Sand Mold Clamping

Final Report

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Project Number: 46.1
Project Sponsor: ESCO
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DISCLAIMER

EXECUTIVE SUMMARY

Project Context

ESCO Incorporated manufactures a variety of steel parts using a sand mold casting process. In this process a clamping device is used to prevent the sand mold from leaking during the pouring process. The current clamp design has several deficiencies including an uneven distribution of the clamping force, mold damage caused by the engagement of the clamping device, and the manual disengagement of the clamp. These factors result in defective parts and time delays in part manufacturing. The MIME capstone design team 46.1 was tasked with creating an improved clamping device that would eliminate these issues and increase profits for ESCO.

Design Process

The team began the design process by analyzing the customer needs and developing corresponding engineering requirements. The second step in the process consisted of researching a variety of clamping designs and design components used both within and outside of the casting industry and evaluating them according to how well they satisfied the required functions. Based on this information the team created four different clamp designs. The four designs were then evaluated against the engineering requirements and ranked in a decision matrix. The concept with the highest ranking was selected as the final design.

Selected Design

The clamp design selected for implementation, shown in Figure 1, is based on two main components: a rack and pinion jack and an adjustable steel footprint. The rack and pinion jack reduces set-up time by combining the clamp height adjustment and clamping force application with handle rotation. The force is applied smoothly, thus avoiding damage to the mold. The adjustable footprint uses steel angle irons that can withstand the high temperatures of the casting process and a slotted connection to accommodate a variety of mold layouts. It also distributes the required clamping force evenly. Finally, the design utilizes two pinned connections that allow the clamping device to disengage automatically from the sand mold.


Figure 1: "Rack and Pinion" sand mold clamping device

Implementation and Testing

The team purchased the "Rack and Pinion" jack from a company in Germany and purchased the remaining parts from local hardware stores. Next, the team performed all of the welding and fabrication for each of the components of the clamp at Oregon State University. The clamp was then assembled and tested on a simulated sand mold. Load cells were used to demonstrate the ability of the clamp to provide the necessary clamping force as well as the force distribution. Additional tests on the clamp were performed including: durability, setup time, maintenance, sand mold clearance, and the ability of the clamp to auto disengage.

Results and Recommendations

The clamp design passed all of the tests. Based on the implementation and testing, modifications were made to improve the functionality of the clamp. First, the team replaced the plastic handle on the jack with an aluminum handle for increased durability. Second, the team added a sheet metal guard around the bottom portion of the rack to prevent damage due to liquid metal splashing onto the rack. In the future, the team recommends replacing the manually operated handle with an attachment that allows for a pneumatic drill to reduce setup time. Additionally, the team recommends adding a torque wrench attachment to the handle to provide a more consistent clamping force each time the clamp is engaged.

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We thank the project sponsor ESCO and their representative, Ryan Carpenter, for providing the time and resources for this project.

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TABLE OF CONTENTS

1 BACKGROUND

1.1 Introduction

The purpose of this senior design project is to design and build an improved clamping device for a sand mold casting process. Sand mold casting is a widely used process in manufacturing to cast a broad variety of metal parts. Sand molds are formed by pressing patterns made of plastic, wood or metal, into tightly packed sand. These molds are made out of two halves: the cope (top half of the mold) and the drag (bottom half of the mold). Together, the two form a cavity which is a replica of the pattern. During the casting process molten metal is poured into the mold. The liquid metal produces a ferrostatic pressure pushing up on the inside of the mold. If left unclamped, the cope will float, causing molten metal to leak from the mold, resulting in a defective part. To prevent defective parts, it is important to ensure that both halves of the mold are secured tightly together [1, p. 10.1 ff].

ESCO, the project sponsor, is a worldwide operator of casting foundries. They currently use a clamping device that is inexpensive and somewhat effective, but it is unreliable, difficult to operate, and introduces other issues to the casting process. To replace the current device, ESCO is looking for a clamp that prevents leakage while maintaining or exceeding the current clamp performance. The intent is to increase their productivity while minimizing the number of defective castings, leading to increased profits. If successful, ESCO will incorporate the new design at foundries in Canada and China.

1.2 Project Description

Projects often change in scope and purpose during the design and build stages. This can cause the project to go off course, directing more effort to the changes and less on the original scope of the project. To ensure the final clamp design meets all the design requirements, it is important to document the original project description. The following is the original project description as provided by the sponsor:

> *The goal of this project is to develop an improved clamping device for use in sand casting foundries operated by ESCO. Current clamping methods are problematic both in difficulty of operation and effectiveness at maintaining mold "closure" during casting. The new clamp design must improve on the current method in place at the foundries. There have been issues with the existing clamps - liquid metal leakage between the cope and drag due to poor clamping force distribution. The new design must distribute clamping force evenly over a given area and provide sufficient clamping force to prevent metal leakage. The new design needs to accommodate numerous fill hole locations as well as being quickly disengaged from the sand mold once the casting process is complete.*
>
> - *Device must accommodate all molds within a specified envelope range.*
> - *Must apply a specified amount of pressure evenly along perimeter of mold.*
> - *Device must disengage automatically as the mold is discharged from the pouring tray and device must remain with the tray.*
> - *Must have an equal or lesser installation time than the current clamping system.*
> - *Devices must be durable and easy to maintain for sustained foundry use (2 years before failure on all moving parts, off the shelf components preferred).*
> - *Device must be made of heat resistant material.*

1.3 Original System

The information on the original clamping system was gained by the team during a 10/15/2012 plat tour of the ESCO facility in Portland, Oregon. The original sand mold clamping system is used in ESCO's foundry in Xuzhou, China. It provides an easy and inexpensive way to apply the necessary clamping force. The following sections describe the current clamp's structure, operation, performance, and deficiencies.

1.3.1 Original System Structure

The current clamping device is part of an assembly line process that produces cast parts. Each mold sits on its own steel carrier deck, shown in Figure 1.1, which is attached to a monorail. The current clamping device then attaches to the carrier deck. The clamp is engaged to the mold at the beginning of the monorail after the mold is loaded on the deck. The carrier decks are then mechanically pulled along the monorail past the metal pouring station where the molten metal is poured into the mold. At the end of the monorail the clamp is released and the mold is removed from the carrier deck. It is important to note that the carrier deck will not change in its overall design, but it could require additional components to attach the new clamping device.

Figure 1.1: Sand mold carrier deck. Photo by Benedikt Bochtler

As seen in Figure 1.2 on the next page, the current clamping device has two parts that connect the carrier deck to the mold. The first part is used to distribute the load across the mold surface. This consists of a piece of angle iron, approximately the length of the mold, with an eyelet welded on the top. The second is used to apply the clamping force. It is a piece of round steal bar that has been bent to an angle of slightly less than 90°. In addition to the two parts, a piece of steel pipe is welded to the carrier deck. This is used to connect the clamping device to the carrier deck. While all parts remain with the carrier deck, this device requires assembly before the clamp is engaged.

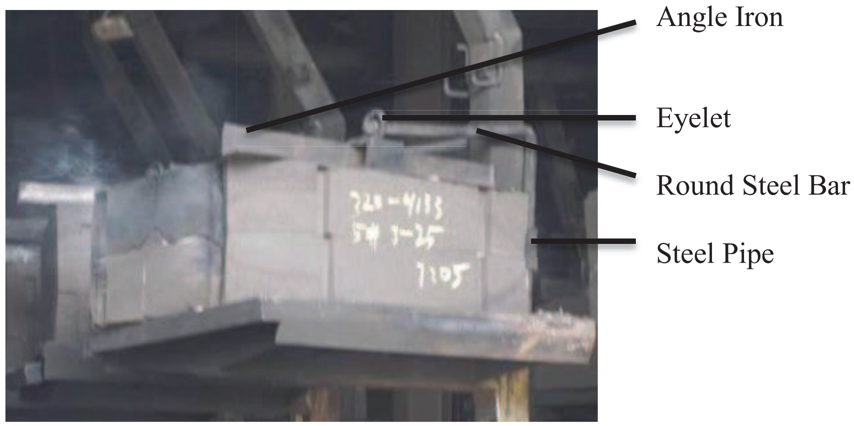


Figure 1.2: Sand mold on a carrier deck in an ESCO foundry, being clamped with their current clamping device. Image provide by ESCO.

The clamp is assembled by sliding one end of the round bar into the carrier deck pipe and the other into the eyelet. Each carrier deck is equipped with two clamps, one for each side of the mold.

1.3.2 Original System Operation

As described above, the current clamping device is assembled by sliding one side of the round bar into the pipe attached to the carrier deck and the other end into the angle iron eyelet. At this point the round bar and the angle iron are adjusted manually to accommodate multiple sprue (fill holes) and riser (holes that accounts for metal shrinkage) layouts. Once the desired footprint is achieved, the clamp is then set by striking the top of the round bar with a hammer, as seen in Figure 1.3. The impact force of the hammer wedges the bar deep into the pipe. As the bar is wedged in the pipe, it begins to elastically deform, causing a reaction force pushing down on the mold. Figure 1.4 on the next page illustrates how the reaction force is achieved. Although the angle iron does apply a force due to its weight, most of the clamping force is due to the reaction force caused by the round bar.

Figure 1.3: The current clamping operation. A hammer is used to set the clamp by striking it. Image provided by ESCO.

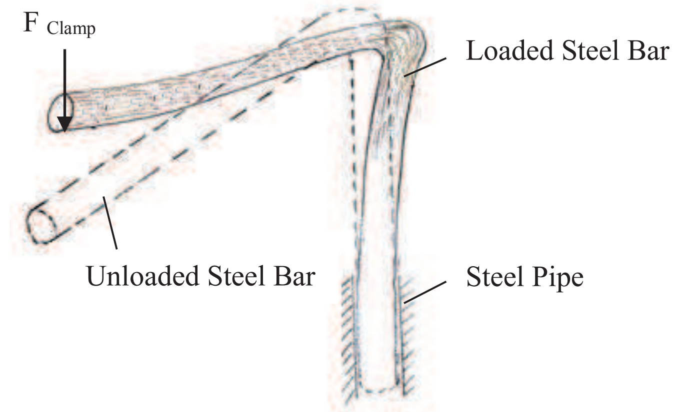


Figure 1.4: The elastic deflection of the round steel bar provides the clamping force.

Once the casting process is complete, the mold is moved from the carrier deck to a conveyor by two hydraulic pistons. These pistons extend forward pushing the mold and the casting onto a conveyor. To prevent the angle iron from being pushed onto the conveyor, the current clamping system must be manually released, introducing both safety issues and increased production time.

1.3.3 Original System Performance

As described above, the current design utilizes two clamps, one on each end of the mold. ESCO has estimated that together, the clamps are capable of applying a total clamping force of 400 lbs, enough to secure the mold tightly together. The clamping system is versatile and can be manually adjusted to fit multiple sprue and riser locations. The setup and removal time for the clamp is 28 and 20 seconds, respectfully. It is made entirely out of steel, making it suitable for the high temperature environment, common in the casting process. The system however does not distribute the clamping force evenly around the parameter of the mold. Figure 1.5 illustrates a displacement finite element analysis (FEA) of one quarter of a mold, showing that the displacement is not uniformly distributed over the mold surface, as the colors show.

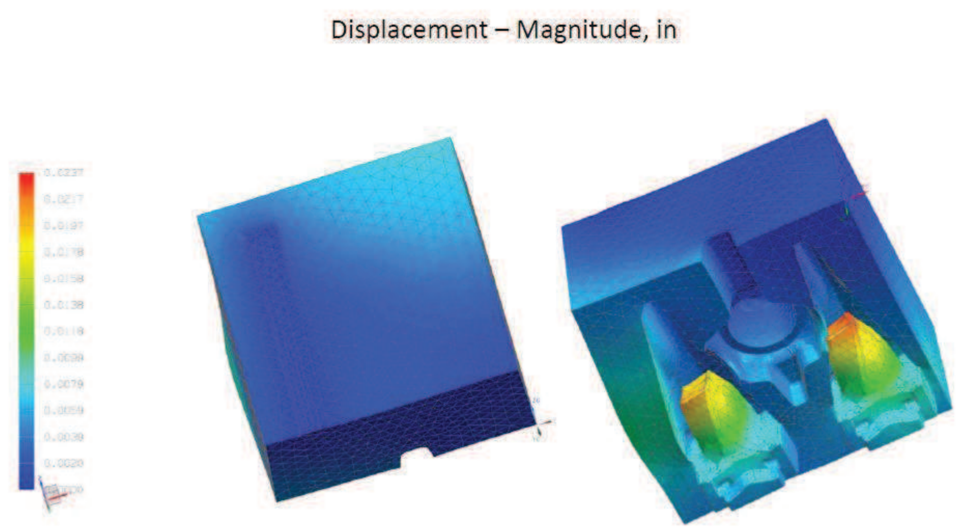


Figure 1.5: FEA for the displacement magnitude of a quarter of the mold. Image provided by ESCO.

1.3.4 Original System Deficiencies

Although the current sand mold clamping system already meets most of the design requirements, three major deficiencies in the clamping device require redesign:

1. **Uneven force distribution.** As seen in Figure 1.5, the current system is not distributing the load evenly over the top surface due to uneven hammering to the steel bars, exposing the mold to possible metal leakage.
2. **Problems with clamp set up.** As described above, a hammer is used to wedge the steel bar into the pipe. Over time the repeated striking and exposure to heat begins to weaken the bar, causing it to deform. The hammering also causes problems with the casting. As the steel bar is struck the vibration causes small pieces of sand to flake off the mold. The sand then falls into the cavity of the mold and causes defects in the casting.
3. **Problems with clamp removal.** After the casting process, the mold is removed from the carrier deck. As described in section 1.3.2 , two hydraulic cylinders are used to push the casting from the carrier deck to a conveyor. When the pistons make contact with the mold, the steel bar, used to apply the force, slips out of the eyelet of the angle iron. The then disengaged angle iron remains on top the mold as it moves onto the conveyor, which is then transported to a cooling bin 100 ft away. This requires additional resources to retrieve the angle iron. To prevent this from happening, the clamp is manually removed, introducing a safety hazard and increasing production time.

2 REQUIREMENTS

The project description provided by ESCO lists several critical design requirements. To ensure these requirements are achieved, it is important to understand each one. This is done by developing customer requirements (CRs), and then engineering requirements (ERs).To ensure the design satisfies the ERs, testing procedures (TP) and design links (DLs) are developed for each one. The following sections cover the CRs, ERs, TPs, DLs and the house of quality (HoQ) that depicts all of these in tabular form.

2.1 Customer Requirements (CRs)

The customer requirements serve as a contract between the customer and the design engineer and are used to describe the performance, features, and general characteristics of a project. The thirteen CRs in Table 1 were developed from the original project description as well as emails from ESCO. Point values adding up to a total of 250 were assigned to twelve of the customer requirements, based on their relative importance to the sponsor. The thirteenth CR was assigned as a low technical effort (LTE) requirement. Although this requirement is not weighted, it must be met to fulfill the customer requirements.

Table 1: Customer requirements and weightings for sand mold clamping device.

Customer Requirements	Weighting
1. **Clamping device shall be able to fit multiple mold sizes.** ESCO uses molds ranging between 18”x18”x12” and 34”x34”x20”. The final design should fit mold sizes within this range.	25
2. **Exposure to elevated temperatures shall not affect device performance and functionality.** Most of surface of the mold ranges between 70-120 °F, reaching up to 800°F near the risers. The final design should function properly at these elevated temperatures.	15
3. **Clamp device shall disengage automatically to prevent binding during mold ejection.** The existing design requires the clamp to be manually disengaged before the mold is removed from the carrier deck, introducing a safety hazard as well as decreasing productivity. The final design should be capable of disengaging without human interaction.	25
4. **Clamping force shall meet or exceed current design.** The current design applies a force of 400 lbs to the mold. The final design should meet or exceed this force.	25
5. **Clamping force shall distribute force evenly on the mold.** A distributed force is required to prevent metal leakage. The final design should distribute the force evenly over the surface of the mold.	20
6. **Clamping footprint shall provide access to multiple sprue and riser locations.** ESCO uses a variety of molds with different sprue and riser locations. The final design should provide access to all mold sprue and riser locations.	25

continued

7. **Device shall remain with the carrier deck.** The current clamp design requires disassembly to prevent being ejected from the carrier deck. The final design should eliminate this step, increasing productivity.	30
8. **Clamping device shall not damage mold.** Sand mold are fragile can damage easily. If damaged, sand could fall into the mold cavity and cause defects in the casting. The final design should not damage the molds.	25
9. **Off the shelf components are preferred.** The clamp could fail due to different reasons. Custom parts require time to fabricate which increase downtime and manufacturing costs. In order to prevent this, the final design should utilize off the shelf components when possible.	10
10. **Functional life of clamp shall be at least 2 years.** The final clamp should be designed to last for 2 years to prevent maintenance costs.	20
11. **Maintenance of device shall be minimizes.** In order to reduce maintenance costs, the final design should require a minimal amount of maintenance.	15
12. **Initial setup shall be less than or equal to current design.** To maintain or increase productivity, the setup time for the final design should not exceed the combined setup and removal time of the current clamping system.	15
13. **The chosen design of both groups must be sufficiently unique.**	LTE

2.2 Engineering Requirements (ERs)

Engineering requirements are developed as a way to measure each customer requirement. Their description must be specific and contain a verifiable quantity. The 14 ERs listed in Table 2 were developed from the customer requirements in section 2.1. Each ER was then given a target and tolerance which reflect the requirements presented by the project sponsor.

Table 2: Engineering requirements, targets and tolerances for sand mold clamping device.

Engineering Requirements	Target(s) / Tolerance(s)
1. **The maximum clearance between the clamp and carrier deck shall be higher than 20".** As described in CR #1, ESCO uses clamps up to 20” in height. To ensure the mold can be loaded onto the carrier deck, the clamping device must not obstruct the motion of the mold. The clamp is designed to sit 24” above the carrier deck with a minimum height greater than 20”.	24” >20”

continued

2. The mold entrance width from the front side of the carrier deck shall not be less than 34". As described in CR #1, ESCO uses molds up to 34” wide. To ensure the mold can be loaded onto the carrier deck, the clamping device must not obstruct the motion of the mold. The clamp is designed with an entrance gap of 40” with a minimum width of 34”.	40” >34”
3. All components shall operate properly at temperatures up to 800°F within 2" of sprue and risers. As described in CR #2, temperatures reach up to 800°F near the risers. This requires the clamping device to operate properly at these elevated temperatures. This engineering requirement is evaluated as a pass or no pass.	Yes N/A
4. Mold shall exit carrier deck with the exclusive use of the ESCO's pistons. As describe in CR #3, the clamp must allow the mold to eject from the carrier deck without human interaction. This engineering requirement is evaluated as a pass or no pass.	Yes N/A
5. Device shall provide a minimum total reaction force of 400 lbs. As described in CR #4, this clamp must provide a clamping force greater than or equal to the existing clamp design. The clamp is designed to supply a force of 500 lbs with a minimum of 400 lbs.	500 lbs ≥400 lbs
6. Device shall equally distribute the force within 20% of the mean value. As described in CR #5, the clamp must equally distribute the force over the surface of the mold to prevent metal leakage. The clamp is designed to distribute the force within 10% of the mean value with a maximum of less than 20%.	10% <20%
7. Clamp footprint shall be adjustable to prevent covering sprue and risers on the provided 5 layouts. As described in CR #6, the clamp must be adjustable, allowing it to fit multiple sprue and riser locations. This engineering requirement is evaluated as a pass no pass.	Yes N/A
8. Device shall attach to the carrier deck. As described in CR #7, the clamp must stay with the carrier deck to reduce production time. This engineering requirement is evaluated as a pass no pass.	Yes N/A
9. The engagement of the clamp shall not crack mold. As described in CR #8, the clamp must not damage the mold. This is primarily to prevent defects in the castings. This engineering requirement is evaluated as a pass no pass.	Yes N/A
10. Force applying device shall consist of parts from a catalog. As described in CR #9, the final design must consist of over the counter parts. This engineering requirement is evaluated as a pass no pass.	Yes N/A

continued

11. **The clamp must operate for 2,700 Cycles before failure.** As described in CR #10, the final design must operate for a specified amount of time. The clamp is designed to last 3000 clamping cycles, but must meet or exceed 2700 clamping cycles.	3000 cycles ≥2700 cycles
12. **The maximum maintenance time shall not exceed 1 hour for every 2 months.** As described in CR #11, the final design requires a minimal amount of maintenance. The clamp is designed to require no maintenance, but must be less than or equal to 1 hr per 2 months.	0 ≤1 hr / 2 months
13. **The clamp setup time shall not exceed 48 seconds.** As described in CR #12, the final design must meet or exceed the time required to setup the current clamp. The clamp is designed with a setup time of 30 sec, but must not exceed 48 sec.	30 sec ≤48 sec
14. **The selected design shall be sufficiently unique between the two groups.** As described in CR #13, the final clamp must be unique between the two groups. This engineering requirement is evaluated as a pass no pass.	Yes N/A

2.3 Testing Procedures (TPs)

Testing procedures (TPs) are developed for each engineering requirement and are used to verify that the design meets the ERs. Each ER is either verified by testing, demonstration, inspection, analysis or expert opinion. The TPs in Table 3 were developed for the 14 ERs in section 2.2. Each TP corresponds to the same numbered ER.

Table 3: Testing procedures for the selected design.

Testing Procedures (ER)
1. **Verification by Testing** The clamping device must sit higher than 20” above the base of the carrier deck to meet the vertical height constraint. The device is tested by raising it to its highest position and measuring the vertical clearance. To pass the test, the vertical clearance must be greater than 20”.
2. **Verification by Inspection** The horizontal clearance of the clamping device must be greater than 34” to meet the horizontal constraints. The device is inspected to show that there are no obstructions that prevent the mold from entering and exiting the carrier deck.
3. **Verification by Analysis** The clamping device must withstand temperatures up to 800°F within 2” from the sprue and risers. The device is analyzed by examining the material properties for all material within the 2” limit. To pass, it must be shown that the materials being analyzed can withstand temperatures up to 800°F.

continued

4.	**Verification by Expert** The clamping device must disengage with exclusive use of hydraulic pistons in ESCOs facility. To pass, the project sponsor must agree that human interaction is not required to disengage the clamping force.
5.	**Verification by Testing** The clamping device must supply a clamping force of at least 400 lbs to prevent metal from leaking during the casting process. The selected design is tested using load cells provided by the project mentor. To pass the test, the applied clamping force must meet or exceed 400 lbs.
6.	**Verification by Testing** The clamping device must distribute the clamping force evenly over the surface of the mold to prevent metal from leaking during the casting process. The test will be conducted using four load cells provided by the project mentor. Three load cells will be placed evenly and in line along the left (facing) side of the carrier deck. The other load cell will be placed on the opposite side of the carrier deck. A brick will be placed in the middle of each load cell. A plywood structure will be place on top of the bricks. The clamping device will engage the top of the plywood structure. The feet of the clamp (angle irons) will be placed symmetrically on top of the plywood structure. The total applied load will be 400 lbs +/- 50 lbs. The software will provide an average value for each of the load cells. For this test only the values of the three load cells that share the same side will be compared. The value of each load cell must be within 20% of the average value of the three cells.
7.	**Verification by Demonstration** The clamping footprint should be adjusted to fit multiple sprue and riser locations to account for a variety of different mold layouts. Five cardboard templates were created with different sprue and riser layouts. The templates must be approved by the project sponsor. The templates are placed on a model sand mold. To pass, the clamping footprint must demonstrate that it does not touch any of the sprue or risers located on any of the five layouts.
8.	**Verification by Inspection** The clamping device must remain with the carrier deck to reduce setup time. To pass the inspection, all components of the clamping device remain with the carrier deck.
9.	**Verification by Expert** The clamping device must not damage the mold. To pass, the project sponsor must agree that the clamping device does not damage the mold.
10.	**Verification by Inspection** The force applying device on the clamp must consist of mostly catalog parts. To pass the inspection, it must be show that the device can be purchased from a catalog.
11.	**Verification by Testing** The clamping device must be able to operate for 2,700 cycles in ESCO’s environment. The device is tested by putting it through 100 cycles while simulation the casting environment with a series of impact and sand accumulation tests. To pass the test, the clamping device must operate for 100 cycles without losing functionality.

continued

12. **Verification by Expert** The maintenance time for the clamping device must not exceed 1 man-hour for every 2 months of operation. To pass, the project sponsor must agree that the clamping device does not require more than 1 man-hour for every 2 months of operation.
13. **Verification by Testing** The setup time for the clamping device must not exceed 48 seconds. Each project mentor tests the device by setting it up 10x. To pass the test, the average setup time must not exceed 48 seconds.
14. **Verification by Inspection** The clamping device must be sufficiently different from the other group design. To pass, the project mentor must agree that the two designs are unique.

2.4 Design Links (DLs)

Design links are developed to show how the various ERs are satisfied by at least one component of the design. The DLs in Table 4 were developed for the design described in Chapter 5. Each design link corresponds to the same numbered ER.

Table 4: Design links for selected design

Design Links
1. **Rack and Pinion Jack** The final clamping design satisfies ER #1 by using a rack and pinion jack. The jack hangs from the neck of the carrier deck and has 20” travel. This allows the jack to fit the multiple mold heights used by ESCO.
2. **Carrier Deck Bracket** The final clamping design satisfies ER #2 by using a bracket that connects the device to the neck of the carrier deck. This allows the clamping device to hang from carrier deck and prevents it from interfering with the molds entering and exiting.
3. **Steel Component** The final clamping design satisfies ER #3 by using steel components for the footprint. The steel components are capable of withstanding elevated temperatures, allowing the clamp to operate properly without being damaged.
4. **Pinned Connection** The final clamping design satisfies ER #4 by using two pinned connections. The pinned connections are located where the clamping device connects to the carrier deck and where the clamping footprint connects to the clamping device. As the mold is removed from the carrier deck the pinned connections act as a breakaway point allowing the clamping force to be disengaged.

continued

5. **Rack and Pinion Jack**

   The final clamping design satisfies ER #5 by using the rack and pinion jack. The selected jack is capable of supplying a force of up to 1000 lbs.

6. **Angle Iron Footprint**

   The angle irons used for the clamping footprint provide a sufficiently large surface to distribute the clamping force over a wide area, fulfilling ER #6.

7. **Slotted Connection**

   The final clamping design satisfies ER #7 by using slotted connections milled into a piece of steel channel. Bolts are welded to the angle iron footpads. These bolts slide into the slotted connection, allowing the angle iron to rotate and move linearly across the surface of the mold.

8. **Carrier Deck Bracket**

   The final design satisfies ER #8 by using a bracket welded to the neck of the carrier deck. The bracket allows the clamping device to be connected to the carrier deck via a pinned connection.

9. **Rack and Pinion Jack**

   The final design satisfies ER #9 by using a rack and pinion jack. The jack is designed to provide continuous adjustment that allows it to smoothly engage while providing the necessary clamping force.

10. **Rack and Pinion Jack**

    The final design satisfies ER #10 by using a rack and pinion jack. The jack can be purchased from many different vendors.

11. **Rack and Pinion Jack and Steel Components**

    The final design satisfies ER #11 by using steel components and a rack and pinion jack. The steel parts are made of A-36 steel. The properties of A-36 steel make it a suitable material for industrial applications. The rack and pinion jack is made of hardened steel and is design to lift 1000 lbs without failing.

12. **Rack and Pinion Jack and Steel Components**

    The final design satisfies ER #12 by using steel components and a rack and pinion jack. The properties of the steel components require almost no maintenance. The rack and pinion jack is durable and, according to its manual, it requires little maintenance.

13. **Rack and Pinion Jack**

    The final design satisfies ER #13 by using a rack and pinion jack. The jack allows the vertical height to be adjusted and the clamping force to be applied in one operation.

2.5 House of Quality (HoQ)

The House of Quality (HoQ) is a diagram used to relate the engineering requirements to the customer requirements. It also shows the weightings of the CRs and the target and tolerance for the ERs. The HoQ for the sand mold clamp is illustrated in the Table 5 on the next page.

Table 5: House of Quality for sand mold clamping device

46.1 Sand Mold Clamping - House of Quality (HoQ)

Customer Requirements	Weighting	Penalty	E1 Score	E2 Score	Engineering Requirement													
					The maximum clearance between the clamp and carrier deck shall be higher than 20"	The mold entance width from the front side of the carrier deck shall not be less than 34"	All Components shall operate properly at temperatures up to 800°F within 2" of sprue and risers	Mold shall exit carrier deck with the exclusive use of the ESCO's pistons	Device shall provide a minimum total reaction force of 400lbf	Device shall equally distribute the force within 20% of the mean value	Clamp footprint shall be adjustable to prevent covering sprue and risers on the provided 5 layouts	Device shall attach to the carrier deck	The engagement of the clamp shall not crack mold	Force applying device shall consist of parts from a catalog	The clamp must operate for 2,700 cycles before failure	The maximum maintenance time shall not exceed 1 hr for every 2 months	The clamp setup time shall not exceed 48 seconds	The selected design shall be sufficiently unique between the two groups
Clamp device shall be able to fit multiple mold sizes	25	-	25	25	x	x												
Exposure to elevated temperatures shall not affect device performance and functionality	15	-	15	15			x											
Clamp device shall disengage automatically to prevent binding during mold ejection	25	-	25	25				x										
Clamping force shall meet or exceed current design	25	-	25	25					x									
Clamping device shall distribute force evenly on the mold	20	-	20	20						x								
Clamping footprint shall provide access to multiple sprue and riser locations	25	-	25	25							x							
Device shall remain with the carrier deck	30	-	30	30								x						
Clamping device shall not damage mold	25	-	25	25									x					
Off the shelf components are preferred	10	-	10	10										x				
Functional life of clamp shall be at least 2 years	20	-	20	20											x			
Maintenance of device shall be minimized	15	-	15	15												x		
Initial set up shall be less than or equal to current design	15	-	15	15													x	
The chosen design of both groups shall sufficiently unique	LTE	-																x
Target(s), with Tolerance(s)	250	-	250	250	24" ≥20"H	40" ≥ 34"	yes	yes	500lbs, ≥400lbs	10% <20%	yes	yes	yes	yes	3000 ≥2700 cycles	0 ≤ 1 h	30 sec < 48 sec	yes
Test Procedure (TP#)					TP #1	TP #2	TP #3	TP #4	TP #5	TP #6	TP #7	TP #8	TP #9	TP #10	TP #11	TP #12	TP #13	TP #14
Design Link (DL#)					DL #1	DL #2	DL #3	DL #4	DL #5	DL #6	DL #7	DL #8	DL #9	DL #10	DL #11	DL #12	DL #13	DL #14

Approval (print name, sign, and date):

Team member 1: Benedikt Bochtler ______________________

Team member 2: John Teeter ______________________

Team member 3: Bobby Thompson ______________________

MIME Advisor: ______________________

Sponsor Mentor: ______________________

Course Instructor: ______________________

3 EXISTING DESIGNS

Re-engineering an existing system requires new design ideas in order to improve the performance of the system. But in order to find suitable concepts for an improved sand mold clamp, it is first necessary to know about existing solutions for clamping molds and similar tasks. This chapter describes various existing solutions to clamp casting molds that were located through background research.

3.1 Design Research

Existing designs for sand mold clamping systems were located using textbooks and the Internet. Textbooks focused mainly on different casting techniques, metallurgy, and processing, but also included references to clamping techniques. The web search was performed using Google services (e.g. Books, Scholar, and Patents), OSU Libraries research databases, and ScienceDirect.com. It was found that the majority of journal research articles focused on high pressure closure mechanisms for injection molding and die casting. However, these mechanisms are still a valuable resource for research on existing designs. A few patents involving sand mold clamping devices were found and are included in the system-level design descriptions.

3.2 System Level

Clamping devices for sand mold casting have to function in a harsh foundry environment and are therefore designed to be simple and robust. The following designs include three general approaches to sand mold clamping, three patents specific to sand mold casting, and one injection mold clamp. Each of the designs satisfies some of the customer requirements (CRs) for this project but fails to satisfy others.

3.2.1 Existing Design #1: Weighting

The simplest way to fulfill most of the customer requirements is to place heavy weights on top of the cope. This method is common in many foundries [2], [3]. The mold weights prevent the cope from floating and as a consequence there is no liquid metal leakage. The clamping force can be adjusted easily by changing the amount of weight placed on the mold (CR #4). By moving the weights around on the surface, the force distribution can be manipulated (CR #5) and access to sprues and risers is ensured (CR #6). A large contact surface also prevents mold damage (CR #8). This clamping system needs no special manufacturing, and is durable with a functional lifetime of much longer than two years (CR #10). However, the weights have to be engaged and disengaged manually or an expensive robot system is needed to handle the weights. Figure 3.1 shows weighted molds prepared for pouring.

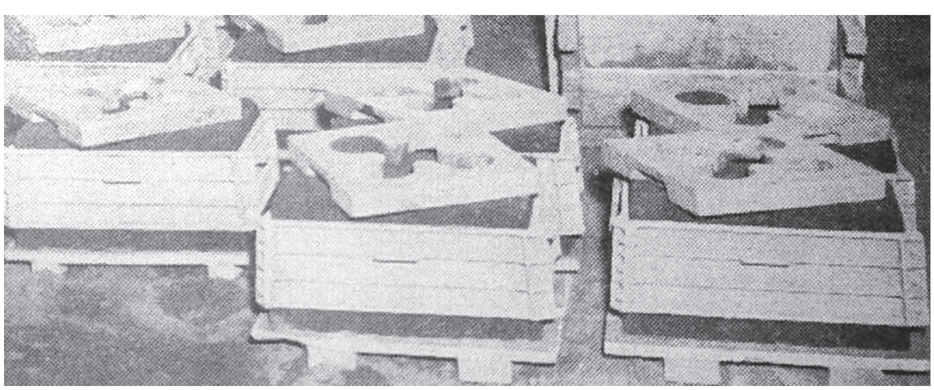
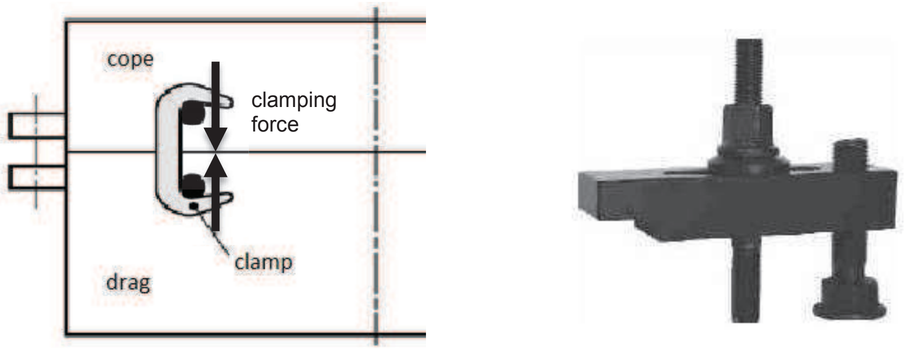


Figure 3.1: Weighted molds for pouring. The weights are used as a clamping device. Source: *[2, p. 162]*.

