Optimize Packaging Design for the Push Block Export

A Major Qualifying Project Report

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Abstract

This project, completed in collaboration with Huazhong University of Science and Technology, was to design a shipping rack for large parts, push blocks, for Caterpillar Suzhou. This project was completed after gathering necessary background information from Caterpillar and outside sources. Using this information, the design process began with brainstorming numerous concepts which were narrowed down, modeled in Pro-E and FEA was performed using ANSYS. The final design was tested theoretically for safe operation then presented to Caterpillar.

Acknowledgements

Our team would like to express our gratitude to Caterpillar Inc. and the employees at the Caterpillar facility in Suzhou. We would like to give special thanks to Paul Watts, Michael Liu, Scott Panse, and Dany Dong. Their help with facility tours, CAD files, information on the current shipping rack, and answering a plethora of questions was vital to this projects success.

We would also like to thank our two advising professors for their assistance, Professors Rong and He. Not only did they help with the project, they also provided assistance in adjusting to life in Wuhan. I would like to thank Huazhong University of Science and Technology for hosting me during the project.

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1 Introduction

Caterpillar Inc is one of the world's main producers of heavy machinery for uses in the construction, mining, and agricultural fields. Available products run a wide range including diesel engines, industrial gas turbines, and tunnel boring machines. Caterpillar also produces military equipment such as armored bridge layers, tank transporters, and the Trojan combat engineering tank.

The Suzhou Industrial Park (SIP) was launched February 1994, through heavy cooperation between China and Singapore. It is one of the fastest growing industrial development zones in the world. SIP is 4% of the land in Suzhou but makes up 25% of its gross domestic product. The Caterpillar branch in Suzhou produces medium wheel loaders and motor graders for worldwide distribution. The facility was designed to meet Leadership in Energy and Environmental Design standards and was awarded gold certification in March 2010.

The objective of this project is to design a new shipping rack for the push blocks for motor graders which are made in Suzhou. The current shipping rack is considered too robust and expensive for export. To reach this objective, an analysis of the current rack will be completed and areas of improvement will be identified. Multiple preliminary ideas will be drafted followed by evaluation to find the best product. The final design will have numerical evidence to confirm that it is the best option.

2 Background Information

2.1 Company Profile

Caterpillar started as Caterpillar Tractor Co. in 1925. It has been a leader in construction and mining equipment and is currently the largest supplier in the world. Caterpillar owns multiple brand names including: "Solar Turbines", MaK", "Olympian", and "MaK". Caterpillar is a global company, with 3500 offices spread through 180 countries.

In response to the increase business development, Caterpillar China Investment Company was founded in 1996. The Beijing based company was the first of seventeen manufacturing facilities that Caterpillar has today. These facilities produce a variety of products including excavators, generators, and motor graders.

This project was based at the Caterpillar plant inside the Suzhou Industrial Park. The park was created in 1994 through collaboration between China and Singapore. This plant specializes in manufacturing medium wheel loaders and motor graders.

Figure 1 A medium wheel loader (left) and a motor grader (right). Both are produced at the Suzhou Caterpillar facility.

2.2 Motor grader group and push block

This project focuses on the push block attachments on the motor graders. The Suzhou facility produces the K-series motor graders: 12K, 120K, 140K, 160K. The different models are generally the same design with variations to size and power. These machines range from 125 hp to 186 hp and 13 to 17 tons.

The push block attachment is a large counterweight that is attached to the front of the motor grader. This extra weight can be needed to correctly operate the motor grader if traction between the machine and ground is a problem.

Figure 2 A Caterpillar motor grader with the push block highlighted.

The current shipping rack and in-house transportation racks are too robust. There is opportunity to reduce the cost of the shipping racks and reduce handling time. The figure below is the two racks currently used in the Suzhou facility.

Figure 3 The shipping rack that brings the racks from the supplier to the Suzhou facility (left). The in-house rack used at the Suzhou facility (right). There are two moving parts which swing down to help hold the push block in place.

The push block is manufactured by a supplier and shipped to Caterpillar, four push blocks at a time. Once arriving at the facility, the push blocks are transferred into the smaller racks, holding only two push blocks. Transferring the push blocks takes about eight minutes, thirty minutes for a shipment of four. A worker uses a ceiling crane and a sling, inserted into the push block, to transfer them. These

racks are taken to get the blocks painted, where the blocks are removed from the rack temporarily. Once painted, the push blocks are placed back into the in-house rack and sent to the assembly line.

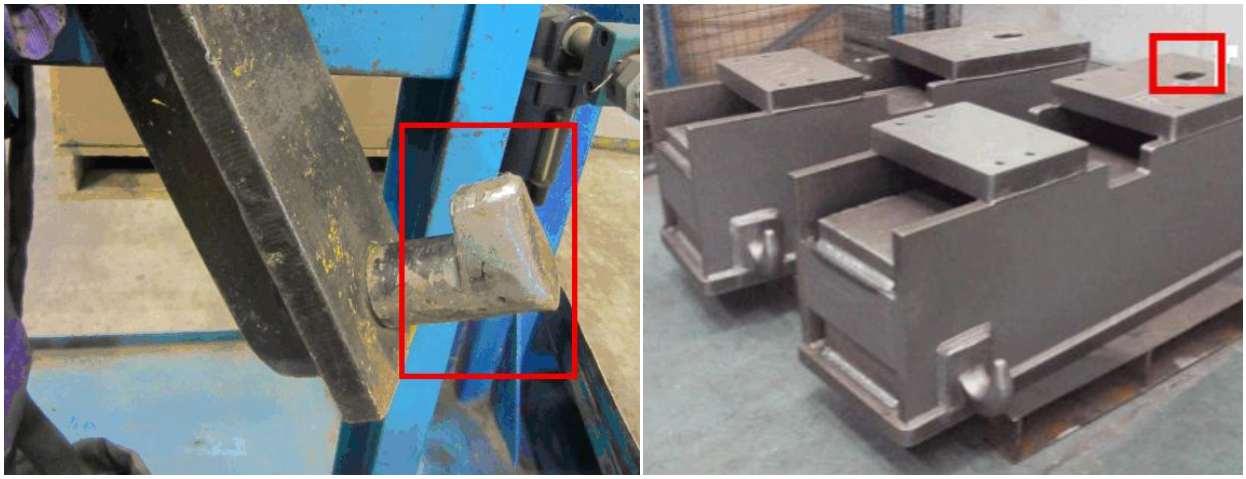


Figure 4 The sling used for transferring the push block from the shipping rack to the in-house rack (left). A push block highlighting the location that sling is inserted for transferring (right).

