Optimization of Caterpillar's 980H Rear Protection System

A Major Qualifying Project Report:
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Abstract

Two WPI students collaborated with four Shanghai University students under Caterpillar Inc. sponsorship to redesign and optimize a rear protection system for custom ordered 980H Wheel Loaders for use in strenuous workplace environments. A final design, meeting all Caterpillar Inc.'s specifications, was created by an iterative design process focusing on innovative and resourceful design ideas, meeting ISO standards, strength, accessibility, safety, aesthetics and simplicity.

Acknowledgments

We would like to thank Brad LaForest and Dong Fengming from Caterpillar Inc. for their continual support during this project. We would also like to thank our Shanghai University Advisors: Professor Guo, Professor Hua, Professor Zhang, and Professor Xiong. Lastly we would like to thank Professor Rong for setting up the project, running the project center, helping us with housing and taking us out to dinner.

We would like to acknowledge our Shanghai University partners Chen Shiyuan (Chen), Gao Jia (Gao), Meng Ziyu (Alex), and Zhao Qingsong (Morgan) for their contributions to the project, helping us adjust to Shanghai, teaching us about Chinese culture and the language.

Authorship

Throughout this Major Qualifying Project Matt Franklin and Marissa Goerke did the majority of the engineering work needed to achieve the objectives of this design project. Matt Franklin focused on the finite element analysis while Marisa Goerke concentrated on more of the SoildWorks modeling. Both partners focused their efforts on different preliminary designs in effort to achieve diverse design solutions. Shanghai University students helped in the verbal brainstorming to solve several design parameters.

The report was jointly written by both WPI partners with Matt Franklin focusing on introduction, literature review, and design specifications while Marissa Goerke was responsible for the methodology, results, analysis, and formatting.

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1.0.0 Introduction

In this section we will discuss the background and introduce the justification for this design project. We will describe the fundamental ideas behind the task at hand. After reading this section the reader should have a more thorough understanding of the problems and the objectives of this design project.

1.1.0 Background

Caterpillar Inc. is a worldwide supplier of manufacturing equipment, engine systems and financial services which earned a gross revenue of $65.9 Billion (CNN, 2014) in 2013. While the company owns many subsidiary companies in different location over the world, the Caterpillar Inc. brand of tractor is manufactured on every continent, except for Antarctica. One such manufacturing plant is located in Suhzou, China just outside of Shanghai. The Suhzou plant produces Medium Wheel Loaders and Motor Graders. Of the tractors fabricated and assembled at this plant some are custom ordered, with specialized and added parts, to better fulfill the customer's needs. These custom made parts are usually made for wealthy customers working in harsh environments. Our project will

Figure 1: Location of Kazakhstan

focus on the redesign and optimization of one of these custom ordered parts specialized for a customer in Kazakhstan, see Figure 1 to the right.

The customer in Kazakhstan works in underground mining and requires added collision protection on the rear end of medium sized Wheel Loaders. Underground mining is one of the three high impact environments that benefit from adding collision protection. The three high risk environments are forestry work, waste management and underground mining as pictured below in Figure 2.

Figure 2: Left to right: Waste Management, Underground Mining, Forestry Work

The current rear protection system design is lacking several important aspects that results in unsatisfactory function. The current design is not high enough to provide sufficient protection to the radiators located on the back of the 980H. Another area for improvement is the harness protection unit. The harness protection unit is the wires and assembly that support

Figure 4: Current Height

Figure 3: Harness

the rear facing lights on the 980H. The pertruding part of the harness directly behind the light is noted in circle in Figure 3 to the right. The current design does not have a hold open on the gate. A hold open is convenient to hold the rear gate open while a worker is inspecting and maintaining the equipment. These three main aspects will be the main focus of this redesign project.

We will look at each of these aspects and tailor the redesigned protection system to these three short comings in attempt to create a more effective and reliable rear projection system. We will brainstorm several different solutions for each of these aspects and combine the best ideas into one final potential design.

Once this final design is developed, more thorough analysis will be done to provide Caterpillar Inc. with an in depth review of the new design. The analysis that will be provided to Caterpillar Inc. will include bolt analysis, nesting analysis, welding and cutting analysis and finally a rough cost estimate. The bolt analysis will be concentrated on the bolts used to fix the rear protection system to the back of the 980H Wheel Loader.

In order to move forward with this plan we must fully understand the background of the 980H and all of the areas of interest. All the relevant information gathered from this initial grasping of the fundamentals can be found in the Project Approach section.

This project focuses on the added rear protection system for the 980H Medium Wheel Loader. However the same protection system may be added to other similar medium sized tractor models. The 980H Medium Wheel Loader weighs 30,159 kilograms under operating condition and has an approximate total length of 30 feet. See Appendix B for more detailed dimensioning (Dimensions, 2014).

Throughout this report terms indicated in the diagram below will be used to describe locations and parts on the 980H Wheel Loader:

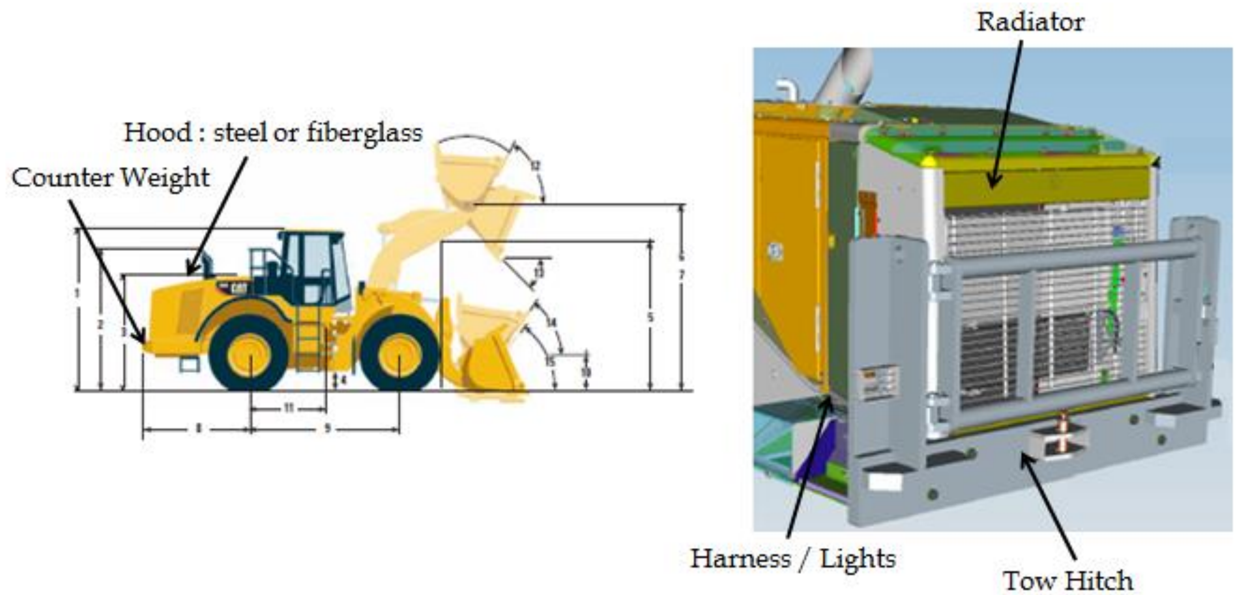

Figure 5: 980H Wheel Loader

On 980H Wheel Loaders that do not require the added rear protection system, there exists a counterweight. This counter weight does offer some rear collision protection but is need in order to balance the moment of the tractor when the bucket raises a heavy load above the ground. This counter weight has a mass of 1357 Kilograms.

The Hood is a protective cover for the entire engine systems located behind the cab of the tractor. This hood is usually made out of fiberglass which allows for easy and less expensive manufacturing, while also offering a weight reduction. A fiberglass hood has the ability to rise and lower, by a hydraulic system, from a pivot point located near the counter weight. However, sometimes a steel hood is needed for extra protection due to external impacts or from thermal damage due to high temperature work environments such as a steel mill. These steel hoods are fixed on the tractor and cannot be lifted because of their heavier weight. To reach the engine systems on a steel hood for maintenance, multiple access doors are used.

The harness system refers to the rear lights as well as the casing, protective hardware, and any wires that are connected to the rear lights. The tow hitch is located in the bottom, center of the rear of the tractor. The tow hitch can be used for a variety of many operational activities but needs to exist so an incapacitated tractor can be towed out by another operational tractor (ie. stuck in the mud). This tow hitch is required by ISO Standard 10532- Towing and Hauling.

Finally there is the radiator located within the hood at the rear end of the tractor. The hood does offer some radiator protection as well as the grill protecting it from large flying debris. However the focus of the added rear protection system is to better protect the radiator and surrounding hood area.

2.0.0 Literature Review

Today's Caterpillar Inc. machines originated from tractors dating back to the Late 1800s. Benjamin Holt founded The Holt Manufacturing Company in 1883, in Stockton, California, which was a leading manufacturer of steam tractor engines. Later, Holt ran into difficulties operating his tractors through the soft farmland ground of the San Joaquin Valley, CA. Therefore, in 1904, Holt removed the wheels from his tractor and successfully implemented a continuous track system. This gave him the needed traction to navigate or crawl through the soft ground. This crawling motion was said to resemble the motion of a Caterpillar. A few years later Holt sold his first tractor with this new continuous track system and also received a patent for his design (The Story of Caterpillar, 2014).

