MacDon®

Quick Change A-Stand Design

Report Prepared for:

Sean Hakansson (Client)

Dr. Paul E. Labossiere, P.Eng. (Course Instructor)

Dr. Sean O'Brien, P.Eng. (Project Advisor)

Aidan Topping (Technical Communication Instructor)

Date of Submission

Wednesday, December 5th, 2018

Prepared by:

TEAM 18

Dongha Kim ______________________________

Yafei Quan ______________________________

Timmy Truong ______________________________

Zetian Zhou ______________________________

Executive Summary

This report presents the final design of the quick-change hydraulic powered A-Stands that successfully meets client's requirements. The main requirement of the client is to reduce the welding fixture changeover time from 45 minutes to 5 minutes. The final design uses a retractable shaft mechanism built into the heads of the drive end and idle end A-Stands. This allows the A-Stand shafts to quickly connect to, and disconnect from, the welding fixture yokes. Therefore, the welding fixtures can be easily lifted off, and lowered onto the A-Stands, improving the welding fixture changeover process compared to the existing A-Stand design.

In the existing A-Stand design, the process requires to move the entire A-Stand to connect to and disconnect from welding fixture yoke. This requires use of forklifts due to the A-Stand shaft being fixed in place to the A-Stand head and the heavy weight of the A-Stand. This is the most time-consuming process in the welding fixture changeover. The retractable shaft design eliminates this process therefore it significantly improves the changeover time. As a limitation of this project, obtaining actual changeover time is not possible due to not having a working prototype. However, because of the simplicity of the new process, the target time can be achieved theoretically.

The final design is achieved by an iterative design process built on the retractable shaft concept which was determined as the best approach to achieve a quick changeover. The performance of the critical components is verified through analytical stress analysis, stress-life analysis, and preliminary finite element analysis (FEA). Standard operating procedure and failure modes and effects analysis are used as a preliminary safety analysis. Preliminary drawings are provided for details of the final design components. In addition, a preliminary cost analysis is conducted for client's reference when weighting the benefits.

The final A-Stand design meets client's requirements making it a successful design. The A-Stands have been determined analytically to support client's required load of 4,000 [lbs] with a safety factor of 3. The A-Stand shafts meet client's requirement for 15-year service life. The final A-Stand design is retrofitted on the existing A-Stand base and is compatible with the existing hydraulic powered gearbox and all the existing welding fixtures. The cost to manufacture the final A-Stand design is $5,540 CAD, which is within client's budget of $8,000 CAD. The overall footprint of the final design (60 x 27.875 [in^2]) is under the client's constrained footprint of 60 x 30 [in^2].

Table of Contents

List of Figures

List of Tables

1. Introduction

Founded in 1949, MacDon Industries has been leading the harvesting equipment manufacturer around the world. In their manufacturing facility in Winnipeg, they have plenty of welding stations to keep up with their production rate. The welding process in manufacturing is important and reducing the time will bring positive results. A welding fixture is used every time they do welding at MacDon, and these fixtures vary in size because the products have varying geometry. Once the welding process is over, the users must change the welding fixture to work on the next task, however, it is not necessary that each welding station is working with same sized welding fixture. The changeover process takes up to 45 minutes because the users must lift the welding fixture using a crane, move the A-Stands to the desired location depending on the size of the welding fixture, and reconnect the A-Stands with the welding fixture.

Representatives from MacDon Industries assigned the team to design a new quick-change A-Stand that reduces the fixture changeover time from 45 minutes to 5 minutes, while maintaining its original functionality and compatibility with existing welding fixtures.

Once the team successfully design a new quick-change A-Stand, the team will provide 3D CAD model and preliminary drawings of the final design, preliminary stress analysis, preliminary cost analysis, and preliminary safety validation to show possible safety issues with the final design.

1.1. Project Background and Objectives

At MacDon, the current changeover process to switch between welding fixtures takes up to 45 minutes depending on the size of the welding fixture (largest welding fixture being longest time, 45 minutes), which occurs multiple times a day. Production rate decreases as more time is wasted changing between welding fixtures which causes loss in revenue. The team must reduce the changeover time to a target of 5 minutes while maintaining its original functionality (rotating and supporting the welding fixture off the floor); and must be compatible with all existing welding fixtures.

1.1.1. Existing A-Stand Design

A thorough understanding of the existing design provides justifications for developing the new design. There are two types of A-Stands used at MacDon: hydraulic powered A-Stands for larger and heavier welding fixtures, and manually powered A-Stands for smaller and lighter welding fixtures. Both types of A-Stands consist of a pair of A-Stands, an idle end freely rotates while a drive end provides the rotating action with a hydraulic powered gearbox. Figure 1 shows the CAD model of the hydraulic powered A-Stands supporting a welding fixture. The largest welding fixtures weigh up to 3,400 pounds and are 17 feet long. The free-standing ability of the A-Stands allow for welding fixtures of various lengths to be used, which is the key reason why A-Stands are not connected directly together. In this report, the team while solely focus on the hydraulic powered A-Stands.

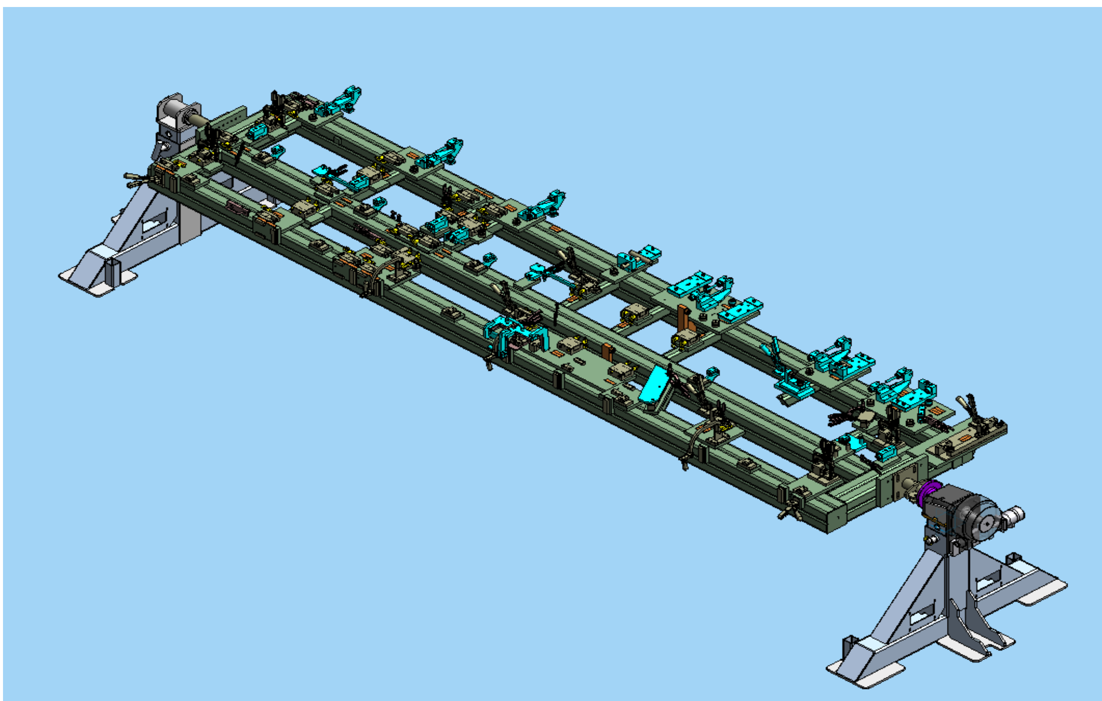


Figure 1: A Pair of Hydraulic Powered A-Stands Supporting a Welding Fixture

The detailed illustrations of the hydraulic powered A-Stands are shown in Figure 2 and Figure 3. The drive end consists of a stand base, a stand head, a stand neck, a lock pin, and a gearbox set. The idle end is structured in an A-Stand supporting the neck, the head and the gearbox. The neck connects the head and the base, and the height of the head can be adjusted using a lock pin. Two support legs are welded at the back side of the base to prevent the stand from tipping over due to the weight of the gearbox.

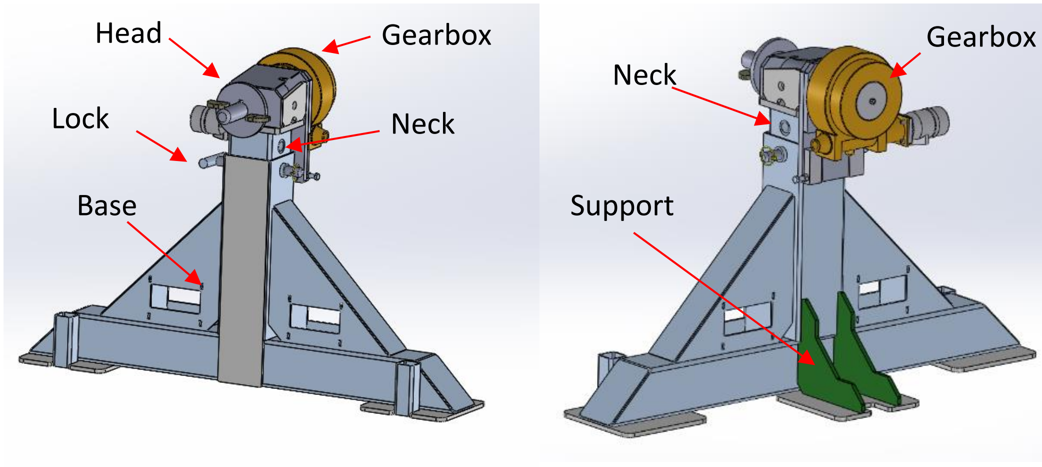


Figure 2: Drive End Hydraulic Powered A-Stand Details

The idle end basically has the same structure as the drive end, except for the gearbox and a slightly different stand head. The details on stand heads are shown in Figure 4.

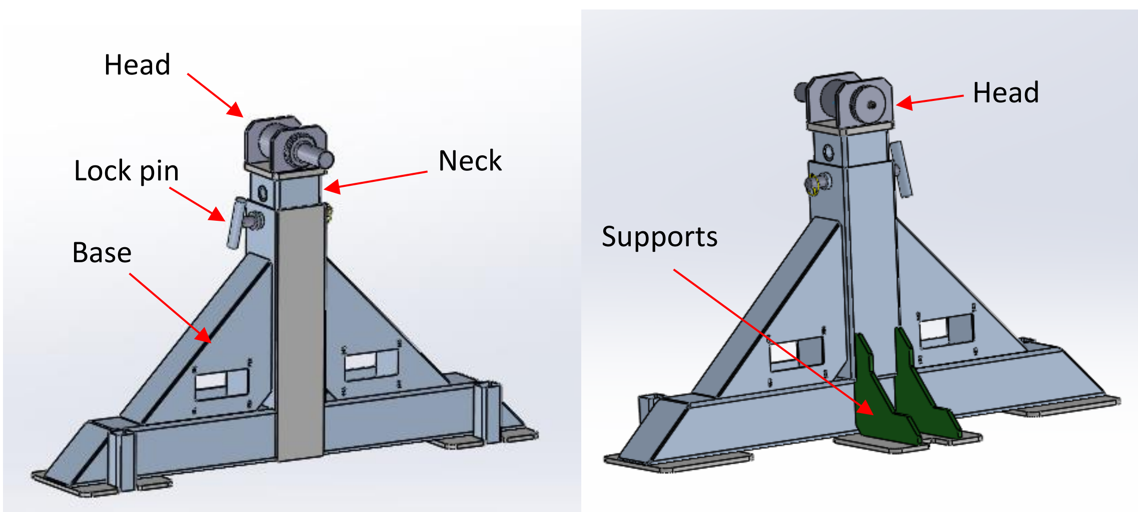


Figure 3: Idle End A-Stand Details

The head on the idle end primarily consists of a housing and a solid shaft. The shaft is connected to the housing with a ball bearing. The drive end head has a similar structure. The housing on the drive end is a little more complicated with several metal plates welded on. A butterfly disc is installed on the shaft of the drive end, providing two tabs which can be matched up and locked the welding fixture yoke using bolts and nuts to allow the welding fixture to be driven by the hydraulic gearbox.

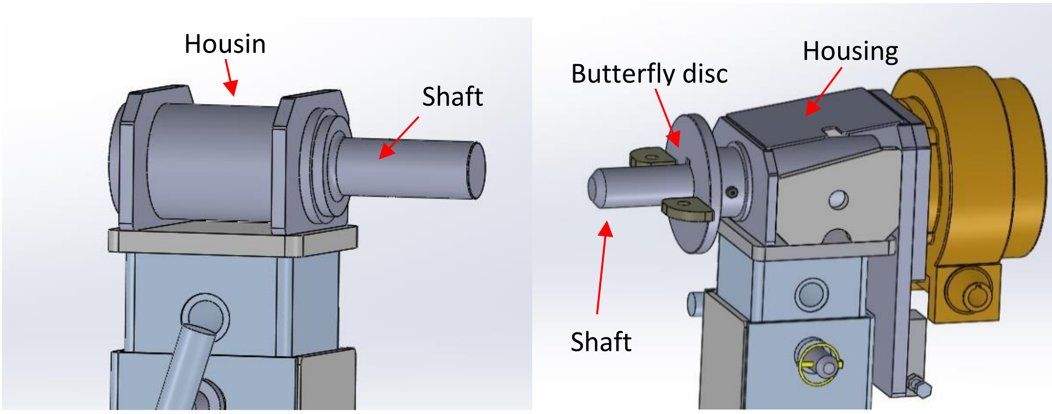


Figure 4: A-Stand Heads Details

Figure 5 shows the welding fixture yoke coupled to the shaft on the drive end. To secure the shaft with the yoke, a pin is inserted through the pin holes and two bolts will be fastened at the bolt holes. For the idle end, only a pin will be used for the connection.

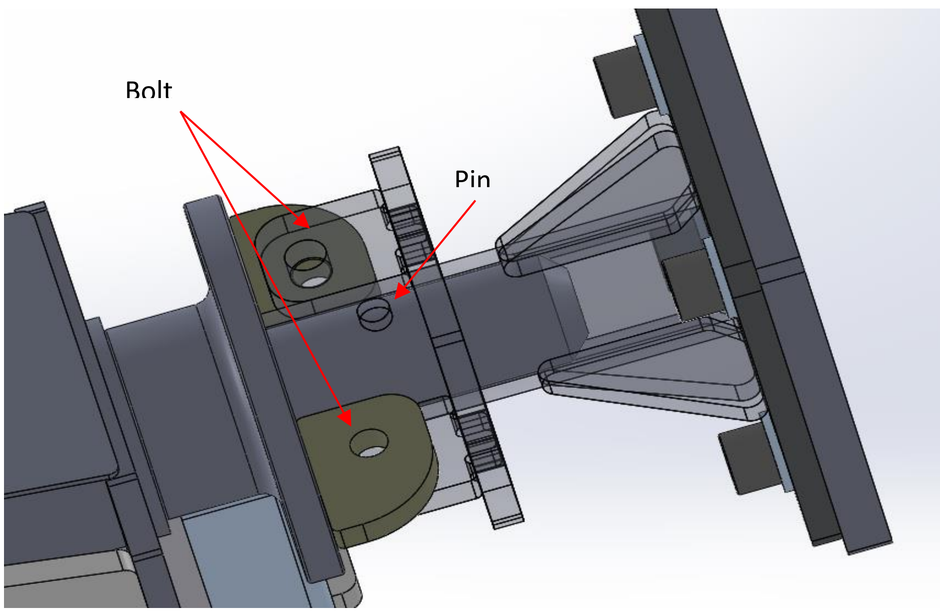


Figure 5: Welding Fixture Yoke Coupling with the A-Stand Shaft

The current welding fixture changeover process requires to move the entire A-Stand to connect to and disconnect from welding fixture yoke. This requires use of forklifts due to the A-Stand shaft being fixed in place to the A-Stand head and the heavy weight of the A-Stand. This process is the most time-consuming process in the welding fixture changeover, because it is difficult to accurately align the A-Stand shafts with the welding fixture yoke using forklifts. This specific process is the main focus area of this project to improve.

1.2. Constraints and Limitations

Several constraints need to be adhered before designing the quick-change A-Stand. The design must be compatible with the existing power system and hydraulic setup for rotating the welding fixture. To reduce workplace injuries, single end user cannot lift anything over 50 pounds, anything heavier requires equipment or more operators. Material used for the final design is constrained to a list of materials available at MacDon or their designated material providers. The footprint of the design must not exceed 60” x 30”. Also, the dimensions of the gearbox must remain the same.

In addition to the constraints, the design is limited by various factors. The team only has 91 days to finish the project, which limits the team in short and tight schedule. Also, the client limited the budget of $8000 CAD per pair of A-Stands. Moreover, since the team does not need to provide any prototype to the client, there will be a limitation on measuring the actual time performance and ease of use on the new design during changeover. Lastly, the equipment that can be used during welding fixture changeover is limited to forklifts and cranes.

1.3. Target Specifications

To successfully design the new hydraulic powered A-Stands, the client’s needs and design metrics were first identified. Both the team and the client were involved in identifying and prioritizing the needs to guide the team with a successful design. The design metrics are then developed to visualize the effect of each client needs on the project. For the customer needs, Table I shows the scale used in the priority ranking and Table II indicates the client needs.

TABLE I. PRIORITY LEVEL RANKING SCALE TABLE

5	Top Priority
4	High Priority
3	Medium Priority
2	Low Priority
1	Optional, not necessary

TABLE II. CLIENT NEEDS TABLE FOR A-STAND

#	NEED	Priority
1	Capable of rotating and supporting fixtures off ground without any failure	5
2	Requires minimal equipment and manpower to perform welding fixture changeover	5
3	The A-Stand is retrofitted with existing A stand frames	3
4	Adaptable to existing welding fixture yoke	4
5	Rotation of welding fixture be operated with existing motor, gearbox and hydraulic setup	5
6	Safe to operate and perform welding fixture change over	5
7	Requires minimal maintenance with minimal wear parts	4
8	Has a long lifecycle of 10 years	4
9	Welding fixture changeover is easy to perform, requiring minimal operation steps	4
10	Enables a quick welding fixture changeover time of 5 minutes	5
11	Economic to produce	3
12	Follows basic DFMA principles to manufacture and assemble	3
13	Lightweight design	2
14	Easy to store	3

For design metrics, Table III is used to rank the importance level for each metrics and Table IV presents the design metrics. Each metrics were assigned a unit of measure, and if a metric cannot be judged by a unit, subjective is used as a unit. The metrics table also illustrates the linkage between customer needs defined in Table II and their relevant metrics.

TABLE III. IMPORTANCE LEVEL RANKING SCALE TABLE

5	Most Significant
4	High
3	Medium
2	Minor
1	Insignificant

TABLE IV. PRODUCT METRICS TABLE

#	Need #'s	Metric	Units	Ideal values	Marginal Values	Importance
1	1,6	Load capacity (a safety factor of 3 applied)	lbs	12000	10200	5
2	2,10	Manpower needed for the changeover	person	1	2	5
3	2,10	Equipment needed for the changeover	piece	1	2	5
4	3,11	Degree of retrofit on the existing bases	%	95%	50%	3
5	4	Compatibility with existing fixture yoke	Yes/No	Yes	Yes	4
6	5	Compatibility with current power setup	Yes/No	Yes	Yes	5
7	8	Part lifecycle	year	15	13	4
8	10	Changeover cycle time	min	5	10	5
9	11,12	Unit manufacturing cost (per A-Stand pair)	CAD $	8000	8000	3
10	12	Simplicity of machining and tooling (per A-Stand pair)	hours	16	24	2
11	2,14	Size (footprint)	Inch × Inch	60 × 30	60 × 30	3

2. Design Optimization

After identifying the project objectives, target specifications, and the inefficient coupling action between the A-Stands and the welding fixture, the team generated several concepts to successfully design a pair of new quick-change A-Stands. Thorough explanations on how the concepts were generated, iterated, and optimized to come up with the final design are shown in this section.

2.1. Design Concept Generation

With a good understanding of the current design, preliminary concepts are generated from internal group brainstorming and external researching. Four different preliminary concepts were generated firstly: namely A-Stand cup design, A-Stand base casters design, supporting frame A-Stand design, and A-Stand Base slit cut design. A screening for preliminary concepts is then performed to determine the best concept approach for the project objective. According to a list of important selection criteria, the cup design is taken for further concept development. With the client's feedback and group discussion, the team decided to not be limited within the cup design, but in general re-design the coupling and decoupling action behind it. To achieve a quick coupling and decoupling method, three further expanded concepts are then developed: Clamping shaft, Sleeve shaft and retractable shaft. A scoring matrix along with a weighting matrix are then utilized to select the most optimal concept. The details of concept generations can be found in Appendix A, and the concept generation process is visualized in Figure 6.