3.2.2 Existing Design #2: Clamping the flask

For many applications it is useful to leave a flask (metal side walls) around the side of the sand mold during the pouring [4]. A flask sticks to the sides of each half of the sand mold. A clamping device is connected to each of the flasks to provide the clamping force. This mechanism can be used for almost all mold sizes (CR #1). Figure 3.2 shows two possible clamping mechanisms. Both clamps lock the flask in place rather than actually applying a clamping force. When a buoyant force acts on the cope after casting, the clamping device prevents the cope from floating. The necessary clamping force gets induced by the clamp during casting and equals the buoyant force. Thus, a certain clamping force cannot always be guaranteed (CR #4). Since the clamps are installed around the outside of the mold, the maximum clamping force is located at the edge and decreases towards the center of the mold. This might lead to a deflection of the interior mold shape in the center. Some flasks provide an edge around their entire perimeter to allow for various clamp locations, which in turn provides a more uniform force distribution (CR #5). These designs are durable (CR #10) and provide access to the entire top surface of the mold for all risers and sprue locations (CR #6). However, the clamps have to be engaged and disengaged manually, which makes them difficult to operate and causes this design to fail CRs #3 and #12.



(a) (b)

Figure 3.2: (a) Clamp attached to the flask. Adapted from *[4, p. 10]*.
(b) Commercial heavy duty mold clamp. Adapted from Jala Sales. (2012). "Heavy Duty Mold Clamp" [Online]. Available: http://www.jalasales.net/heavy-duty-clamp.htm

3.2.3 Existing Design #3: Hobby Sand Casting Clamp

While the tools used in sand casting as a hobby are not as strong or efficient as the industrial designs, they still provide insight into clamping techniques. The clamping system used by hobbyist Eugene Sargent, shown in Figure 3.3 is simple. There are only two different parts to this clamp system. Pony clamps are used to provide the clamping force while a plywood board is used to distribute the applied force evenly across the top of the mold [5]. To install the clamp one pony clamp at a time is engaged. The pony clamp is quickly adjusted to the proper height by disengaging the metal wedges in the handle. The part of the clamp with the handle on it can slide over the steel bar and adjust to the required height. While turning the threaded handle through a nut the slider wedges on the steel bar and locks in place. By turning the handle further the threads provide a final clamping force onto the mold. The turning causes the threads to move vertically and as the pony clamp is already locked, the force that the threads provide is applied to the wooden board.

The advantages of the system in Figure 3.3 are the adjustability of the clamp (CR #1), the use of off the shelf parts (CR #9), and the fact that it is easily maintained (CR #11). The clamp does not meet many other customer requirements; as it is not very strong (CR #4), cannot withstand high temperatures (CR #2) and is unable to auto disengage (CR #3).

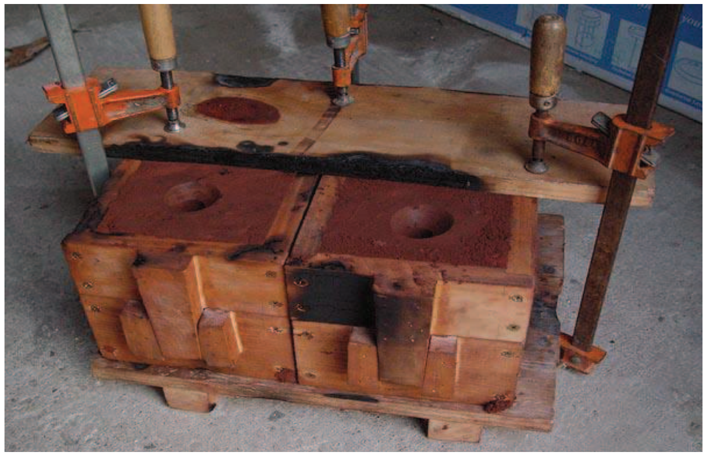


Figure 3.3: Sand Casting Clamp. Source: *[5]*

3.2.4 Existing Design #4: US Patent 2581040

Figure 3.4 shows the sand mold clamp patented in US 2581040 [6]. Its functional mechanism is explained in the patent. The clamp encloses three sides of the sand mold (2) and the feet of the clamp (15) grasp around the bottom edge. The clamping force is distributed along the whole topside, which satisfies CR #5. The clamp fits different mold heights by adjusting the threaded nut (14) after the clamp has been put onto the mold (CR #1). A clamping force is provided by pushing down the lever (10) which is connected to a disc (9) that is mounted off center. The rotation of the disc around its axle pulls the feet (15) closer to the cross bars (3, 4) on top of the mold and provides a "great" clamping force [6]. Unfortunately the patent does not specify the maximum provided force. The clamp has to be installed and removed manually which violates CR #3. Furthermore movable parts are likely to fail after extensive use before a lifetime of two years.

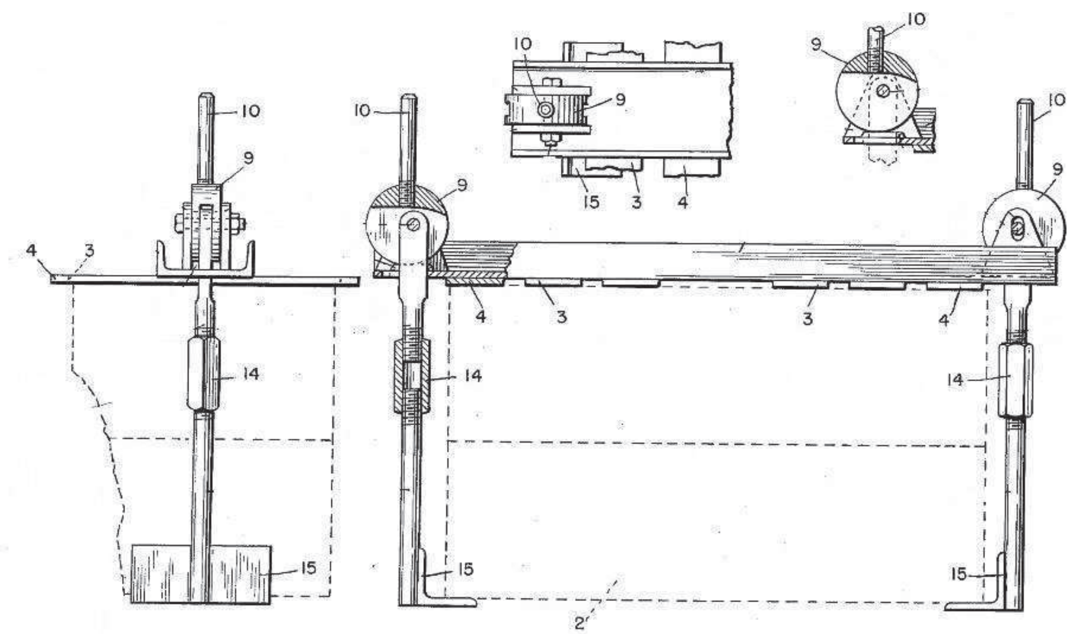


Figure 3.4: CAM actuated adjustable mold clamp. Source: *[6]*.

3.2.5 Existing Design #5: US Patent 5048593

US Patent 5048593 [7] provides an apparatus for weighting and lateral support of box-less sand mold parts. The apparatus is shown in Figure 3.5. This sand mold clamp uses a weight iron (1) to apply the necessary clamping force in vertical direction. The force can be adjusted by increasing the used weight to fulfill CR #4. Besides only applying a vertical force, this clamping design also offers lateral support to the sand mold. Two L-shaped arms (9, 10) connect the top part of the device with two clamping plates (4, 5) that support the flanks of the mold. At (16, 17) and (31, 32) the arms are bolted to the top part of the clamp which allows the arms and the clamping plates to rotate around the the weight iron (1). When installed onto a mold, the heavy clamping plates are pulled towards the center of the mold by gravity as their rotation axle is located at (16, 17) over the center of the mold.

This design even protects the mold flanks from being damaged and fulfills CR #8. The clamp can be attached without the need of screws or threads and can be lifted off the carrier deck (8) after the casting process. However, an automatic disengagement as required in CR #3 is not possible. The design of the weight iron on top of the mold only allows access to defined sprue and riser locations and cannot be adapted to different molds without reconstruction. CR # 6 cannot be met.

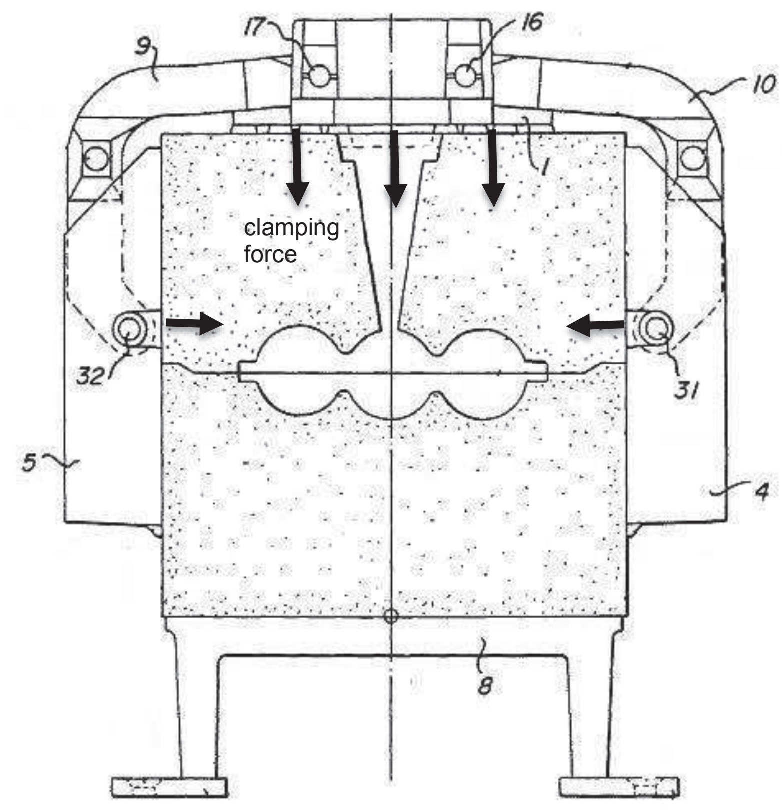
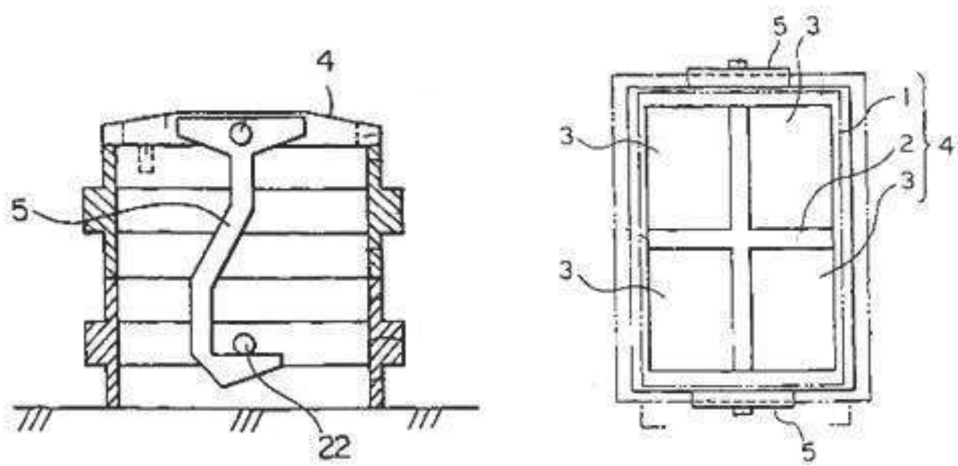


Figure 3.5: Apparatus for weighting and lateral support of box-less sand mold parts. Adapted from *[7]*.

3.2.6 Existing Design #6: European Patent 0844037

A sand mold clamp design that fits many of the customer needs was patented by M. Naitot [8]. The design can be used with sand molds with flasks (container around the sand mold) or without flasks. It is comprised of a grid frame (4), designed to allow access to multiple sprue and riser locations (CR #6), and two swinging hooks (5). Figure 3.6 shows a drawing of the design. After the cope and drag are stacked, the grid frame is placed on top of the cope. Once it is in place, the hooks swing down and locks onto the attachments mounted on the drag flask (22) or the carrier deck. Locking the hooks in place causes a small reaction force which pushes down on the mold.

The advantages of this design include; an even force distribution over the mold surface area (CR #5), access to multiple sprue and riser locations (CR #6), a quick set up time (CR #12), and a high functional lifetime (CR #10).



(a) (b)

Figure 3.6: (a) Side View and (b) Top View of the clamping device patented in European Patent 0844037. Source: *[8]*

3.2.7 Existing Design #7: Toggle clamp

Besides sand mold casting, many other molding processes require clamping devices. It is helpful to consider some of these designs to get a broader insight into clamping designs in general. Injection molding requires clamping forces up to several thousand kN [9]. Such forces can only be applied through sophisticated clamping devices. Figure 3.7 shows a five-point double-toggle clamp mechanism for injection molding, in both locked (a) and opened (b) position.

The toggle clamp uses the high mechanical advantage of the linkage to apply the clamping force [10]. A hydraulic cylinder (actuating cylinder) pushes a crosshead link with two mechanical knee levers into its locked position and this motion moves the mold sides together [9]. Due to the high mechanical advantage a relatively small closing cylinder is sufficient to provide a high amount of force. The clamping force is initially provided by the hydraulic system, but as soon as the knee lever is locked, the mechanical components provide the clamping force and the hydraulic pressure can be relieved. A clamping force that is many orders of magnitude higher than required in CR #4 is provided. In order to open the mold again after injection, the hydraulic cylinder pulls back the knee lever from its locked position and the mold sides separate. This design offers automatic disengagement as required in CR #3.

A significant amount of research has been done to find solutions on how to evenly distribute the clamping force on the mold and how to optimize the set up time of the injection process. Each of which refers to our CRs #5 and #12. An optimal design for a toggle clamp can be found by mathematical calculations as shown in [11]. To allow a long functional lifetime and minimize maintenance (CRs #10 and #11) friction effects on the toggle mechanism under high stress have to be considered, as done in [12].

An injection molding toggle clamp may not adjust easily to different mold sizes (CR #1) and may also restrict access to sprues and risers (CR #6), without redesigning the shape of the pressure plates.

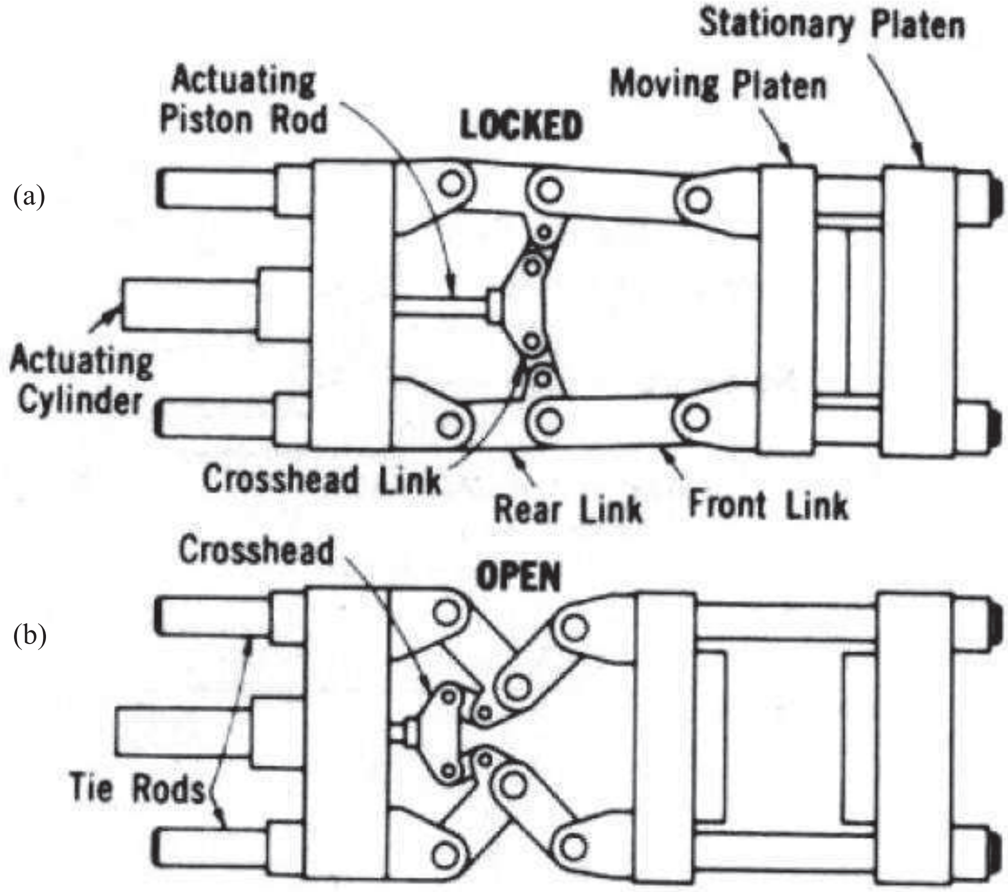


Figure 3.7: A five-point double-toggle mold-clamping mechanism for injection molding. (a) shows the clam in locked position and (b) in open position. Source: *[9]*

3.3 Subsystem Level

Each of the previously described clamping devices consists of subsystems that are used to accomplish specific functions. In order to properly evaluate how well each subsystem completes a specific function, a functional decomposition is created. The functional decomposition of the sand mold clamp, shown in Figure 3.8, is based on the customer requirements. A general clamping device system consists of five functions: vertical height adjustment, footprint adjustment, application of the clamping force, distribution of the clamping force, and disengagement. Once each function has been defined, different design solutions are researched to create the subsystems of a clamping device. The following subsystems are not necessarily directly related to the above system designs, but they are good options for creating a new system design.

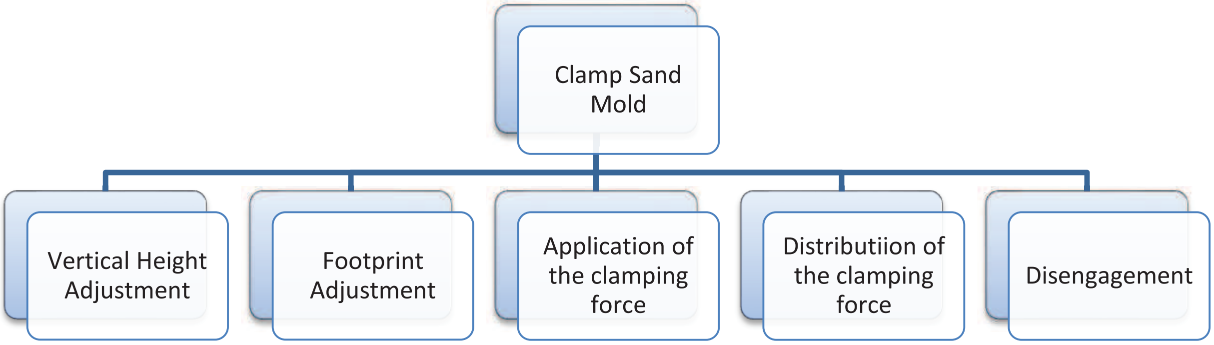


Figure 3.8: Functional decomposition of the sand mold clamp.

3.3.1 Subsystem #1: Vertical Height Adjustment

A mechanism is needed to adjust the clamping device to different sand mold heights as required in CR #1. The following designs are easy to operate but use different methods to make the linear height adjustments.

3.3.1.1 Existing Design #1: Rack and Pinion

A rack and pinion gear set is used to convert rotational motion into linear motion [13, pp. 1.34-35]. In most cases the rotation of the pinion gear is used to drive the linear motion of the rack gear. The speed and distance at which the rack gear moves depends on the pitch diameter of the pinion gear. Also, in this design the linear motion of the rack gear is infinitely adjustable by the rotation of the pinion gear.

The rack and pinion gear is a common component used in many different applications (CR #9). One example of the application of a rack and pinion gear set is the rack and pinion steering used in automobiles. In this case the pinion gear is rotated by the operator from the steering wheel. The pinion gear moves the rack gear, which is attached on each end to tie rods. The tie rods are then connected to the wheels. The push and pull movement of each tie rod causes each respective wheel to pivot, thus turning the automobile.

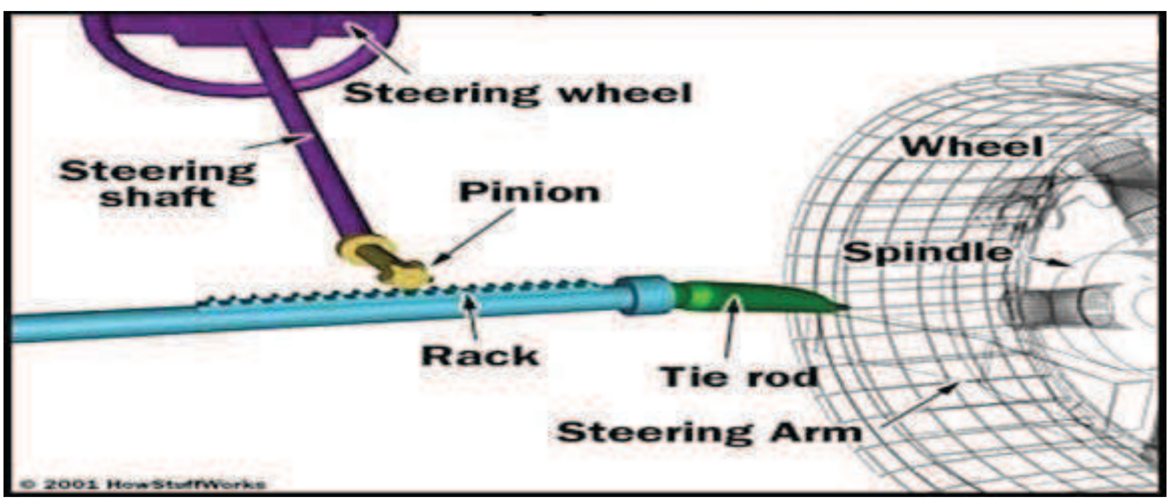


Figure 3.9: Sample application for a rack and pinion gear. Source: HowStuffWorks. (2001). "How Car Steering Works" [Online]. Available: http://auto.howstuffworks.com/steering2.htm

3.3.1.2 Existing Design #2: Nut and Bolt

A threaded rod with a nut can also be used to convert rotational motion into linear motion [14, pp. 19.8-9]. Similar to the rack and pinion design, a threaded rod is also infinitely adjustable. In this case either the rod is restrained or the nut is restrained. If the nut is restrained the rod is rotated and it is the rod that translates. If the rod is restrained the nut translates as it is rotated. A threaded rod is a common component (CR #9) and is usually made of steel which performs well in high heat applications (CR #2). An example of this type of motion transformation is a C-clamp. As seen in Figure 3.10, the C-clamp design restrains the nut and allows the rod to translate through the nut. The handle that is attached to the threaded rod is used by the operator to spin the rod to the desired position.

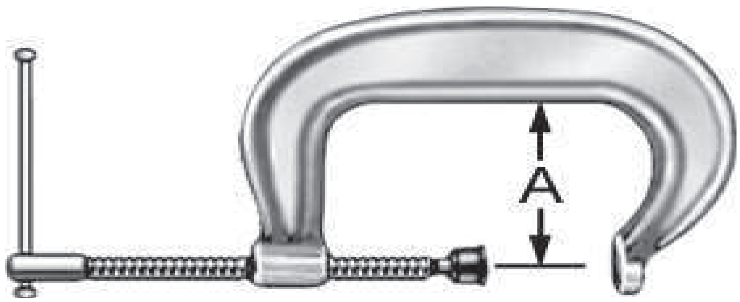


Figure 3.10: C-clamp as an example for a nut and bolt thread. Source: McMaster-Carr. (2012). "C-Clamps" [Online]. Available: http://www.mcmaster.com/#standard-c-clamps/=l3vssn

3.3.1.3 Existing Design #3: Height adjustable crutch

A mechanism that allows fast adjustment to different sizes can be found on medical crutches (CR #12). Figure 3.11 shows the height adjustable crutch claimed in US patent RE32815 [15]. This mechanism adjusts the length of the crutch with the push of a button. Two telescoped pipes (32, 38) are fixed by two pins (56) that penetrate both pipes. The pins are connected to a spring (58) and can be pushed into the pipes. The relative position of the pipes to each other can be changed while the pins are pushed in. As soon as the holes in both pipes are congruent again, the spring pushes the pins out and they lock the pipes again.

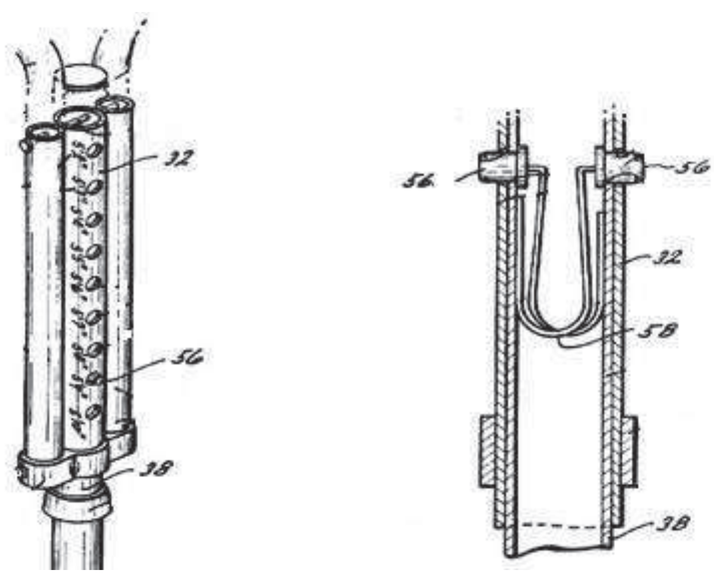


Figure 3.11: Height adjustable crutch. Source: *[15]*

3.3.2 Subsystem #2: Footprint Adjustment

The footprint of the clamping device needs to be adjustable to provide access to different sprue and riser locations (CR #6). The following designs fulfill this requirement while also being constructed to withstand the high temperatures of the casting environment (CR #2).

3.3.2.1 Existing Design #1: Lazy Susan Turntable

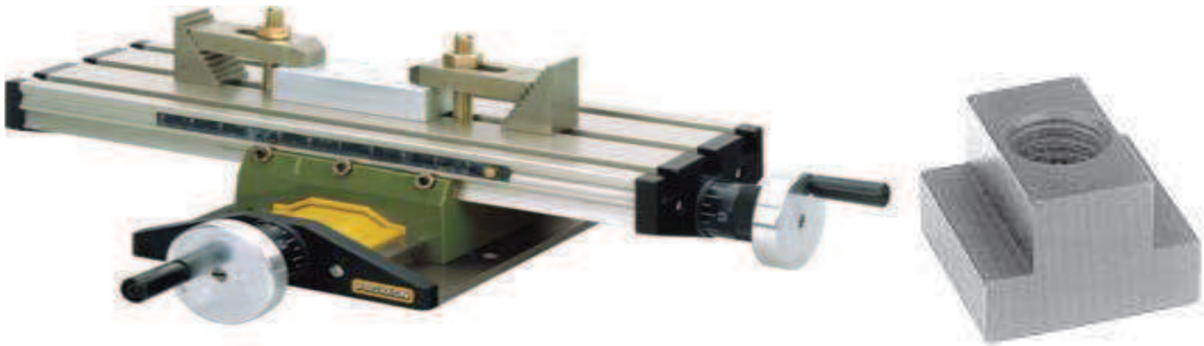
One way to adjust the footprint is to attach the feet of the clamp to a ball thrust bearing. This type of bearing allows the footprint to spin 360 degrees about the center of the clamp. Pictured in Figure 3.12 is a Lazy Susan turntable. The ball thrust bearing in the turntable allows the operator to rotate the top of the table until the desired location is achieved. Similarly, if the feet of the clamping device are connected to a ball thrust bearing, the operator can turn the device until the feet of the clamp are not in a position to interfere with the sprue and risers. The advantage of a ball thrust bearing is that the mechanism is able to handle large thrust loads [14, p. 8.17]. Thus, when the clamping mechanism applies a clamping force to the mold, and consequently the thrust bearing, the bearing does not fail.

Figure 3.12: Industrial Turntable [MCM]. Source: McMaster-Carr. (2012). "Permanently Lubricated Industrial Turntables" [Online]. Available: http://www.mcmaster.com/#turntables/=l3vtnv

3.3.2.2 Existing Design #2: Slotted Connection

A different type of industrial design that provides adjustment in a linear direction is a T-nut that slides inside of a T-slot [14, p. 9.66]. In this design the fixed side of the table has a T-slot machined into it. A T-nut slides along the slot until the desired location is reached. At that time a bolt passes through the movable part and threads into the T-nut, thus securing the part to the table.

The small milling table in Figure 3.13 (a), demonstrates the use of T-slots. The table has three T-shaped slots that run the length of the table. A T-slot nut, shown in Figure 3.13 (b), connects to a bolt and together they slide along the slot until the desired location is achieved. The bolt is then tightened into the nut to secure the clamp to the working piece.



(a) (b)

Figure 3.13: (a) Milling table with T-slots. Source: MTI Corp. “Milling table” [Online]. Available: http://mtixtl.com/mt-115precisionmicrodrillingmachineupto8000rpmwithtwo0018diadiamonddrills.aspx
(b) T-slot nut. Source: All American Products Co. “Tooling components: Nuts” [Online]. Available: http://www.allamericanproducts.com/toolng/nuts.htm

3.3.2.3 Existing Design #3: Trailer Hitch

A simple method for adjusting the location of the footprint is to attach the feet to a piece of metal that slides on the inside of a smaller but similarly shaped piece of metal. An example of this type of adjustability can be seen in Figure 3.14. A common trailer hitch design uses a large piece of square tube that is permanently attached to the underside of a truck. The ball hitch is attached to a smaller piece of square tube. Since the outside dimensions of the smaller square tube are slightly less than the inside dimensions of the larger square tube, the smaller tube can slide in and out of the larger tube. This adjustability allows the user to increase or decrease the distance of the ball hitch from the truck.

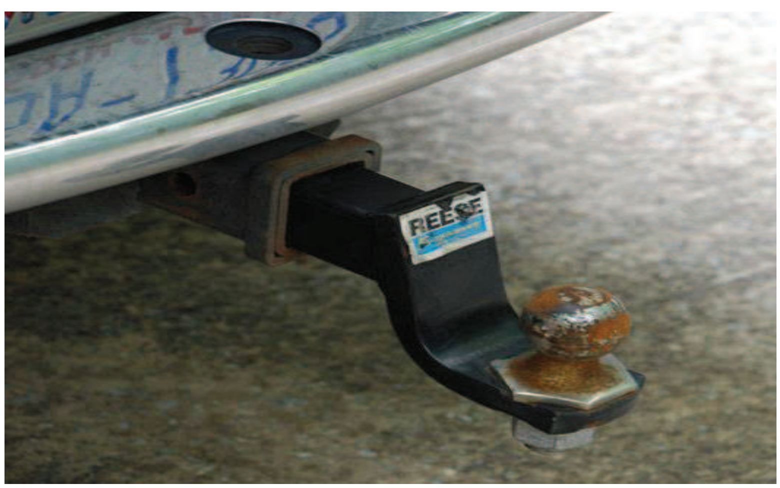


Figure 3.14: Trailer hitch. Source: AboutTrucks. “Draw Bar Installed in Receiver Hitch” [Online]. Available: http://trucks.about.com/od/truckaccessory/ig/Trailer-Hitch-Parts/Receiver-Hitch-Installed.htm

3.3.3 Subsystem #3: Application of the clamping force

After the clamp is in position, a clamping force has to be applied in order to prevent liquid metal from leaking out of the mold. The clamping force has to be equal or greater than the buoyant force applied to the cope, but smaller than the failure stress of the sand mold. The following designs are common mechanisms (CR #12) that can be used fulfill CR #4.

3.3.3.1 Existing Design #1: Scissor Jack

A scissor jack is a commonly used tool that people use to change a flat tire on their car. As seen in Figure 3.15, a scissor jack is placed underneath the bottom side of the car. The operator then turns the handle of the jack until the side of the car is lifted slightly off the ground. The lifting force of the clamp is created using the torque input of the operator to turn a threaded rod through a fixed nut connected to linkages. As the threaded rod turns through the nut, the linkages are drawn together, exerting an upward force to any object sitting on top of the jack. The advantage of using a threaded connection to apply a force is that there is tabular information relating the size of the threaded rod, the input torque, the tensile strength of the rod and the allowable applied axial load [14, pp. 19.15-16].

Figure 3.15: Scissor jack underneath a car. Source: AboutTires. "Raise the car" [Online]. Available: http://tires.about.com/od/tire_wheel_galleries/ig/change_tire_gallery/jacked.htm

3.3.3.2 Existing Design #2: Trailer Jack

A trailer jack applies a force using the same mechanical mechanism as the scissor jack, but with two major differences. The first difference is that the trailer jack uses a vertical movement of a nut on a threaded rod to adjust the height and also to apply a lifting force. The second difference is that the threaded components of the trailer jack are protected by a steel tube. As the hand crank on the trailer jack is rotated, small gears turn a screw that is attached to an inner steel tube. This steel tube then extends or retracts from the inside of the outer tube. As seen in Figure 3.16, the input handle turns two bevel gears which then turn a screw on the inside of the jack housing. The threads and other moving parts are never exposed to the outside.

