980H Port Package Rear Bumper Redesign

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Executive Summary

Customer satisfaction is at the heart of every successful business and is achieved by creating a product that meets and even exceeds the customer’s needs. Caterpillar Inc. is a global leader in industrial equipment, attachments, and power solutions, and maintains this position because of high levels of customer satisfaction. Through a long history of customer support, Caterpillar Inc. communicates with customers for feedback to innovate products. Caterpillar Inc. offers standard and custom products driven by customer needs.

Caterpillar (Suzhou) Co., Ltd. (CSCL) is a factory in Suzhou, China that produces medium wheel loaders for markets in Asia, Europe, Africa, and South America. The Growth Solutions department of CSCL customizes medium wheel loaders such as the Cat® 980H (980H) for customers with unique needs. One of the areas handled by Growth Solutions is the harbor environment, in which a specific set of 980H modifications is called “port package.”

Working with Growth Solutions engineer Dong Fengming (Dany), a group of mechanical engineering students from Worcester Polytechnic Institute and Shanghai University redesigned the 980H port package rear bumper. The existing design lacked sufficient protection to critical components of the 980H and also needed a rear camera mounting bracket. The group emailed and interviewed the project sponsor to understand the problem from the customer’s point of view and define the product need. Three designs evolved over the course of the project following sponsor feedback and advice, and were proven comparably durable to CSCL’s most recent design using computer simulations under the same conditions. Ultimately, the team chose the Double Door design because it ameliorated an alignment issue as well as workplace safety. Furthermore, a manufacturing cost estimate deemed the Double Door design profitable.

Abstract

Completed in Shanghai, China and sponsored by Caterpillar (Suzhou) Co., Ltd., a team of mechanical engineering students from Shanghai University and Worcester Polytechnic Institute redesigned the rear bumper of a Cat® 980H medium wheel loader (980H). Communication with the project sponsor clarified the product need and provided feedback for an iterative design process incorporating dynamic and static computer simulations. Of three designs created, the team chose one with additional functionality, greater user safety, comparable durability, and significant profitability. For future designs, the team recommends material substitution, center of gravity consideration, and finite element analysis preparation.

Acknowledgments

We are grateful that Caterpillar Inc. offers opportunities to students that challenge their capability to solve real-world problems. The project was an enriching experience that tested theory in practice. The group would like to acknowledge the experienced individuals whose guidance and assistance greatly improved the quality of the project outcome. Dong Fengming (Dany) from Growth Solutions at Caterpillar (Suzhou) Co., Ltd. for clarifying the project and providing feedback that helped create better designs. Professor Rong Yiming (Kevin) and Professor Zhang Jinsong for their continuous feedback and advice which led to the exploration of new design considerations and ideas. Graduate student “Quint” for guiding us through the process of creating reliable computer simulations. And, most importantly, our project partners Lin Huan, Cao Shuang (Lea), and Jiang Hongrui (Vivian), for their diligent work ethic, creative design collaboration, help with creating computer simulations, outstanding communication skills, and tour of several cultural hotspots in Shanghai, China.

Authorship

The information contained within this report is a collection of research, communication with the project sponsor, advice from the project advisors, and creativity within the group. Cesar Pelli wrote the executive summary, abstract, acknowledgements, authorship, introduction, background, methodology, design, finite element analysis, manufacturing cost analysis, future recommendations, and conclusion, and compiled and edited the report. Luis Vargas outlined the design section with information and images, and contributed to the future recommendations and conclusion. Lin Huan, Cao Shuang (Lea), and Jiang Hongrui (Vivian) collaborated in the rear bumper design process, created designs and drawings for the rear signal light protection systems, and contributed to the discussion of conclusion and recommendations.

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1.0 Introduction

Customer satisfaction is the lifeblood of every business. Manufacturing a quality product that meets all customer needs is necessary to maintain business relations. It has been said that quality is free, but lack of quality generates cost. In the demanding industry of construction, shaping the natural topography of terrain requires quality heavy duty equipment and customers need a reliable manufacturer. Caterpillar Inc., the world's leading manufacturer of construction and mining equipment (and much more), provides this service through outstanding customer support and production of standard and customized heavy duty equipment.

The Caterpillar (Suzhou) Co., Ltd. (CSCL) produces medium wheel loaders such as the Cat® 980H (980H). The project sponsor is a division of CSCL known as Growth Solutions, which tailors medium wheel loaders for customers with unique needs. The 980H "port package" is for harbor customers and transforms the 980H into the Cat® 980H2 (980H2) by including a window guard, additional standing plates, a modified steel roof, and a rear bumper. Compared to the 980H, annual production volume of the 980H2 is low, and significant consideration is given to provide a reliable product and justify the cost of production.

This report explains the 980H port package rear bumper redesign to address existing issues. The group communicated with the project sponsor to clarify the product need and project requirements, designed using an iterative process, and compared the durability of the new designs to the existing one using static and dynamic simulations. The chosen design modifies the rear bumper door and improves rear signal light protection by dampening the impact force of collision. It proved comparably durable during computer simulations and profitable using a manufacturing cost analysis. This report includes background information, a methodology, findings, future recommendations, and a conclusion.

2.0 Background

The background provides information about product design, Caterpillar Inc., the Cat® 980H (980H), the project description, materials, and finite element analysis. Understanding these topics provides insight towards the impact of the project, as well as the group's design process and analysis. A section about product design explains the interdependence of design, material selection, and manufacturing processes. The section about Caterpillar Inc. describes company values that influenced the design process. Certain aspects of the 980H provide reason for the redesign. A summary of the communication with the project sponsor provides the project description and redesign requirements. Material information and selection criteria are described to provide the rationale for material selection and future recommendations. Lastly, a finite element analysis section explains the reason computer simulations were chosen for analysis.

2.1 Product Design

In a globally competitive market, a company's first priority is manufacturing a high-quality product at the lowest possible cost, which requires understanding many complex intertwining factors such as product design, material selection, and manufacturing processes. When considering the cost of overhead such as equipment and real estate, design may only cost a small amount of the production process. Design however, may determine as much as 80% of the cost of production (Kalpakjian & Schmid, 2014). Thus, designers must consider the available materials and manufacturing processes to create a world class product. "World class" indicates high levels of quality for producers and consumers by international standards, but its definition continuously evolves due to innovation (Kalpakjian & Schmid, 2014). The increasing variety of improved materials and processing make design of a world class product challenging; a world class product depends on the design, material, and production process.

Selecting the appropriate material depends on functional requirements of a product and the economics of production. A designer considers a material’s mechanical, physical, chemical properties as well as its manufacturability. Manufacturing process selection depends on production economics such as volume, variety, and overhead. In addition, moving particular responsibilities to an outside firm, a business tactic referred to as outsourcing, may be beneficial because it allows a manufacturer to focus its resources. Product design is a balance between meeting customer needs and selecting appropriate and economically-sound materials and manufacturing processes.

2.2 Caterpillar, Inc.

Caterpillar Inc. is the world’s leading manufacturer of construction and mining equipment, natural and diesel-gas engines, turbine generators, and diesel-electric locomotives (Caterpillar, About Caterpillar, 2013). The company is a global leader in industrial equipment, attachments, and power solutions and generated almost $56 billion in sales and revenue in 2013 (Caterpillar, Corporate Overview Presentation, 2014), currently standing at #42 in the Fortune 500 (Fortune, 2014). Caterpillar Inc. employs nearly 115,000 full-time workers and emphasizes a culture of integrity, excellence, teamwork, and commitment (Caterpillar, Corporate Fact Sheet, 2014). Caterpillar Inc. uses customer feedback and focuses on making progress through productive and sustainable means (Caterpillar, About Caterpillar, 2013).

Figure 1: Caterpillar Inc. industrial products

Sustainability means carefully using resources to meet current needs so that future generations can do the same. In the words of Caterpillar Inc., this means “leveraging technology and innovation to increase efficiency and productivity with less impact on the environment” (Caterpillar, Company Sustainability, 2013). One method of sustainability that Caterpillar Inc. excels at is remanufacturing, which achieves reduction of cost and environmental impact. Products are designed with core components that last multiple life-cycles to be rebuilt to the latest specifications in the event of replacement or repair. In this manner, raw materials are reduced, reused, recycled, and reclaimed (Caterpillar, Remanufacturing, 2013). Cat Reman reduces the need for resources and offers products at a fraction of the cost of a new one. For these reasons, the project redesign maintains similarity to the existing design and the selected material is recyclable.

2.3 Cat® 980H Medium Wheel Loader

A wheel loader is a large vehicle that lifts heavy loads and moves them to a different location. Wheel loaders have arms and a variety attachments that can tilt to release the load, and are not to be confused with bulldozers, which have tracks instead of wheels. There are three varieties of wheel loaders: compact, medium, and backhoe, which are for small environments, large carrying capacity, or lowering the attachment below the wheelbase, respectively (eHow, 2014).

The 980H is a medium wheel loader that features a world class cab for operator efficiency, performance series buckets for better material retention, and electro-hydraulics for low-effort fingertip controls. The 980H is designed to optimize control of the vehicle and increase productivity (Caterpillar, Wheel Loaders 980H, 2014). It runs on a Cat® C15 ACERT with an engine idle management system for selecting environment-specific idle speed. It also has a Cat® planetary power shift transmission that features autoshift for choosing between manual or automatic shift modes. Command Control Steering (CCS) allows the operator to complete one turn of the loader with ±70º rotation, compared to the two or three time 360º rotation with conventional steering. However, though CCS is intended to reduce operator fatigue, the turning sensitivity may increase the risk of collision in narrow workspaces.

Protecting the engine is a steel hood that tilts open for maintenance and has side service doors for quality checks of engine oil and coolant levels (Figure 2). The engine cooling system (ECS) has nine cooling fins per inch and a perforated grill to prevent most airborne debris. When the ECS requires maintenance or cleaning, the perforated grill opens like a door (Figure 3). The 980H comes with a counterweight that is fixed by four bolts below the engine cooling system, with rear signal lights nested on the sides (Figure 4). The counterweight is made of Q235 carbon steel, which is explained in sections 2.5 and 2.7. Though the hood and grill protect the engine, they are susceptible to damage because the counterweight does not cover them.

Figure 2: Tilted engine hood and side access doors

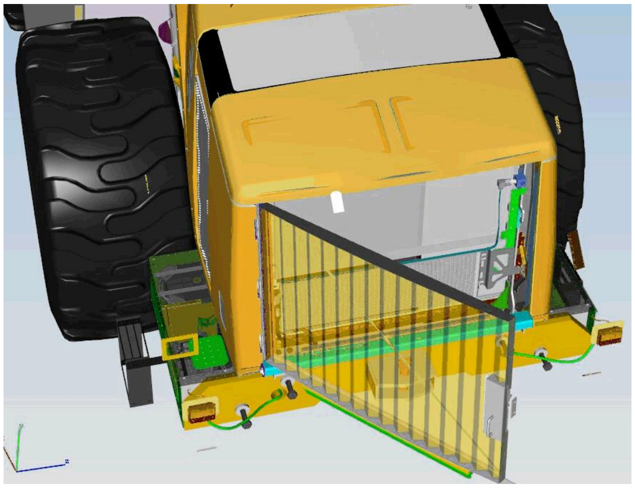


Figure 3: Perforated engine grill

Figure 4: 980H counterweight and rear signal lights

2.4 Project Description and Requirements

Founded in the United States in 1925, Caterpillar Inc. can now be found in over 180 countries addressing global issues in energy, trade, and infrastructure (Caterpillar, Corporate Overview Presentation, 2014). Of over two dozen facilities in China, the project sponsor facility is located in Suzhou, China. The Caterpillar (Suzhou) Co., Ltd. (CSCL) facility produces medium wheel loaders and motor graders for markets in Asia, Europe, Africa, and South America. The contact at CSCL, Dong Fengming (Dany), works as an engineer for Growth

Solutions, a department that provides customer support for four areas with unique demands: steel mills, block handling, industrial applications, and harbor management (Figure 5).

Figure 5: Steel mill, block handling, woodland, and harbor management

The project applies to harbor management hence the "port package" title. Harbor management includes loader movement within vessels, and around docks and terrain. The 980H port package includes a steel hood and window guard to protect the cabin from falling debris, additional standing platforms for clearing debris, and a rear bumper for additional protection of the hood and grill (Fengming, 2014). The port package will be added to the future model of the 980H, the 980H2, for which production volume is very low. In particular, the rear bumper is necessary because the size of the 980H with narrow vessel workspaces results in a high number of collisions, especially in reverse where the hood and grill suffer damage. To reduce the likelihood of rear-end collisions, the customer requested an optional rear camera. In addition, the low-level placement of the rear signal lights results in frequent breakage and relocation to a higher position resolves the issue.

The given information collectively forms the project problem statement, "the current rear bumper lacks sufficient hood, grill, and rear signal light protection, and also a rear camera mounting bracket." The redesign requirements include a weight of 1,330 kg with a closely similar center of gravity, protection of the hood, grill, and rear signal lights while simultaneously allowing the hood and grill to open freely, and lastly, addition of a rear camera mounting bracket. The class of allowable materials is carbon steel, which is recyclable and also has a variety of grades with different properties such as density, strength, resistance to wear, and machinability. CSCL will not change materials or processing without justification because required documentation and customer approval adversely affect production time (Fengming, 2014). The main aspect of this project is the rear bumper redesign, but material selection is equally important due to the weight caused by density, the resulting effects of computer simulations, and also cost and availability.

2.5 Steel

Steel is an alloy with metallurgical properties that allow continuous recycling without degradation. It is the most recycled material on the planet at a rate of 88% in 2012 (AISI, Steel is the World's Most Recycled Material, 2014). Approximately 40% of steel is manufacturing using a basic oxygen furnace (BOF), while the remaining 60% using electric arc furnace (EAF) (AISI, How Steel is Made, 2014). The difference between BOFs and EAFs, is that BOFs are limited to an average of 30% recycled steel, while EAFs can use 100% recycled steel. After primary manufacture, steel is processed to impart different properties including strength, hardness, and ductility (SCI, BCSA, & TATA, 2014). Composition, structure, processing history, and heat treatment affect the properties and behavior of materials (Kalpakjian & Schmid, 2014). The iron-carbide phase diagram (Figure 6) provides a guide for the results of future processing methods such as annealing, normalizing, and quenching and tempering. Each processing method shapes the material microstructure in different ways, which affects the material’s properties and behavior. Without going into detail, the diagram describes phases of steel that depend on carbon content and temperature. A phase is a physically distinct and homogeneous portion of a material with its own characteristics and properties (Kalpakjian & Schmid, 2014). Each phase has distinct properties and steel can be processed to achieve those desired.

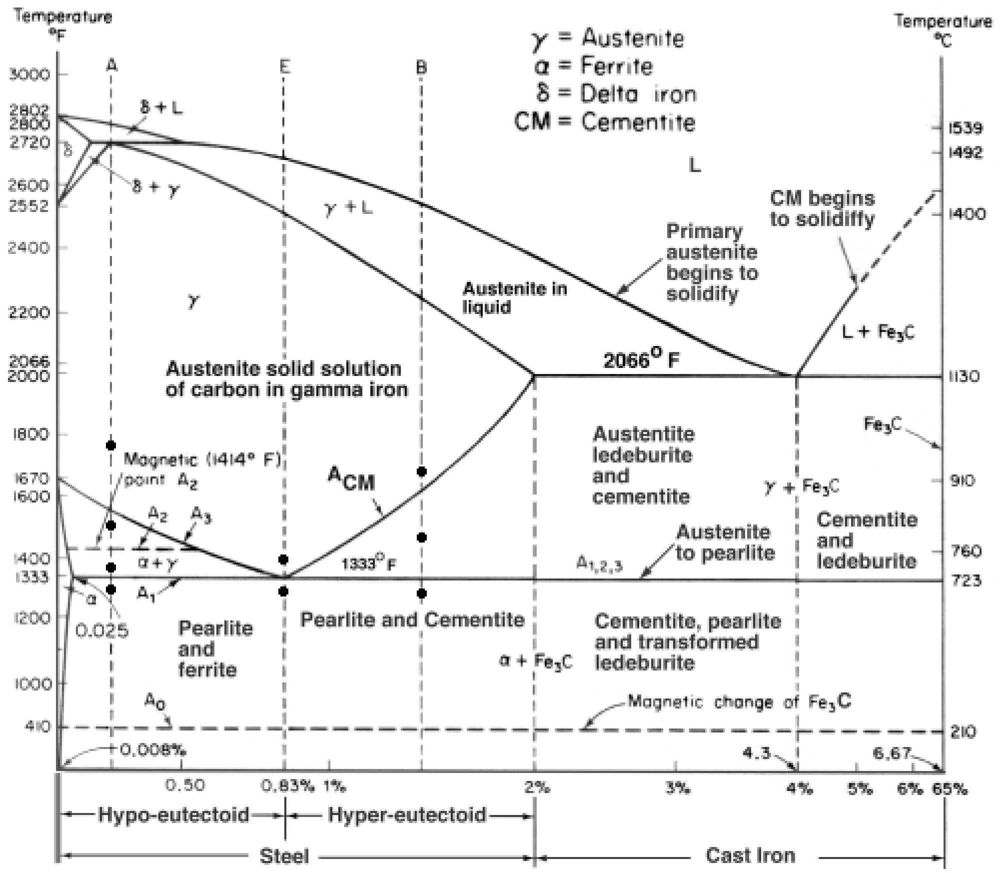


Figure 6: Iron-carbide phase diagram

At the top of the diagram where temperature is highest, the alloy is in liquid phase. As temperature is reduced and molten steel solidifies, separate crystals nucleate in random locations and combine to form a crystalline structure known as a grain. The number and size of the grains depend on the time the metal is allowed to cool; the longer the time, the larger the grains and the fewer there will be. As grains grow, they impede one another and form grain boundaries. Phases such as austenite, pearlite, and ferrite are characterized by grain orientation. A fine grained material is typically stronger because more grain boundaries have dislocations that entangle during plastic deformation (Kalpakjian & Schmid, 2014).

Cold working is a processing method that plastically deforms material. Through material compression, cold working entangles grain boundary dislocations, thereby increasing strength and hardness, but reducing ductility and toughness. A cold worked material can be heat treated using methods such as annealing, normalizing, or quenching and tempering, to refine grain size and restore ductility. Annealing reheats the metal to eliminate residual stresses caused by plastic deformation thereby increasing ductility and grain size, which reduces strength and hardness. Normalizing reheats the steel to a particular temperature and maintains it at that temperature for a while before cooling to refine the microstructural grain size and recover ductility and toughness. In the quenching and tempering process, the metal is cooled from a high temperature rapidly to prevent grain growth and make the alloy stronger, and then reheated below the normalizing temperature to restore ductility. This process is commonly used because mechanical properties can be carefully controlled using time and temperature and the resulting material is typically tougher, which allows it to withstand greater deformation before failing. The widely adopted Unified Numbering System (UNS) designates normalized materials with N and quenched and tempered materials with Q (SCI, BCSA, & TATA, 2014).

2.6 Quantifying Mechanical Properties

The most common method for measuring a material's strength, ductility, and toughness is the tension test. A standard tensile test-specimen is prepared and pulled apart using an increasing load to measure the elongation. The values of engineering stress (the force divided by cross-sectional area), and engineering strain (the instantaneous length divided by the initial length), are plotted on the stress-strain curve to determine three points: plastic deformation, maximum engineering stress, and material fracture (Figure 7). The linear portion of the stress strain curve indicates linear-elastic material behavior and ends at the yield strength. In the elastic region, a load causes atomic bonds to stretch, but removing the load returns the bonds to their initial position. After exceeding the yield strength, the material undergoes plastic deformation up to the ultimate strength. In the plastic region, a load causes atomic bonds to break and grains slip against one another. Removing the load allows the material to recover to some extent but it remains stretched. At the ultimate strength, the engineering stress reaches a maximum and the material will begin to form voids within and eventually fracture. Strength is associated with the yield strength, ductility with the percent elongation that occurs prior to fracture, and toughness with the area underneath the entire curve. Alloys of steel have various levels of strength, ductility, and toughness, as a product of the microstructure and alloyed constituents.

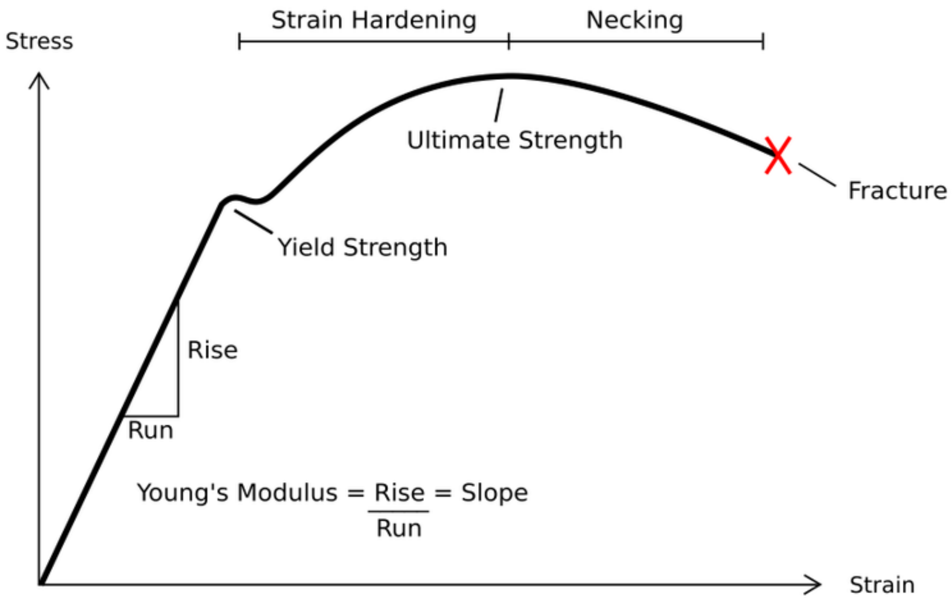


Figure 7: Stress-strain diagram

2.7 Carbon Steel

Carbon steels are classified by their proportional weight of carbon content. Carbon increases the strength, hardness, and wear resistance of steel, but in large amounts, reduces weldability, ductility, and toughness. Low-carbon steel, otherwise known as mild steel, has less than 0.30% carbon and is used for common industrial products (Kalpakjian & Schmid, 2014). Medium-carbon steel has between 0.30% and 0.60% carbon content and is used in machinery.

