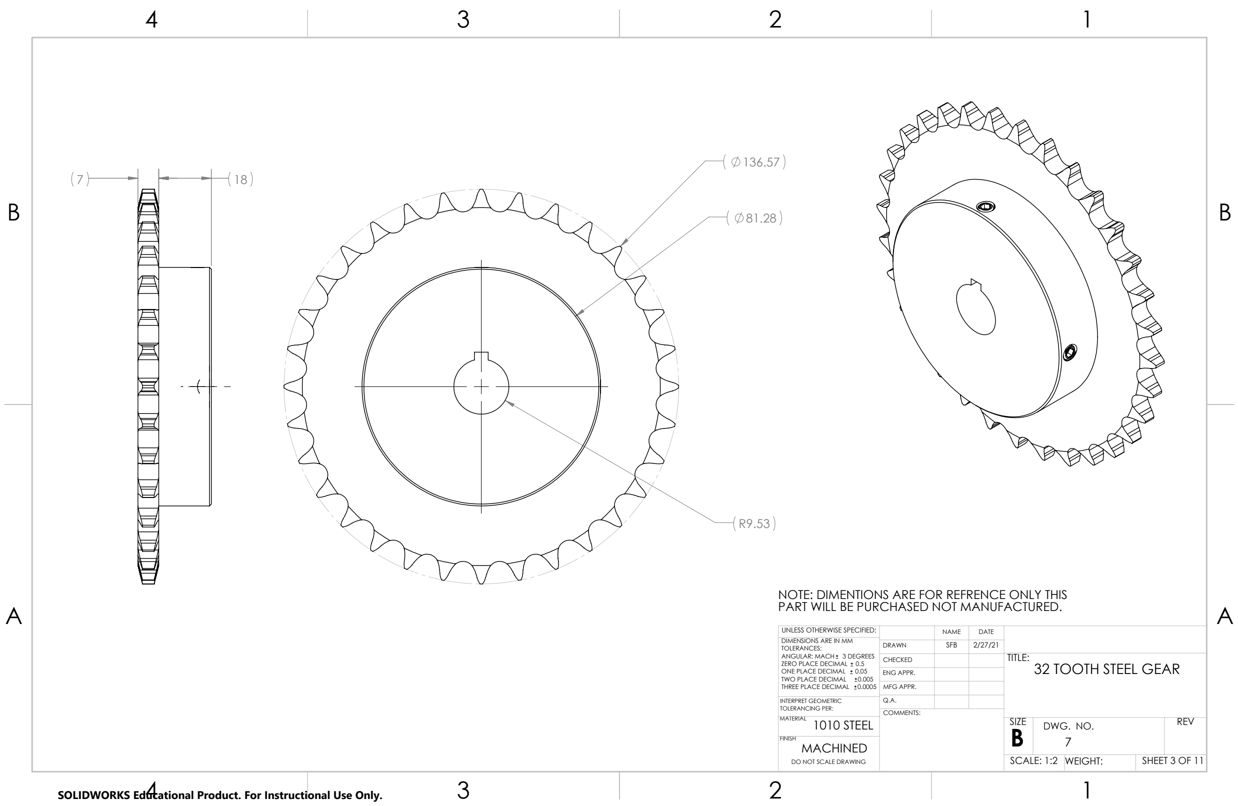
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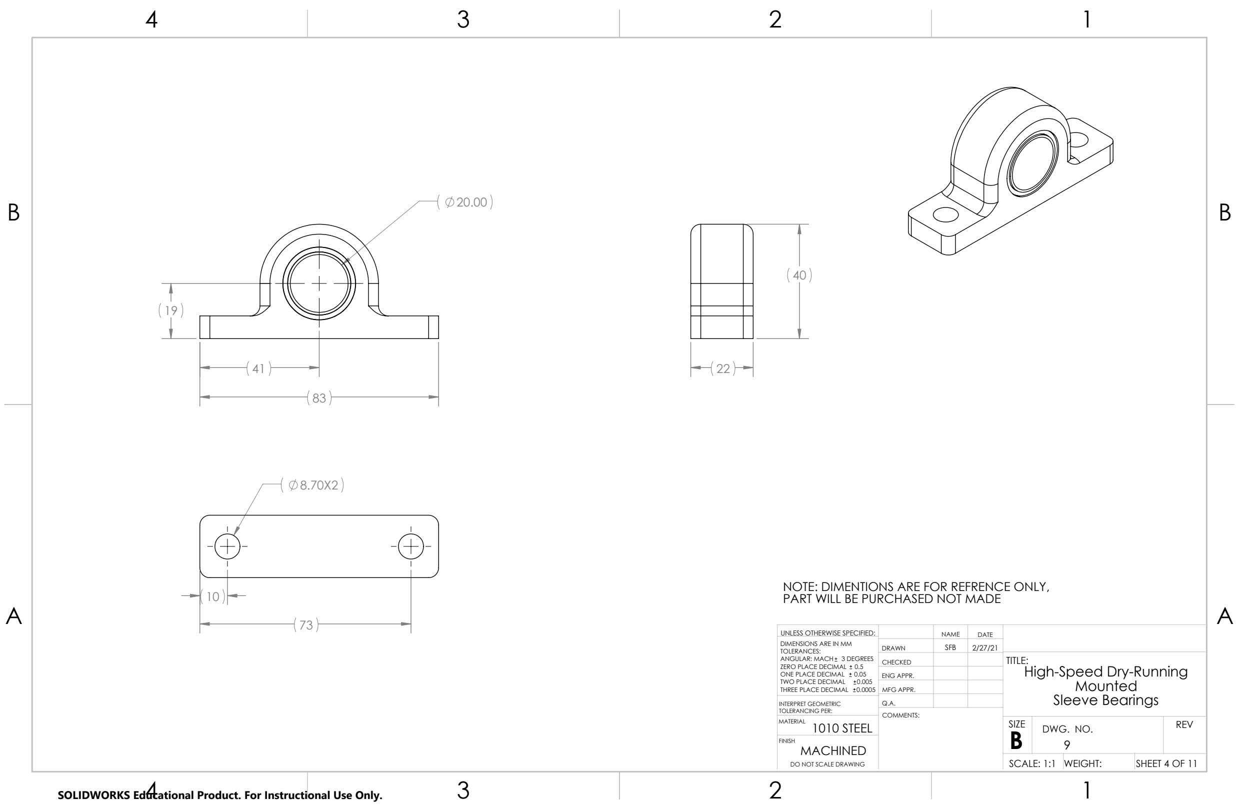