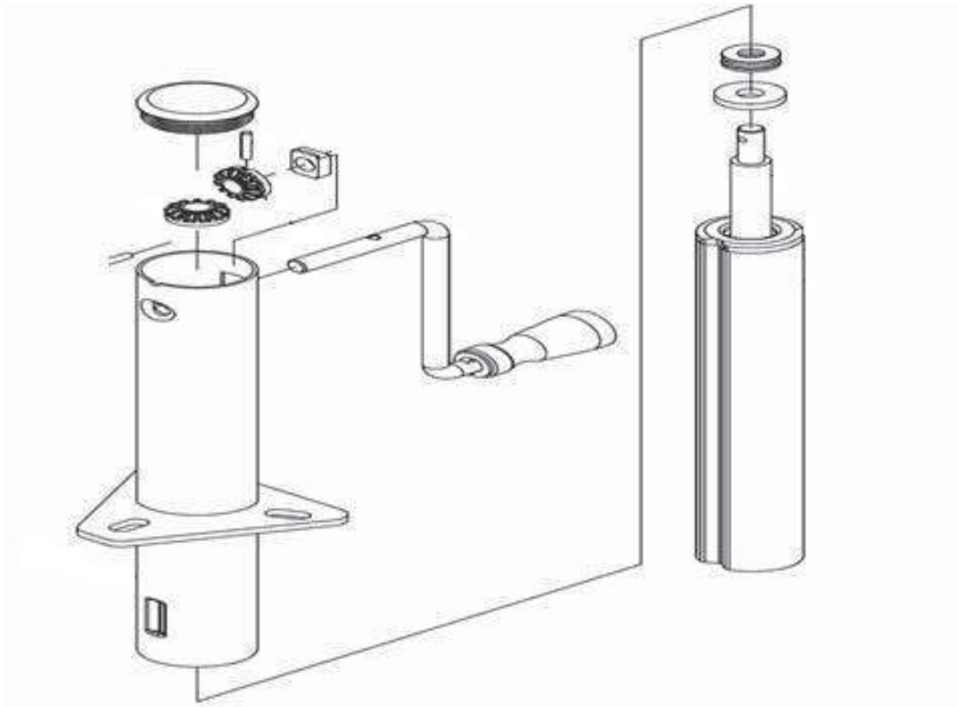


Figure 3.16: Assembly drawing of a trailer jack. Source: Ultra-Tow. “Side-Wind Trailer Jack” [Online]. Available: http://www.northerntool.com/images/downloads/manuals/603635.pdf

3.3.3.3 Existing Design #3: Worm Gear

A worm gear set is a mechanism that can also apply a clamping force. The worm gear setup is used to transmit rotational motion between two shafts that are at 90° from each other [16, p. 674]. As seen in Figure 3.17, a worm gear set is comprised of a worm, which looks like a screw, and a worm wheel. In a single-envelope gear set up, the rotation of the worm rotates the worm wheel. The difference between a worm gear set and other gear sets is that with the proper geometries the transmission of power is always from the worm to the worm wheel. This can be advantageous in situations where the output gear should never drive the input gear.

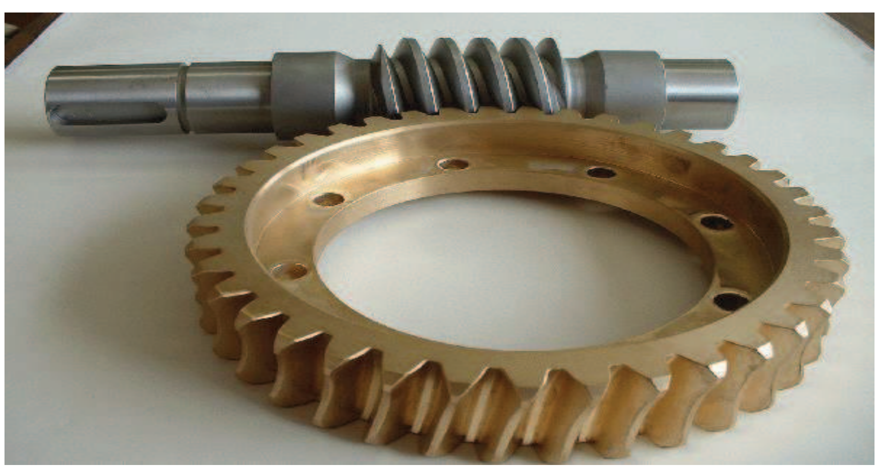


Figure 3.17: Worm gear set. Source: Premier Gear. (2005). “Worm Gears” [Online]. Available: http://www.premier-gear.com/worm_gears.htm

Worm gear sets are often found in gear boxes and electrical actuators. The worm gear in Figure 3.18 is part of a gear box that is used to open a buttery fly valve that in turn allows water to flow in a pipe. In this example the worm gear is supplying the necessary power from the input wheel to turn the valve, while also preventing the water in the pipe from closing the butterfly valve.

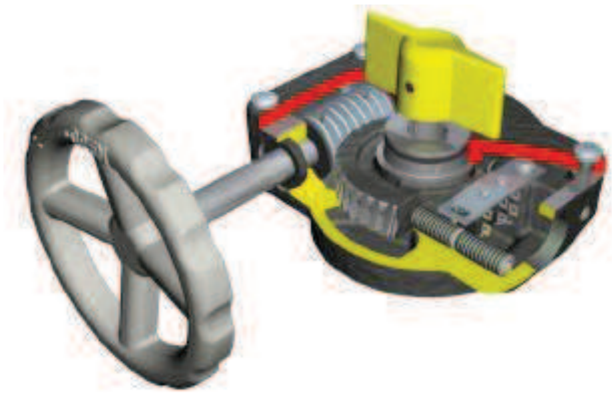


Figure 3.18: Gear Box with Worm Gear. Source: Rotork. "FB - Quarter-Turn Fire Protection" [Online]. Available: http://www.rotork.com/en/product/index/fbquarterturnfireprotection

3.3.4 Subsystem #4: Distribution of the clamping force

Even if the total applied clamping force is high enough to compensate for the buoyant force on the cope, liquid metal leakage might still occur due to an uneven force distribution. Therefore, the clamping force has to be distributed evenly over the top surface of the sand mold (CR #5). Force distribution in general works through increasing the effective surface area of the applied force.

3.3.4.1 Existing Design #1: Steel Shapes

The distribution of the clamping force can be achieved with the use of standard steel shapes. Low carbon steel is a common industrial material because it is machinable and weldable, tough and ductile, and it is cheap to produce [17, p. 360]. Steel is also commonly produced in a variety of different shapes. The shapes that are applicable to the sand mold clamping situation include; angles, rectangles and round bars. These shapes can be cut to a desired length and set on top of the mold to distribute the clamping force.

The use of steel shapes is a proven method for distributing force in sand mold clamping devices. The current clamp set up, as seen in Figure 1.2, uses steel angle iron to distribute the clamping force. Another example is the system design shown in Figure 3.4. This design uses a steel channel to distribute the force across the top of the mold.

3.3.4.2 Existing Design #2: Caster Wheels

Wheels are also a common method of distributing a force from an object to the ground. The advantage of wheels is that they not only support a normal force, but they also provide mobility to the object they support. As seen on the next page in Figure 3.19, caster wheels come in all different types of materials, including cast iron. This particular caster has a 1250 lbs. capacity which satisfies CR #4. A steel caster would be able to function at high temperatures (CR #2), while still supporting the clamping force.

Figure 3.19: Cast Iron Caster Wheel. Source: The Caster Guy. “Steel Casters” [Online]. Available: http://thecasterguy.com/medium-duty-casters-steel-casters-c-1_197_200/steel-medium-duty-6-x-2-swivel-caster-p-2252

3.3.4.3 Existing Design #3: Swivel Pads

A swivel pad is a mechanism that uses a ball joint to connect the shaft of the clamp to the foot pad. The ball shaft connection allows for a certain amount of swing angle between the shaft and the foot pad [14, p. 15.2]. This allows the foot pad to fully engage any object even if the object is not placed directly perpendicular to the clamping shaft. Most common C-clamps utilize this function (CR #9). As seen in Figure 3.20, the foot pad connected to the end of the threaded shaft is able to adjust to any angle relative to the shaft and the non-adjustable steel pad on the opposite side. The advantage of using a swivel pad is that the clamping device and the object being clamped do not have to be perpendicular to each other.

Figure 3.20: C-clamp with swivel pad. Source: StartWoodworking. (2010). “Clamps for Woodworking” [Online]. Available: http://www.startwoodworking.com/post/clamps-woodworking

3.3.5 Subsystem #5: Disengagement

Customer Requirement #3 requires that the clamping device shall be able to disengage from the carrier deck without the assistance of an operator. The following mechanisms are designed to be used in conjunction with the two ejection pistons used to disengage the mold, as described in section 1.3.2 .

3.3.5.1 Existing Design #1: Pinned Connection

A pinned connection is commonly found in many different linkage setups (CR #9). These linkage set ups are based on the fact that a pinned connection cannot resist an applied moment. An example of an effective use of a pinned connection can be seen in the injection molding clamp design in Figure 3.7. In

Figure 3.7 (a) the locked position corresponds to the moment when the front link and the rear link are aligned in a straight line. In this position a large axial force can be applied through the linkages and the pin to apply a clamping force. In Figure 3.7 (b) the actuating cylinder retracts and pulls the crosshead link into the middle of the clamp. The crosshead link pulls the pin that connects the rear link and the front link out of alignment. Once the linkages are no longer in a straight line, they are no longer able to resist the applied force and the clamping mechanism is disengaged.

3.3.5.2 Existing Design #2: Rollers

Heavy duty steel rollers are an effective means of transporting heavy objects. The conveyor line in Figure 3.21 connects numerous rollers together. An object placed on one end of the conveyor is pushed to the other end with little effort. The ease with which a heavy object moves on top of the rollers is due to the bearings connecting the outside cylinder of the roller to an inner shaft. Ball bearings are designed to spin freely on a shaft and to offer no resistance to a horizontally applied force. Depending on the type of the roller used, CR #4 can be satisfied. Also, rollers are a common mechanical part that can be purchased off the shelf (CR #9).

Figure 3.21: Conveyor line with rollers Source: Nationwide Industrial Supply. “Conveyors” [Online]. Available: http://www.nationwideindustrialsupply.com/Conveyors/

3.3.5.3 Existing Design #3: Steel sleeves

A steel sleeve is used to slide along the outside of a similarly shaped piece of metal. As long as the sleeve has a larger inside diameter then the outside diameter of the piece it is traveling on, the sleeve travel without a significant amount of resistance. While the shower curtain in Figure 3.22 is not an industrial design, it is still a good example of the movement of the rings sliding on a single pipe. A more industrial example is used in the current clamp design. As seen in Figure 1.2, the angle iron has a metal ring welded to the top leg. The ring has a larger diameter then that of the solid steel round bar used to apply the clamping force. The loose fit between the bar and ring provides an easy method of connecting and adjusting the two parts.

Figure 3.22: Shower Curtain with sliding rings.
Source: ApartmentTherapy. (2010). “Shower Curtains” [Online]. Available: http://www.apartmenttherapy.com/extra-long-shower-curtains-112120

4 DESIGNS CONSIDERED

Engineering designs problem are usually solved through a variety of design concepts. New ideas are generated after defining the customer and engineering requirements and researching existing designs that satisfy the different functions of a sand mold clamp. In this chapter, four designs are described that approach the five functions of a sand mold clamp in different ways (see Figure 3.8 for the functional decomposition). The advantages and disadvantages of the designs are also addressed and linked to the appropriate customer requirements. The design's performance for each CR is rated on a 1 to 10 point scale, with 10 being the highest and 1 the lowest score. These values are used in a decision matrix in Chapter 5.1. All components of these designs are derived from concepts that have been described in Chapter 3.

4.1 Design #1: Scissor jack and frame with sliding crossbars

The first design considered consists of two main components: a scissor jack and a frame with sliding crossbars. The design concept is illustrated in Figure 4.1. The top end of a scissor jack is bolted to a round steel tube which is welded to the carrier deck. The scissor jack allows vertical height adjustment and provides the clamping force. The other end of the jack is attached to the steel frame with sliding cross bars. The welded frame is pyramid shaped and built out of steel rods. The tilted rods carry the horizontal rectangular part of the frame. Four flat steel crossbars with two welded eyelets on each end are able to slide on the horizontal rod. The frame with sliding crossbars performs three functions of the sand mold clamp. It provides an adjustable footprint, distributes the clamping force, and allows the mold to be pushed off the carrier deck from the backside (auto disengage).

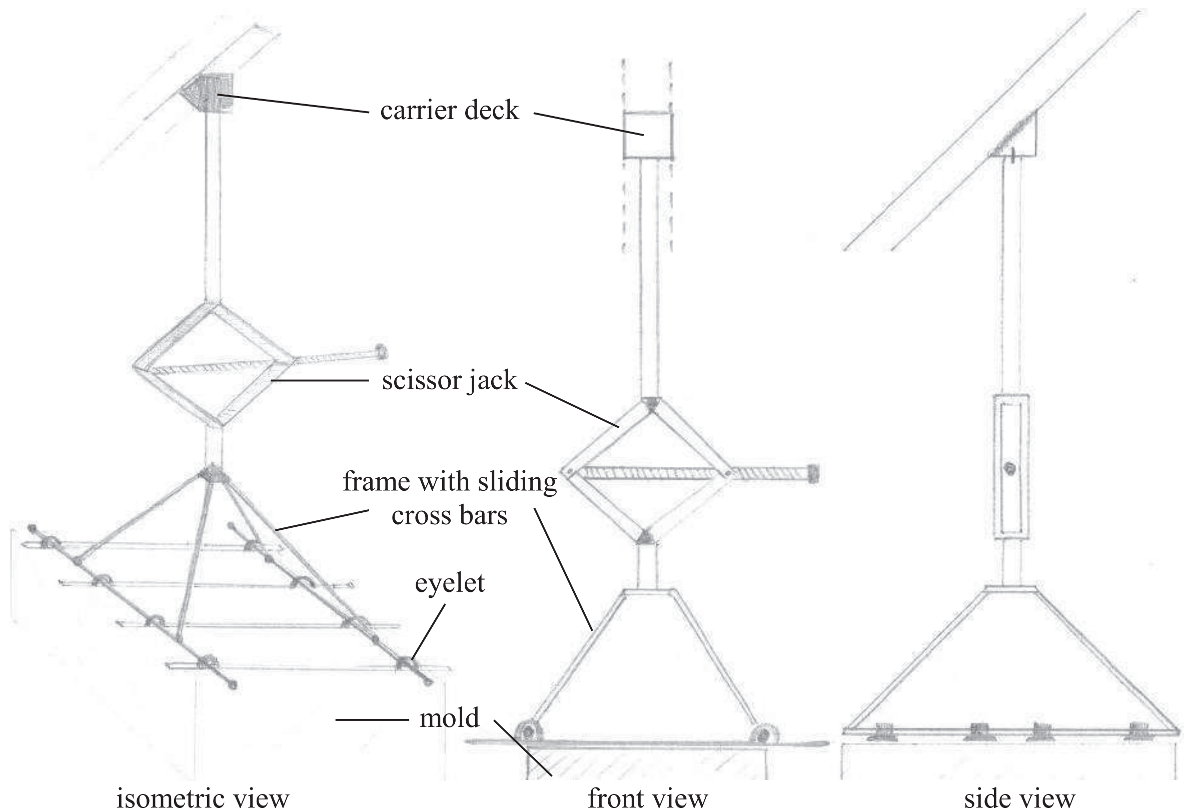


Figure 4.1: Design concept #1: Scissor jack and sliding crossbars.

This design covers all the required functions including a scissor jack for height adjustment and application of a clamping force and a frame with sliding crossbars to adjust the footprint, distribute the force, and allow the mold to disengage automatically. Table 6 summarizes the design's ability to satisfy the customer requirements.

Table 6: Achieved and problematic CRs for Design #1.

Favorable CRs (9-10 Pts)	Neutral CRs (6-8 Pts)	Problematic CRs (1-5 Pts)
#2: withstand elevated temperatures (9)	#1: fit multiple mold sizes (7)	#3: disengage automatically (5)
#4: adequate clamping force (10)	#8: do not damage mold (7)	#6: provide access to sprue and risers (5)
#5: distribute force evenly (9)	#11: maintenance minimized (6)	#9: off the shelf components (5)
#7: remain with carrier deck (10)	#12: decrease set up time (8)	#10: functional lifetime greater than 2 years (5)

4.1.1 Function #1: Vertical Height Adjustment

The vertical height adjustment function (CR #1) is accomplished in this design through the use of a mechanical scissor jack. Mechanical scissor jacks are continuously variable and can be adjusted to accommodate any required mold height. As noted in [18], the operation range for many scissor jacks is 20”, whereas the different mold sizes only require 8” of vertical adjustment. Figure 3.6 shows a typical mechanical scissor jack. The main advantage of a mechanical scissor jack for this project is its simplicity. The process of adjusting the clamping device in height is simply done by cranking the handle. No locking mechanism or multiple step process is necessary. This guarantees a quick set up that fulfills CR #12.

A disadvantage of the scissor jack is that it requires the operator to use two hands to crank the jack. This might be ergonomically unfavorable. A second disadvantage of this design is that liquid metal might splash onto the scissor jack during the casting process and damage its threads. This would lead to a shorter functional lifetime and interfere with CR #10. Splashing could be prevented by installing splash guards around the jack. As the scissor jack is an off the shelf component (CR #9), it could also be easily exchanged if it gets damaged.

Figure 4.2: Stromberg Carlson Scissor Jack - 24" Lift - 5,000 lbs *[18]*

4.1.2 Function #2: Footprint Adjustment

To adjust the footprint to different sprue and riser locations on the mold surface, the operator can slide the crossbars on the frame to different positions. By doing this, different parts of the surface can be left blank and allow access to the sprues and risers to fulfill CR #6. The advantage of this design is its robustness due to the use of simple mechanical parts. One constraint of this design is that the footprint is only adjustable in terms of sliding the flat steel crossbars in one direction. This only allows a limited number of possible footprints. Furthermore, the dimensions of the frame are about the size of the biggest sand mold in use and it might interfere with the pouring process. However the construction of the frame is wide open and still allows access to most parts of the mold surface.

4.1.3 Function #3: Application of the Clamping Force

The clamping force is applied by the same scissor jack that allows the vertical height adjustment. A minimum clamping force of 400lb can be ensured (CR #4), as most devices provide a total force of 5000 lbs [18]. Using the scissor jack to accomplish both, the function of height adjustment and applying the clamping force becomes a single step process. A force is applied to the mold surface by continuing to crank the jack after the clamping device touches the mold. This makes the clamp operation fast and simple and is the main advantage of combining two functions in one component of the clamp. Finally, the clamping force is applied smoothly which prevents the mold from being damaged (CR #8). The disadvantages of the scissor jack are the same as described in section 0.

4.1.4 Function #4: Distribution of the Clamping Force

The clamping force is distributed over the whole mold surface by the crossbars and the solid steel frame. The crossbars provide a sufficiently big surface to prevent peaks in the clamping tension on the mold. As the dimensions of the frame are bigger than the sand mold, force distribution is not limited to the center of the mold but also to the edges of the mold. There are no disadvantages to this design concerning the function of distributing the clamping force and CR #5 is met.

4.1.5 Function #5: Disengagement

When the mold gets pushed of the carrier deck after the casting process, the sliding crossbars allow the mold to move a certain way without binding it. As the sand mold disintegrates at this time of the casting process the resulting clamping force is less than the initial force. As long as the clamp allows the mold to overcome the static friction when it gets pushed off, it should not hinder the mold disengagement (CR #3). The benefit of this design is that the component that allows for the adjustment of the footprint also facilitates the disengagement. This reduces the number of necessary components and eases the manufacturing process of the clamp. However, the frame and the crossbars are not off the shelf parts but have to be manually welded.

4.2 Design #2: Rotating Jack

The rotating jack design uses four main components to meet the functional requirements of a sand mold clamp. As seen in Figure 4.3, these components include a pin, a hand crank trailer jack, one permanently lubricated turntable, and four swivel pads. In this design the entire clamping assembly is permanently attached to the carrier deck with the use of a connection pin. The pinned connection allows the mold to disengage automatically when the pneumatic pistons push on the mold. The pin connects the top of the carrier deck to the top of the trailer jack. The bottom of the trailer jack is bolted to a turntable that is used to adjust the footprint. The turntable is welded to a steel frame that attaches to four swivel pads, which are used to distribute the clamping force to the top of the mold. Together these components form a design that satisfies the basic functions of a sand mold clamp.

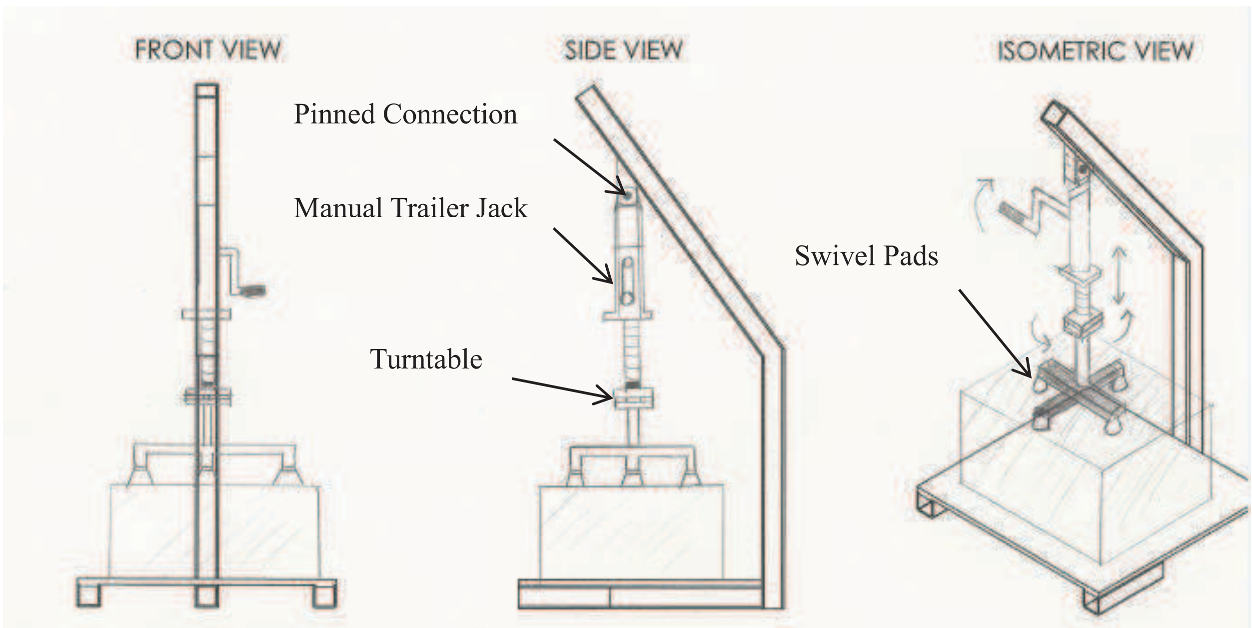


Figure 4.3: Design concept #2: Rotating Jack design

The rotating jack design fulfills the functional requirements for the sand mold clamp. Table 7 summarizes the designs ability to satisfy the custom requirements.

Table 7: Achieved and problematic CRs for Design #2.

Favorable CRs (9-10 Pts)	**Neutral CRs (6-8 Pts)**	**Problematic CRs (1-5 Pts)**
#4: adequate clamping force (10)	#2: withstand elevated temperatures (8)	#1: fit multiple mold sizes (6)
#6: provide access to sprue and risers (9)	#3: disengage automatically (7)	#5: distribute force evenly (5)
#7: remain with carrier deck (10)	#8: do not damage mold (7)	#11: maintenance minimized (5)
#12: decrease set up time (10)	#9: off the shelf components (8)	
	#10: functional lifetime greater than 2 years (7)	

4.2.1 Function #1: Vertical Height Adjustment

A side-wind trailer jack as seen in Figure 4.4 operates as a normal trailer jack with the advantage of having the hand crank located on the side of the jack. The screw mechanism in the jack provides a continuously variable vertical height adjustment similar to the nut and bolt subsystem discussed in section 3.3.1.2. The system satisfies ER #1 which calls out a vertical adjustment of at least 20”. This particular jack fulfills this requirement with a vertical travel adjustment of 28 ½”. The advantages of this jack are the same as for the scissor jack with the added advantage of not having exposed threads that could be damaged (CR #10). However, there are two disadvantages to this design. First, the internal workings of the gears and screw require lubrication (CR #11). The hot and dirty environment that the clamp needs to operate in may require that the trailer jack receive more maintenance than is acceptable. Second, if the height has to be adjusted by a height of ten inches or more, the operator may have to turn the crank handle thirty or more revolutions, which is not ideal for worker ergonomics.

Figure 4.4: Trailer Jack. Source: NorthernTool. “Ultra-Tow Side-Wind Trailer Jack” [Online]. Available: http://www.northerntool.com/shop/tools/product_200463057_200463057

4.2.2 Function #2: Footprint Adjustment

The footprint in this design is adjusted using a turntable as discussed in section 3.3.2.1 . The four swivel pads must contact the top of the mold without touching the sprue or any of the randomly located risers as specified in CR #6. Before engaging the clamping mechanism the operator can rotate the footprint to the desired location. This is accomplished without rotating the trailer jack. The turntable is bolted to the bottom of the trailer jack and welded to the footprint structure, effectively separating the two halves of the clamping device. The advantage with this design is that it is easy to use and the ball bearings are permanently sealed, so they never require maintenance (CR #11). The disadvantage of the turntable is the limited amount of adjustability. The turntable allows the footprint to spin in a continuously variable circle, but the radius of the circle does not change. Since the radius does not change it is possible that one of the foot pads might interfere with a riser or sprue.

4.2.3 Function #3: Application of the Clamping Force

The rotating jack design converts the lifting force of the trailer jack into a clamping force. As the operator turns the crank handle, the top of the trailer jack pushes against the upper portion of the carrier deck while the bottom of the trailer jack applies an equal amount of force to the top of the mold. The trailer jack in Figure 4.4 has a load capacity of 5,000 lbs which easily satisfies the 400 lb force requirement in ER #4.

The advantage of this design is the mechanical advantage that is supplied by the threads and the crank handle. The disadvantage of this design is that the jack can supply ten times the required amount of force, and there is no method for the operator to know the amount of force being applied by the jack. If the operator over torques the jack it may cause damage to the mold and cause the device to fail CR #8.

4.2.4 Function #4: Distribution of the Clamping Force

The force is distributed in the rotating jack device with the use of four swivel pads. The clamping force is distributed through the four pads, which are spread apart in a rectangular foot print. The four points are symmetrically distributed in order to apply an evenly distributed force as required by CR #5. The advantage of this design is the swivel adjustment in the pads. The extra flexibility provided by the swivel adjustment ensures the bottom of the pad fully engages the top of the mold, even if the clamp is not flush with the top of the mold. The disadvantage of this design is that the swivel pads may fail due to the high heat environment (CR #2).

4.2.5 Function #5: Disengagement

The pinned connection at the top of the rotating clamping device is the main component of the disengagement function. When the mold is initially clamped, a force is applied vertically through the center axis of the pinned connection. In this situation the pinned connection only resists a translation motion by an applied force. After the casting process has completed, two pneumatic cylinders push on the side of the mold, forcing the mold off the carrier deck. Since a pinned connection does not resist an applied moment, the clamping device begins to rotate about the pinned as the mold moves off the carrier deck. As soon as the clamping device is no longer in a vertical position it is no longer able to apply a vertical force to the mold and is thus disengaged. The advantage of this design is that an operator is not required to disengage the device from the mold (CR #3). Pins are also common parts and can be purchases at a variety of different places, satisfying CR #9. The disadvantage of the pinned connection is that it must be aligned in the vertical position, increasing setup time.

4.3 Design #3: Box Frame Roller

Another design considered by the team is the Box Frame Roller Design. The design consists of eight rollers, two worm gears, two rack gears, four pinion gears, square tubing, and flat bar. These components make up two main parts, the box frame and the roller assembly. As seen in Figure 4.5, the box frame is constructed of square tubing and is welded to the four corners of the carrier deck. The box frame has the two worm gears and two rack gears connected to the side of the frame, with the worm gears fitted with cranks. These cranks are used to raise and lower the device. The roller assembly consists of two rows of rollers held together by a frame constructed of flat bar. Slots are cut into the sides of the roller frame allowing the rollers to be adjusted. The roller assembly attaches to the box frame and is adjusted using the worm gears on the box frame and pinion gears on the corners of the roller assembly. The design works by rotating the two cranks attached to a worm gear, causing the pinion gears spin, and the roller assembly to lower. The following sections describe how this design satisfies each of the clamping functions.

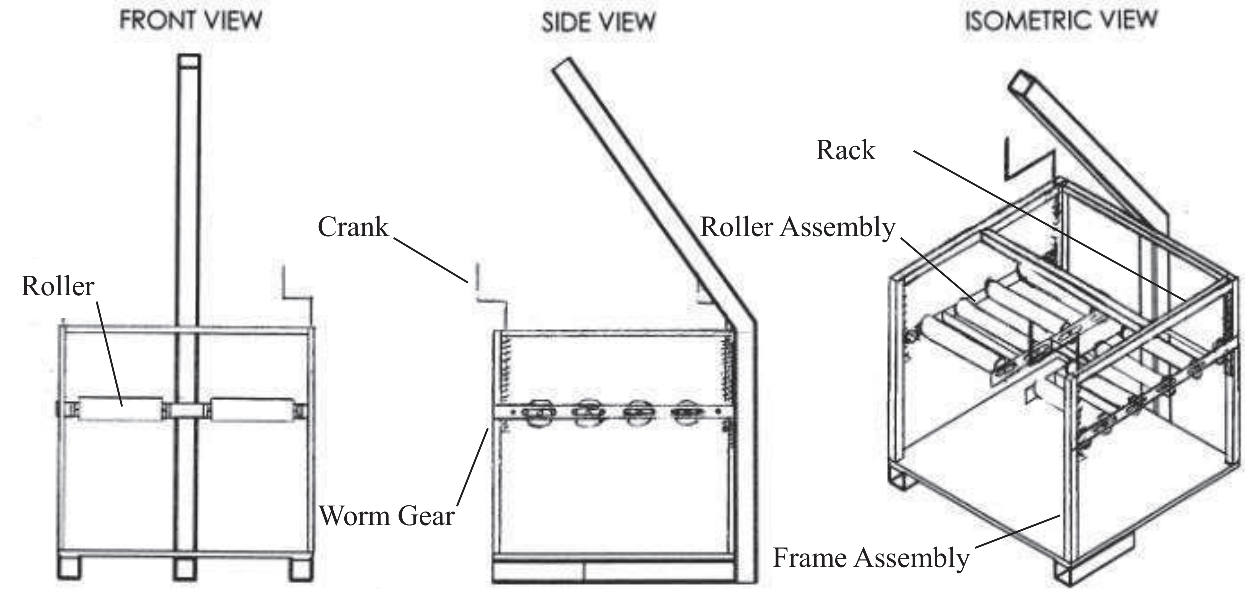


Figure 4.5: Design concept #3: Box Frame Roller design

The box frame roller clamp provides a unique way to achieve the customer requirements. Table 8 summarizes the designs ability to satisfy the custom requirements.

Table 8: Achieved and problematic CRs for Design #3

Favorable CRs (9-10 Pts)	**Neutral CRs (6-8 Pts)**	**Problematic CRs (1-5 Pts)**
#3: disengage automatically (9)	#1: fit multiple mold sizes (7)	#6: provide access to sprue and risers (5)
#4: adequate clamping force (10)	#2: withstand elevated temperatures (6)	#9: off the shelf components (4)
#5: distribute force evenly (9)	#8: do not damage mold (7)	#10: functional lifetime greater than 2 years (4)
#7: remain with carrier deck (10)	#11: maintenance minimized (6)	#12: decrease set up time (5)

4.3.1 Function #1: Vertical Height Adjustment

In order for the clamp to fulfill CR #1, the clamping assembly must be able to fit molds 12” to 20” in height. This is done using the two worm gears. Due to their design, worm gears can vary in length, allowing the device to accommodate different mold heights. Long worm gears are difficult to find and could require the gear to be machined, resulting in issues with ER #10. As described above, the vertical height is adjusted by rotating two hand cranks. These hand cranks sit at chest level and provide a simple and ergonomic way of achieving the desired height. Each rotation of the worm gear moves the pinion gear one tooth allowing the device to make fine adjustments, and reducing the chances of damaging the mold (CR #8). One disadvantage is that the fine adjustment and the two cranking points could increase setup time (CR #12). Another disadvantage is that molten metal splashes while being poured and could cause molten metal to harden between the gears. This would require maintenance time to repair (CR #11).

4.3.2 Function #2: Footprint Adjustment

The clamping device must not only fit multiple mold heights but also a variety of different sprue and riser locations, as presented in CR #6. This design allows the clamp footprint the be adjusted using slots, as described in section 3.3.2.2 , cut into the roller assembly. Each roller has two pins which extend out each end of the roller. These pins fit into the slot on the roller assembly allowing the roller to be adjusted forward and backward. This device does not require the roller to be locked in place, allowing it to be quickly and easily adjusted, and reducing setup time (CR #12). The disadvantage is that the roller is limited to moving within the slot range and therefore it limits the clamping footprints. This limited footprint could prevent this design from passing CR #7.

4.3.3 Function #3: Application of the Clamping Force

The next function of the clamping device is the application of the clamping force. This, like the vertical height adjustment, is done by rotating the two worm gears. After the roller assembly comes in contact with the mold each additional rotations of the crank applies a clamping force to the mold. The advantages and disadvantages to using the worm and pinion gears to apply a clamping force are similar to the ones described in section 4.3.1, with an additional disadvantage. As described above, the clamping force is applied by rotating two worm gears. The disadvantage is that it may be difficult to rotate the two worm gears at the same rate causing the roller assembly to bind or preventing an evenly distributed load (CR #5)

4.3.4 Function #4: Distribution of the Clamping Force

Another function of the clamping device is to distribute the clamping force across the surface of the mold. This is done using the roller assembly described in section 4.3. The main advantage is that the clamping force is distributed evenly over the surface of the mold along each of the rollers, assuming the force is applied properly from the two worm gears. The disadvantage is that the force is applied over a thinner area, which could damage the edges of the mold (CR #8).