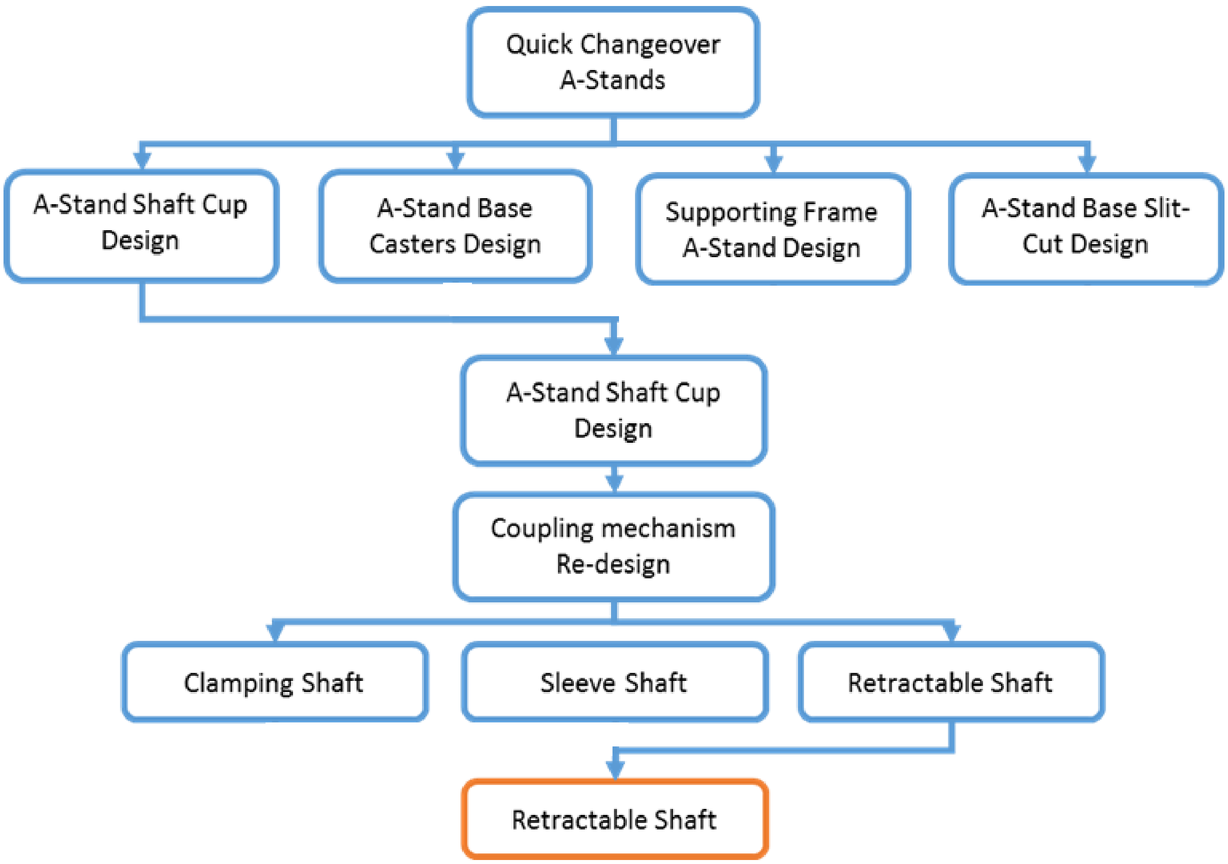


Figure 6: Quick Changeover A-Stands Design Concept Generation Flow Chart

As shown in the flowchart, the retractable shaft concept was chosen to be further developed. In the following sections, the iterative processes of the retracting mechanisms on the shaft for both the drive end and the idle end will be shown.

2.2. Drive End

This section presents the iterations of the hydraulic powered, drive end A-Stands. The retractable shaft concept proposed on the idle end A-Stand is implemented to the drive end of the A-Stand. Two initial iterations were made on the drive end before the final design iteration of the hydraulic powered drive end A-Stand.

2.2.1. Drive End Design Iteration#1

The drive end A-Stand shaft was designed in this first iteration to retract from the welding fixture yoke. This allows for a quick change between welding fixtures because it eliminates moving entire drive end A-Stand to pull shaft out of welding fixture yoke. Drive end iteration #1 is shown in the following Figure 7.

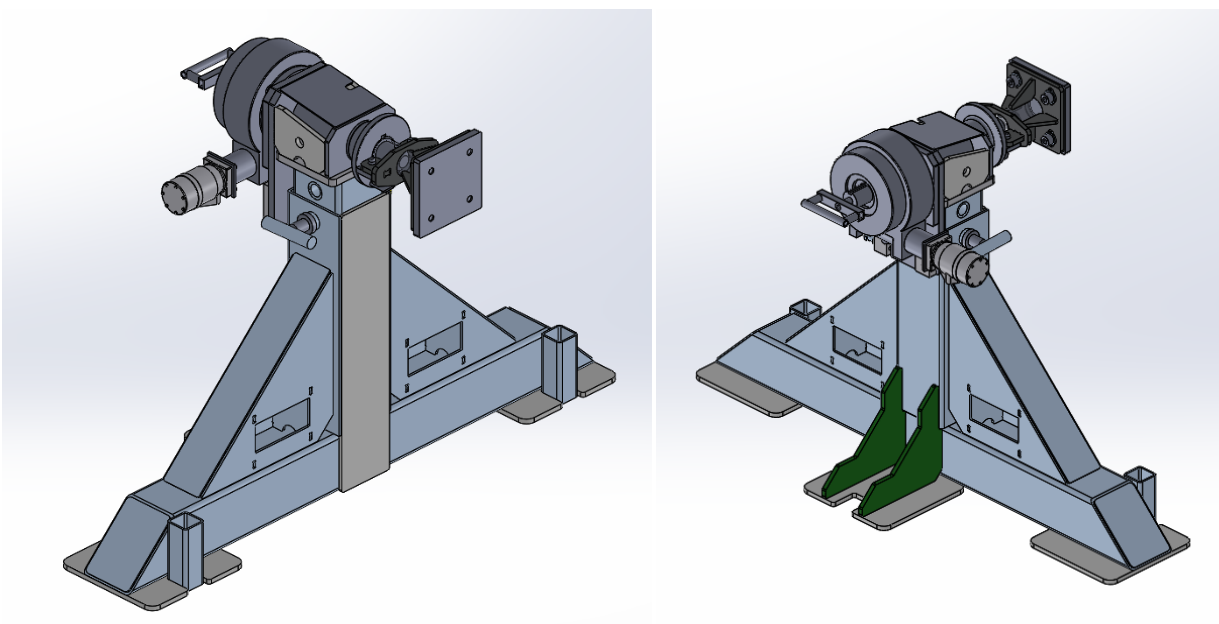


Figure 7: Drive End Iteration #1

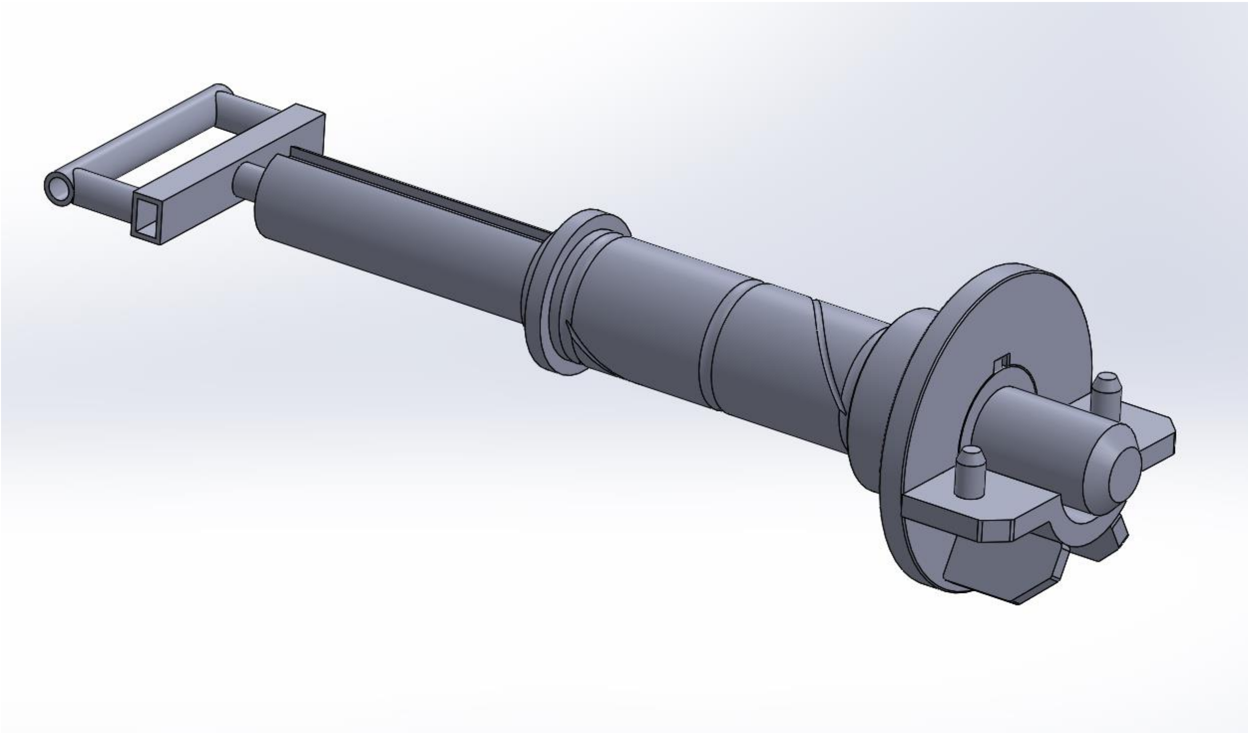


Figure 8: Drive End Iteration #1, Retractable Shaft Assembly

Figure 8 shows the retractable shaft assembly. The shaft assembly reuses current drive end A-Stand support housing and gearbox to be housed. The major differences between iteration #1 shaft assembly and current A-Stand shaft is that it is divided into two main components now. They are the retractable shaft and shaft sleeve.

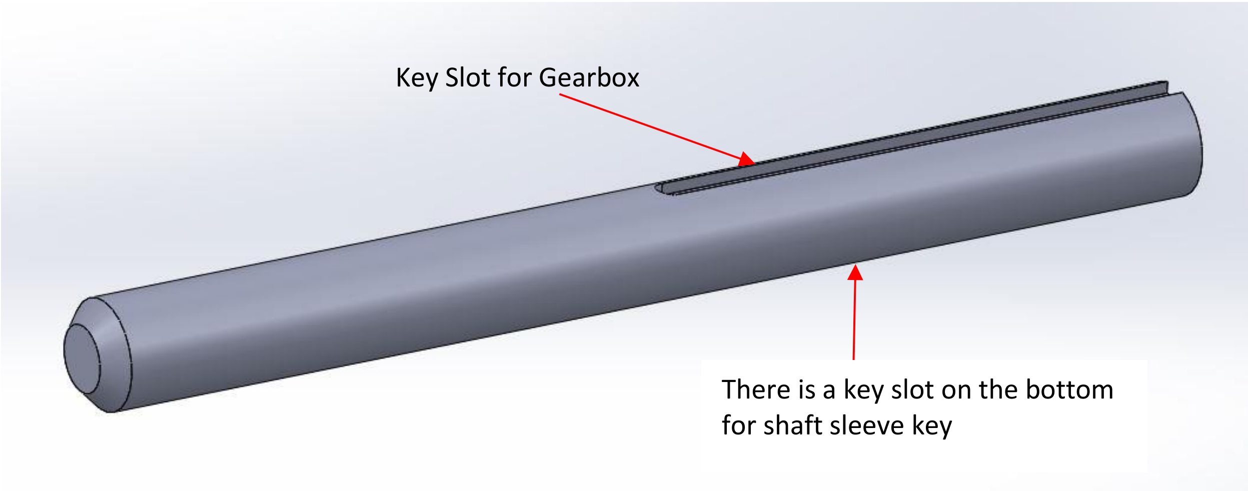


Figure 9: Drive End Iteration #1, Retractable Shaft

Figure 9 is the retractable shaft and contains two key slots on the top and the bottom. The top keyway slot is to connect with the hydraulic gearbox key, and the bottom keyway slot is to connect with the shaft sleeve. Both the top and the bottom keyway slots are extended longer than the actual key length so that the shaft can retract.

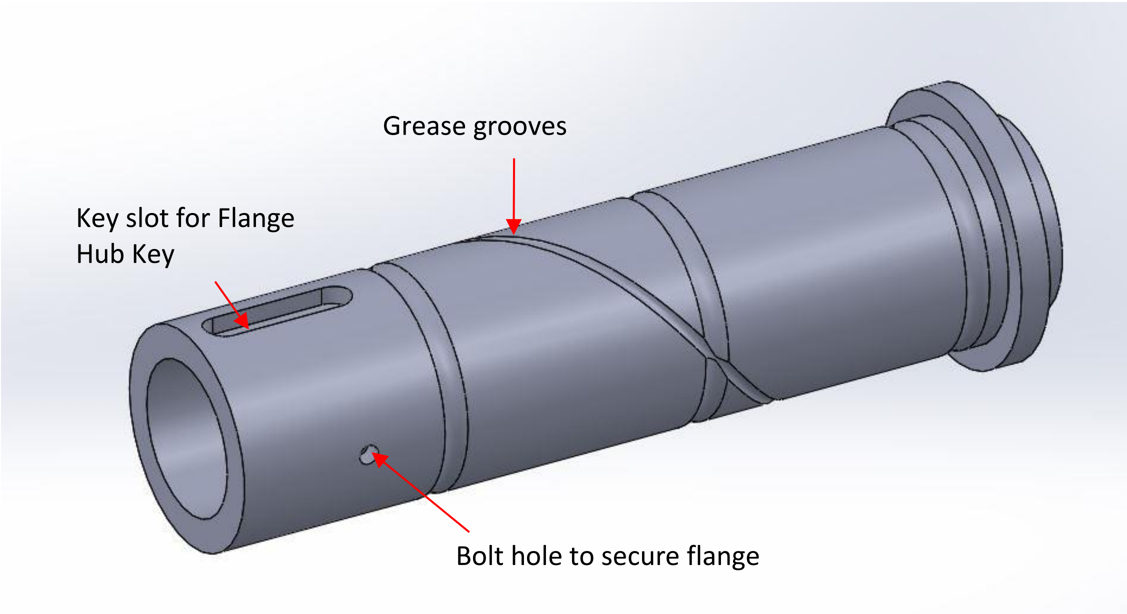


Figure 10: Drive End Iteration #1, Shaft Sleeve

Figure 10 shows the shaft sleeve of the drive end iteration #1. The sleeve maintains the same dimensions so that the support tube of the A-Stand remains the same. The sleeve also maintains the same grease grooves of the existing design, so lubrication method does not change as well. The left end of the shaft sleeve shown in Figure 10 is where the flange hub is connected using key slot and bolt.

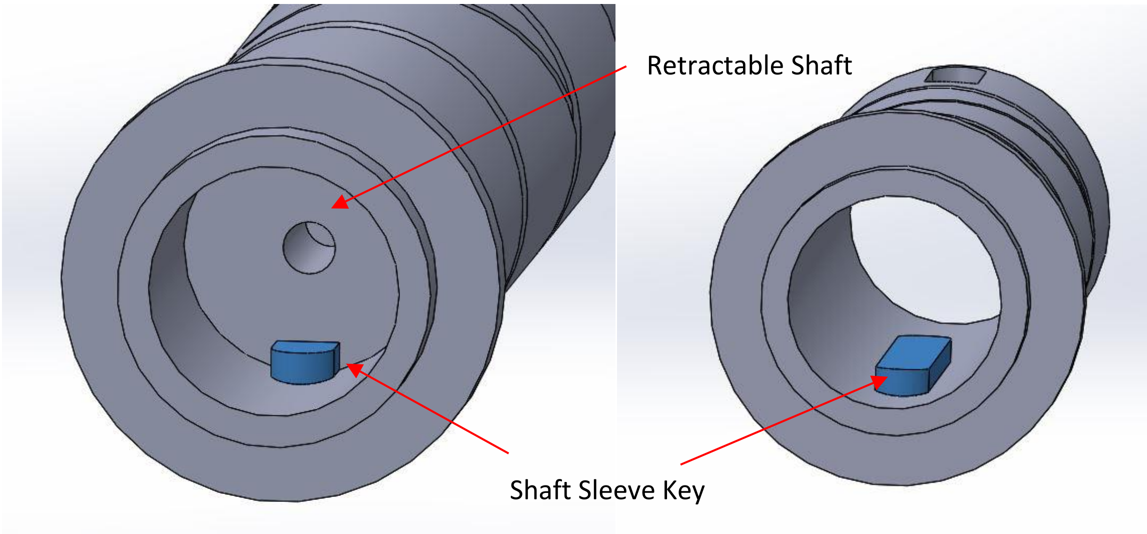


Figure 11: Drive End Iteration #1, Outboard Side of Shaft Sleeve

Figure 11 shows the outboard side of the shaft sleeve and the internal shaft sleeve key which as highlighted in blue. The internal key is used so that the shaft sleeve rotates with the shaft. The retractable shaft is driven by the gearbox and therefore drives the shaft sleeve.

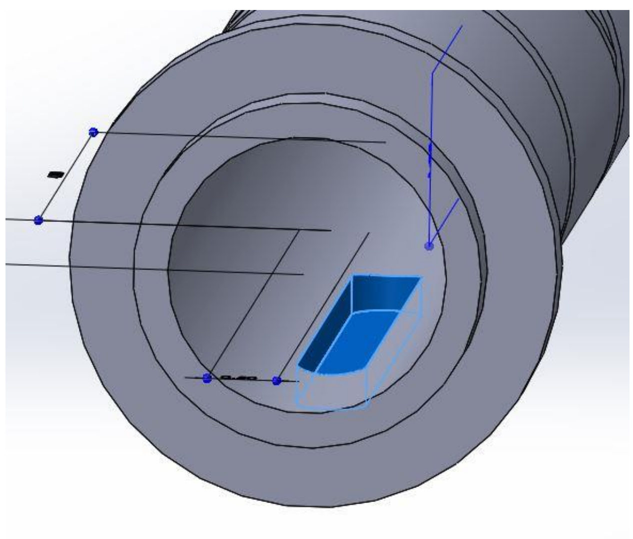


Figure 12: Drive End Iteration #1, Shaft Sleeve Internal Key Slot

From Figure 12, the internal key slot of the sleeve is highlighted in blue. It does not cut all the way to the outboard end of the shaft sleeve so the internal shaft sleeve key stays in one spot. This makes the key act as a stopping mechanism to prevent the shaft from being pulled all the way during the welding fixture changeover.

Current problem with this design is the difficulty in machining this feature. From research in manufacturing techniques, this feature is very expensive and might not be feasible.

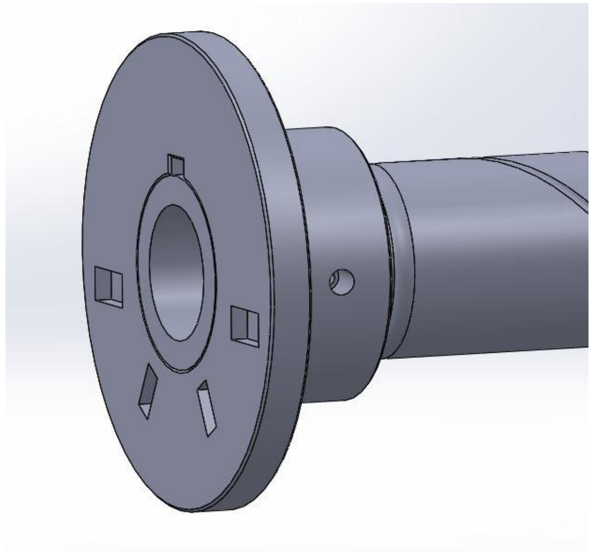


Figure 13: Drive End Iteration #1, Flange Hub

The flange Hub is shown attached to the A-Stand shaft sleeve with a key and a bolt in Figure 13. There are cut-outs on flange face to attach the flange hub cup. The flange hub cup is used to allow the welding fixture to be lowered onto the A-Stands. There are two locating pins welded onto the cup which helps aligning the welding fixture and provide rotation. This flange assembly is shown in Figure 14.

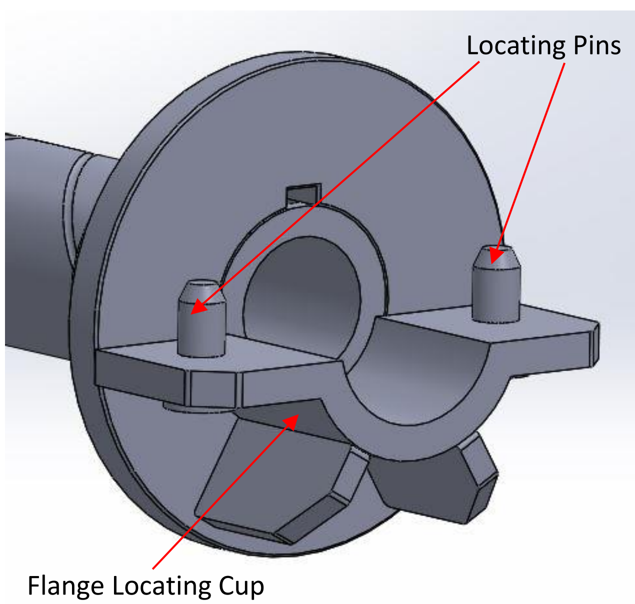


Figure 14: Drive End Iteration #1, Flange Hub and Flange Locating Cup

The dimension of the locating pins and the cup match with the current welding fixture yoke, so that the current yokes can be reused. Figure 15 and Figure 16 show the retractable shaft assembly applied to the hydraulic powered drive end A-Stand, with the A-Stand shaft as shown in blue color, engaged and disengaged with the welding fixture yoke, respectively.