3 Methodology

In order to produce a successful design, our efforts needed to have direction and checkpoints throughout the project. Our main tasks are listed below:

- Clearly define the project
- Brainstorm a variety of preliminary designs
- Evaluate and modify designs to optimize results
- Objectively decide and recommend best design

When work began on each step, a more detailed plan was formulated to ensure the larger task would be completed effectively.

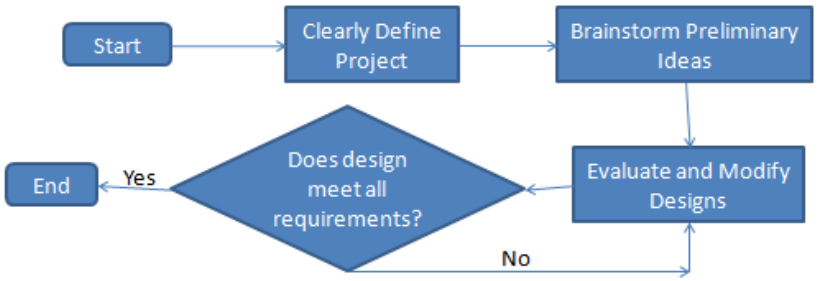


Figure 5 Methodology flow chart used in design process.

3.1 Defining the Project

The current design holds four push blocks, standing up. The rack itself has dimensions of 1.3x1.3x1.45 meters and weighs 185kg. Using this information, we calculated that the rack takes up .4225m^2 of floor space and the rack's weight per part would be 46.25kg.

Figure 6 Picture of the current shipping rack with 2 push blocks loaded.

When the parts arrive at the Suzhou facility, the push blocks are removed from the shipping rack and placed onto the in-house rack, a process that takes approximately 30 minutes for a worker to complete. The push block is 885kg and requires a special sling to be moved safely. With about 190 shipments per year, there are 95 man hours used every year unloading these shipping racks.

The main goal of our new design is to save Caterpillar money. They are a business and lower costs is an enormous driving force for change. By proving that our design could save the company money there is a better chance for implementation. The main areas of the design where money can be saved are:

- Reduction in material
- Lower or eliminating time needed to transfer push blocks to in-house rack
- Reducing the amount of floor space that the shipping rack occupies
- Increasing lifespan of shipping rack by reducing the threat of rust

Through emails with our contacts at Caterpillar we were able to gather key information necessary for understanding what the company wanted in our design. It was very helpful having contacts who work for the company as we were able to gather information that would normally be very difficult such as CAD files, costs of racks, and detailed information about the in-house processes. Having a strong understanding of the problem was vital to focusing our efforts.

3.2 Preliminary Designs

Having multiple preliminary designs was our second main objective. We had a tour of the Caterpillar facility in Suzhou at the beginning of the project, during which we were constantly discussing ideas that came to us while we gathered information. Seeing other racks used at the plant was also useful for finding small details in the design that we could implement into our projects, an example of this would be the hoof that many racks had.

By brainstorming a large amount of preliminary designs we could work on exploring more creative options which would lead to improvement in the final product. When brainstorming, nothing was ruled out right away. Even if a design as a whole did not accomplish our goals, a small part of the design could be taken from it and implemented on another design.

3.3 Evaluation and Modification of Designs

Our preliminary designs we evaluated on attributes such as weight, floor space, and number of parts per unit volume. By comparing these numbers to the current rack we were able to quickly eliminate preliminary designs that showed little improvement or those that went in the wrong direction.

A second visit to the Suzhou plant also gave us the opportunity to discuss the designs in more detail. We gained feedback from the Caterpillar employees which helped us reach the final design. These discussions were kept fairly informal, talking over lunch and during another walk around the facility. The most important part of this second visit was to confirm that the project was heading in the right the direction.

3.4 Deciding Final Design

Analytically proving that our recommended design was the final and the most difficult part of this project. We had to show through calculations which showed the rack being safe to use in the facility and finite element analysis.

Caterpillar employees told us that safety was the most important consideration so calculations were performed to simulate processes that the rack would need to withstand:

- Loading and unloading of push blocks into the rack
- A forklift carrying and placing a rack filled with push blocks
- Transportation while inside a truck
- Transportation on a ship

To ensure that the rack was physically sound, we used FEA to confirm that during operation there would be no failures. To simulate the large forces that would be present during operation we used finite element analysis in the programs ANSYS with 3D models created in Pro-E. Another point to check was that the rack would be compatible with the forklifts at the Suzhou plant. We measured the forklifts during one of the visits and got more specifications through email.

4 Design Process

4.1 Understanding Current Inadequacies

Understanding the current inadequacies of the current rack design was the leading objective of our project. From the information provided by Caterpillar we were able to learn that the safety is of security for the current rack moving around during transportation has led to no injury up to now. However, the current shipping rack that is designed for CSCL (Cat Suzhou China Ltd) is too robust and expensive for export.