High-carbon steel contains more than 0.60% carbon and is used for applications requiring high strength and resistance to wear such as cutting tools.

The American Society for Testing and Materials (ASTM) and American Iron and Steel Institute (AISI) designate grades of carbon steels using the digits 10XX, 11XX, and 12XX, where XX is the carbon content in hundredths of a percent. Simple carbon steels are denoted by 10XX, resulfurized carbon steels are 11XX, and rephosphorized and resulfurized carbon steels are 12XX. 11XX and 12XX carbon steels have sulfur or both phosphorous and sulfur added to improve machinability. Q235 is a low-carbon steel with a carbon content of 0.15 to 0.20% that has been heat treated through quenching and tempering (Steel-grades, 2011). The name comes from the UNS nomenclature, but the ASTM name is A36. The internet provides conflicting information regarding material properties for both Q235 and A36, therefore the material chosen for the designs and computer simulations is AISI 1020, which has a carbon content of 0.20%.

2.8 Material Substitutes

Although carbon steels are selected for their increased strength, hardness, and resistance to wear, alternative materials include stainless steel and advanced high strength steel. Stainless steel is characterized by corrosion resistance, high strength, and ductility, and is desirable in this project because the presence of air borne salinity may pose the threat of stress corrosion cracking. Traditionally, materials such as carbon steel can be protected through coatings or surface treatment, but stainless steel does not require this process. The resistance to corrosion in stainless steel is caused by behavior called passivation, where chromium present within the alloy reacts with oxygen in the air and develops a protective chromium-oxide film. The naturally protective layer inhibits the corrosive deterioration of stainless steel and benefits manufacturers by eliminating the need of adding protective coatings or surface-treatment following production.

Another potential material substitute or design additive is advanced high-strength steel (AHSS), a relatively new class of steel used in the crashworthy design of automobiles. AHSS is stronger and lighter than other forms of steel, thus benefitting protection and fuel-efficiency (AISI, Automotive, 2014). At this time however, AHSS often requires manufacturing expertise that is not yet standard and if repair is necessary, specialists are required to verify the integrity of the repaired AHSS structure (Tamarelli, 2011). Without a doubt, material substitution could yield numerous benefits, but is not a requirement of this project. This project requires selection of an appropriate carbon steel to fulfill the weight requirement and provide material data for computer simulations.

2.9 Finite Element Analysis

Even if a product fulfills all of its functional requirements, it must also withstand customer use to a reasonable extent. Unfortunately, designs can be complex and continuously evolving, therefore real world testing is costly and can fail to produce comprehensive results. However, finite element analysis (FEA) is a cost effective method of estimating a product's behavior. The finite element method approximates the physical behavior of a system by representing the system as a large number of simple interrelated building blocks called elements (SAS IP, Inc., 2013). The elements are comprised of a system of points called nodes connected by a mesh (Widas, 1997). The mesh applies material and structural data, and connects the reaction caused by forces between nodes. Using a valid finite element model, a design can be stressed and analyzed. FEA is used prior to manufacturing to verify the performance of a design and refine the design accordingly (Widas, 1997).

FEA requires high-performance computers and companies such as the National Crash Analysis Center (NCAC) utilize low-cost parallel computing solutions to reduce simulation time

(NCAC, Simulation and Advanced Computing Research, 2014). In terms of a vehicle collision, the standard procedure for creating a finite element vehicle model requires reverse-engineering the actual vehicle. This is because designs are proprietary and companies are not required to provide the schematics. According to the NCAC (NCAC, Vehicle Modeling Laboratory, 2014), the procedure includes:

1. Applying tape over an entire vehicle to get an accurate representation of the geometries
2. Digitizing every component using a seven-degree-of-freedom coordinate measuring machine
3. Disassembling all vehicle components
4. Collecting mass and material thickness data for vehicle and individual parts,
5. Identifying all parts and connections
6. conducting center-of-gravity calculations
7. Executing material property tests for component strength
8. Creating a computerized “mesh” grid of the vehicle using advanced computer codes
9. Reconnecting all parts accurately, including spot welds, rigid body constraints, joints, springs and dampers

It should be noted however, that larger models have more elements, which increases simulation time. The time constraint of the project and lack of computer resources prevented the group from reverse engineering the 980H or creating a representative body to add to the bumper during simulation. Therefore, finite element computer simulations using the same conditions provided comparative data between the group’s designs and the existing one.

3.0 Methodology

The goal of this project was to improve protection of the 980H hood, grill, and rear signal lights, and add a rear camera mounting bracket. To achieve the goal, the group pursued the following objectives.

1. Learn the project sponsor’s strategy and the impact of the project.
2. Define the product need.
3. Realize three designs using an iterative design process.
4. Analyze and compare all designs using specifications and computer simulations.

3.1 Understanding the Sponsor’s Goals and Project Impact

Caterpillar Inc. is well-known for quality industrial products. A review of the company ideology helped understand the impact of the project and design by the same standards. Caterpillar Inc.’s website expresses a strong emphasis on productivity and sustainability. Improving the protection of the hood, grill, and rear signal lights, would maintain a productive work day by reducing the likelihood of breaking those components. Moreover, an improved bumper that reduces the need for repairs prevents unwanted resource consumption. Maintaining a design similar to the original also offered the benefit of maintaining product core that can be remanufactured, further reducing the need for raw materials.

3.2 Defining the Product Need

The group exchanged emails with the sponsor and conducted a face-to-face interview at the Caterpillar (Suzhou) Co., Ltd. (CSCL) facility to gain as much information as possible and focus its efforts. The initial project information described redesigning a 980H port package rear bumper to act as a counterweight, protect the hood, grill, and rear signal lights while allowing the hood and grill to open freely, and have a rear camera bracket. The term port package was undefined, and the required weight, opening of hood and grill, allowable materials, camera dimensions, and environmental operating conditions were not specified. Communication was critical to the success of the project.

Emails provided the information excluded from the initial description, and within the second week, the group received a model of the existing design for the bumper, which allowed for dimensional adjustments and minor design revisions. To discuss more specific details and share progress, the group scheduled a future interview and provided a progress report with images of the most recent designs and simulation results, as well as questions regarding the existing design and production process. During the interview, the sponsor shared customer feedback regarding the existing design and feedback for the group’s designs, as well as answers to the prepared questions. The group’s Chinese members facilitated communication during the interview by translating for the English speaking members. The interview brought clarity and future potential for design.

3.3 Iterative Design Process

The group used the initial project description, requirements, and photos to begin the design process. Ideas were brainstormed using inspiration from prior knowledge of truck designs as well as existing bumper design methodologies found on the internet. In addition, background in design and manufacturing provided prior knowledge including the strength of certain geometries or their manufacturability. In the first few weeks, the project description and requirements were clarified. Concepts were realized using CAD software and simulated throughout development to test their durability. The project sponsor gave feedback for the second iterations and discussed which areas needed more attention. A week after the interview, the project sponsor changed employment and could no longer provide feedback, but the group had enough information to finalize the designs.

3.4 Design Analysis, Computer Simulations, and Comparison

The design process and specification analysis are described in section 4.0, and the computer simulations used to prove each design's durability is described in section 5.0. Designs were compared by the size of the rear bumper with door(s) closed and open, weight, number of parts, and results of static and dynamic simulations. The size of each design varied when doors were closed due to the design of the hinges, and varied when doors were open due to the length of the doors, the design of hinges. The weight was a strict requirement and each design came as close as possible to 1,330 kg. The number of parts were used to compare the designs in terms of potential manufacturing time. Both static and dynamic computer simulations were performed under the same conditions to provide comparison between designs. A comprehensive computer simulation was not feasible because calculating the effects of a body as large as the 980H would have taken days to run. Furthermore, the design geometries had flaws that caused errors during simulation. In the event of an undetected flaw, computer simulations would experience general failures after hours of running. To minimize the chance of flaws, each design was simplified using the same procedure, described in section 5.0. The simulations were performed at a velocity of 11.5 m/s because this is the maximum speed of the 980H in reverse. The group wanted to test the designs in the most extreme condition that the operator could control.

4.0 Design

Design requirements and specifications were clarified in the first three weeks. The group received an initial description with pictures, asked questions to clarify design specifications, and conducted an interview for additional details. Beginning the project, the design requirements were general and included the following:

- Protection for the hood, grill and signal lights
- Free opening of the hood and grill
- Counterweight for the 980H
- Addition of a rear camera mounting bracket

Images were also included with the description to demonstrate the difference between the 980H counterweight and 980H port package rear bumper. The images provided a rough idea of the hood and grill and current state of protection, but did not explain how the hood and grill open; it was assumed that they open outward. Moreover, the rear camera dimensions and weight of the counterweight were not specified or available on the internet. The design process began through observation, and details were clarified through communication with the sponsor. The picture of the existing rear bumper shows that the bumper is made of two main components: the frame and the door (Figure 8).

The main frame is made of a base plate, two corner trapezoids, and two side posts each made of two perpendicular plates in the x and z axes with rectangular holes for the rear signal lights. The door is made of two horizontal tubes and four plates, and is the first defense for the hood and grill in case of a rear-end collision. It uses a simple hinge and pin design to lock and attach to the main frame, and does not show a camera bracket but indicates the desired location is at the top of the door.

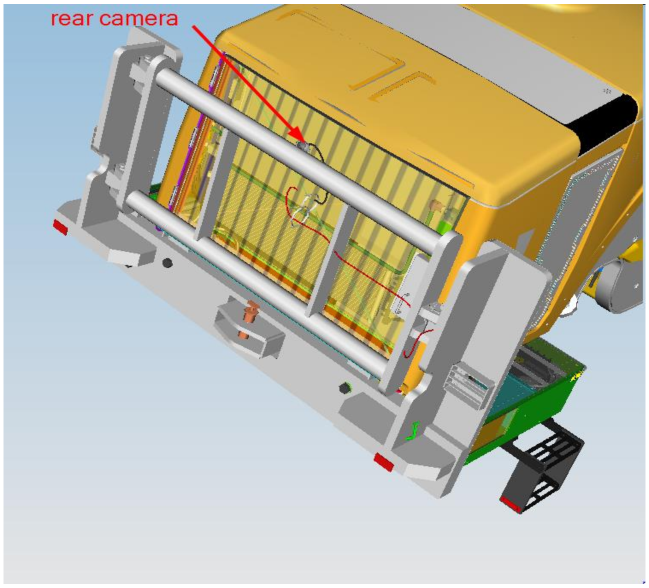


Figure 8: Provided image of initial rear bumper

4.1 Preliminary Designs

The preliminary designs were made using the information given at the beginning of the project. The first preliminary design was based off of the initial rear bumper image but changed the main frame and the door. The design, called Hanging Door design, uses a hanging door (Figure 9) and preserves the use of a hinge and pin design to lock, located at the top and sides of the door. The main frame posts were modified so that the door could rotate 180˚.

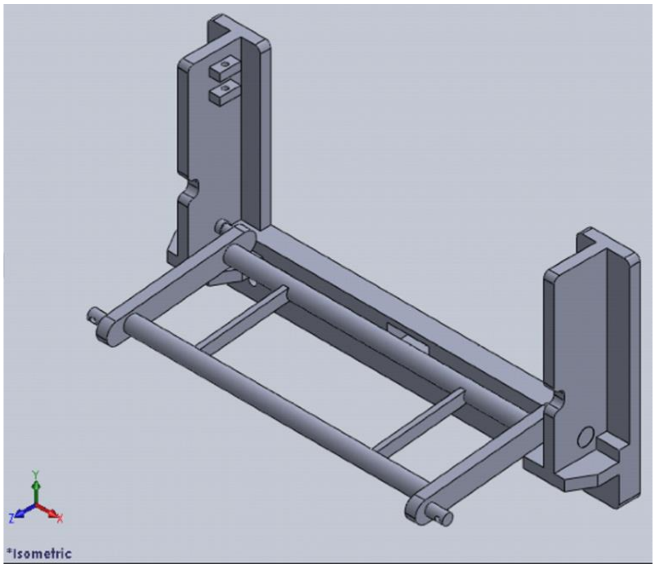


Figure 9: Hanging Door design

The second preliminary design, called the Double Door desisgn, used the frame from Figure 8, but uses two doors instead of one. The doors are locked using pins and mounted to the frame using hinge structures at the sides (Figure 10).

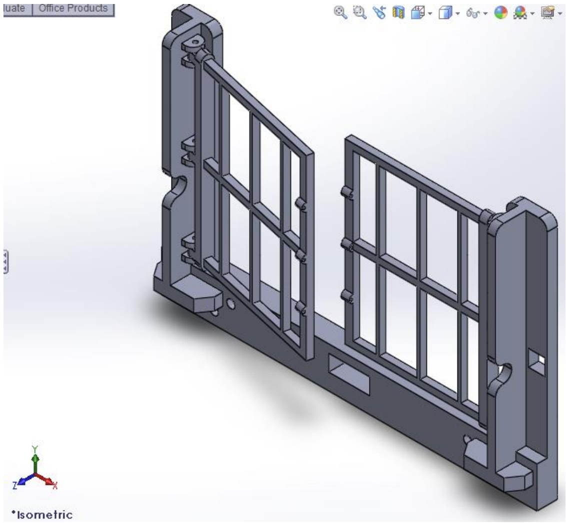


Figure 10: Double Door design

The third preliminary design, called Crab Door design, used completely different posts and an added functionality. By eliminating the z-axis plates, bent tubes come out of the post plates to act as hinges for the door, which can open from the left or right side (Figure 11). The idea behind this design is that bent tubes absorb more energy during impact.

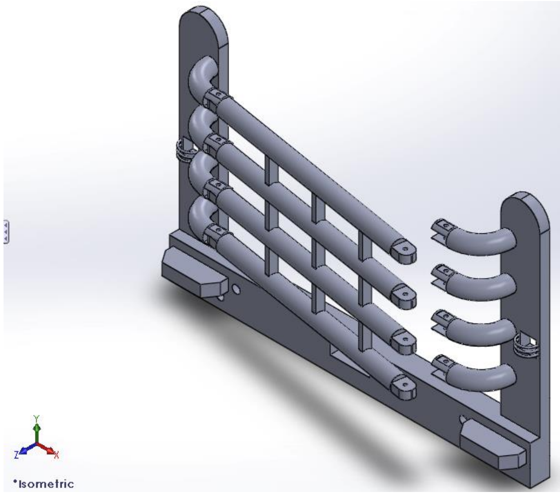


Figure 11: Crab Door design

4.2 First Design Iteration

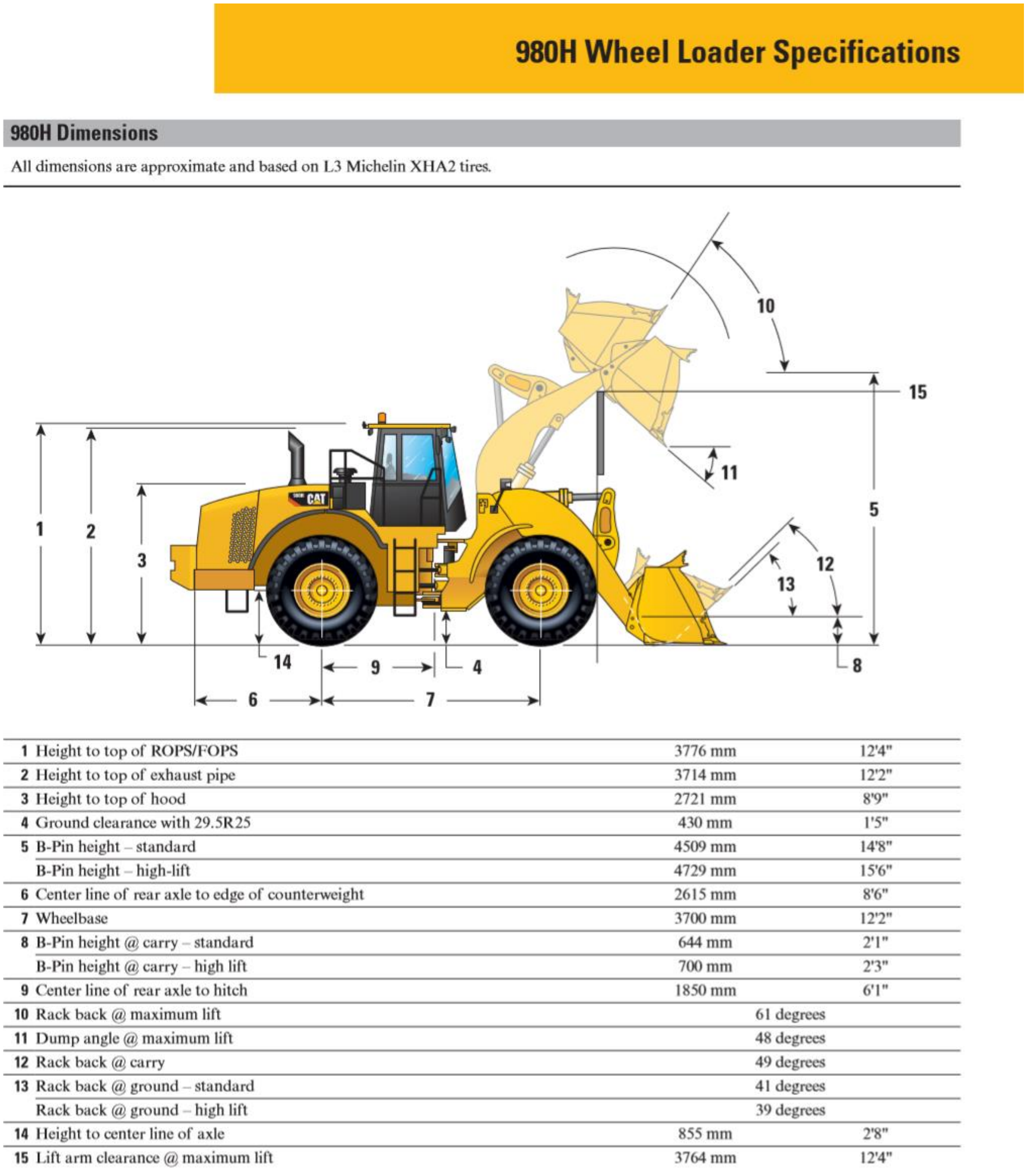
After the first week, the group emailed questions to the project sponsor for additional information. In the second week, a response explained additional design requirements as follows:

- The weight cannot exceed 1,330 kg.
- The existing bumper is made of common carbon steel.
- It cannot affect the turning radius.
- The hood and the grill open outwards.
- The rear bumper is assembled to the 980H using four strong bolts.

Prior to making changes, the Crab Door design was eliminated because it seemed unrealistic and replaced with the Single Door design. The Single Door design uses the initial main frame, round bars in the door, and can also open from either side (Figure 16).

Following this decision, the group updated the designs using information from the email. In addition, the group found the 980H product manual using internet searches and used certain dimensions (Figure 12) to change the height of the frame. The first design iterations are shown by figures 14 through 16.

Despite revisions, the major problem with the Hanging Door design is that the door weighs almost 180 kg, which no single worker could lift and close. The group thought of light-weighting the door through material substitution, but believed it could potentially compromise the integrity of the entire design. The Hanging Door design was maintained at this stage so that feedback from the project sponsor during a future interview could provide a professional opinion.



980H Wheel Loader Specifications

980H Dimensions

All dimensions are approximate and based on L3 Michelin XHA2 tires.

1	Height to top of ROPS/FOPS	3776 mm	12'4"
2	Height to top of exhaust pipe	3714 mm	12'2"
3	Height to top of hood	2721 mm	8'9"
4	Ground clearance with 29.5R25	430 mm	1'5"
5	B-Pin height – standard	4509 mm	14'8"
	B-Pin height – high-lift	4729 mm	15'6"
6	Center line of rear axle to edge of counterweight	2615 mm	8'6"
7	Wheelbase	3700 mm	12'2"
8	B-Pin height @ carry – standard	644 mm	2'1"
	B-Pin height @ carry – high lift	700 mm	2'3"
9	Center line of rear axle to hitch	1850 mm	6'1"
10	Rack back @ maximum lift	61 degrees	
11	Dump angle @ maximum lift	48 degrees	
12	Rack back @ carry	49 degrees	
13	Rack back @ ground – standard	41 degrees	
	Rack back @ ground – high lift	39 degrees	
14	Height to center line of axle	855 mm	2'8"
15	Lift arm clearance @ maximum lift	3764 mm	12'4"

Figure 12: 980H Dimensions

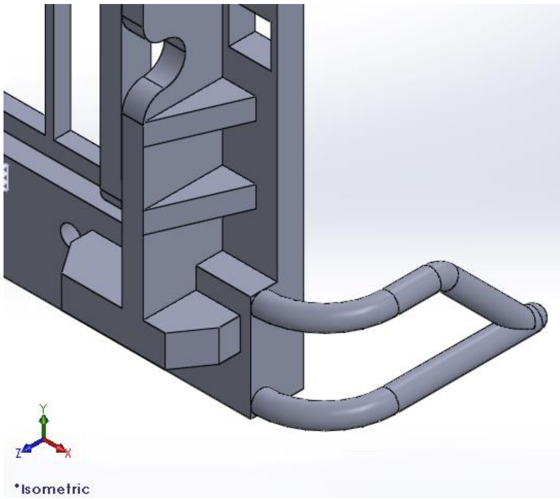


Figure 13: Side protection and triangular main frame supports

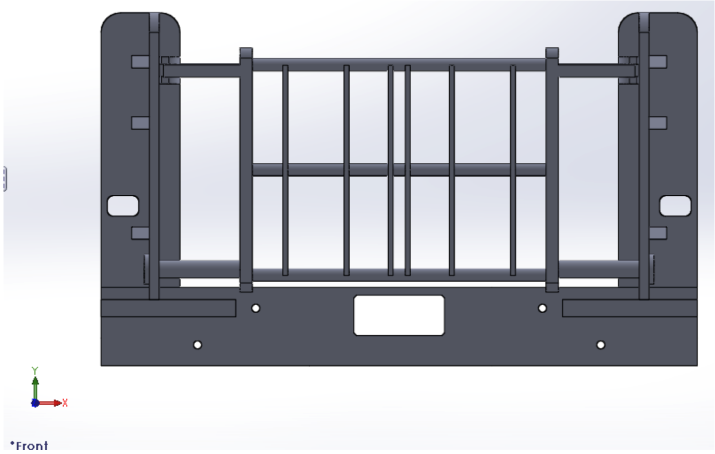


Figure 14: Hanging Door design

Figure 15: Double Door design

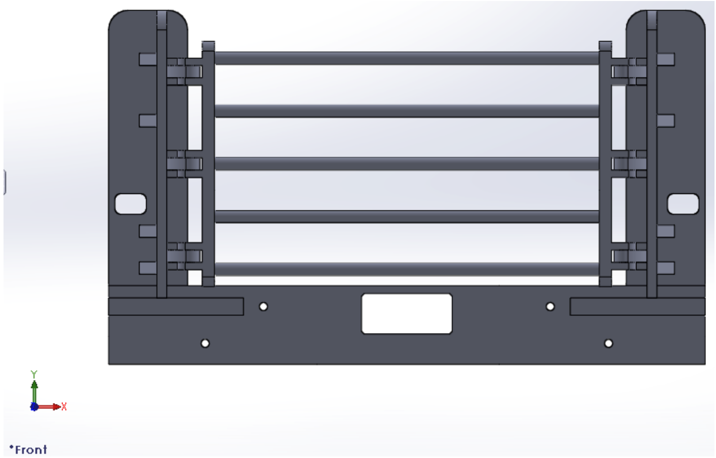


Figure 16: Single Door design

4.3 Second Design Iteration

Prior to an interview, the group requested and received the model for the most current bumper design (Figure 17), which provided exact dimensions for the rear bumper and its components, including a rear camera mounting bracket. The dimensions of the main frame in the group's designs were updated to those of the existing design and rear camera mounting brackets were added to all the designs using the camera dimensions. The most important features of the main frame are shown in Table 1, each of which were incorporated into the group's designs and placed in the same location with the same dimensions as the existing bumper.