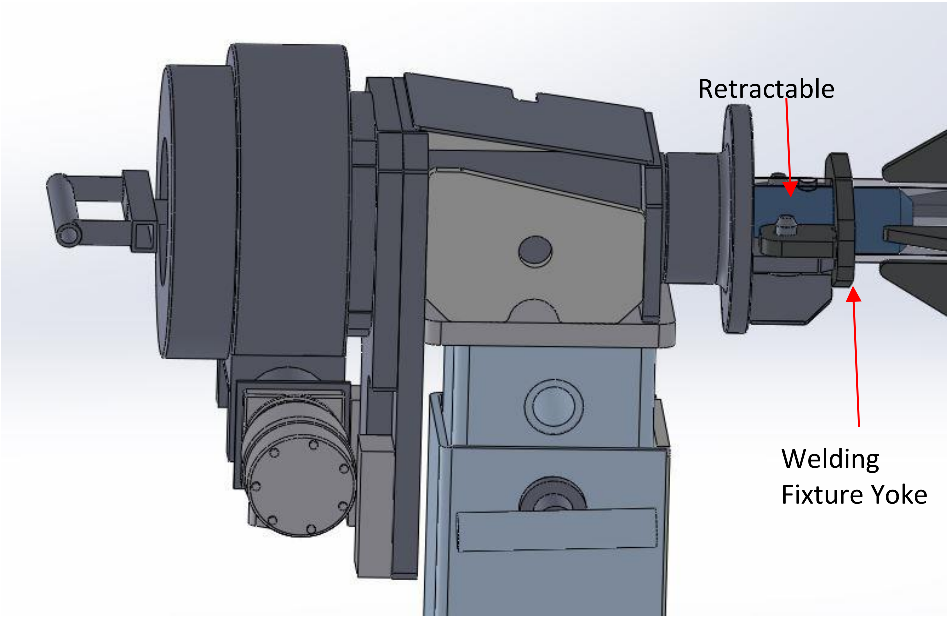


Figure 15: Drive End Iteration #1, Retractable Shaft Engaged with the Welding Fixture

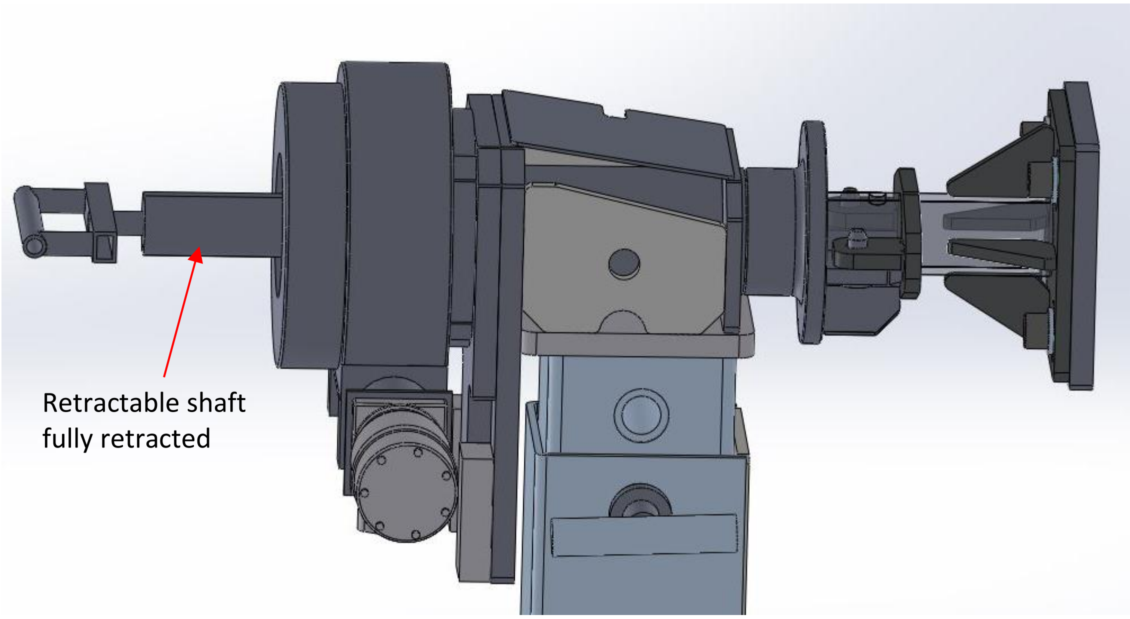


Figure 16: Drive End Iteration #1, Retractable Shaft Disengaged with Welding Fixture Yoke

Another problem with this iteration is the key used for the retractable shaft and the gearbox. There is no mechanism to prevent key from sliding out with the shaft when retracted from the welding fixture yoke, which can be seen in Figure 17.

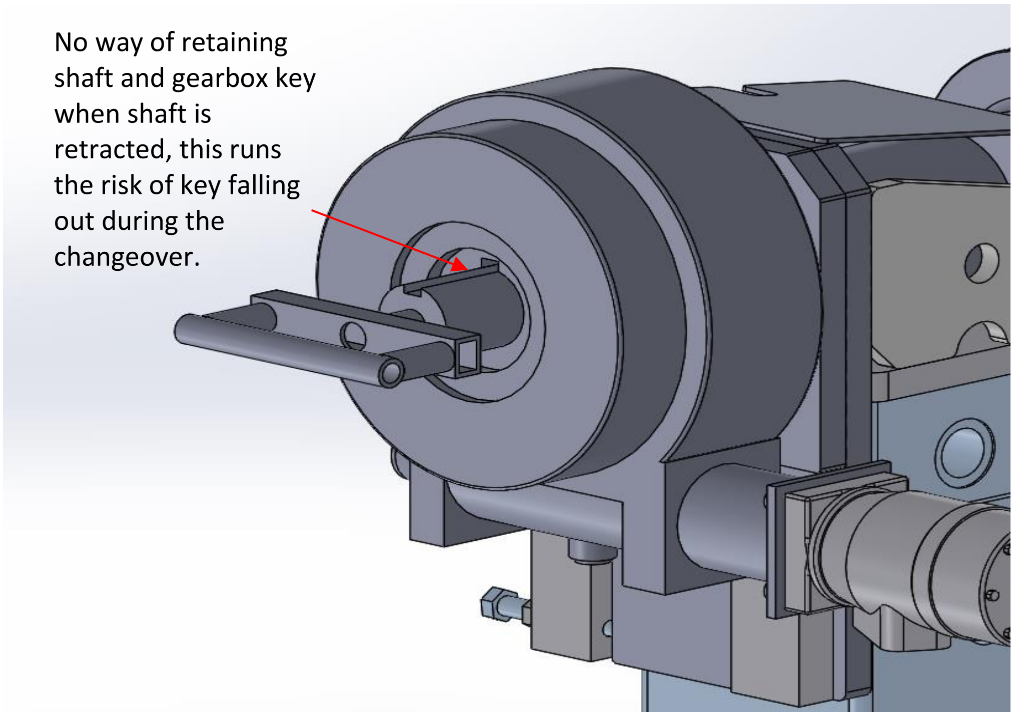


Figure 17: Drive End Iteration #1, Gearbox and Retractable Shaft

In this iteration, troubles in determining solution to eliminate the resistance when retracting the shaft due to friction between the shaft, the shaft sleeve and the gearbox. There is little to no room to add linear bearings on the shaft sleeve to reduce the friction between the sleeve and the shaft. Current solution is adding grease grooves on the shaft, so grease can be used to reduce friction. However, this exposes grease to the environment when shaft is retracted, allowing risk of grease becoming contaminated with dirt. Over time, the grease will get dirty enough where a gritty substance is created causing wear between the shaft and the sleeve.

2.2.2. Drive End Design Iteration#2

For the iteration #2 of the drive end of the hydraulic powered A-Stand, main changes were on the shaft sleeve and the retractable shaft. The shaft sleeve and the retractable shaft was redesigned to solve the problem in machining the internal key slot in the shaft sleeve which was shown in Figure 12. The redesign of the shaft sleeve and the retractable shaft also fixed the problem where the gearbox and the shaft key falling out when shaft is retracted which was shown in Figure 17. Figure 18 shows the hydraulic powered drive end A-Stand iteration #2.

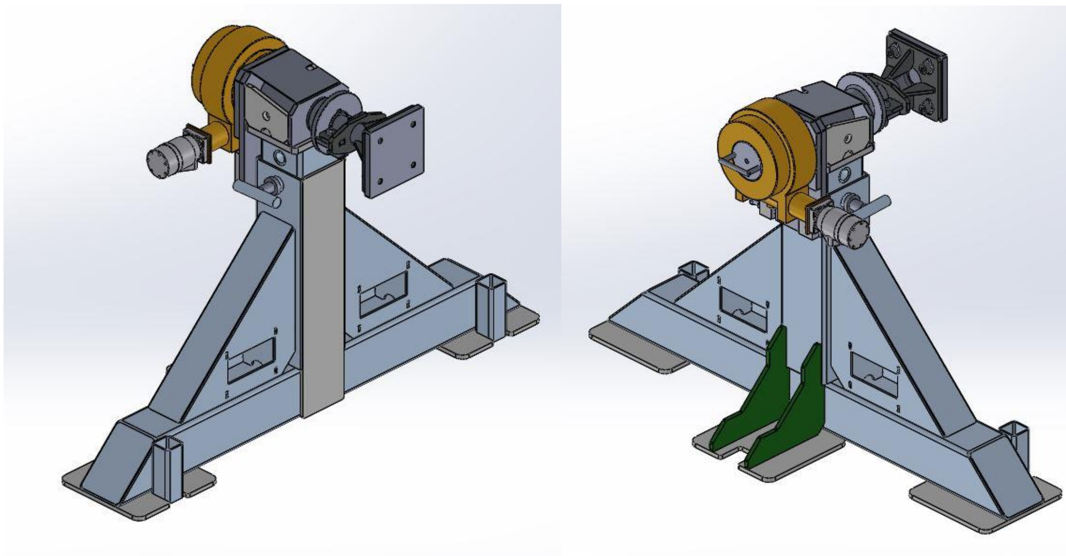


Figure 18: Drive End Iteration #2

Figure 19 shows the second iteration of the retractable shaft assembly for the drive end. When compared externally with the first iteration, which was shown in Figure 8, the changes can be seen. First is the handle for the retractable shaft. Secondly, the shaft sleeve has been extended now all the way to the shaft handle.

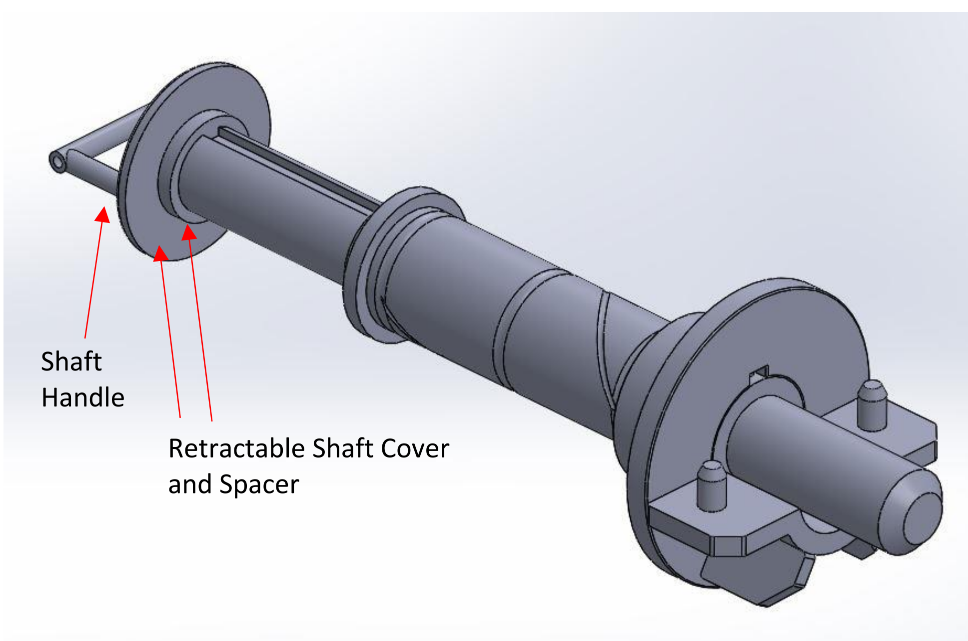


Figure 19: Drive End Iteration #2, Retractable Shaft Assembly

The handle was redesigned so that manufacturability and assembly is easier by using less parts and using the same stock rods. Iteration two uses a standard rod throughout the handle portion with dimensions of: 0.50 [in] outer diameter (OD) and 0.26 [in] inner diameter (ID). The handle is then welded onto the retractable shaft cover as illustrated in Figure 19. The retractable shaft cover and the spacer is used to match internal stepped profile of the gearbox to prevent the shaft from sliding out from inboard side.

Changes to the retractable shaft assembly were made externally and internally. Externally, the shaft sleeve was extended so that the key to transfer rotational drive from gearbox is now applied to the shaft sleeve and not the retractable shaft like in the first iteration. Internally, the shaft sleeve was given an internal shoulder as the retractable shaft was given an external shoulder to act as the stopping mechanism to prevent the shaft from being pulled all the way out when retracted. This shoulder feature is shown in Figure 20.

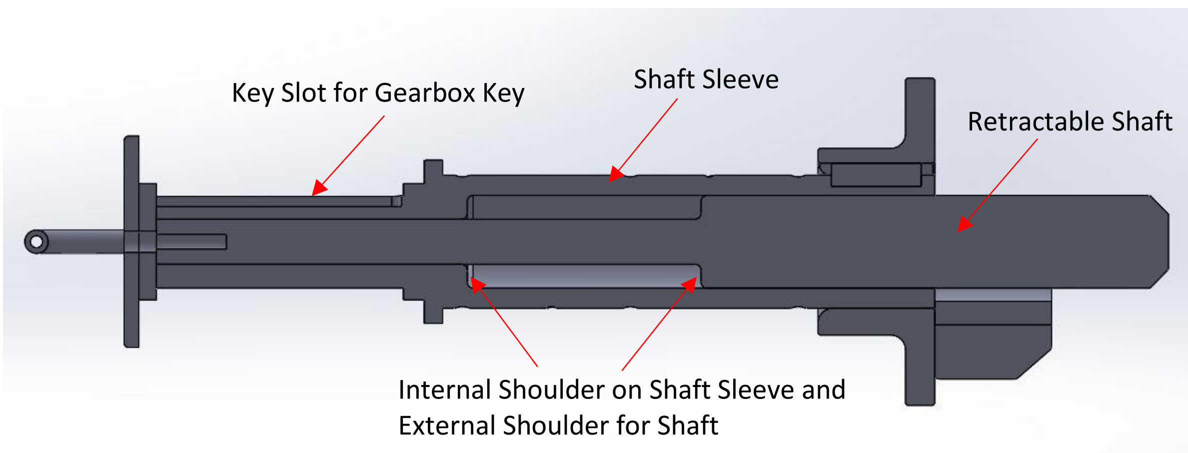


Figure 20: Drive End Iteration #2, Retractable Shaft Assembly, Cross-Sectional View

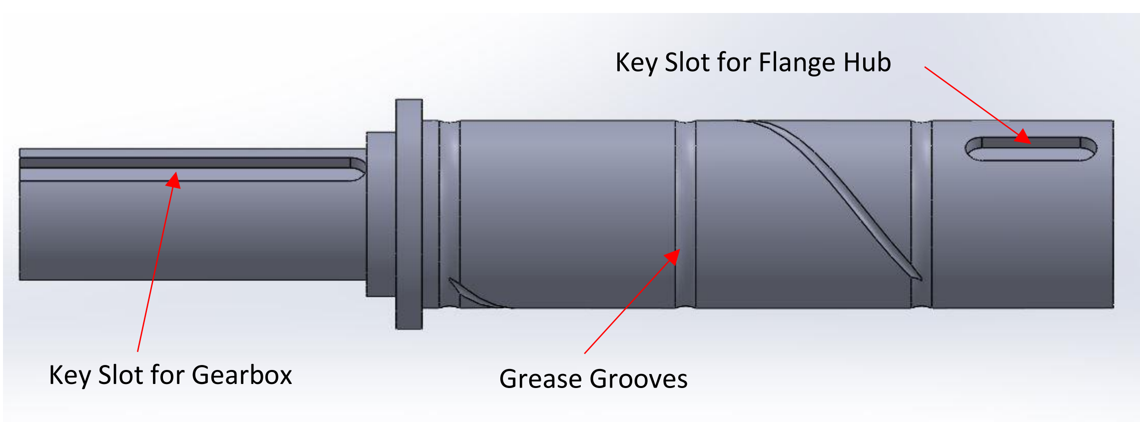


Figure 21: Drive End Iteration #2, Shaft Sleeve

The shaft sleeve of the second iteration of the drive end shaft assembly uses same dimensions as first iteration of the shaft sleeve until the gearbox portion. This portion of the shaft sleeve was added in this second iteration. The gearbox portion of the shaft sleeve matches with the internal dimension of the gearbox, so that the current gearbox can be reused. Same grease grooves are used from current shaft design for lubrication, as shown in Figure 21.

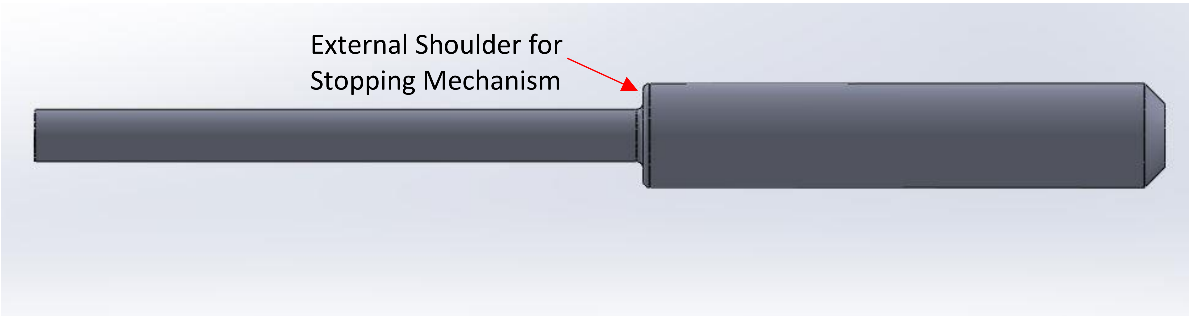


Figure 22: Drive End Iteration #2, Retractable Shaft

Figure 22 shows the profile of the retractable shaft for the second iteration of the drive end. The external shoulder can be seen in Figure 22 and it acts as a stopping mechanism to prevent the shaft from being pull all the way during the retraction. The largest diameter of the shaft is two inches to match with the current welding fixture yoke so that they can be reused. The smallest diameter of the shaft is one inch.

The retracting mechanisms of the shaft remains the same as the first iteration as shown in Figure 15 and Figure 16. A cross-sectional view of the shaft assembly when the shaft fully retracted can be seen in Figure 23.

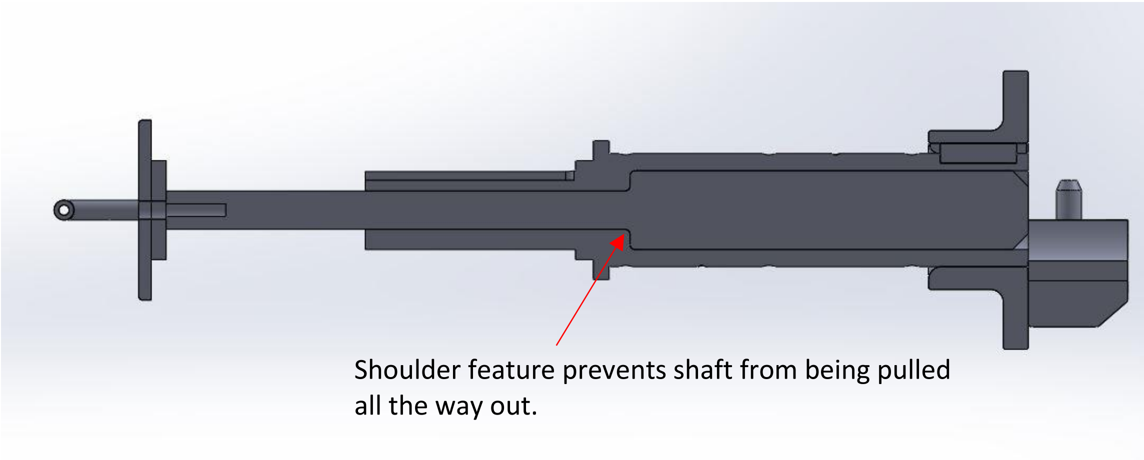


Figure 23: Drive End Iteration #2, Shaft Assembly Fully Retracted

The second iteration of the drive end iteration solves the internal key slot machining problem on the shaft sleeve and the risk of the gearbox key from sliding out during the retraction of the shaft in the first iteration. However, this iteration still faces the problem with the internal friction between the shaft and the sleeve which makes the sliding shaft difficult. In this iteration, grease will still be used between the shaft sleeve and the shaft as in the first iteration.

2.3. Idle End

In this section, the iteration processes that were performed to optimize the idle end of the A-Stands will be explained. The first iteration is to optimize the design that can possibly meet the client needs, and the second iteration is performed to simplify the design.

2.3.1. Idle End Design Iteration #1

Based on the retractable shaft concept, the first design iteration of the idle end was generated. The design overview is illustrated in Figure 24.

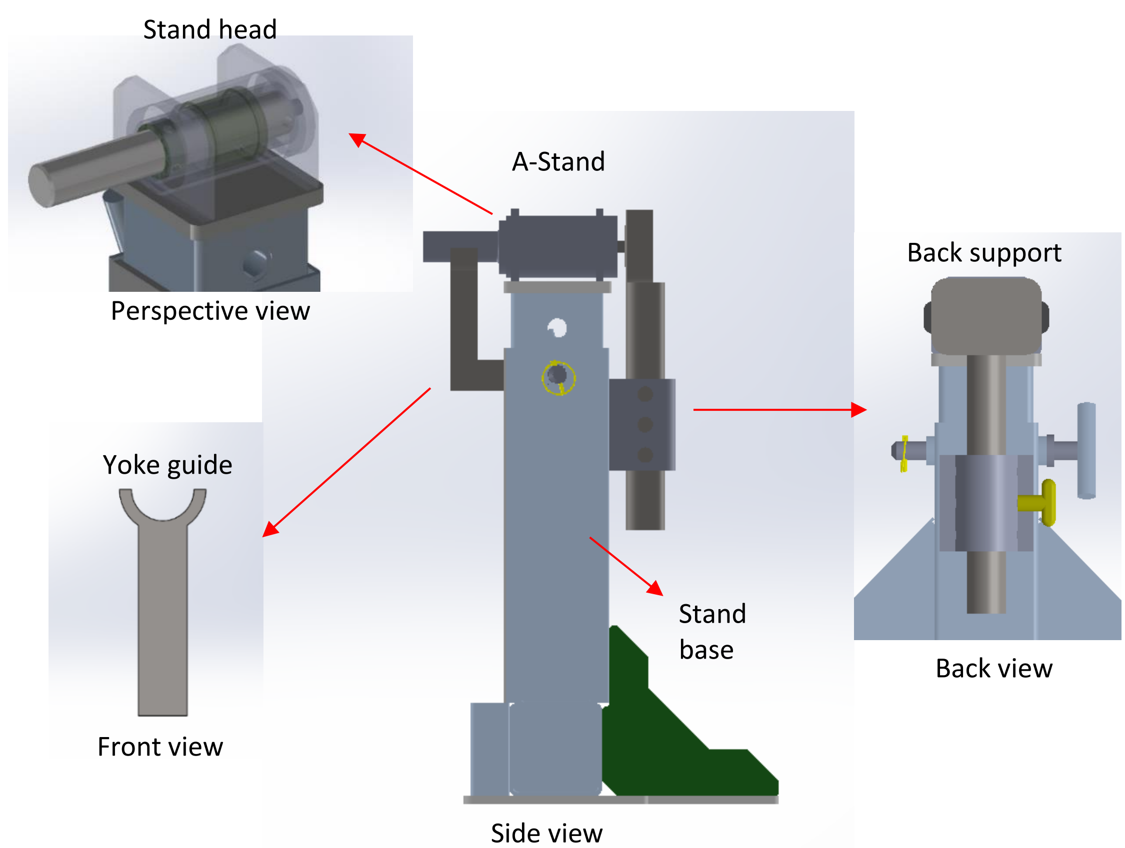


Figure 24: Overview of A-Stand Idle End Design Iteration #1

The design primarily consists of three sections: a stand head, a yoke guide and a back support. The A-Stand base remains the same as the existing design.