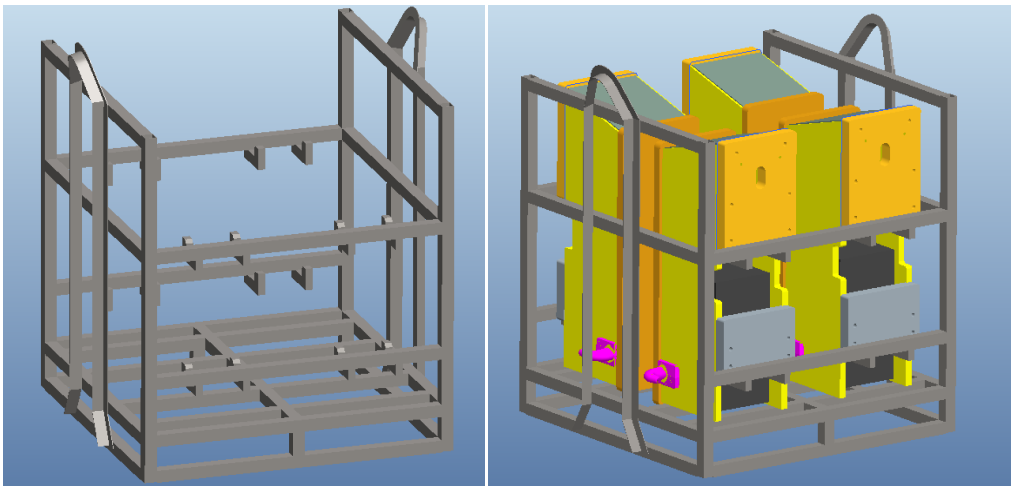


Figure 7 3D model of current rack with no push blocks (left) and fully loaded (right)

Table 1 Dimensions and weight of the current shipping rack

PCS PER CONTAINER	OUT SIDE DIMENSIONS (MM)			WEIGHT PER PACKAGING (KG)	
	L	W	H	PART	GROSS
4	1300	1300	1450	3540	3725

The current design holds four push blocks standing up. The total mass of the empty rack is 186kg, so we can conclude that the mass for each block space is 46.3kg.

4.2 Initial Ideas on Possible Structures

Because of the effect that the position has on the hooks which protrude from the push blocks, our initial ideas focused a lot on saving space by staggering the hooks. This reduces the space needed to put push blocks into the rack.

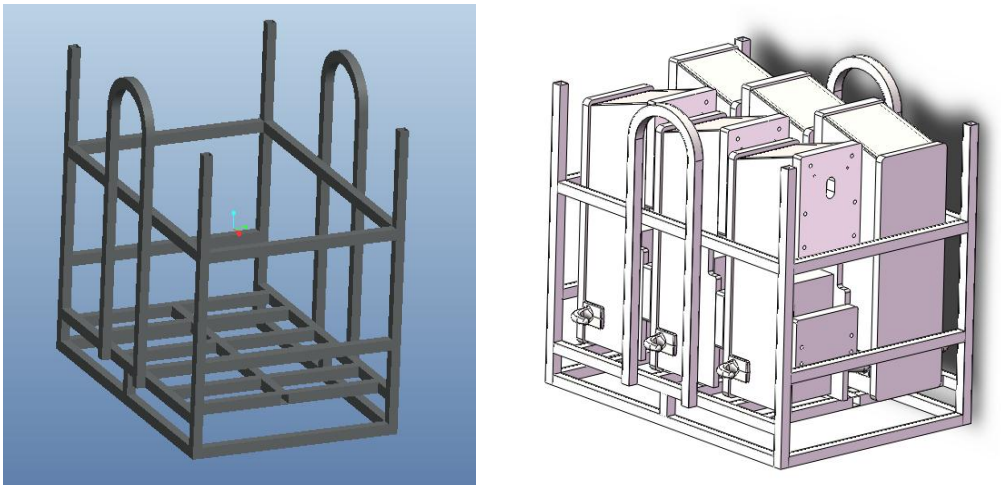


Figure 8 Preliminary Design 1: Rack holding 6 push blocks standing up.

The total mass of the rack is 176kg, and is approximately 29kg for per block, which reach to 32% weight reduction.

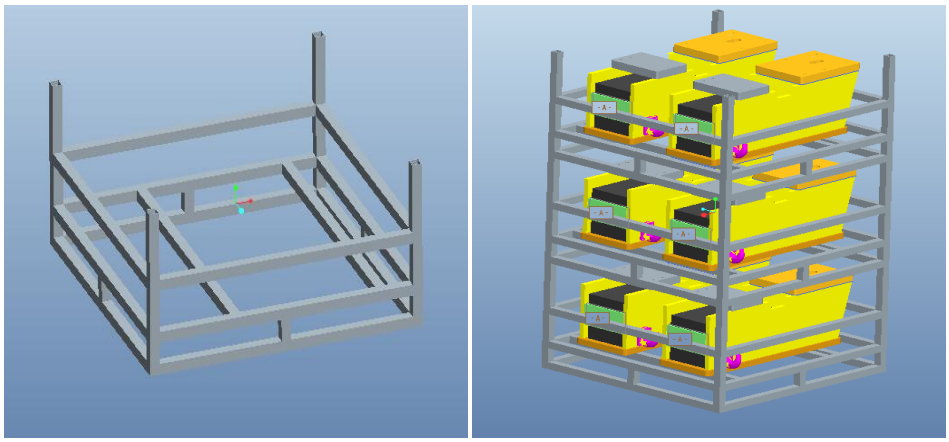


Figure 9 Preliminary Design 2: Rack holding 2 push blocks lying down.

The total mass of the rack is 114kg, and is 57 for per block, which lead to 21% weight increase. (Admittedly, after our second time to Caterpillar, we realize that the full-loading racks may not be stackable given that it is too heavy, however, at the brainstorm process, any creative ideas should be brought up and considered) There was also the possibility of this racking being able to go straight from the truck to use on the floor, eliminating the need to transfer the push blocks.