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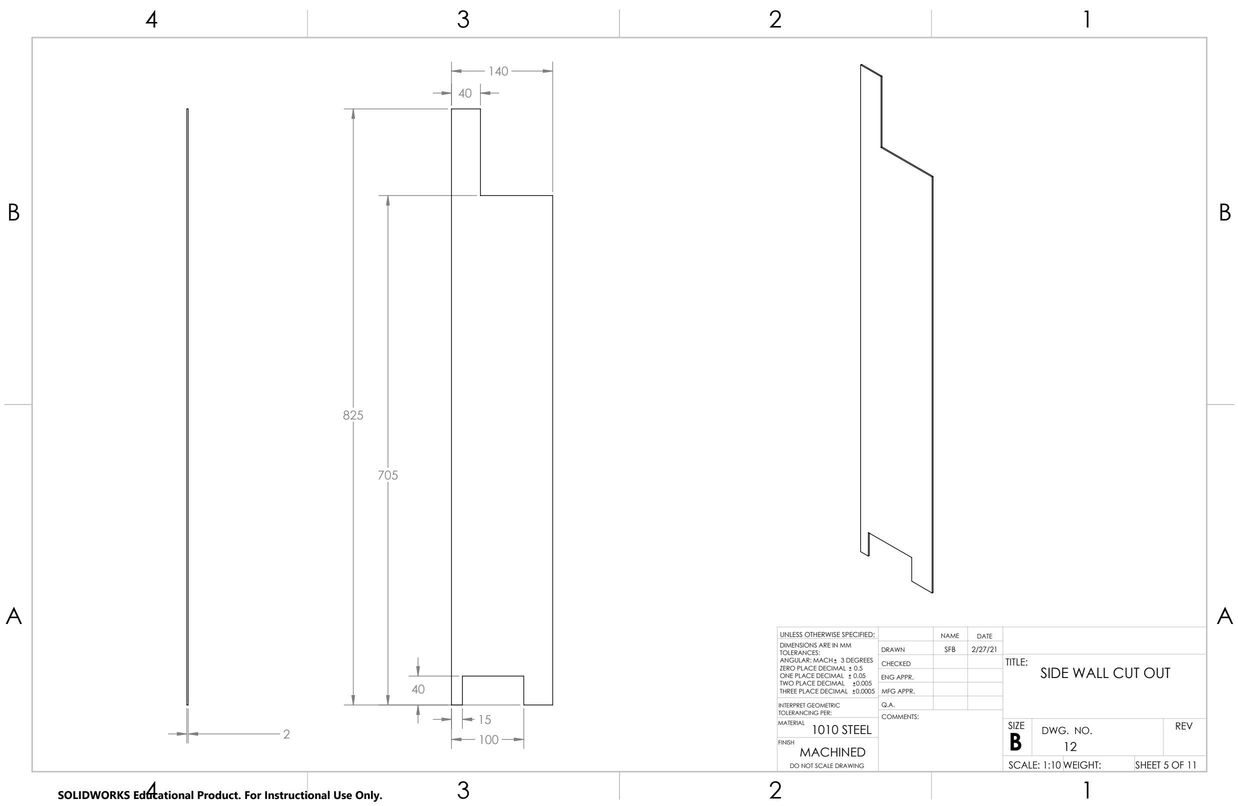

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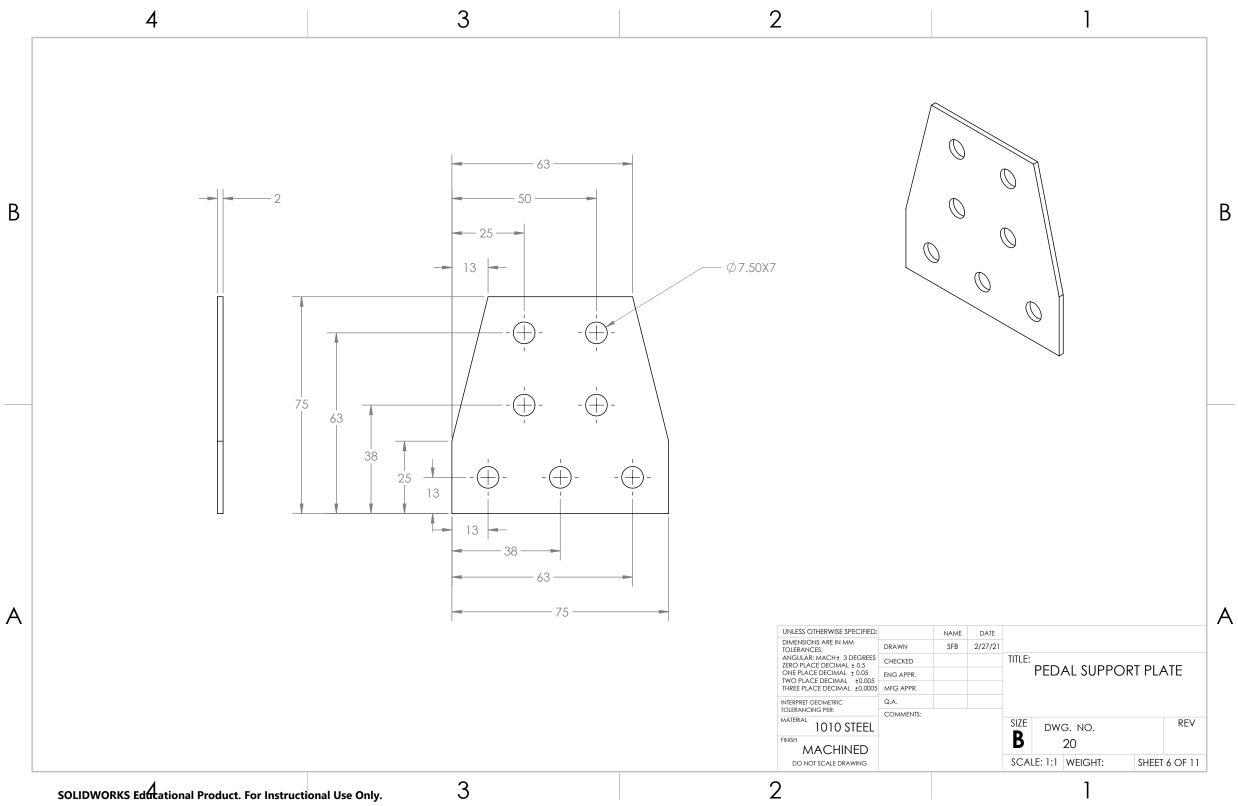