The details of the stand head design are shown in Figure 25. The design primarily consists of a solid shaft, an inner housing, an outer housing, a rotary-motion ball bearing and a linear-motion ball bearing. The concept of this design is to use two different types of bearings to allow the shaft for both retracting and rotating motions.

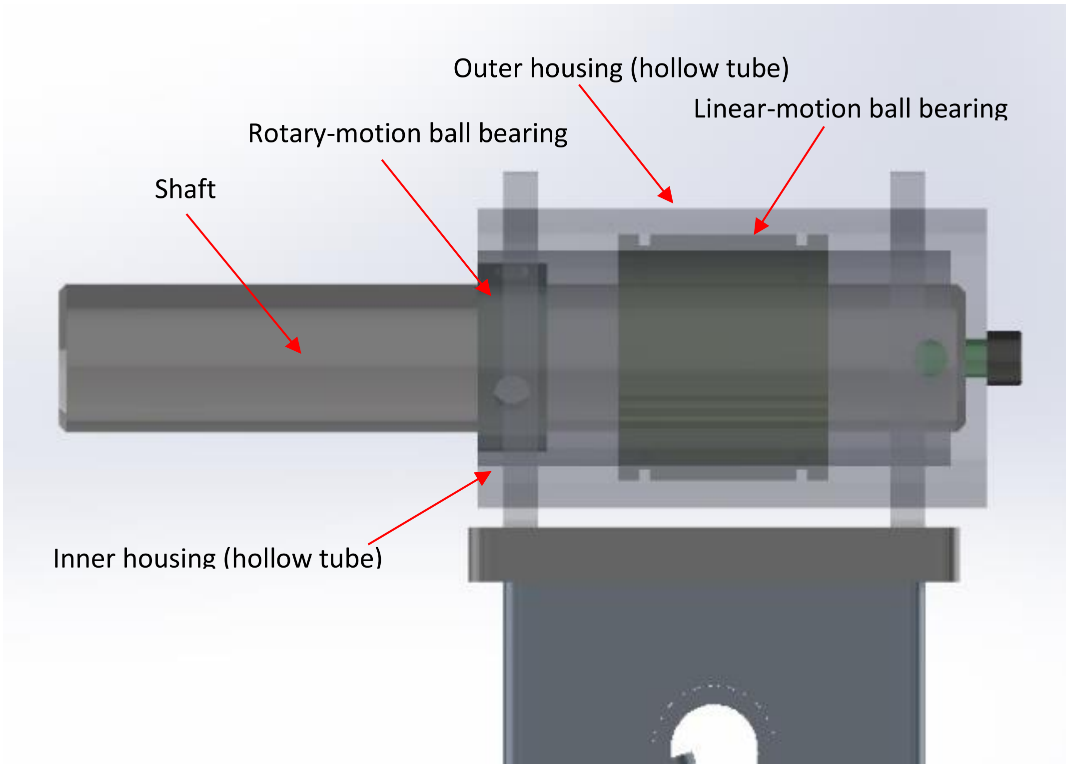


Figure 25: Details of Stand Head of the A-Stand Idle End Design Iteration #1

The rotary-motion ball bearing is placed in between the solid shaft and the inner housing. The linear-motion ball bearing is placed in between the inner housing and the outer housing. The linear-motion ball bearing enables the shaft together with the inner housing to smoothly slide in the outer housing when being retracted.

Both the inner housing and the outer housing are designed to be hollow tubes. The outer housing is fixed on the A-Stand base, while the inner housing will move with the shaft. As shown in Figure 26, the inner housing moves with the shaft when the shaft is being retracted.

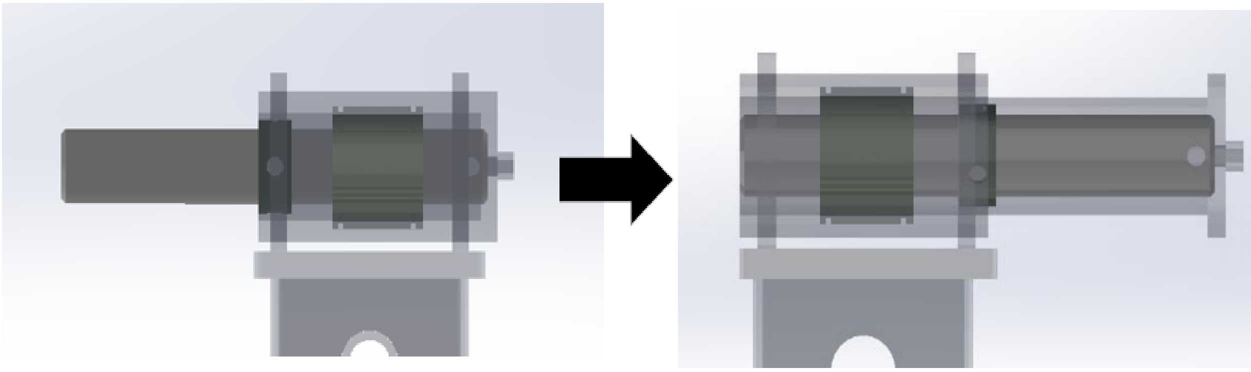


Figure 26: Retracting Motion of A-Stand Idle End Design Iteration #1

The feature of a yoke guide is designed to ease the aligning process during the changeover. The yoke guide is designed as a cup shaped support that is attached to the A-Stand base. The inner surface of the yoke guide cup is designed to be aligned with the shaft. As long as the yoke is placed on the guide, the operators can accurately slide the shaft into the yoke. A close view of the fixture yoke stands on the yoke guide coupling with the shaft is shown in Figure 27, and the fixture yoke is shown in transparent in the figure.

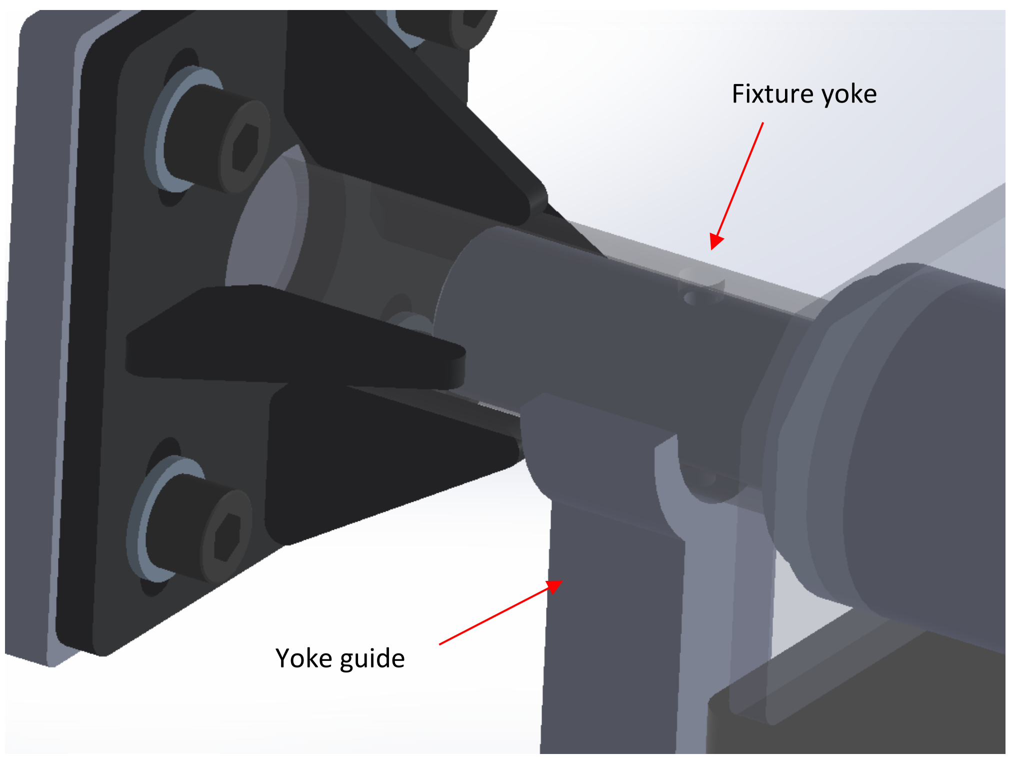


Figure 27: Coupling of the Fixture Yoke and Yoke guide in Idle End Design Iteration #1

In addition, a back-support feature is designed to prevent the shaft from moving in the axial direction. Although there should be minor axial force acting on the shaft when the A-Stand is in use, the back support is added to the design as a safety feature. It prevents the shaft from sliding in the housing. The support is a rigid support piece welded on the top of a tube. The height of the back support can be adjusted by using a quick release pull pin. The support will be retracted downwards when the shaft needs to be pulled out and lifted back in place to prevent the shaft from sliding. The retracting motion is shown in Figure 28.

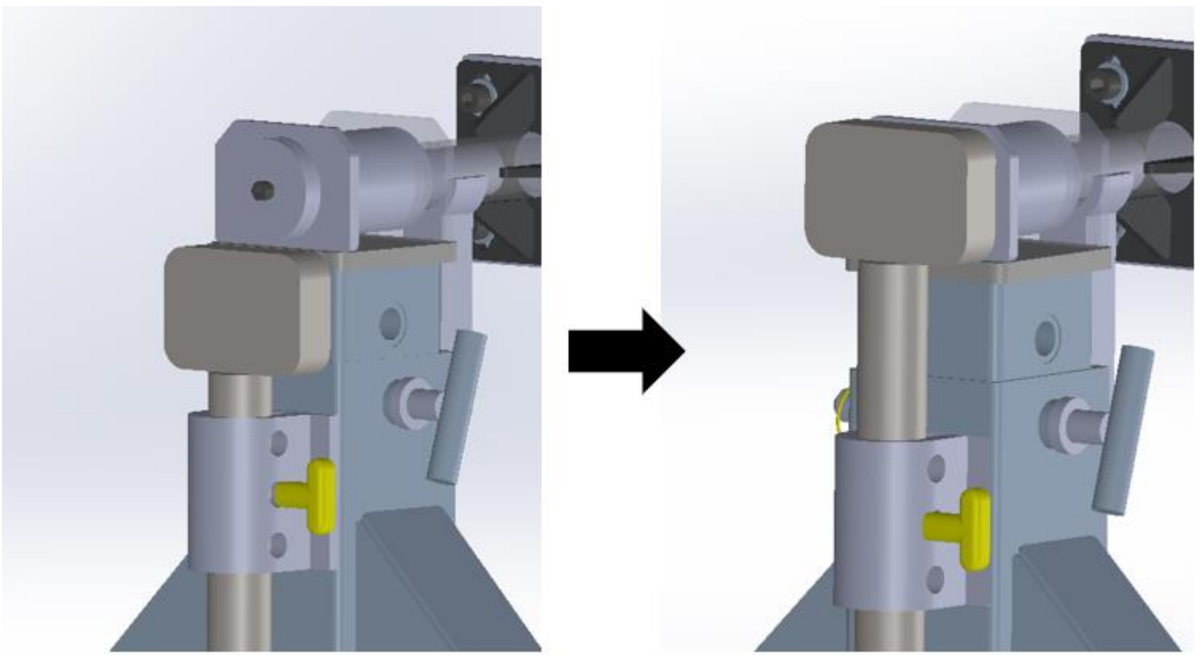


Figure 28: Retracting Motion of the Back Support in Idle End Design Iteration #1

2.3.2. Idle End Design Iteration#2

The second design iteration on the idle end is built on the same concept used in the first iteration. The primary optimization is that the second iteration integrates all the features into less parts. The details of the optimized design are shown in Figure 29.

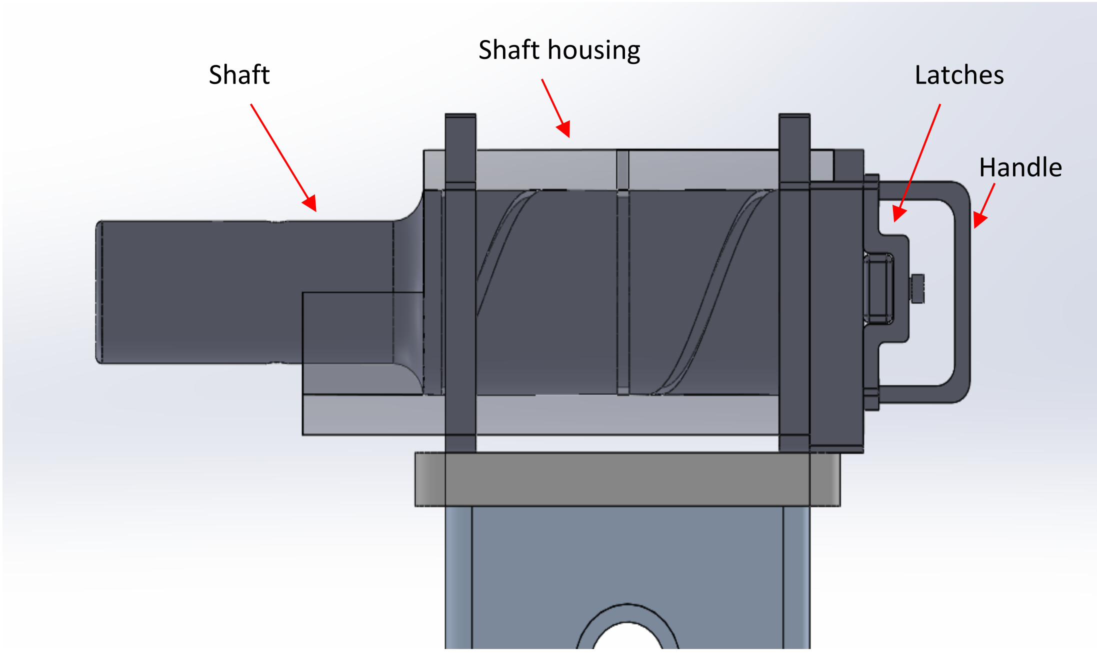


Figure 29: Overview of A-Stand Idle End Design Iteration #2

The design primarily consists of a shaft, a shaft housing, a handle and two latches. The shaft is designed to be a solid step-down shaft with groove spread over the thicker portion. Such design concept is the shaft used in the existing A-Stand. The grooves are used to contain grease lubricant. The grease decreases the friction between the shaft and the shaft housing, easing the retracting and rotating motion. As shown in Figure 30, the grooves consist of three circular grooves and a helical groove along the shaft body. Such design enables the grease to penetrate evenly over the shaft.

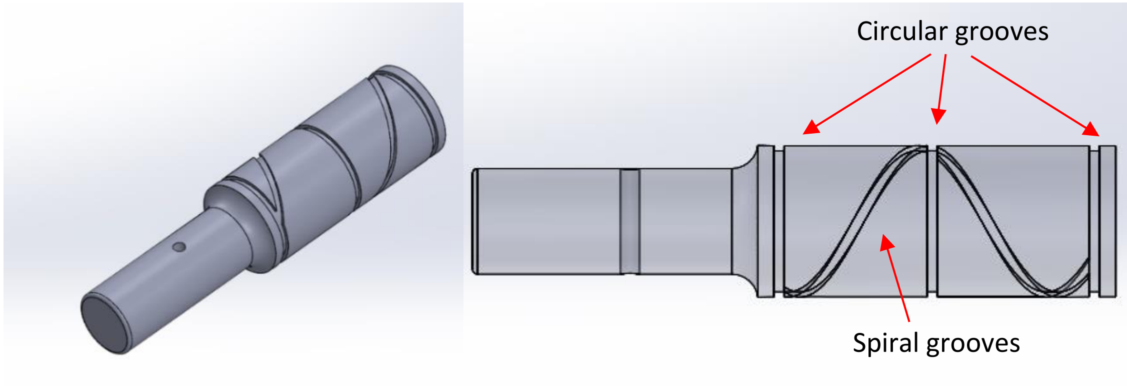


Figure 30: Details of the Shaft Design in A-Stand Idle End Design Iteration #2

Since the functionality of the A-Stand does not require the shaft to rotate continuously or slide frequently, the grease will provide sufficient smoothness to reduce the friction. Compared to using bearings, such feature is more economic and easier to replace. The direct validation of such feature is that it is used in the existing A-Stand and it worked well.

The new shaft housing features a one-piece self-aligning structure that combines the housing and the yoke guide together. It is a one-piece hollow tube with a cut out at one end. As shown in Figure 31, the portion of the housing highlighted in yellow is in a simple hollow tube structure, and it functions as a housing to fix the shaft. The portion in green is the half-cut portion, functioning as an aligning yoke guide. Compared to design iteration#1, this design eliminates the need for an additional add-on yoke guide.

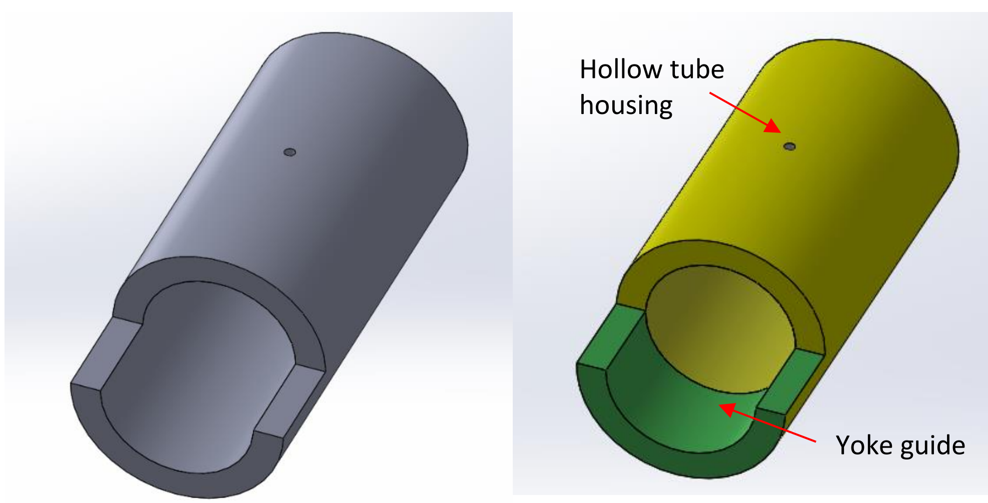


Figure 31 Details of the Shaft Housing Design in A-Stand Idle End Design Iteration #2

The inner diameter of the housing is designed to accommodate the fixture yoke. When the fixture yoke is placed on the housing as shown in Figure 32 , the yoke is automatically aligned with the shaft. Such feature greatly reduces the difficultly in aligning and coupling the fixture yoke to shaft in a changeover.

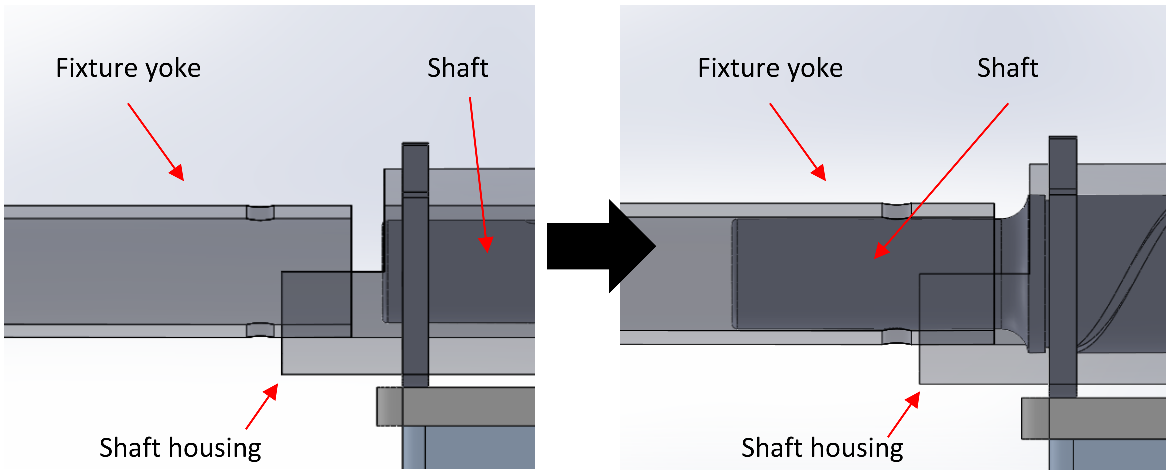


Figure 32: Illustration of Coupling Fixture Yoke to Shaft with Shaft Housing, Side View

Moreover, instead of the add-on back support in design iteration #1, two slide latches are used to secure the shaft in this design. Latches are small and easy-to-use tools that are widely used in various applications. Compared to the back support in design iteration#1, the latches are more economic, user-friendly and easier to accommodate in the design. They can be attached on the plate that goes around the shaft housing as shown in Figure 33. The spacing blocks are used to align the latches to the back side of the shaft.