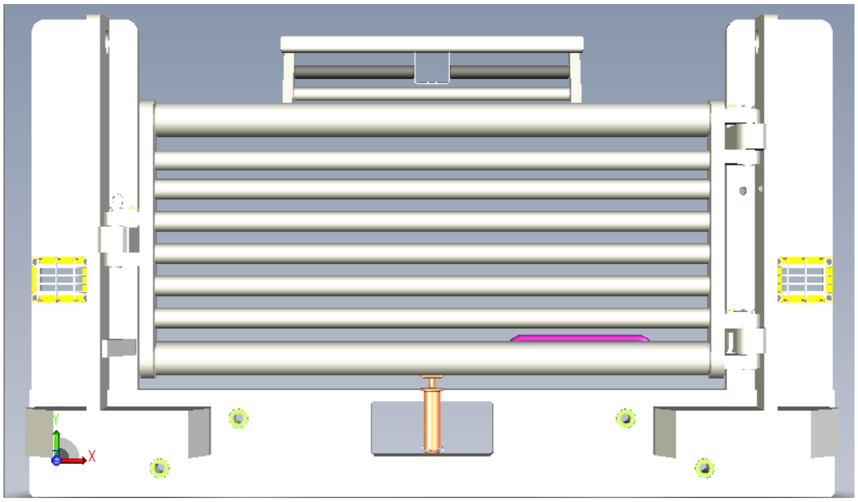


Figure 17: Existing Rear Bumper

Existing main frame dimensions				
	Parts			
Dimension	**Base**	**X-axis Plate**	**Z-axis Plate**	**Corner Trapezoids**
Height (m)	0.32	1.12	1.17	0.14
Length (m)	2.44	0.30	0.04	0.55
Depth (m)	0.09	0.04	0.22	0.18

Table 1: Dimensions of existing bumper features

Using the dimensions of the pieces outlined in Table 1, the group updated each design. Following updates to dimensions, rear camera mounting brackets were made for all the designs. Both the Hanging Door and Double Door designs had a mounting bracket consisting of two bars; a round bar to hold the camera frame in place, and the rectangular bar for rigidity and protection (Figure 18 and Figure 20). The Single Door design rear camera mounting bracket is attached to the top hinge support of the main frame, and is formed by two bent tubes with the camera frame in the middle (Figure 19).

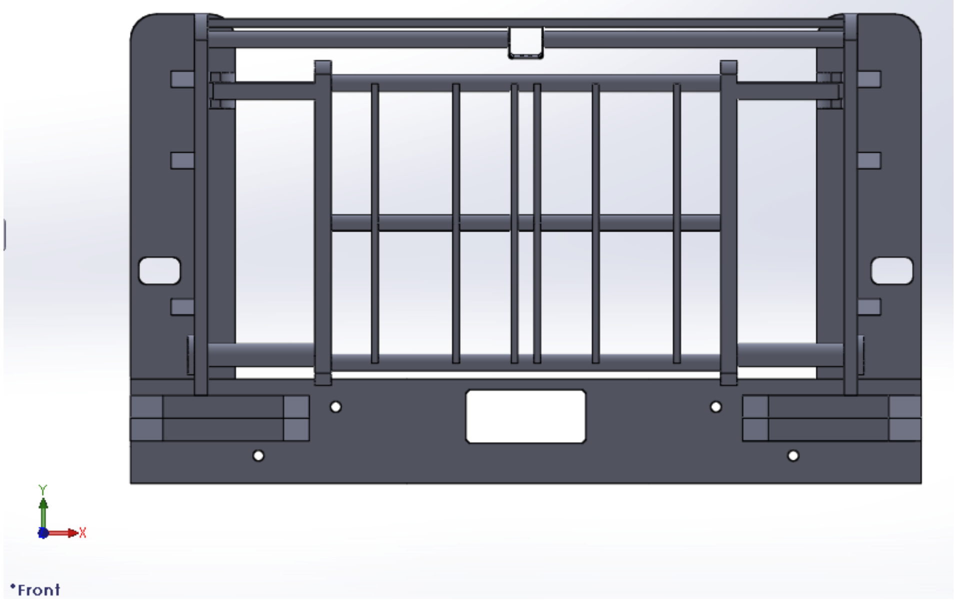


Figure 18: Hanging Door with rear camera mounting bracket

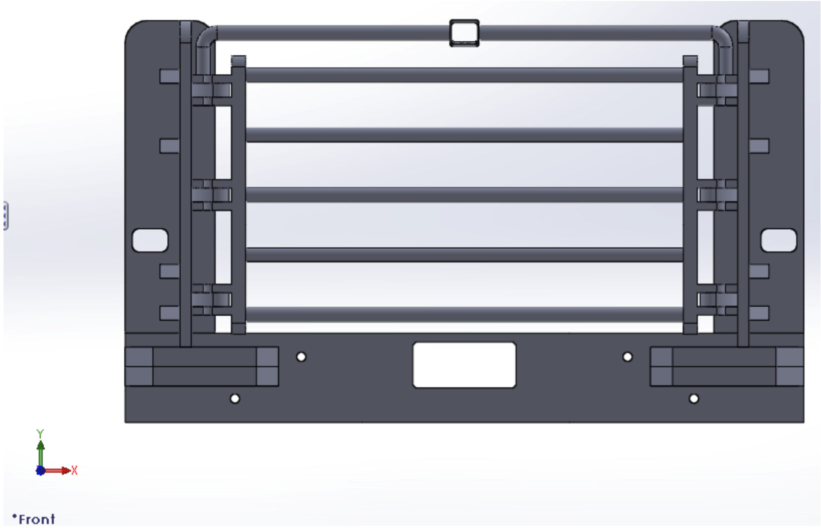


Figure 19: Single Door with rear camera mounting bracket

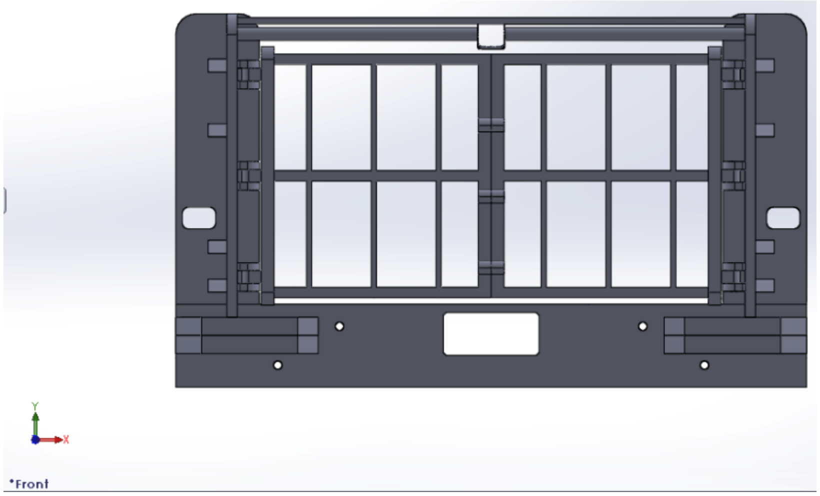


Figure 20: Double Door with rear camera mounting bracket

The group's concern of the weight of the door in the Hanging Door design was confirmed by the project sponsor and the design was eliminated. The Double Door design became preferable because the existing design's door was so heavy that it would bend at the hinges and cause alignment problems during closing; splitting the door into two would make each door lighter and ameliorate the issue. However, it was suggested by the project sponsor to find more ways of addressing the problem. Following the meeting, it was identified that all three current designs failed to satisfy one of the requirements: the camera brackets blocked the hood from opening. Thus, the camera bracket designs were updated in the next iteration.

4.4 Third Design Iteration

The interview provided a focus, feedback, and additional project requirements, including:

- The same center of gravity as the existing design
- Lifting eyes in the main frames of all bumper designs
- A door-holding mechanism
- Rear signal light protection designs

To begin meeting the new requirements, the Hanging Door design was replaced with the Crab Door design, which returned because project advisor Professor Zhang suggested that bent beams would help dissipate the energy during a collision. The preliminary Crab Door design was changed by reincorporating the z-axis plates and updating the dimensions of the main frame. In addition to replacing the Hanging Door Design, the rear camera mounting brackets were redesigned to allow the hood to open. The mounting bracket design for the Single Door and Crab Door designs was adopted from the existing design (Figure 21) and added to the middle of the top of each design (Figure 22). The mounting bracket for the Double Door design is divided between the doors and fixed at the top (Figure 23).

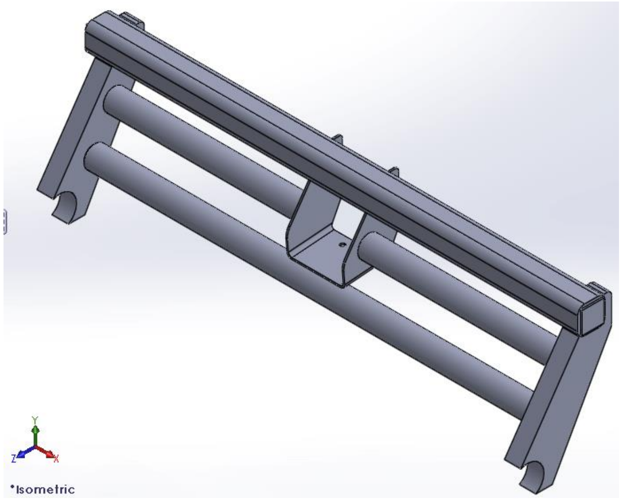


Figure 21: Existing rear camera mounting bracket

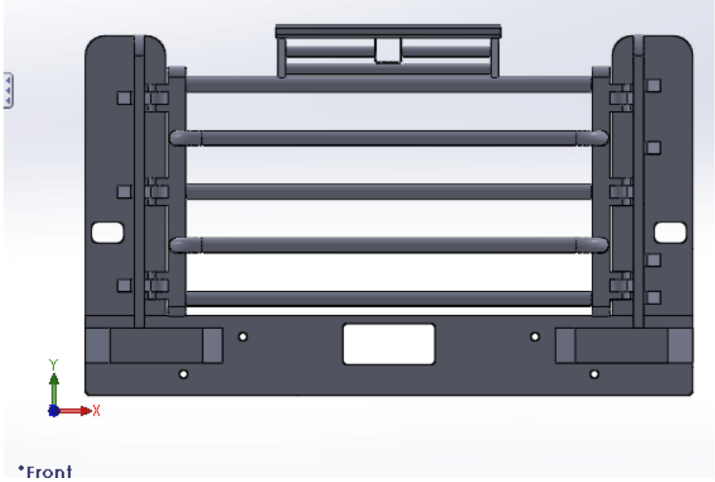


Figure 22: Crab Door design with z-axis plates and rear camera mounting bracket

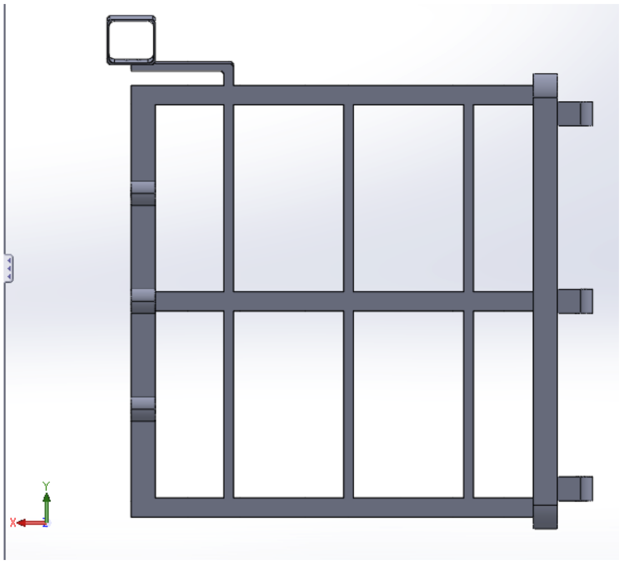


Figure 23: Double Door rear camera mounting bracket

With elimination of the Hanging Door design and fixes to the rear camera mounting brackets, three components including the lifting eyes, door-holding mechanisms, and additional locking mechanisms were added to the designs. The lifting eyes are two holes located in the top of the z-axis plates (Figure 24) used during installation of the rear bumper to the 980H.

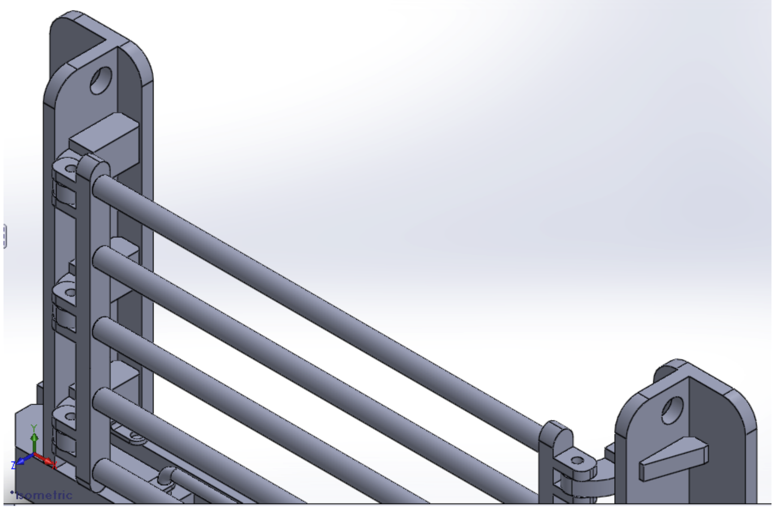


Figure 24: Lifting Eyes

In addition to the lifting eyes, the existing rear bumper incorporated use of a bent tube with a pivot point used to hold the door open and prevent injury. The functionality is demonstrated in sequence by Figures 25 through 27.

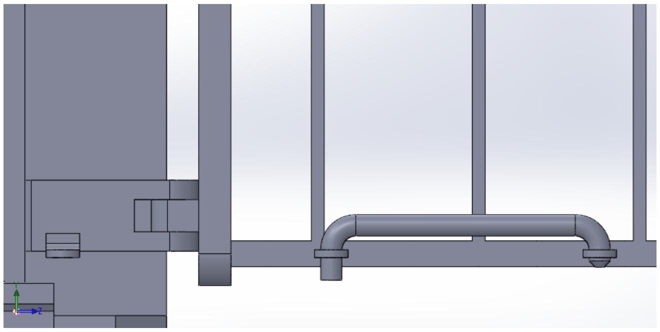


Figure 25: Initial position; handle held by door

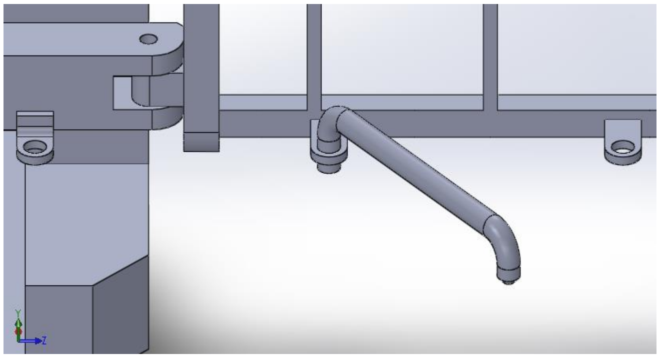


Figure 26: Handle during 180˚ rotation

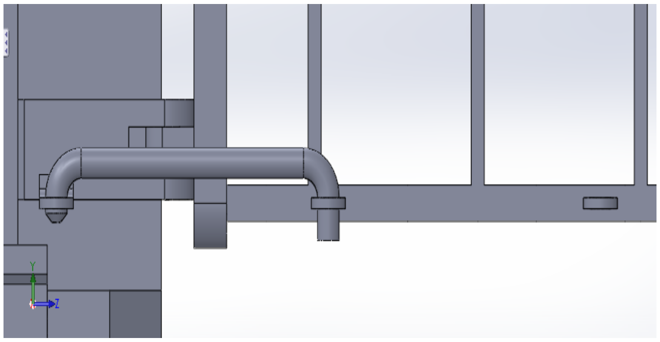


Figure 27: Handle held by frame and in lock position

The final adjustment made to the Double Door design during the third iteration included locking mechanisms used to help address the alignment issue. The first design idea, called Support Triangle (Figure 28), uses triangular supports on the bottom of the door fixed at the base of the main frame to raise the doors to the same height during locking. The next idea, called Vertical Pin, uses multiple vertical pin hinges that lie upon one another to increase the areas of contact and distribute stress more evenly (Figure 29). Another design idea, called Vertical Puzzle Pin, uses notches on the doors so that hinges can be placed on the rear door and interlock with holes on the front door (Figure 30). The final lock design was inspired from the lock of an average truck (Figure 31).

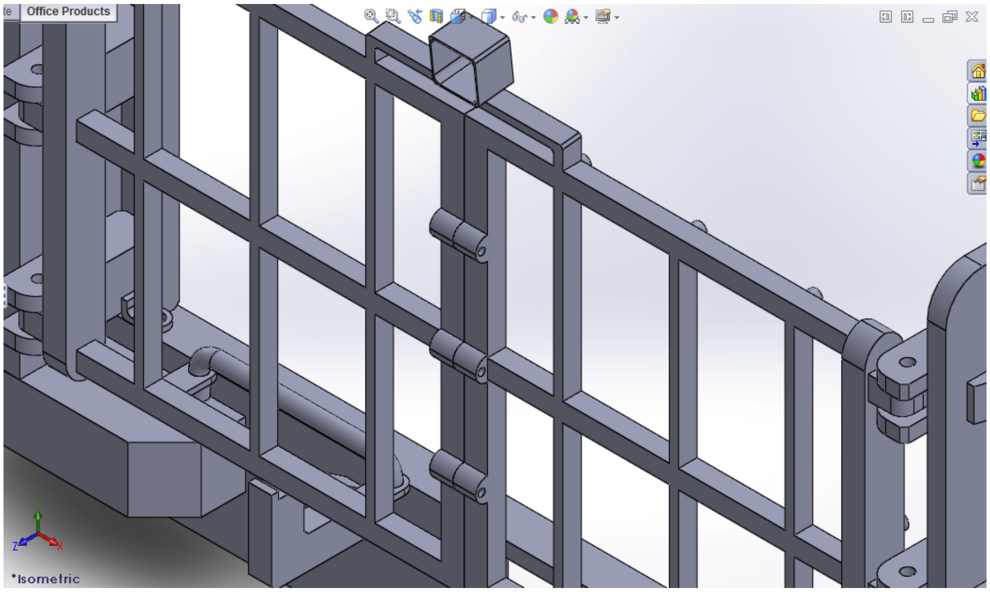


Figure 28: Support Triangles for horizontal pins

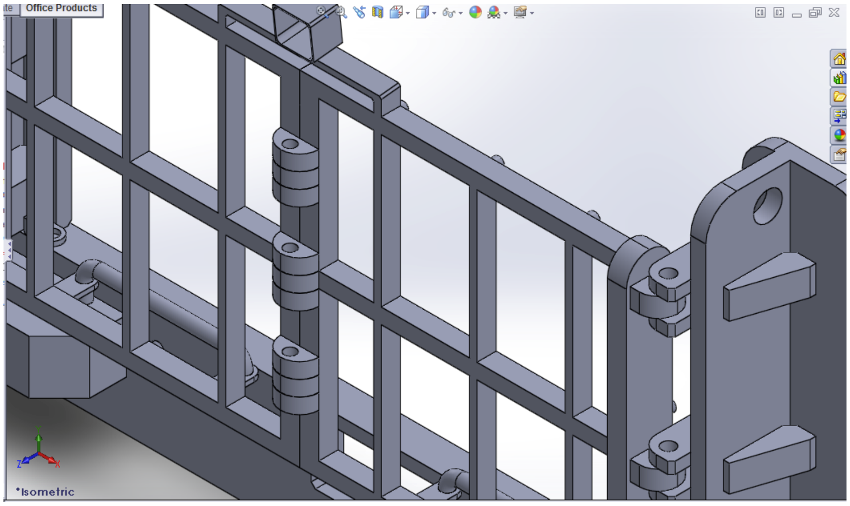


Figure 29: Vertical Pin

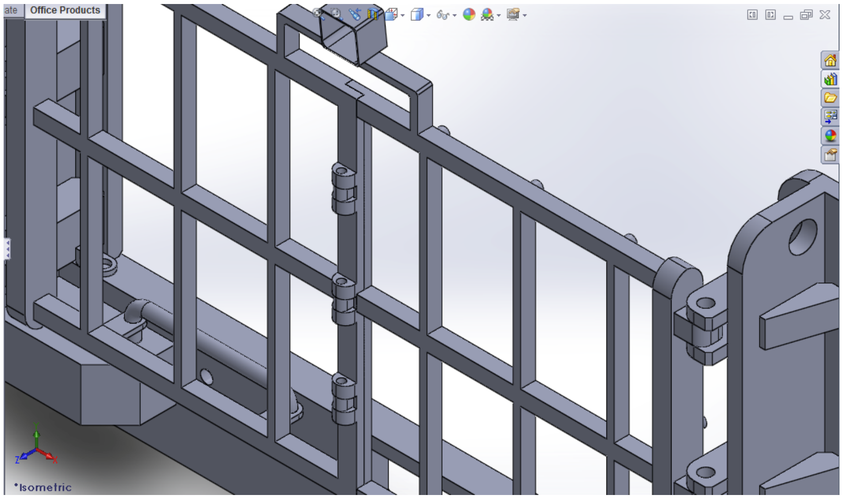


Figure 30: Vertical Puzzle Pin

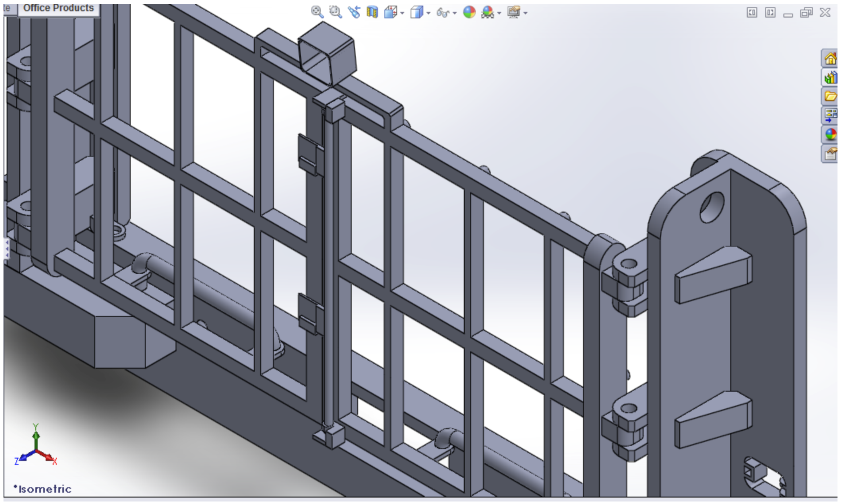


Figure 31: Truck Lock

Table 2 counts the number of pieces associated with each lock design.