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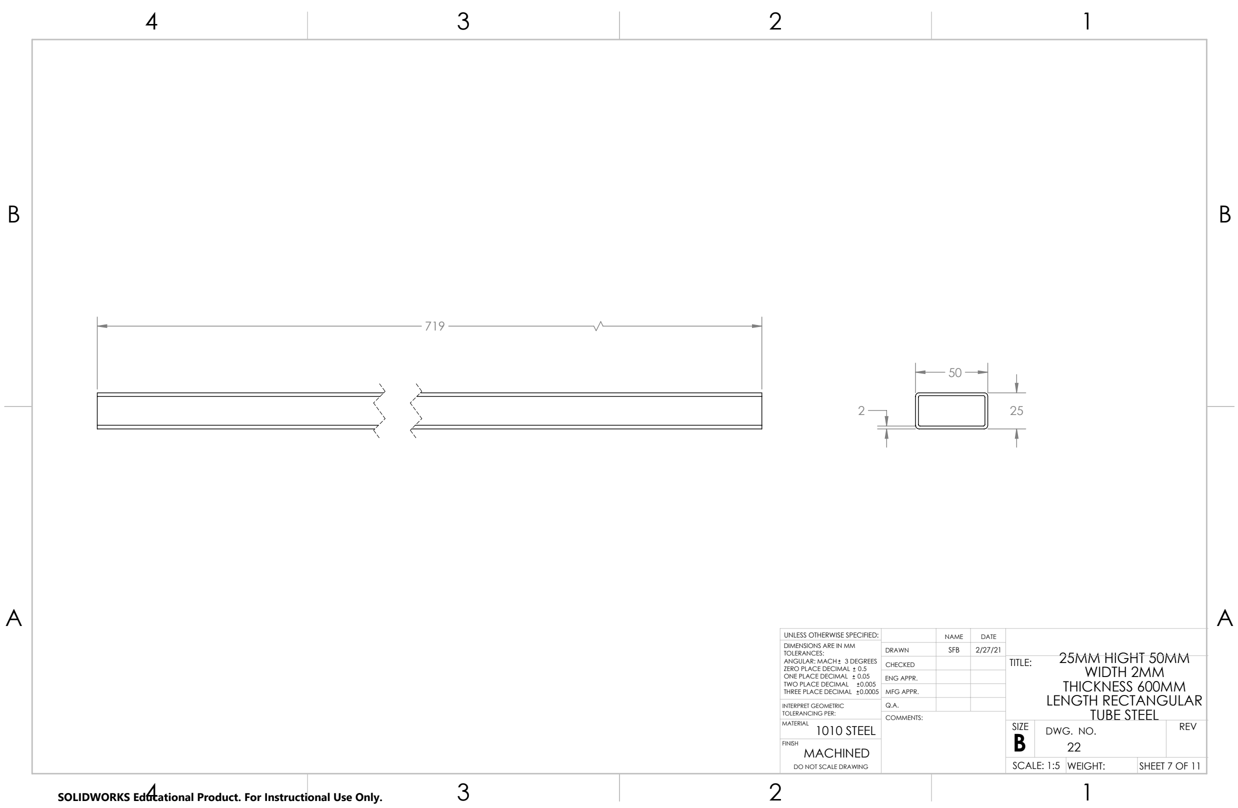
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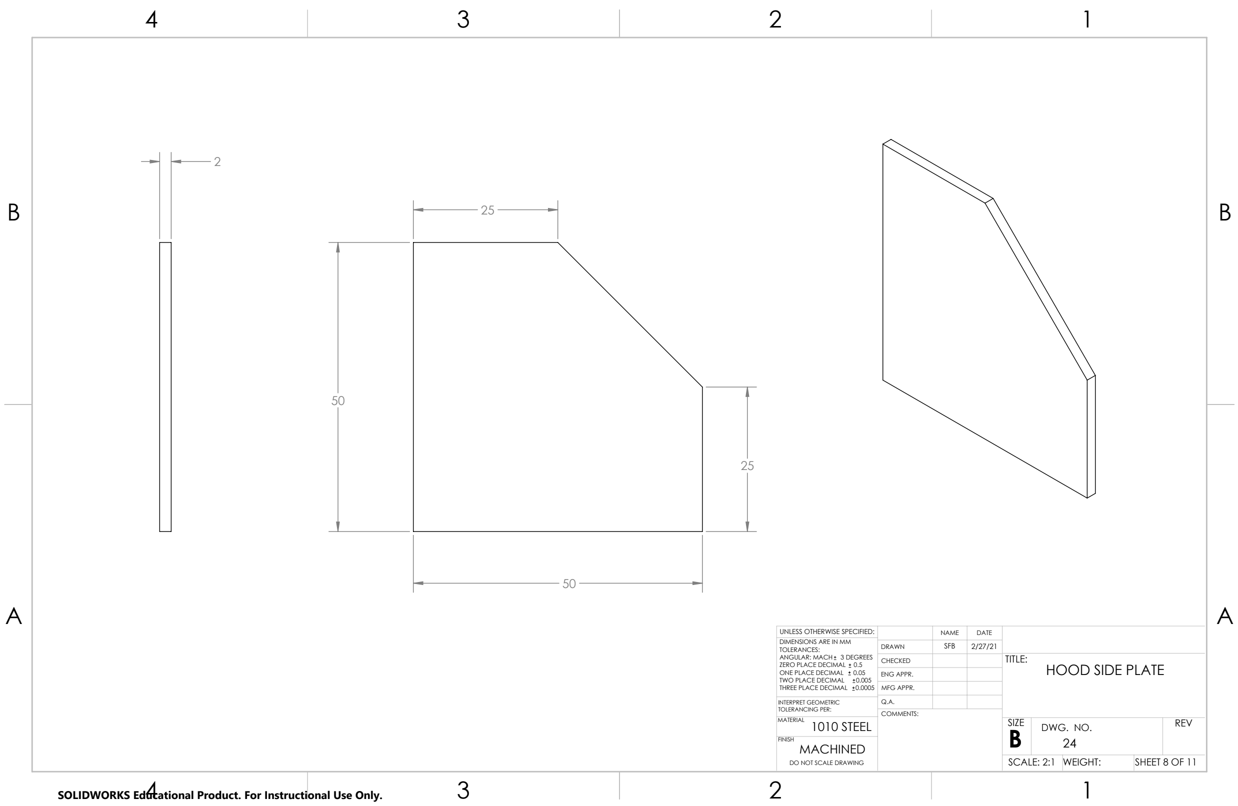
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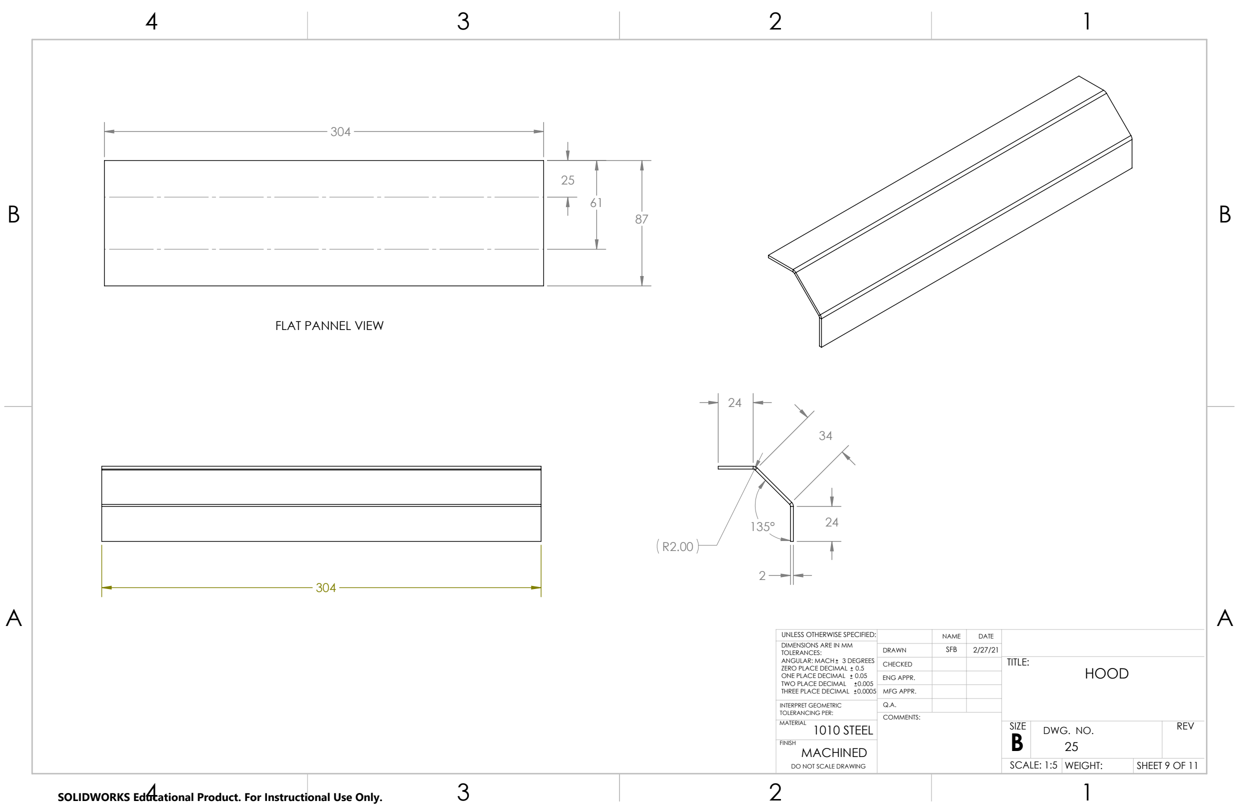