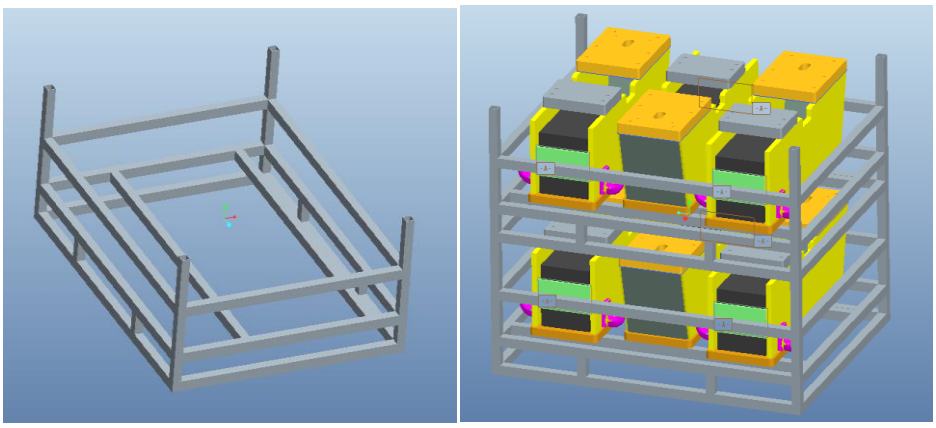


Figure 10 Preliminary Design 3: rack holding 3 push blocks lying down.

The total mass of the rack is 126kg, and is 42kg for per block, which reach to a 11% weight reduction. Once again, there was the possibility to eliminate transfer time. From the initial ideas that brought up above, we made an initial brief analysis and comparison as below:

Table 2 Comparison of preliminary designs and current shipping method. The mass of the rack is directly related to the cost to manufacture.

Comparison of different designs				
	Current rack	Design 1	Design 2	Design 3
Mass(kg)	185	176	114	126
Loading Quantity	4	6	2	3
Mass/Quantity	46.3	29	57	42
Volume (m^3)	2.451	2.608	1.511	1.764
Volume/Quantity	0.613	0.435	0.755	0.588

From the table above, we can see the difference between the current rack and the initial possible structures. What is important is that we realize that the cost and weight are directly related and should be focused on. This initial brainstorming and design iteration will illuminate and direct our next design attempts.

4.3 Company Feedback

As set in the schedule, we made a second visit to the Suzhou facility in the fifth week of the project. in this trip, we were well welcomed by the company and got more useful information about the racks and some feedback to our preliminary design.

The feedback we received included:

- The weight of 6 push-blocks are out of the capacity of forklift.
- The rack is just designed for transportation, it's unnecessary to think about protecting the painting stuff before reaching the facility.
- There is no need to design foldable part for the rack, which will cost a lot in manufacturing.
- Each push-block should have enough room to de placed in the rack
- Because the rack filled with cargo is too heavy to be stacked, there's no need to consider about the stacking process.
- The main purpose of redesigning the racks is to reduce the cost and weight, but not to make it multifunctional

4.4 Additional Analysis of Current Rack

From the information given by CAT, the weight of current rack is 185kg. Measured by ourselves during the tour of the facility, the dimension of current section is 50 *50mm, and 3.5mm in thickness.

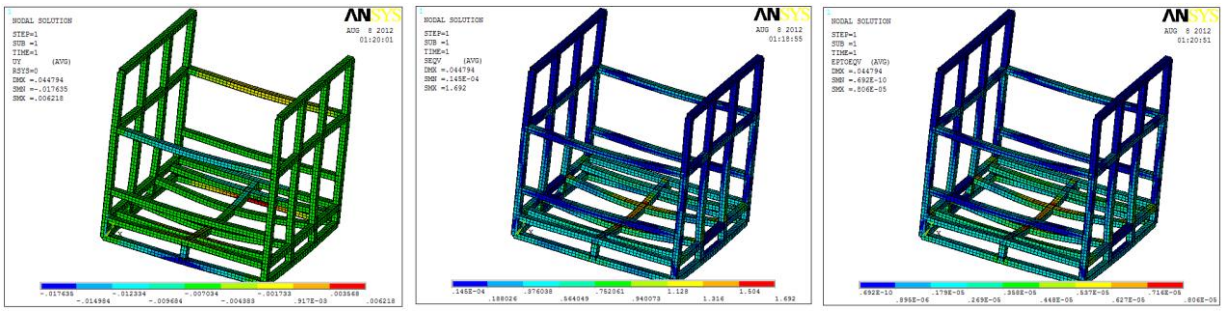


Figure 15 On left, von Mises strain nephogram. Middle, von Mises stress nephogram. Right, Y component of displacement nephogram of current rack.

From these above FEA analysis, the maximum strain is .0062 and a maximum stress of 1.682 MPa. This analysis gives an idea of where material could be removed and where it needs to be increased.

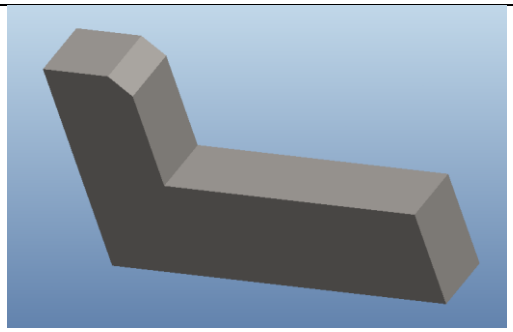
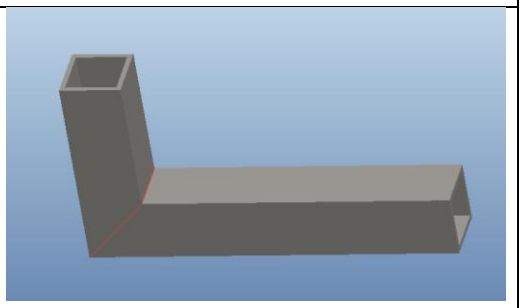
4.5 Redesign of Securing Component

The securing component of the current rack, shown below, is solid steel and provides more support to the push block than necessary. Unlike the bottom of the shipping rack, this component keeps the push block from moving in the xy plane. However these forces are small compared to the vertical force.