In 1910, Holt and his nephew Pliny Holt purchased the bankrupt Colean Manufacturing Co. plant in Peoria, Illinois and started operation as The Holt Caterpillar Company. At this point The Holt Caterpillar Company was shipping tractors to international customers, including England, France and Russian governments for agricultural purposes. At the start of World War I these tractors were re-purposed for military efforts. Once the United States entered the war, the company then formed a strong relationship with the U.S. Army Ordnance Department, which greatly increased its production of tractors. When the war ended Holt Caterpillar Company had to go into debt due to the sudden drop in demand (ACMOC, 2013).

C.L Best Gas Tractor Company, Holt's major competitor, had also taken on debt due to the drop in demand after World War I. So after a long history over legal battles and market share, the two financially struggling companies, Holt Caterpillar and C.L. Best Gas Tractor, merged to form the Caterpillar Tractor Company. This new company continued to grow strong throughout the Great Depression and again found an increase in production during World War II. During the war, Caterpillar produced over 50,000 tractors for military use. After World War II, Caterpillar began to open plants overseas, expanding its worldwide market. From the 1950s until today Caterpillar Inc. has been growing through sales as well as many company acquisitions (The Story of Caterpillar, 2014).

Today Caterpillar Inc. is the leading manufacturer of heavy equipment. Caterpillar Inc. has over 130,000 employees and is listed as number forty-two in the Fortune 500 companies with over $69 billion in revenue. Recently in 2010, Caterpillar Inc. divided its products and services into three main categories: Machinery, Engines and Financial products(CNN, 2014).

Among many other international locations, Caterpillar Inc. has established a strong presence in China. Caterpillar Inc. first appeared in Beijing, China, in 1996, to help the country's rapidly growing industry and continuous construction. Now Caterpillar Inc. has expanded to twenty-three different manufacturing plants throughout the country. Most of these facilities are located near the coast line so more convenient shipping methods are available (History, 2014).

Some of Caterpillar's machinery produced in China are used to serve the Chinese market and its demand for equipment, however many of their products are shipped to other neighboring countries. Although China is has many rapidly growing industries, their economy does not favor the sale of Caterpillar Inc. equipment. Caterpillar Inc. machinery is of the highest quality and is very durable compared to other companies' products. However along with this high quality and durability also comes a high price tag compared to other available products.

Right now, China has a very low wage rate which make it more appealing in many industries to hire many workers and purchase low end machinery rather than invest in a higher priced product and have little money left over for a work force. So while a low wage rate might help Caterpillar Inc. in their manufacturing labor cost, on a macro scale it would be beneficial for the company if China's wage rate rose. This would force industries to lessen their work force and instead purchase their higher end products to replace the lost labor.

Caterpillar Inc. does own a more affordable, machinery manufactures called SEM or Shandong Engineering Machinery. SEM was bought by Caterpillar Inc. in 2008 and improved through the advance knowledge of

Caterpillar Inc. to become a competitive company both in China's and the world wide machinery market. Typical customers of SEM products are smaller or new industries that have a short operational future, which makes a low initial cost important. This wholly owned subsidiary of Caterpillar Inc. allows them to reach a customer base that their high cost products cannot. However it is important to Caterpillar Inc. not to mix up the practices and methods between the 2 different companies so that CAT's high end products do not suffer in quality and that SEM's affordable products does not increase in cost.

For this Major Qualifying Project, our team of students has been working with Caterpillar Inc. engineers from their manufacturing plant in Suzhou, China. This Suzhou plant was founded in 2006 and built at an incredible speed during the 2008 recession in the United States. Once finished, production began almost immediately. Before construction, this plant had the advantage of analyzing other Caterpillar Inc. facilities in China and optimized their floor layout. A significant improvement was making one continuous manufacturing line for one machine type, instead of separating into two different lines as other facilities had done. This Suzhou plant has two different lines for the production of Medium Wheel Loaders and motor graders. Their production mainly serves market in Asia Pacific, Russia, Commonwealth of Independent States, Africa, Middle East and South America.

3.0.0 Methods

Following the project background and context we are able to begin on the project approach. First, we discuss the objectives of this project to clearly state what we wish to accomplish. We have laid out our project specifications in this section with an explanation which states the assumptions taken and justification for each project requirement. These design specifications are based on our sponsor's needs, our project objectives, and our understanding of the problem statement. The problem statement is as follows:

The current rear protection system does not sufficiently protect the harness system or the top of the radiators. The rear protection gate does not have a hold open mechanism.

From this problem statement we have organized methodology below.

Step 1: Background Research

As shown in the first half of this report, the first step we took was to gain a bigger picture of the scope of this engineering project. Research was done into the history of Caterpillar Inc., its competitors and products. After reading the project description, more research was done in the area of familiarizing ourselves with Wheel Loaders and the design of rear protection systems.

Several rear protection systems currently in use were examined from a far to gain a general idea what the market perceives as the norm and what “sufficient protection” looks like for less risky tasks.

Step 2: Identify a Problem and Need

It is important to fully understand the problem and the need before embarking on an engineering design project. In order to understand the problem with the current designs we visited the Caterpillar Inc. factory plant on the 28th of October 2013. There we observed the factory layout and assembly line and spoke with Brad LaForest and Dong Fengming. As mentioned previously Brad LaForest is a lead manager for the Suhzou Caterpillar Inc. plant, Earthmoving Division and over sees the production lines of the medium Wheel Loader and motor grader tractors that are built there. Danny is a Caterpillar Inc. Engineer who was our main contact for technical questions regarding the redesign on the protection system. We then discussed the needs and justifications for the design of a new rear protection system. We were also able to secure a few pictures and skeleton SolidWorks models of the old rear protection system. Examples of some of these resources are shown below.

Figure 6: Original Rear Protection Design (Picture and SolidWorks Model)

These models would prove to be very useful in the evaluation and comparison stages of our methodology.

Step 3: Define Project Objectives

With the information gained during the Caterpillar Inc. factory visit and our initial questions answered we could define our objectives into something more concrete. Our objective is to produce a new design for the rear protection system for the radiator and harness for a 980H Wheel Loader, which will:

1) Meet all Caterpillar Inc. design specifications

2) Exceed the performance of the original protection system design

Step 4: Define Design Specifications

From these concrete objectives we were able to formulate our first draft of the project specifications. These primary specifications opened the door to begin brainstorming about ways to design a rear protection system that satisfied these requirements.

Step 5: Generate Design Options

Once the beginnings of possible solutions were starting to form around each requirement we were able to put together sketches of ideas and eliminate different approaches. A few example to these approaches that were eliminated in the sketch stage include a horizontally originated hinge so the rear protection gate could swing down and become stairs up to the radiators. The gate of the rear protection system was going to be too massive to purse this design further then the drawing board. Another design option that got the axe early on was implementing large hinges that wrapped completely around the side protections supports of the rear protection system. This eliminated much of the hanging stresses on the smaller hinges on the original design but also exposed the hinges to deformation from side collisions which proved to be a fatal design flaw.

Step 6: Model the Potential Protection Systems

These design options were crafted into more well thought out designs and were solidified into SolidWorks models. Three primary designs were created by combining various interpretations of the design options brainstormed in the previous step. Each of these there designs are showcased and explained in detail in the results section.

Step 7: Obtain Feedback and Rank Designs in Matrix Form

With distinct designs modeled in SolidWorks a portion of our team took a second trip to the Caterpillar Inc. factory to present our ideas and gain feedback, perspective and evaluation on our ideas. This trip helped us further narrow down the needs and wants for the project outcome and most important areas to focus our efforts on. We also used a matrix suggested by Caterpillar Inc. to evaluate how well each of the designs met our specifications. This Matrix can be found in Appendix C.

Step 8: Modify and Redesign Process

Firstly, during this section of the process the design specifications needed to be reevaluated, modified and expanded upon to fully cover the goals of the objectives as the design project shifted into its final stages. A new emphasis was placed on the manufacture, assembly and cost analysis.

Step 9: Design Selection Process

The final design was created from a selection of a designs pooled from the three primary designs. This design was also evaluated through the same matrix to assess if the design met all requirements. Once we were sure the design met or exceeded expectation we moved forward to comparison analysis.

Step 10: Final Analysis and Comparison Process

To evaluate the effectiveness of the new design we compared it to with the old design in every specification and other aspects not included in the design requirements. Other comparison were made on welding distances, assembly, manufacturability, and a primitive cost analysis. We could not do a thorough cost analysis because without Caterpillar’s cost numbers for overhead it was impossible to create an accurate cost analysis. We did however price the materials used in the design and look at the implications of welding and cutting costs.

Step 11: Identify Areas Needing Improvement

After the final analysis we spoke with our sponsors and when over the designs and our analysis and they followed up with another idea on how to improve the design. This idea fell in the areas needing improvement because with no time left to make improvements we were not able to address the idea.

4.0.0 Design

Before we could begin the design process our team needed to create a list of performance measures to ensure that all our models met the design specifications. Some of these performance measures are very specific and have quantitative measures tied with tolerances while others are qualitative measurements. These value of these qualitative performance measure will first be determined by our team through a Pough Matrix evaluation (see Appendix C). However in the end the value of these qualitative measures will be determined through discussion with Caterpillar Inc. engineers. We will use all of these performance measures to compare and evaluate potential designs.

4.1.0 Measurable Design Specifications

The following section will go into more detail in each of the aforementioned design specifications and how each will be measured numerically.

The material readily available and used for manufacturing the rear protection system can be one of the following steels or a combination:

- ASTM A36, A370
- SAE Grades 1008 through 1025
- BS 4360
- DIN 17100
- JIS G3505, G4051
- AFNOR A35-501 Q
- GB 699, 700, 1591

All of these steels have very similar properties, including density and yield strength (Fengming, 2013). In our analysis of our designs we assumed the use of ASTM A36 which has average properties that represent all these steel materials. The density used is 7850 kilograms per cubic meter and the yield strength is 200 million Pascals.