Lock Mechanism	Number of parts
Support Triangles	8
Vertical Pin	9
Vertical Puzzle Pin	9
Truck	9

Table 2: Number of parts in each lock design

4.5 Rear Signal Light Protection Systems

At this stage in the project, the group turned its focus to create rear signal light protection systems. The first system was inspired by cam followers (Figure 32) and is called Follower design.

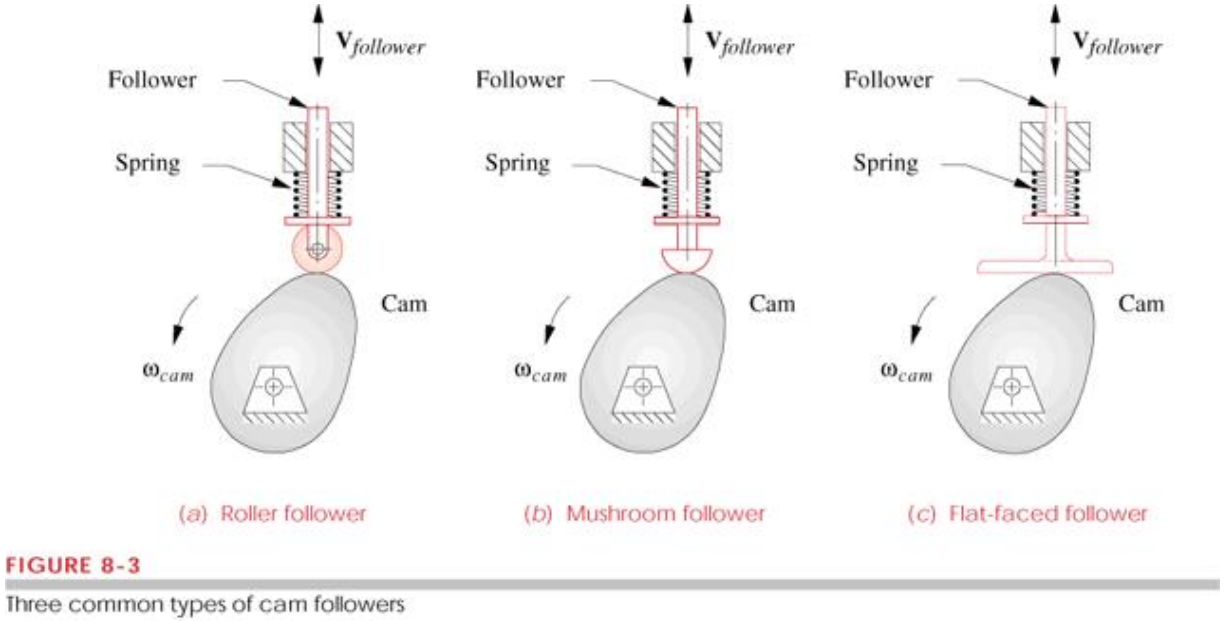


Figure 32: Cam Follower

The Follower design is formed by a box, sliding body, light, rubber cushion, and light guard (Figure 33). The Follower design allows the light to slide back during a rear-end collision. The small bumps in the box act as static cams to hold the light in place during impact (Figure 34) and the rod at the end of the sliding body acts as the follower. The box is channeled on the sides to constrain the sliding body and keep it aligned. The box is welded to the rectangular holes in the main frame (Figure 35).

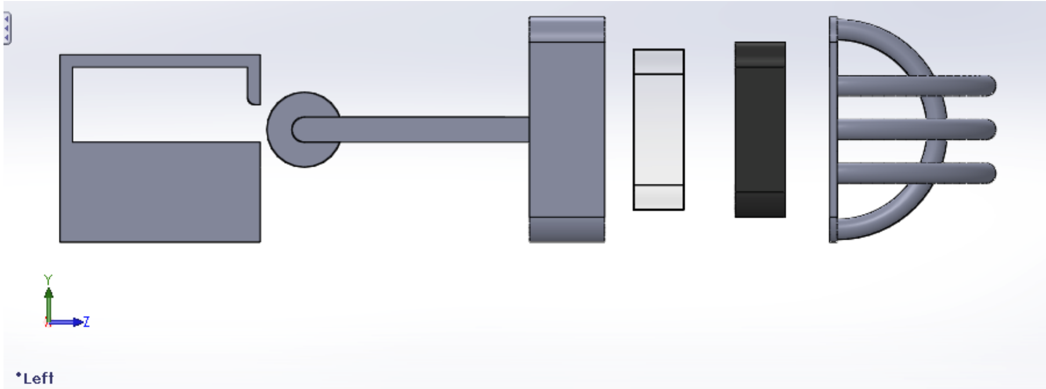


Figure 33: Parts of the Follower design

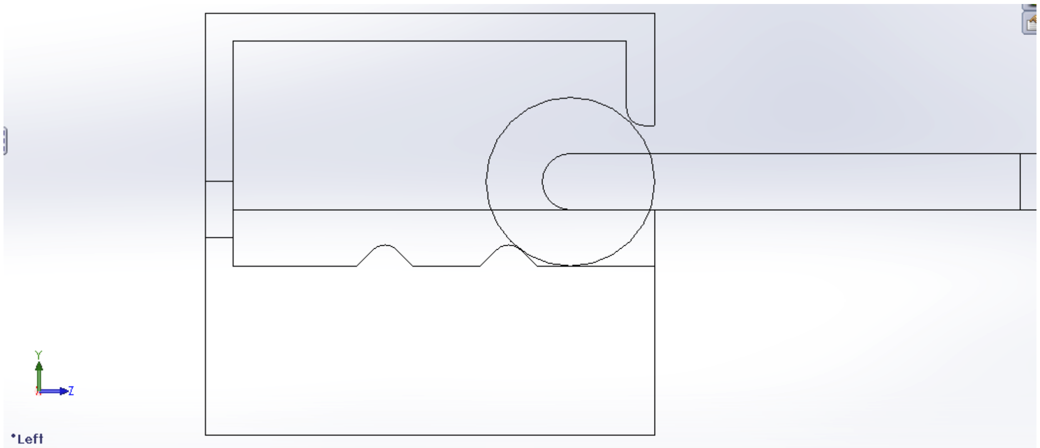


Figure 34: Transparent view of the Follower design

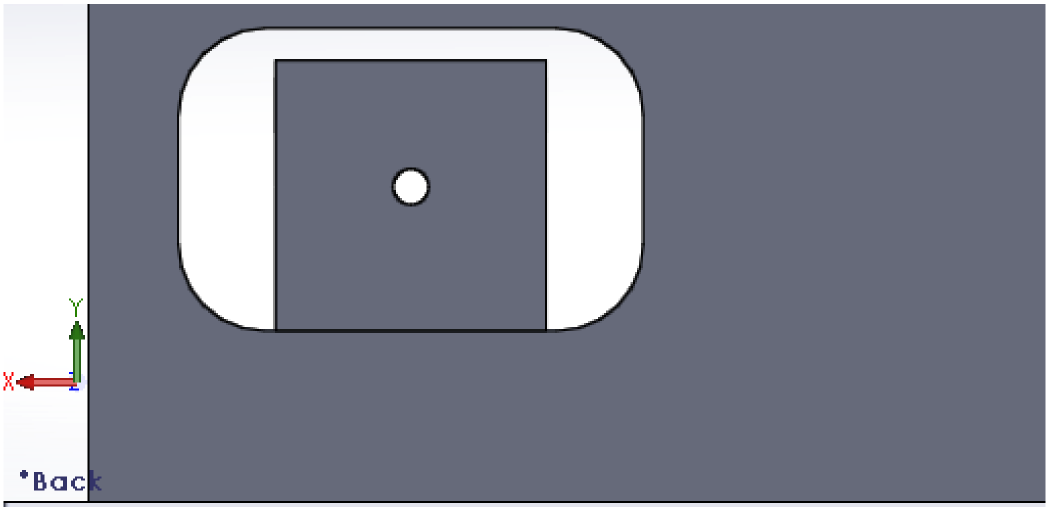


Figure 35: Box welded to the main frame

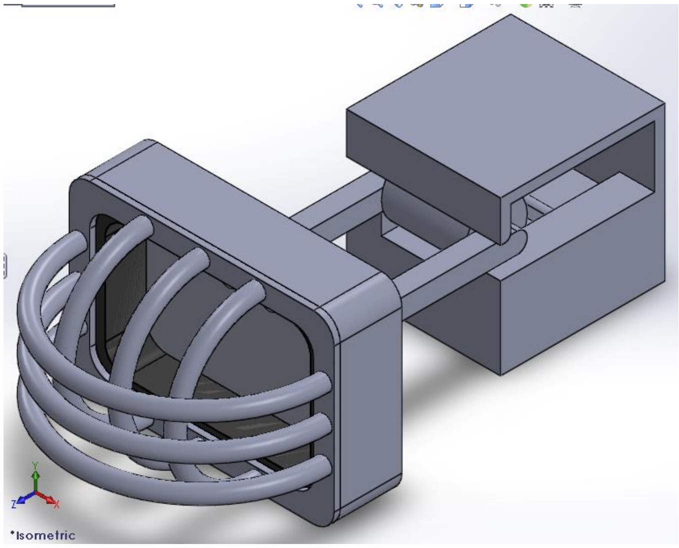


Figure 36: Follower Assembly

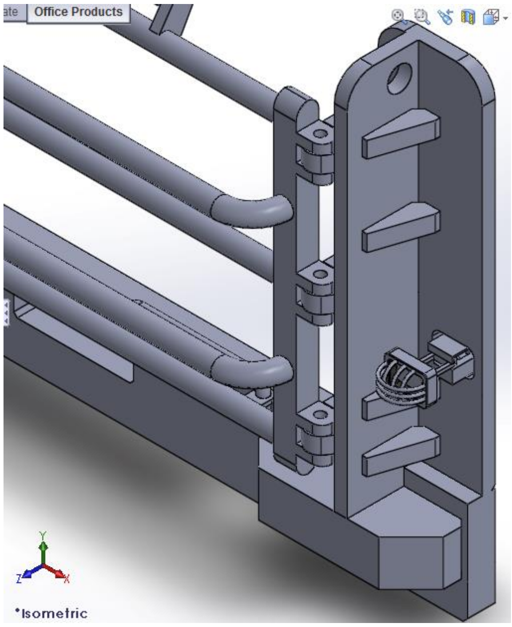


Figure 37: Follower place in the rear bumper

The next light protection system was inspired by the rack and pinion gear mechanism (Figure 38). The Rack and Pinion design is composed of a pinion gear, rack gear, light frame, rubber cushion, and light guard (Figure 39). The rack gear is placed in a groove in the hole for the rear signal light on the main frame, and the pinion gear is attached to the light frame using a small pin, thus allowing the protection system to dampen the effects of collision in the event of a side impact (Figure 41).

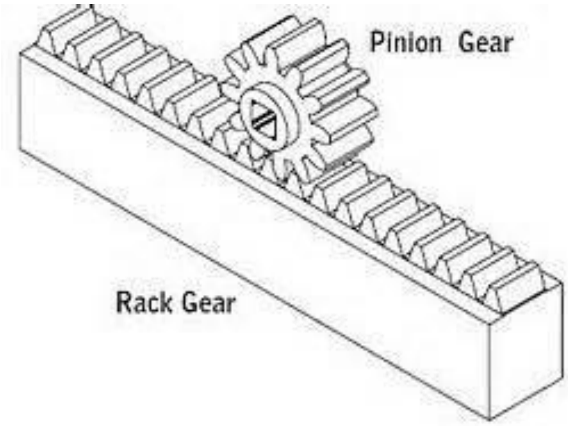


Figure 38: Rack and pinion gear mechanism

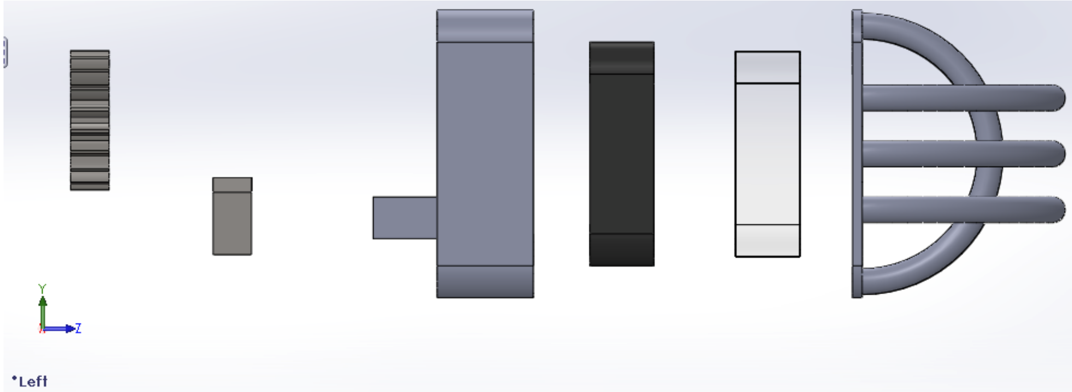


Figure 39: Rack Pinion parts

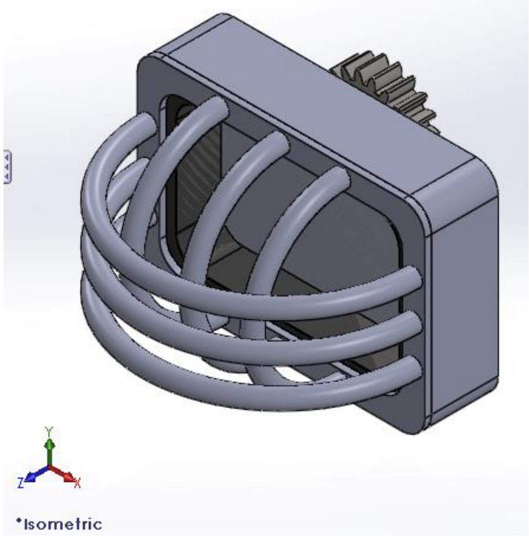


Figure 40: Rack Pinion assembly

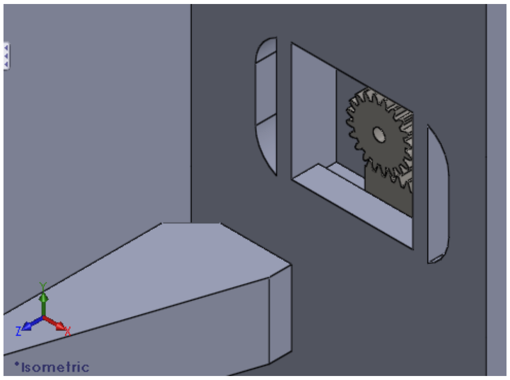


Figure 41: Rear view of Rack and Pinion located on the main frame

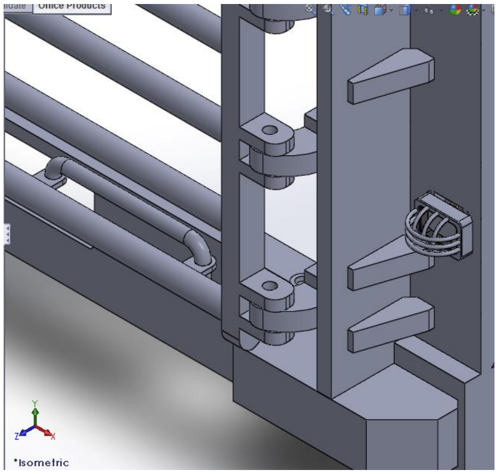


Figure 42: Front view of Rack and Pinion located on the main frame

The last rear signal light protection system was inspired by the Grashof slider-crank (Figure 43).

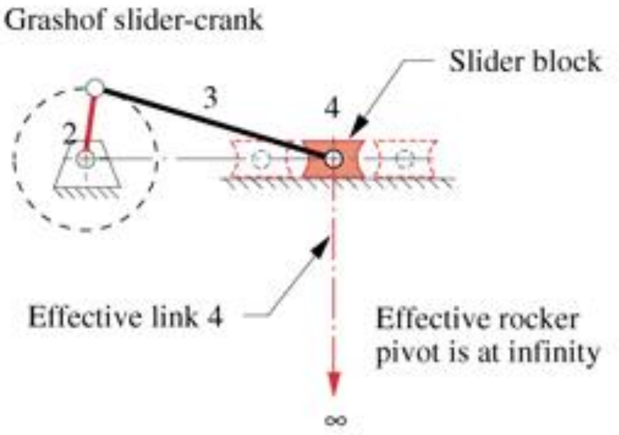


Figure 43: Grashof slider-crank

The Grashof slider-crank is a four bar crank-rocker linkage transformed into a four bar slider-crank. The Four Link design is formed by three links and pins, one rubber cushion, one slider block, one light, and one light guard (Figure 44).

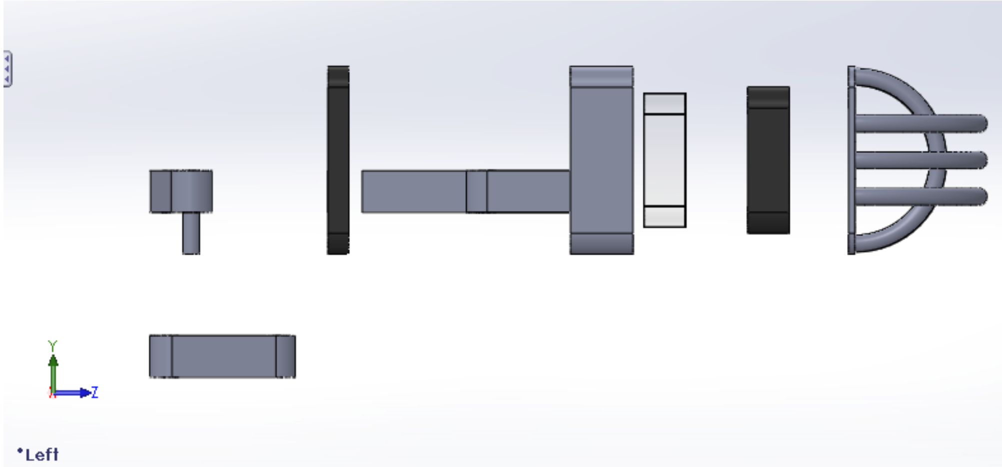


Figure 44: Four Link parts

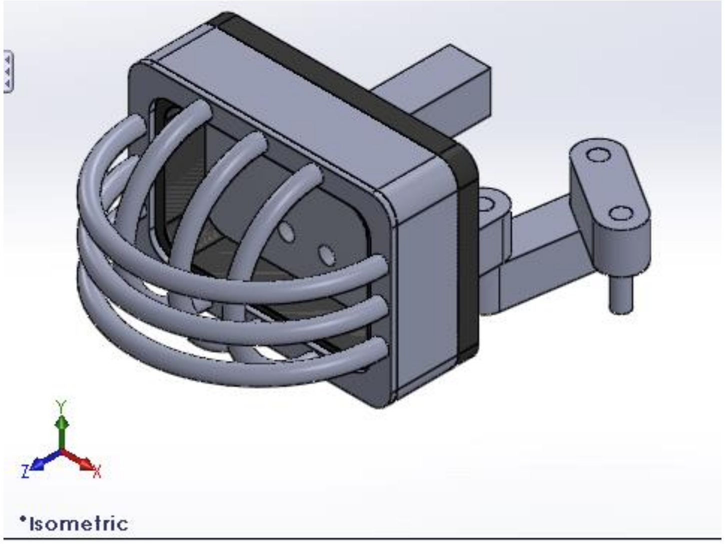


Figure 45: Four Link assembly

The Four Link assembly is installed in the main frame using a hinge mechanism for one of the links and a hollow square for the sliding block as exhibited (Figure 46). The advantage of using the slider-crank design is that the light protection will dampen the effects of impact in the event of either a side or rear-end collision. The hollow square acts as the ground for the rocker and keeps the light cage properly oriented.