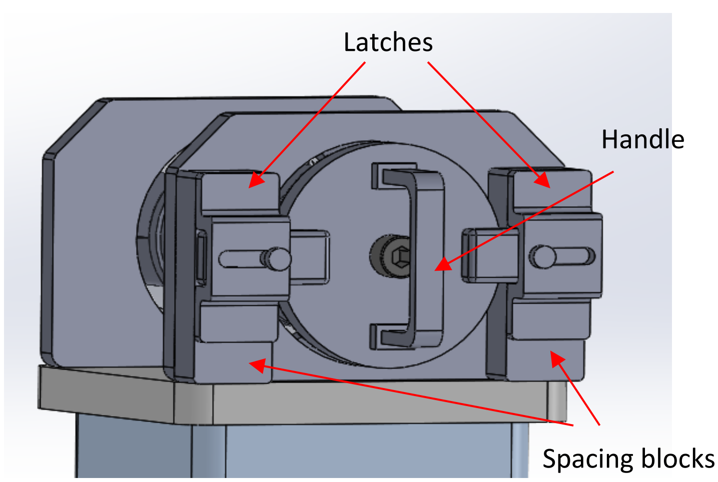


Figure 33: Details of Latches in A-Stand Idle End Design Iteration #2

A simple handle is also added to the design (shown in Figure 33) for better operator ergonomic, as it provides secure grip and eases the retracting motion.

As shown in Figure 34, the latches lock the shaft in the housing when it is supporting the welding fixture and unlock the shaft when a fixture changeover is needed.

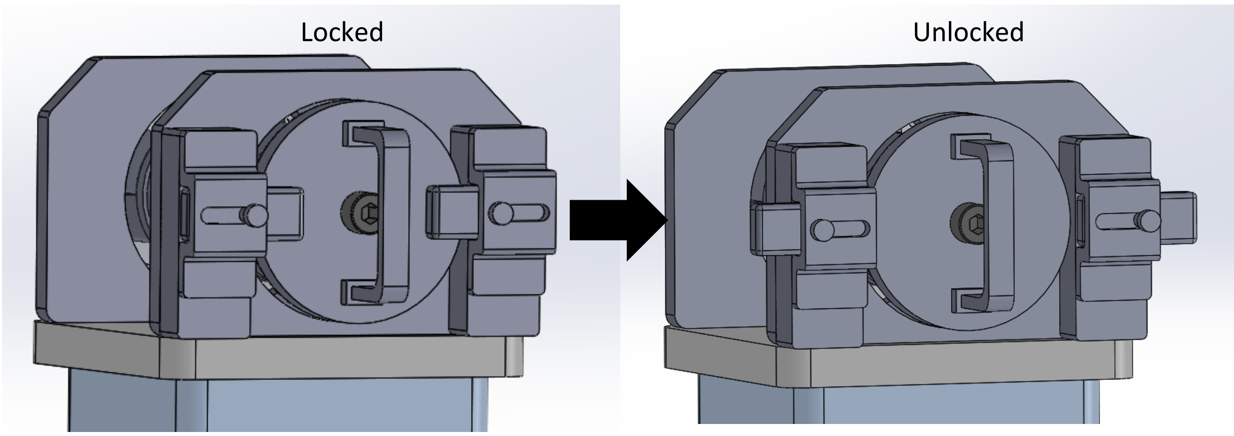


Figure 34: Illustration of latches' locking and unlocking in A-Stand Idle End Design Iteration #2

Once the shaft is unlocked, the operator can retract the shaft as shown in Figure 35, thereby to decouple it from the fixture yoke.

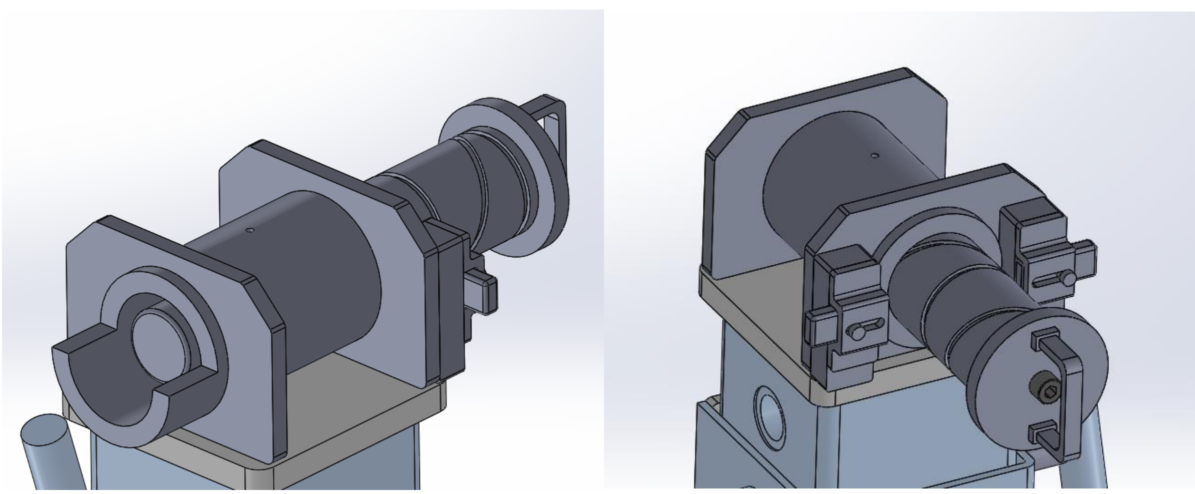


Figure 35: Illustration of a Retracted Shaft in A-Stand Idle End Design Iteration #2

2.4. Further Design Optimization

To further develop the design, preliminary FMEA (Failure Mode and Effect Analysis) was performed as an optimizing process. It helps identifying potential failures and preventing them. The details of the FEMA are shown in Table BI and Table BII in Appendix B.

According to the FMEA performed, it can be summarized that tipping over and exposing grease are the two primary issues for both the drive end and idle end designs. A-Stands' tipping over induced by unbalanced support can lead to serious personal injury or property damage. The existence of exposed grease will result in multiple undesired circumstances on the shop floor, such as grease catch on fire, grease get contaminated and dirty the work place. Moreover, the idle end's shaft housing cup can experience significant wear over time. As a result, inboard support legs and oil-embedded rings will be added to both ends. In addition, a layer of anti-wear material will be added to idle end's yoke guide.

2.4.1. Inboard support legs

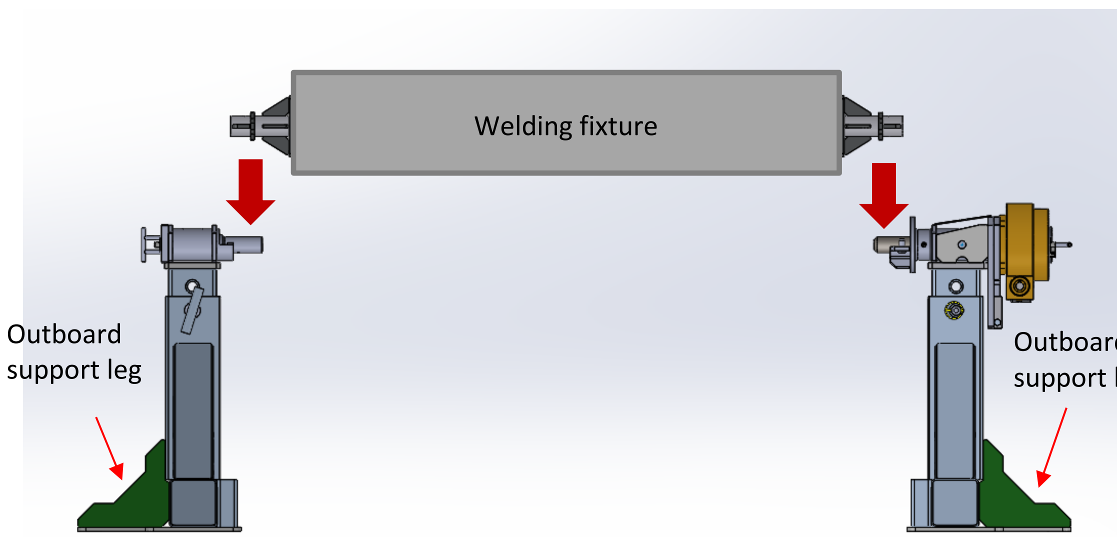


Figure 36: Illustration of Lowering Welding Fixture Vertically on A-Stands

According to the iterative design result, both A-Stand ends will utilize retractable shafts to perform a quick welding fixture changeover. By using such approach, the welding fixture can be vertically placed on the A-Stands as shown in Figure 36. It greatly simplifies the welding fixture changeover process. Meanwhile, it causes an issue that the A-Stands are now likely to tip over inwards as there is no inboard supports. To solve the issue, inboard support legs will be added to the final design for providing balanced supports.

2.4.2. Oil-embedded sleeve bearing

An oil-embedded sleeve bearing is a porous bronze bearing that will release a thin layer of oil on the bearing's surface when in use [1]. The principle behind the oil-embedded bearing is that the bearing layer will transfer a small amount of material to form a lubricating film that directly in contact with the moving parts [2]. As shown in Figure 37, the pink area represents the lubricating film.

[redacted]

Figure 37: Illustration of Oil-embedded sleeve bearing [3]

The lubricating film allows for a smooth movement as well as a longer life cycle of the moving component. Proper lubricating is critical to the oil-embedded bearings, especially for the initial run-in period if the bearing [2]. Compared to grease, oil has a much lower viscosity, which makes it easy to clean and less likely to get contaminated. The overflow of the lubricant is also less likely to be happened when using oil-embedded bearing, for the oil-film is almost too thin to overflow. In addition, it eliminates the needs for machining the grooves for grease on the shaft, which makes the design more cost-friendly and require less maintenance.

2.4.3. Delrin® Acetal Resin layer

Delrin® acetal resin is a highly engineered thermoplastic that is widely used in various industrial applications, especially for high load mechanical applications. It features properties of low friction, high wear resistance, high stiffness, high strength as well as a naturally slippery surface [4]. It is also available in various sizes and shapes, which makes it an ideal choice for the anti-wear material to be used in the design.

3. Final Design

After thorough and detailed iterating processes for both the drive end and the idle end of the A-Stands, the team was successfully able to come up with the final design that meets the target of this project. That is, improving the coupling action between the A-Stands and welding fixture yoke using the retractable shaft mechanism. In this section, detailed explanation of the final design for the A-Stand pair will be presented. Also, the proposed deliverables including; a preliminary stress analysis, a preliminary cost analysis, and validations of safety will be presented in this section.

3.1. Final Quick-Change A-Stand Design

This section presents the final design of the hydraulic powered A-Stands. Both the drive end and idle end incorporating the retractable shaft concept. The drive end and idle end are presented separately, and their component are shown in detail in their respective sub-section. Detailed drawings can be found in Appendix D.

3.1.1. Final Design Hydraulic Powered A-Stand Drive End

The final design of the drive end of the quick-change A-Stand with hydraulic power is presented in this sub-section. Compared to the current hydraulic powered drive end, the only changes made are; to the shaft, additional inboard support leg, and two safety latches attached onto the gearbox.

Both Figure 38 and Figure 39 show the drive end of the final design. The inboard side is the side where the welding fixture is connected to, and the outboard side is where the hydraulic gearbox (yellow colour in figures) is attached to, where the shaft handle is located. The shaft handle is used by the operator to provide a secure and easy grip and retract A-Stand shaft to allow disconnection from the welding fixture. The two safety latches can be seen on the side of the gearbox.

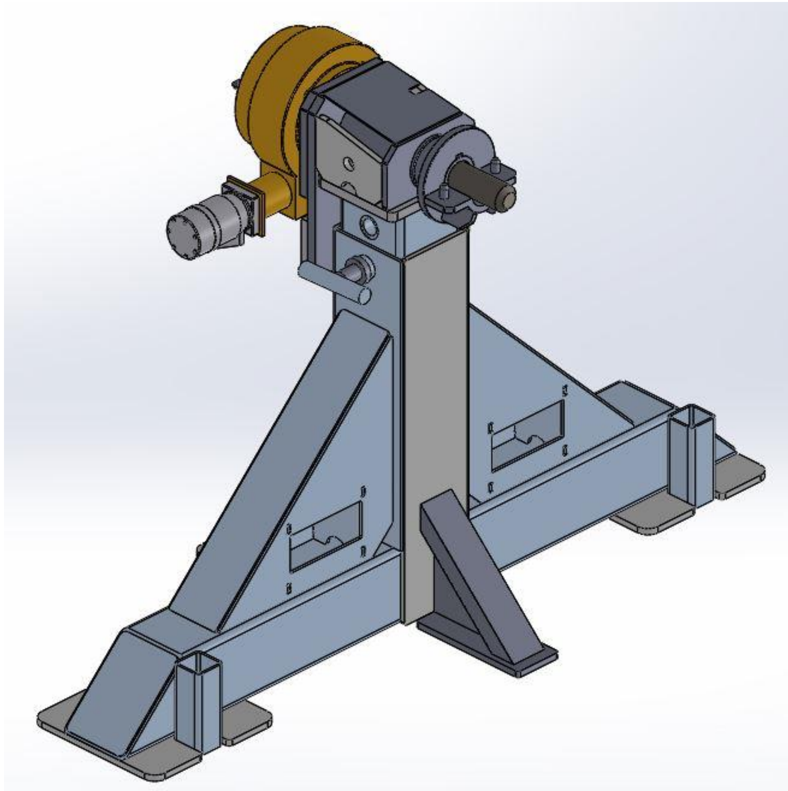


Figure 38: Final Design of Quick Change, Hydraulic Powered Drive End A-Stand, Inboard Side

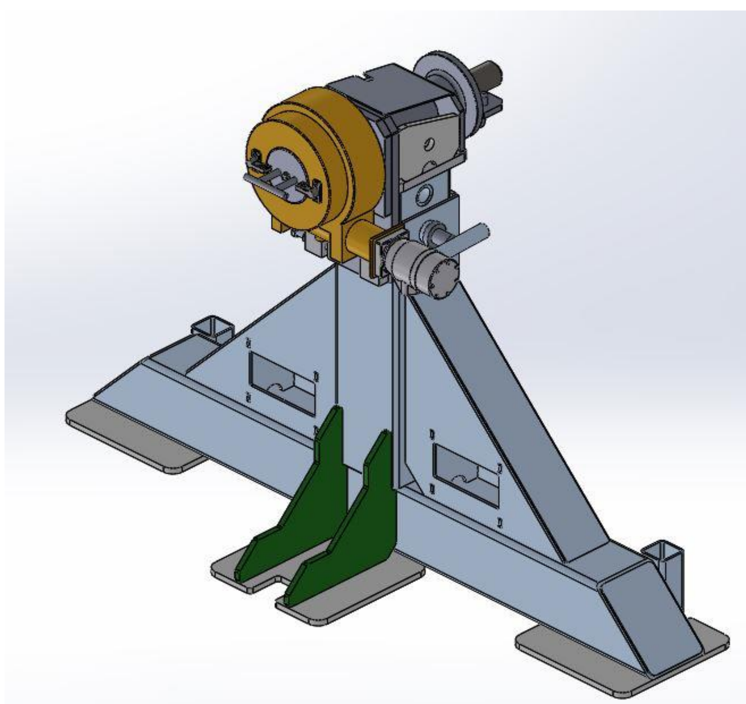


Figure 39: Final Design of Quick Change, Hydraulic Powered Drive End A-Stand, Outboard Side

From this point on in this section, the drive end of quick-change A-Stand with hydraulic power will now be referred to as the final drive end design. As the existing design of hydraulic powered A-Stand is now referred to as the existing drive end design.

The final drive end design features the team solution of a retractable shaft that allows for quick welding fixture changeover. This quick changing, retractable shaft mechanism is discussed further in detail in a later subsection of this final drive end design section.

First, this section will cover all the components of the final drive end design that are changed from the existing drive end design.

3.1.1.1. Final Design Drive End Shaft Assembly

The major change from the existing drive end design to the final drive end design is the design of the shaft. The final drive end design features a quick change, retractable shaft to allow a quick disconnection and connection to the welding fixture yoke as shown in Figure 40 and Figure 41.

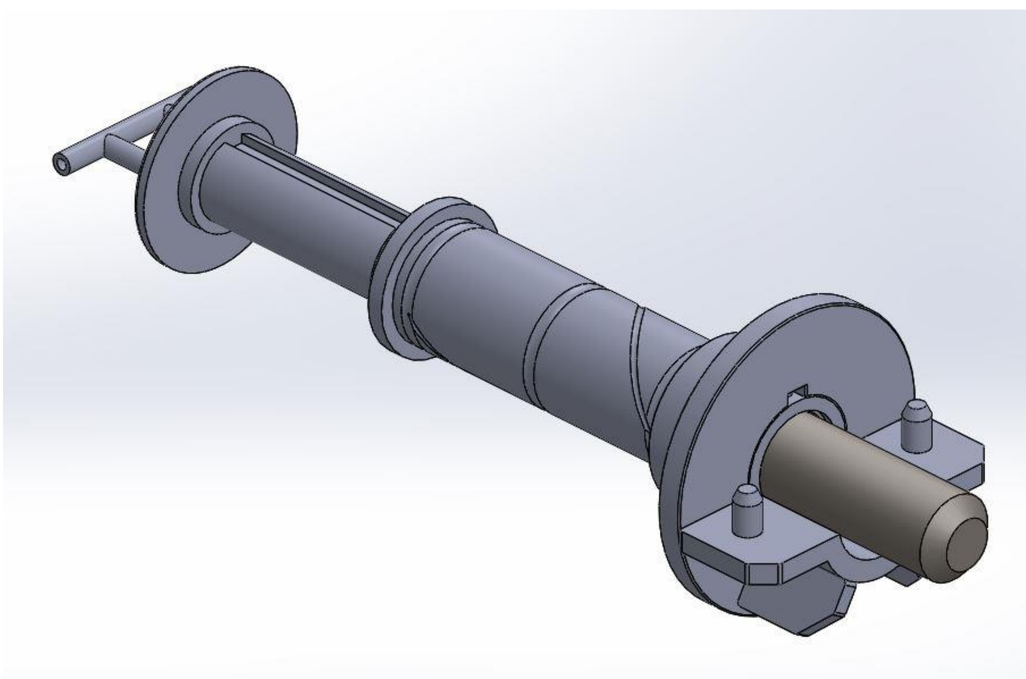


Figure 40: Final Drive End Retractable Shaft Assembly

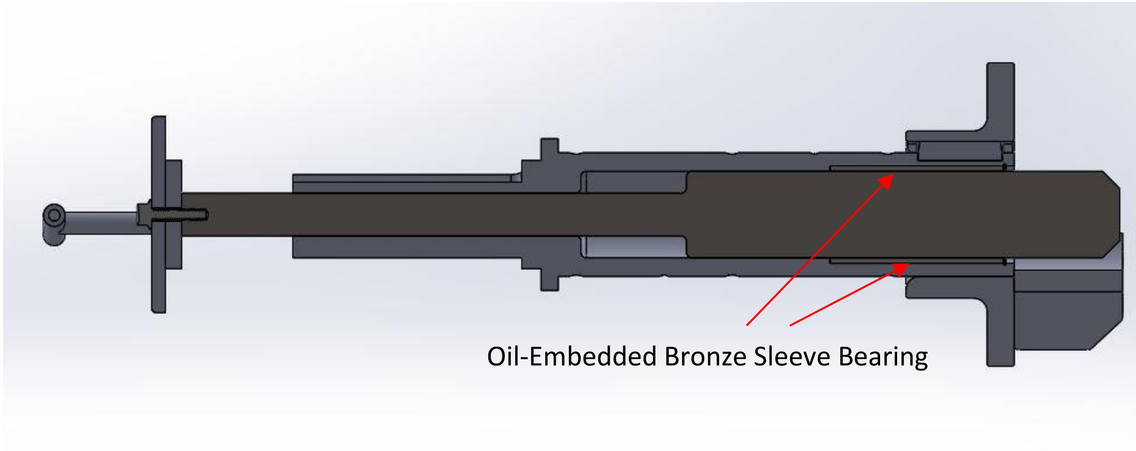


Figure 41: Cross-Sectional View of Final Drive End Retractable Shaft Assembly

The shaft from the current A-Stand design is separated into two main components in the final design. A sleeve that goes around the shaft which allows the shaft to retract, while a support tube housing of the A-Stand maintains the sleeve's position.

This shaft in the existing drive end is now split into two main components in the final drive end design shaft assembly: the retracting shaft and the outer shaft sleeve.

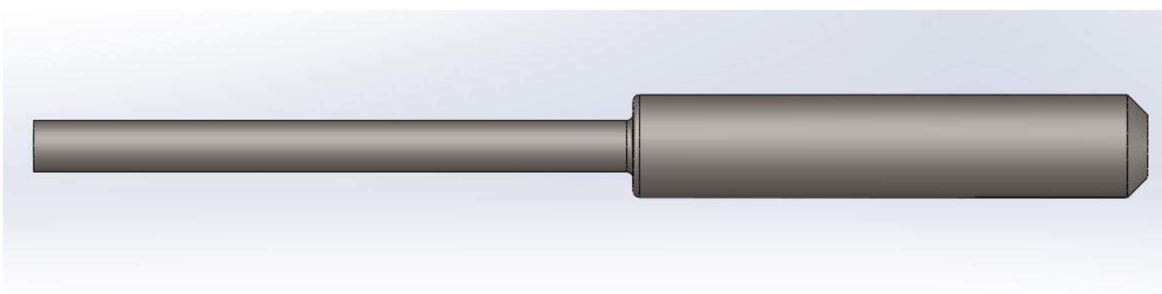


Figure 42: Final Drive End Design, Retractable Shaft, Side View

Figure 42 is the retractable shaft of the final drive end design, with a shoulder preventing the shaft from being pulled all the way out when retracting the shaft.