Figure 16 Securing component on the current rack. It is made of solid steel even though there is a low amount of force applied.

It is recommended that instead of using a solid piece of steel, a square piece is used, with a small amount of cutting and welding to achieve the correct shape.

Table 3 Redesign of the securing component.

Comparison of the located blocks	The current located blocks	New design
The 3D model		
Material	Steel Q235	Steel Q235 (Square steel)

Manufacturing method	Forging	Cutting and welding
Mass	2.74kg	0.54kg

The manufacturing process of the limiting component in three steps:

1. Cut a piece of square steel and to the correct length.
2. Then use the cutter bar to make a incision. Its angle is 90 degree.
3. Then weld the incision in the three lines.

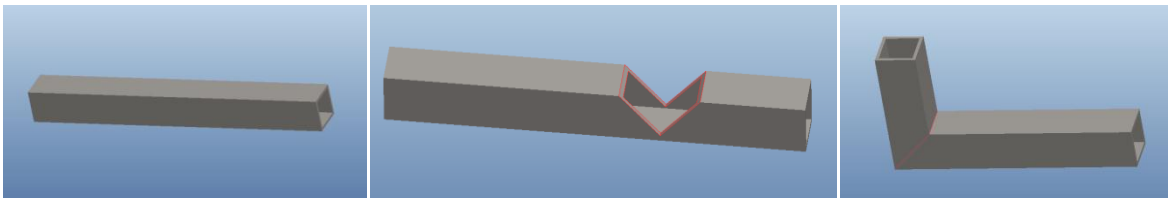


Figure 14 Three steps for manufacturing limiting component.

This new design lowers the weight by a significant amount. With each shipping rack having 16 of these components, there will be a decrease of 39.6kg.

4.6 Reduction of Cross-section

In this final portion of the design process, FEA was utilized to continually check if there was room for reduction in material. The tables of FEA analysis can be found in Appendix C. The process started with 4 similar models to find the best to begin our redesign at (Appendix C, #1).

The maximum stress found was 90.49MPa. With a safety factor of 2.2, this is an allowable stress. At this point all steel had dimensions of 25*25mm with 3mm thickness. However, when impact forces are taken into consideration (Appendix C, #2) The von Mises stresses and strain are unacceptably high. The dimensions are changed to:

Table 4 Dimensions and thickness after considering impact forces.

	Dimensions	Thickness
Square Steel Sections	35*35mm	36*36mm
Angle Steel Sections	3mm	3mm

This increase in material brought the maximum stress to 112.86MPa (Appendix C, #3). This was still slightly above the allowable stress of 106.8MPa. Using the FEA nephogram there was a concentration of stress in the corners. To combat this concentration 8 ribs were added to produce the following model:

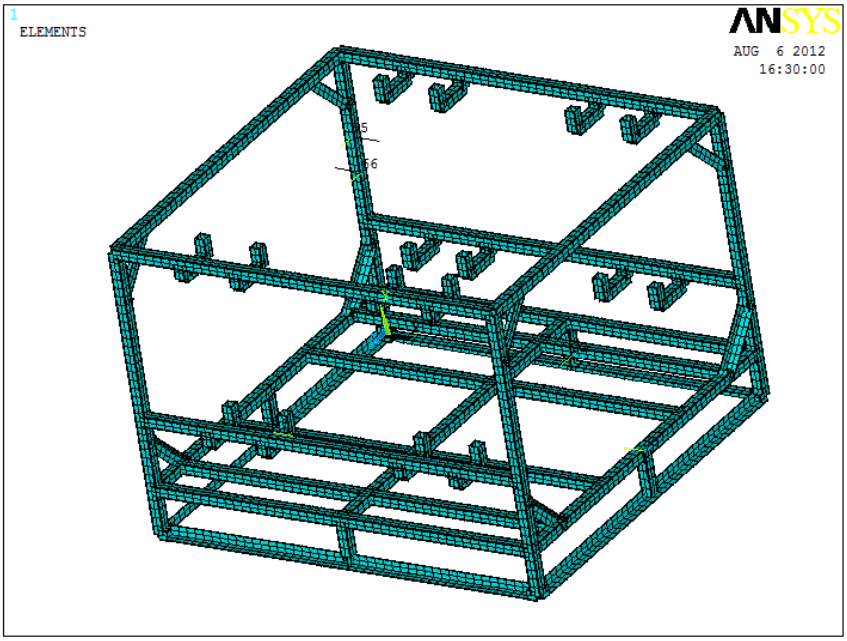


Figure 14 3D model of design after the addition of ribs.

This lowered the maximum stress to 98.8MPa (Appendix C, part #4). There was still some room for improvement. Some areas of the rack had very little stress applied and could have some material removed. The final change was to replace 6 bars with Angle steel with dimensions 30*30mm and a thickness of 3mm. These bars are shown in red below.

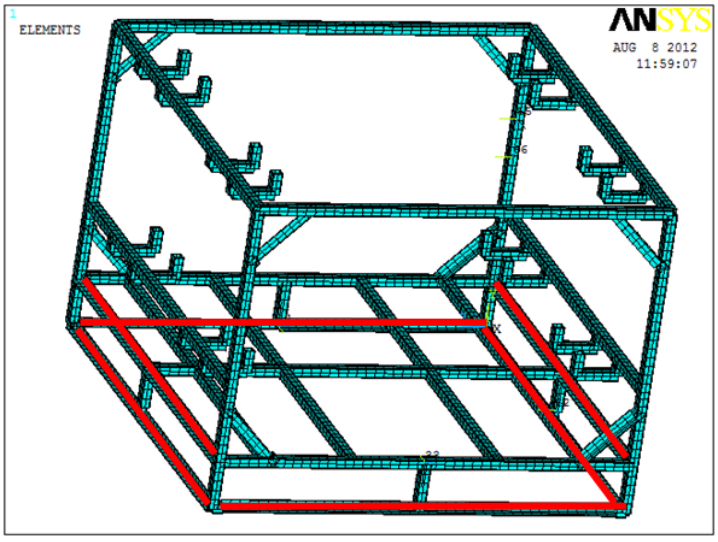


Figure 15 Final design with the 6 unique bars highlighted. Highlighted bars are 30*30mm with a 3mm thickness. Other bars are 30*30mm with a 3.5mm thickness.