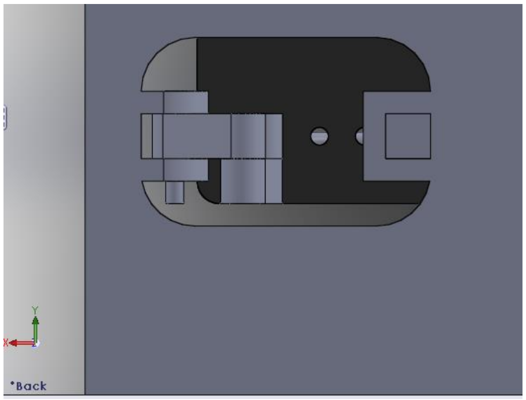


Figure 46: Four Link located on the main frame

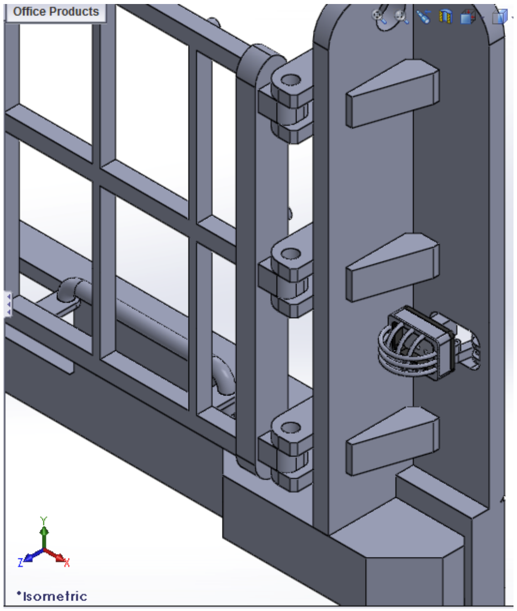


Figure 47: Four Link place in the rear bumper

Table 3 outlines the number of parts required for each rear signal light protection system.

Light Protection	Number of parts
Follower	34
Rack Pinion	28
Four Link	36

Table 3: Number of part of the light protection designs

4.6 Final Designs

The rear signal light protection systems are excluded from the final Single, Crab, and Double Door rear bumpers because they are independent of the design. Tables four and five count the number of parts of each design’s main frame and door, respectively. The part count for the door includes hold-open handles and mounting bracket pieces. The part count for the Double Door design excludes parts from the associated locking mechanisms.

Main Frame	**Number of parts**
Single Door	22
Crab Door	22
Double Door	19

Table 4: Number of parts in the main frame

Door Design		**Number of parts**
Single		26
Crab		26
Double	Left	17
	Right	16

Table 5: Number of parts in the door

Compared to the existing rear bumper, the final Single and Crab, and Double Door designs have a main frame with triangular blocks for rigidity. Both the Single and Crab doors have with fewer rods that can be opened from the left or right side (Figure 48). The Crab Door design however, bends two rods for additional rigidity (Figure 49). The similarity of the Single and Crab Door designs to the existing design is beneficial for manufacturing because the process is assumed to be the same. The main benefit of the Double Door design (Figure 50) is dividing the weight of a single door into two, which would be safer for workers. Although it has the most parts, it utilizes simple geometry and should not be cumbersome to manufacture.

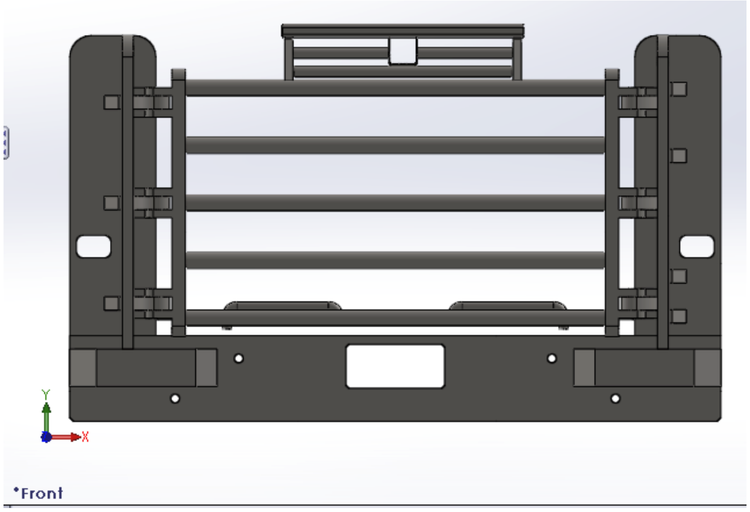


Figure 48: Final Single Door design

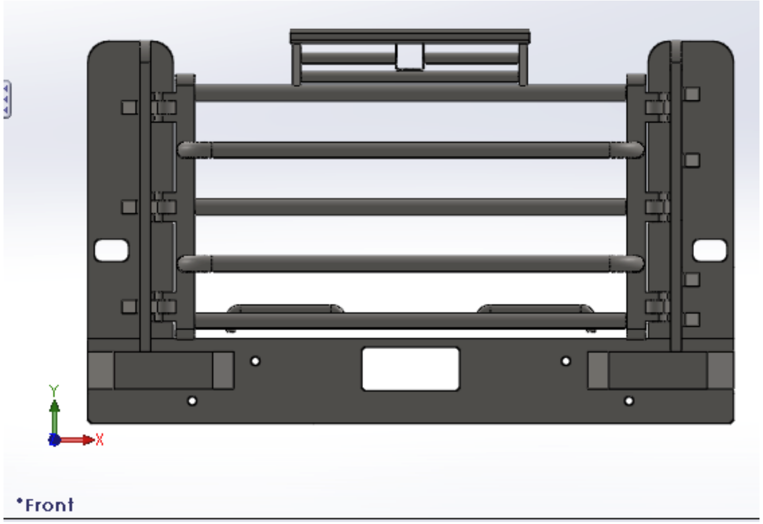


Figure 49: Final Crab Door design

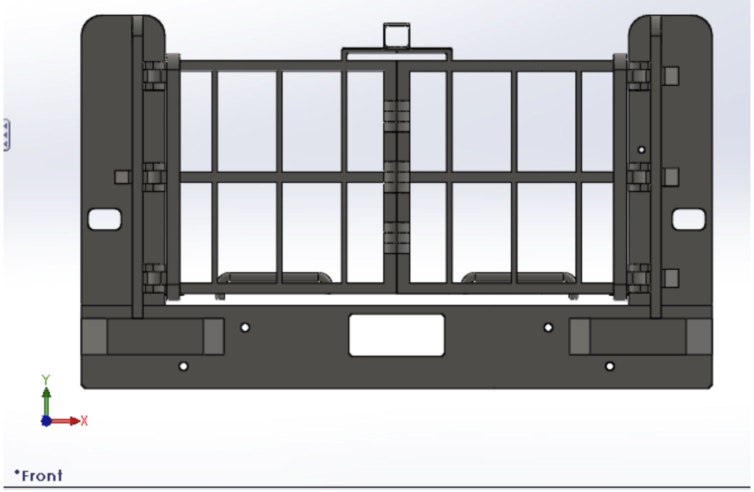


Figure 50: Final Double Door design

4.7 Final Choice and Drawing

Choosing the rear bumper and rear signal light protection system was based on an evaluation of functionality; Table 6 summarizes the specifications for the final designs.

Assembly		Height (m)	Length (m)	Depth Doors Closed (m)	Depth Doors Open (m)	Material	Weight (Kg)	Total number of parts
Existing		1.44	2.44	0.34	2.14	AISI 1020	1327.85	69
Single Door		1.44	2.44	0.33	2.12	AISI 1020	1327.85	48
Crab Door		1.48	2.44	0.41	2.14	AISI 1020	1327.11	48
Double Door	Support triangles	1.44	2.44	0.32	1.26	AISI 1020	1331.79	60
	Vertical Pin	1.44	2.44	0.31	1.26	AISI 1020	1434.25	61
	Vertical Puzzle Pin	1.44	2.44	0.31	1.26	AISI 1020	1362.57	61
	Truck	1.44	2.44	0.31	1.26	AISI 1020	1309.08	61

Table 6: Dimensions, weight, and number of parts in each design

The Double Door design was selected because the depth while the doors are open is much lower than the other designs so it occupies less space. The doors are also lighter and safer to lift in the event of bending and alignment issues. Though the number of parts is greater, it should not take significantly longer to manufacture. The Truck Lock was chosen for the Double Door design because the other designs required more changes to the door. The Four Link rear signal light protection system was chosen because it dampened impact from multiple directions and was easier to attach to the bumper.

A full assembly of the Double Door, Truck Lock, and Four Link designs is shown below (Figure 51). Excluding the rubber cushions and aluminum rear signal light guard, the chosen material is AISI 1020. The size of the complete assembly is shown in the drawing that follows (Figure 52).

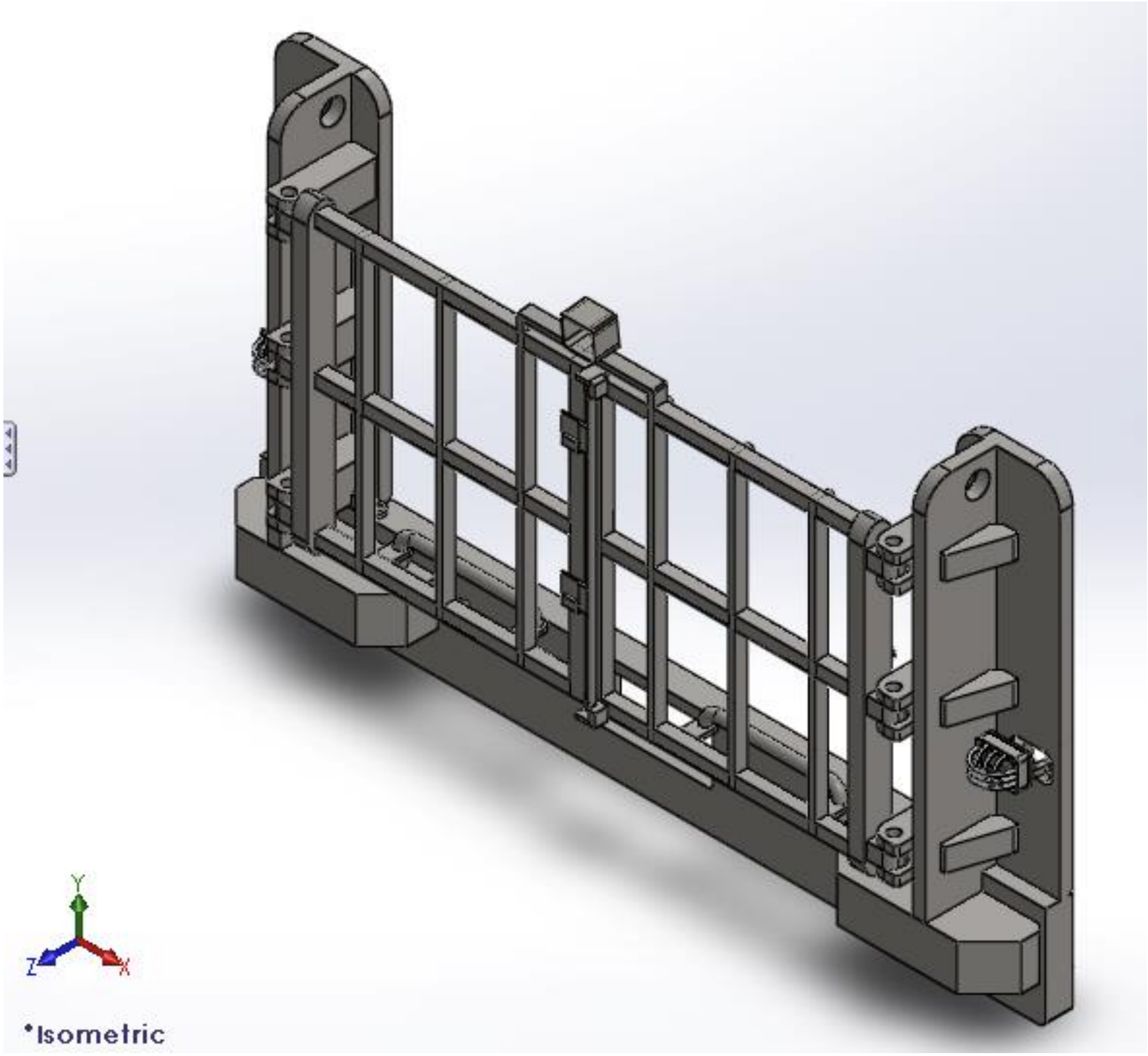


Figure 51: Double Door Rear Bumper

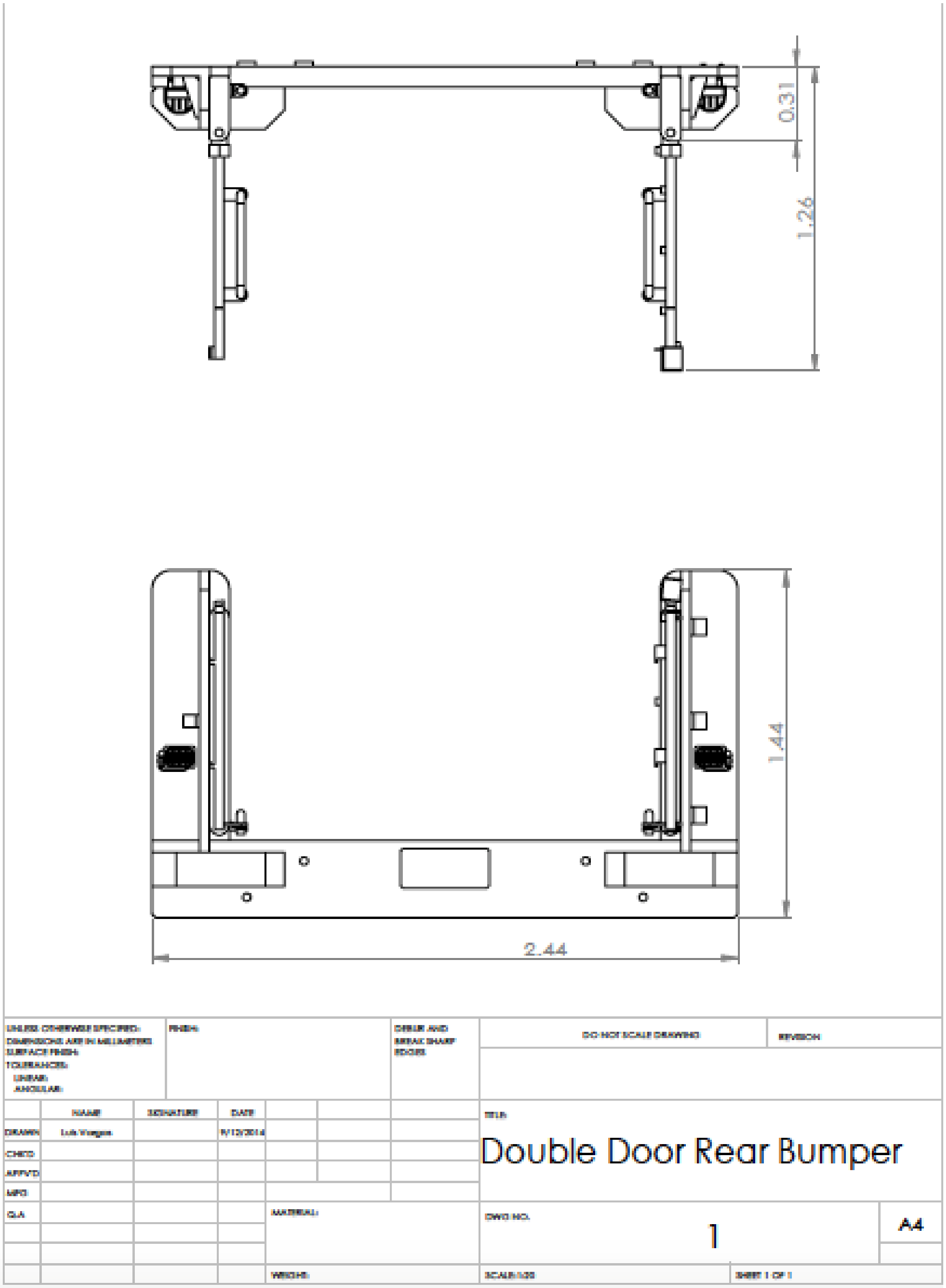


Figure 52: Double Door Assembly Drawing by Luis Vargas

5.0 Finite Element Analysis

Because designs continually changed throughout the project, the group collected static and dynamic collision data using finite element computer software ANSYS. Both simulation strategies provided stress analysis data including *total deformation* and *equivalent (von-Mises) stress*. S*tatic structural* analysis used fixed supports where bolts secured the bumper to the 980H and *explicit dynamic* analysis involved colliding rear bumper models with a wall. A comprehensive simulation requires a complete finite element model, which in this case refers to the 980H and rear bumper. The simulations of this project utilized only rear bumper models because adding a body the size of the 980H impractically increased simulation time. The group attempted to use a smaller representative body but the material density adjustment could not be compiled by the program. Dynamic simulations required powerful computers, took significant time, and failed in the presence of minor flaws in models. Therefore, the group simplified rear bumper models to the main frame and door(s) and created a successful procedure for *static structural* and *explicit dynamic* simulations, described in Appendix A.

5.1 ANSYS Explicit Dynamic Results

Screenshots of the dynamic solutions are displayed in the following pages. The results were only used to compare the designs to each another because scenarios excluded the 980H. The images demonstrate areas of deformation and stress, which vary depending on the arrangement of doors and hinges. The existing bumper experiences most deformation and stress in the door because it protrudes farther than the main frame and collides first with the wall. The same is true for the hinges of the Single Door design, bent beams of the Crab Door design, and truck lock of the Double Door design. All bumpers perform generally the same, with the exception of the Double Door design, which experiences less stress and deformation.