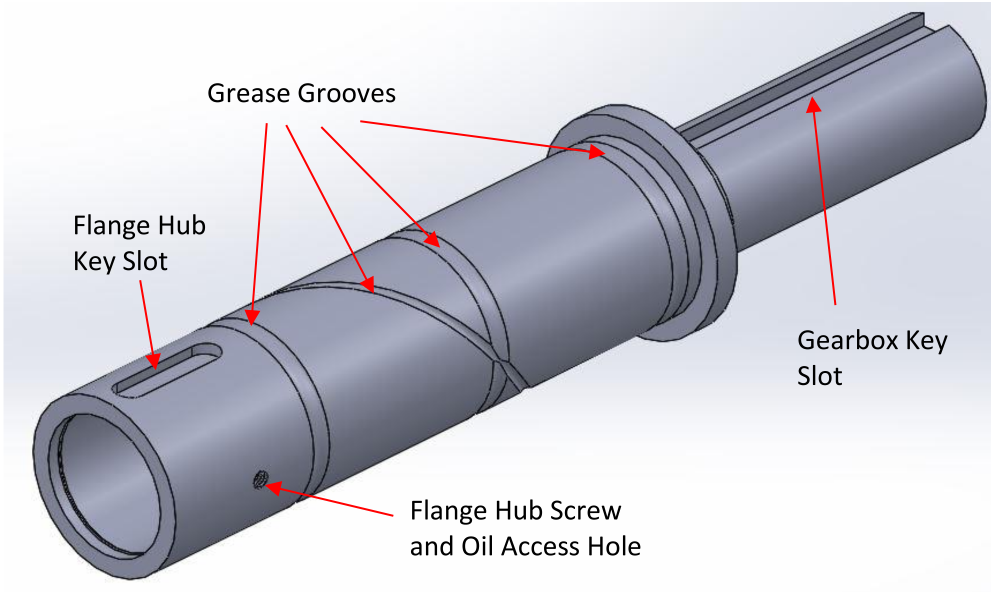


Figure 43: Final Drive End Design, Outer Shaft Sleeve

Figure 43 shows the outer shaft sleeve in the final drive end design. The outer shaft sleeve uses same grease grooves as the existing drive end shaft for lubrication during rotation from gearbox and can be lubricated in the same way as existing drive end design. The hole in the left end (inboard end of A-Stand) of the sleeve has two purposes: to fix the flange hub onto the outer shaft sleeve using 316 stainless steel shoulder screw (Part # 97345A619 from McMaster Carr [5]) just like existing drive end shaft design and as an access point to lubricate the oil-embedded bronze sleeve bearing as a part of maintenance. The key slot in the left of Figure 43 is used to allow the flange hub to rotate with the sleeve just as the existing drive end shaft design.

The key slot at the right end of the shaft is to connect the output gear of the hydraulic gearbox that provides the rotation to the welding fixture. The key in the existing drive end design is reused and the sleeve has the same diameter as the existing drive end shaft, so it is compatible with the existing hydraulic gearbox.

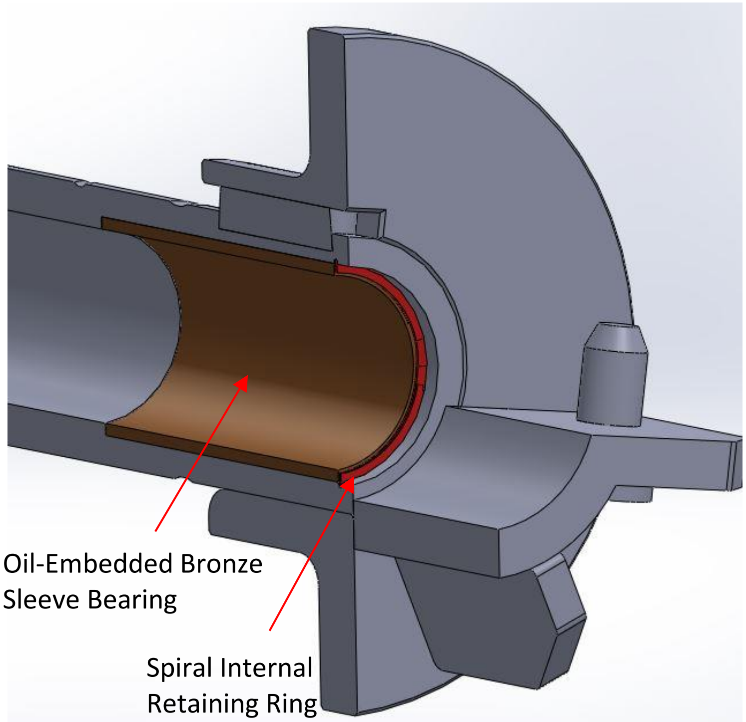


Figure 44: Internal View of Outer Shaft Sleeve

As shown in Figure 44, an oil-embedded bronze sleeve bearing (Part # 6391K28 from McMaster Carr [6]) is used to reduce the friction between the shaft and the sleeve when the shaft is being retracted. The bearing is rated for a load of 16,000 [lb] which is over the load of the welding fixture. The bronze sleeve bearing is held in place by machined internal shoulder in the outer shaft sleeve and a spiral internal retaining ring (Part # 92602A260 from McMaster Carr [7]) coloured red in Figure 44. The spiral internal retaining ring is held in place with internal ring groove inside the outer shaft sleeve.

The flange hub design of the existing drive end has changed in the final drive end design. The current flange hub design which can be seen in Figure 2 has only two butterfly tabs mounted on the inboard face of the flange hub that are used to hold onto the welding fixture yoke. The new flange hub design is physically larger to allow it to fit over the new outer shaft sleeve and has a new flange locating cup mounted onto the inboard face of the final drive end flange hub. A key and a bolt are used on the flange hub assembly to prevent the hub from dislocating. The team decided to use a key and a bolt instead of welding onto the sleeve because the existing design does not have a weld.

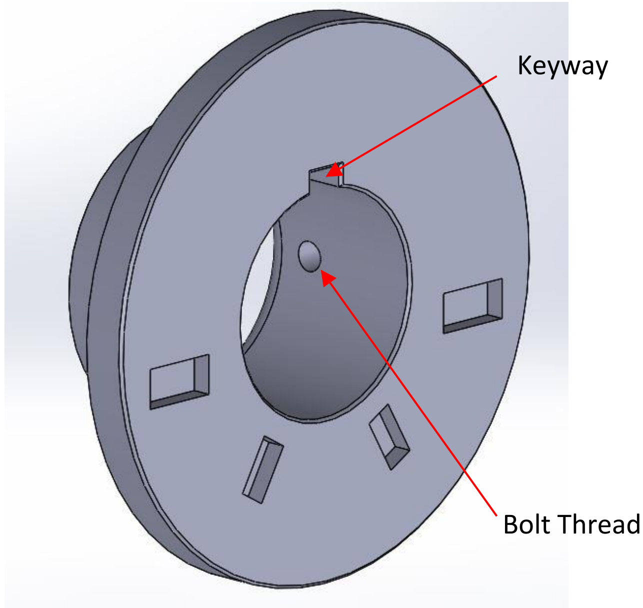


Figure 45: Final Drive End Design, Flange Hub

Figure 45 shows the final drive end flange hub design. It can be seen on the inboard face of the flange hub that there are locating slots to help align the flange locating cup to ensure alignment with retracting shaft and welding fixture yoke. The keyway and bolt thread used to attach to the shaft sleeve are also shown.

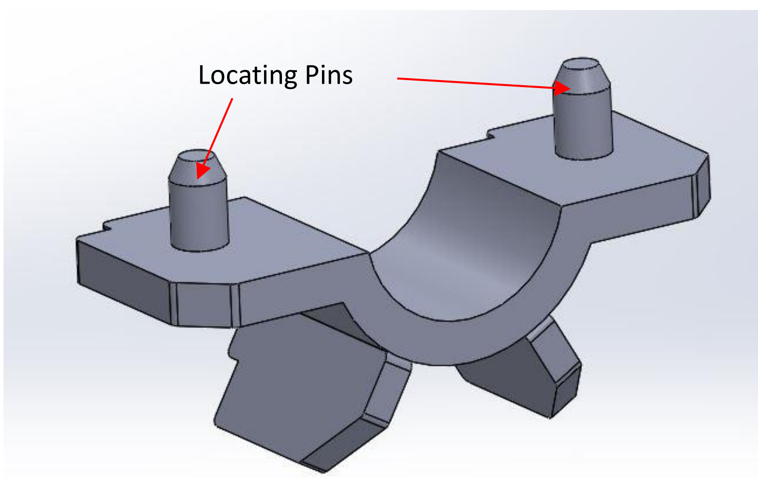


Figure 46: Final Drive End Design, Flange Locating Cup

Figure 46 shows flange locating cup that is used to align the welding fixture yoke when welding fixture is lowered onto the A-Stands. This feature allows for quick alignment allowing the final drive end shaft design to engage with welding fixture yoke easily. Two locating pins in the flange cup assembly match the holes of the existing welding fixture yoke so that they can be aligned. Two reinforcement gusset plates are used under flange locating cup to help ensure flange locating cup can support the load of the welding fixture. The Flange locating cup assembly is welded together and to the face of the flange hub.

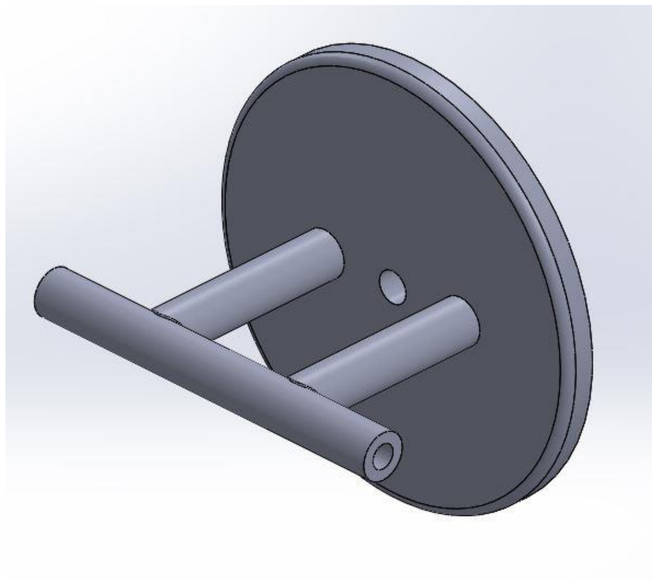


Figure 47: Final Drive End Design, Shaft Handle

The shaft handle of the final drive end design is shown in Figure 47. The shaft handle allows operator to have secure grip when pulling or pushing shaft. Handle is made from standard sized section piping that are welded together and to the handle disk. Handle is attached to the retractable shaft using a flanged hex head screw (Part # 92979A257 from McMaster-Carr [8]).

Figure 48 shows the use of an intermediate spacer between shaft handle disk and the end of the retracting shaft. This is used due to the stepped geometry inside the hydraulic gearbox.

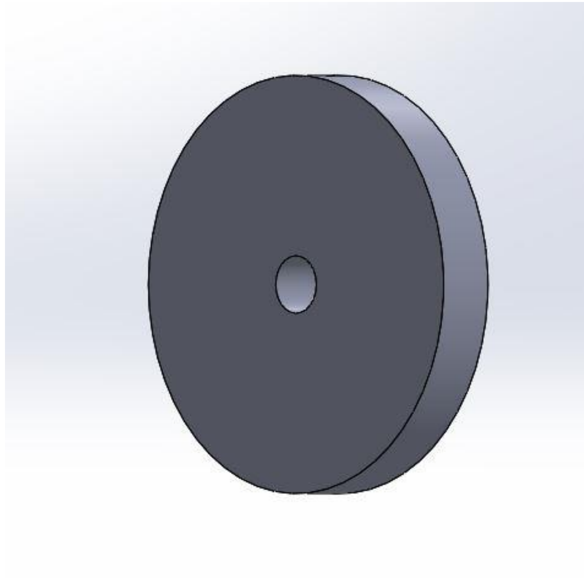


Figure 48: Final Drive End Design, Shaft Handle, Intermediate Spacer

In Figure 49, intermediate spacer is between shaft handle disk and outer shaft sleeve.

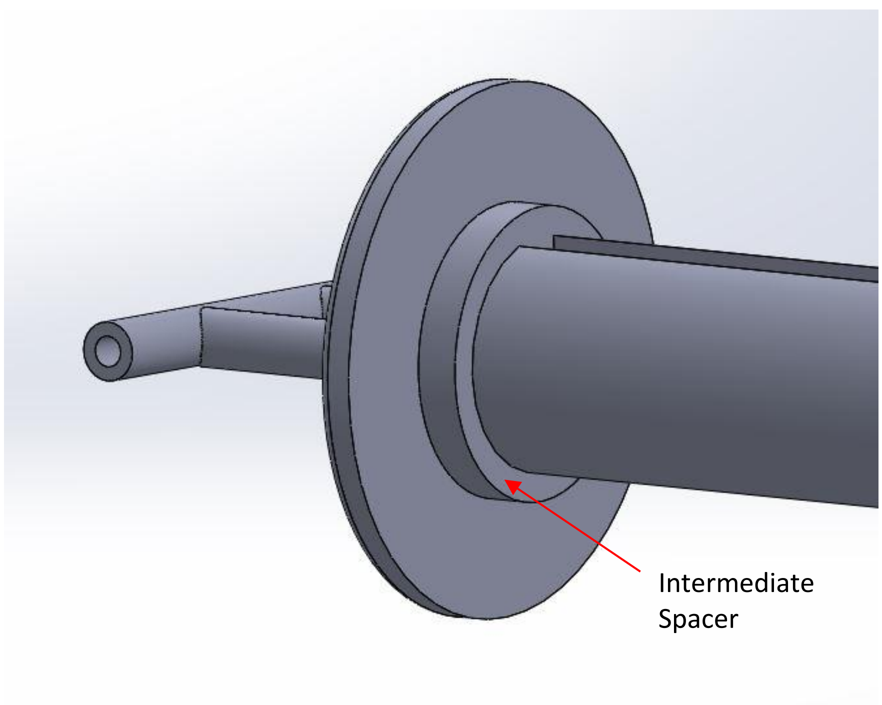


Figure 49: Final Drive End Design, Retractable Shaft Assembly, Handle End

Figure 50 shows the internal stepped geometry of the hydraulic gearbox.

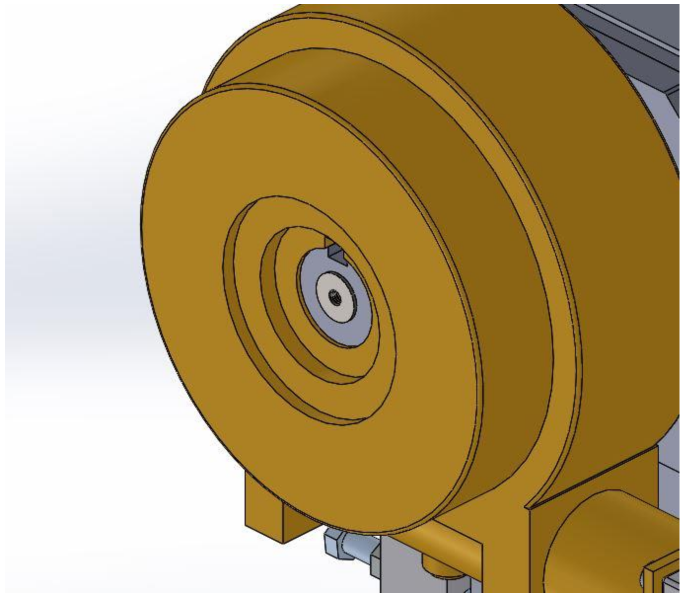


Figure 50: Final Drive End Design, Hydraulic Gearbox, Internal Stepped Geometry

Figure 51 shows the two safety latches (Part # 1512N11 from McMaster Carr [9]) used on the side of the hydraulic gearbox and shaft handle disk to ensure that shaft is not accidently retracted while supporting the welding fixture. The two latches are to be welding onto the outboard face of the hydraulic gearbox to avoid drilling into the gearbox.

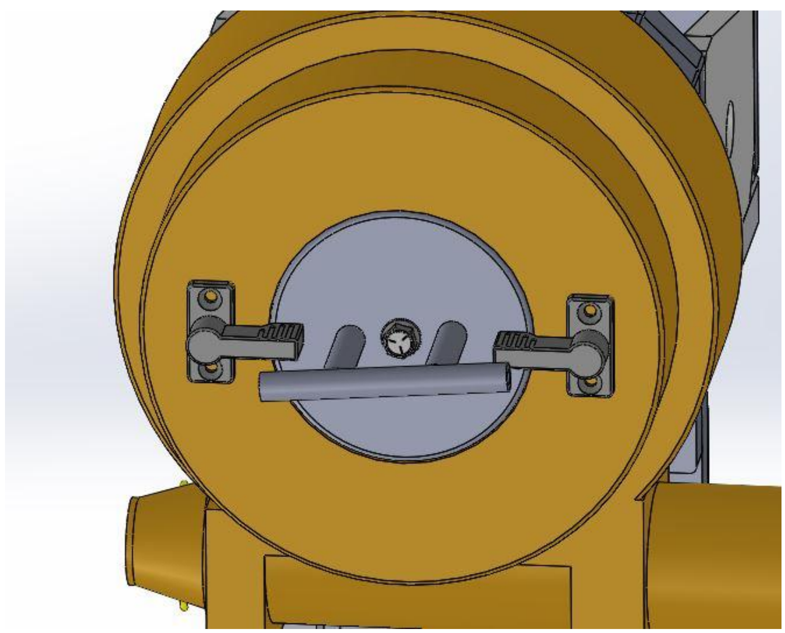


Figure 51: Final Drive End Design, Outboard Side, Hydraulic Gearbox

Figure 52 is the safety latched used to prevent shaft from being accidently retracted.

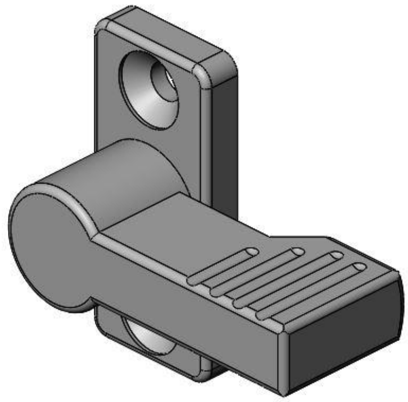


Figure 52: Safety Latch

3.1.1.2. Final Drive End Design, Retractable Shaft Assembly Housing

The same support tube used in the existing drive end design is used to house the final drive end retractable shaft assembly. The final drive end support tube housing is shown in Figure 53.

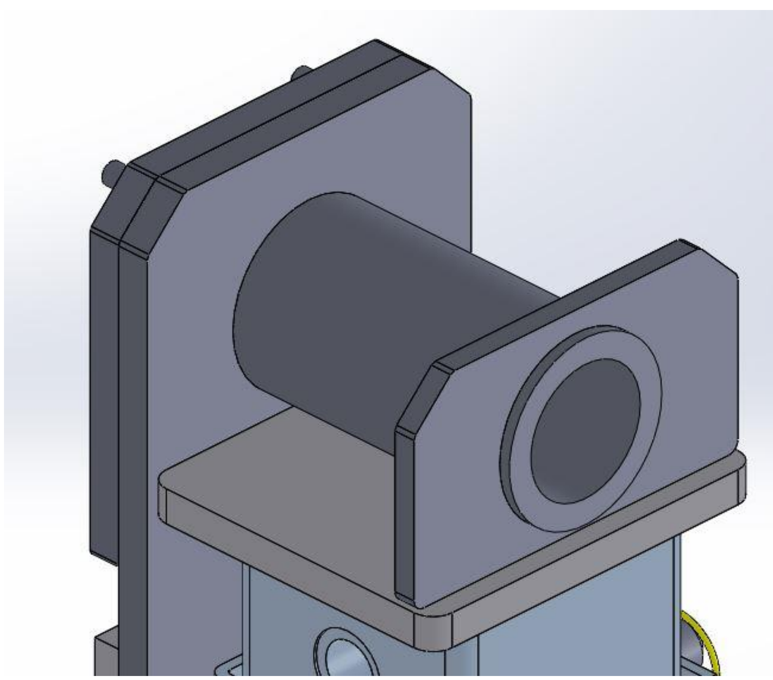


Figure 53: Final Drive End Design, Support Tube Housing

3.1.1.3. Inboard Support Leg

The final drive end design uses an inboard support leg to prevent A-Stands from tipping over inward when the welding fixture is initially lowered onto A-Stands before engaging A-Stand shafts. The inboard support leg can be seen in Figure 54 and Figure 55. The leg is made from rectangular tubing cut at 45 degrees at the ends and welded onto A-Stand column and base plate. A gusset plate of 0.375 [in] is welded between the leg and base plate for extra reinforcement. The support leg tube and gusset plate are then welded to the inboard face of the A-Stands which can be seen in Figure 38.

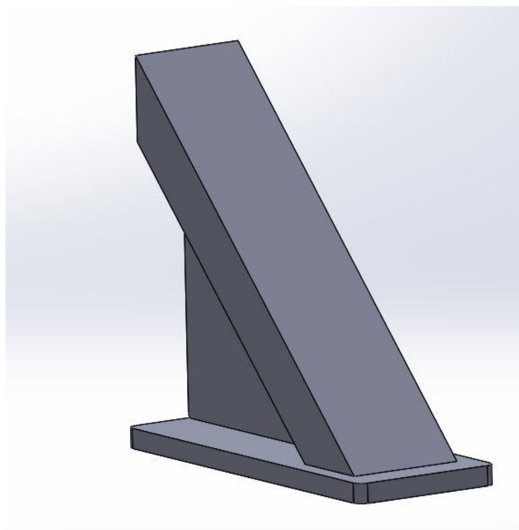


Figure 54: Final Drive End Design, Inboard Support Leg

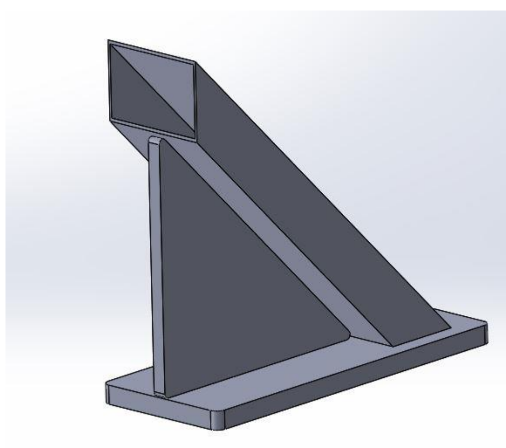


Figure 55: Final Drive End, Inboard Support Leg, Rectangular Tubing

3.1.1.4. Retracting Shaft Mechanism of Final Drive End Design

The final drive end design uses the retractable shaft for performing welding fixture changeover shown in Figure 56 and Figure 57. Figure 56 shows the shaft retracted so welding fixture can be lifted off the A-Stand.