4.1.1 Radiator Protection

The rear protection system needs to be at least as tall as or taller than the radiator guard. The current design does not cover the top of the radiator and therefore does not adequately protect the radiator. Both the rear protection system gate and the rear protection system frame need to withstand strong impacts to protect the radiator and rear hood of the 980H.

This specification will be measured by assessing whether the rear protection system is as tall as the rear hood of the loader. We will measure the impact resistance of the rear protection system gate and the rear protection system frame using SolidWork's finite element analysis.

In order to sufficiently protect the radiators and the hood, the rear protection system needs to extend at least 1.1 meters above the top surface of the tow hitch, with a top horizontal width of at least 1.7 meters.

The rear protection system's frame needs to allow for a fiberglass hood to be raised so that engine parts may be accessible for maintenance. This is a simple pass or fail specification.

4.1.2 Rear Protection System Strength

This next performance measure attempts to evaluate the needed strength of the rear protection system in order to survive a rear collision. Our new design should be as strong as or stronger than the original Caterpillar Inc. design. Through discussion with Bradley LaForest, an engineer at the Caterpillar Inc. plant Suzhou, we came to the understanding that for any rear collision the tractor would likely be operating in first gear. For the 980H Wheel Loader this means the maximum collision velocity would be 5 MPH or 2.235 m/s. We initially started to evaluate the needed strength of the rear protection system assuming the tractor would collide perpendicularly to a fixed wall (a wall that does not move). We then turned to an impact force equation:

$$\text{Impact force [N]} = \frac{(1/2) \times \text{Mass} \times \text{Velocty}^2}{\text{Slow down Distance}}$$

The operating mass of the 980H Wheel Loader is 30519 kilograms and our collision velocity was determined to be 2.235 meters per second. Since we are analyzing a collision with a fixed wall the slow own distance would simply be the deformation in the rear protection system. This deformation needs to be small, we chose 2.5 centimeters, which makes an impact force of over three million Newtons. This is an impractically large assumption.

$$3{,}048{,}985 \text{ [N]} = \frac{(1/2) \times 30519 \times 2.235^2}{0.025}$$

Next we analyzed this impact force on the original rear protection system model using a Finite Element Analysis feature in SolidWorks. The frame was fixed at the four bolt locations. These four bolts are used to secure the rear protection system to the 980H main frame, and a three million newton force was applied to all the outer most surfaces of the rear protection system frame as shown in Figure 6. The material used in every Finite Element Analysis test was ASTM A36 Steel, one of many acceptable steels for rear protection system production as previously explained. The results of this test are shown below in Figure 6.

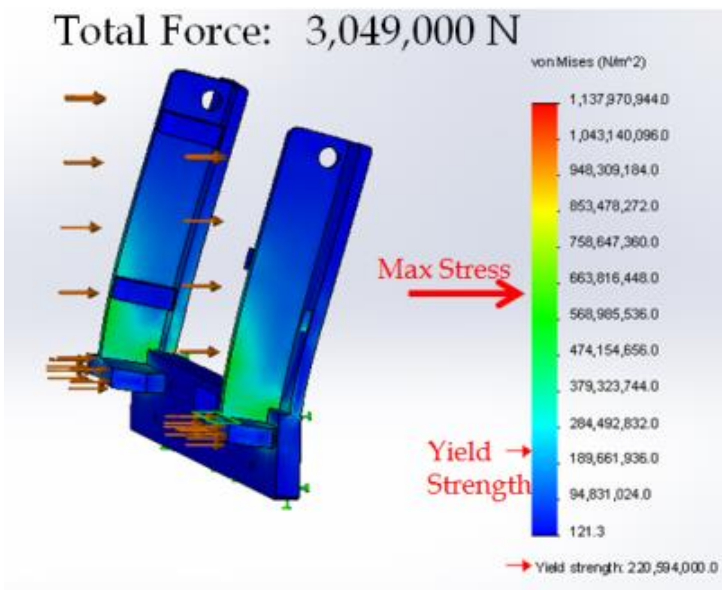

Figure 7: Original Frame Collision Test

With this large impact force the original rear protection system model failed. As seen in the Von Mises diagram above the max stress that occurs in this impact is approximately 600 thousand Pascals. This is much higher than the 220 thousand Pascals yield strength of steel. From here, we kept the same simulation but simply lowered the impact force until the original rear protection system could survive the impact. The results of the final simulation are shown below in Figure 7.

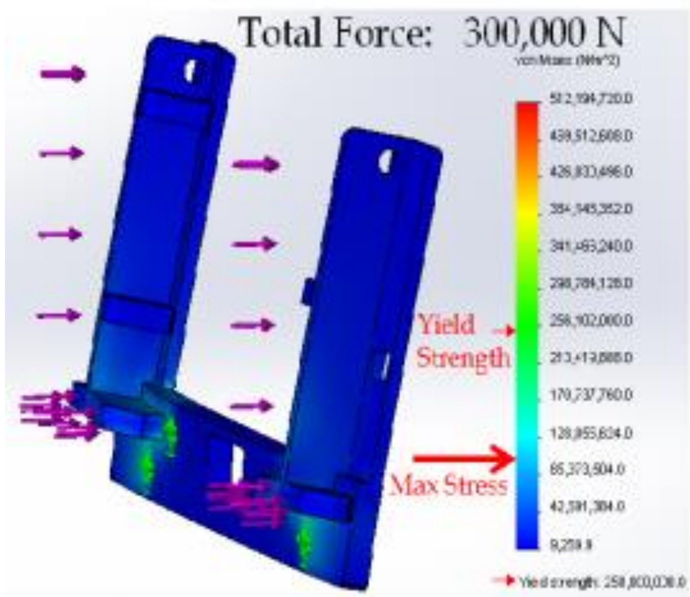

Figure 8: Adjusted Frame Test

This shows that the original rear protection system design could reasonably withstand a 300 thousand Newton impact force. With this applied force the max stress is around 100 thousand Pascels, which is well below the material's yield strength. To put this value in perspective, this impact force is slightly greater than the force the full operating weight of the tractor exerts on the ground. This force will be our performance measure for the strength of our rear protection system designs. Our designs should at least be able to withstand a 300 thousand newton impact force.

4.1.3 System Weight Requirement

Our next performance measure regards the weight of the rear protection system. The system takes place of a counter weight on the rear of the tractor and therefore needs to be a specific weight in order to correctly balance the tractor's raised bucket load It is important not to over shoot this weight restriction because with more rear weight customers tend to overload the tractor with a larger bucket sizes which causes part failures and costly damage to the 980H's systems. After discussion with Caterpillar Inc. engineers, we determined an optimal rear protection system weight of 1357 Kilograms with an acceptable tolerance of within 40 Kilograms.

4.1.4 Hold Open Mechanism

There are both qualitative and quantitative performance measures for the gate hold open mechanism. Qualitatively the hold open needs to be easy to use and it should be simple and efficient in terms of manufacturing and cost. Quantitatively the hold open needs to be durable and reliable. If the gate is opened on a slope it could potentially swing close while a worker is tending to the radiator. Therefore the hold open needs to be strong enough to resist the gate closing on a slope. In order to overestimate the needed strength we assumed the hold open would be used on a maximum slope of 30 degrees. The forces on the hold open would depending of the design of the gate and the design of the hold open. Therefore our quantitative performance measure for the hold open is that it resists the closing motion of the gate on a 30 degree slope.

4.1.5 AS Harness Protection

The following performance measure is in accordance with ISO Standard number 12509 regarding the location of the rear lights as shown in Appendix A. This ISO states the requirement the height of the lights off the ground and the minimum from the side of the tractor. However for our designs it is only relevant to consider the distance the lights are from the side of the tractor, height is not important because this will change with tractor types. The widest point of the tractor is the bucket and ISO 12509 specifies that the distance from the edge of the light to the edge of the bucket should be less than or equal to 400 millimeters as shown in Figure 7 below. However it is important to note that the diagram is not in accordance with the ISO. The 980H Wheel Loader can be equipped with a narrow bucket, but for our design performance measure and evaluation we will assume it is equipped with a wide bucket of width 3533 millimeters.

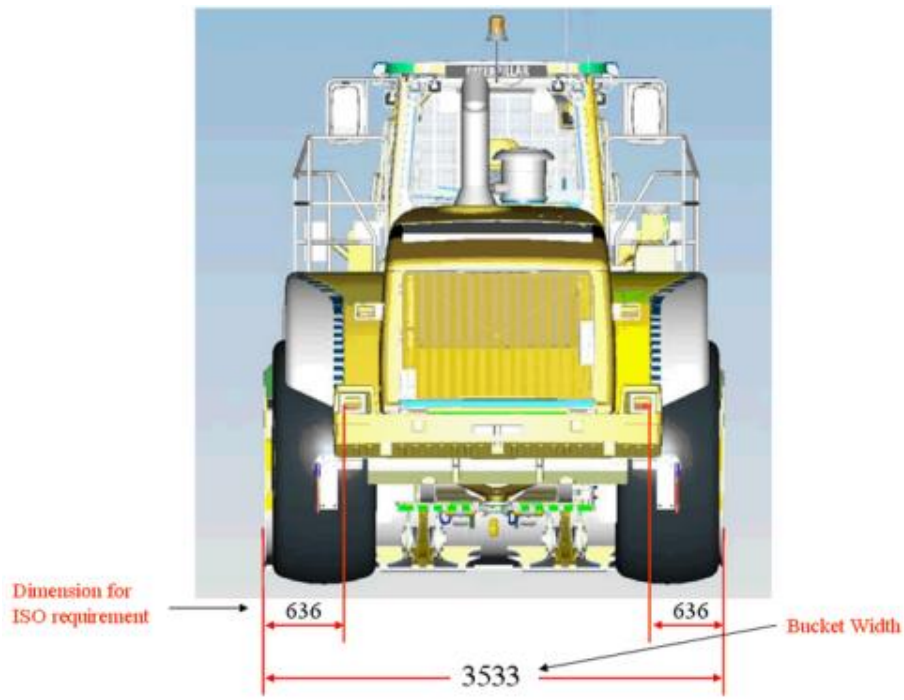

Figure 9: Safety Lights Standard

Another facet of AS Harness protection is assuring that the tractor looks finished and has no exposed wires. The lights need to be visible from the rear end of the loader at high angles, so the design cannot obstruct the view of the lights. The harness wires should not be exposed to the outside environment, but also allows access to hardware for maintenance and repair. While there are many ways to achieve the performance measure it is important to Caterpillar Inc. that this is done with a simple and cheap solution, which means no extra welding or machined grooving to protect the wire.