With this design the maximum stress is 92MPa (Appendix C, #5). This is well under our allowable stress of 106.8MPa with an included safety factor of 2.2.

5 Cost Analysis

To estimate the manufacturing cost of a single rack, which mainly consists of the material costs, painting and welding costs. From above we know that the mass of the final rack design is 70kg. And from Caterpillar we know that the mass of the current rack is 210kg while the cost of current rack is 1580 RMB, including the material cost and other cost. For the material cost, the cost per ton of Q235 was 4500 RMB, which was obtained from the Chinese website Alibaba and the cost of our rack was estimated by using its weight. So we can infer that the material cost of the current design is 4500/1000*210=945 RMB while the cost of the final rack design is 4500/1000*70=315 RMB. Furthermore, we can draw that the rest of the current rack cost is 1580-915=635 RMB, which can be used as a reference resources for the final rack design. As a result, the rest cost of the final rack design must be reduced accordingly because of the reduction of the weight.

Besides, the cost of making guide structure was also estimated using the information on Alibaba. The welding cost was found by using the standard labor hourly rate in China and multiplying it with the estimated number of hours needed to make our rack. The cost of making rack was found to be around 820 Yuan.

Table 5 Estimation of manufacturing costs for new shipping rack.

estimation of manufacturing cost	
item	cost(RMB)
Material Cost	350
guide structure	200
paint	20
welding or manufacturing cost	250
total	820

6 Conclusions

We conclude that our final design meets Caterpillar's requests. Our objectives for weight reduction and cost reduction have been meet and exceeded. Our rack is able to hold 4 push blocks during static and dynamic use. Through our methodology, we created preliminary designs, narrowed them down through analysis and feedback. The final design was created through extensive finite element analysis. We are proud to present our new push block shipping rack to Caterpillar.

Appendix A - Project Charter

Caterpillar Suzhou China (Ltd) Project Charter

6th March 2012, 2011

Project Title: Optimize Packaging design for the Push Block Export

Business Case:

The "Push-Block" is a counter weight situated on the front of the Motor grader and is commonly use to push machines if they have traction problems in difficult ground conditions, hence the name "Push-Block" The Motor Grader Product Group currently manufactures 3 different product families: K, M and M2 Series. The push block design between these families is common and creates the possibility to manufacture in China and source world wide.

Opportunity Statement:

CSCL (Cat Suzhou China Ltd) has developed a local supplier to manufacture the K-Series Push Block and the same supplier has been selected to manufacture the M and M2 Series for our Brazilian and United States Facilities. The current shipping rack that is designed for CSCL (Cat Suzhou China Ltd) is too robust and expensive for export and there is an opportunity to reduce the cost and weight of the design

Goal Statement:

Y1 = Low Cost Export Shipping Rack

X1 = Finite Element Analysis (FEA)
X2 = Low cost materials
X3 = Easy loading and Unloading

Tools or Skills Required:

The team will need to understand and learn the following to enable the project to be successful:

- 3D model software, Pro/e is preferred
- 2D drawing is necessary

Project Timeline and Team:

The project team should submit a list of activities and planned completion dates.

Team:

Michael liu is the MWL Engineering Team Leader based in Suzhou and they will serve as the team's primary contact related to project questions and learning material.

Appendix B - Process and forces present during loading

Loading

1. Putting four push blocks into one rack, which has four stop blocks to limit the position of the push blocks. In this procedure, the company uses the sling to hook the hole of each push block in order to move it vertically. In the loading process, the push block should be moved behind the stop blocks to avoid a collision. When the push block gets past the stop blocks, it is moved towards and is lowered a short distance before the final position, in which the push block is locked into place.

Sling used for transportation of push block.

Given the numerical definition of the impact acceleration and the impact.

Because the falling process is stable, we can estimate that the maximum of the speed of the push block before the final position is about 0.15m/s. This information was obtained from the workers in Caterpillar while discussing the spray-painting process. The movement of the push block is smooth and the data from the company shows that the push block should be hoisted 5 meters for 20 minutes, making the lifting speed 0.25m/s. So the estimated impact is given by the equation:

$$F_z = mg + \frac{mv}{t}$$

Given that the metal collision time is in the rank of percentage of seconds, we set t as 0.05 seconds, so we can conclude that F_z=12.8*m.

2. The process of using the forklift to carry the rack with four push blocks consists of three phases, forklift lifting, transportation, and the placing the rack down.

Forklift lifting process: Give the numerical definition of the ascending acceleration and the impact.

The average velocity obtained from the plant is 0.25m/s. From this, the most ascending acceleration, with time as 20s and dividing the ascending height into three parts equally, we can conclude that the acceleration is 0.05m/s². Using a safety factor of 2.5 (as suggested in *mechanics of materials*), the maximum acceleration is 0.125 m/s^2. The supportiveness:

$$F_z = mg + ma = (9.8 + .125)m = 9.925m$$

During transportation, we also must consider the acceleration of the forklift forward and backward.

Defining the acceleration of the forklift forward and backward:

The maximum velocity of the forklift is 20km/h (5.6m/s). The next step is to estimate the maximum acceleration forward and backward. Assuming a time of 3s, then the acceleration is a=1.9m/s^2.

The static and dynamic friction coefficient between Steel and steel without lubrication is 0.15.

Thus the friction is:

$$f = \mu mg = .15 * 9.8m = 1.47m$$

To conclude, the applied force from push block on the rack is

$$F_x = ma - f = 1.9m - 1.47m = .43m$$

Fx=ma-f=1.9m-1.47m=0.43m.