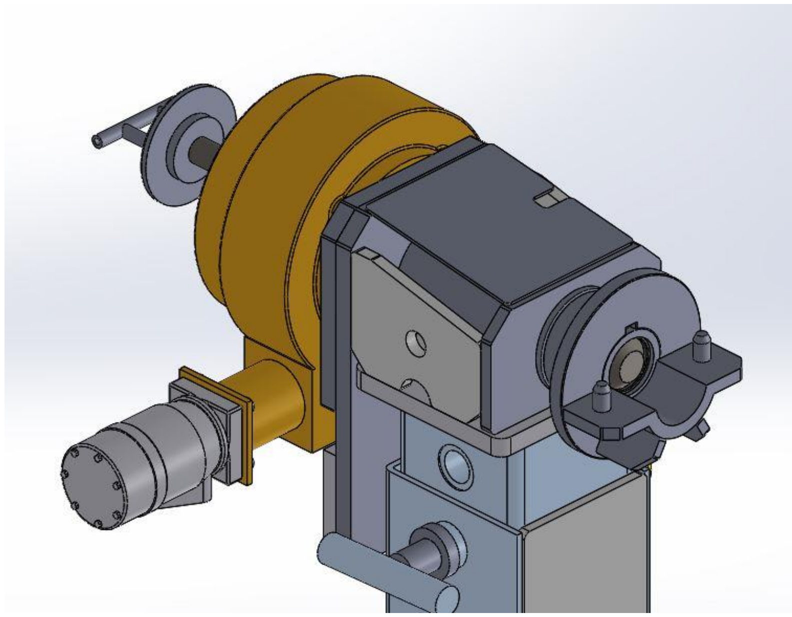


Figure 56: Final Design Drive End, Shaft Retracted

Figure 57 shows shaft in the engaged position where shaft goes into the welding fixture yoke and supports the welding fixture.

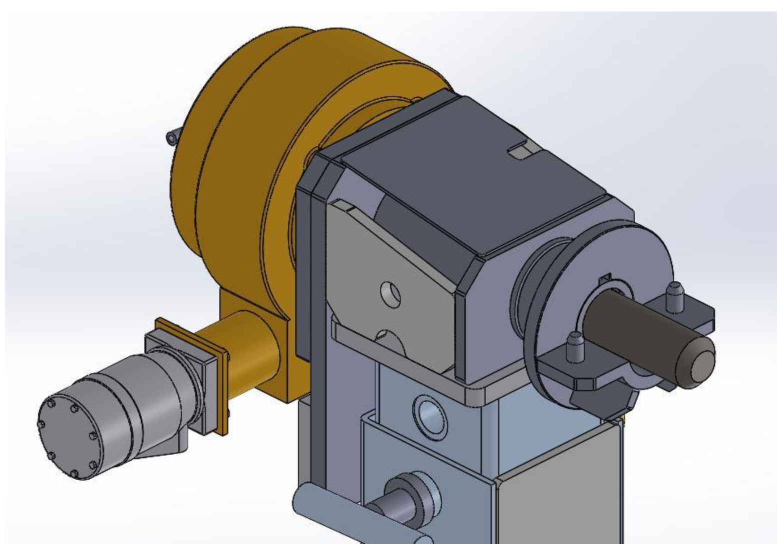


Figure 57: Final Drive End Design, Shaft Engaged

Figure 58 shows the shaft retracted from the welding fixture yoke that is made transparent. Figure 58 also shows the locating pins of the flange locating cup engaged with welding fixture yoke tabs. With the shaft in this retracted position, welding fixture can be lifted off A-Stand and changed with another welding fixture.

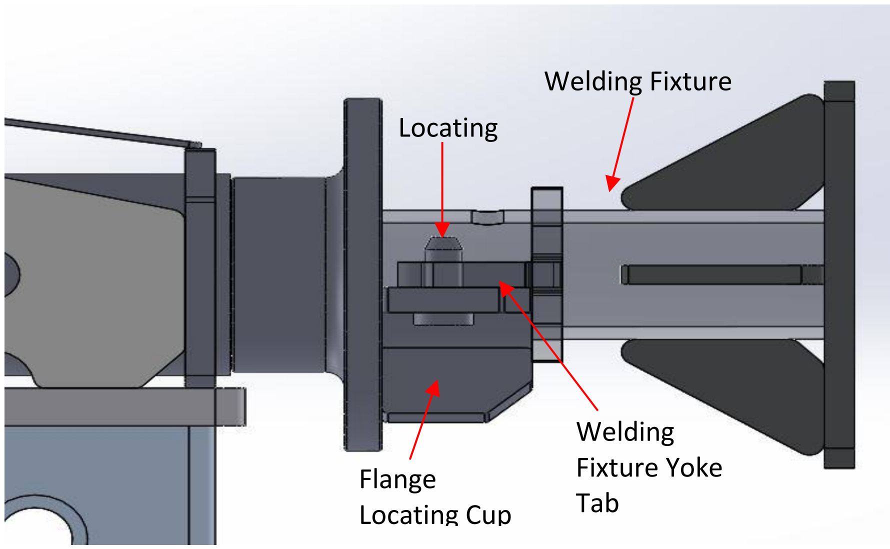


Figure 58: Final Drive End Design, Shaft Retracted from Welding Fixture Yoke

Figure 59 shows the shaft of the final drive end design engaged with the welding fixture yoke. With the shaft engaged, welding fixture is now secured and can be rotated for access when operators are welding.

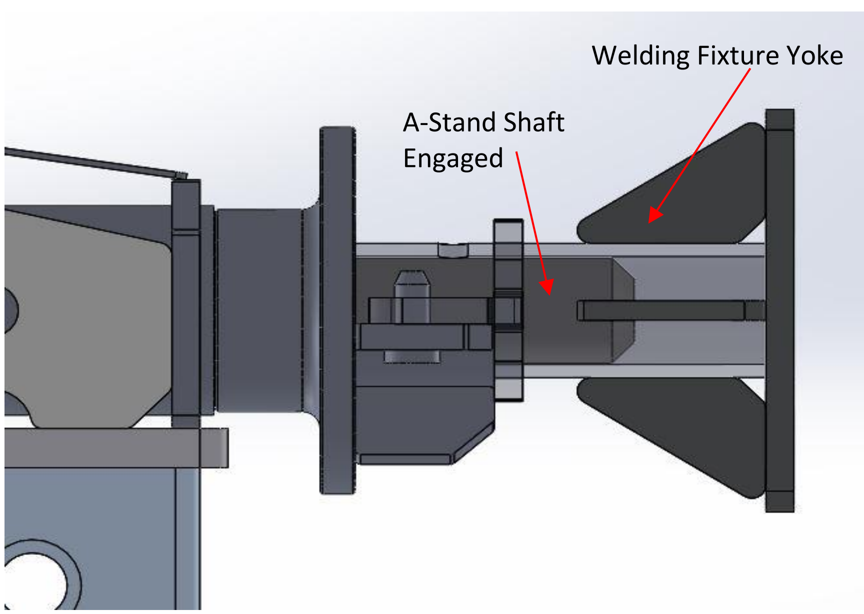


Figure 59: Final Drive End Design, Shaft Engaged with Welding Fixture Yoke

3.1.2. Final Design Hydraulic powered A-Stand Idle End

The final detailed design of the quick change, hydraulic powered, idle end, A-Stand is presented in this section. The new design is primarily developed on the A-Stand head portion, the A-Stand base section uses the same design of existing stand base with an additional inboard supporting leg. The additional inboard supporting leg adapts the identical design used in final design of A-Stand drive end. The presentations of the idle end final design are shown in Figure 60 and Figure 61.

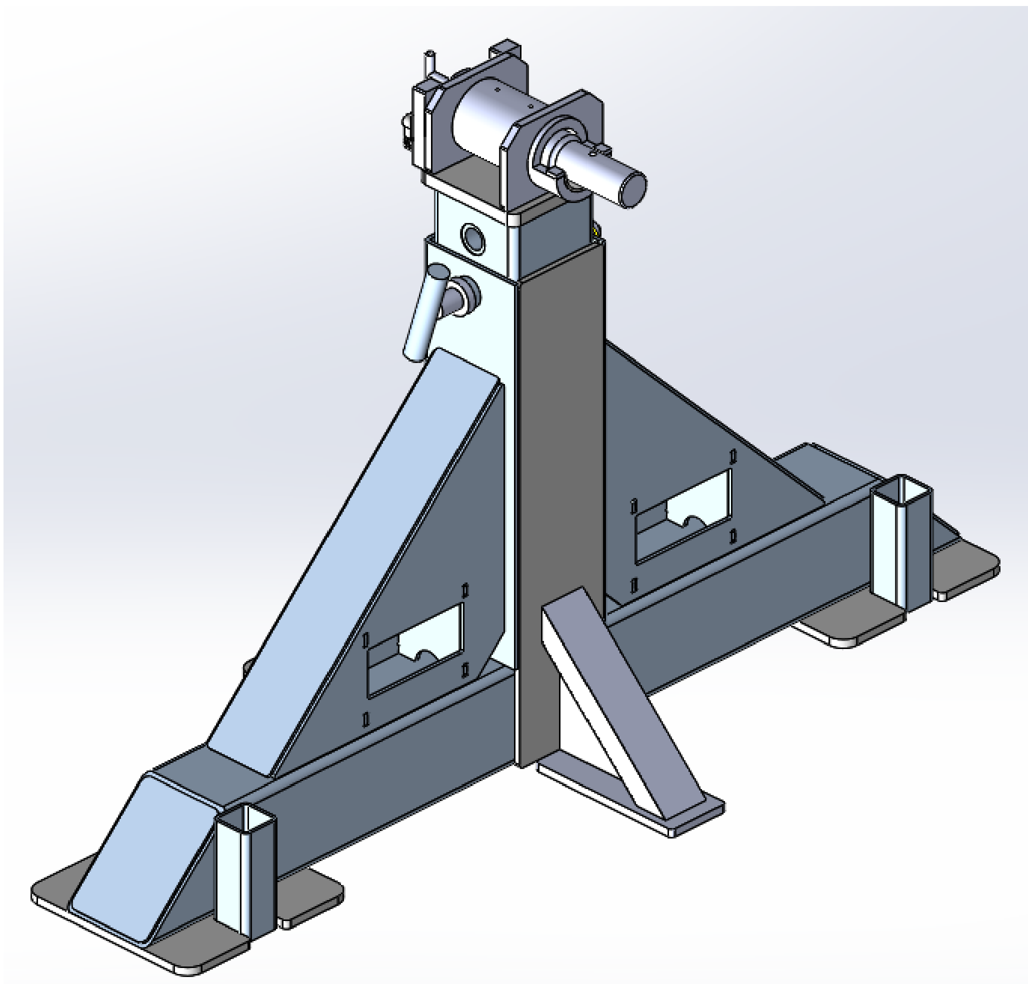


Figure 60: Final Design of Quick Change, Hydraulic Powered Drive End A-Stand, Inboard Side

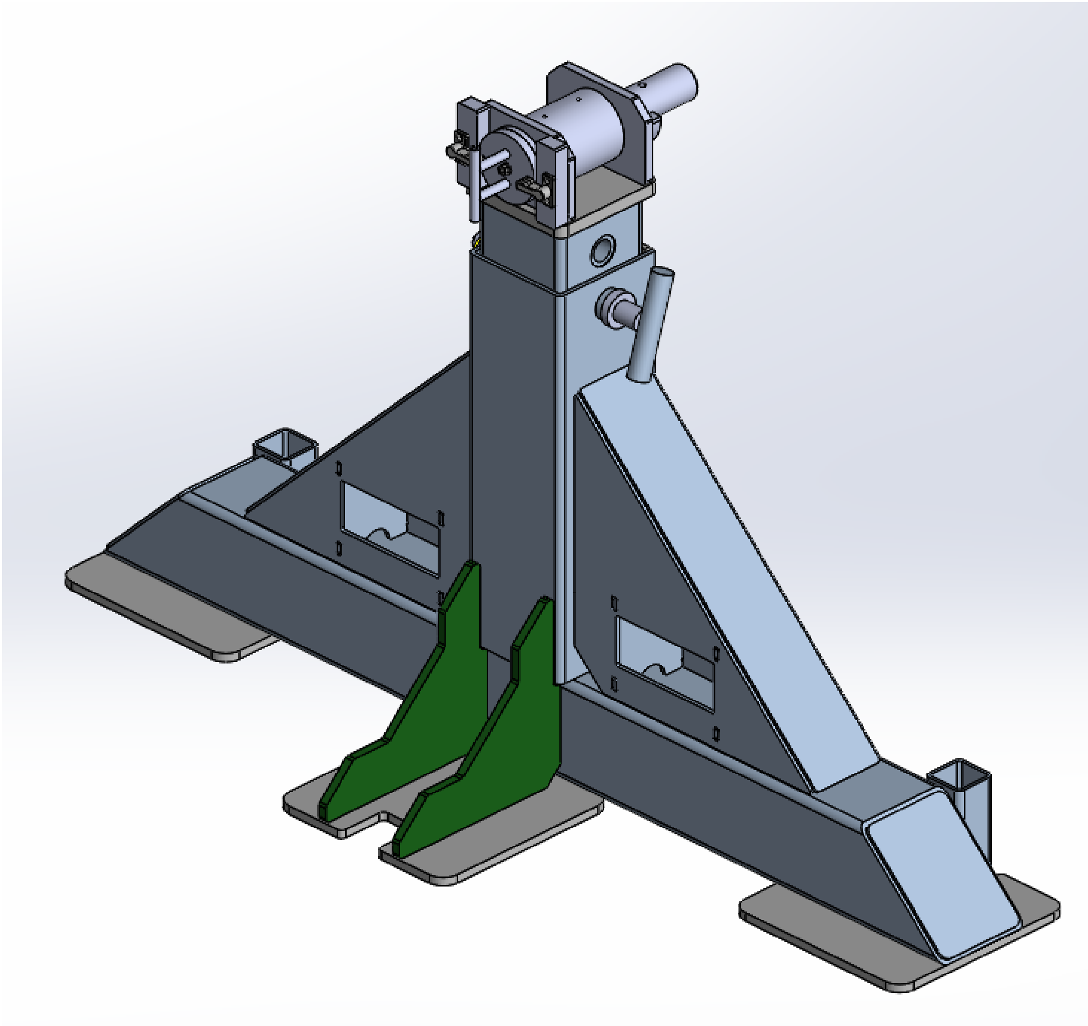


Figure 61: Final Design of Quick Change, Hydraulic Powered Drive End A-Stand,

The head design consists of two primary sections; which are a shaft and a shaft housing as shown in Figure 62. The details of each section will be shown in the following sections.

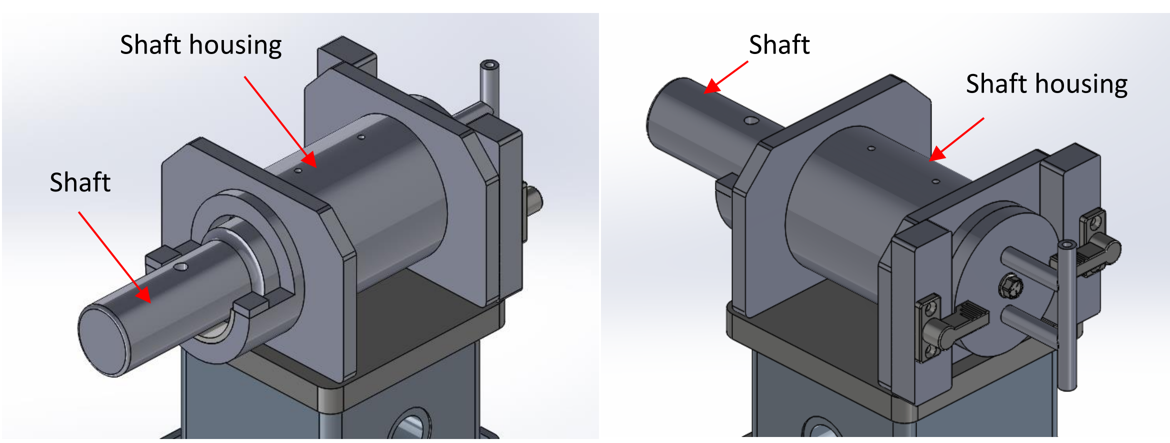


Figure 62: Final Idle End A-Stand Head Assembly

3.1.2.1. Final Design Idle End Shaft

A solid step-down shaft is utilized as the retractable shaft for the idle end. As shown in Figure 63, the shaft design adapts a similar concept as the shaft in the existing A-Stand.

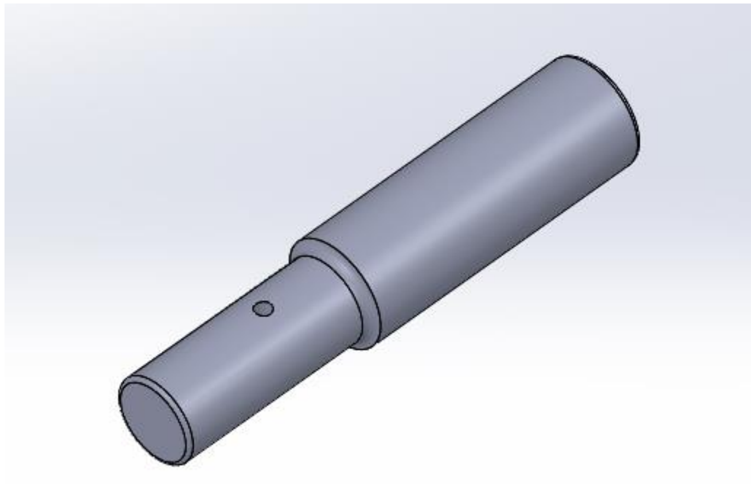


Figure 63: Solid Step-down Shaft in Final Idle End Design

The portion of smaller diameter of the shaft goes into the fixture yoke, and the larger diameter portion of the shaft goes into the designed shaft housing. The smaller diameter shaft portion is designed to have the same diameter as the existing shaft, so it will perfectly fit in the existing fixture yokes.

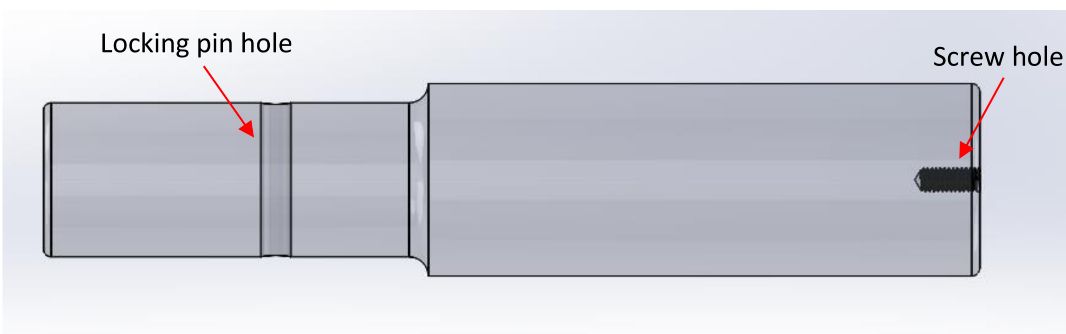


Figure 64: Solid Step-down Shaft in Final Idle End Design, Side View

As illustrated in the picture Figure 64, there is a locking pin hole on the shaft and a screw hole centered at its back end. The locking pin hole is a through hole for a locking pin, which is used to connect the fixture yoke and the shaft. As shown in Figure 65, a locking pin with rounded wire retainer connects the shaft and the fixture yoke, and this is the current connecting approach that operators use on the existing A-Stands.

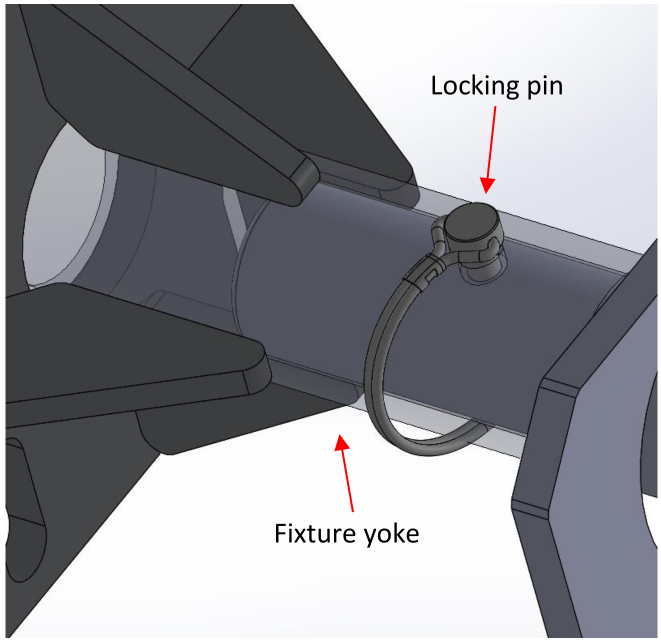


Figure 65: Welding Fixture Yoke Connects to Shaft with a Locking pin

The screw hole is designed for a flanged hex head screw (Part # 92979A257 from McMaster-Carr [8], which connects a disc plate to the shaft as shown in Figure 66. For the ease of retracting the shaft, a handle is designed to be welded to the disc plate. The handle design is identical to the one on the drive end to keep design consistency.