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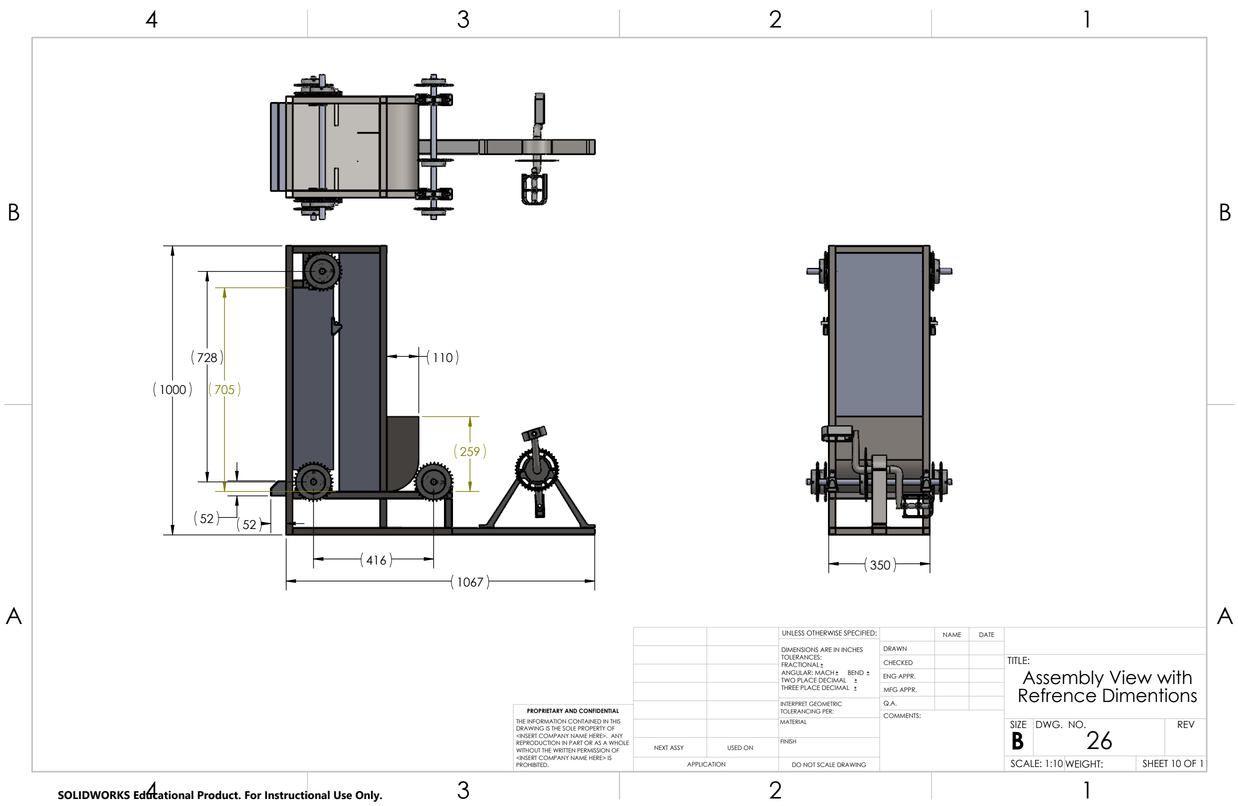
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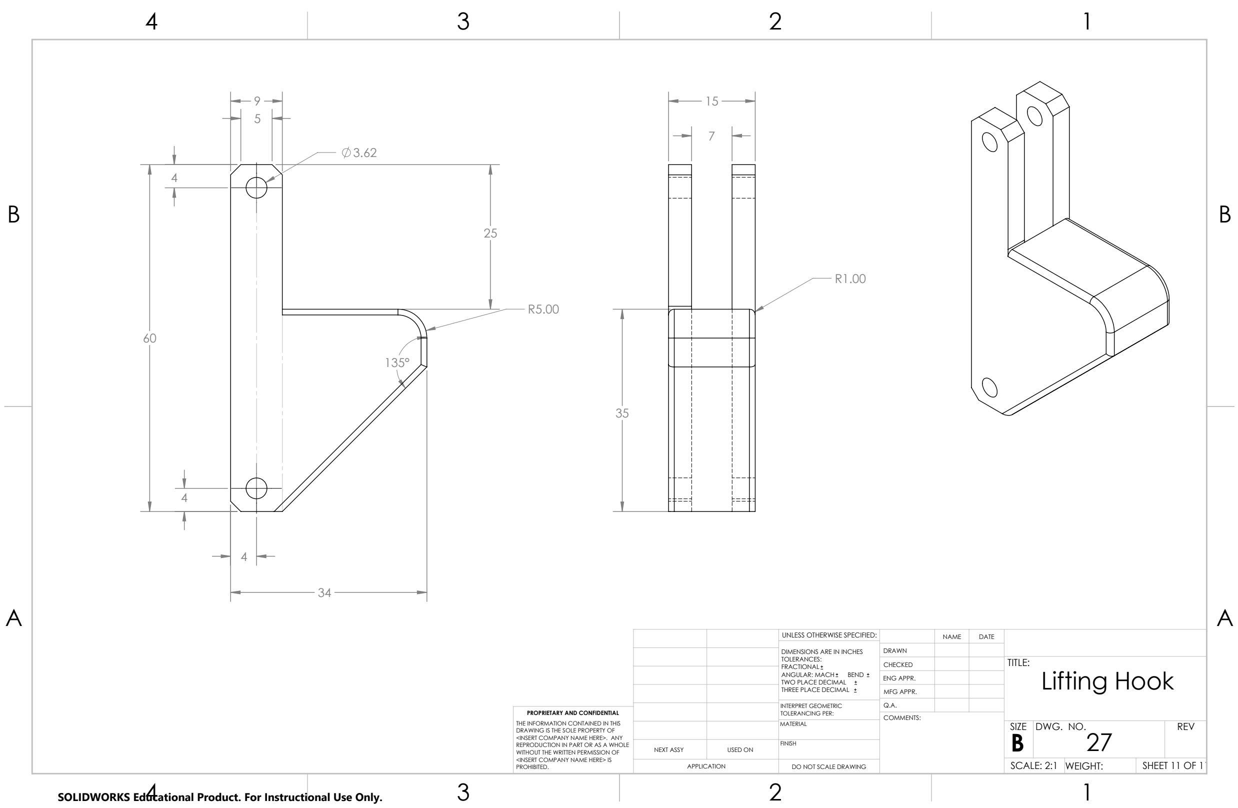
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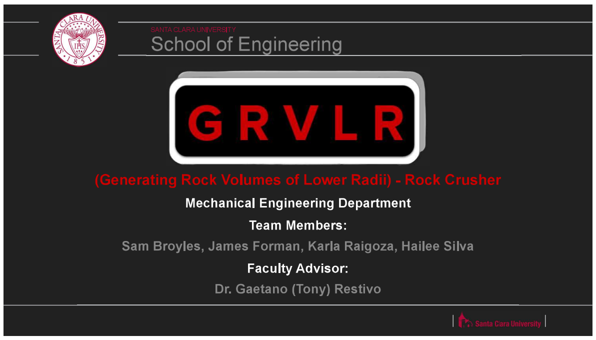
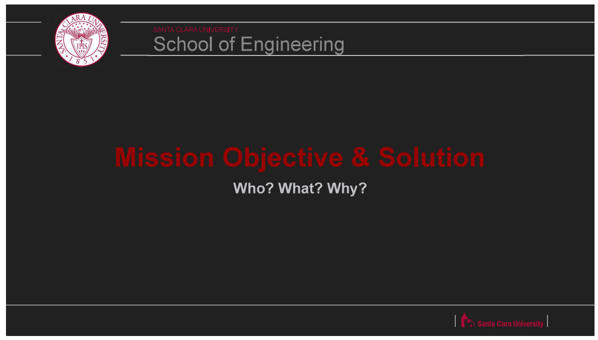
E Senior Design Conference Presentation