4.1.7 Aesthetics

Since, as previously discussed, this rear protection system is a custom part and costs the costumer more than what is included with the standard tractor, it is important that the protection system is aesthetically pleasing. With this extra payment the costumer should receive an incorporated customized part that is cohesive with the rest of the tractor.

This design specification will be measured by review and approval by Caterpillar Inc. officials.

4.1.8 Tow Hitch Accessibility

The rear protection system cannot infringe on access to the tow hitch on the body of the 980H. The tow hitch is an invaluable resource in problematic situations where a Wheel Loader needs to be rescued from an area where it can no longer maneuver on its own. Tow hitches can also serve as a place to help other tractors in need. Therefore, the tow hitch needs to be easily accessible and not blocked by the rear protection system in any way.

4.2.0 Hold Open Design Options

We looked at a few different hold open types before choosing a type to use for our rear protection system hold open. The following three figures show a variety of hold open ideas ranging from simple pins to sliders.

Figure 10: Piston and Pin Style Hold Open Mechanism

Figure 11: Slider Hold Open Mechanism on Loader Radiator Guard

Figure 12: Pin and Curved Lock Hold Open Mechanism

When selecting a hold open pin idea we kept in mind the strength the mechanism needed in order to hold the gate open. The gate is a heavy part and needs a sturdy hold open. We also focused on keeping the hold open design options simple and easy to manufacture and use.

5.0.0 Preliminary Design Ideas

In this section we will cover three of the designs that we predicted would be the most viable of all the ideas we had brain stormed as a team.

5.1.0 Taller Design with Simple Pin

The simplest design idea is to raise the height of the current rear protection system to protect the top of the radiator and add a hold open. Below is our first preliminary design where the rear protection device is raised to match the height of the rear hood.

Figure 13: Left Current Height of Gate, Right: Desired Height

This simple gate design also requires a hold open. Below is the simple pin hold open idea that was implemented in this first preliminary design.

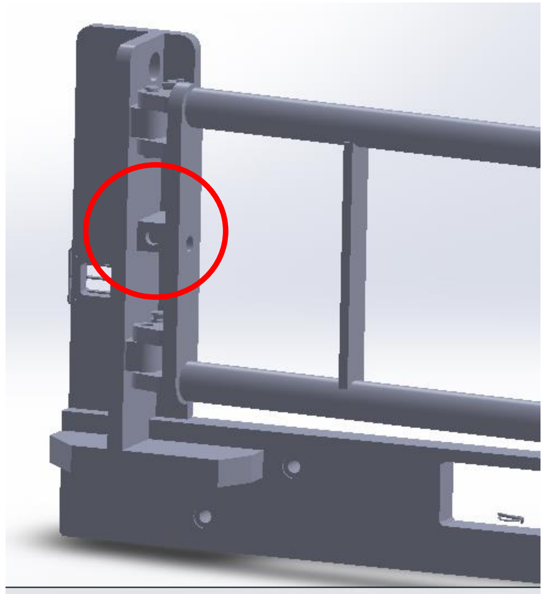

Figure 14: Simple Pin Hold Open

The pin used in this simple pin hold on mechanism is the same pin used to lock the gate closed when the loader is in service. This way there are no additional parts and the same part that is already in stock now has two uses, doubling its effectiveness.

5.1.1 Cylinder Upright Design

The next preliminary design idea was to create a new frame that was cylindrical in form to provide more protection in the event of a rear end collision. The reason for this is cylinders are a stronger shape as shown by the equations shown below.

$$I_{Bar} = h^3b/12$$
$$= (.26)^3(.04)/12$$
$$= \mathbf{5.86 \times 10^{-5}}$$

$$I_{Cyliner} = \pi(d_o^4 - d_i^4)/64$$

$$= \pi(.26^4 - .22^4)/64$$

$$= \mathbf{1.09 \times 10^{-4}}$$

Working from the fact that the moment of inertia of the cylinder shape is strong we built a design from this idea. The rough outline of this idea is shown below.

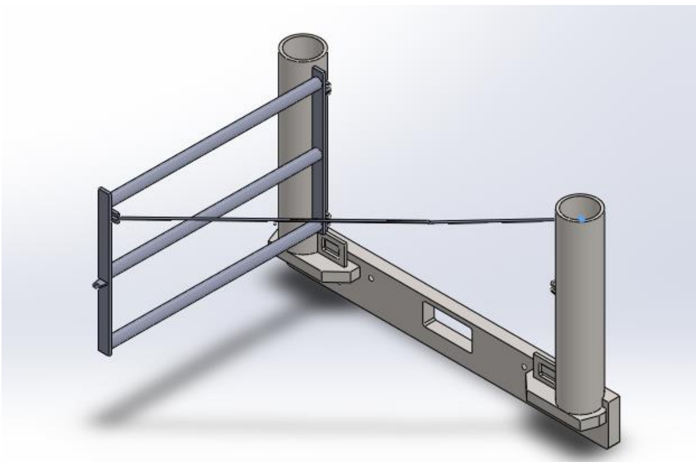

Figure 15: Cylinder Upright Design

The hold open chosen for this protection system was a slightly more complex slider arm hold open bar mechanism. The device would fold up and secure against the gate while the loader is in service.

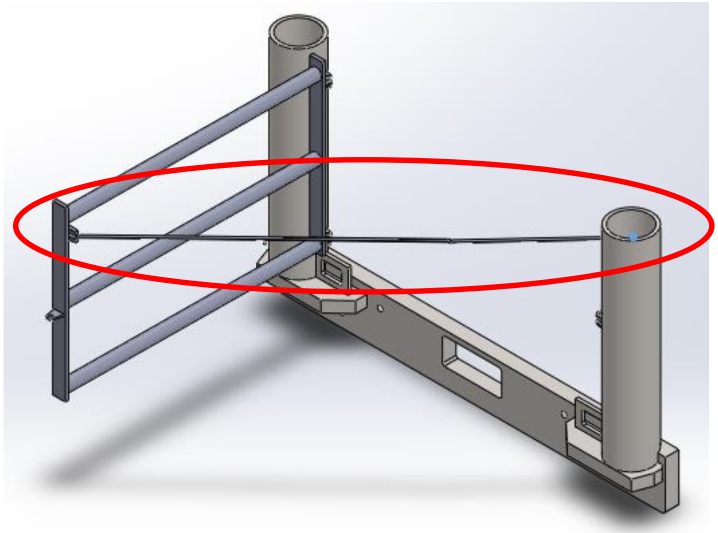

Figure 16: Cylinder Uprights Hold Open Mechanism

This hold open would use a slider to lock the bendable arm into place and a peg on the cylindrical upright to hold the gate open. When not in use the arm would be folded and secured to the gate.

5.1.2 Bent Upright/Cross Bar Design

Our finial preliminary design consisted of a T shaped upright, similar to the taller design, but the frame would bend over the hood. Also, instead of a gate to access the radiator, there would be sliding cylindrical bars that lock in place using a pin system. This design can be seen in the figure below.

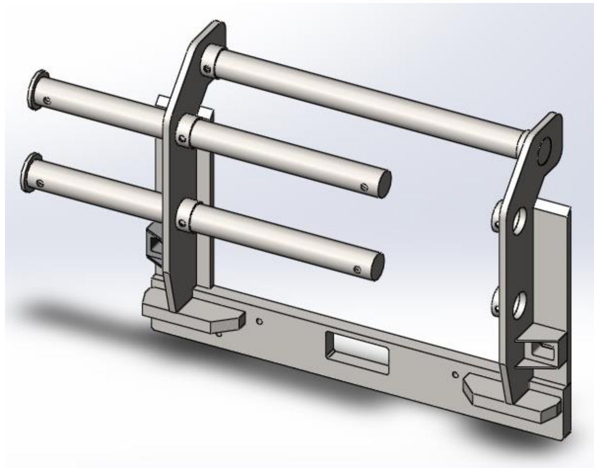

Figure 16: Bent upright design

No hold open mechanism would be needed for this design because the cross bars can be slid open and once the pin holes are aligned a pin can be used to lock the bars open. When the bars are slid open three pins would be in use, but when the bars are closed six pins would be used to secure the system. The cross bars would be hollow.

6.0.0 Results

In this section we explain the how we incorporate many of the features of our preliminary designs into a final design result. We will describe how we tested and evaluated each preliminary design for proper performance specifications and what modifications would take place to result in our final design.

6.1.0 Taller Design with Simple Pin

This design was the simplest of the first three preliminary designs. This design takes the original design and raises it to match the height of the loaders hood. The design is pictured below.