4.3.5 Function #5: Disengagement

The final function of the clamping device, used to satisfy CR #3 is to allow the casting to be ejected from the carrier deck without human interaction. This function is accomplished by using eight rollers. To eject the casting from the carrier deck, ESCO uses two hydraulic pistons. When the mold is ready to be removed, the pistons push from the back of the carrier deck, destroying the mold and knocking the casting onto a conveyor. As the pistons push on the mold the rollers spin preventing the mold from binding. The advantage of using industrial rollers is that they are able to operate at high temperatures (CR #2). The disadvantage is that the rollers could require periodic maintenance (CR #11).

4.4 Design #4: Rack and Pinion

The rack and pinion design uses a combination of unique components to meet the functional requirements. It is made up of a rack and pinion jack, a steel channel, and two pieces of angle iron. As seen in Figure 4.6, the rack and pinion jack is attached to the neck of the carrier deck using a pinned connection, which is then attached to the center of the channel by another pinned connection. The two pieces of angle iron are connected to the channel through slots cut into the channel, allowing the angle irons to slide and rotate. The device works by cranking the handle of the jack until the angles come in contact with the mold surface. Once this is achieved, any additional cranking of the handle applies a clamping force to the mold. The following sections describe how this design satisfies the functions of the clamp.

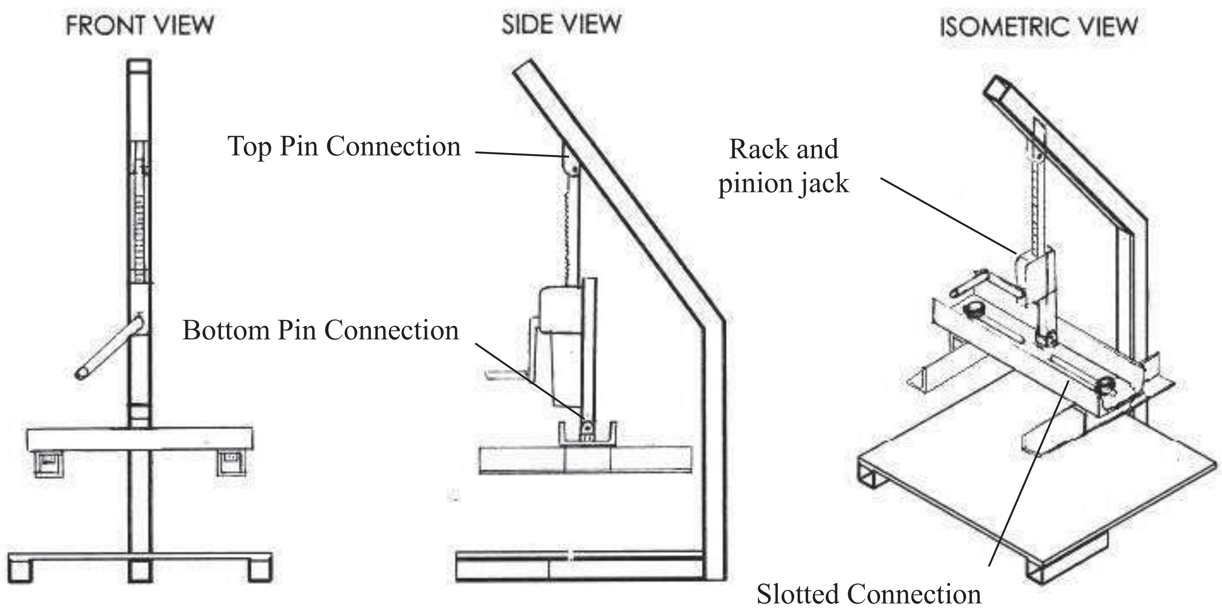


Figure 4.6: Design concept #4: Rack and Pinion design

The rack and pinion clamp design satisfies the customer requirements. Table 9 summarizes the designs ability to satisfy the custom requirements.

Table 9: Achieved and problematic CRs for Design #4.

Favorable CRs (9-10 Pts)	Neutral CRs (6-8 Pts)	Problematic CRs (1-5 Pts)
#1: fit multiple mold sizes (9)	#3: disengage automatically (8)	
#2: withstand elevated temperatures (9)	#5: distribute force evenly (8)	
#4: adequate clamping force (10)	#6: provide access to sprue and risers (8)	
#7: remain with carrier deck (10)	#8: do not damage mold (7)	
#10: functional lifetime greater than 2 years (9)	#9: off the shelf components (7)	
#12: decrease set up time (9)	#11: maintenance minimized (7)	

4.4.1 Function #1: Vertical Height Adjustment

To satisfy CR #1, the clamping device is required to fit any mold between 12” and 20” in height. To account for the variety of mold heights, this design utilizes a rack and pinion jack, with a 2 ½ ft long rack gear. As the jacks handle is turned it rotates a worm gear, causing the pinion gear to turn, moving the body of the clamp up and down the rack gear. This device, seen in Figure 5.9, provides a quick way of adjusting the height, reducing setup time and satisfying CR #12. It is made of steel and cast iron components that make it robust, increasing the life expectancy (CR #10) and reducing the required maintenance (CR #11). The rack and pinion jack can be purchase online, allowing the design to also satisfy CR #9. One disadvantage with the rack and pinion jack is the exposed rack gear. During the pouring process, molten metal tends to splash. The splashed molten metal could harden between the rack teeth, preventing the device from operating properly.

Figure 4.7: Rack and Pinion Jack. Source: Haacon. (2011). “Rack & Pinion Jack with self-locking worm gear” [Online]. Available: http://www.haacon.de/media/produkte/zahnstangenwinde1524.pdf

4.4.2 Function #2: Footprint Adjustment

To account for multiple sprue and riser locations, the design uses a slotted connection, similar to the one describe in section 3.3.2.2. The slots are cut into the steel channel to allow the pieces of angle iron to move linearly across the mold while the bolt connecting the angle iron to the channel allows the angle iron to rotate, satisfying CR #6. The channel is 34” long and spans horizontally across the carrier deck. As seen in Figure 4.6, the slots extend from the center of the channel outwards; allowing the clamp to fit multiple mold widths, which satisfy CR #1. The disadvantage of using slotted connections is that they are exposed to molten metal splashes. If the molten metal hardens in the slot it could limit the linear motion of the angle iron, requiring maintenance (CR #11).

4.4.3 Function #3: Application of the Clamping Force

As with the vertical adjustment, a rack and pinion jack is used to apply the clamping force. Once the clamping footprint comes in contact with the mold surface any additional rotation applies a clamping force. The selected rack and pinion jack supplies a force of 1000 lbs, easily satisfying CR #4. Similar to the other clamping designs, the rack and pinion jack is a single step process that combines the adjustment of the clamps vertical height with the application of a clamping force. This reduces the setup time, satisfying CR #12. The disadvantage with this device is that it is capable of supplying a clamping force of 1000 lbs and could damage the mold, failing CR #8.

4.4.4 Function #4: Distribution of the Clamping Force

This design distributes the clamping force using two pieces of angle iron, similar to ESCO's current clamping device. Although the primary reason for the current clamp redesign is the distribution of force, the new design transfers the force to the angle over a larger area and therefore is expected to distribute the force more evenly. This would satisfy CR #5. Another benefit to using angle iron is that it is robust, satisfying the CRs #2, #11, and #12. Providing the two pieces of angle iron properly distribute the clamping force, there are no disadvantages to using angle iron.

4.4.5 Function #5: Disengagement

To allow the mold to disengage without binding on the clamping device, and satisfying CR #3, this design utilizes two pinned connections. These pinned connections are located between the rack and pinion jack and the carrier deck, and the rack and pinion jack and the channel. The top pinned connection acts as a pivot point for the clamp assembly, allowing it to swing forward as the mold is removed from the carrier deck. The bottom pinned connection acts as a pivot point for the clamp footprint, preventing the angle iron from binding on the mold as the mold is removed. The pins used for the connections can range in size and material making them suitable for almost any application. They are also a common component satisfying CR #9.

5 DESIGN SELECTED

Design #4, “Rack and Pinion”, has been selected for prototype development because it scored highest on an objective concept evaluation. The design is simple to manufacture and promises the best performance in the categories specified by the customer requirements. The decision process and the performed concept evaluation are described in Section 5.1. Section 5.2 is used to fully describe the features of Design #4.

5.1 Rationale for Design Selection

The design selection process requires an evaluation according to objective criteria. The customer requirements are used as the objective evaluation criteria because they concisely describe all of the required tasks of the sand mold clamp. To take the implementation process for the project into account, manufacturability and availability of components are also considered.

The process of concept evaluation and selection is based on the decision matrix method [19]. Each concept considered is evaluated on each criterion by assigning a number value between 1 and 10. A point value of 10 is given for an ideal solution to the problem while a point value of 1 is the result of a poor solution. The point values assigned in Chapter 4 are multiplied by the importance factor of each criterion and then summed up for the individual design. The importance factor is the weight value that was assigned by the project sponsor. The selected design is the concept with the highest overall score. Table 10 shows the decision matrix. The justification for the assigned scorings of each criterion is given below the table.

Table 10: Decision Matrix

Goal: Design selection for further development			**Design**			
Decision Criteria		**Weight**	**#1**	**#2**	**#3**	**#4**
1	Clamp device shall be able to fit multiple mold sizes	25	7	6	7	9
2	Exposure to elevated temperatures shall not affect device performance and functionality	15	9	8	6	9
3	Clamp device shall disengage automatically to prevent binding during mold ejection	25	5	7	9	8
4	Clamping force shall meet or exceed current design	25	10	10	10	10
5	Clamping device shall distribute force evenly on the mold	20	9	5	9	8
6	Clamping footprint shall provide access to multiple sprue and riser locations	25	5	9	5	8
7	Device shall remain with the carrier deck	30	10	10	10	10
8	Clamping device shall not damage mold	25	7	7	7	7

continued

9	Off the shelf components are preferred	10	5	8	4	7
10	Functional life of clamp shall be at least 2 years	20	5	7	4	9
11	Maintenance of device shall be minimized	15	6	5	6	7
12	Initial set up shall be less than or equal to current design	15	8	10	5	9
13	Manufacturability	30	7	8	5	8
14	Availability of components	30	9	9	9	9
	Total		102	109	96	118
	Weighted Total		**2305**	**2450**	**2225**	**2645**
	Rank		**3.**	**2.**	**4.**	**1.**

Discussion of assigned values

1. Clamp device shall be able to fit multiple mold sizes

   All four of the designs are able to adjust to different mold heights in the required range of 8”. The angle irons forming the footprint of design #4 can easily be adjusted to different mold widths and require no frame around the outer borders. Design #4 allows the greatest adjustability to the mold size. Design #1 and #3 both require a frame that is big enough to cover the biggest surface that is used. Therefore these frames are oversized for the smaller molds. Design #2 allows no adjustment of its footprint size at all.

2. Exposure to elevated temperatures shall not affect device performance and functionality

   All parts contacting the mold surface are only built out of temperature resistant steel for all considered designs. Design #3 requires a frame to move along a slot close to the hot mold surface which might cause problems at elevated temperatures. For the other designs all moving parts are sufficiently far away from the mold surface and are not affected by temperature increases.

3. Clamp device shall disengage automatically to prevent binding during mold ejection

   Design #3 promises the best performance for this task as the rollers on the mold surface apply almost no friction during the mold ejection. However, the clamping force is still applied during the ejection process. Design #4 allows the clamping device to pivot when the mold gets pushed off the carrier deck and does also not bind the mold. The crossbars of design #1 can only slide a certain distance before they lock and design #2 only offers one pivot point at the top which could cause a torque during mold ejection. Both designs might still allow auto disengagement but their performance is slightly worse.

4. Clamping force shall meet or exceed the current design

   All of the mechanical systems considered are capable of providing a clamping force that exceeds the required force by one order of magnitude.

5. Clamping device shall distribute force evenly on the mold

   Design #1 and #3 both cover large parts of the mold surface and allow an even force distribution. Design #4 covers less of the surface but still allows to adjust the footprint to get an even force distribution. Design #2 only pushes onto four spots on the mold surface. For big mold sizes these spots might not be close enough to the edge of the mold to supply a sufficient force around the mold.

6. Clamping footprint shall provide access to multiple sprue and riser locations

   The less of the mold surface that is covered by the clamping device, the easier sprue and risers can be accessed. Design #2 allows an almost maximal access to the mold surface. Design #4 is only slightly worse as the angle irons can be turned as to not interfere with sprue and risers. Design #1 and #3 do not cover the whole mold surface, but their frames span the whole mold, limiting access to the sprue and risers.

7. Device shall remain with the carrier deck

   All the considered designs are either bolted or welded to the carrier deck and have no loose parts.

8. Device shall not damage the mold

   In the current clamping design, the mold is damaged from sharp impacts caused by the hammer strike. All of the considered clamping designs allow a smooth application of the clamping force and are unlikely to damage the mold. However all devices are able to provide a force that is high enough to crack the mold if they are misused by the operator.

9. Off the shelf components are preferred

   For most of the designs off the shelf components are used to apply the clamping force. The only exception is design #3, which could require custom parts. These movable components are most likely to fail and therefore should be easily purchased. All the designs use off the shelf fasteners. However, structural parts are mainly custom built. The amount of manufacturing time to replace those parts is also taken into account.

10. Functional life of clamp shall be at least 2 years

    Solid steel parts are unlikely to fail as long as they are properly dimensioned for the applied stresses. Failures are mainly expected for moving parts, including turntables and threads due to wear and splashes of liquid metal. Design #4 has no exposed threads and uses robust bolt connections to allow the clamp to pivot. Design #2 has also no exposed threads but uses a turntable and designs #1 and #3 have exposed threads.

11. Maintenance of device shall be minimized

    All designs could require cleaning and greasing of the force applying components.

12. Initial set up shall be less than or equal to current design

    Design #2 provides the fastest set up time, requiring only the steel frame to be manually adjusted and the trailer jack to be cranked down. The set up time of design #4 is slightly longer, requiring two pieces of angle iron to be adjusted before cranking the rack and pinion jack. Design #1 and #3 require a longer set up time due to the complexity of their footprint.

13. Manufacturability

    Manufacturability is not one of the customer requirements for this project but should be considered. It affects the production costs and the general feasibility of the design. Therefore, manufacturability is weighted as high as the highest weighted customer requirement. Design #2 and #4 should both be easy to manufacture. No tight tolerances are needed and no extensive welding is necessary. The frame of design #1 requires more manufacturing time. Design #3 would require the most manufacturing time due to its box frame design.

14. Availability of components

    All of the considered designs use parts and components that are available.

The selected design should have the highest total score without an individual criterion score of less than 4. As seen in Table 9, design #4 has the highest overall score and does not fail a single requirement. Therefore design #4 is selected as the final design.

5.2 Design Description

All aspects of the chosen “Rack and Pinion” design are fully described in this section. Included are the drawings of the overall assembly and of the individual components. Also included are the engineering calculations and FEA simulations that are used to justify the size and material of the components.

5.2.1 Overall Assembly

The overall assembly of the “Rack and Pinion” sand mold clamping device is shown in Figure 5.1. The assembly has four major components: a rack and pinion jack, a square tube, a C-channel, and two pieces of angle iron.

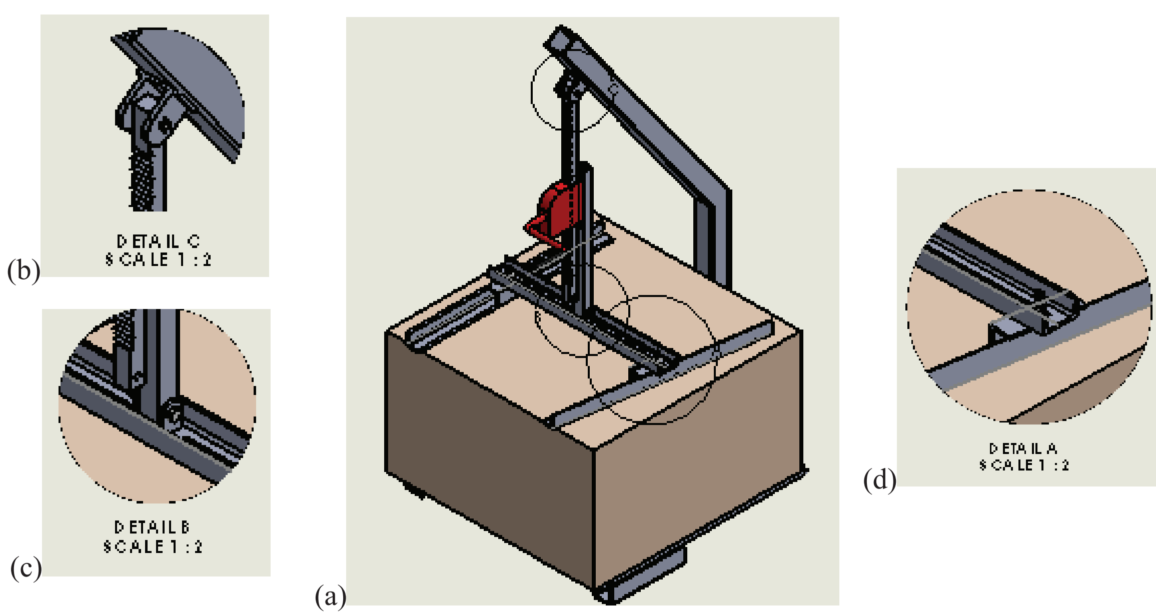


Figure 5.1: (a) Overall assembly of the “Rack and Pinion” sand mold clamping device.
(b), (c), (d) Detail drawings as indicated in (a).

The rack and pinion jack is attached to the neck of the carrier deck using a bolted connection. The housing of the jack is than bolted to the upper end of a steel square tube. Attached to the bottom end of the square tubing, via a bolted connection, is a steel C-channel. Finally, the angle iron is bolted to the C-channel through slots milled in the channel. Further engineering drawings with dimensions are presented in Appendix A.

5.2.2 Selected Materials

Material selection is important due to the harsh environments found in casting foundries. Components made of steel and cast iron were selected for this design based on their yield strength and their resistance to elevated temperatures.

ASTM A36 is an example of a common and affordable structural steel, the material properties of which are provided in Appendix B. This low carbon steel is capable of withstanding temperatures up to 842 °F and has a minimum yield stress of 36 kpsi. (See in Appendix B). ASTM A36 is also available in a variety of different shapes and sizes. An additional benefit to this material is its ability to be machined and welded. All custom-built parts of the design are fabricated out of ASTM A36 steel.

The fabricated components of the clamping device are connected using steel bolts. Steel bolts are available in a variety of different strength values, commonly referred to as grades. As the grade of the bolt increases, so does the strength of the bolt. The advantage of using higher grade bolts is that a higher strength is achieved without increasing the diameter of the bolt. Grade 8 bolts have been selected for this design for their high strength.

5.2.3 Part Design

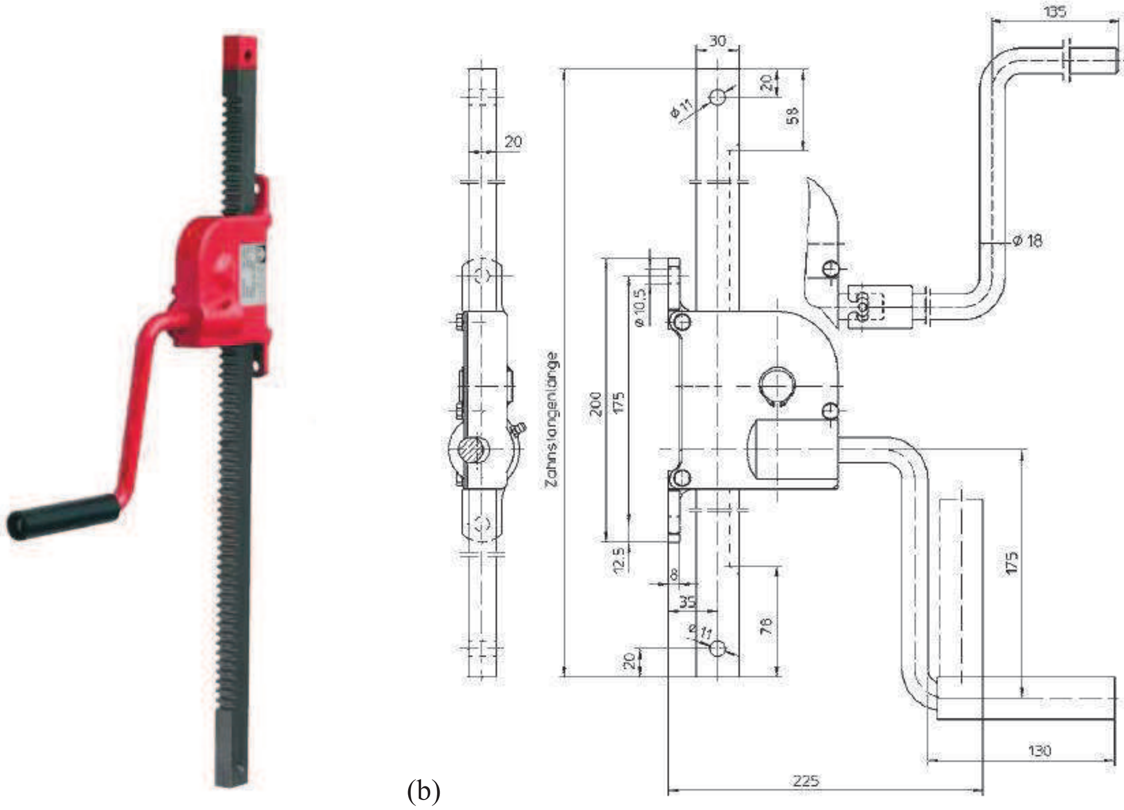
After selecting the proper material for all the components of the design; hand calculations, computer simulations, and product manuals are needed to ensure that each part functions as designed. The dimensions for all of the fabricated parts are constrained by the standard steel dimensions available from the steel supplier. These standard part dimensions are also used along with the material properties of ASTM A36 to provide the boundary conditions for all of the computer simulations. Detailed and dimensioned part drawings for all parts can be found in Appendix A.

5.2.3.1 Rack and Pinion Jack

The centerpiece of the chosen design is the rack and pinion jack shown in Figure 5.2. This jack is a Haacon 1524.0,5 rack and pinion jack with self-locking worm gear. All technical parameters are specified in the Haacon catalog in Appendix C. With a rack length of 735 mm, this device provides a vertical lift of 530 mm (≈ 20"). The permissible push and pull load is 500 kg (≈ 1100 lbs), which easily exceeds the required load of 400 lbs. A gear ratio of 1:20 allows a lift of 9.4 mm per crank turn with a max input crank force of 160 N.

The top of the rack has an 11 mm diameter hole that is used to bolt the jack to the carrier deck. The selection of appropriate bolts for this connection is discussed in Section 5.2.3.5 together with all other bolts used in the design.

The rack and pinion jack is built entirely out of cast iron and steel. These materials allow the device to operate at elevated temperatures. The positioning of the jack in the assembly guarantees a minimum distance of 17” between the moving jack parts and the mold surface. According to ESCO’s engineers, ambient air in these regions only reaches about 120°F. The functionality of the rack and pinion jack is not affected by these temperatures.



(a) (b)

Figure 5.2: Picture (a) and drawings (b) of the the Haacon 1524.0,5; Rack & Pinion Jack with self-locking worm gear. Source: Haacon catalog, see Appendix C

5.2.3.2 Square Tube

A steel square tube serves as a connection between the rack and pinion jack and the C-channel at the bottom of the clamp. Figure 5.3 shows a isometric drawing of the square tube.

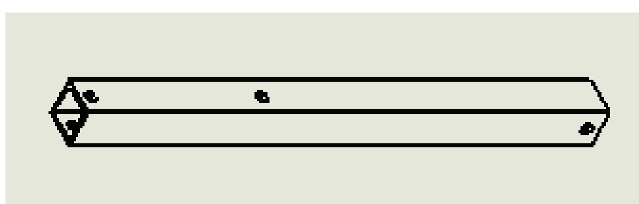


Figure 5.3: 1.5”x1.5” square steel tube.

The advantage of using a square tube is its ability to withstand bending stress almost as well as a similarly sized piece of solid steel, but with a smaller amount of weight. This advantage is due to the fact that the main contribution to the second moment of area is provided by the outer areas of the shape. The distance from the center of the structure has a quadratic influence, thus exerting a larger influence on the ability of the shape to resist a bending stress. The ideal shape for optimizing the second moment of area is a round tube. However, a square tube provides four even surfaces that allow for easier mounting of the rack and pinion jack to the tube.

A 21” long 1.5”x1.5” square tube with a wall thickness of 1/8” has been selected because it is available and affordable. The 1.5” width of the tube provides sufficient surface area for the rack and pinion jack to mount to the side of the tube. Two, 11 mm diameter holes with a center-to-center distance of 175 mm are drilled into the tube to be used to bolt the jack to the tube. Finally, a 0.5” diameter hole is drilled at the bottom to connect the tube to the C-channel via a 0.5” bolt.

The clamping device has to provide a load of at least 400 lbs to fulfill CR #4, and since the square tube attaches the clamping device to the mold it too has to carry this load. Calculations showing that the chosen dimensions for the square tube out of ASTM A36 steel are sufficient are shown in Appendix D. In addition, Figure 5.4 shows a FE-analysis for the stress magnitude of the square tube under a load of F=400 lbs. The simulation states that the maximum stress on any part of the tube is less than 2.18 kpsi (15 MPa), whereas the yield strength of the material is 36 kpsi (250 MPa). This provides a safety factor of 16 against plastic deformation of the square tube.

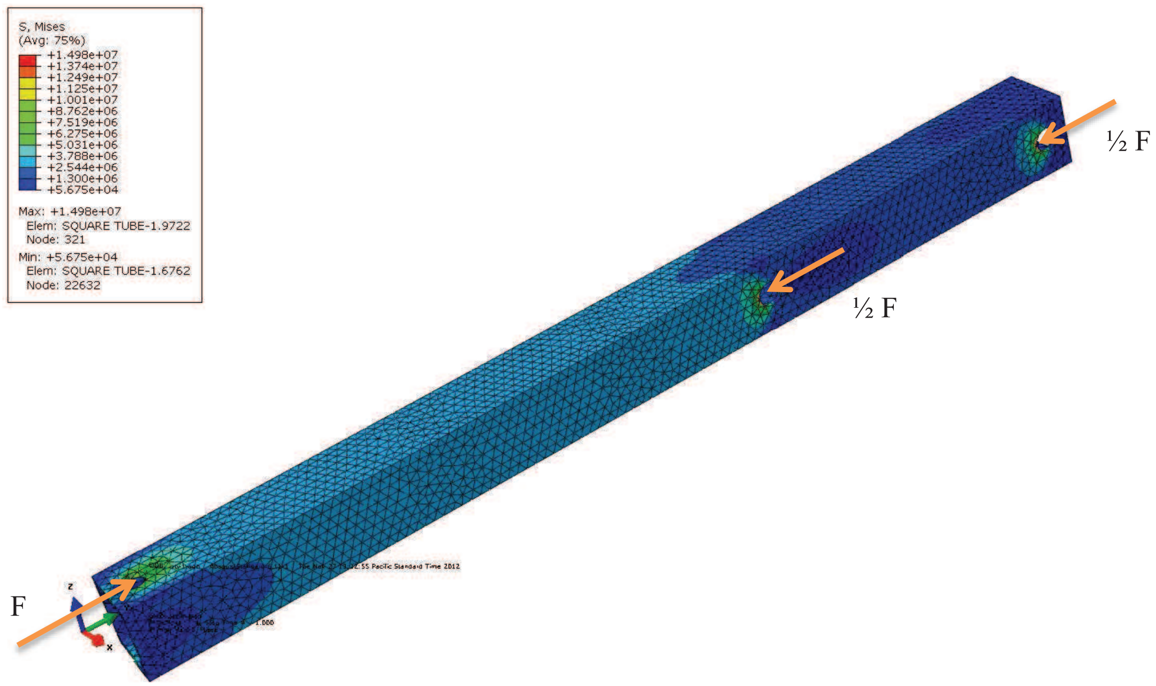


Figure 5.4: FEA for the stress magnitude of the square tube under a load of 400 lbs.

Thus, the selected dimensions of the square tube are strong enough to carry the applied load between the rack and pinion jack and the C-channel.

5.2.3.3 C-channel

The C-channel shown in the drawings in Figure 5.5 facilitates the adjustability of the footprint and initiates the force distribution.

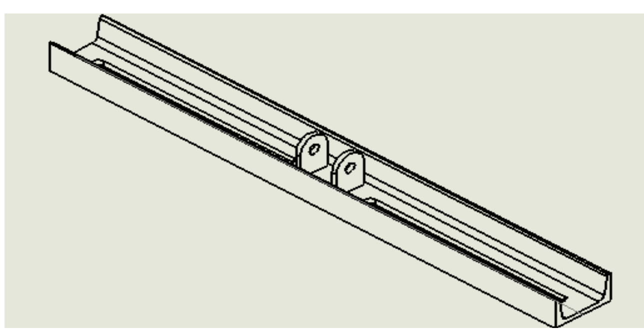


Figure 5.5: C-shaped standard channel C3 x with two slotted holes and two brackets.

A C-shape “Standard Channel” C3 x with outer dimensions of 3”x1.5” and a thickness of ¼” made of ASTM A36 steel has been selected. Two brackets with a 0.5” hole are welded to the center of the channel as shown in the drawings. The brackets allow the C-channel to bolt the square tube. A slotted hole with a width of 0.5” and a length of 10.5” is milled into the flat section of the C-channel on each side of the brackets. The angle irons are inserted into these holes with bolts that allow them to loosely slide and rotate inside of the slot.

The main task of the C-channel is to transfer the clamping force to the angle irons. Due to this task and the design of the clamp, the channel experiences a bending moment. The clamping force is applied to the center of the channel that rests on the angle irons. The maximum bending moment is applied when the angle irons are spread as far apart as possible. By choosing a C-shaped channel, the section modulus against bending is increased in comparison to a flat steel plate.

Figure 5.6 shows an FE-analysis for the stress magnitude of the C-channel. A load of F=400 lbs is applied through a bolt onto the brackets while the angle irons are used as a bearing on the endings of the channel. The simulation shows that the maximum stress on any part of the C-channel is less than 9.57 kpsi (66 MPa), whereas the yield strength of the material is 36 kpsi (250 MPa). This provides a safety factor of 3.7 against plastic deformation of the channel. Additional hand calculations also confirm this result, as seen in Appendix D.

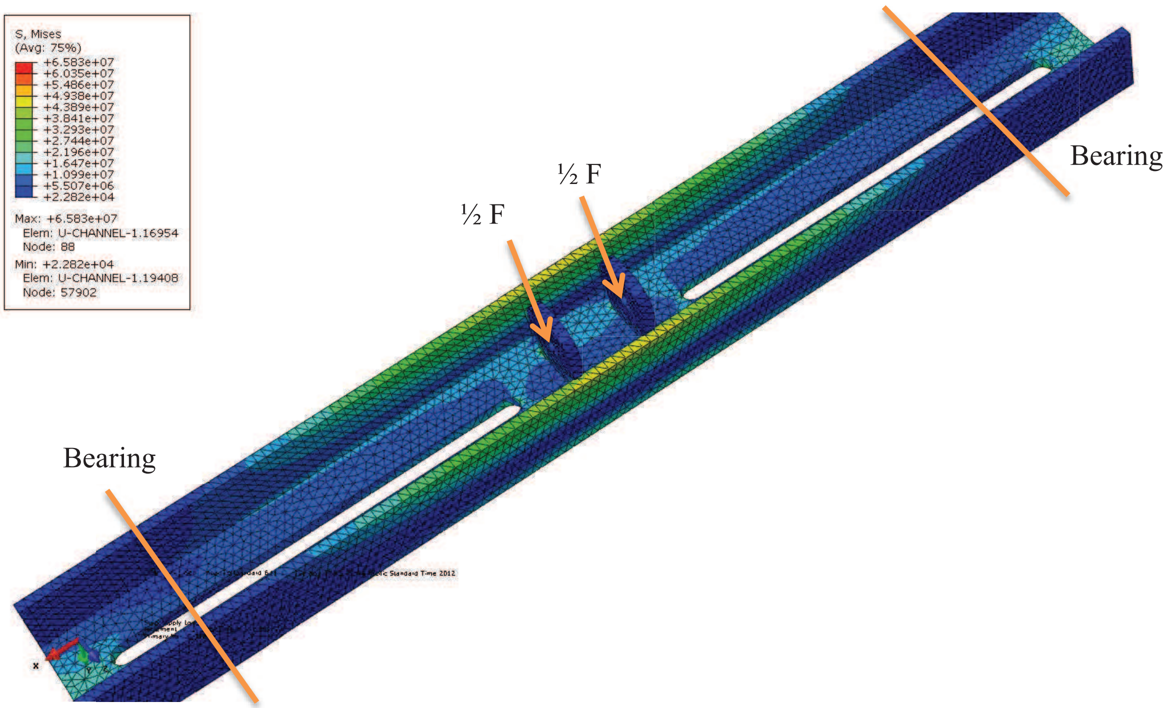


Figure 5.6: FEA for the stress magnitude of the C-channel under a bending load of 400 lbs.

The chosen channel design is strong enough to distribute the applied load onto the angle irons and allows the angle iron to be moved back and forth.

5.2.3.4 Angle Iron

Two 2” angle irons are used to apply and distribute the clamping force onto the mold surface. As shown in Figure 5.7 the angle irons are 32” long and have a mounting bolt welded onto their center. A 6” long piece of 2” angle iron is flipped over and welded onto the main part. A bolt is inserted through this piece and welded in place. This bolt connects the angle iron to the slotted hole in the C-channel. This connection is used to attach the angle iron to the channel while still allowing horizontal movement and rotation within the channel. The bolt does not transmit any clamping force and is therefore not a critical component in terms of stress analysis.