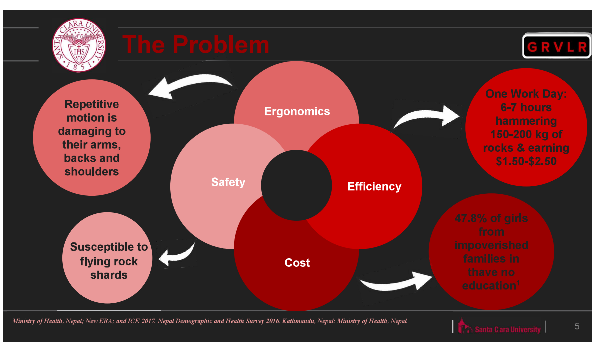
School of Engineering
GRVLR
(Generating Rock Volumes of Lower Radii) - Rock Crusher
Mechanical Engineering Department
Team Members:
Sam Broyles, James Forman, Karla Raigoza, Hailee Silva
Faculty Advisor:
Dr. Gaetano (Tony) Restivo
Santa Clara University



School of Engineering
Mission Objective & Solution
Who? What? Why?
Santa Clara University

Reality of Widows in Nepal
GRVLR
01
Citizenship Rights
02
Social Ostracization
03
Inheritance Rights
Once married, legally not entitled to inheritance from birth family
Once widowed, culturally not entitled to inheritance from husband
Santa Clara University
3

Rock Crushing in Nepal
GRVLR
Santa Clara University
4



The Problem
GRVLR
Repetitive motion is damaging to their arms, backs and shoulders
Ergonomics
One Work Day: 6-7 hours hammering 150-200 kg of rocks & earning $1.50-$2.50
Safety
Efficiency
Cost
Susceptible to flying rock shards
47.8% of girls from impoverished families in thave no education[1]
Ministry of Health, Nepal; New ERA; and ICF. 2017. Nepal Demographic and Health Survey 2016. Kathmandu, Nepal: Ministry of Health, Nepal.
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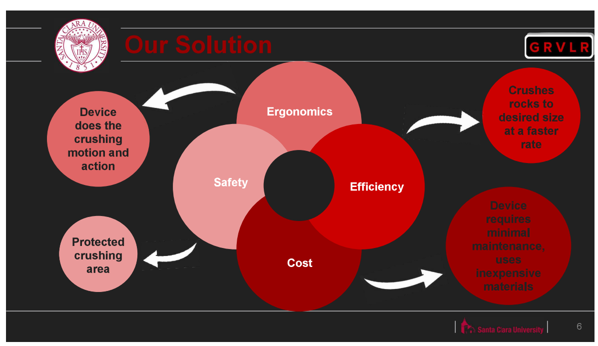

Our Solution
GRVLR
Device does the crushing motion and action
Ergonomics
Crushes rocks to desired size at a faster rate
Safety
Efficiency
Cost
Protected crushing area
Device requires minimal maintenance, uses inexpensive materials
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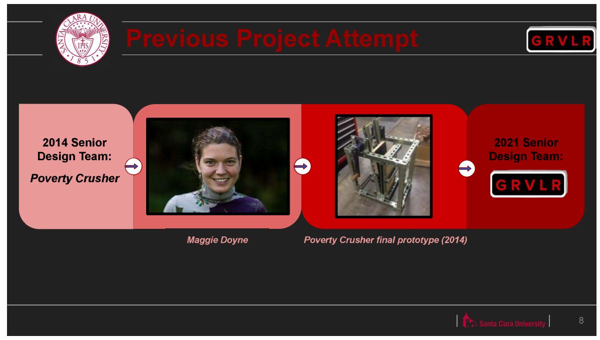
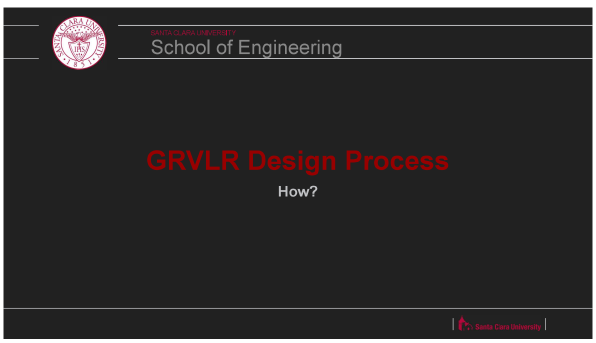
GRVLR Purpose and Mission
GRVLR
The GRVLR device will:
1. Improve upon the hammer method in the four criteria: ergonomics, efficiency, safety, and cost
2. Supplement their income enough to keep their children in school
SCHOOL CROSSING
Himalayan Climate Initiative
A Nepalese woman crushing stone with a hammer, Himalayan foothills, Nepal. March 2021.
Non-Governmental Organization GRVLR Partner
7


Previous Project Attempt
GRVLR
2014 Senior Design Team:
Poverty Crusher
2021 Senior Design Team:
GRVLR
Maggie Doyne
Poverty Crusher final prototype (2014)
8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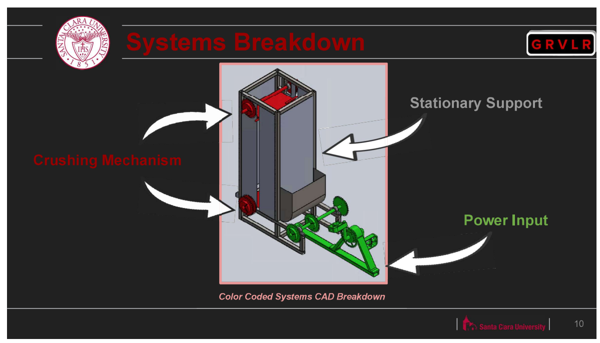
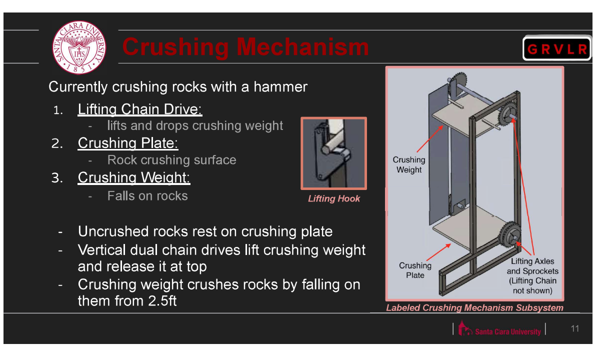
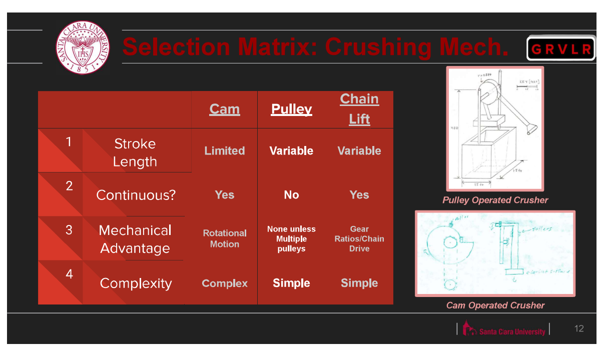
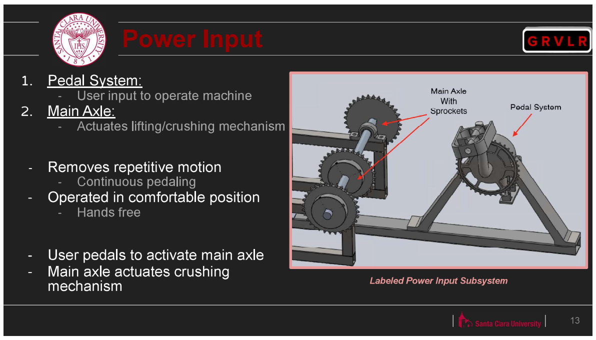
GRVLR Design Process
How?