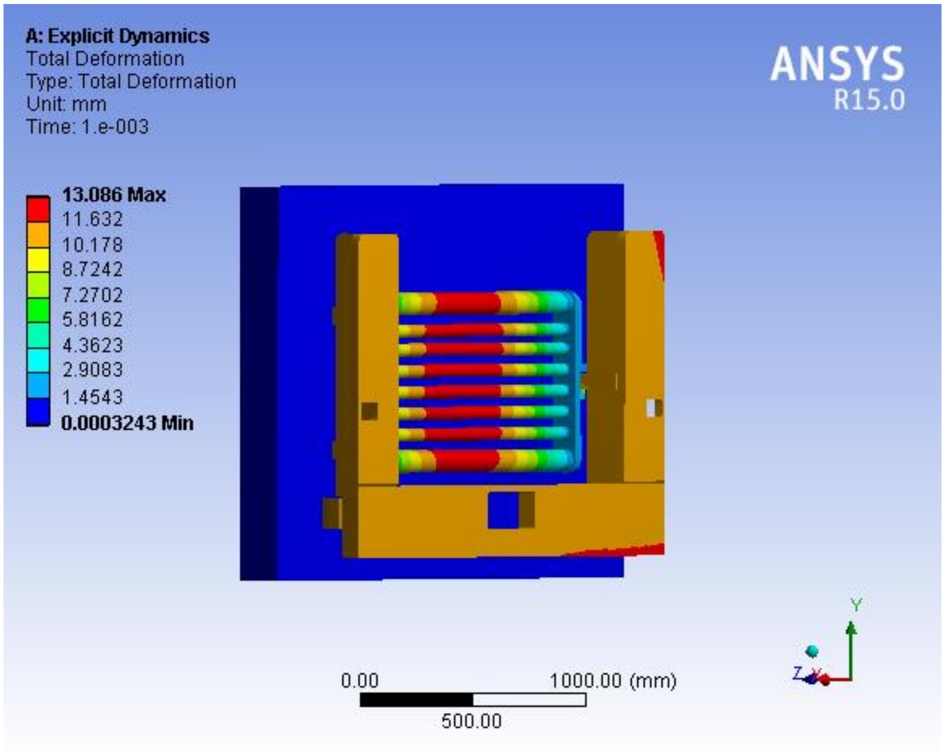


Figure 53: Dynamic deformation of existing bumper

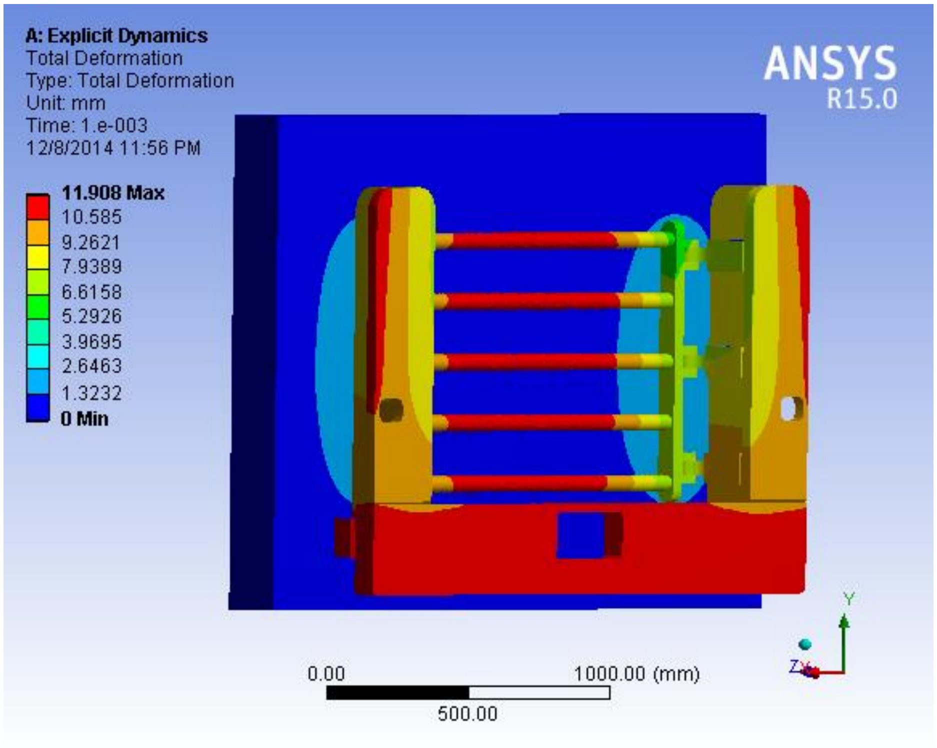


Figure 54: Dynamic deformation of Single Door design

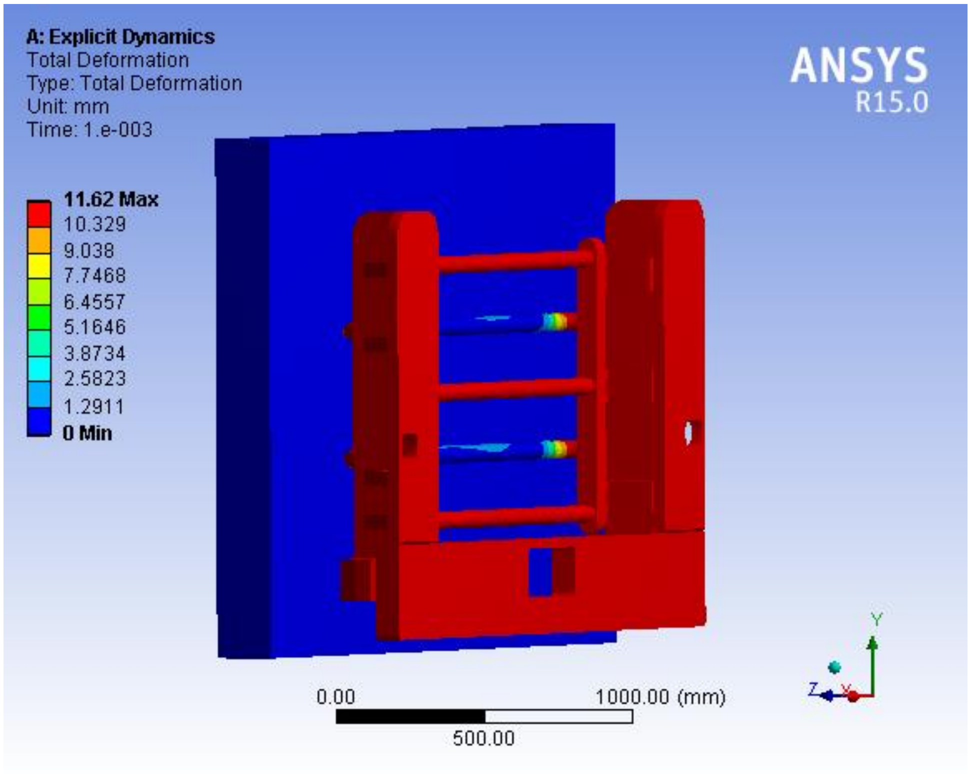


Figure 55: Dynamic deformation of Crab Door design

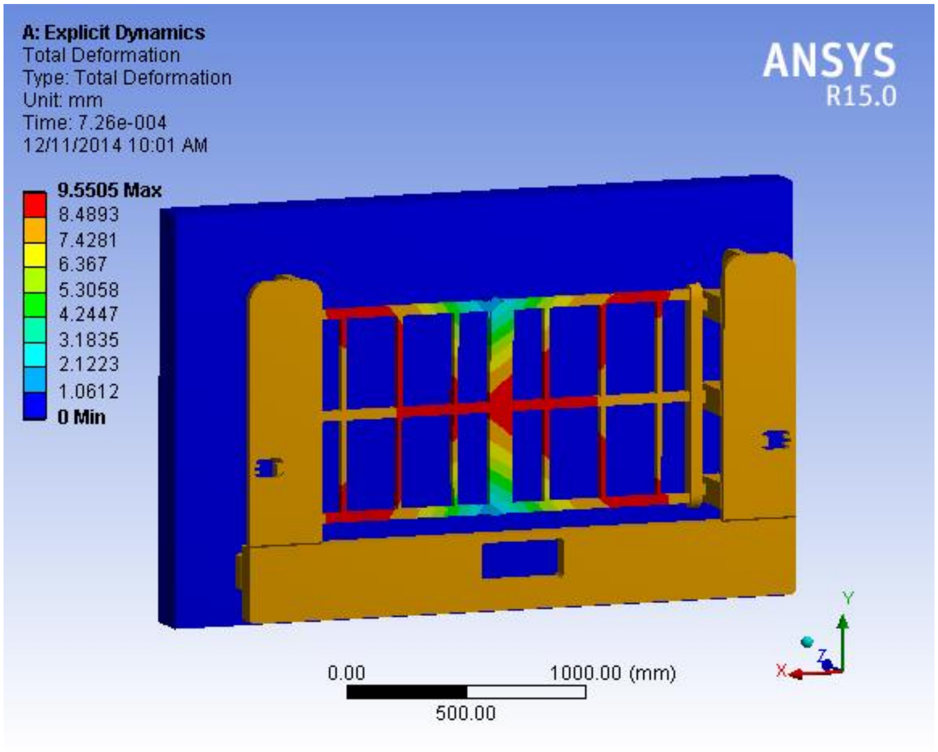


Figure 56: Dynamic deformation of Double Door design

Explicit Dynamic Total Deformation (mm)				
	Current Design	**Single Door**	**Crab Door**	**Double Door**
🟥	13.086	11.908	11.62	9.5505
🟧	11.632	10.585	10.329	8.4893
🟨	10.178	9.2621	9.038	7.4281
🟩	8.7242	7.9389	7.7468	6.367
🟩	7.2702	6.6158	6.4557	5.3058
🟦	5.8162	5.2926	5.1646	4.2447
🟦	4.3623	3.9695	3.8734	3.1835
🟦	2.9083	2.6463	2.5823	2.1223
🟦	1.4543	1.3232	1.2911	1.0612

Table 7: Comparison of dynamic deformation

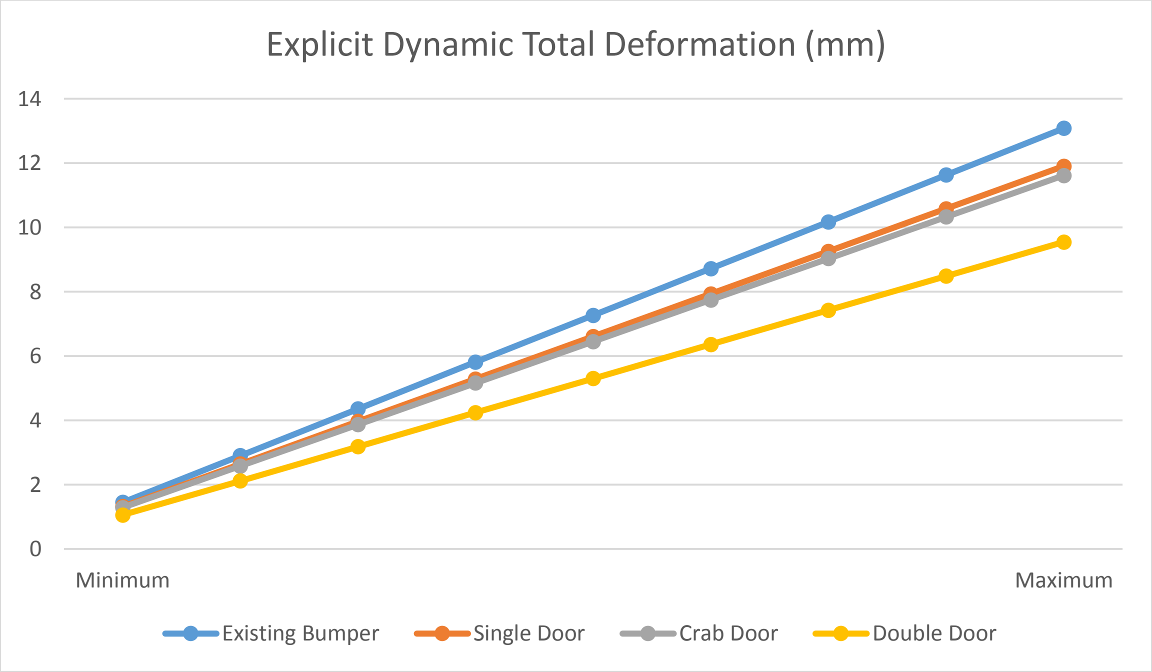


Figure 57: Comparison of dynamic deformation

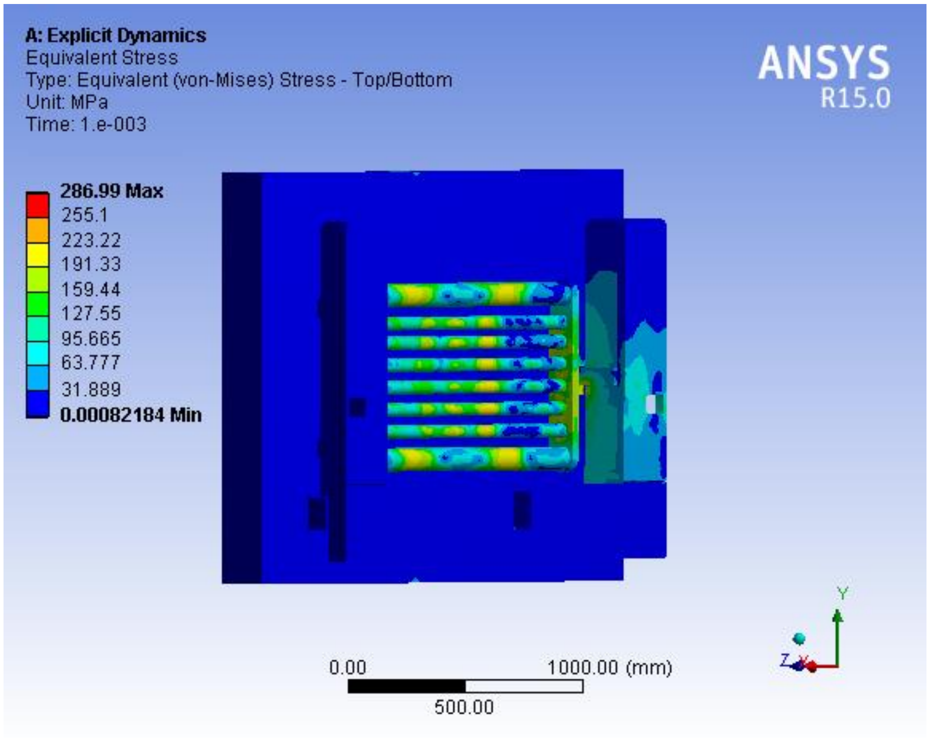


Figure 58: Dynamic stress distribution in existing bumper

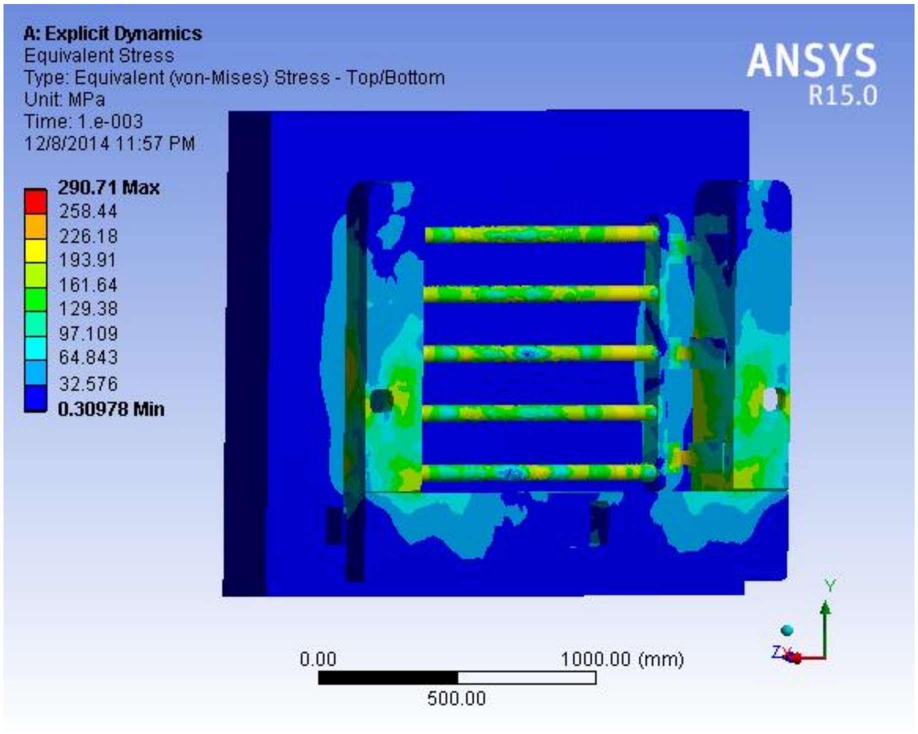


Figure 59: Dynamic stress distribution in Single Door design

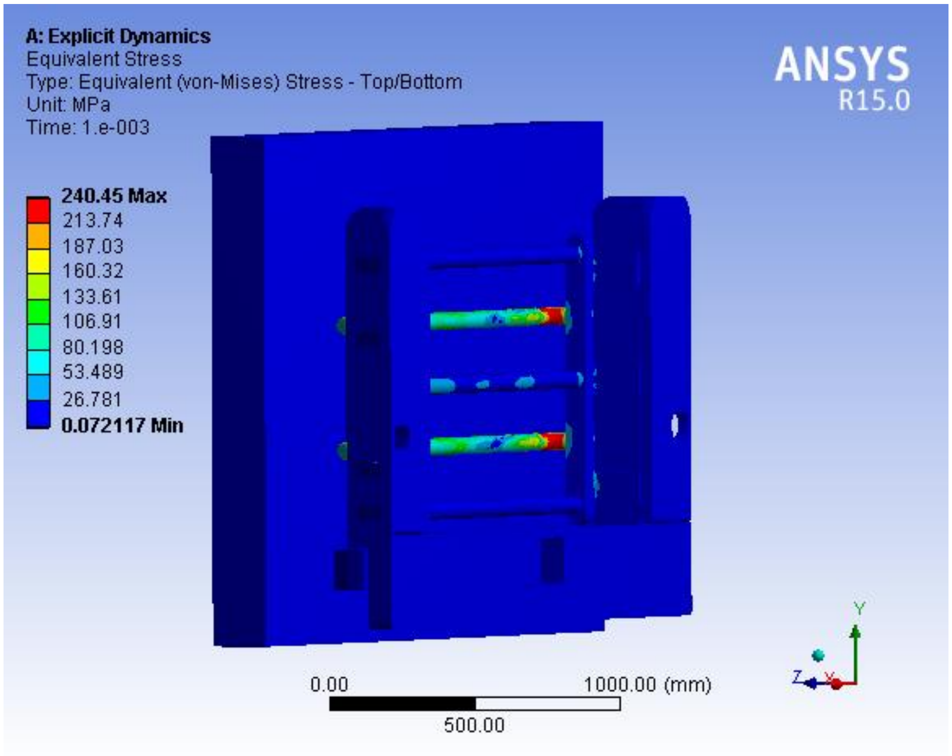


Figure 60: Dynamic stress distribution in Crab Door design

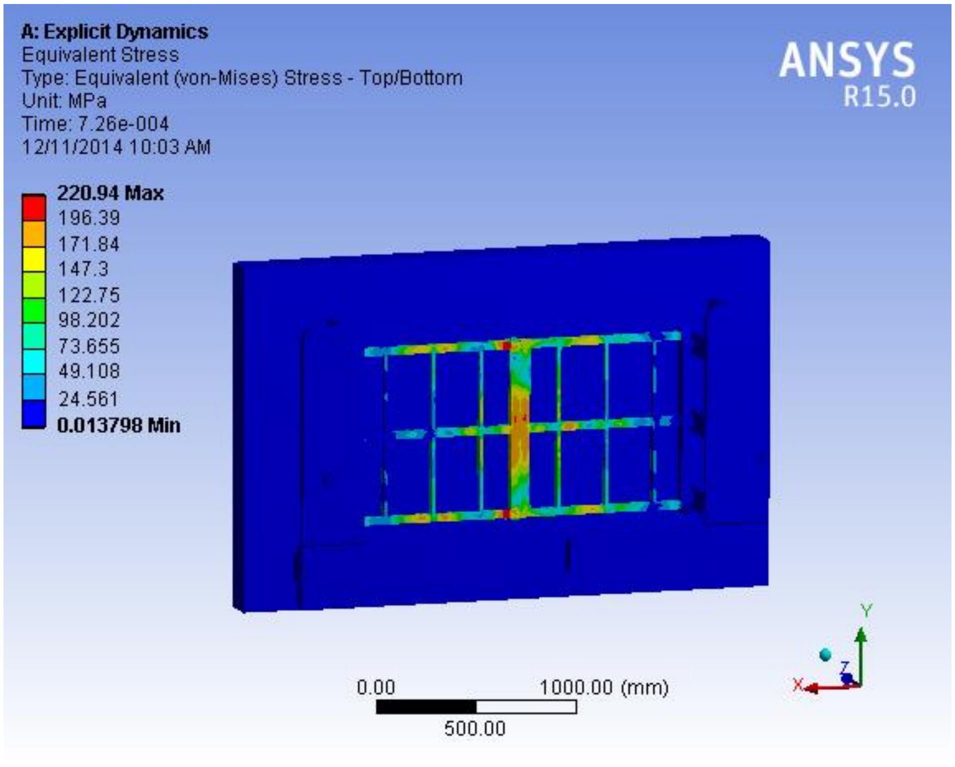


Figure 61: Dynamic stress distribution in Double Door design

***Explicit Dynamic* Equivalent (von-Mises) Stress (MPa)**				
	Existing Bumper	**Single Door**	**Crab Door**	**Double Door**
🟥	286.99	290.71	240.45	220.94
🟧	255.1	258.44	213.74	196.39
🟨	223.22	226.18	187.03	171.84
🟩	191.33	193.91	160.32	147.3
🟩	159.44	161.64	133.61	122.75
🟦	127.55	129.38	106.91	98.202
🟦	95.665	97.109	80.198	73.655
🟦	63.777	64.843	53.489	49.108
🟦	31.889	32.576	26.781	24.561

Table 8: Comparison of dynamics stress distribution

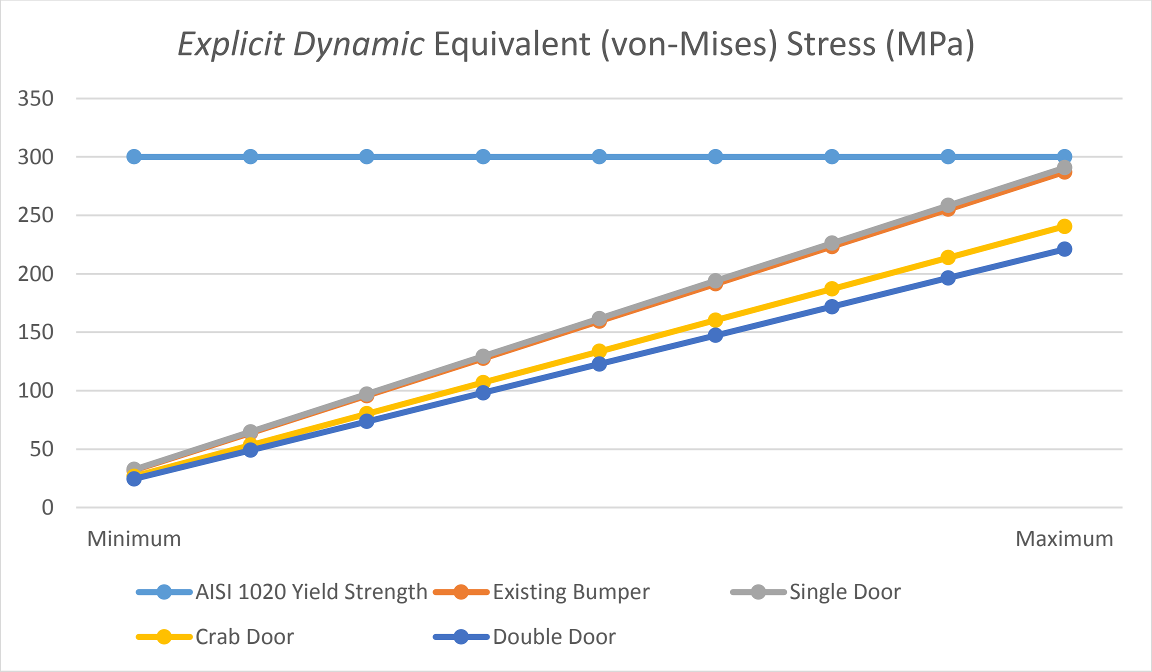


Figure 62: Comparison of dynamic stress distribution

5.2 ANSYS Static Structural Results

Screenshots of the static solutions are displayed in the following pages. The results only compare the designs to one another because the bumper would never experience a static load of such a magnitude. The images demonstrate areas of deformation and stress, which vary depending on the arrangement of doors and hinges. The existing bumper experiences most deformation and stress in the door because the door protrudes from the main frame. The same is true for the hinges of the Single Door design, bent beams of the Crab Door design and truck lock mounts of the Double Door design. The existing design shows significantly more stress than the other designs for unknown reasons, but the remaining results are comparable and tabulated after the images.