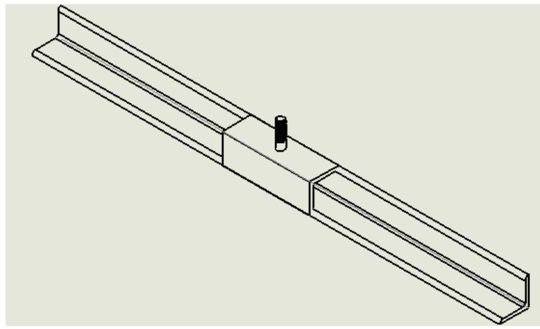


Figure 5.7: 2” angle iron with mounting bracket and bolt.

The functionality of angle irons to apply and distribute the clamping force has already been proven by ESCO, as their current design (see section 1.3) uses angle irons for the same purpose. The shape of the angle irons embodies a good compromise between a high section modulus, a sufficiently large surface area to contact the mold, and weight reduction compared to a solid bar.

When both angle irons are arranged symmetrically in the slotted holes, both carry half the clamping force. In the worst case however, one angle iron is positioned as close as possible to the center of the C-channel and the other one is at the far end of the channel. This leads to a force distribution, where the angle iron in the center carries the entire load. Therefore the FA-analysis in Figure 6.3 covers the case where a total load of F=400 lbs is applied to only one angle iron. The force is applied to the surface of the flipped over piece of angle iron by the bottom side of the C-channel. According to the simulation, the maximum stress on the angle iron is less than 1.16 kpsi (8 MPa). As the yield strength of the steel is 36 kpsi (250 MPa), there is a safety factor of 31 against plastic deformation.

The functionality of the angle irons is not affected by elevated temperatures on the mold surface. Up to 850 °F the material properties of steel do not change significantly. Considering that the maximum applied stress is only 1.16 kpsi, the temperature has no measurable impact on the deflection behavior of the angle iron.

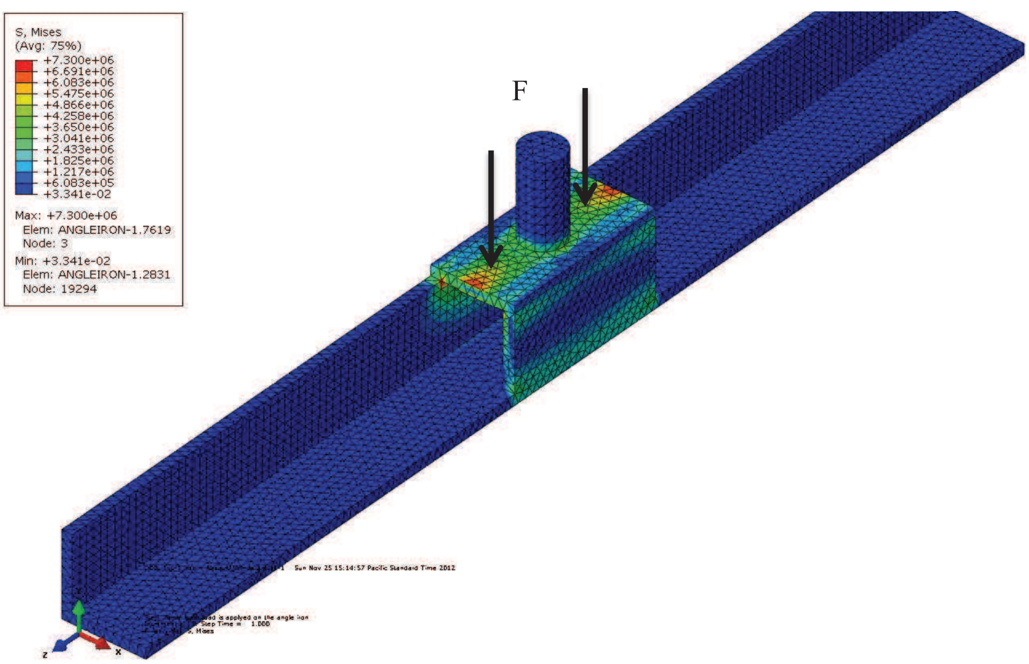


Figure 5.8: FEA for the stress magnitude of one angle iron under a load of 400 lbs.

Using 2” angle iron to distribute the force over the mold surface is a durable and inexpensive design.

5.2.3.5 Bolts

The chosen rack and pinion design uses six bolts to connect the five parts to each other and the carrier deck. The locations of these bolts are shown in Figure 5.9 and the calculations verifying the strength of the bolts can be found in Appendix D. Only one calculation on the smallest diameter of the four bolts is required since this bolt carries the maximum load. In this calculation a safety factor of 3 was selected and the resulting yield strength was then compared with the minimum proof strength of a Grade 8 bolt (120 kpsi, [16, p. 433]). All of the selected bolt sizes and steel grades are listed in Table 11.

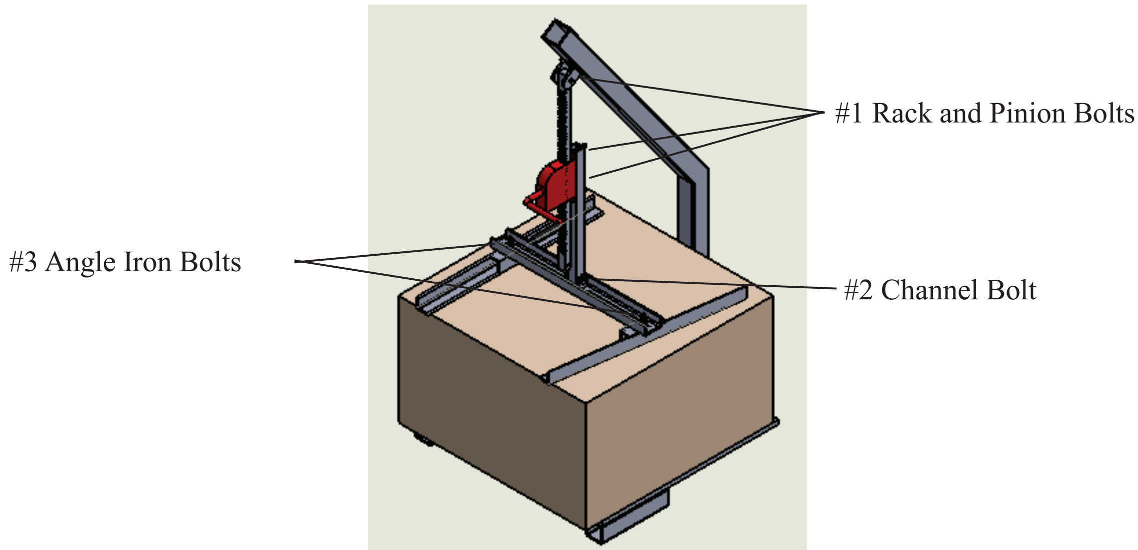


Figure 5.9: Positions of bolts in the rack and pinion sand mold clamp assembly.

Table 11: Size and grade of used bolts.

#	Name	Quantity	Size	Grade
1	Rack and Pinion Bolt	3	⅜"-16 x 2 ¾"	Gr. 8
2	Channel Bolt	1	½"-13 x 2 ¾"	Gr. 8
3	Angle Iron Bolt	2	½"-13 x 2"	Gr. 8

The bolts used to connect the angle irons to the C-channel do not carry any of the clamping force. They only ensure the positioning of the angle irons and carry the weight of the angle irons while the clamp is not in use. A strength verification calculation for these bolts is not necessary.

6 IMPLEMENTATION

A project implementation plan provides detailed instructions on how to implement the design. It is used to answer the who, what, when, and where aspects of the project's implementation and to ensure all customer needs are met. For the selected design, the implementation plan will include purchasing material and parts, fabricating parts, and assembling the clamping device. The following sections describe the project implementation plan in more detail.

6.1 Implementation Timeline

The Gantt chart in Figure 6.1 represents the implementation timeline for the selected clamping device. The first step in the project implementation was to order the parts for the design. This was completed during the winter break to ensure all parts arrived before construction of the prototype at the start of winter term.

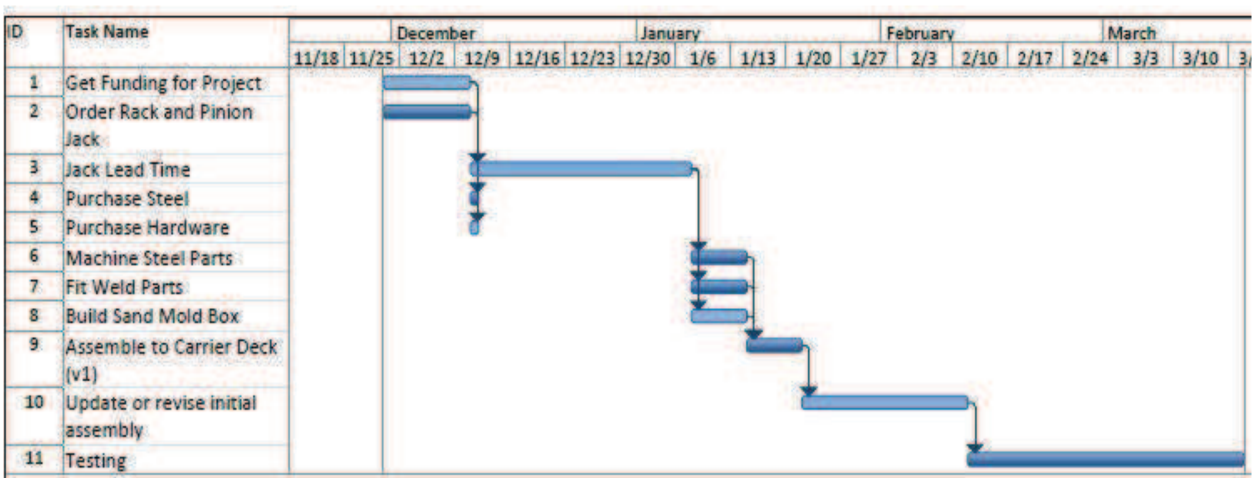


Figure 6.1: Proposed Gantt Chart Timeline

The only item requiring shipping for this design was the rack and pinion jack. It is the primary part of the design and had a lead time of three weeks. The dimensions of the jack dictate the exact sizes of the fabricated parts, and were therefore required before the machining of these parts. To ensure fabrication would begin on time, the rack and pinion jack was ordered at the beginning of winter break. The steel and the hardware for the design were purchased locally as needed.

Once the rack and pinion jack arrived, the construction of the prototype began. The construction included fabricating the steel parts, assembling the clamping device and attaching the device to the carrier deck. The first week of winter term was dedicated to fabricating the steel parts. The fabrication included: machining the steel parts, fit welding the parts together, and constructing a model sand mold. Following this week of fabrication, the next week was dedicated to the assembly all of the parts and the attachment of the prototype to the carrier deck. Over the following three weeks, the process of fabrication and assembly was repeated multiple times until a satisfactory version was achieved.

The final six weeks of the term were dedicated to the testing of the device. The tests revealed a couple of weakness in the design. The final six weeks of the term were used to fix these weaknesses in the design before the final presentation.

6.2 Bill of Materials

The first step in the implementation plan was to purchase the necessary parts to build the prototype. All of the parts that were purchased are listed in the Bill of Materials (BoM) in Appendix E. Included for each part in the BoM is the quantity to be purchased, the vendor, the part number and the listed price for each item.

Included in the BoM is the rack and pinion jack. The jack was the most expensive part due to the complexity of mechanism and because it was built in Germany. The manufacturer, Haacon, quoted the total cost of obtaining the jack at $400.00. The price quote included $200.00 to purchase the jack and $200.00 for the shipping costs.

The remaining parts of the design found in the BoM were purchased from local vendors in Oregon in order to avoid shipping costs. The team purchased the steel needed to fabricate the custom parts from Coyote Steel in Eugene, Oregon for $109.51. The hardware necessary to connect all of the parts was purchased from Eugene Fastener in Eugene, Oregon for $5.02. The wood studs for the sand mold model were purchased at Lowe's for $18.19. The total amount spent on the final prototype was $532.90.

6.3 Fabrication

The second step of the implementation plan was to fabricate all of the custom parts from the purchased steel. The members of the team completed all of the machining and welding in the machine shop at OSU. The machining included: cutting each piece of steel to the proper length, drilling holes in the flat bar and square tube steel, and milling slots in the C-channel. A metal cutting band saw, a drill press and a milling machine were used to complete the machining for each respective part. The fully machined parts for the channel assembly and the angle iron footprints can be seen in Figure 6.2.

Figure 6.2: Fabricated parts for the angle iron footprint and the C-channel prior to welding.

Upon completion of the machining, the following parts were welded using a MIG welder: the angle iron footprints, the C-channel and the carrier deck connection bracket.

The angle footprints were fabricated by welding together a ½”-13 x 2” bolt and two pieces of angle iron, as illustrated in Figure 6.3. The bolt was first slid through the hole cut in the smaller piece of angle iron. Once the bolt was in place, it was then welded to the angle iron. The smaller piece of angle iron was then welded to the larger piece. The part drawings and assembly drawing for the angle footprint are shown in Appendix A.

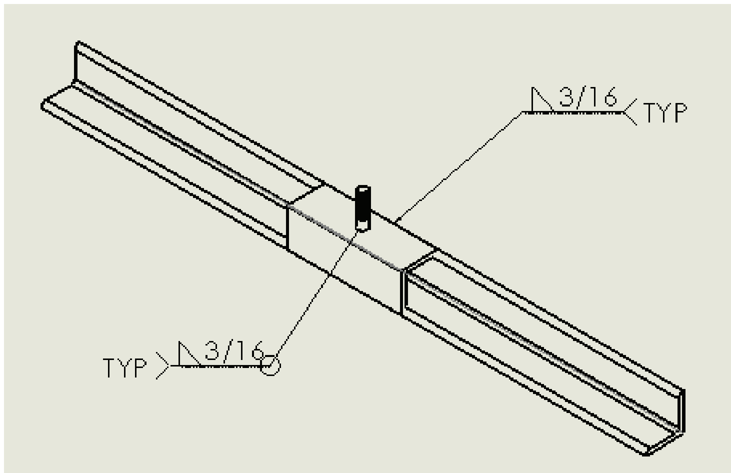


Figure 6.3: Angle iron footprint.

The C-channel was fabricated by welding two pieces of flat bar to the inside of the channel, as seen in Figure 6.4. The pieces of flat bar were welded in the center of the channel spaced 2” apart. The part drawings and assembly drawing for the C-channel can been seen in Appendix A.

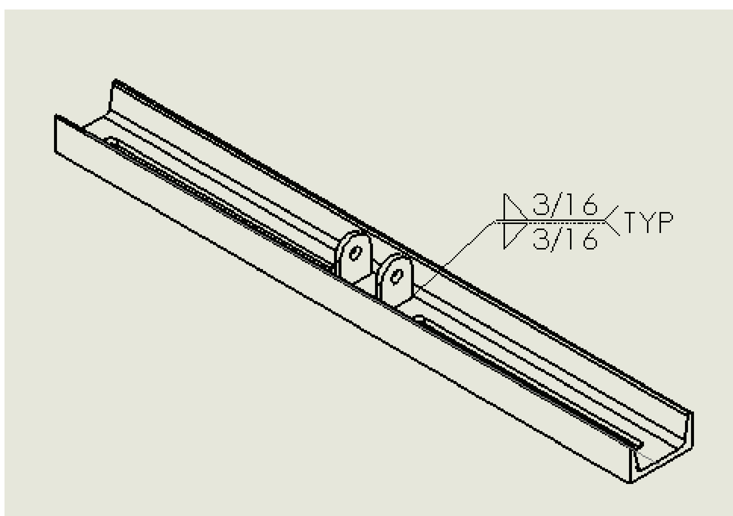


Figure 6.4: C-channel.

The final part to be welded was the carrier deck connection bracket. The bracket was fabricated by welding two pieces of flat bar to another piece of flat bar. An image of the bracket can be seen in Figure 6.5. The two flat bars that form the pinned connection were spaced 2” apart and welded to the other piece of flat bar. The part drawings and assembly drawing for the carrier deck connection bracket can be seen in Appendix A.

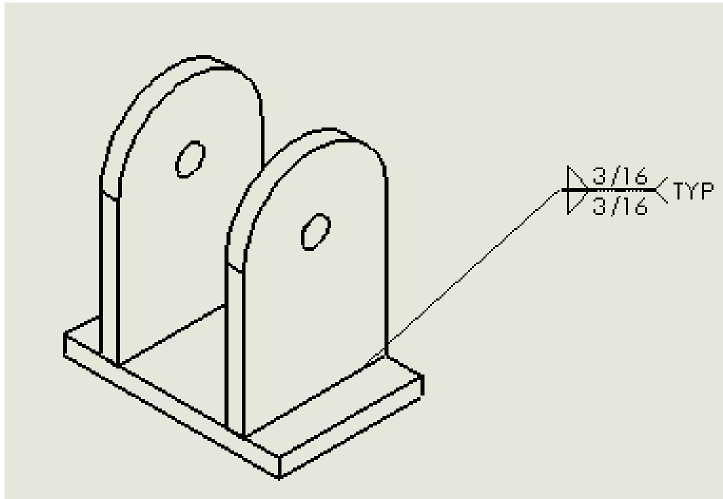


Figure 6.5: Carrier deck connection bracket.

The welding was done as part of an iterative process with the assembly step of the implementation plan. For the initial assembly, the welded connections were partially welded to allow the team to check if all of the parts would fit together. Once satisfied with the setup, the team completed the welding on the partially welded joints.

6.4 Assembly

The final step in the implementation plan was the assembly of the prototype. The clamping device was assembled by connecting: the angle footprints to the C-channel, the C-channel to the square tube, the square tube to the rack and pinion jack, the rack and pinion jack to the carrier deck bracket, and finally the carrier deck bracket to the neck of the carrier deck.

The first step in the assembly was to attach the angle footprints to the C-channel. This was done by sliding the bolt attached to the angle footprint into the slot milled into the C-channel. Once the angle was in place, a ½" hex nut was threaded onto the bolt and welded to prevent the angle from falling off. Figure 6.6 show what the device should look like after completing this step.

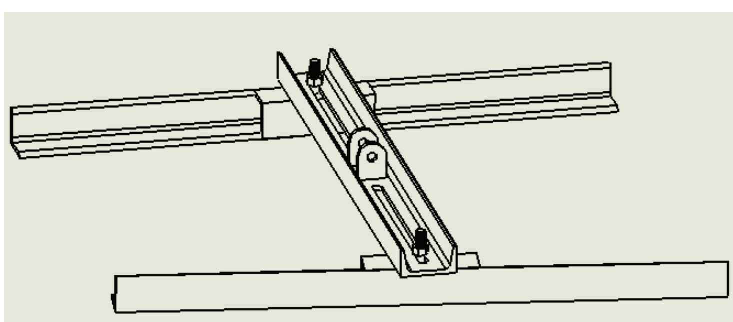


Figure 6.6: Assembly after the first step.

Next, the square tubing was attached to the C-channel bracket via a bolted connection, as illustrated in Figure 6.7. This step required a ½"-13 x 2 ¾" bolt and a ½ hex nut.

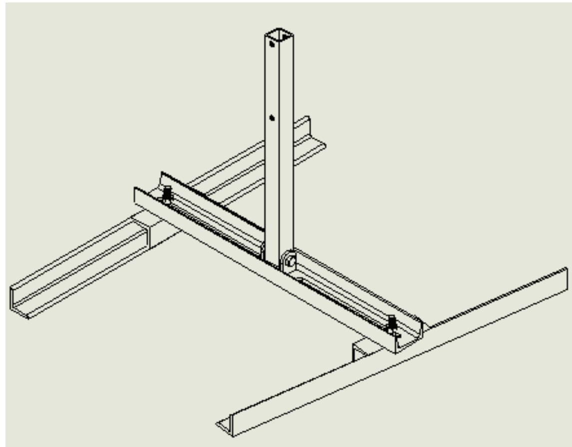


Figure 6.7: Assembly after the second step.

To complete the clamping device, the rack and pinion jack was bolted to the other end of the square tubing. This step required two M10-1.5 x 60mm bolts and two M10-1.5 hex nuts. The result of this step is illustrated in Figure 6.8.

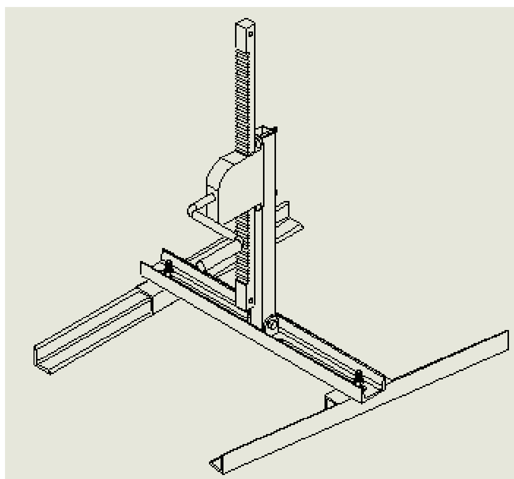


Figure 6.8: Assembly after the third step.

Before attaching the clamping device to the carrier deck, the carrier deck connection bracket needs to be welded to the carrier deck. The bracket will be centered on the neck of the carrier deck directly over the center of the carrier deck base. The result of this step is illustrated in Figure 6.9.

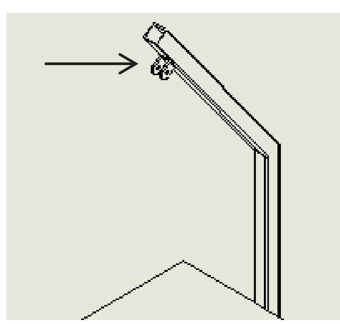


Figure 6.9: Assembly after the fourth step.

The final step of the assembly was to connect the clamping device to the carrier deck. This step required a M10-1.5 x 60mm bolt and a M10-1.5 hex nut. The result of this step is illustrated in Figure 6.10.

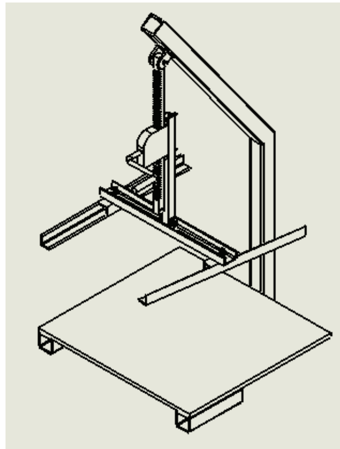


Figure 6.10: Final assembly.

The assembly was completed by the team in the Graf Hall using tools provided by the team members and the OSU machine shop. Figure 6.11 shows the completed design attached to the carrier deck. Included in Figure 6.11 is a sheet metal guard around the rack that was added due to testing results.

(a) (b)

Figure 6.11: (a) shows the total overview and (b) a close up of the assembled mold clamping device.

7 TESTING

Testing was performed over a six week period. During this time, design modification were identified and implemented. The following sections provide the detailed testing results for all final tests.

7.1 Testing Procedures and Results

The testing procedures from Section 2.3 were performed as written to evaluate each engineering requirement. Each test is given a pass or fail grade followed by the detailed results. For tests that resulted in a failed grade, a proposed redesign is included.

Testing Procedure #1 – Pass

The clamping device must sit higher than 20" above the top of the carrier deck. A target was set of 24" with a tolerance of >20". This test was performed by raising the device until it reached its maximum height. A measuring tape was used to measure from the lowest point on the clamping device to the top surface of the carrier deck. The final measurement was 26" which satisfies ER#1. This test was verified by taking a picture of the measurement, Figure 7.1.

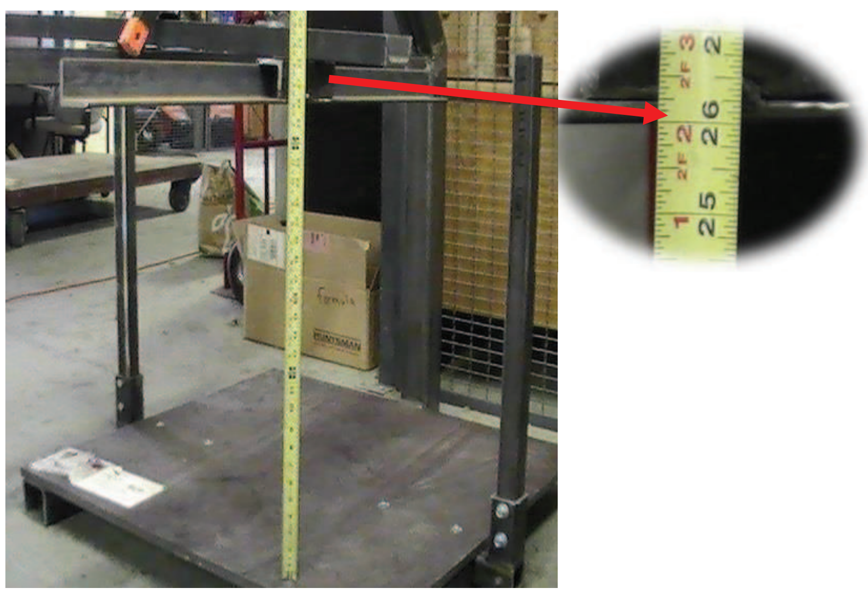


Figure 7.1: The figure shows how TP #1 was performed, leading to a measurement of 26"..

Testing Procedure #2 – Pass

The clamping device must meet a horizontal clearance of 34". A target of 40" was set with a tolerance of >34". This was tested by performing an inspection of the clamping device at its highest position. The clamping device has no obstructions that prevent the mold from entering the carrier deck and therefore satisfies ER#2.

Testing Procedure #3 – Pass

All parts of the clamping device, within 2" of the top of the mold, must withstand temperatures up to 800°F. This was tested by first measuring the device to determine the components that would be within the 2" range. Only parts made of low carbon steel are within the 2" range. The material data sheet (in Appendix B) shows that the durability of low carbon steel is acceptable for temperatures up to 842°F. This satisfies ER#3.

Testing Procedure #4 – Pass

The clamping force of the device must disengage with exclusive use of hydraulic pistons in ESCO's facilities, as stated in ER#4. The clamping device was evaluate by the project sponsor and determined that the device satisfies this requirement.

Testing Procedure #5 – Pass

As stated in ER#5, the device must supply a minimum clamping force of 400lbs. A target of 500lbs was set with a tolerance of ≥400lbs. For this test, load cells were placed at the corners of the wooden box. A picture of the setup can be seen in Figure 7.2. To test the force, the clamping device was lowered until the angle iron footpads came in contact with the load cells and then lowered an additional half turn of the rack and pinion jack handle. The forces from each load cell were then summed to find the total clamping force. The clamping force was found to be 529lbs which satisfies ER#5.

Figure 7.2: Load cell setup to measure the total load applied by the clamp.

Testing Procedure #6 – Pass

As stated in ER#6, the device must distribute the clamping force within 20% of the mean value along the sides of the sand mold. This was tested by aligning three load cells evenly along one side of the carrier deck and one load cell centered on the other side of the carrier deck. A brick was centered on each load cell. A wooden box was then place on top of the bricks. The clamping device was engaged to the top of the wood box until a total applied force of ~450lbs was reached. This method was repeated five times while adjusting the angle iron footpad from the center of the mold to the outside of the mold. The average force for each test run was calculated to determine the percent difference from the mean for each of the three load cells. The results for this tests ranged from 15.1% to 19.1%, which is within the allowed range of deviation. The results can be seen in Appendix F.

Testing Procedure #7 – Pass

The clamping device must adjust to fit multiple sprue and riser locations as specified in ER#7. This testing procedure utilized five mold layouts that were approved by the project sponsor. This test was performed by arranging cardboard cutouts on the surface of a wooden box to match the approved mold layouts. The clamping footprint was then adjusted so it would not touch the cutouts. The footprint did not touch any of the cardboard cutouts and therefore satisfies ER#7. An example of this test can be seen in Figure 7.3.

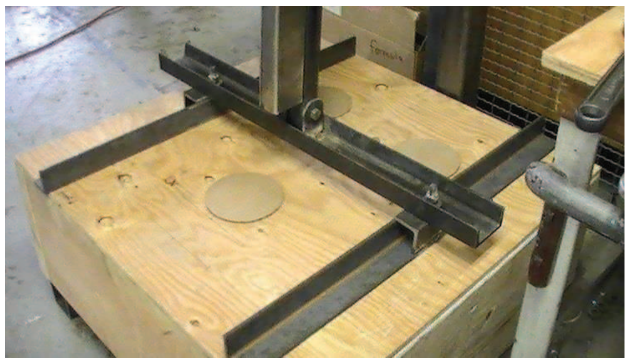


Figure 7.3: Test setup for TP #7. Round cardboard cutouts can be seen on top of the wooden box.

Testing Procedure #8 – Pass

As stated in ER#8, the clamping device must remain with the carrier deck. This test was performed by examining the device. The device bolts to steel bracket that is welded to the carrier deck, which satisfies ER#8.

Testing Procedure #9 – Pass

The clamping device must not damage the mold during engagement as stated in ER#9. The device was examined by the project sponsor and it was determined that the low impact of the clamping device would not damage the mold. This satisfies ER#9.

Testing Procedure #10 – Pass

ER#10 states that the force applying device of the clamp must consist of parts form a catalog. The force applying device for this design is a rack and pinion jack that was purchased online from the Haacon Group website. The data sheet for the rack and pinion jack can be seen in Appendix C.

Testing Procedure #11 – Pass

To satisfy ER#11 the clamping device must operate for 2700 cycles before failure. The device was tested by putting it through 100 cycles while performing a series of high impact (striking with a hammer) and sand accumulation tests (throwing sand in the gears). The camp operated through all 100 cycles with no issues and therefore satisfies ER#11.

Testing Procedure #12 – Pass

The clamping device must not exceed 1 hour of maintenance time for every 2 months of operation. The maintenance of the device was split into two categories: required maintenance for the rack and pinion jack, and overall device maintenance. Based on the operation and maintenance manual, supplied by Haacon Group, the only maintenance required for the jack is lubrication once per year. The required maintenance of the overall device was evaluated by the project sponsor. It was identified that the high temperature of the casting facility could damage the plastic handle of the jack. It was also found that molten metal splashing during the pouring process could adhere to the rack. Both of these issues would increase maintenance time. The design was changed to include an aluminum handle and a steel guard to cover the rack. These can be seen in Figure 7.4. The device was reevaluated by the project sponsor and it was determined that the device satisfied ER#12. The technical drawings can be viewed in Appendix A.

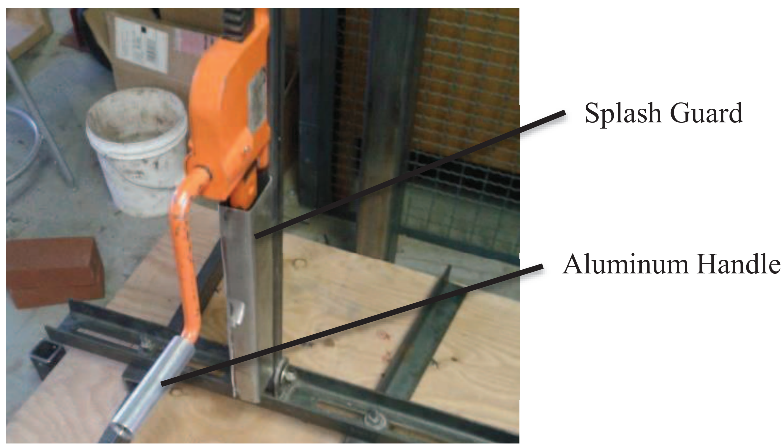


Figure 7.4: Newly installed splash guard and aluminum handle on the clamp.

Testing Procedure #13 – Pass

The setup time for the clamping device must not exceed 48 seconds as stated in ER#13. The device was tested by having each project mentor setup the camp 10 times. The average setup time for each mentor was 16 and 21.8 seconds respectively, and therefore satisfies ER#13.

Testing Procedure #14 – Pass

To satisfy ER#14 the clamping design needs to be significantly different from the competing groups design. The project mentors verified this requirement was satisfied.

8 CONCLUSIONS AND RECOMMENDATIONS

This last Chapter of the report summarizes the experience gained during the course of the MIME Capstone design project and gives recommendations on how to further proceed with the current prototype.

8.1 Project Experience

During the course of the MIME Capstone design project the design team was guided through all the steps of a well-structured design process. At the beginning of the project, a concise description of the design problem to be solved was provided to the Capstone team. By analyzing the problem and researching possible solutions, different designs were developed and finally the most promising one was implemented, tested and improved.

For all members of the design team there were many unknowns at the beginning of the fall term 2012. The most important question was, how well the team would work together. Forming a team can be challenging due to different personalities within the group. However, the teambuilding process in our group was uncomplicated and a pleasant working atmosphere was established that remained throughout the project. Having a friendly atmosphere was the basis for many productive group meetings and a successful completion of the project.

The first step in our design process was to understand the objectives of the project. By talking to the sponsor we gained a better idea of what had to be designed and started developing a set of customer requirements that described all of the needs of our sponsor, ESCO. While developing customer requirements for a well-defined problem was not difficult, it turned out to be more challenging to assign measurable engineering requirements to the CRs. Requirements, such as CR #8 “Clamping device shall not damage mold,” were difficult to quantify, even though the requirement was fully understood. Developing these CRs and ERs helped to better understand the current clamping design used by ESCO. Current design problems that were not obvious at the beginning became obvious when the current design was compared to the newly developed requirements.

The Capstone team began to research background information on clamping devices for mold casting once the problem was understood. Background research on sand mold clamping systems was harder than expected. Books, articles and patents on mold clamping mainly focused on sophisticated and expensive systems for high pressure injection molding or die casting. The importance of clamping sand molds was briefly addressed, however few solutions were provided. Thus, the team selected the designs that were as similar to the current situation as possible for design ideas.

Finally, a few relevant designs were selected and described. Next, five design functions of a sand mold clamp were developed using a functional decomposition. The functional decomposition broke down the system into basic functions, allowing the design to be solved in a series of small designs rather than one large design.

The process of concept generation is the most creative part of the design process. Our team started by individually brainstorming designs based on the many concepts we researched. Individual brainstorming sessions were followed by group meetings where each group member presented his ideas and gained new ideas by looking at the designs of the other group members. This iterative process was repeated until four preliminary designs were selected. In retrospective, many of the first ideas and concepts seem misguided after reviewing the drawings. However, this illustrates how the understanding of the design requirements improves during the life of the project.