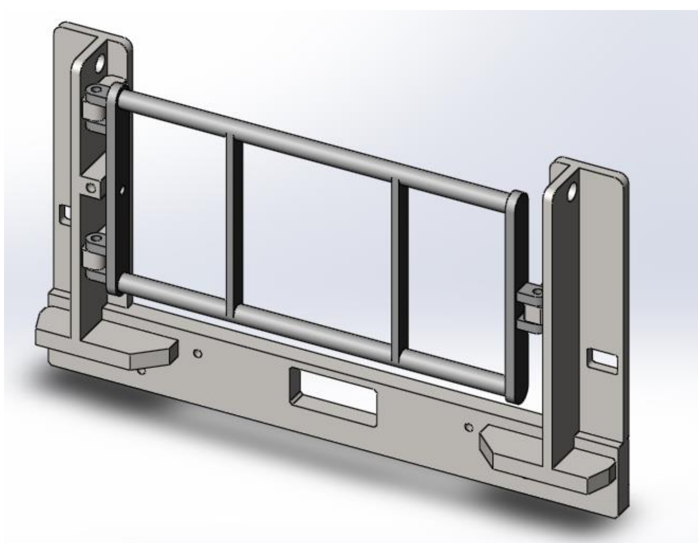

Figure 17: Taller Design with Simple Pin

This design implemented a simple pin hold open that used the same pin used to lock the gate closed to lock the gate open when the loader was under maintenance.

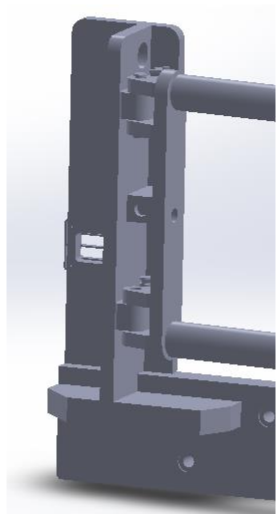

Figure 18: Simple Pin Hold Open Mechanism

6.1.1 Pros and Cons

This design was simple and easy to transition to from the original rear protection system. This would be the most inexpensive redesign option because the only new costs would come from the added material.

This design does not address the lights and harness protection and leaves them just as exposed as the original model. The pin used in the hold open is placed into the added hold open socket. This socket has a cylindrical shape and could be easily impeded by debris in a normal work environment. This could jeopardize the functionality of the hold open leaving room for improvement in this area.

6.2.0 Cylindrical Upright Design

This design used cylindrical uprights to increase the impact strength of the rear protection system as shown below.

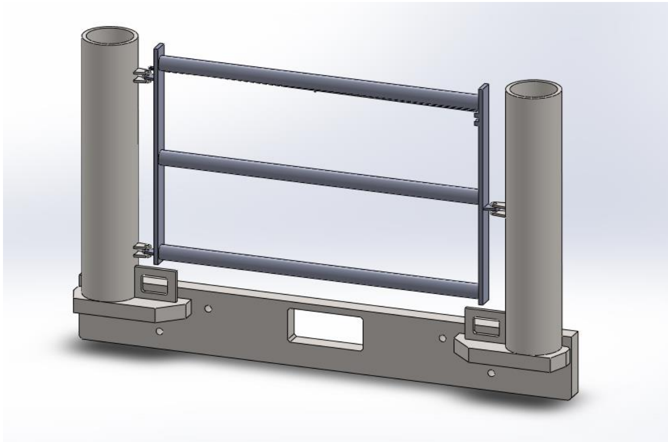

Figure 19: Cylindrical Upright Design

This design implemented a folding arm hold open. The design was secured above the maintenance worker to allow for minimum interference from the hold open during maintenance. The lights are place inside the two uprights which protect them more than in the original design.

6.2.1 Pros and Cons

This design has the highest performance in withstanding rear collisions. The cylinder shape also eliminates much of the welding distance needed in other designs. The cylinders also provide a perfect place to conceal and protect the harness wire.

The hold open however is far too complex and is susceptible to bending and deformation. The hold open also requires many new moving parts and cause vibration and noise issues while the loader is in service.

Finally this design, despite being strong does not aesthetically match the design of the 980H loader. This design would look out of place and awkward on the back end of any heavy machinery.

6.3.0 Bent Uprights

This design went through several iterations before it was considered as primary design option. The first iteration is shown in the finite element analysis tests below.

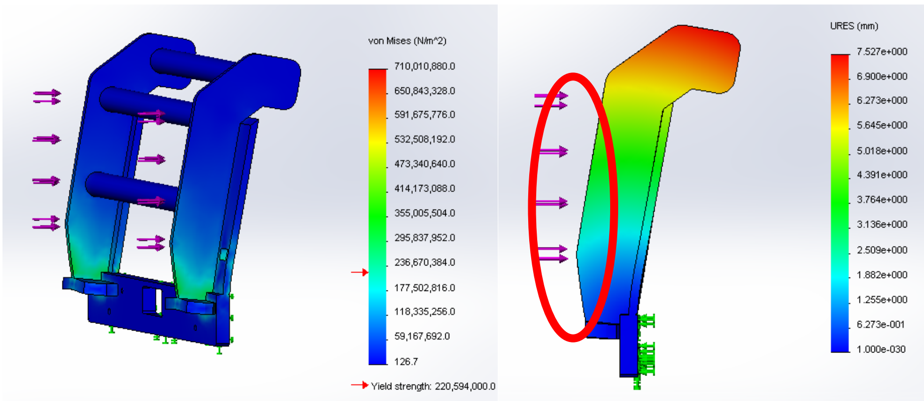

Figure 20: FEM Analysis of the First Iteration of the Bent Upright Design

This design started with having a small bend in the uprights, indicated by the red circle above. When this design underwent finite element analysis we found that this bend, focused the collision force higher on the protection system, which increased the applied moment, and would cause material deformation due to the high forces. This design was then modified to remove this bend and as shown below. Now the applied collision forces would be more distributed towards the bottom of the protection system, where it is secured to the tractor, therefore cause less bending moment. With this alteration the design passed the impact specifications.

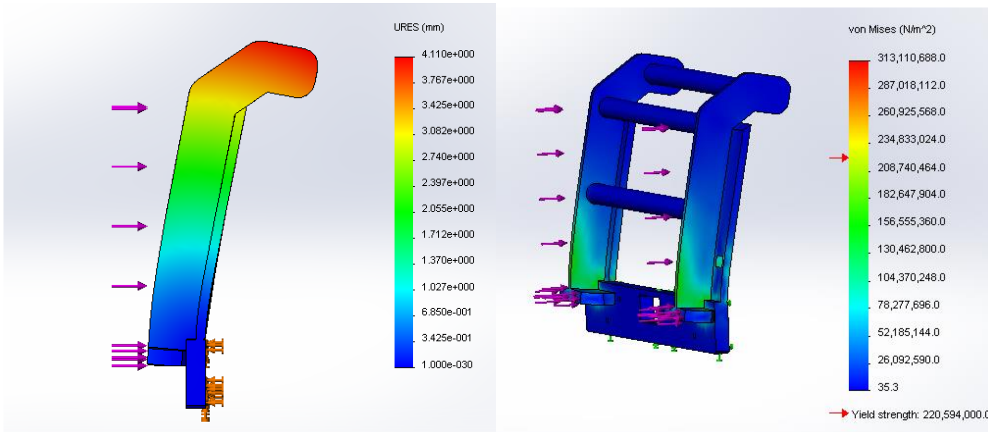

Figure 21: FEM Analysis Second Iteration of Bend Uprights

Once all the impact specifications were met this design could be analyzed in other ways. The final iteration is shown below. The lights are protect in the same way as the original rear protection device.

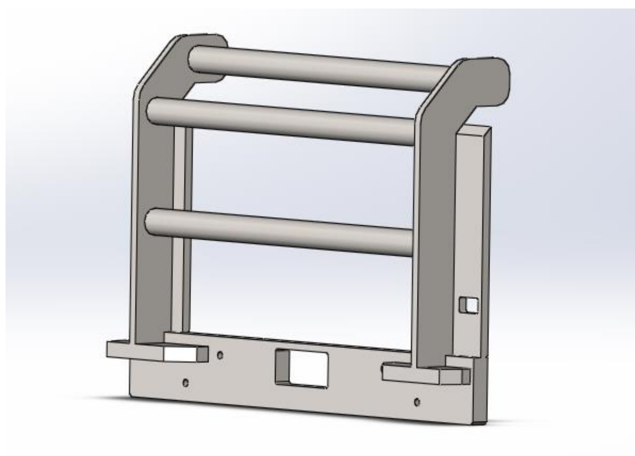

Figure 22: Bent Upright Design

This design had the most complex hold open we attempted to entertain. This pin in the view below would be removed and the cross bars would slide out from the side of the frame of the protection device.

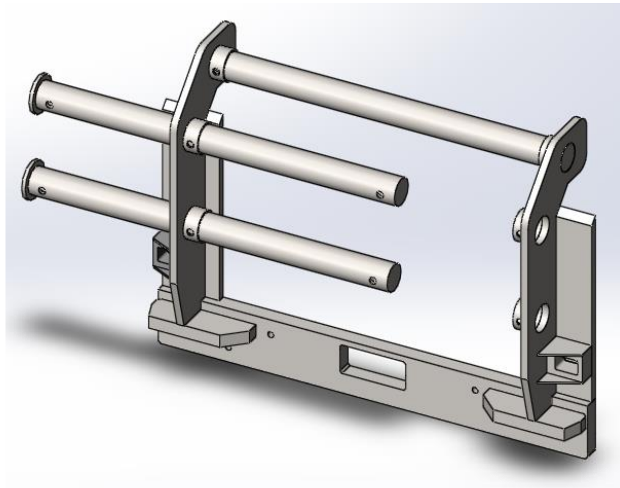

Figure 23: Bend Upright Hold Open Mechanism

6.3.1 Pros and Cons

This design added protection to the sides and the top of the hood of the loader. This added protection also increased the protection of the radiators. This design is most aesthetically pleasing of all the preliminary designs. It matches the design and look of the 980H Loader.