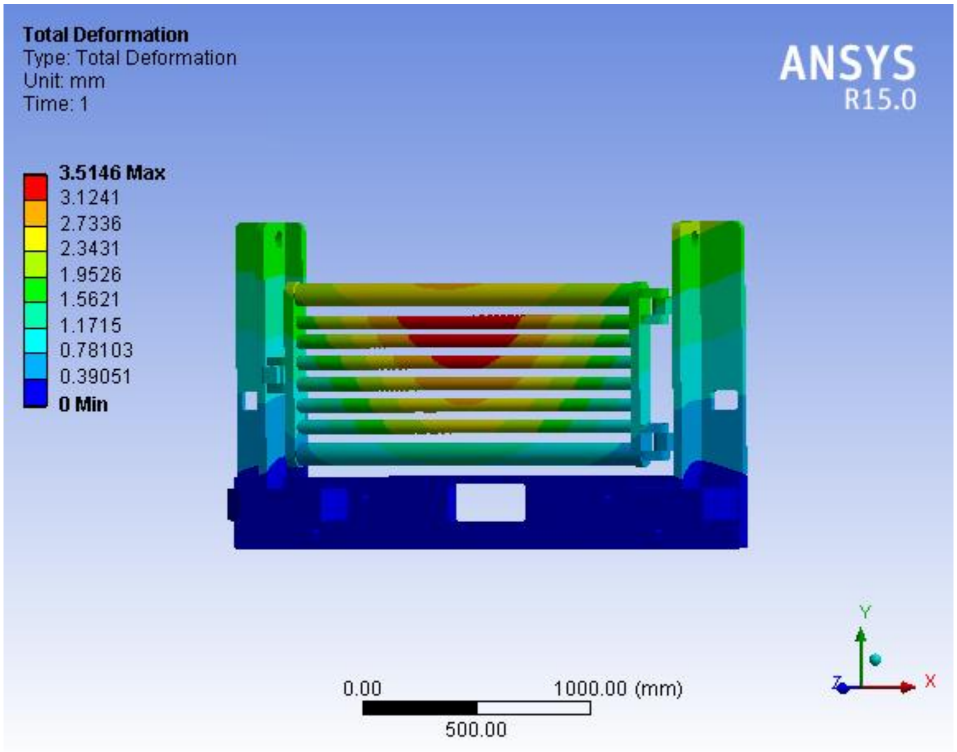


Figure 63: Static deformation of existing bumper

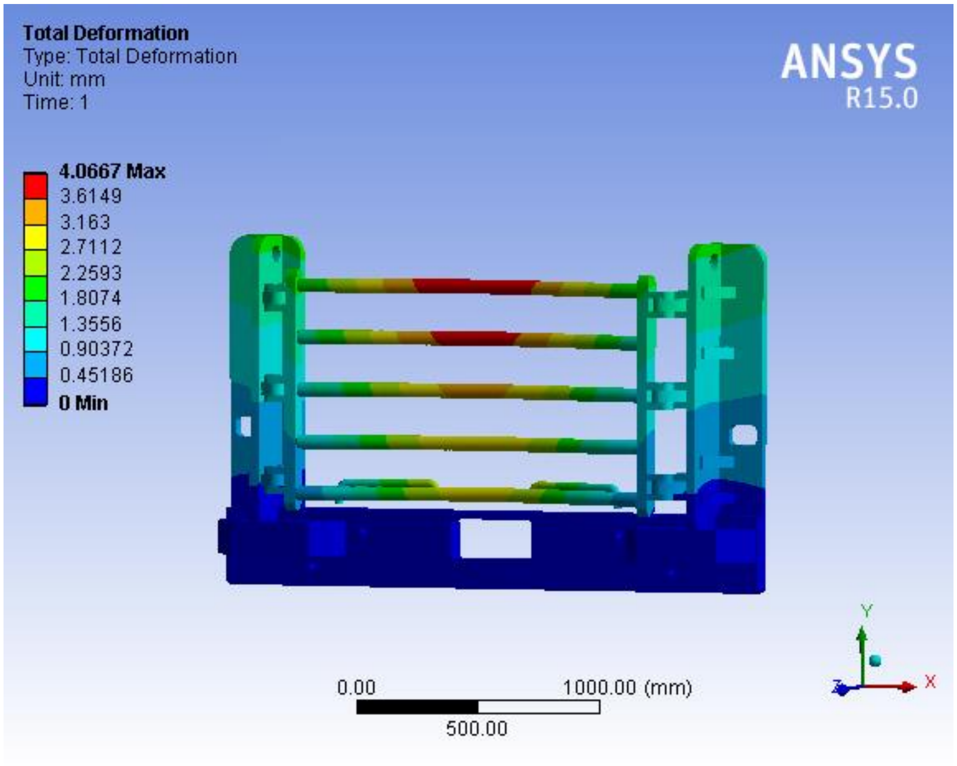


Figure 64: Static deformation of Single Door design

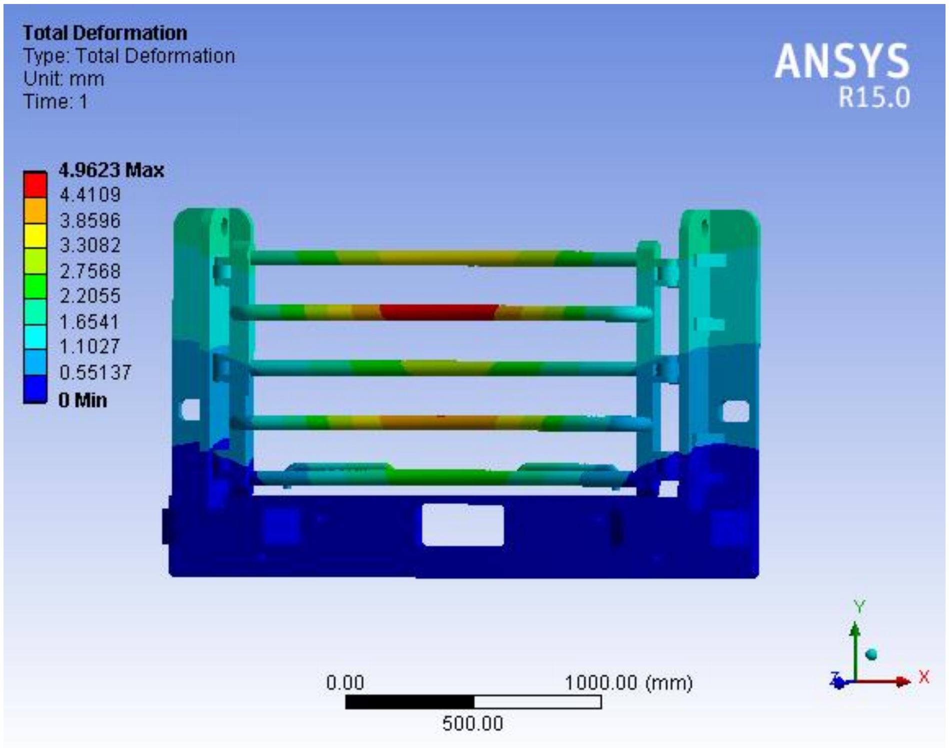


Figure 65: Static deformation of Crab Door design

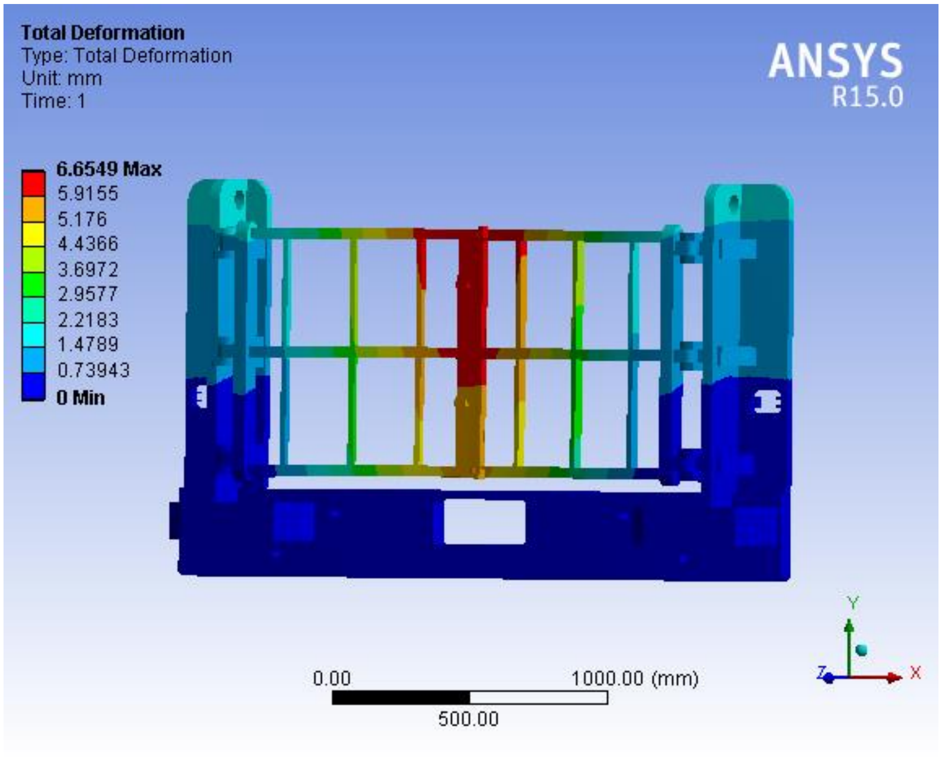


Figure 66: Static deformation of Double Door design

Static Structural Total Deformation (mm)				
	Existing Bumper	**Single Door**	**Crab Door**	**Double Door**
🟥	3.5146	4.0667	4.9623	6.6549
🟧	3.1241	3.6149	4.4109	5.9155
🟨	2.7336	3.163	3.8596	5.176
🟩	2.3431	2.7112	3.3082	4.4366
🟩	1.9526	2.2593	2.7568	3.6972
🟦	1.5621	1.8074	2.2055	2.9577
🟦	1.1715	1.3556	1.6541	2.2183
🟦	0.78103	0.90372	1.1027	1.4789
🟦	0.39051	0.45186	0.55137	0.73943

Table 9: Comparison of static deformation

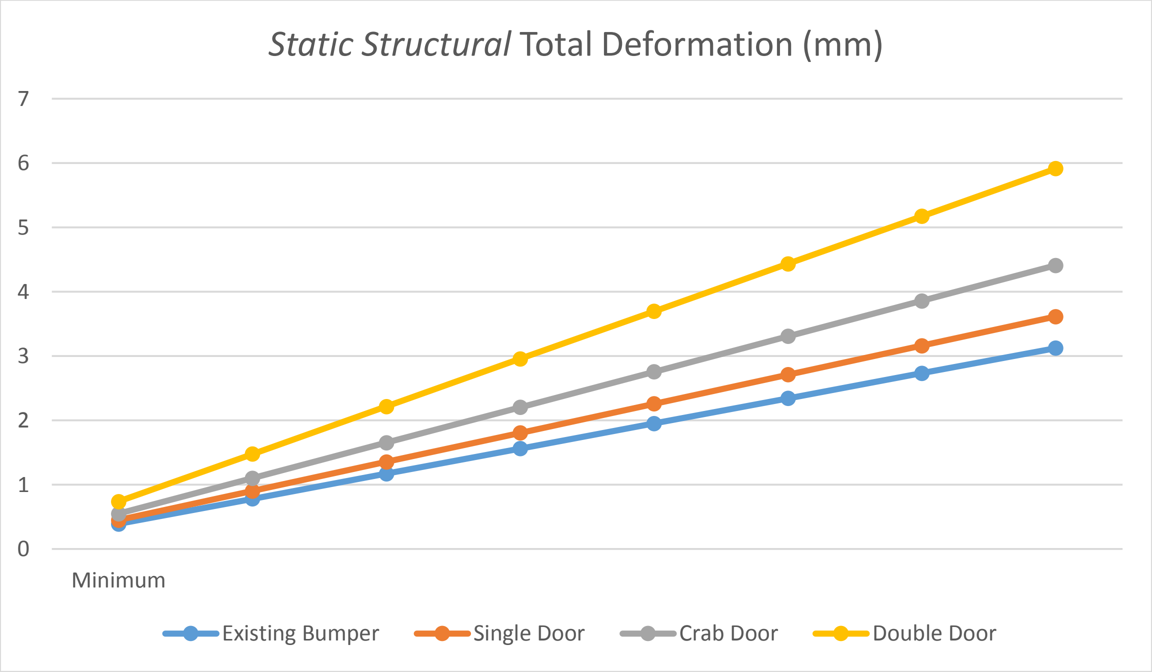


Figure 67: Comparison of static deformation

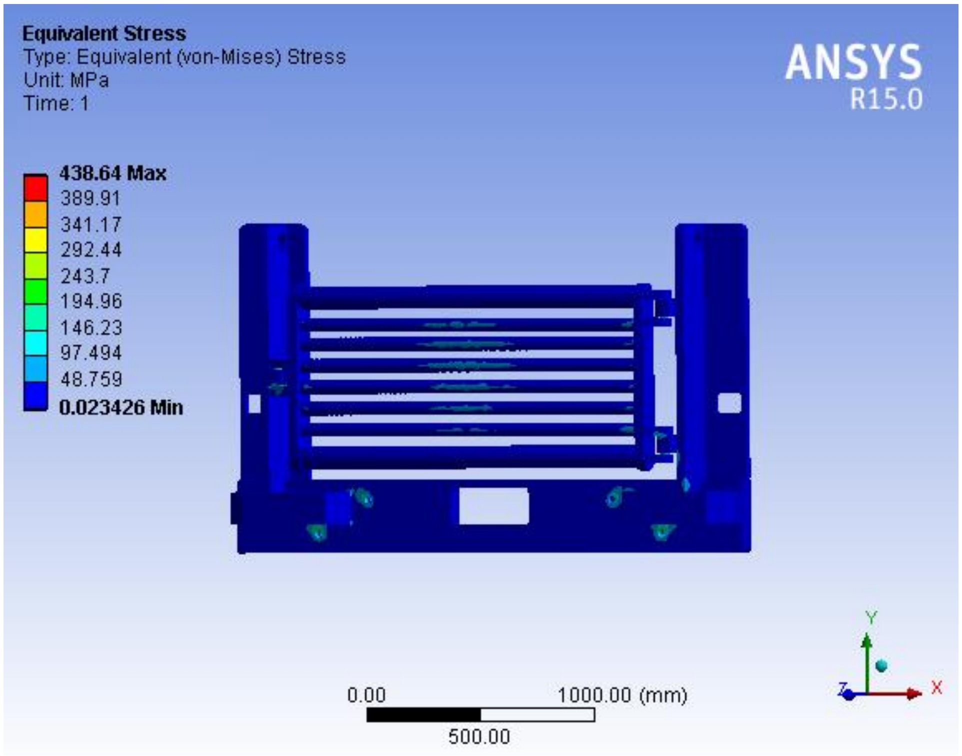


Figure 68: Static stress distribution in existing bumper

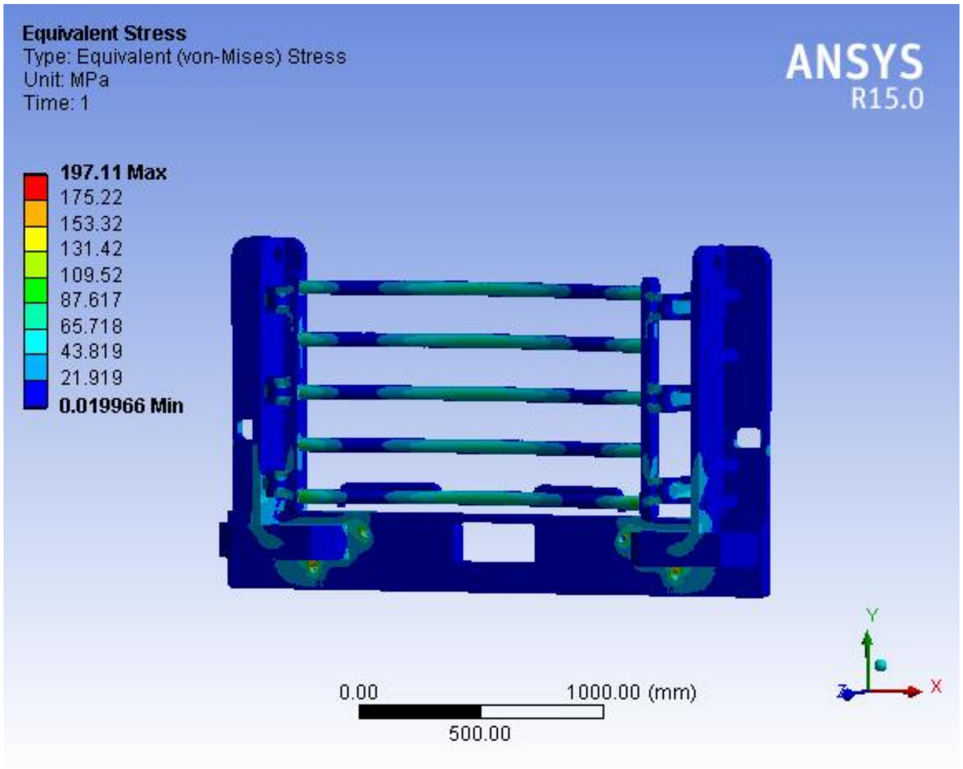


Figure 69: Static stress distribution in Single Door design

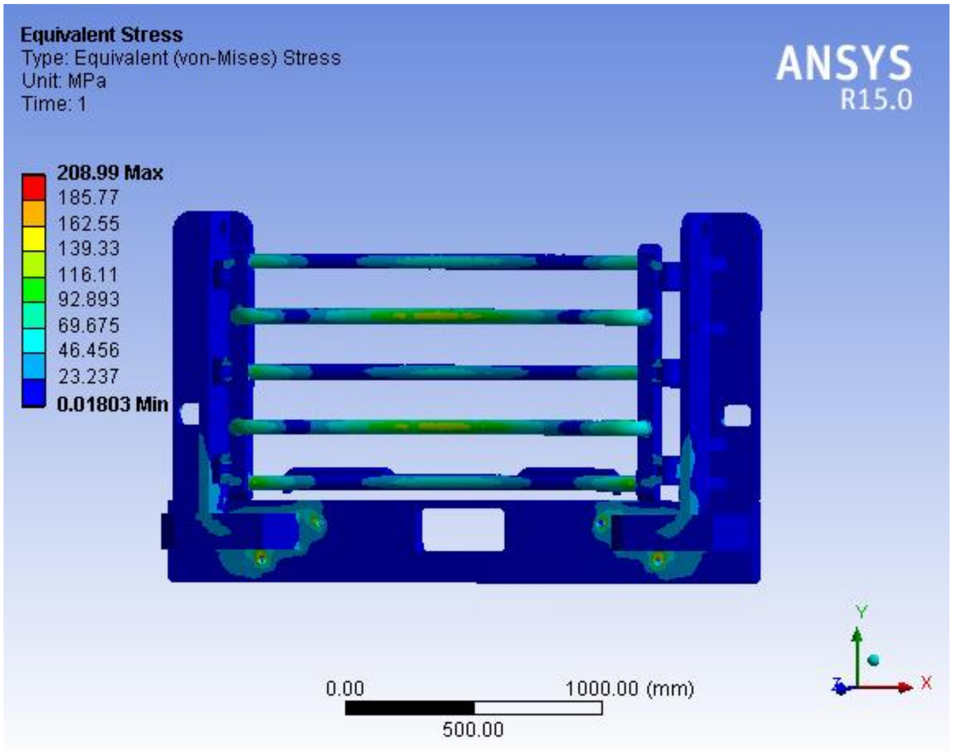


Figure 70: Static stress distribution in Crab Door design

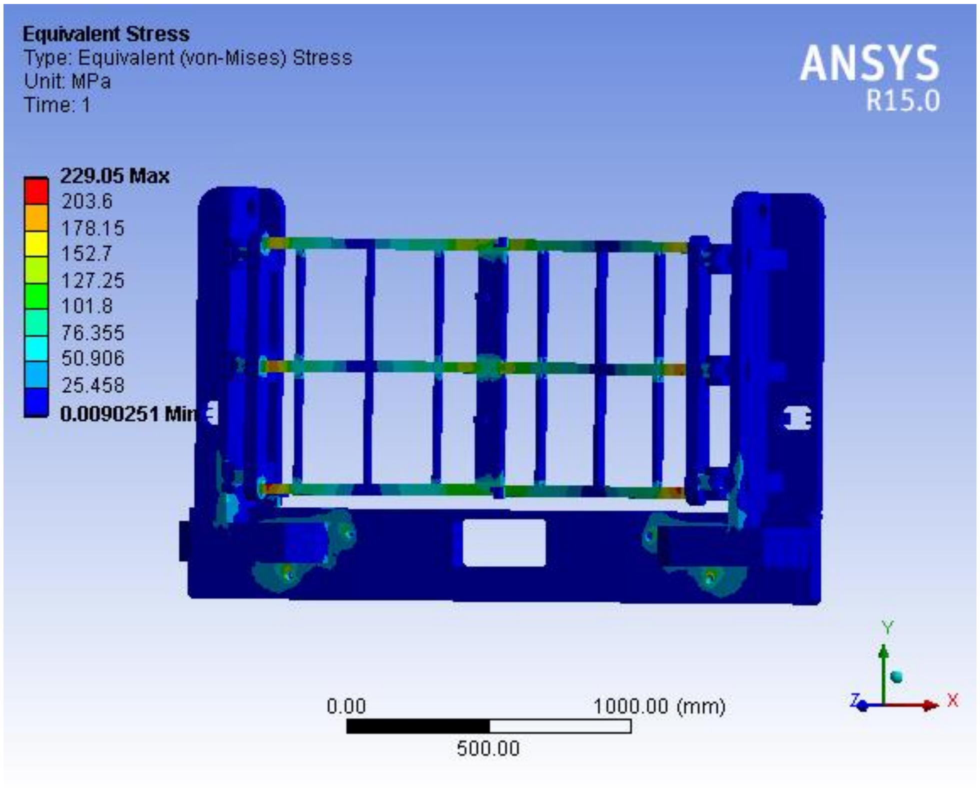


Figure 71: Static stress distribution in Double Door design

Equivalent (von-Mises) Stress (MPa)				
	Existing Bumper	**Single Door**	**Crab Door**	**Double Door**
🟥	438.64	197.11	208.99	229.05
🟧	389.91	175.22	185.77	203.6
🟨	341.17	153.32	162.55	178.15
🟩	292.44	131.42	139.33	152.7
🟩	243.7	109.52	116.11	127.25
🟦	194.96	87.617	92.893	101.8
🟦	146.23	65.718	69.675	76.355
🟦	97.494	43.819	46.456	50.906
🟦	48.759	21.919	23.237	25.458

Table 10: Comparison of static stress distribution

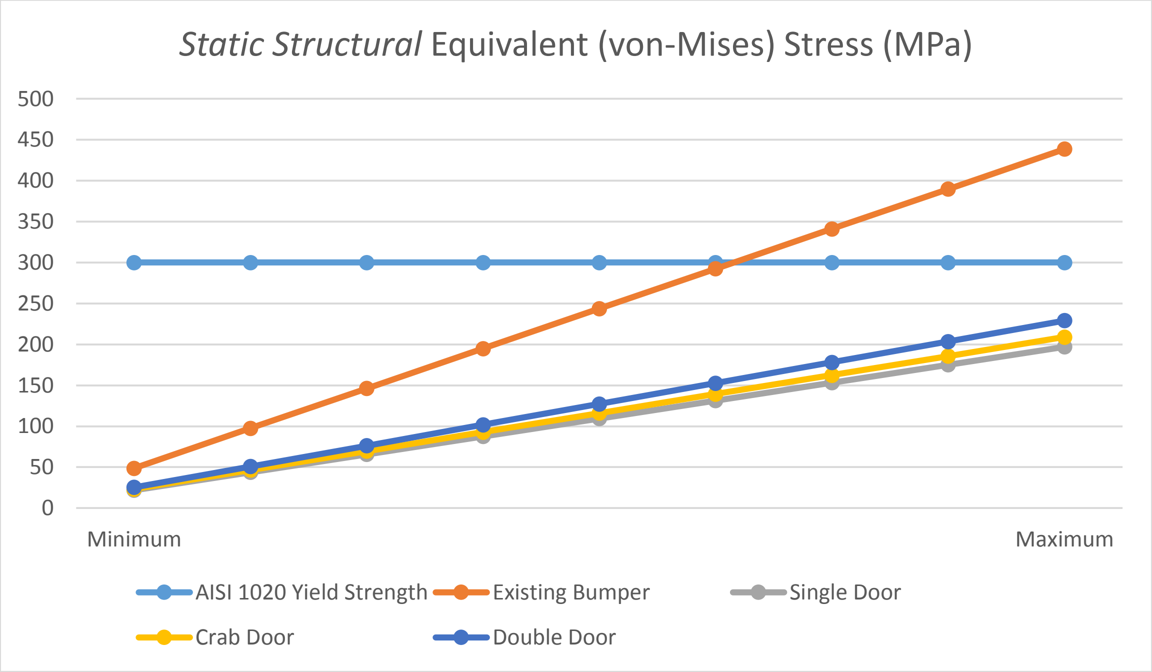


Figure 72: Comparison of static stress distribution

6.0 Manufacturing Cost Analysis

Design may only cost a fraction of the total expense of manufacturing, but can determine as much as 80% of the cost of production (Kalpakjian & Schmid, 2014). A finished design allows estimation of manufacturing cost, which is a preliminary assessment for production. A cost function sums direct and indirect expenses and provides the estimate (Perry, Green, & Maloney, 1997). Direct or prime expenses include raw materials, operating labor, utilities, and miscellaneous costs such as maintenance and repairs. Indirect or overhead expenses include quality inspection, logistics, and payroll. The typical cost structure of a multinational company (MNC) operating in the heavy machinery industry (such as Caterpillar Inc.) indicates that raw material procurement amounts to the greatest percentage of cost of goods sold (COGS) (Figure 73). Although this analysis only calculates the cost of the rear bumper, the percentages uphold for all components of the 980H and are additive (Equation 1).