For the process of design selection we decided to use a decision matrix. This tool allowed the design team to remove personal preferences from the design selection process. Using a decision matrix was useful to settle design conflicts within the team. After the final design was selected it was developed in detail and justified by calculations and simulations.

For the implementation, the design team decided to do all of the manufacturing without outside resources. The rack and pinion jack was the only part of the design that required ordering at an early stage. It was ordered before the winter break and arrived at the beginning of winter term 2013. This allowed the design team to start the implementation right away. Structural steel parts and hardware were purchased at a local vendor, avoiding any delays due to delivery times. Machining of the parts was entirely done at the OSU machine shop. Thanks to the well thought out design of the parts, no problems occurred and the machining was done in a timely manner. The welding of the parts was also done by the team members. It turned out to be more complicated to guarantee tight tolerances for welded parts compared to machined parts. Distortion due to heat influence was likely to occur, thus different fixtures were used to minimize this effect on the assemblies. This part of the implementation process increased the team's awareness of the importance of design for fabrication. After gaining some experience on how our design warped after welding, we managed to fabricate a quality and functional product.

After the implementation of the design, the remainder of the term was spent testing and revising the design. A majority of the testing procedures were good measurements for the customer requirements. These did not need to be changed and clearly defined the characteristics of a sand mold clamp. However, there were two testing procedures that did not fully address the required properties.

- TP #6 is testing the force distribution of the clamp. When the TP was written during fall term, the design team was unaware of how the force distribution would be tested. Therefore the TP was worded vaguely and did not exactly describe how to measure the force distribution. After the team received the load cells to measure the force distribution at the beginning of the winter term, the TP had to be further specified with a petition to change the TP. This procedure helped the design team to learn how to plan a design process while some information is not available.

  ER #6 refers to the CR that requires an even clamping force distribution over the sand mold. The intention of the CR is to guarantee that the clamp will prevent liquid metal leakage by distributing a sufficient clamping force around the edges of the mold. But, without having an original sand mold and access to sophisticated force measuring equipment it is not possible to measure the exact force distribution. Our TP (#6) for this includes measuring the clamping force on three load cells along one side of the carrier deck. As only rigid bodies are used to push on the load cells, the force distribution is much more sensitive to surface irregularities on the load cells than it would be on a sand mold. The test shows that the clamp distributes force on the edges of the mold, but does not allow to simulate the exact distribution that would occur on a real sand mold.

- ER #11 requires the clamp to operate for more than 2700 cycles before failure. It is almost impossible to simulate this number of cycles given the vaguely defined and changing environmental conditions in the foundry. Our TP required the clamp to operate for 100 cycles under intensified conditions. The design passed the test, but it remains vague if the testing conditions can be considered as an appropriate testing environment. Still, this TP might be one of the best ways to test for durability given the fact that the team did not have access to the sand casting foundry to test the design.

The last important experience that was made by the design team was working on a fixed project budget. Thanks to our sponsor ESCO the budget for the project was more than sufficient. Coming up with a inexpensive design and doing all machining and welding ourselves we managed to cut the expenses to roughly half of the budget (see Appendix E: Bill of Materials (BoM)).

8.2 Recommendations

After the sand mold clamp was implemented and tested the remaining question is, where the project should go from here. The clamp fulfills all Customer Requirements and is therefore ready for testing and implementation in one of ESCO's foundries. Its usage will lead to increased productivity in the foundry.

The data gained by testing the clamp prototype indicates that the design is ready to be used in a foundry, as all customer requirements were met or exceeded. The design is adjustable to many mold sizes for different casting parts and allows access to a variety of sprue and riser locations. The clamp supplies a clamping force above 500 lbs and evenly distributes this force over the perimeter of the mold. Not only does the clamping force of the new design exceed the force of the current design, but the force can also be applied easier and more ergonomically. The cranking motion that is necessary to apply the force leads to a smooth engaging process that does not cause mold damage, whereas installing the current clamp with a hammer causes sharp impacts. The sharp impacts occasionally cause parts of the mold to break off, leading to defective parts. The operation of the new clamp requires a setup time of approximately 20 seconds and disengages automatically after the casting process is finished. Thus, the overall operation time for the clamp is cut in half compared to the current design. Since the clamp is permanently attached to the carrier deck, it does not need extra storage space. The design is very robust, withstands elevated temperatures and impacts, and is protected against splashes of liquid metal. This leads to a functional lifetime of the clamp of more than two years with minimal maintenance.

The new clamping design shows better characteristic values than the old clamp and will lead to an increase in productivity for the foundry. Therefore the design should be tested and implemented in one of ESCO's foundries.

Even though the project was finished successfully there is one recommendation to the design that would further improve the functionality of the clamp. Instead of manually cranking the handle of the rack and pinion jack to engage the clamp, a pneumatic drill with a torque wrench should be used. The steel rod holding the handle would be cut off and replaced with a nut. This would allow the pneumatic drill to operate the jack. Figure 8.1 illustrates how this design change would be implemented.

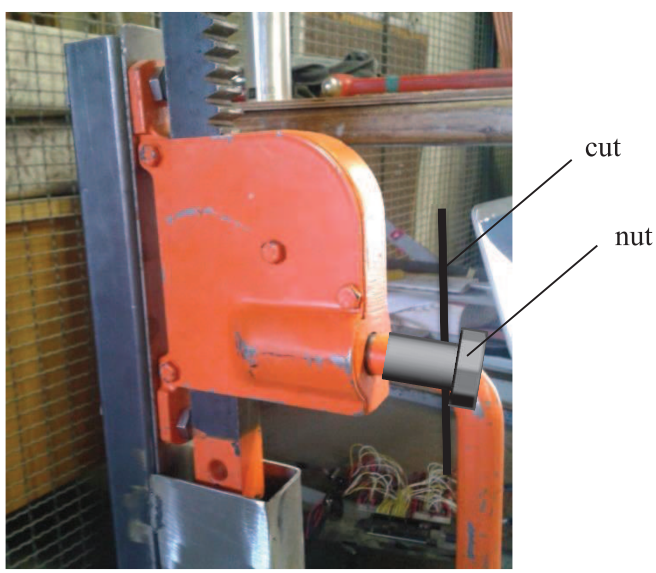


Figure 8.1: Substituting the handle with a nut to accommodate a pneumatic drill.

The use of a pneumatic drill with a torque wrench provides two main advantages. First, the process of adjusting the height of the clamp to the sand mold would reduce setup time. The pneumatic drill achieves a higher rotational speed than a manually operated handle. Second, the clamping force would be applied more accurately. A torque wrench provides the same amount of clamping force every time the clamp is engaged. This would guarantee the optimal clamping force and make the process highly reproducible, reducing the number of defective parts.

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Appendix A: Assembly and Part Drawings

List of Drawings

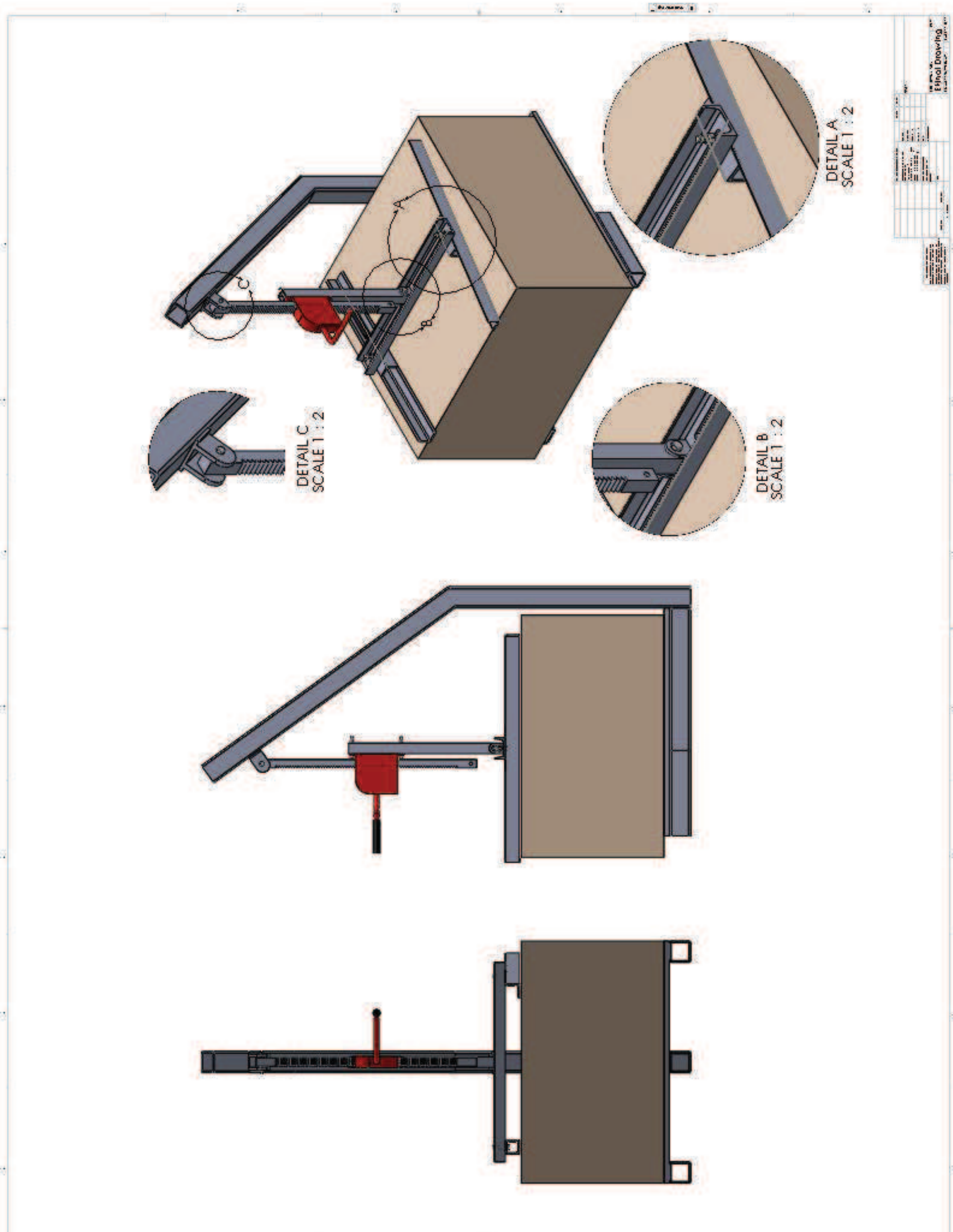


Figure A. 1: Final assembly

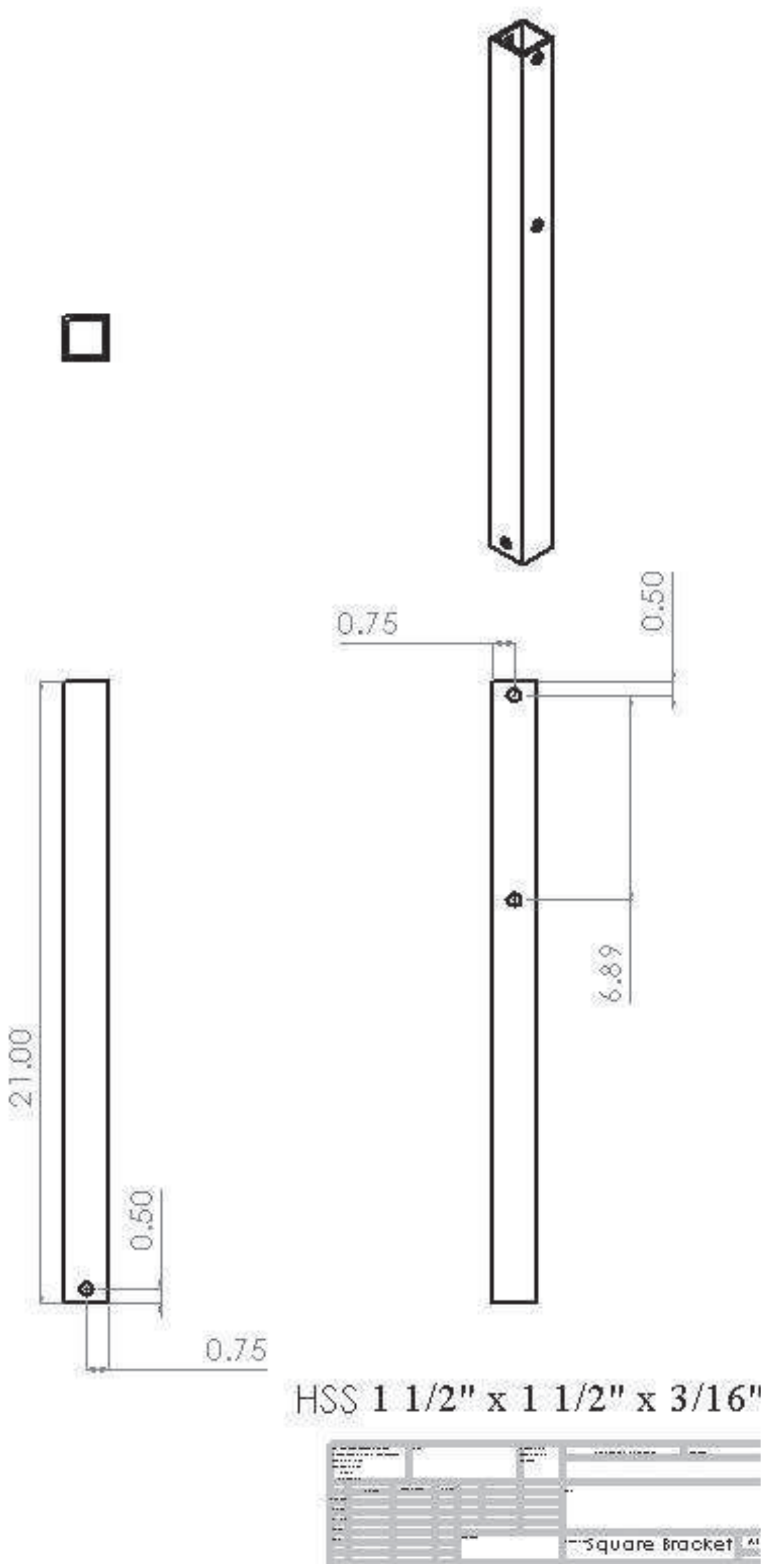


Figure A. 2: square tube

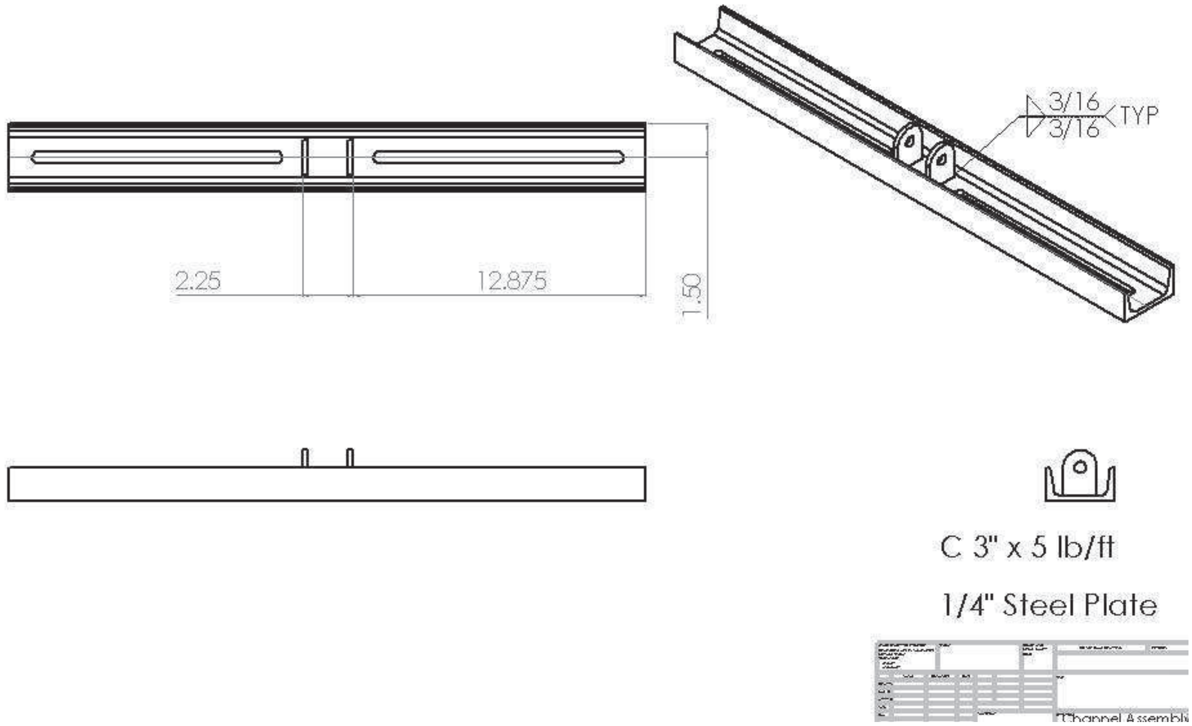


Figure A. 3: C-channel assembly

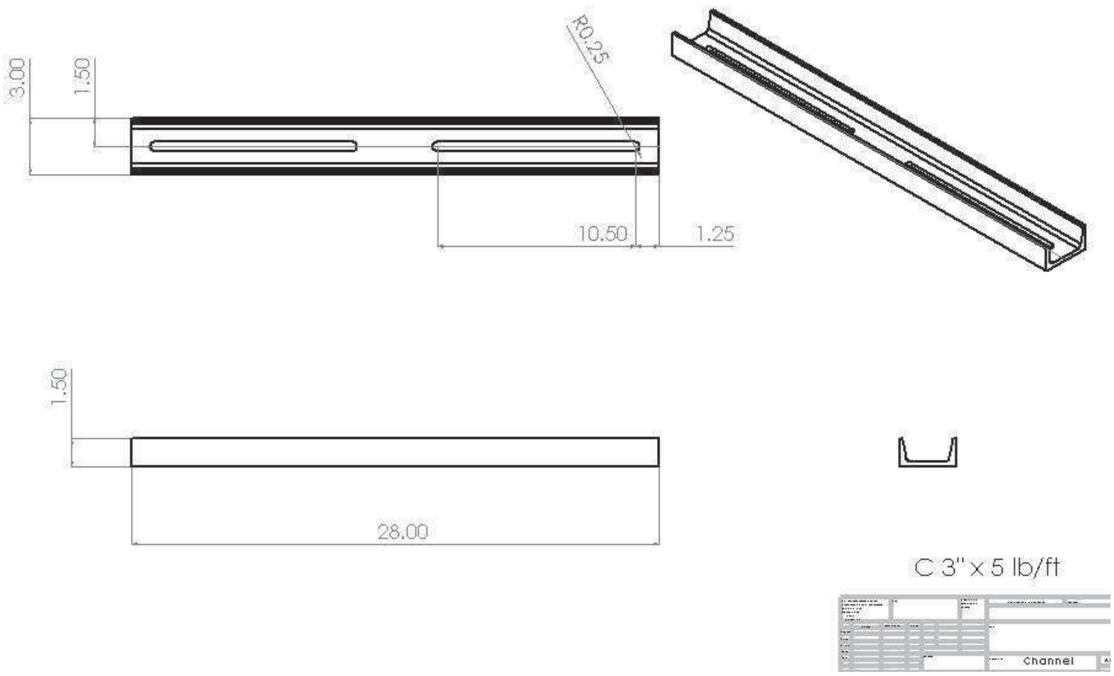


Figure A. 4: C-channel

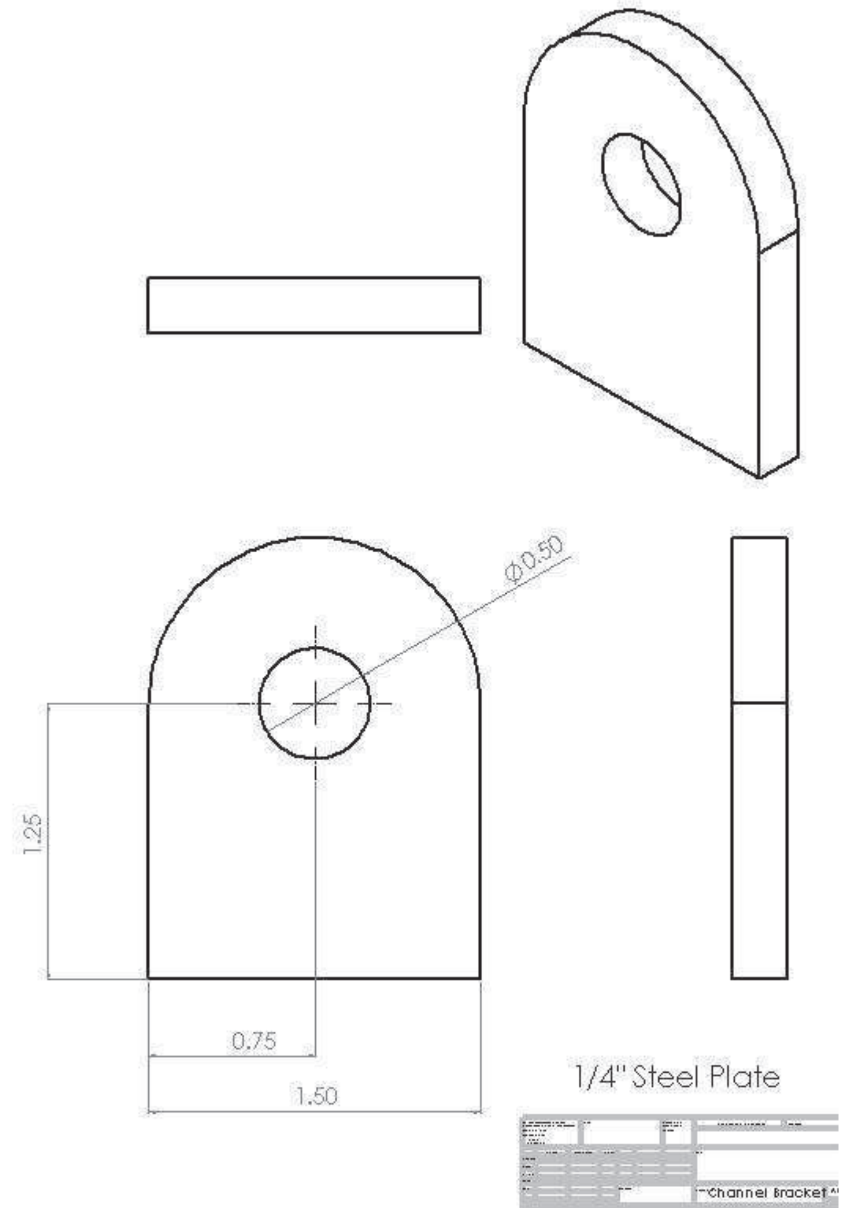


Figure A. 5: C-channel bracket

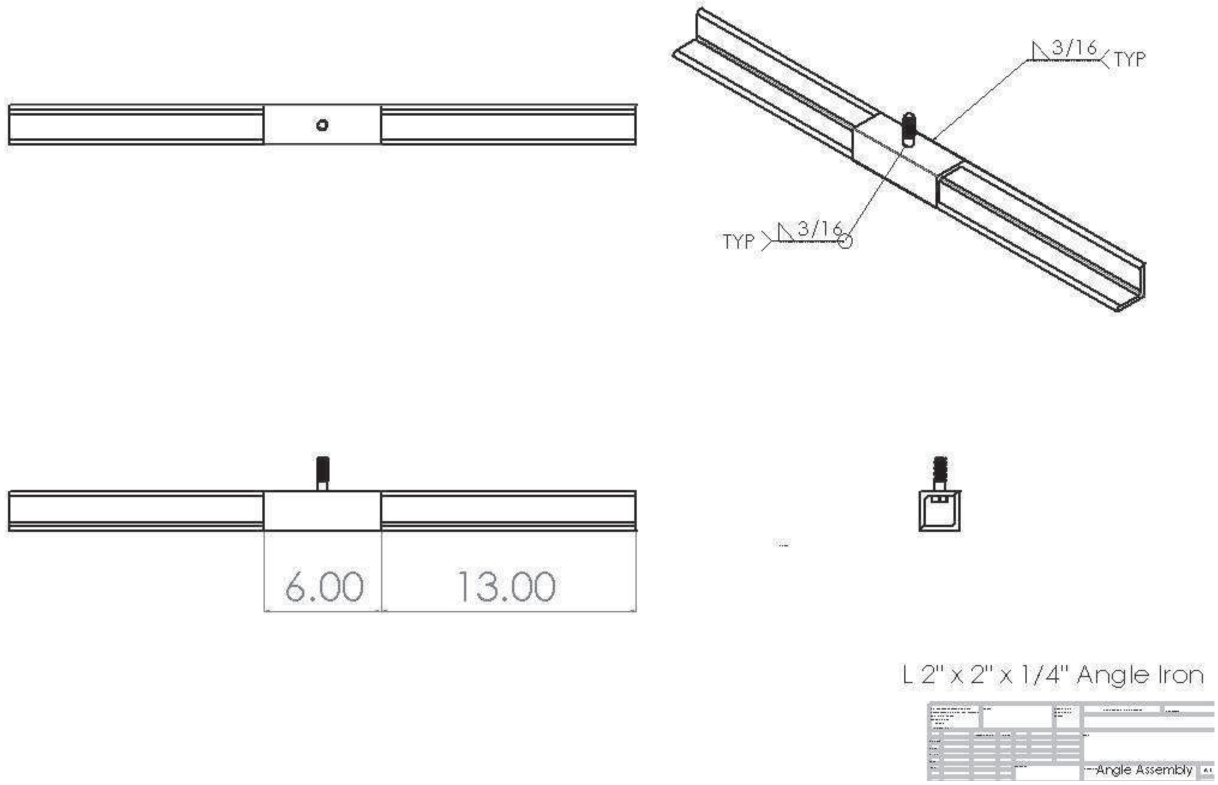


Figure A. 6: Angle irons assembly

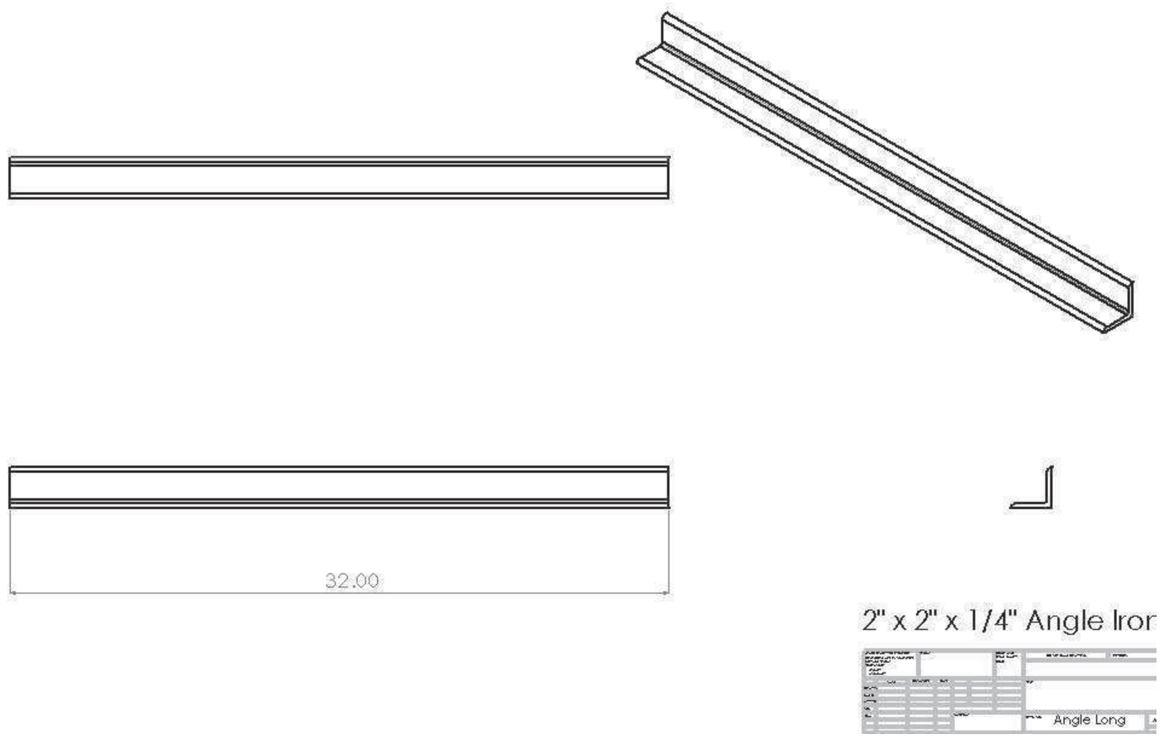


Figure A. 7: Angle iron (long)

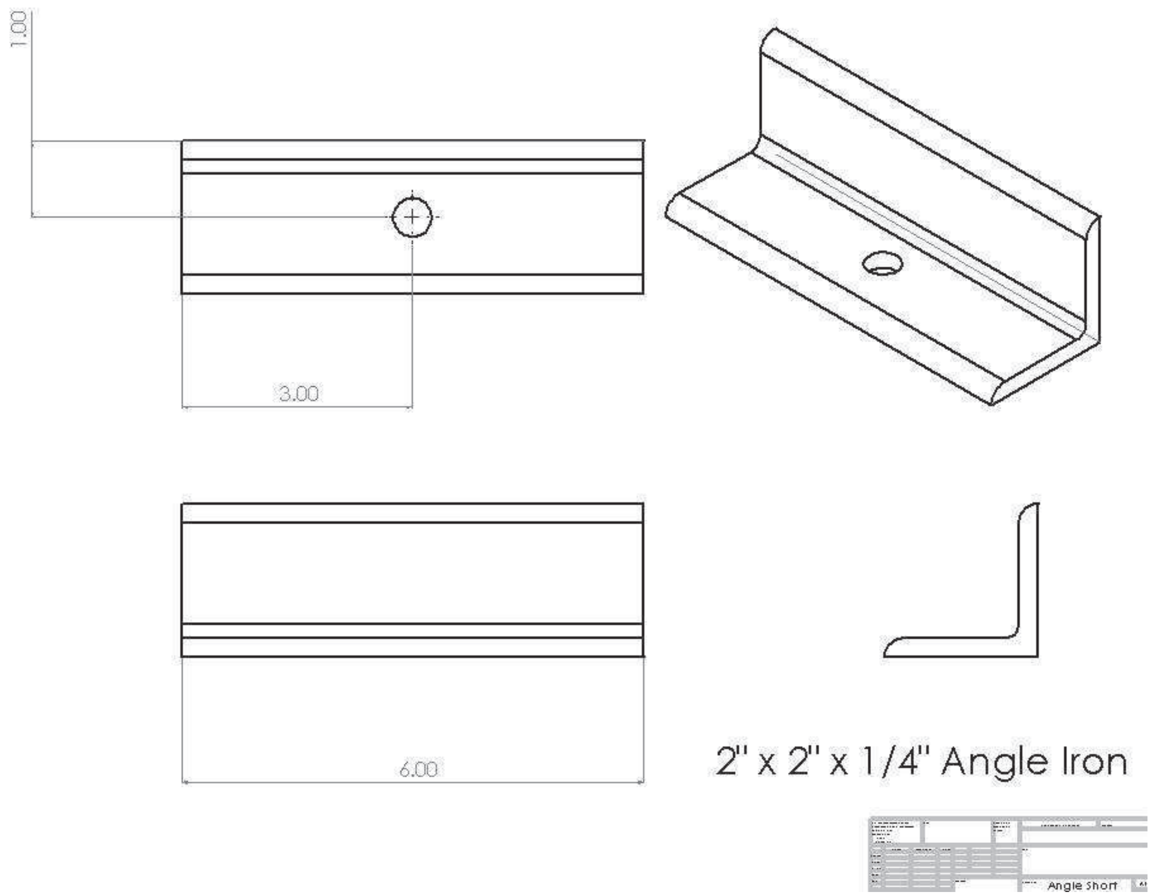


Figure A. 8: Angle iron (short)