The design of the hold open is the weakest part of this idea. Because of the how the cross bars are removed they become a susceptible to interference from rust or small deformations which is not conducive to the work environment that the 980H loader will be submersed in. There are also many pin that hold the cross bars in place. These could be lost or deformed easily and without the pins the cross bars and therefore the rear protection system would be rendered disabled.

6.4.0 Compilation of Ideas for Final Design

The three main positive points that came from the preliminary designs are the simple pin hold open, the protection benefits from the bend uprights design and the aesthetics of the bent upright design.

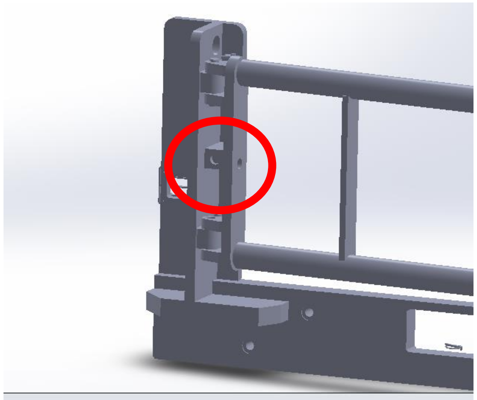

Figure 24: Desired Hold Open Mechanism

The hold open for the final design will follow the same line of thinking as this simple pin hold open shown above. If the same pin can be used to secure the gate both open and closed would be the ideal design idea.

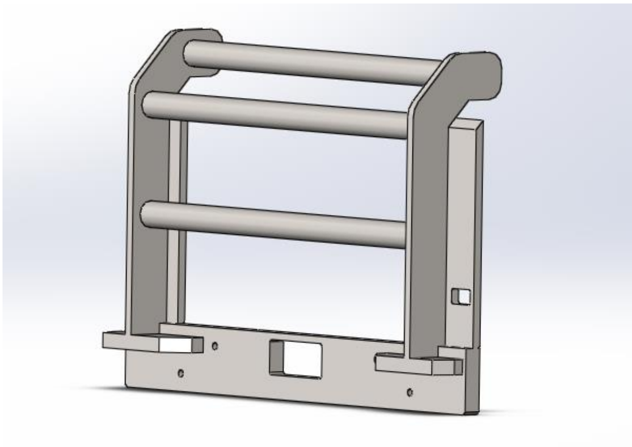

Figure 25: Desired Aesthetics for Final Design

The aesthetics from the design above match the appearance of the 980H Loader. The final design needs to model the looks of this design's uprights.

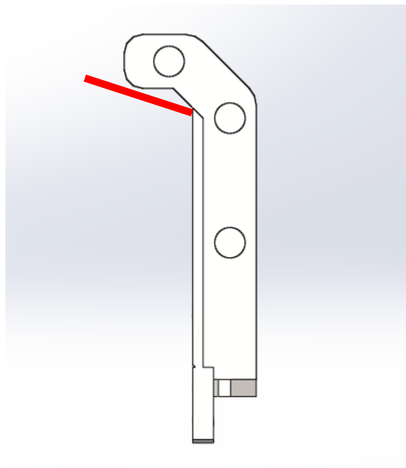

Figure 26: Angle of Bend Upright Frame

One modification to be done to the protection and aesthetics of the bend uprights model is the angle of the bend should match the 980H Loader's hood angle rather than being at 90 degrees. The red line in the above figure represents the slope of the tractors hood.

These aspects were combined into the secondary designs as shown below.

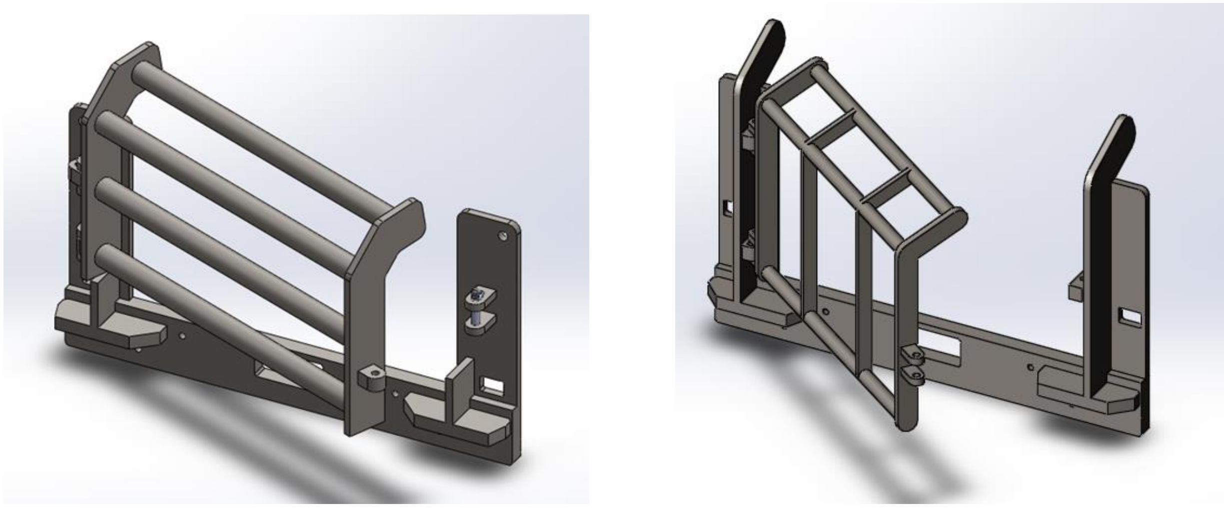

Figure 27: Secondary Designs: Left: Option One, Right: Option 2

Both these design use the same vertical simple pin hold open as shown in figure 30 below. This pin is the same pin used to lock the gate closed when the loader is in service.

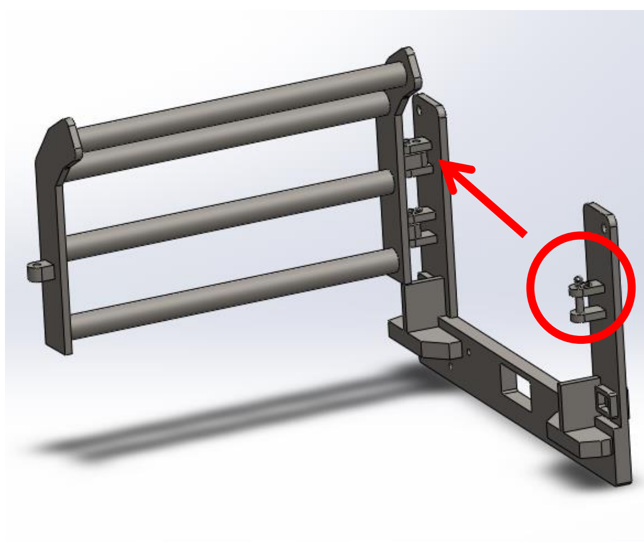

Figure 28: Locking Pin Also Used to Hold Gate Open

The figures below show the gate in its open and closed orientations.

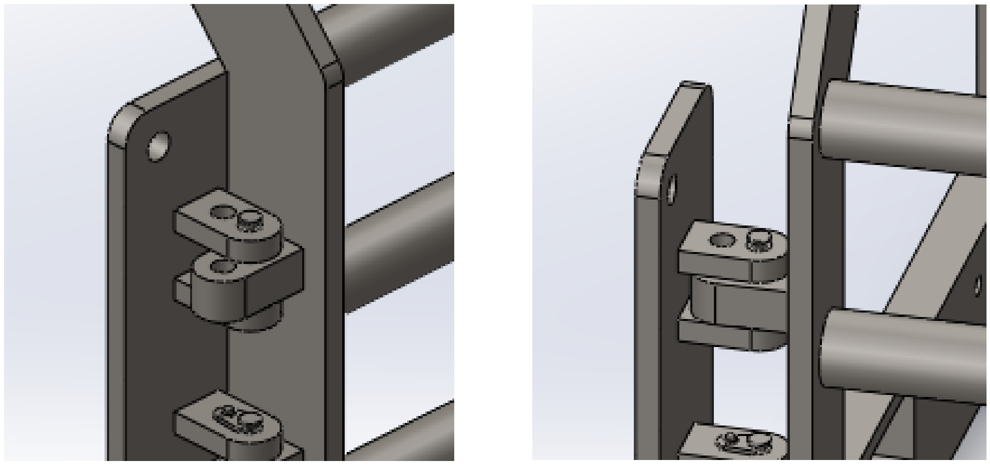

Figure 29: Left: Closed, Right: Open

Both these secondary designs meet all the criteria and specifications. Below we show the pros and cons of each of these designs.

6.4.1 Pros and Cons

The hold open has been altered so is now a vertical pin and socket that will not be impeded by any debris from the surrounding work environments. Both bend angles match the slope of the hood. Option one has significantly less welding then option two. Option one is also more aesthetically pleasing so option one will move on to the next section, analysis and discussion.

7.0.0 Analysis and Discussion

In this section we will analyze our final design by comparing it to the original design. We will also discuss the how the design meet specific requirements. This section will try to encompass the ideas and the reasoning behind the final design.

7.1.0 Harness Protection

The harness protection was needed to make the 980H rear protection system well rounded and give it a finished look without speeding much time, energy and money to secure the lights harness. The harness protection device installed would bolt onto the back of the rear protection frame. The same bolt holes would hold a spacer in the front of the frame to lift the lights away from the frame to be more visible from large angles behind the 980H loader.