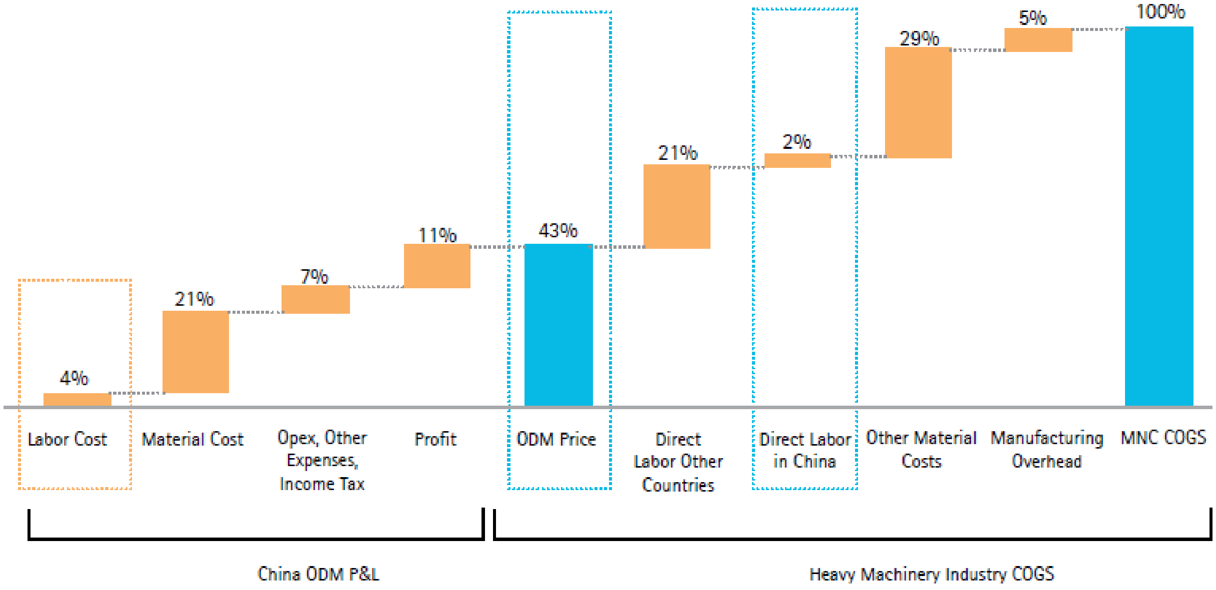


Figure 73: Multinational Company Cost of Goods Sold in the Heavy Machinery Industry (Accenture, 2011)

$$COGS_{980H} = \sum_{i=1}^{n} (COGS_{component\ i} + \cdots + COGS_{component\ n})$$

Equation 1: Additive property of COGS

Assume that Caterpillar (Suzhou) Co., Ltd. (CSCL) is a Chinese original design manufacturer (ODM). The cost of a standard 980H is approximately \$350,000, but the cost of the 980H2 with the additional cabin hood, window guard, standing plates, and rear bumper is approximately \$650,000 (Fengming, 2014). Assuming the bumper accounts for one quarter of the \$300,000 increase, the rear bumper is profitable if the COGS is less than \$75,000. Using the percentage of the bulk material cost, 21% (Figure 73), the COGS of the rear bumper is determined (Equation 2).

$$\left(COGS_{rear\ bumper}(\$) = \frac{Cost_{material}}{0.21} \right) \leq \$75{,}000\ to\ be\ profitable$$

Equation 2: COGS of the rear bumper and estimated profitability

The rough bulk materials estimate (Equation 3) depends on the weight of the material in tons and price per ton. The weight of material can be found by multiplying the volume of necessary stock material by the material density and converting to tons. The estimated volume of stock material estimate of the Double Door design excludes superficial features such as the rear camera mounting bracket, Truck Lock, and Four Link rear signal light protection system because their weight is insignificant in comparison to the main frame and door.

$$Cost_{material}(\$) = \left(\frac{Volume_{material}(m^3) * Density_{material}(\frac{kg}{m^3})}{1000\,\frac{kg}{ton}} \right) * \frac{Average\ Price\ (\$)}{ton}$$

Equation 3: Rough bulk materials estimate function

Dimensions for the major pieces of the main frame and door are taken from the drawings (Appendix A) and then translated into stock material dimensions. The smallest dimension is used to find the required thickness of the stock material. The length and width are calculated by finding pieces of the same thickness and adding them to a single piece of stock material. An additional eight centimeters is added to both the length and width of the stock material to account for machine tolerances and the distance removed by tooling. An additional centimeter is added to the thickness for surface finishing operations.

	Dimensions (m)			**Stock Material Dimensions (m)**			
Piece	X	Y	Z	Length	Width	Thickness	**Volume (m^3)**
Base	2.44	0.32	**0.09**	0.40	2.52	**0.10**	$V_1 = 0.1008$
Corner (2)	0.55	**0.14**	0.26	0.63	0.60	**0.15**	$V_2 = 0.0567$
X-axis plate (2)	0.32	1.12	**0.04**	4.00	1.20	**0.05**	$V_3 = 0.2400$
Z-axis plate (2)	**0.04**	1.12	0.32				
Door (2)	0.84	0.85	**0.04**				
Door frame (2)	**0.05**	0.97	0.08	1.26	0.24	**0.06**	$V_4 = 0.0181$
Door hinges (6)	0.07	**0.05**	0.07				
Frame hinges (12)	0.08	**0.03**	0.27	0.90	0.32	**0.04**	$V_5 = 0.0115$

Table 11: Major piece dimensions converted to stock material

The total volume of stock material in Table 11 is 0.4271 m^3. Multiplying by Q235 density, 7,850 kg/m^3, the total weight is 3,353 kg. Using supplier Tianjin Larry Co., Ltd., the price per ton of Q235 carbon steel ranges between $500 and $900 (TLCL, 2014) so an average of $700 is chosen. Using Equation 3, the rough bulk material estimate is approximately $2,350.00. Plugging this value into Equation 2, the Double Door design costs approximately $11,200.00. Hence, according to the aforementioned cost structure and assumptions, this design is profitable.

7.0 Future Recommendations

Though the project met the sponsor’s requirements, the time constraint of the project prevented evaluation of certain items that should be reviewed in the future. In terms of materials, advanced high strength steel (AHSS) is still in development and should be reviewed in the future. AHSS provides a lighter and stronger alternative to carbon steel and can be used to fortify existing structures well beyond the ability of carbon steel. With regards to the design, the center of gravity (COG) should be evaluated. The project required that the rear bumper function as the counterweight, which balances the 980H while carrying a full load. The same center of gravity (COG) should be used to maintain this equilibrium. Each design’s COG is slightly different than the existing design, though the difference is negligible in comparison to the size of the rear bumper. However, if problems arise, the designer should add or remove features where necessary because COG is independent of weight. The final recommendation is an early review of the finite element method to understand computer simulation setups and results. Finite element software requires significant computer resources and a workstation should be reserved for this purpose. In addition, a complete finite element model should be prepared for comprehensive results. Information such as the COG of the 980H should be collected to explore practical methods of including a representative body.

8.0 Conclusion

Through collaborative effort between Shanghai University and Worcester Polytechnic Institute, the group achieved the project goal by providing three innovative designs that solved the inadequacies of the initial design. The final choice made by the group was the Double Door design because of its functionality. Each door is lighter than the original and would bend less and in the event of bending, the lighter weight would be safer for workers to lift and realign. Furthermore, the Truck Lock was a solution that could circumvent alignment issues, and a Four Link rear signal light protection system could dampen the effects of impact, though these speculations were not proven. Superficial features such as washers between the bumper and 980H and wire-harness mounts were included in designs but not used for major decisions. Computer simulations excluded superficial features due to errors, but ultimately proved that the durability of each new design was comparable to the existing design. Moreover, a manufacturing cost analysis showed that the design was profitable. This project was a phenomenal experience providing an opportunity for using theory in practice. Each group member learned to evaluate the product design process and communicate with those from a culture different than their own. The trip to China was an outstanding cross-cultural and educational experience. The group hopes that its designs provide inspiration to others and that the report will be useful in the future.

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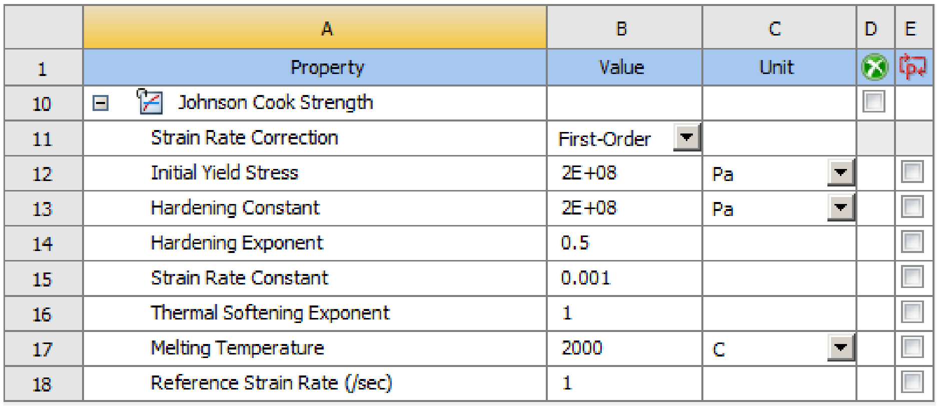
Appendix A: Computer Simulation Procedures

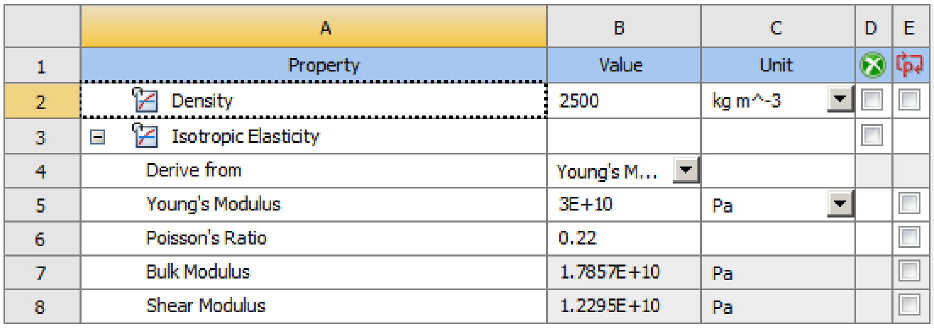
A.1 ANSYS Explicit Dynamic Procedure

The group first defined *engineering data* by adding the *Johnson Cook Strength* property to the steel material used (Figure 74). The *Johnson Cook Strength* property provided material information in the event of plastic deformation; without it, ANSYS would experience general failures because the material could no longer deform after elastic deformation. The wall used a material with properties similar to concrete (Figure 75). Alternatively, the default material *Concrete NL* can be used. After selecting the appropriate materials, SolidWorks assemblies had to be exported as Parasolid (.x_t) files to be imported by ANSYS *Design Modeler* and begin geometry simplification.



	A	B	C	D	E
1	Property	Value	Unit		
10	Johnson Cook Strength			☐	
11	Strain Rate Correction	First-Order			
12	Initial Yield Stress	2E+08	Pa		☐
13	Hardening Constant	2E+08	Pa		☐
14	Hardening Exponent	0.5			☐
15	Strain Rate Constant	0.001			☐
16	Thermal Softening Exponent	1			☐
17	Melting Temperature	2000	C		☐
18	Reference Strain Rate (/sec)	1			☐

Figure 74: Johnson Cook Strength plasticity data for steel



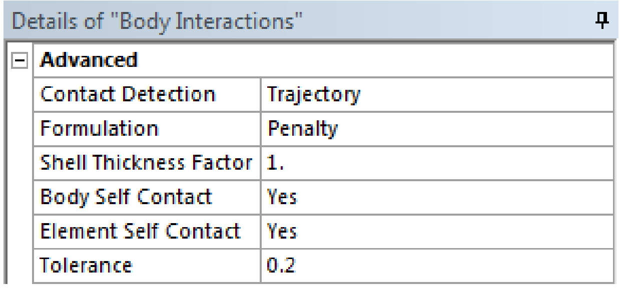
	A	B	C	D	E
1	Property	Value	Unit		
2	Density	2500	kg m^-3	☐	☐
3	Isotropic Elasticity			☐	
4	Derive from	Young's M...			
5	Young's Modulus	3E+10	Pa		☐
6	Poisson's Ratio	0.22			☐
7	Bulk Modulus	1.7857E+10	Pa		☐
8	Shear Modulus	1.2295E+10	Pa		☐

Figure 75: Concrete material properties

Geometry simplification began by deleting superficial features from the main frame and door(s). *Slice by surface* cut small protrusions from surfaces and *body delete* removed them from the geometry. Next, *fill* filled all holes including the lifting eyes and four bolt mounting holes. Slicing by surfaces often created cuts through the main frame and door and reassembly required using *create boolean*. Extruding cylinders within hinges created pins and ensuring that the parts of the bumper collided cohesively with the wall required using *create boolean*. After simplifying the rear bumper design, selecting the foremost faces using *create plane* with a z-axis *RMB translation* of one millimeter provided the plane for wall creation at a distance that would minimize simulation time.

Using *sketch*, a rectangle centered symmetrically about the vertical and horizontal axes with dimensions of 2,750 by 1,750 millimeters ensured complete contact between the wall and the bumper during collision. Extruding the rectangle a distance of 200 millimeters created a thick wall, which prevented breaking during collision. *Mid-surface* added a preventative measure for shattered walls. After simplifying the geometry and creating the wall, next was simulation setup.

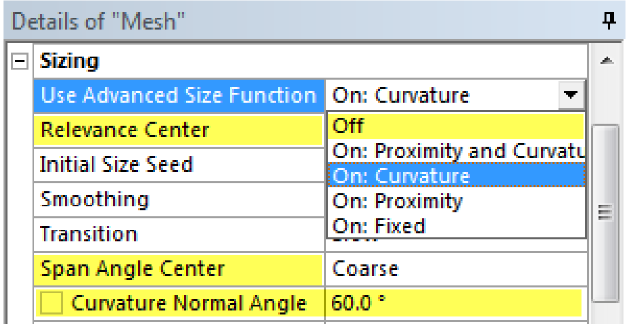
ANSYS sets a default material for solids so the rear bumper and wall material had to be specified. To prevent the bumper from passing through the wall during collision, body interactions had to be specified as well (Figure 76). The group used the *element quality* mesh metric of at least 0.7 average and adjusted mesh parameters to keep the number of elements below or around 150,000. This required adjusting relevance size, relevance center, span angle center, or using an advanced size function *on curvature* with a curvature normal angle of 60° (Figure 77).The procedure was trial and error because sometimes a high quality mesh could be achieved but there would a significant number of elements, or vice versa.



Details of "Body Interactions"

Advanced	
Contact Detection	Trajectory
Formulation	Penalty
Shell Thickness Factor	1.
Body Self Contact	Yes
Element Self Contact	Yes
Tolerance	0.2

Figure 76: Body Interactions



Details of "Mesh"

Sizing	
Use Advanced Size Function	On: Curvature
Relevance Center	
Initial Size Seed	
Smoothing	
Transition	
Span Angle Center	Coarse
☐ Curvature Normal Angle	60.0 °

Figure 77: Mesh Parameters

After creating a quality mesh with approximately 150,000 elements, the program was ready for setup. The bumper used a *velocity* of 11.5 m/s directed towards the wall. The *analysis setting* used a maximum of 20,000 cycles and end time of one millisecond to reduce simulation time. The wall was *simply supported* at its edges so that it would not move during the collision. Using the described method, the program ran successfully and completed each simulation within 12 to 18 hours.

A.2 ANSYS Static Structural Procedure

Static simulations used *Johnson Cook Strength* plasticity data but excluded a wall. The received model of the existing bumper excluded a piece in the rear camera mounting bracket. Thus, the only necessary simplification was removal of mounting brackets from all models, and addition of cylinders within hinges and locks to simulate pins. Using a mesh with *element quality* of 70% or greater and maximum of 150,000 elements, the next step was to apply a static load. In reality the only static load would be the force of gravity, but a force caused by collision was calculated and used to compare the deformation and stress of each design. Initially the force value was obtained using the impact force equation (Equation 4).

$$F = \frac{0.5 * mv^2}{s}$$

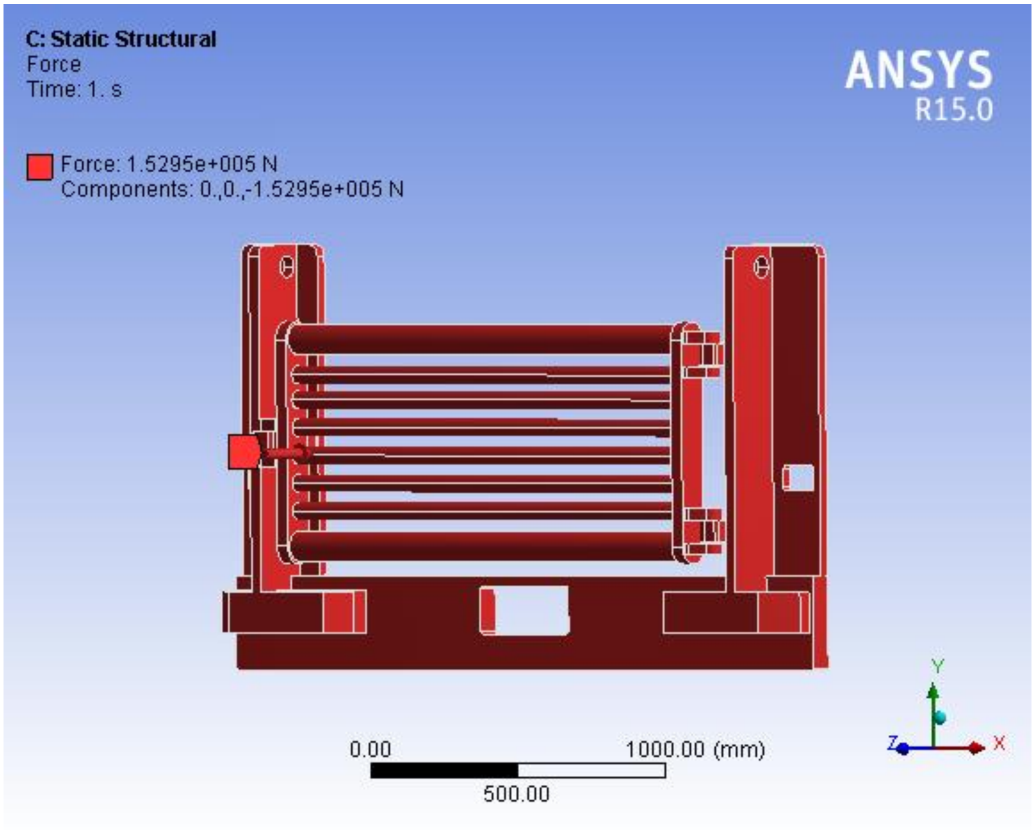
Equation 4: Impact Force Equation

The impact force equation is typically used for vehicles with a crush zone of compressible distance "*s.*" The 980H however, does not have a crush zone, so the group used an alternative method of calculating the force value, the impulse-momentum equation (Equation 5).

$$F_{average} * \Delta t = m * \Delta v$$

Equation 5: Impulse-Momentum Equation

To be consistent with dynamic simulations, only the mass of the bumper was used at a velocity of 11.5 m/s. However, because the impulse-momentum equation calculates average force, a change in time of 100 milliseconds was used to allow the average force to stabilize. A calculated force of 152,950 N was applied to all bodies by right-clicking the space around the geometry and clicking *select all bodies,* and was directed straight into the rear face of the bumper. Fixed supports were applied where the bumper is bolted to the 980H. Data for *total deformation* and *equivalent (von-Mises) stress* were collected in minutes at a time.



C: Static Structural
Force
Time: 1. s

🟥 Force: 1.5295e+005 N
Components: 0.,0.,-1.5295e+005 N

Figure 78: All bodies selected and force directed straight into rear-end.