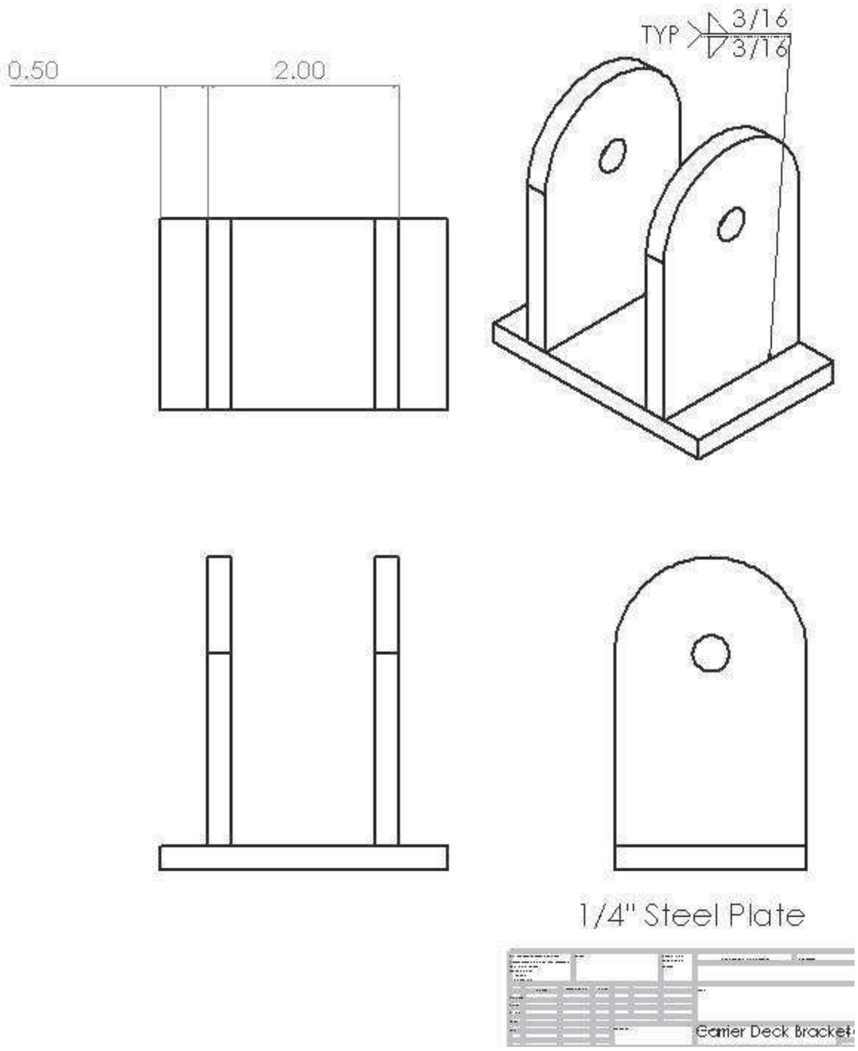


Figure A. 9: Carrier deck bracket assembly

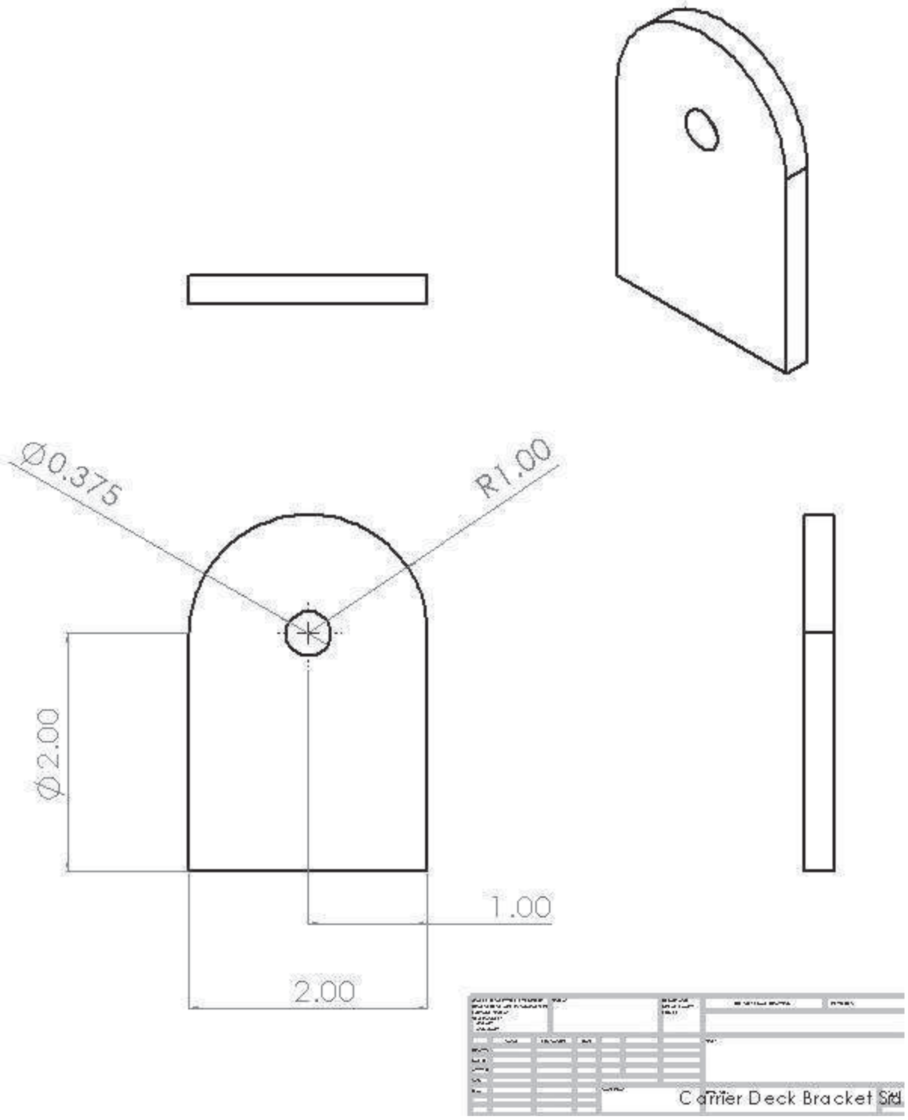


Figure A. 10: Carrier deck bracket side

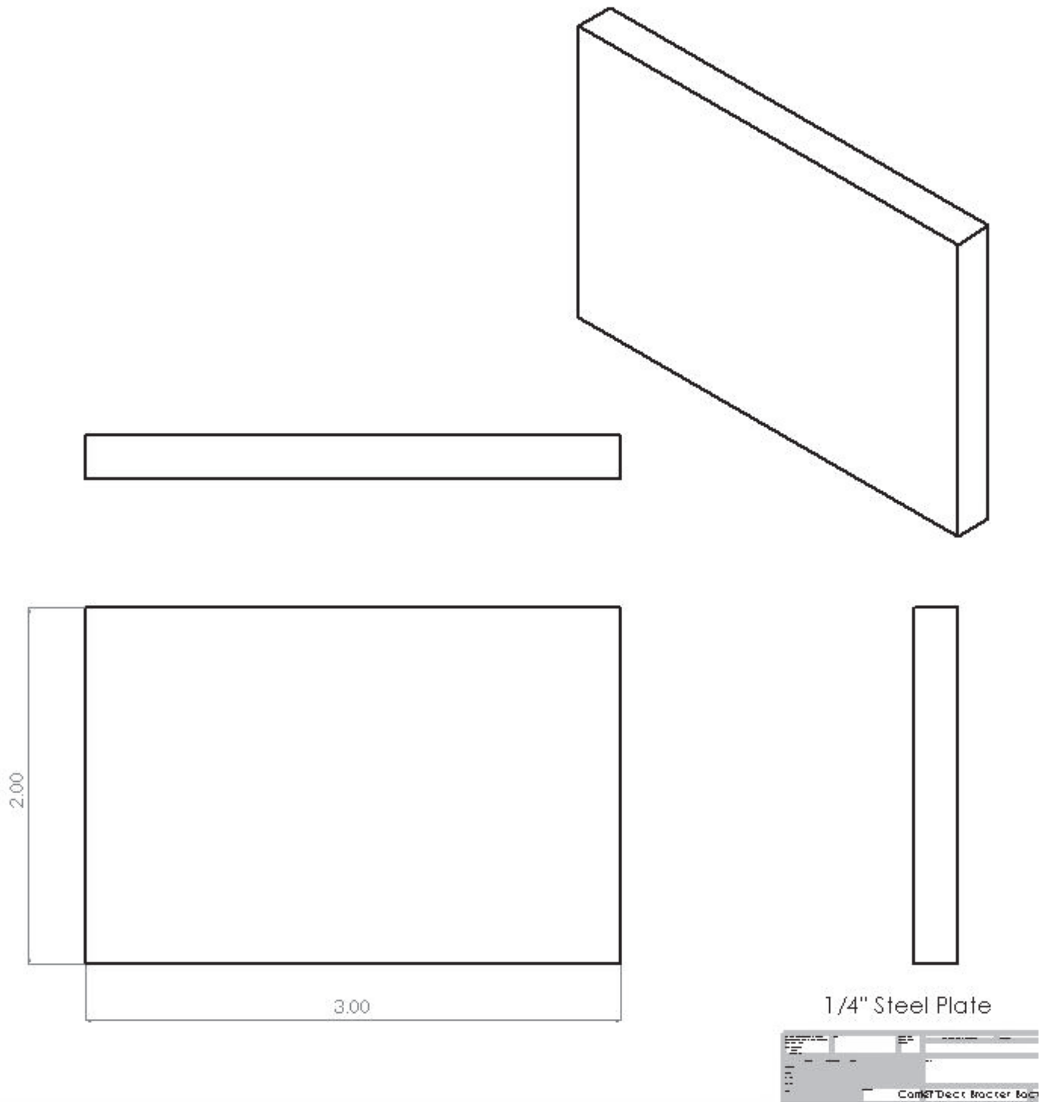


Figure A. 11: Carrier deck bracket back

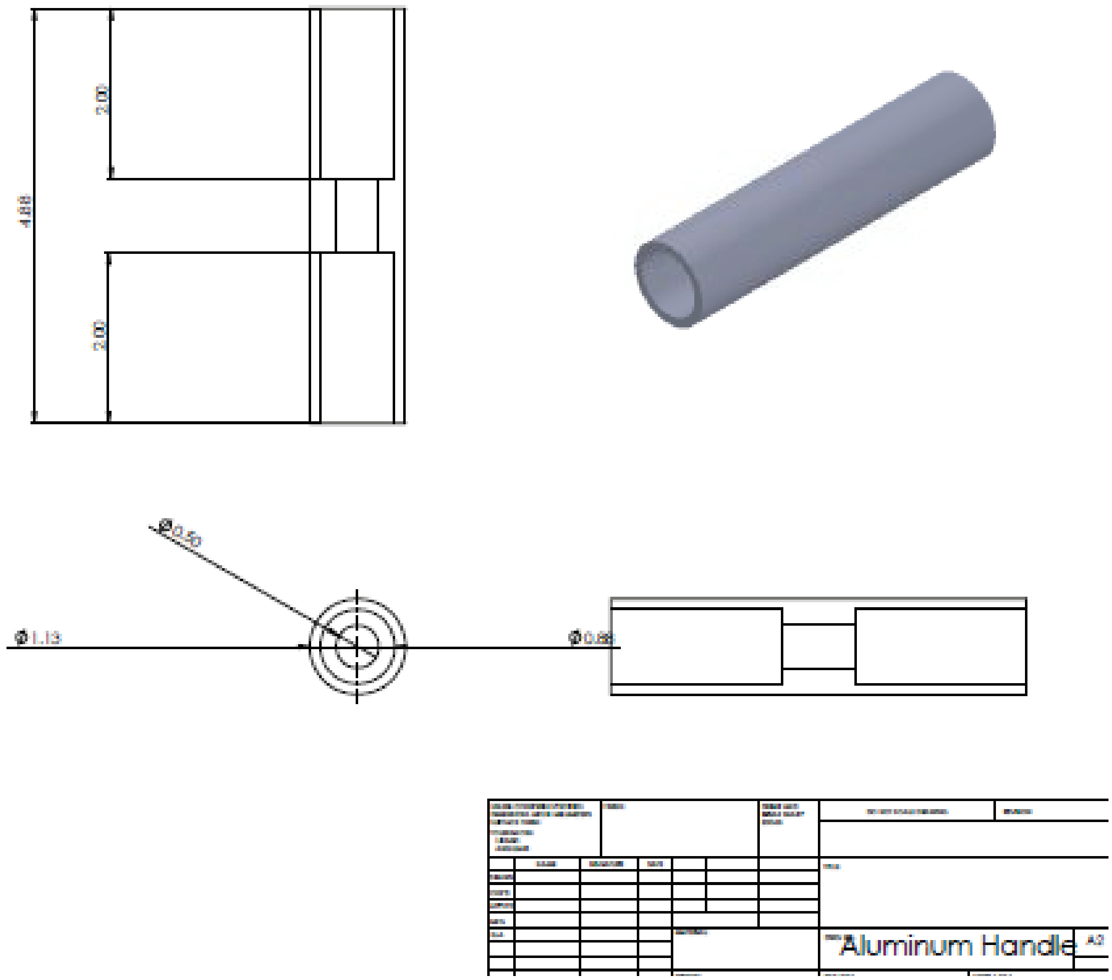


Figure A. 12: Aluminum handle

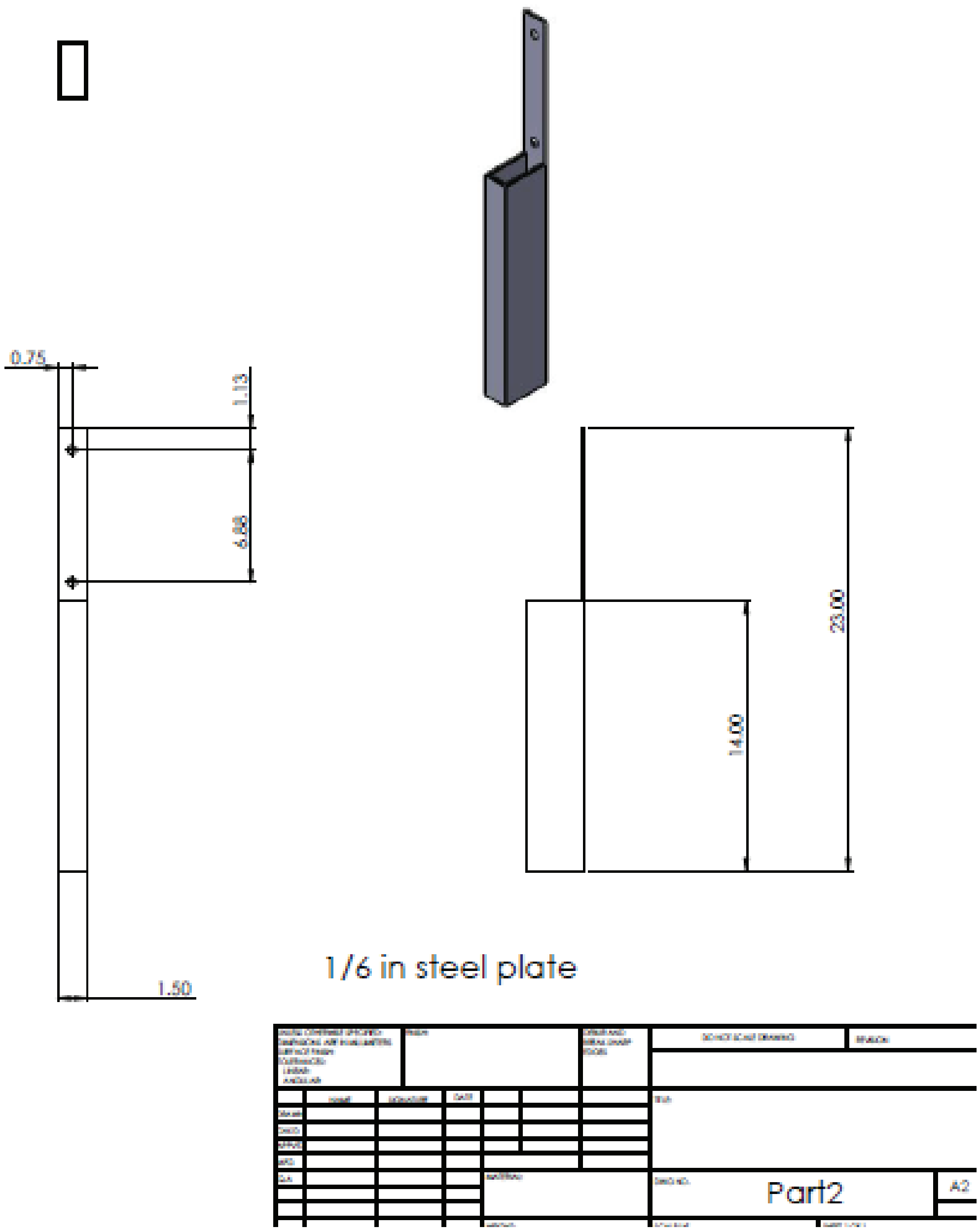


Figure A. 13: Splash guard

Appendix B: Material Specifications

Designation: A36/A36M – 08

Standard Specification for Carbon Structural Steel[1]

This standard is issued under the fixed designation A36/A36M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope*

1.1 This specification[2] covers carbon steel shapes, plates, and bars of structural quality for use in riveted, bolted, or welded construction of bridges and buildings, and for general structural purposes.

1.2 Supplementary requirements are provided for use where additional testing or additional restrictions are required by the purchaser. Such requirements apply only when specified in the purchase order.

1.3 When the steel is to be welded, a welding procedure suitable for the grade of steel and intended use or service is to be utilized. See Appendix X3 of Specification A6/A6M for information on weldability.

1.4 The values stated in either inch-pound units or SI units are to be regarded separately as standard. Within the text, the SI units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system is to be used independently of the other, without combining values in any way.

1.5 The text of this specification contains notes or footnotes, or both, that provide explanatory material. Such notes and footnotes, excluding those in tables and figures, do not contain any mandatory requirements.

1.6 For structural products produced from coil and furnished without heat treatment or with stress relieving only, the additional requirements, including additional testing requirements and the reporting of additional test results, of A6/A6M apply.

2. Referenced Documents

2.1 *ASTM Standards:*[3]

A6/A6M Specification for General Requirements for Rolled Structural Steel Bars, Plates, Shapes, and Sheet Piling

A27/A27M Specification for Steel Castings, Carbon, for General Application

A307 Specification for Carbon Steel Bolts and Studs, 60 000 PSI Tensile Strength

A325 Specification for Structural Bolts, Steel, Heat Treated, 120/105 ksi Minimum Tensile Strength

A325M Specification for Structural Bolts, Steel, Heat Treated 830 MPa Minimum Tensile Strength (Metric)

A500 Specification for Cold-Formed Welded and Seamless Carbon Steel Structural Tubing in Rounds and Shapes

A501 Specification for Hot-Formed Welded and Seamless Carbon Steel Structural Tubing

A502 Specification for Rivets, Steel, Structural

A563 Specification for Carbon and Alloy Steel Nuts

A563M Specification for Carbon and Alloy Steel Nuts (Metric)

A668/A668M Specification for Steel Forgings, Carbon and Alloy, for General Industrial Use

A1011/A1011M Specification for Steel, Sheet and Strip, Hot-Rolled, Carbon, Structural, High-Strength Low-Alloy, High-Strength Low-Alloy with Improved Formability, and Ultra-High Strength

A1018/A1018M Specification for Steel, Sheet and Strip, Heavy-Thickness Coils, Hot-Rolled, Carbon, Commercial, Drawing, Structural, High-Strength Low-Alloy, High-Strength Low-Alloy with Improved Formability, and Ultra-High Strength

F568M Specification for Carbon and Alloy Steel Externally

[1] This specification is under the jurisdiction of ASTM Committee A01 on Steel, Stainless Steel and Related Alloys and is the direct responsibility of Subcommittee A01.02 on Structural Steel for Bridges, Buildings, Rolling Stock and Ships.

Current edition approved May 15, 2008. Published June 2008. Originally approved in 1960. Last previous edition approved in 2005 as A36/A36M – 05. DOI: 10.1520/A0036_A0036M-08.

[2] For ASME Boiler and Pressure Vessel Code Applications, see related Specifications SA-36 in Section II of that Code.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

***A Summary of Changes section appears at the end of this standard**

TABLE 1 Appurtenant Material Specifications

NOTE 1—The specifier should be satisfied of the suitability of these materials for the intended application. Chemical composition or mechanical properties, or both, may be different than specified in A36/A36M.

Material	ASTM Designation
Steel rivets	A502, Grade 1
Bolts	A307, Grade A or F568M, Class 4.6
High-strength bolts	A325 or A325M
Steel nuts	A563 or A563M
Cast steel	A27/A27M, Grade 65–35 [450–240]
Forgings (carbon steel)	A668/A668M, Class D
Hot-rolled sheets and strip	A1011/A1011M, SS Grade 36 [250] Type 1 or Type 2 or A1018/A1018M, SS Grade 36 [250]
Cold-formed tubing	A500, Grade B
Hot-formed tubing	A501
Anchor bolts	F1554, Grade 36

Threaded Metric Fasteners (Metric) (Withdrawn 2012)[4]

F1554 Specification for Anchor Bolts, Steel, 36, 55, and 105-ksi Yield Strength

3. Appurtenant Materials

3.1 When components of a steel structure are identified with this ASTM designation but the product form is not listed in the scope of this specification, the material shall conform to one of the standards listed in Table 1 unless otherwise specified by the purchaser.

4. General Requirements for Delivery

4.1 Structural products furnished under this specification shall conform to the requirements of the current edition of Specification A6/A6M, for the specific structural product ordered, unless a conflict exists in which case this specification shall prevail.

4.2 Coils are excluded from qualification to this specification until they are processed into a finished structural product. Structural products produced from coil means structural products that have been cut to individual lengths from a coil. The processor directly controls, or is responsible for, the operations involved in the processing of a coil into a finished structural product. Such operations include decoiling, leveling or straightening, hot-forming or cold-forming (if applicable), cutting to length, testing, inspection, conditioning, heat treatment (if applicable), packaging, marking, loading for shipment, and certification.

NOTE 1—For structural products produced from coil and furnished without heat treatment or with stress relieving only, two test results are to be reported for each qualifying coil. Additional requirements regarding structural products produced from coil are described in Specification A6/A6M.

5. Bearing Plates

5.1 Unless otherwise specified, plates used as bearing plates for bridges shall be subjected to mechanical tests and shall conform to the tensile requirements of Section 8.

5.2 Unless otherwise specified, mechanical tests shall not be required for plates over 1½ in. [40 mm] in thickness used as bearing plates in structures other than bridges, subject to the requirement that they shall contain 0.20 to 0.33 % carbon by heat analysis, that the chemical composition shall conform to the requirements ofTable 3 in phosphorus and sulfur content, and that a sufficient discard shall be made to secure sound plates.

6. Materials and Manufacture

6.1 The steel for plates and bars over ½ in. [12.5 mm] in thickness and shapes with flange or leg thicknesses over 1 in. [25 mm] shall be semi-killed or killed.

7. Chemical Composition

7.1 The heat analysis shall conform to the requirements prescribed in Table 3, except as specified in 5.2.

7.2 The steel shall conform on product analysis to the requirements prescribed in Table 3, subject to the product analysis tolerances in Specification A6/A6M.

8. Tension Test

8.1 The material as represented by the test specimen, except as specified in 5.2 and 8.2, shall conform to the requirements as to the tensile properties prescribed in Table 2.

8.2 Shapes less than 1 in.^{2} [645 mm^2] in cross section and bars, other than flats, less than ½ in. [12.5 mm] in thickness or diameter need not be subjected to tension tests by the manufacturer, provided that the chemical composition used is appropriate for obtaining the tensile properties in Table 2.

9. Keywords

9.1 bars; bolted construction; bridges; buildings; carbon; plates; riveted construction; shapes; steel; structural steel; welded construction

TABLE 2 Tensile Requirements[A]

Plates, Shapes,[B] and Bars:	
Tensile strength, ksi [MPa]	58–80 [400–550]
Yield point, min, ksi [MPa]	36 [250][C]
Plates and Bars:[D,E]	
Elongation in 8 in. [200 mm], min, %	20
Elongation in 2 in. [50 mm], min, %	23
Shapes:	
Elongation in 8 in. [200 mm], min, %	20
Elongation in 2 in. [50 mm], min, %	21[B]

[A] See the Orientation subsection in the Tension Tests section of Specification A6/A6M.
[B] For wide flange shapes with flange thickness over 3 in. [75 mm], the 80 ksi [550 MPa] maximum tensile strength does not apply and a minimum elongation in 2 in. [50 mm] of 19 % applies.
[C] Yield point 32 ksi [220 MPa] for plates over 8 in. [200 mm] in thickness.
[D] Elongation not required to be determined for floor plate.
[E] For plates wider than 24 in. [600 mm], the elongation requirement is reduced two percentage points. See the Elongation Requirement Adjustments subsection under the Tension Tests section of Specification A6/A6M.

[4] The last approved version of this historical standard is referenced on www.astm.org.

TABLE 3 Chemical Requirements

NOTE 1—Where ". . ." appears in this table, there is no requirement. The heat analysis for manganese shall be determined and reported as described in the heat analysis section of Specification A6/A6M.

Product	Shapes[A]	Plates[B]					Bars[B]			
Thickness, in. [mm]	All	To ¾ [20], incl	Over ¾ to 1½ [20 to 40], incl	Over 1½ to 2½ [40 to 65], incl	Over 2½ to 4 [65 to 100], incl	Over 4 [100]	To ¾ [20], incl	Over ¾ to 1½ [20 to 40], incl	Over 1½ to 4 [100], incl	Over 4 [100]
Carbon, max, %	0.26	0.25	0.25	0.26	0.27	0.29	0.26	0.27	0.28	0.29
Manganese, %	...	...	0.80–1.20	0.80–1.20	0.85–1.20	0.85–1.20	...	0.60–0.90	0.60–0.90	0.60–0.90
Phosphorus, max, %	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Sulfur, max, %	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Silicon, %	0.40 max	0.40 max	0.40 max	0.15–0.40	0.15–0.40	0.15–0.40	0.40 max	0.40 max	0.40 max	0.40 max
Copper, min, % when cop per steel is specified	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20

[A] Manganese content of 0.85–1.35 % and silicon content of 0.15–0.40 % is required for shapes with flange thickness over 3 in. [75 mm].
[B] For each reduction of 0.01 percentage point below the specified carbon maximum, an increase of 0.06 percentage point manganese above the specified maximum will be permitted, up to the maximum of 1.35 %.

SUPPLEMENTARY REQUIREMENTS

These requirements shall not apply unless specified in the order.

Standardized supplementary requirements for use at the option of the purchaser are listed in Specification A6/A6M. Those that are considered suitable for use with this specification are listed by title:

S5. Charpy V-Notch Impact Test.

S30. Charpy V-Notch Impact Test for Structural Shapes: Alternate Core Location

S32. Single Heat Bundles

S32.1 Bundles containing shapes or bars shall be from a single heat of steel.

In addition, the following optional supplementary requirement is also suitable for use with this specification:

S97. Limitation on Rimmed or Capped Steel

S97.1 The steel shall be other than rimmed or capped.

SUMMARY OF CHANGES

Committee A01 has identified the location of selected changes to this standard since the last issue (A36/A36M – 05) that may impact the use of this standard. (Approved May 15, 2008.)

(1) Added information to Table 1 on forgings (carbon steel) and anchor bolts.

Low carbon steel

Description

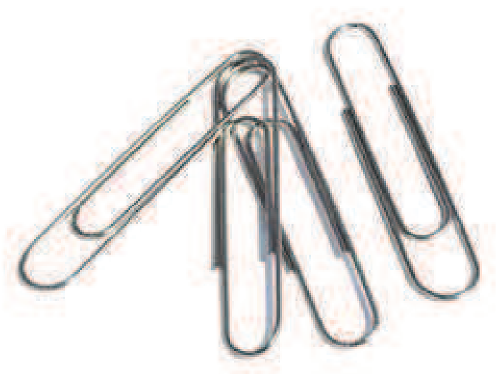
The material

Think of steel and you think of railroads, oilrigs, tankers, and skyscrapers. And what you are thinking of is not just steel, it is carbon steel. That is the metal that made them possible - nothing else is the same time so strong, so tough, so easily formed - and so cheap. Carbon steels are alloys of iron with carbon and, often a little manganese, nickel, and silicon. Low carbon or "mild" steels have the least carbon - less than 0.25%. They are relatively soft, easily rolled to plate, I-sections or rod (for reinforcing concrete) and are the cheapest of all structural metals - it is these that are used on a huge scale for reinforcement, for steel-framed buildings, ship plate and the like.

Composition (summary)

Fe/0.02 - 0.3C

Image



Caption

Mild steel, the world's most versatile material.

General properties

Density	7.8e3	-	7.9e3	kg/m^3
Price	* 0.669	-	0.736	USD/kg
Date first used ("-" means BC)	1610			

Mechanical properties

Young's modulus	2e11	-	2.15e11	Pa
Shear modulus	7.9e10	-	8.4e10	Pa
Bulk modulus	1.58e11	-	1.75e11	Pa
Poisson's ratio	0.285	-	0.295	
Yield strength (elastic limit)	2.5e8	-	3.95e8	Pa
Tensile strength	3.45e8	-	5.8e8	Pa
Compressive strength	2.5e8	-	3.95e8	Pa
Elongation	0.26	-	0.47	strain
Hardness - Vickers	1.05e9	-	1.69e9	Pa
Fatigue strength at 10^7 cycles	* 2.03e8	-	2.93e8	Pa
Fracture toughness	* 4.1e7	-	8.2e7	Pa.m^0.5
Mechanical loss coefficient (tan delta)	* 8.9e-4	-	0.00142	

Thermal properties

Melting point	1.48e3	-	1.53e3	°C
Maximum service temperature	* 350	-	400	°C
Minimum service temperature	* -68.2	-	-38.2	°C
Thermal conductor or insulator?	Good conductor			

Thermal conductivity	49	-	54	W/m.°C
Specific heat capacity	460	-	505	J/kg.°C
Thermal expansion coefficient	1.15e-5	-	1.3e-5	strain/°C

Electrical properties

Electrical conductor or insulator?	Good conductor			
Electrical resistivity	1.5e-7	-	2e-7	ohm.m

Optical properties

Transparency	Opaque

Processability

Castability	3		
Formability	4	-	5
Machinability	3	-	4
Weldability	5		
Solder/brazability	5		

Durability: water and aqueous solutions

Water (fresh)	Acceptable
Water (salt)	Limited use
Soils, acidic (peat)	Acceptable
Soils, alkaline (clay)	Acceptable
Wine	Unacceptable

Durability: acids

Acetic acid (10%)	Limited use
Acetic acid (glacial)	Unacceptable
Citric acid (10%)	Unacceptable
Hydrochloric acid (10%)	Unacceptable
Hydrochloric acid (36%)	Unacceptable
Hydrofluoric acid (40%)	Unacceptable
Nitric acid (10%)	Unacceptable
Nitric acid (70%)	Unacceptable
Phosphoric acid (10%)	Unacceptable
Phosphoric acid (85%)	Unacceptable
Sulfuric acid (10%)	Unacceptable
Sulfuric acid (70%)	Unacceptable

Durability: alkalis

Sodium hydroxide (10%)	Excellent
Sodium hydroxide (60%)	Acceptable

Durability: fuels, oils and solvents

Amyl acetate	Excellent
Benzene	Excellent
Carbon tetrachloride	Excellent
Chloroform	Excellent
Crude oil	Excellent
Diesel oil	Excellent
Lubricating oil	Excellent
Paraffin oil (kerosene)	Excellent
Petrol (gasoline)	Excellent

Silicone fluids	Excellent
Toluene	Excellent
Turpentine	Excellent
Vegetable oils (general)	Excellent
White spirit	Excellent

Durability: alcohols, aldehydes, ketones

Acetaldehyde	Limited use
Acetone	Excellent
Ethyl alcohol (ethanol)	Acceptable
Ethylene glycol	Acceptable
Formaldehyde (40%)	Unacceptable
Glycerol	Excellent
Methyl alcohol (methanol)	Acceptable

Durability: halogens and gases

Chlorine gas (dry)	Acceptable
Fluorine (gas)	Excellent
O2 (oxygen gas)	Limited use
Sulfur dioxide (gas)	Acceptable

Durability: built environments

Industrial atmosphere	Limited use
Rural atmosphere	Acceptable
Marine atmosphere	Limited use
UV radiation (sunlight)	Excellent

Durability: flammability

Flammability	Non-flammable

Durability: thermal environments

Tolerance to cryogenic temperatures	Unacceptable
Tolerance up to 150 C (302 F)	Excellent
Tolerance up to 250 C (482 F)	Excellent
Tolerance up to 450 C (842 F)	Acceptable
Tolerance up to 850 C (1562 F)	Unacceptable
Tolerance above 850 C (1562 F)	Unacceptable

Eco properties

Embodied energy, primary production	*	2.5e7	-	2.77e7	J/kg
CO2 footprint, primary production	*	1.72	-	1.9	kg/kg
Recycle		✓			

Supporting information

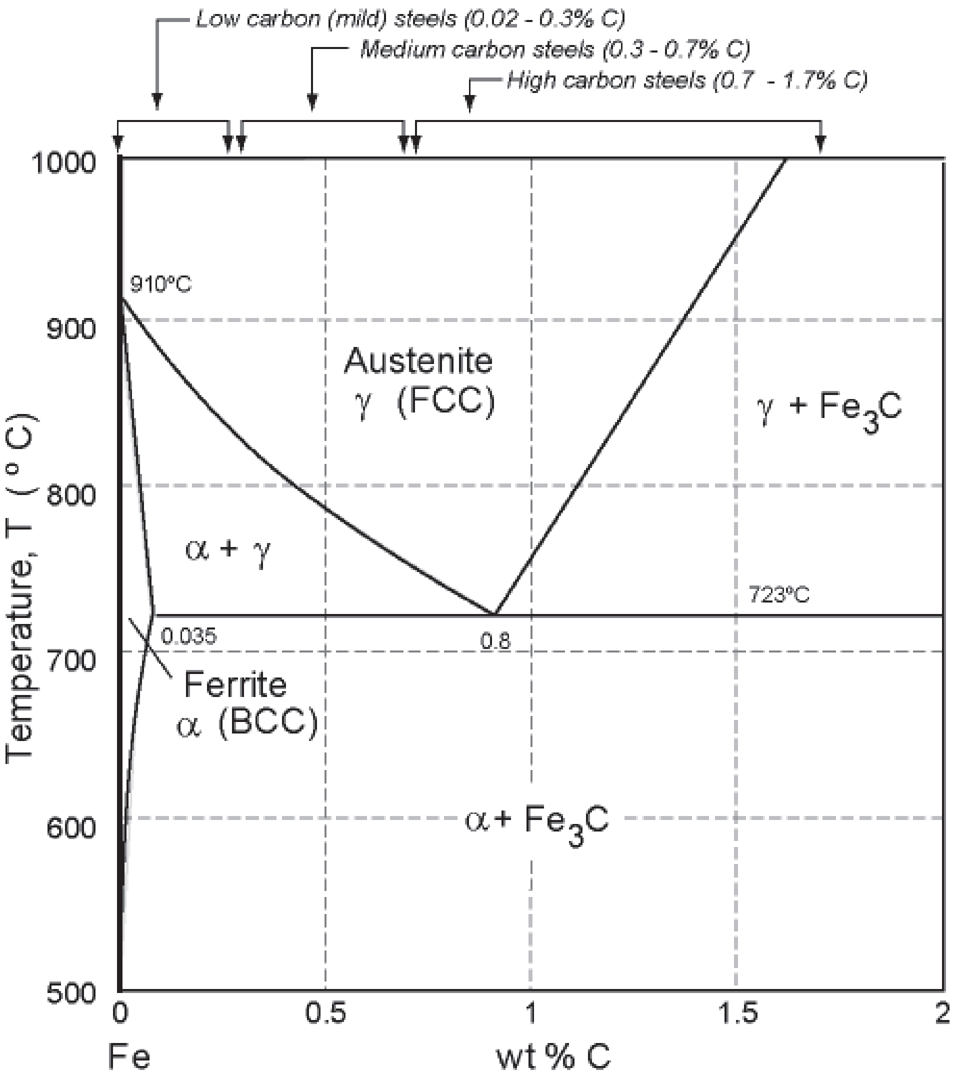
Design guidelines

Hardenability measures the degree to which it can be hardened in thick sections. Low carbon steels have too little carbon to harden much, and have poor hardenability - additional alloying elements are used to increase it (see Low alloy steels).