In the loading process, the rack with four push blocks will be loaded into the truck using a forklift, which will be loaded into the container for export.

If the process is the same as the picture above, then it is necessary for us to consider the forklift loading platform tilt angle α.

From our research, the largest climbing degree of the no-load forklift (3-5t) is 20% while the degree of full-load forklift is 18%. We set the degree at 20% for calculating the maximum value of α.

tan α *100%=20%, so α =11.3°
from tan θ = μ ,we can draw that θ =arctan0.15=8.53° < α
So the force received by the side of the rack is given by:

$$F_x = mg\sin\alpha - \mu mg\cos\alpha = .48m$$

If the company does not use the loading platform, then the method is below:

Forklift placing process: we need to define the maximum acceleration of the placing process and the impact contacting with the ground.

Set the impact as:

$$F = mg + \frac{mv}{t}$$

With v = 0.25m/s and t = 0.05s, we conclude that F_z=14.8m.

3. The transportation while in a vehicle

Defining the acceleration of driving and braking, the maximum tilt angle and the corresponding acceleration of the upper and lower vibration:

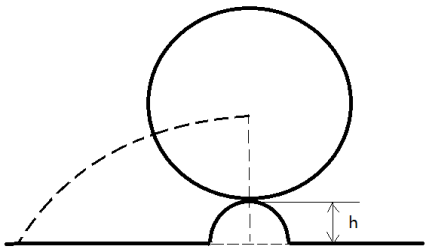
The speed limit of highway on trucks is 100m /s, and the dynamic friction coefficient of truck tires while sliding is 0.7. Thus, the maximum acceleration is:

$$a = \mu g = 6.86 \frac{m}{s^2}$$

The maximum slope of the vehicle is 30%, and the maximum angle of the slope, β, is given by the equation:

$$100 \tan \beta = 30\% \ \therefore \ \beta = 16.7°$$

To simplify the obstacle negotiation process of truck tires, road condition is divided into different situations between pits and bulges. Since the vehicle collision with the ground while falling from the bulges will which result in a shorter reaction time than other situations, this



process is selected to estimate the freight conditions. Pictured above, the highest prominence is regarded as h = 0.2m according to road conditions. Using the kinematic equations is:

$$gt = v$$

$$\frac{1}{2} g t^2 = h$$

Solving for v (the velocity at impact): v=1.98m/s

Using momentum theorem ：

$$F_z t' - mgt' = mv$$

The contact time is estimated as t´=0.2s according to the contact situation of the tire and the ground. Solve for F_z, the instant impact, F_z=19.7m

4. For the shelves, the loading process and the transport process of the container are necessary to consider about.
   To analysis the loading process of the container, we need to define the maximum rise and fall acceleration.

To analysis the transport process of the container, we need to define the maximum tilt angle.

Analysis of the impact of the loading process:

A special machine is generally used for loading and unloading the containers at the port. According to the test, the impact allowed within the strength of the container, in addition to instant contact with the ground, is shown in Table 1. The impact recorder is mounted on the bottom of the container while tested.

Table 1 shows that in the loading process, the horizontal and vertical maximum impact values are 1.1g and 1.8g respectively. The longitudinal maximum impact value during the stop process is 2.1g. In the unloading process, the horizontal, longitudinal and vertical maximum impact values are 2.4g, 1.5g and 4.2g respectively.

The friction coefficient of static and dynamic friction between steel without lubrication is 0.15.

So the friction is given using the following formula:

$$f = \mu mg = 1.47m$$

Therefore: The horizontal maximum impact value is:

$$F_x = 2.4mg - f = 22.05m$$

The longitudinal maximum impact value is:

$$F_y = 1.5mg - f = 13.23m$$

The vertical maximum impact value is:

$$F_z = 4.2mg + mg = 50.96m$$

The impact of container loading and unloading:

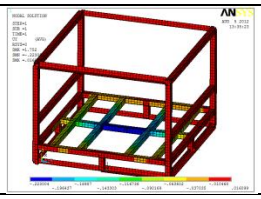
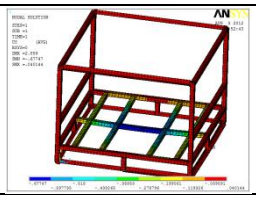
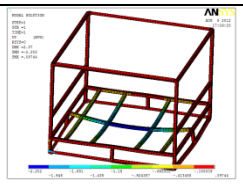
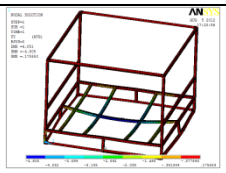
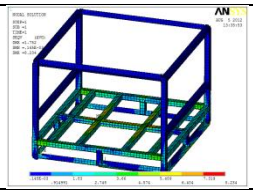
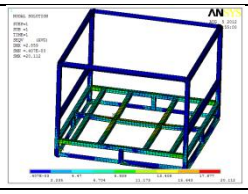
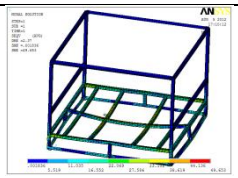
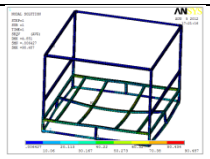
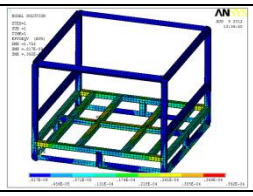
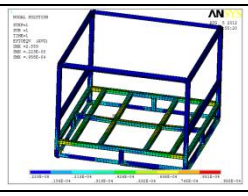
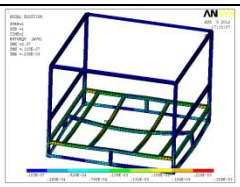
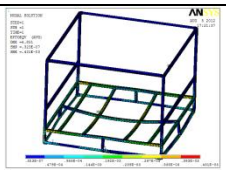
the measured direction		lateral direction	longitudinal direction	vertical direction
straddle carrier	uplifting	0.2g	0.2g	0.4g
	run	0.6g	2.0g	0.8g
	stop	0.6g	2.1g	0.9g
	descend	1.1g	1.1g	1.8g
crane	uplifting	1.5g	0.1g	0.3g
	temporary stop on board	1.0g	0.3g	1.2g
	loading on board	2.4g	1.5g	4.2g
	uplifting	0.2g	—	—
	temorary stop on quay	0.3g	0.4g	1.4g
	unloading in factory	1.4g	0.2g	1.4g