Systems Breakdown
GRVLR
Stationary Support
Crushing Mechanism
Power Input
Color Coded Systems CAD Breakdown
10


Crushing Mechanism
GRVLR
Currently crushing rocks with a hammer
1. Lifting Chain Drive:
- lifts and drops crushing weight
2. Crushing Plate:
- Rock crushing surface
3. Crushing Weight:
- Falls on rocks
Lifting Hook
- Uncrushed rocks rest on crushing plate
- Vertical dual chain drives lift crushing weight and release it at top
- Crushing weight crushes rocks by falling on them from 2.5ft
Crushing Weight
Crushing Plate
Lifting Axles and Sprockets (Lifting Chain not shown)
Labeled Crushing Mechanism Subsystem
11


Selection Matrix: Crushing Mech.
GRVLR
Cam
Pulley
Chain Lift
1 Stroke Length
Limited
Variable
Variable
2 Continuous?
Yes
No
Yes
3 Mechanical Advantage
Rotational Motion
None unless Multiple pulleys
Gear Ratios/Chain Drive
4 Complexity
Complex
Simple
Simple
Pulley Operated Crusher
Cam Operated Crusher
12


Power Input
GRVLR
1. Pedal System:
- User input to operate machine
2. Main Axle:
- Actuates lifting/crushing mechanism
- Removes repetitive motion
- Continuous pedaling
- Operated in comfortable position
- Hands free
- User pedals to activate main axle
- Main axle actuates crushing mechanism
Main Axle With Sprockets
Pedal System
Labeled Power Input Subsystem
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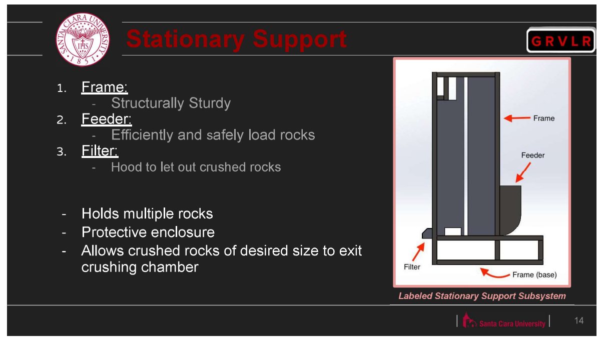
Stationary Support
GRVLR
1. Frame:
- Structurally Sturdy
2. Feeder:
- Efficiently and safely load rocks
3. Filter:
- Hood to let out crushed rocks
- Holds multiple rocks
- Protective enclosure
- Allows crushed rocks of desired size to exit crushing chamber
Frame
Feeder
Filter
Frame (base)
Labeled Stationary Support Subsystem
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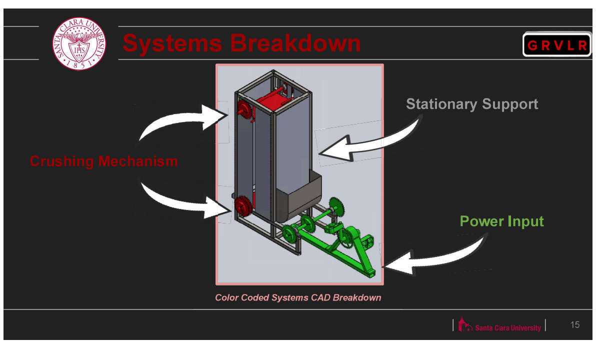
Systems Breakdown
GRVLR
Crushing Mechanism
Stationary Support
Power Input
Color Coded Systems CAD Breakdown
Santa Clara University
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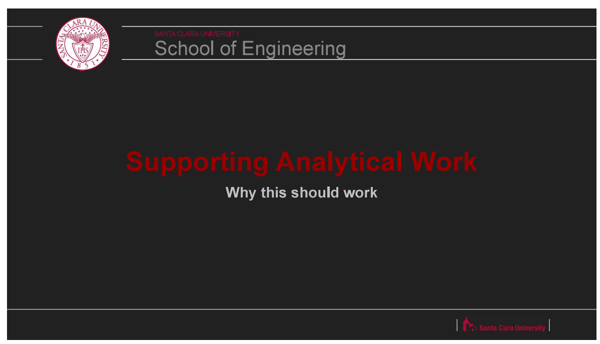
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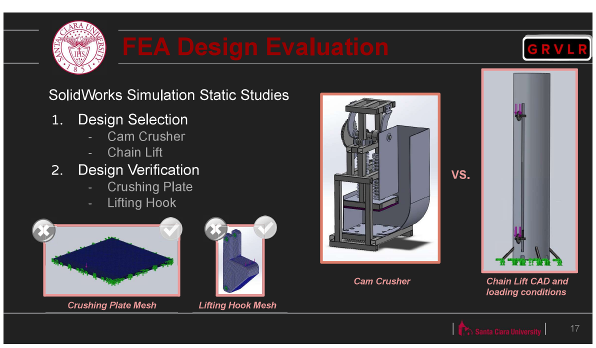
Supporting Analytical Work
Why this should work
Santa Clara University