Technical notes

The two standard classifications for steels, the AISI and the SAE standards, have now been merged. In the SAE-AISI system, each steel has a four-digit code. The first two digits indicate the major alloying elements. The second two give the amount of carbon, in hundredths of a percent. Thus the plain carbon steels have designations starting 10xx, 11xx, 12xx or 14xxx, depending on how much manganese, sulfur and phosphorus they contain. The common low-carbon steels have the designations 1015,1020, 1022, 1117,1118; the common medium carbon steels are 1030,1040, 1050, 1060, 1137, 1141, 1144 and 1340; the common high alloy steels are 1080and 1095. More information on designations and equivalent grades can be found in the Users section of the Granta Design website, www.grantadesign.com

Phase diagram



Phase diagram description

Low carbon steels are alloys of iron (Fe) with 0.02 - 0.3% carbon (C), for which this is the phase diagram.

Typical uses

Low carbon steels are used so widely that no list would be complete. Reinforcement of concrete, steel sections for construction, sheet for roofing, car body panels, cans and pressed sheet products give an idea of the scope.

Links

Reference

ProcessUniverse

Producers

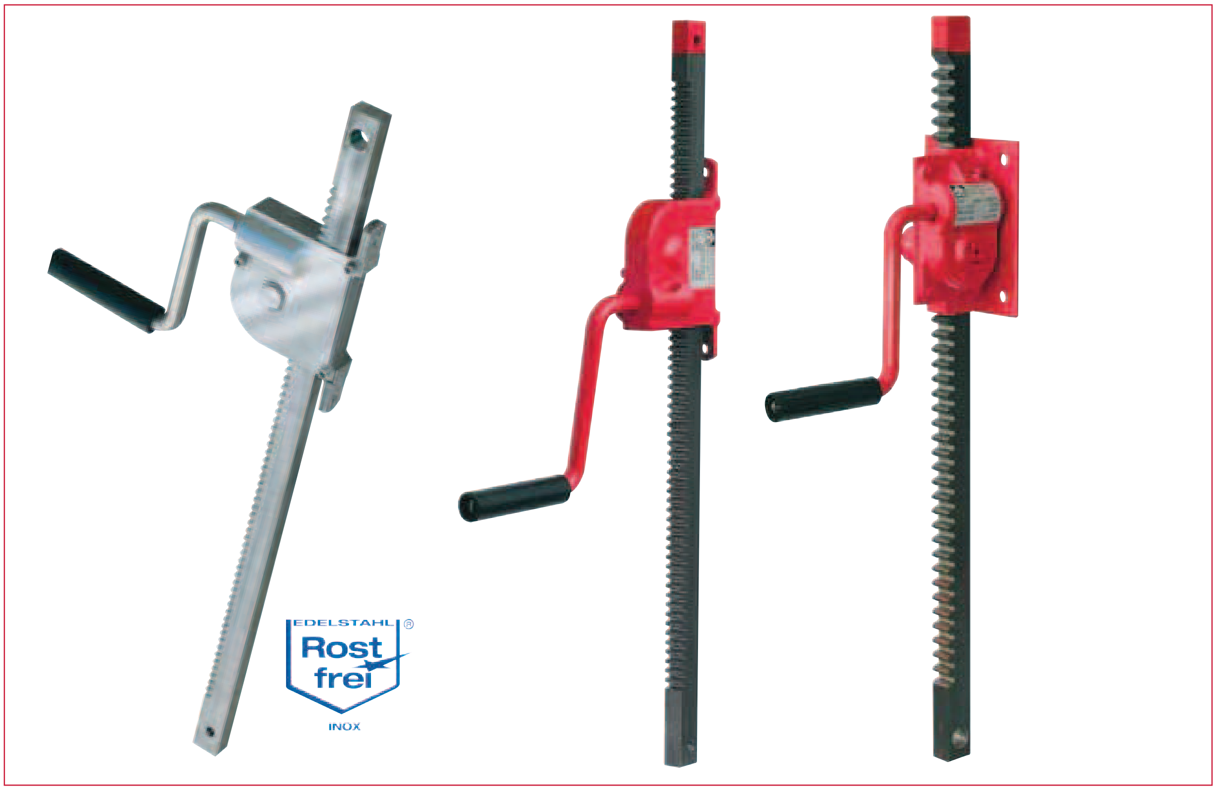
Appendix C: Vendor Data Sheets

Zahnstangenwinde mit Schneckengetriebe 1524.0,5; 1555.1

Rack & Pinion Jack with self-locking worm gear 1524.0,5; 1555.1

Treuils à crémaillère à vis sans fin 1524.0,5; 1555.1

haacon



Zahnstangenwinde zum Heben, Senken, Verstellen und Fixieren von Bauteilen, Geräten, Maschinen, etc.

- **extrem leichtgängiges, selbsthemmendes Schneckengetriebe, für Zug- und Druckbelastung**
- **feste Kurbel mit Klappgriff oder abnehmbare Kurbel (Type 1524)**
- **robuste Ausführung, gefräste Zahnstange und gehärtete Triebteile, für den Einsatz im Freien geeignet**
- **Sonderausführungen gegen Aufpreis:**
  - **andere Hub- und Baulänge**
  - **andere Kurbelausführung**
  - **unterschiedliche Befestigungsmöglichkeit**
  - **andere Oberflächenvergütung**

Rack & pinion jack for lifting, lowering, adjusting and fixing of mechanical components, devices, machines, etc.

- extremely easy functioning, self-locking worm gear, for pushing and pulling applications
- fixed folding handle or removable handle (type 1524)
- robust version with milled rack and hardened gears, for indoor and outdoor applications
- special versions against additional charge:
  - an other lift or length
  - an other crank version
  - an other fixing possibility
  - an other surface treatment

Treuil à crémaillère pour lever, abaisser, ajuster et fixer des pièces, appareils, machines, etc.

- facile à utiliser, grâce à engrenage à vis autoblocant, approprié pour pression et traction
- manivelle fixe et repliable ou manivelle démontable (type 1524)
- version robuste avec crémaillère fraisée et pièces de commande durcies,
- pour application à l'intérieur et à l'extérieur
- versions spéciales pour charge supplémentaire :
  - autre course et longueur de la crémaillère
  - autre version de manivelle
  - autre possibilité de fixation
  - autre traitement de surface

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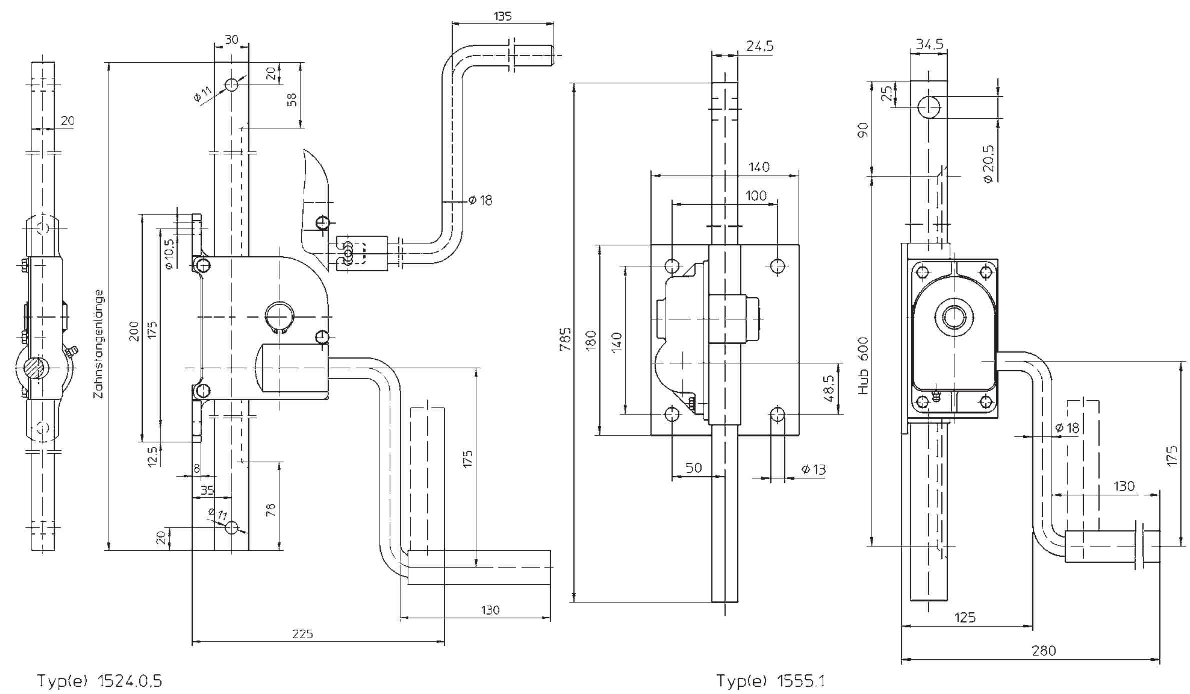
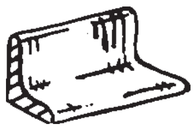
098103 [Ausg.: 005 - 07/2011 VWM/em]

Technische Daten
Technical data
Caractéristiques techniques



Bestell-Nr. Order N° N° Code	**Typ** Type Type	**Hub** lift course	**Zahnstangenlänge** Rack length longueur crémaillère	**Material** Material Finition
200 075	**1524.0,5**	530	735	Guß, Stahl / cast iron, steel / acier moulé, acier
210 668	**1524.0,5**	530	735	Edelstahl rostfrei / stainless steel / acier inox
209 390	**1524.0,5**	1000	1205	Guß, Stahl / cast iron, steel / acier moulé, acier
209 443*	**1524.0,5**	1050	1225	Guß, Stahl / cast iron, steel / acier moulé, acier
210 660	**1524.0,5**	1000	1205	Edelstahl rostfrei / stainless steel / acier inox
200 076	**1555.1**	600	785	Guß, Stahl / cast iron, steel / acier moulé, acier
*** Abnehmbare Kurbel /** removable crank / manivelle démontable				

Technische Daten	**Technical data**	**Caractéristiques techniques**	**1524.0,5**	**1555.1**
zul. Last (Zug/Druck)	permissible load (push/pull)	capacité de levage (pression/traction)	0,5 t	1 t
Bauhöhe	overall height	hauteur hors-tout	735 / 1205 mm	785 mm
Hub	lift	course	530 / 1000 mm	600 mm
Übersetzung	gear ratio	rapport	1 : 20	1 : 18
Hub/Kurbelumdrehung	lift/crank turn	course/tour de manivelle	9,4 mm	3,5 mm
Kurbeldruck	crank force	effort manivelle	160 N	160 N
Gewicht	weight	poids	5,7 / 7,7 kg	9 kg



ANGLE, BAR SIZE
SMALL ANGLE UNDER 3"

SIZE IN INCHES	EST. WT. PER FT. POUNDS	WT. PER 20' BAR, POUNDS
1/2x1/2x		
1/8	**.38**	7.6
3/4x3/4x		
1/8	**.59**	11.8
1x1x		
1/8	**.80**	16.0
3/16	**1.16**	23.2
1/4	**1.49**	29.8
6 **1-1/4x1-1/4x**		
1/8	**1.01**	20.2
3/16	**1.48**	29.6
1/4	**1.92**	38.4
1-1/2x1-1/2 x		
1/8	**1.23**	24.6
3/16	**1.80**	36.0
1/4	**2.34**	46.8
5/16	**2.86**	57.2
3/8	**3.35**	67.0
1-3/4x1-3/4x		
1/8	**1.44**	28.8
3/16	**2.12**	42.4
1/4	**2.77**	55.4

GALVANIZED AVAILABLE

SIZE IN INCHES	EST. WT. PER FT. POUNDS	WT. PER 20' BAR, POUNDS
2x1-1/2x		
1/8	**1.44**	28.8
3/16	**2.12**	42.4
1/4	**2.77**	55.4
2x2x		
1/8	**1.65**	33.0
3/16	**2.44**	48.8
1/4	**3.19**	63.8
5/16	**3.92**	78.4
3/8	**4.70**	94.0
2-1/2x1-1/2x		
3/16	**2.44**	48.8
1/4	**3.19**	63.8
5/16	**3.92**	78.4
2-1/2x2x		
3/16	**2.75**	55.0
1/4	**3.62**	72.4
5/16	**4.50**	90.0
3/8	**5.30**	106.00
2-1/2x2-1/2x		
3/16	**3.07**	61.4
1/4	**4.10**	82.0
5/16	**5.00**	100.0
3/8	**5.90**	118.0
1/2	**7.70**	154.0

ANGLE, STRUCTURAL
STRUCTURAL ANGLE 3" & OVER ASTM A-36

SIZE IN INCHES	EST. WT. PER FT. POUNDS	WT. PER 20' BAR, POUNDS
3x2x		
3/16	**3.07**	61.4
1/4	**4.10**	82.0
5/16	**5.00**	100.0
3/8	**5.90**	118.0
7 1/2	**7.70**	154.0
	FORMED ANGLE INQUIRE	
3x2-1/2x		
1/4	**4.50**	90.0
5/16	**5.60**	112.0
3/8	**6.60**	132.0
1/2	**8.50**	170.0

SIZE IN INCHES	EST. WT. PER FT. POUNDS	WT. PER 20' BAR, POUNDS
3x3x		
3/16	**3.71**	74.2
1/4	**4.90**	98.0
5/16	**6.10**	122.0
3/8	**7.20**	144.0
7/16	**8.30**	166.0
1/2	**9.40**	188.0
3-1/2x2-1/2x		
1/4	**4.90**	98.0
5/16	**6.10**	122.0
3/8	**7.20**	144.0
1/2	**9.40**	188.0

CHANNEL, BAR SIZE

SMALL CHANNEL
UNDER 3"

8

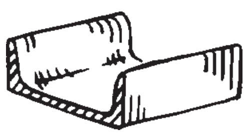
SIZE IN INCHES	WT. PER FT. POUNDS	WT. PER 20' BAR, POUNDS	SIZE IN INCHES	WT. PER FT. POUNDS	WT. PER 20' BAR, POUNDS
3/4x3/8x1/8	**.56**	11.2	**1-3/4x1/2x3/16**	**1.55**	31.0
1x1/2x1/8	**.83**	16.6	**2x1/2x1/8**	**1.43**	26.6
1-1/4x1/2x1/8	**1.01**	20.2	**2x9/16x3/16**	**1.76**	35.2
1-1/2x1/2x1/8	**1.12**	22.4	**2x1x1/8**	**1.78**	35.6
1-1/2x3/4x1/8	**1.17**	23.4	**2x1x3/16**	**2.57**	51.4

CHANNEL, JUNIOR

JUNIOR CHANNEL
(STAIR STRINGERS)
SPECIAL SHAPES

9

CHANNEL DEPTH x WT./FT.	WEIGHT PER FT. POUNDS	WEB THICKNESS INCHES	FLANGE WIDTH IN INCHES	CHANNEL DEPTH x WT./FT.	WEIGHT PER FT. POUNDS	WEB THICKNESS INCHES	FLANGE WIDTH IN INCHES
8 x	**8.5**	*3/16	1-7/8	**10 x**	**8.4**	*3/16	1-1/2
10 x	**6.5**	*3/16	1-1/8	**12 x**	**10.6**	*3/16	1-1/2



CHANNEL, STRUCTURAL

STANDARD CHANNEL
(AMERICAN STD.)
C-SHAPES ASTM A-36

10

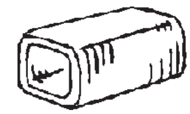
DESIGNATION DEPTH in Inches x WEIGHT Per Ft. Lbs. (Nominal Size)	WEIGHT Per Foot Lbs.	DEPTH Section in Inches	in Inches	FLANGE Thickness (Average) in Inches	WEB Thickness in Inches	Area of Section In.^{2}	Section Modulus Sx In.^{3}	**Surface Area Foot of Length.^{2}
C3 x	**4.1**	***3**	**1-3/8**	**1/4**	**3/16**	1.21	1.10	.89
(3x1-1/2)	**5.0**	**3**	**1-1/2**	**1/4**	**1/4**	1.47	1.24	.91
	6.0	**3**	**1-5/8**	**1/4**	**3/8**	1.76	1.38	.97
C4 x	**5.4**	**4**	**1-5/8**	**5/16**	**3/16**	1.59	1.93	1.11
(4x1-5/8)	**6.25**	**4**	**1-5/8**	**5/16**	**1/4**	1.82	2.10	1.12
	7.25	**4**	**1-3/4**	**5/16**	**5/16**	2.13	2.29	1.13
C5 x	**6.7**	**5**	**1-3/4**	**5/16**	**3/16**	1.97	3.00	1.33
(5x1-3/4)	**9.0**	**5**	**1-7/8**	**5/16**	**5/16**	2.64	3.56	1.35
C6 x	**8.2**	**6**	**1-7/8**	**5/16**	**3/16**	2.40	4.38	1.54
(6x2)	**10.5**	**6**	**2**	**5/16**	**5/16**	3.09	5.06	1.56
	13.0	**6**	**2-1/8**	**5/16**	**7/16**	3.83	5.80	1.58
C7 x	**9.8**	**7**	**2-1/8**	**3/8**	**3/16**	2.87	6.08	1.76
(7x2-1/8)	**12.25**	**7**	**2-1/4**	**3/8**	**5/16**	3.60	6.93	1.78
	14.75	**7**	**2-1/4**	**3/8**	**7/16**	4.33	7.78	1.83
C8 x	**11.5**	**8**	**2-1/4**	**3/8**	**1/4**	3.38	8.14	1.98
(8x2-1/4)	**13.75**	**8**	**2-3/8**	**3/8**	**5/16**	4.04	9.03	1.99
(CONTINUED)	**18.75**	**8**	**2-1/2**	**3/8**	**1/2**	5.51	11.00	2.02

***APPROX. DIMENSIONS FOR DETAILING ONLY**
THE ROUNDING OFF OF DECIMAL DIMENSIONS TO FRACTIONS CAN LEAD TO AN ACCUMULATION OF DIFFERENCES (SEE A.I.S.C. MANUAL)

FORMED CHANNEL AVAILABLE

**FOR PAINTING & SANDBLASTING SURFACE AREA (ALL AROUND) SQUARE FOOT Ft^2 PER FOOT OF LENGTH

TUBING, SQUARE
ORNAMENTAL & STRUCTURAL



SIZE IN INCHES	WALL THICKNESS	EST. WT. PER FT. POUNDS
1/2 x 1/2 x	.049	**.301**
	.065	**.385**
5/8 x 5/8 x	.049	**.367**
	.065	**.495**
3/4 x 3/4 x	.049	**.46**
	.065	**.607**
	.083	**.75**
	.095	**.84**
	.120	**1.03**
7/8 x 7/8 x	.049	**.52**
	.065	**.68**
	.083	**.89**
	.095	**.98**
	.120	**1.23**
1 x 1 x	.049	**.63**
	.065	**.83**
	.083	**1.04**
	.095	**1.17**
	.109	**1.32**
	.120	**1.43**
1 1/4 x 1 1/4 x	.049	**.80**
	.065	**1.05**
	.083	**1.32**
	.095	**1.49**
	.109	**1.69**
	.120	**1.84**
	.188	**2.75**
1 1/2 x 1 1/2 x	.049	**.95**
	.065	**1.27**
	.083	**1.60**
	.095	**1.81**
	.109	**2.06**
	.120	**2.25**
	.188	**3.54**
	.250	**4.11**
1 3/4 x 1 3/4 x	.065	**1.49**
	.083	**1.88**
	.095	**2.14**
1 3/4 x 1 3/4 x	.120	**2.66**
	.188	**3.68**
2 x 2 x	.065	**1.69**
	.083	**2.16**
	.095	**2.46**
	.120	**3.07**
	.188	**4.32**
	.250	**5.41**
2 1/4 x 2 1/4 x	.188	**5.07**
	.250	**7.01**
2 1/2 x 2 1/2 x	.120	**3.89**
	.188	**5.59**
	.250	**7.11**
3 x 3 x	.120	**4.70**
	.188	**6.87**
	.250	**8.81**
	.313	**10.58**
	.375	**12.17**
3 1/2 x 3 1/2 x	.120	**5.61**
	.188	**8.15**
	.250	**10.51**
	.313	**12.70**
	.375	**14.70**
4 x 4 x	.120	**6.34**
	.188	**9.42**
	.250	**12.21**
	.313	**14.83**
	.375	**17.27**
	.500	**21.63**
4 1/2 x 4 1/2 x	.188	**10.70**
	.250	**13.91**
5 x 5 x	.120	**7.96**
	.188	**11.97**
	.250	**15.62**
	.313	**19.08**
	.375	**22.37**
	.500	**28.43**

TELESCOPING TUBING INQUIRE

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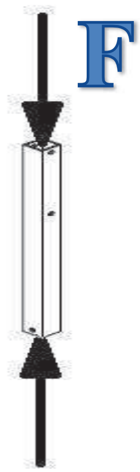
Appendix D: Calculations

Static Failure Analysis for the Steel Tube in Compression



Free Body Diagram

Given Information

- F = 400lbf (applied force provided by the jack)
- OD = 1.5 inches
- ID = 1.26 inches
- n = 3 (safety factor)

Find

- Sy = Yield Strength (kpsi)

Assume

- Distortion-Energy Theory for ductile materials in compression

Distortion-Energy Theory Equation

$$\sigma' = \frac{F}{A} = \frac{Sy}{n}$$

Area Equation (including the ½ inch through hole):

$$A = \left(1.5 * (1.5 - .5)\right) - 1.26\text{^}2$$

$$A = 0.0876\ in\text{^}2$$

Solve for Sy:

$$Sy \geq \frac{(F * n)}{A}$$

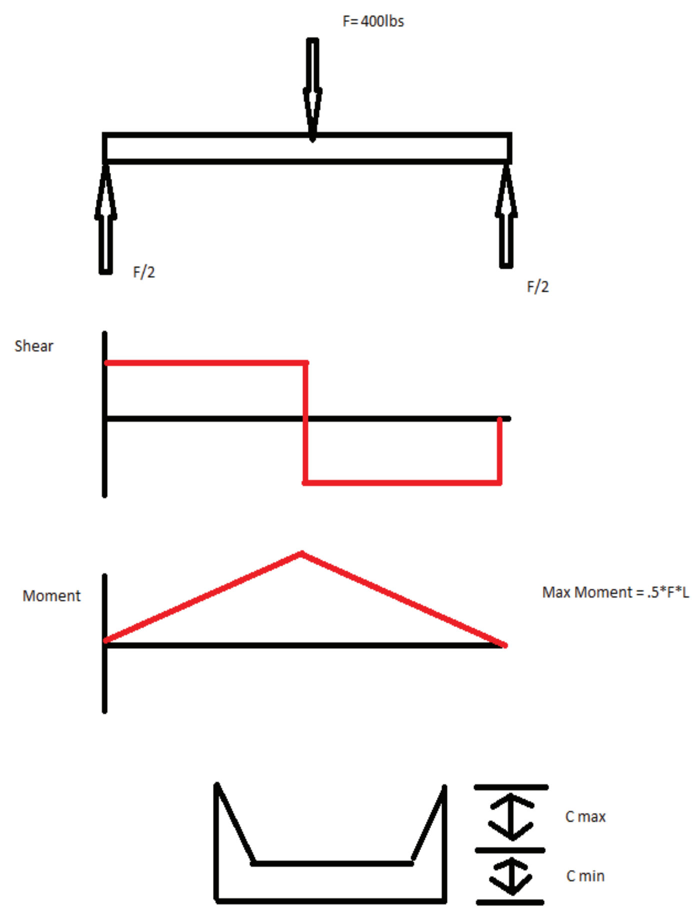
$$Sy \geq \frac{(400lbf * 3)}{0.0867}$$

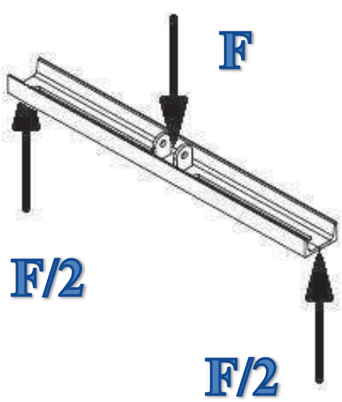
Answer:

$$\boldsymbol{Sy \geq 13.84\ kpsi}$$

13.84 kpsi is well below the yield strength of ASTM A-36 steel (36 kpsi)

Static Failure Analysis for the steel channel assuming beam theory





Free Body Diagram

Given Information

- F = 400lbf (applied force provided by the jack)
- Total Length = 28 inches
- L (half of total length) = 14 inches
- I (second-area moment) = 1.85 in^4
- C (maximum magnitude in the y direction) = 1.06 in
- n = 3 (safety factor)

Find

- Sy = Yield Strength (kpsi)

Assume

- Distortion-Energy Theory for ductile materials

Distortion-Energy Theory Equation with Beam Moment Calculation

$$\sigma' = \frac{F * L * C}{2 * I} = \frac{Sy}{n}$$

Solve for Sy:

$$Sy \geq \frac{(n * F * L * C)}{2 * I}$$

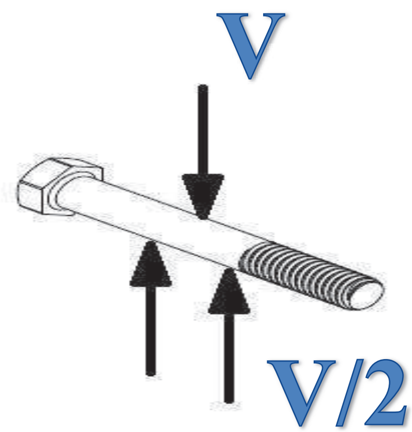
$$Sy \geq \frac{(3 * 400lbf * 14in * 1.06in)}{2 * 1.85in\text{^}4}$$

Answer:

$$\boldsymbol{Sy \geq 4.82\ kpsi}$$

4.82 kpsi is well below the yield strength of ASTM A-36 steel (36 kpsi)

Static Failure Analysis for a Bolted Connection in Pure Shear



Free Body Diagram

Given Information

- V = 400lbf (applied force provided by the jack)
- D = 0.375 inches (diameter of bolt)
- n = 3 (safety factor)

Find

- Sy = Yield Strength (kpsi)

Assume

- Distortion-Energy Theory for ductile materials in pure shear

Distortion-Energy Theory Equation

$$\tau_{xy} = \frac{V}{A} = \frac{Sy}{(\sqrt{3}) * n}$$

Area Equation:

$$A = \frac{\pi * (D)^2}{4}$$

$$A = \frac{\pi * (0.375)^2}{4} = 0.1104\ in^2$$

Solve for Sy:

$$Sy \geq \frac{(F * \sqrt{3} * n)}{A}$$

$$Sy \geq \frac{(400lbf * \sqrt{3} * 3)}{0.1104}$$

Answer:

$$\boldsymbol{Sy \geq 18.83\ kpsi}$$

18.83kpsi is much lower than the 120 kpsi proof strength of a grade 8 bolt!

Appendix E: Bill of Materials (BoM)

B.O.M. Sand Mold Clamp

Item	Quantity	Vendor	Item #	Description	Length (ft)	Lb per Foot	Price per Foot	Price per Unit	Price
Jack	1	Haacon	1524.0.5	Rack and Pinion Jack					$ 200.00
Jack	1	Haacon		Shipping					$ 200.00
Flat Bar	1	Coyote Steel		2"x1/4"	4'		$ 2.18		$ 7.36
Sheet	1	Coyote Steel		1 lot 7# @48					$ 3.36
Angle Iron	1	Coyote Steel		2"x2"x1/4	10'	3.19	$ 2.45		$ 26.27
Angle Iron	1	Coyote Steel		2"x2"x1/4	42"	4.1	$ 7.10		$ 12.92
Angle Iron	1	Coyote Steel		2"x2"x1/4	53"	5.41	$ 2.15		$ 15.79
C-Channel	1	Coyote Steel		3# 1/4#	60"				$ 29.00
Square Tube	1	Coyote Steel		1.5" 0.12 wall	60"				$ 11.15
Flat Bar	3	Coyote Steel		1/4"x2"	24"				$ 3.66
M10 Hex Cap Screw	2	Eugene Fastener	138138	UNC, Steel			$ 0.55		$ 1.10
M10 Flat Washer	2	Eugene Fastener	135800	UNC, Steel			$ 0.05		$ 0.10
M10 Hex Nut	2	Eugene Fastener	58128	Steel			$ 0.15		$ 0.30
1/2 Grade 5 Screw	2	Eugene Fastener	58126	Steel			$ 0.45		$ 0.90
1/2x13 Hex Nut	2	Eugene Fastener					$ 0.10		$ 0.20
1/2 Flat Washer	2	Eugene Fastener					$ 0.10		$ 0.20
1/2 Cap Screw	1	Eugene Fastener					$ 1.00		$ 1.00
1/2 Hard Flat Washer	1	Eugene Fastener					$ 0.20		$ 0.20
1/2 Grade 8 Nut	1	Eugene Fastener	136036	Steel			$ 0.15		$ 0.15
M10 Screw Coarse	1	Eugene Fastener					$ 0.85		$ 0.85
M10 Nut	1	Eugene Fastener					$ 0.15		$ 0.15
M10 Flat Washer	1	Eugene Fastener					$ 0.05		$ 0.05
3/4" Round Stock	1	OSU Machine Shop		Aluminum	6				$ -

B.O.M. Sand Mold Clamp Testing Supplies

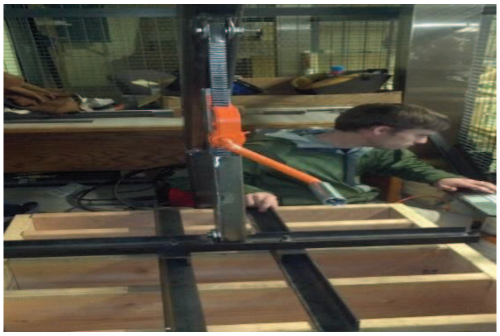
2"x12"x10"	1	Lowes		Wood Studs					$ 6.34
2"x12"x8"	1	Lowes		Wood Studs					$ 9.86
Sand	1	Lowes		Sand					$ 1.99

Eugene Fastener	$ 5.20
Haacon Total	$ 400.00
Coyote Steel Total	$ 109.51
Lowes Total	$ 18.19
Total	**$ 532.90**

Appendix F: Testing Results

Testing Procedure #6 – Pass

TEST #1



68	92	174	81
68	93	174	81
68	92	174	80
68	92	174	81
68	92	174	81
68	92	174	81
68	92	174	81
68	93	174	81
68	92	174	81
68	93	174	81
68	92	174	81

Calculation (forces in lbf):

- **68/92/81 Average=80.3**

Maximum Deviation: (80.3-68)/80.3 = 15.3%

TEST #2

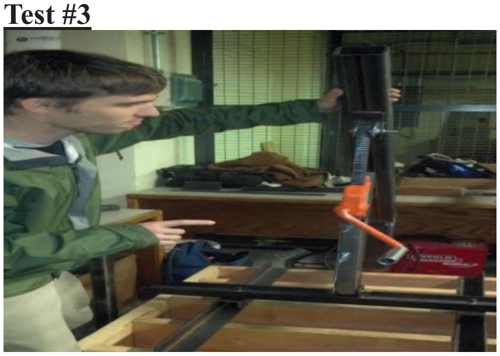
72	94	179	79
73	94	179	78
73	94	179	78
73	94	180	79
72	94	180	79
73	94	180	79
73	94	179	78
73	94	180	78
73	94	179	78

Calculation (forces in lbf):

- **73/94/78 Average=81.7**

Maximum Deviation: (94-81.7)/81.7 = 15.1%

Test #3



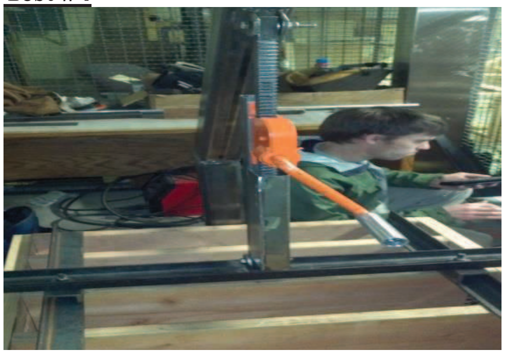
78	96	183	72
78	96	183	72
78	96	183	72
78	96	183	72
78	96	183	72
78	96	183	72
78	96	183	72

Calculation (forces in lbf):

- **78/96/72 Average=82**

Maximum Deviation: (96-82)/82 = 17.1%

<u>Test #4</u>

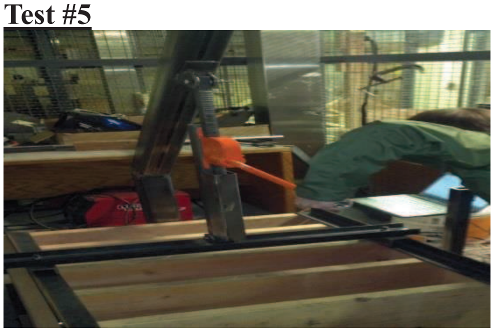


73	89	170	61
74	89	170	61
74	89	170	61
74	89	170	60
74	89	170	61
74	89	170	61
73	89	170	61
74	89	170	60

Calculation (forces in lbf):

- **74/89/61 Average=74.7** **Maximum Deviation: (89-74.7)/74.7 = 19.1%**

<u>Test #5</u>



70	91	219	70
70	91	219	70
71	91	219	70
71	91	219	70
70	91	218	70
70	91	218	70
70	91	218	70
71	91	218	70
70	91	218	70

Calculation (forces in lbf):

- **70/91/70 Average=77** **Maximum Deviation: (91-77)/77 = 18.1%**