Table 6 Waterway container transport machinery and environmental conditions, (Z. Min Zhao, S. Li Qin)

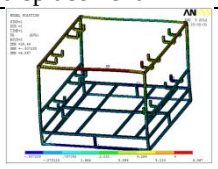
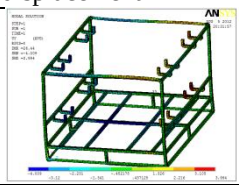
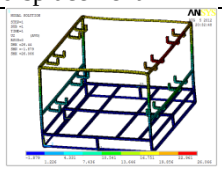
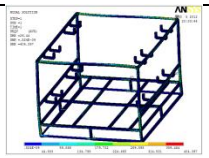
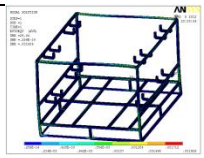
5. Caterpillar will unload the cargo when the racks with the push blocks are transported to the factory. The process is divided into several aspects below:
    - Using the forklift to move the cargo down from the trunk. In this movement, the maximum lifting acceleration and the maximum tilt angle of the forklift loading platform will be the same as in procedure 2.
    - Using the forklift to transport the cargo to the proper position in the factory. In this movement, define the acceleration of the forklift forward and backward. The method is the same as procedure 2.
    - Using the forklift to put the cargo down. In this movement, defining the downward acceleration of the forklift and the impact contacting with the ground would be the same as procedure 2.

Appendix C - FEA Analysis for cross-section reduction

1 Beginning models:

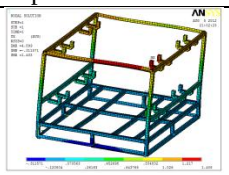
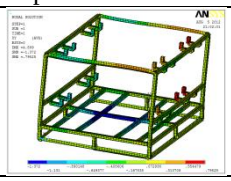
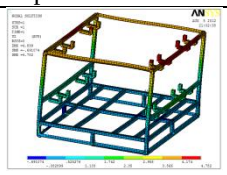
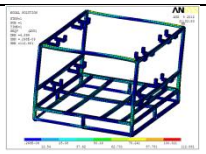
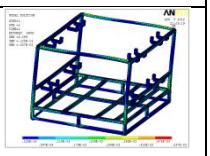
	Model 1	Model 2	Model 3	Model 4
Section	Square steel 50*50*3.5 Angle steel 50*50*3.5	Square steel 40*40*3 Angle steel 40*40*3	Square steel 30*30*3 Angle steel 30*30*3	Square steel 25*25*3 Angle steel 25*25*3
Profile	Square steel: four bars on the bottom and the two bars on the top. Angle steel: all other bars.			
Y component of displacement nephogram				
Maximum Y component of displacement(mm)	0.223	0.677	2.202	4.805
Von Mises stress nephogram				
Maximum von Mises stress(MPa)	8.234	20.112	49.653	90.487
Von Mises total strain nephogram				
Maximum von Mises total strain	0.392e-4	0.958e-4	0.236e-3	0.431e-3

2. FEA analysis when impact force is taken into consideration:

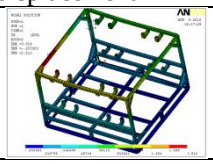
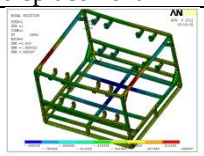
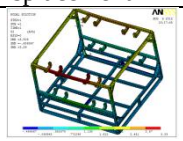
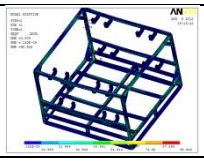
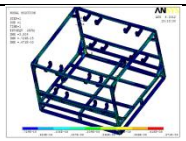
	X component of displacement	Y component of displacement	Z component of displacement	Von Mises stress	Von Mises total strain
nephogram					

Maximum value	6.867mm	4.009mm	26.066mm	404.397MPa	0.001926

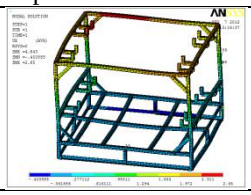
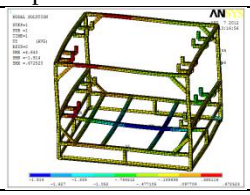
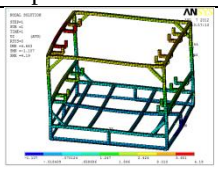
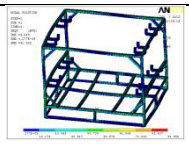
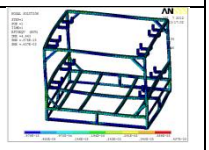
3. After changing the cross-section in model 4 to 35*35mm for square sections, 36*36mm for angle sections, and a thickness of 3mm:

	X component of displacement	Y component of displacement	Z component of displacement	Von Mises stress	Von Mises total strain
nephogram					
Maximum value	1.408mm	1.372mm	4.782mm	112.861MPa	0.537e-3

4. After the addition of ribs in 8 of the corners:

	X component of displacement	Y component of displacement	Z component of displacement	Von Mises stress	Von Mises total strain
nephogram					
Maximum value	1.812mm	0.965mm	3.29mm	98.846MPa	0.471e-3

5. After replacing 6 bars of square steel with angle steel on the bottom portion of the rack:

	X component of displacement	Y component of displacement	Z component of displacement	Von Mises stress	Von Mises total strain
nephogram					
Maximum value	2.66mm	1.914mm	4.19mm	91.582MPa	0.437e-3

Bibliography

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