FEA Design Evaluation
GRVLR
SolidWorks Simulation Static Studies
1. Design Selection
- Cam Crusher
- Chain Lift
2. Design Verification
- Crushing Plate
- Lifting Hook
VS.
Crushing Plate Mesh
Lifting Hook Mesh
Cam Crusher
Chain Lift CAD and loading conditions
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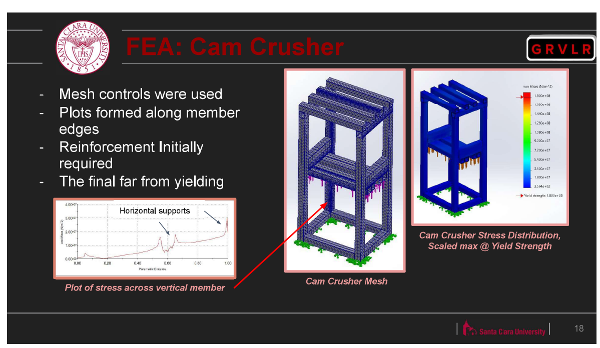
FEA: Cam Crusher
GRVLR
- Mesh controls were used
- Plots formed along member edges
- Reinforcement Initially required
- The final far from yielding
Horizontal supports
Plot of stress across vertical member
Cam Crusher Mesh
Cam Crusher Stress Distribution, Scaled max @ Yield Strength
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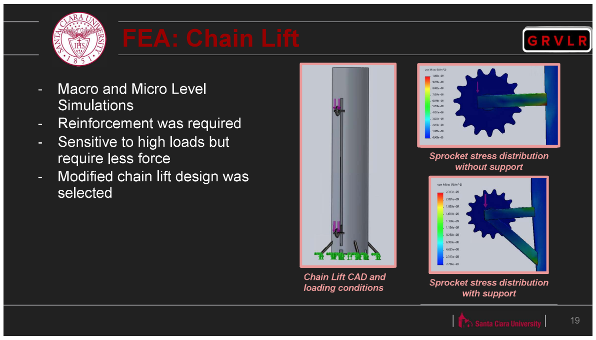
FEA: Chain Lift
GRVLR
- Macro and Micro Level Simulations
- Reinforcement was required
- Sensitive to high loads but require less force
- Modified chain lift design was selected
Chain Lift CAD and loading conditions
Sprocket stress distribution without support
Sprocket stress distribution with support
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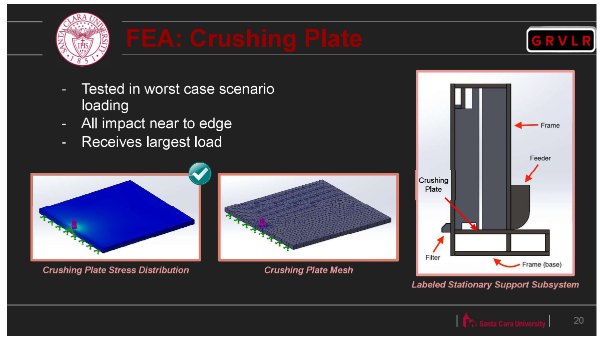
FEA: Crushing Plate
GRVLR
- Tested in worst case scenario loading
- All impact near to edge
- Receives largest load
Frame
Feeder
Crushing Plate
Filter
Frame (base)
Crushing Plate Stress Distribution
Crushing Plate Mesh
Labeled Stationary Support Subsystem
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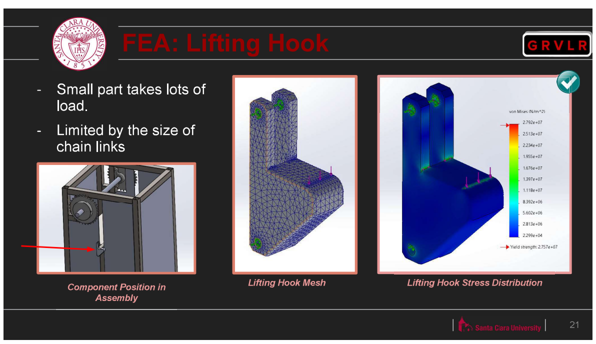
20


FEA: Lifting Hook
GRVLR
- Small part takes lots of load.
- Limited by the size of chain links
Component Position in Assembly
Lifting Hook Mesh
Lifting Hook Stress Distribution
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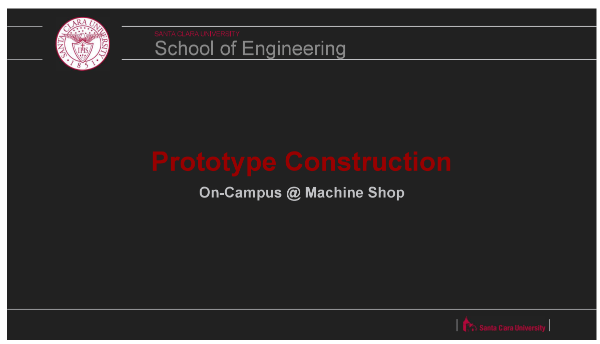
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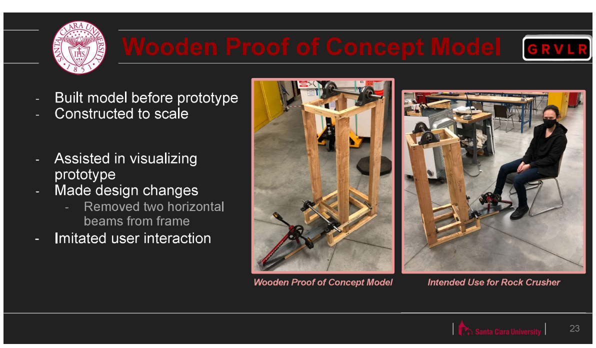
Prototype Construction
On-Campus @ Machine Shop
Santa Clara University