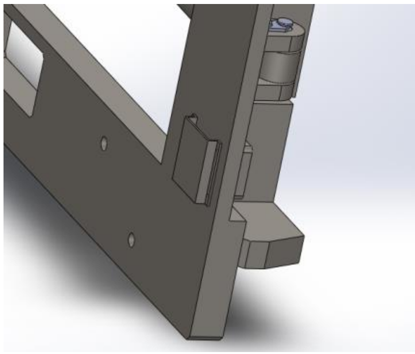

Figure 30: Placement of Harness Protection Device on Frame

Ideally the harness protection plate would cover the wires from the back of the protruding part of the taillight to the gap between the rear protection system and the 980H main frame where the harness connects with the battery box.

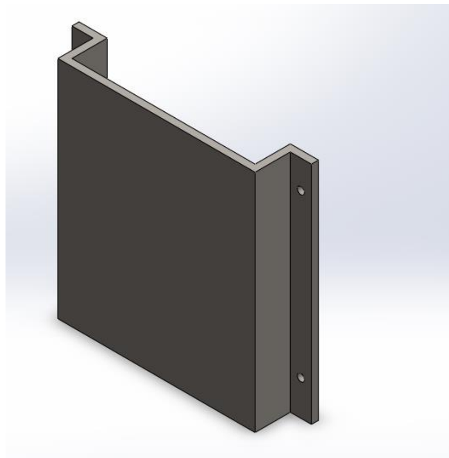

Figure 31: Harness Protection Plate

This is a simple addition that implements in stock bolts and nuts and only requires two new parts, the plate and the spacer. This two parts are simple and could be bought from an outside supplier. This design eliminates need for any extra welding or cutting which makes it a very lost cost solution.

7.2.0 Bolt Analysis

We tested the forces subjected on the four bolts that hold the frame of the rear protection system to the main frame of the 980H loader body. These bolt span the 25 mm gap that is between the two frames as shown in the figure below. This gap allows for the harness wires to reach the battery box.

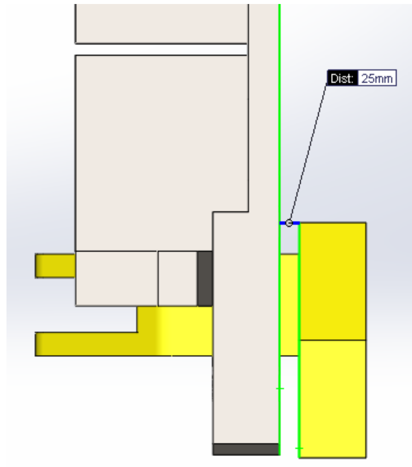

Figure 32: Gap Between Rear Protection System Frame and Main Frame

After putting the bolts into SolidWorks they were tested with a 3426 Newton forces which comes from the weight of the rear protection system dispersed over the 4 bolts. These resultant stresses are shown in the figure below. The yield strength is 620 million Pascals which is much higher than the 45 million Pascal stress that the bolts experience. This shows that the four bolts are more than enough to secure the two frames together.

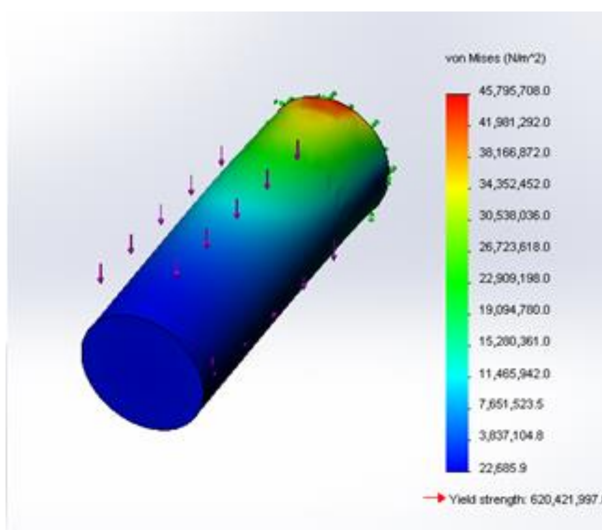

Figure 33: FEM Analysis of Bolts

7.3.0 FEM Analysis

Next came the FEM structural analysis of the frame and cross bar gate of the rear protection system. Both parts where subjected to an impact consisting of the entire weight of the 980H loader. Both parts were only secured by the areas on their frames that would be in contact with other parts (e.i. the bolt taps on the frame and the hinge joints on the cross bar gate).

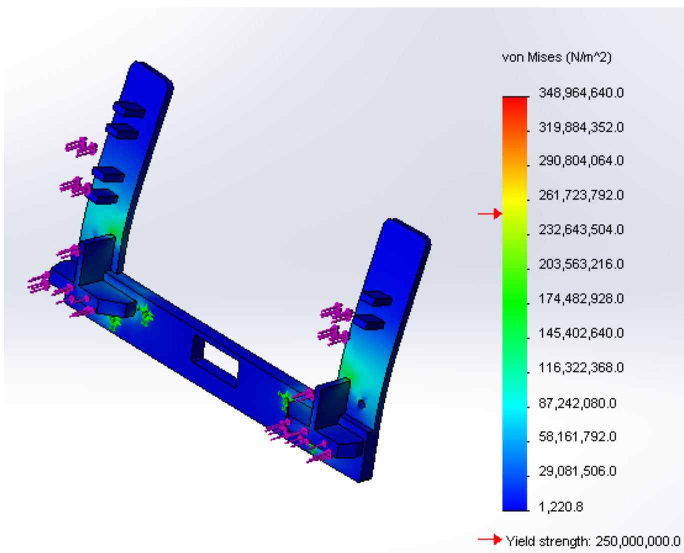

Figure 34: Stresses Experienced on Frame

The frame was tested with a forces of 300,000 Newtons. The yield strength is shown by the small red arrow in the figure above. As you can see the stresses experienced by the frame do not exceed the yield strength of the material and any deformation in a collision of this magnitude would be elastic.

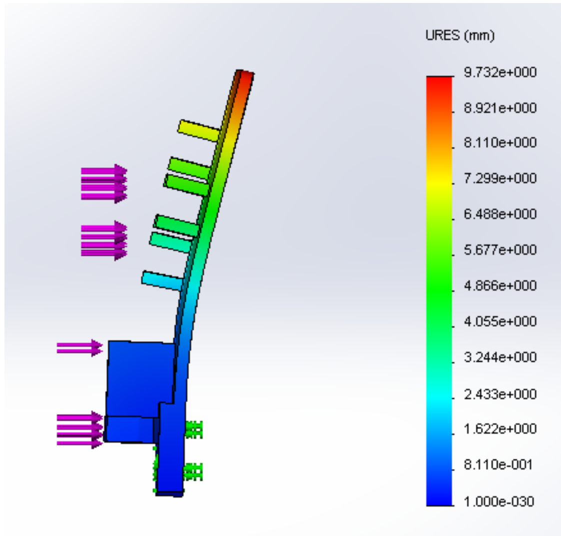

Figure 35: Displacement of Frame

This displacement caused by this collision would be 9.73 millimeters. This would not endanger any of the vital part behind the rear protection system and not damage the frame.

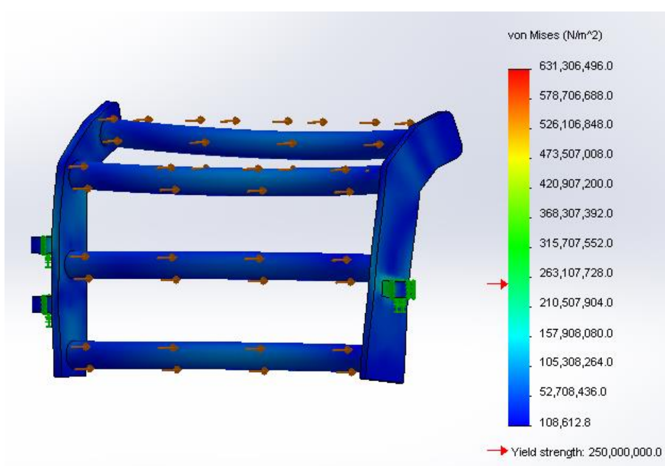

Figure 36: FEM on Cross Bars

We next tested the cross bar design in an impact of 300,000 Newtons. The fixed point on this test were solely the hinges with is vastly underestimating the force that this cross bar model can withstand. In reality the cross bar portion of the system would be pressed up against the frame creating the same T-shaped frame and in the original frame design. This support from the back would render the rear protection system much more strong then either of the FEM testing done on the individual parts.

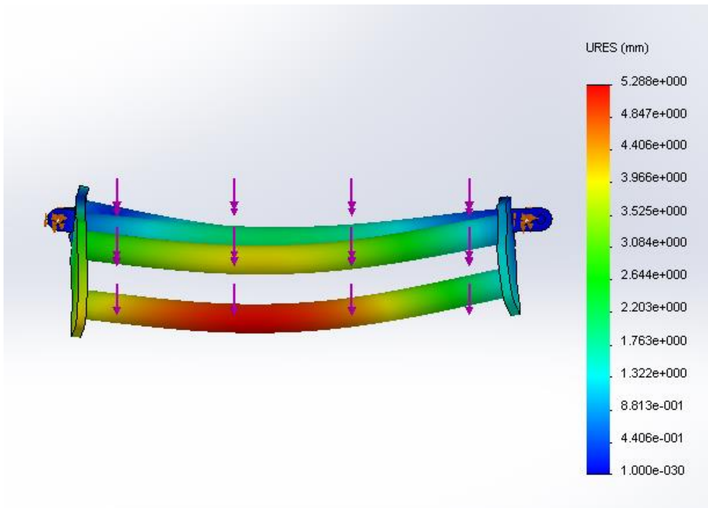

Figure 37: Impact Displacement on Cross Bars

As you can see in the above figure the FEM analysis shows that in this rear impact the cross bars would elastically bend about 5.28 mm. This is a very small deformation and would not be permanent, therefore this is an acceptable amount of deformation.

7.4.0 Manufacturing and Assembly Analysis

In order to plan for the manufacture and assembly process we mapped out nesting diagrams for all the parts in the assembly that need to be manufactured rather than purchased from outside suppliers. All the part that are 40 millimeters are nest on one 40 millimeter thick sheet of metal and the

85 millimeter thick parts are nested on another sheet together. The nesting diagrams are shown below.

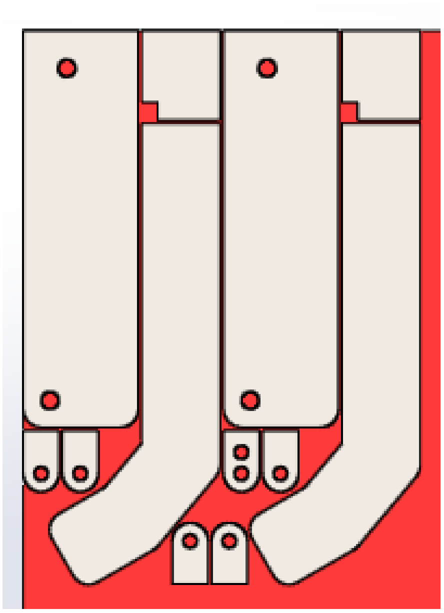

Figure 38: 40 Millimeter Thick Sheet

The parts are nest in such a way to reduce material waste and number of cuts needed to extract the parts from the original sheet.

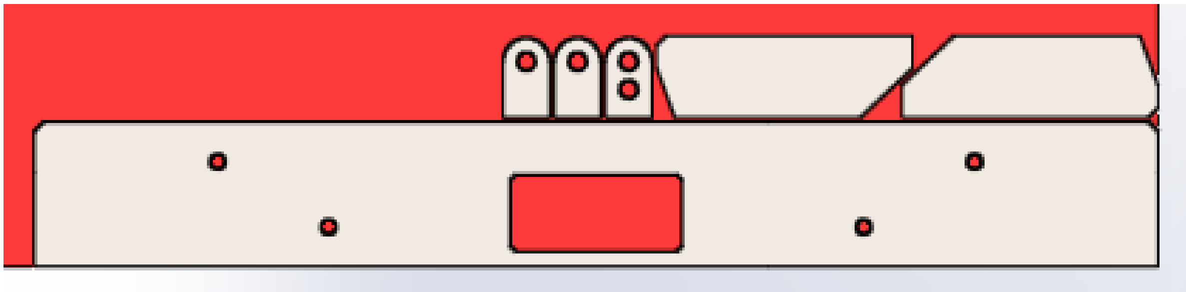

Figure 39: 85 Millimeter Thick Sheet

The next area in assembly that needed to be addressed is the assembly of the rear protection system in relation to the entire 980H loader.

The rear protection system is a very heavy component that needs to be bolted on to the back end of the 980H main frame. This predicament was solved by adding host hole as shown below.

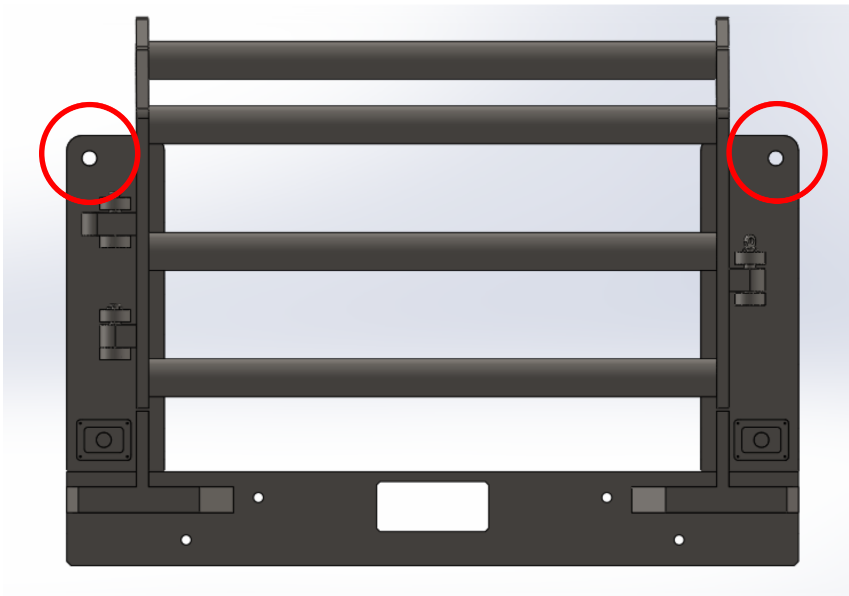

Figure 40: Hoist Holes

The hoist holes allow for the assembly cranes to lift the rear protection device into place during the assembly of the 980H loader.

7.2.0 Welding Analysis

Since we had no information on Caterpillar Inc.'s welding costs and overhead we had to compare the welding costs in a different manner. The following two diagrams show the highlighted seams that need to be welded during assembly.

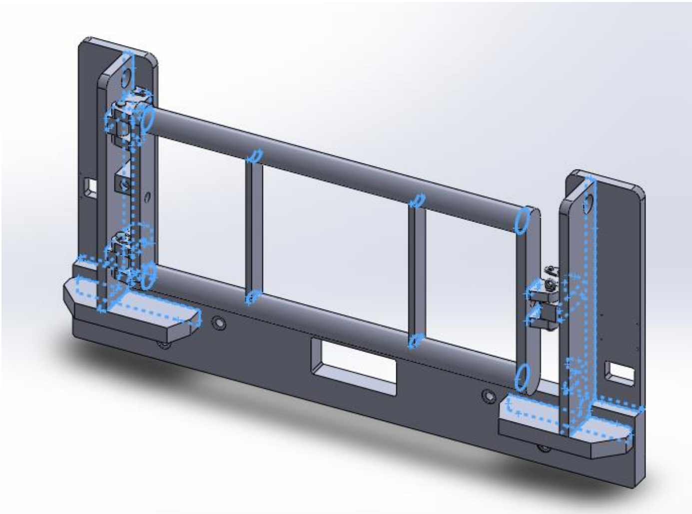

Figure 41: Original Rear Protection Systems Weld Seams

The orginal design had 15.25 meters of welding in ninty different welds. The the T-shape frame is a very long and therefore very expensive weld. The final design eliminated the need for the T-shape weld which reduces the amount of welding needed significantly.

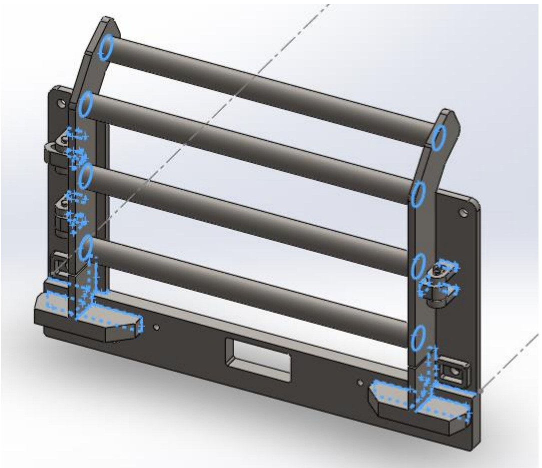

Figure 42: Final Design Rear Protection Systems Weld Seams

The final design has approximately twenty percent less welding solely in distance. The final design had 12.19 meters of welding in 84 welds. This reduces the time, energy and money it takes to produce this design.

8.0.0 Conclusions

Overall this design project has provided Caterpillar Inc. with potential design solutions for a future rear protection device that meets the requirements they provided to us. This will allowed them to develop a rear protection system that is more cohesive and pleasing to future customers looking to better protect their heavy machinery. Our designs could influence the look and functionality of rear protection systems for not only the 980H but for any type of heavy machinery which needs added protection from its work environment. In this way this rear protection system is adding Caterpillar Inc. in meeting their company goals of providing the most durable, best heavy machinery products on the market.

This design project exposed our team to real world designing. This includes understanding and implementing design restraints relating to manufacturing, cost, assembly, and aesthetics. We also gained experience communicating and interacting with professional engineers.

A huge portion of this design project was our international collaboration with our Shanghai University student group members. Intergroup communications was a challenge that we faced on a daily basis. Some students in the six person team had never worked on a group project before and there was a great divide between how students from WPI functioned in a group setting and the Shanghai University students. The angle at which goals and group work was approached from was slightly different which posed some difficulties. These complications were all a learning experience that gained us an insight on how to work with and through language, background and cultural barriers. Our strengths and weakness were heavily played upon in our group dynamic. We were able to help our Shanghai University group partners with their English and presenting skills, where they were able to help us understand how to better communicate and express ourselves to non-native English speakers.

In conclusion, this project had countless benefits for Caterpillar Inc., our Shanghai University partners and was an invaluable keystone in our undergraduate careers.

9.0.0 Recommendations

The design we created covers the all the given parameters provided by Caterpillar Inc. and exceeds the effectiveness of the original rear protection system. The cost analysis we did for this design project was very minimal. This was due to lack of information because of company trade secrets, but we were able to compare our new optimized design to the original design instead. It is our recommendation that with the information we have provided in the report a better cost analysis could be performed to have a better idea of the benefits of using our design.

After the final presentation it was brought to our attention that the hinges on the old design had a design flaw that we were not aware of and therefore did not address in our redesign process. Therefore another recommendation we have would be to continue research and explore new hinge designs that could be integrated with our optimized design.

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