Wooden Proof of Concept Model
GRVLR
- Built model before prototype
- Constructed to scale
- Assisted in visualizing prototype
- Made design changes
- Removed two horizontal beams from frame
- Imitated user interaction
Wooden Proof of Concept Model
Intended Use for Rock Crusher
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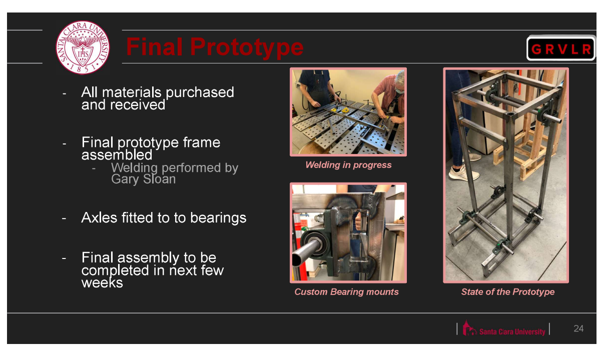
Final Prototype
GRVLR
- All materials purchased and received
- Final prototype frame assembled
- Welding performed by Gary Sloan
- Axles fitted to to bearings
- Final assembly to be completed in next few weeks
Welding in progress
Custom Bearing mounts
State of the Prototype
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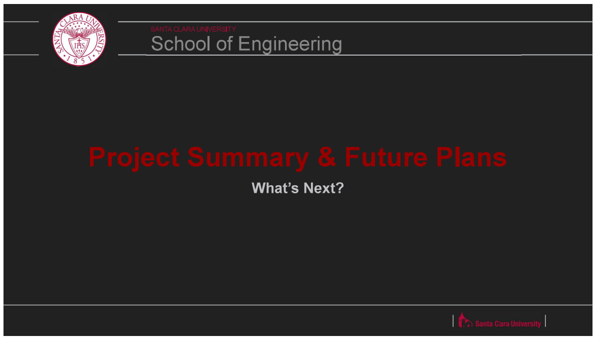
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Project Summary & Future Plans
What's Next?
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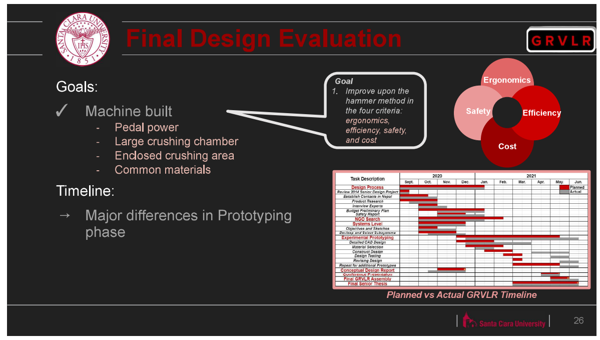
Final Design Evaluation
GRVLR
Goals:
✓ Machine built
- Pedal power
- Large crushing chamber
- Enclosed crushing area
- Common materials
Goal
1. Improve upon the hammer method in the four criteria: ergonomics, efficiency, safety, and cost
Ergonomics
Safety
Efficiency
Cost
Timeline:
→ Major differences in Prototyping phase
Planned vs Actual GRVLR Timeline
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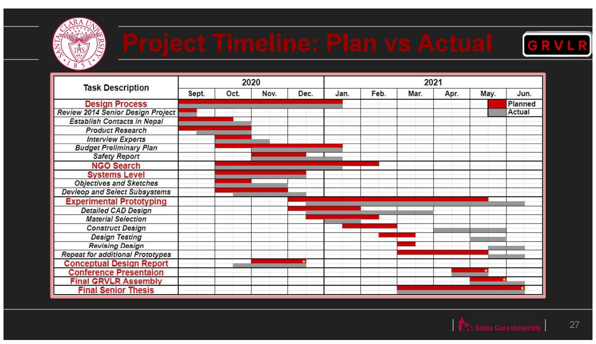
Project Timeline: Plan vs Actual
GRVLR
Task Description
2020
2021
Sept.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May.
Jun.
Planned
Actual
Design Process
Review 2014 Senior Design Project
Establish Contacts in Nepal
Product Research
Interview Experts
Budget Preliminary Plan
Safety Report
NGO Search
Systems Level
Objectives and Sketches
Devleop and Select Subsystems
Experimental Prototyping
Detailed CAD Design
Material Selection
Construct Design
Design Testing
Revising Design
Repeat for additional Prototypes
Conceptual Design Report
Conference Presentation
Final GRVLR Assembly
Final Senior Thesis
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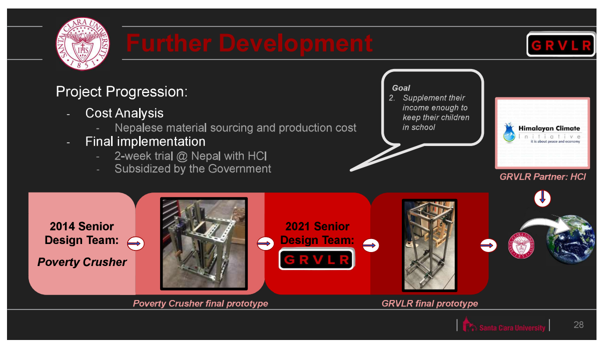
Further Development
GRVLR
Project Progression:
- Cost Analysis
- Nepalese material sourcing and production cost
- Final implementation
- 2-week trial @ Nepal with HCI
- Subsidized by the Government
Goal
2. Supplement their income enough to keep their children in school
Himalayan Climate Initiative
GRVLR Partner: HCI
2014 Senior Design Team:
Poverty Crusher
2021 Senior Design Team:
GRVLR
Poverty Crusher final prototype
GRVLR final prototype
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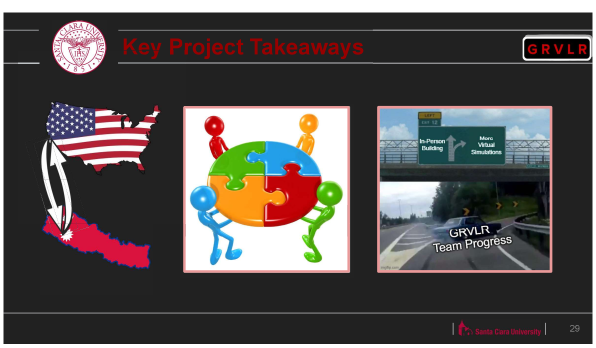
Key Project Takeaways
GRVLR
In-Person Building
More Virtual Simulations
GRVLR Team Progress
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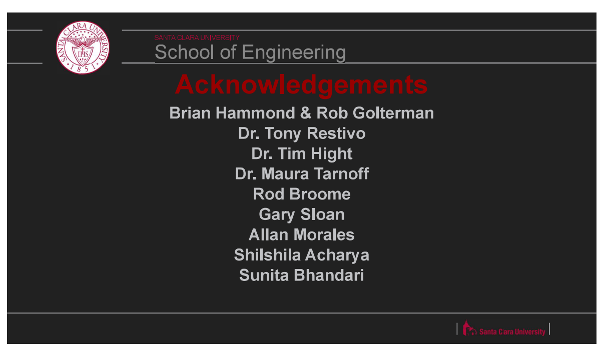
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Acknowledgements
Brian Hammond & Rob Golterman
Dr. Tony Restivo
Dr. Tim Hight
Dr. Maura Tarnoff
Rod Broome
Gary Sloan
Allan Morales
Shilshila Acharya
Sunita Bhandari
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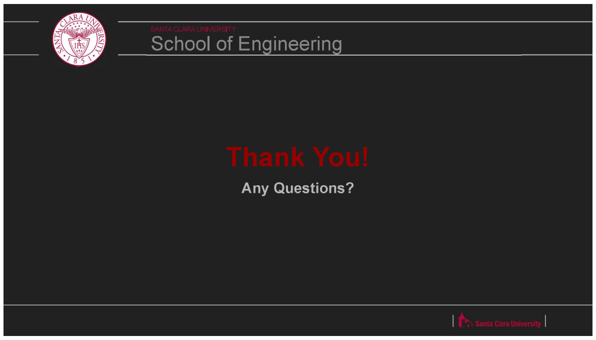
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Thank You!
Any Questions?
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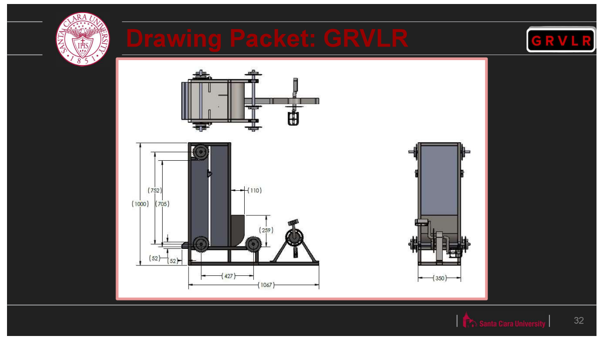
Drawing Packet: GRVLR
GRVLR
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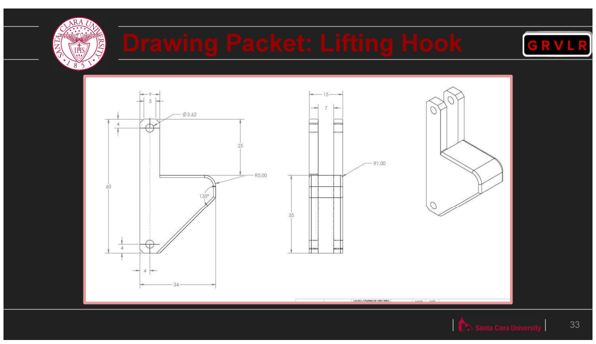
Drawing Packet: Lifting Hook
GRVLR
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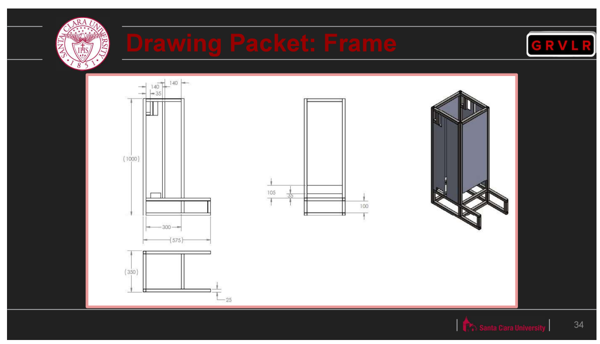
Drawing Packet: Frame
GRVLR
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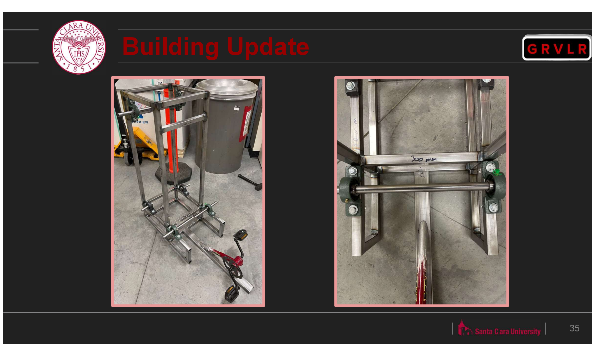
Building Update
GRVLR
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