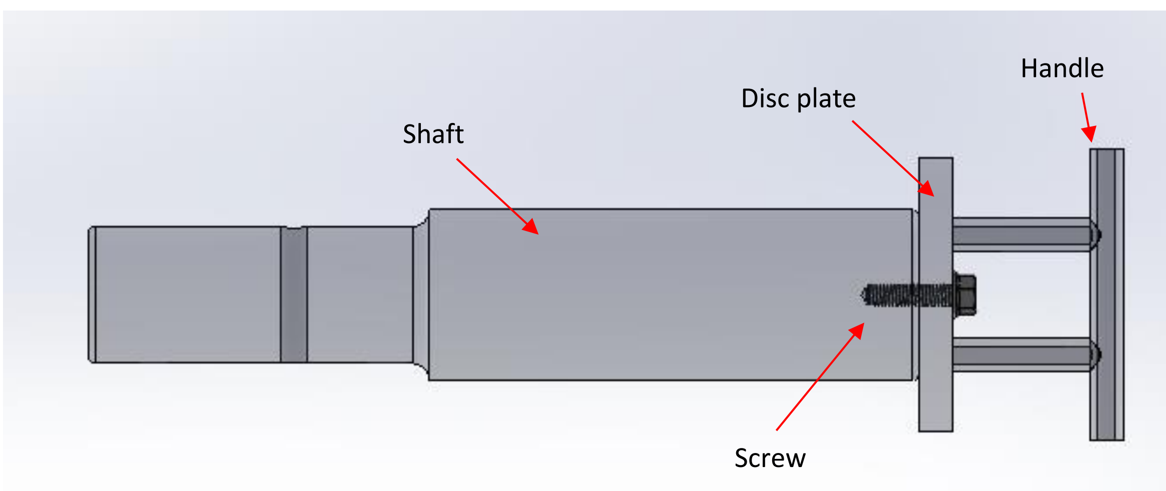


Figure 66: Final Design Idle End Shaft Assembly, Side View

3.1.2.2. Final Idle End Design, Shaft Housing Assembly

The final design of the shaft housing is illustrated in Figure 67. It consists of four different type of components: a hollow tube, support plates, spacing blocks and safety latches.

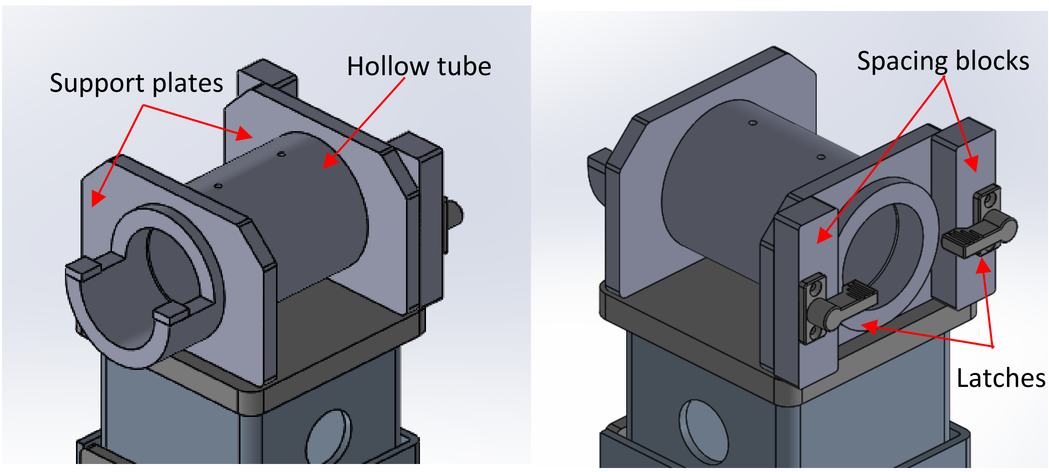


Figure 67: Shaft Housing in Final Idle End Design, Shaft Housing

The support plates were used in the existing design. As shown Figure 68, the plate has a circular cut in the middle, which allows the hollow support tube to go through. The same support plates in the existing A-Stand are used in the new design.

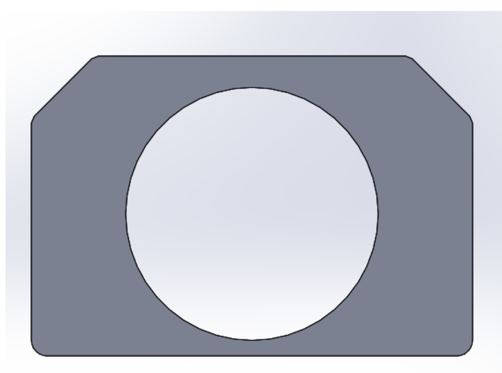


Figure 68: Support Plate in Final Idle End Design, Shaft Housing

The design of hollow tube is illustrated in Figure 69. It is a hollow tube with a cup-shaped cut out at one end. Both inner and outer diameters of the tube are designed to be the same as the existing design, so it will fit in the support plates.

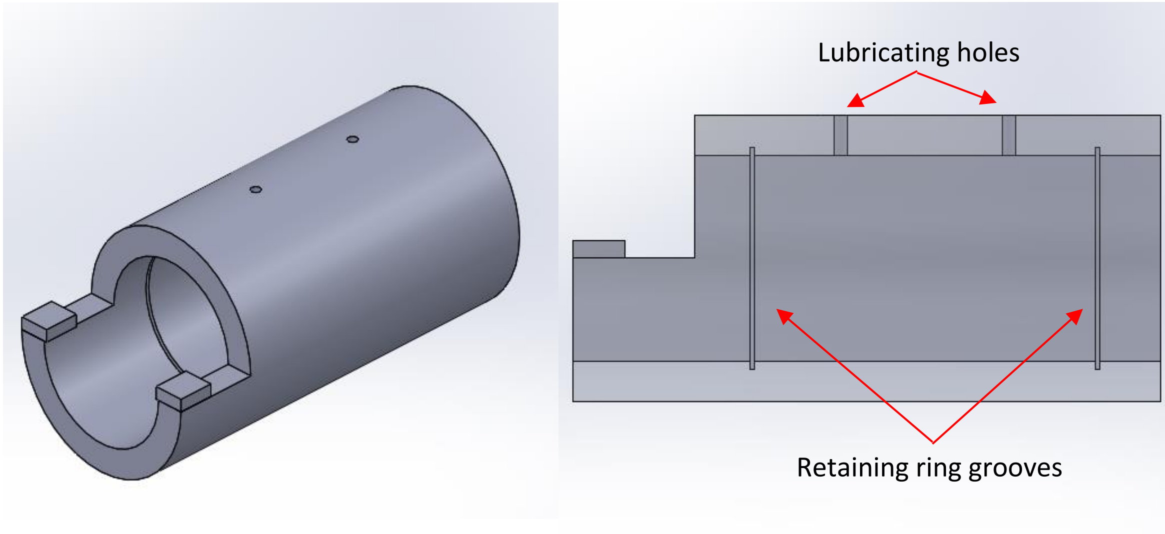


Figure 69: Hollow Tube in Final Idle End Design, Shaft Housing

The shaft goes into the shaft housing and is connect to the housing with two oil-embedded sleeve bearings. As shown in Figure 69, lubricating holes and retaining ring grooves are cut on the tube body to accommodate the mechanical components used in the design. Two oil-embedded sleeve bearings (Part#6391K689 from McMaster-Carr [6]) are placed in the housing to reduce the friction for rotating and sliding motion. As shown in Figure 70 , to secure the sleeve bearings (in brown), two spiral internal retaining rings (Part#92370A331 from McMaster-Carr [7]) are used.

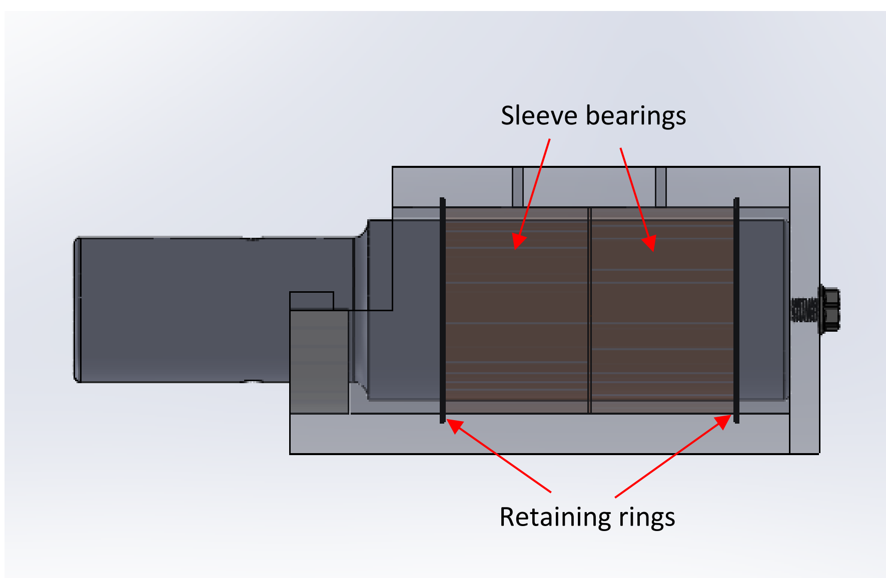


Figure 70: Shaft and Shaft Housing assembly with Sleeve bearings and Retaining Rings, Shaft Housing

In addition, two small tabs are designed to be welded at the top surface of the cup to hold a Delrin® acetal resin layer as shown in Figure 71. Such anti-wear material layer prevents wear on the cup, and meanwhile, it can act as an easy-change sacrificial material.

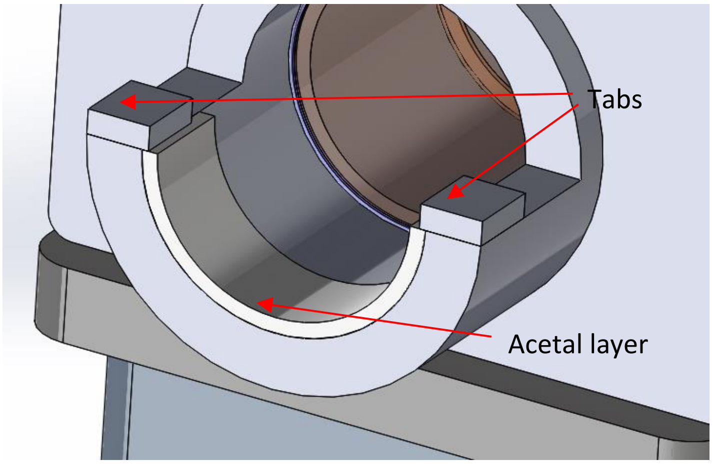


Figure 71: Illustration of Acetal Layer Held in the Housing Cup with Tabs, Shaft Housing

At the back of the support plate, two turn latches are used to secure the shaft as a safety feature. To accomadate the original A-Stand base design, two solid retangular spacings blocks are added to ensure the alignment of back plate and latches. The identical latches used in the drive end final design are adapted in this idle end design, and the latches will be welded to the spacing blocks as shown in Figure 72.

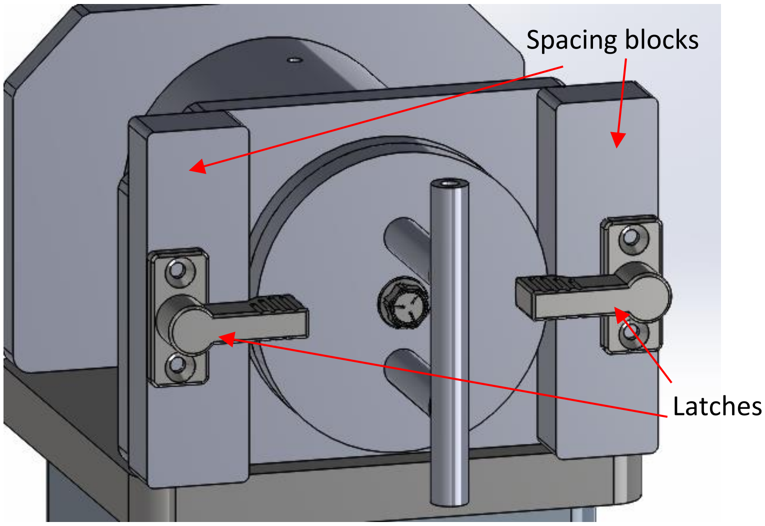


Figure 72: Safety latches and Spacing Blocks in Final Idle End Design, Shaft Housing

Such feature prevents any potential axial movement of the shaft when supporting welding fixture. In addition, it prevents the shaft from sliding out while the stand is transported, for the stand are not always standing horizontally when being moved.

3.1.2.3. Retracting Shaft Mechanism of Final Idle End Design

Similar to drive end, idle end design uses retractable shaft for performing welding fixture changeover. The retractable shaft in retracted position and in engaged position are shown in Figure 73 and Figure 74 respectively.

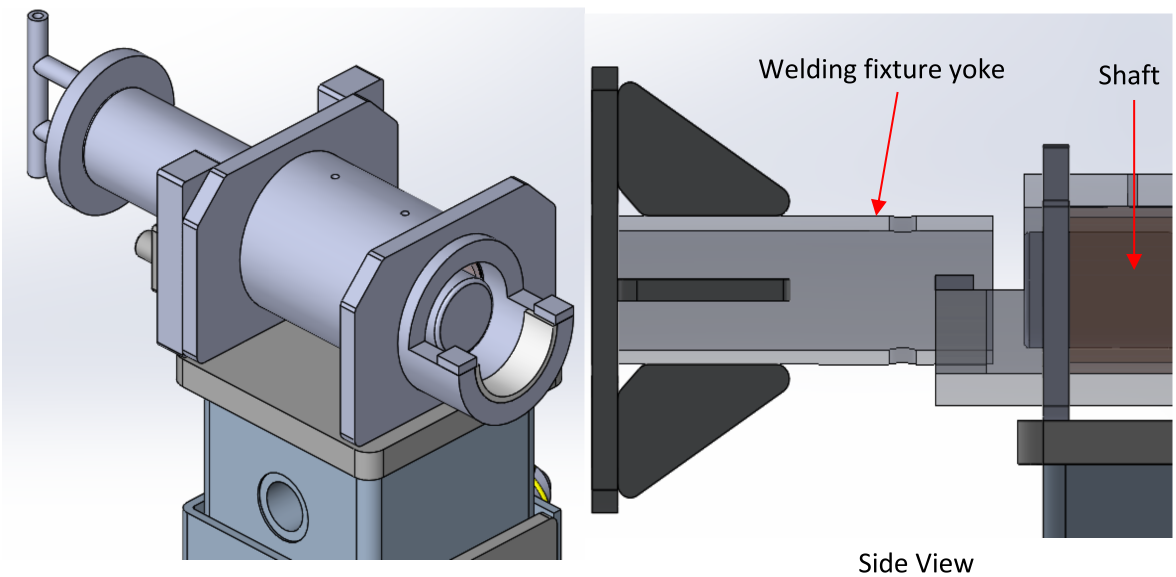


Figure 73: Final Design Idle End, Shaft Retracted

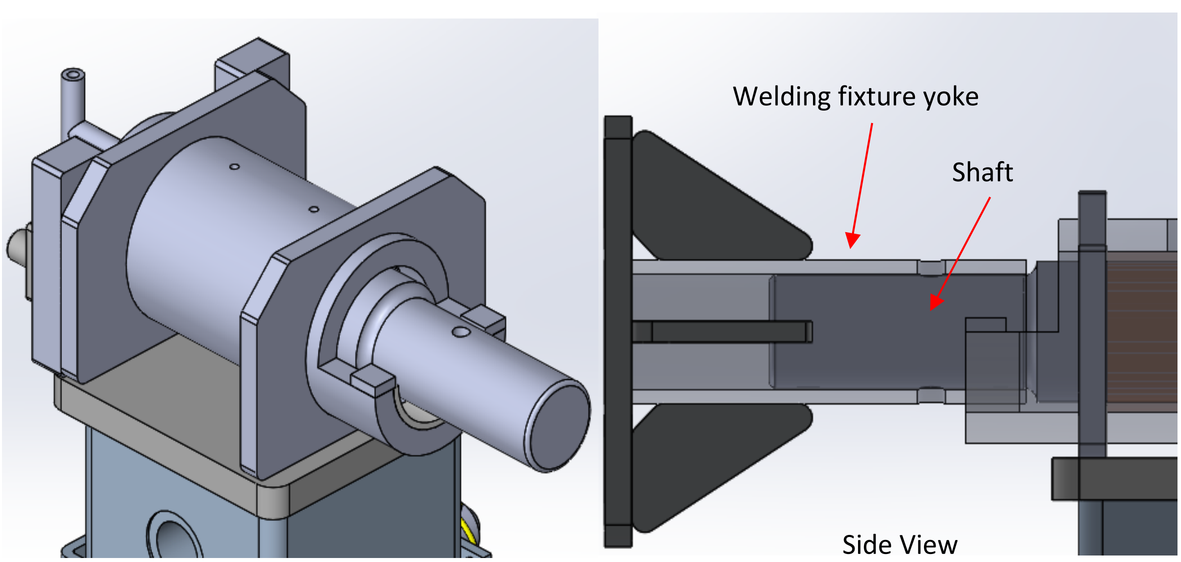


Figure 74: Final Design Idle End, Shaft Engaged

3.2. Preliminary Stress Analysis

In this section, preliminary stress analysis is done on the critical components of the final design of both drive end and idle end quick change A-Stands. To is to ensure and validate that components of the A-Stands do not fail under the intended load they must support. These critical components are:

- Drive End A-Stand Shaft
- Idle End A-Stand Shaft
- Inboard Support Legs of the A-Stands

To start, main assumptions made in this section are stated in the following sub-section.

3.2.1. Assumptions

Reused components from the current existing A-Stand design do not require stress analysis because they have proven to not fail during operation at MacDon. These components are:

- The support tubes in the head of the A-Stands that house the retractable shaft assemblies in both drive and idle ends.
- A-Stand base
- A-Stand outboard support legs
- Drive End Gearbox
- Gearbox and shaft key
- Flange Hub and Shaft sleeve key

When stress analysis is performed on a critical component, its surrounding parts are assumed rigid and fixed so that all stress is kept within the critical part and not transfer to surrounding parts. This creates the worst-case scenario for the critical component. In reality, the stress in critical components will be lower because they are transferred to other surrounding parts by deflection.

It is assumed that the welding fixture is balanced, therefore when placed on the A-Stands, the applied load is shared equally between the drive end and the idle end. The load of the heaviest welding fixture plus the work piece is assumed to be 4000 [lb]. Therefore, the drive end and the idle end are to support 2000 [lb] multiplied by the safety factor of 3. Therefore, for stress analysis of the drive end and the idle end shafts, the applied load is 6000 [lb] on each.

The torque applied to the shaft assembly is ignored because the welding fixture is not put on constant rotation with high angular velocity. In actual practice, welding fixtures are rotated to set angles and stay there for a period of time so that welders can have easy access to the work piece on the welding fixture.

3.2.2. Analytical Stress Analysis

To validate the critical components that are stated above do not fail, the team performed analytical analysis. For each part, the maximum stress and expected life cycle is calculated in this section.

3.2.2.1. Stress Analysis of Drive End A-Stand Shaft

In this section, stress analysis is performed to the drive end shaft of the quick-change A-Stand design. The drive end A-Stand shaft is connected to the welding fixture through the welding fixture yoke. The yoke is a tube that is assumed to apply a distributed surface load on the top cylindrical face of the shaft shown in Figure 75.

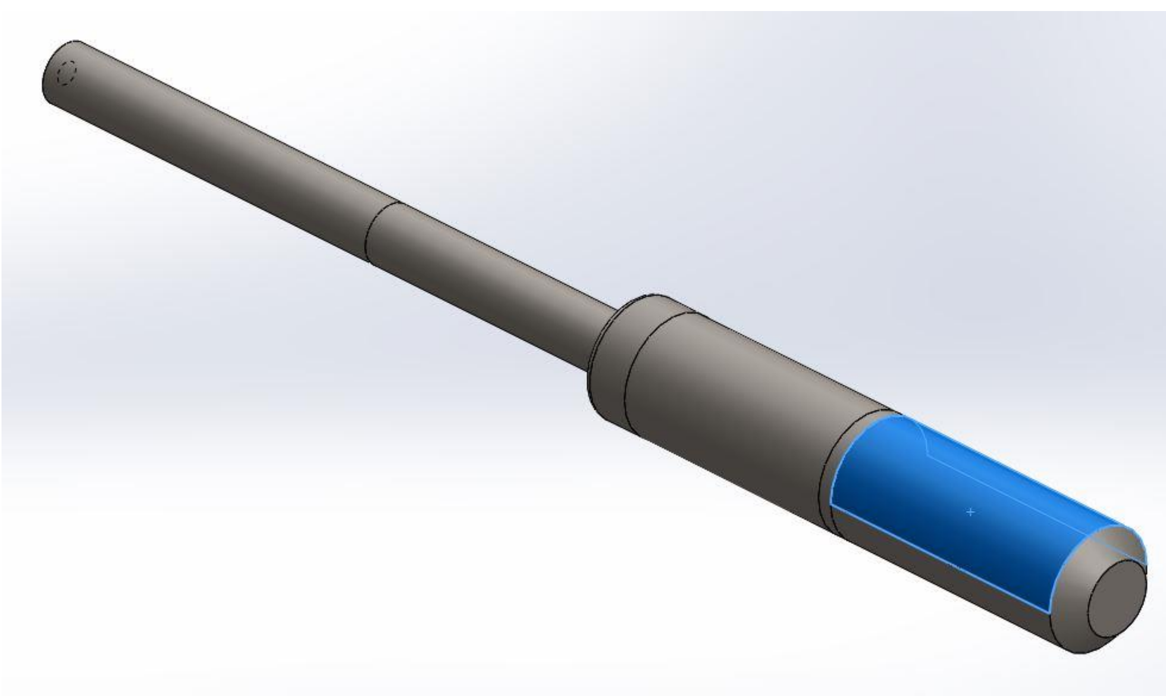


Figure 75: Drive End Shaft, Vertical Downwards Load is Placed on Highlighted Blue Surface

For two-dimensional analytical stress analysis, load from welding fixture is simplified to a distributed load that is applied onto the drive end shaft. Specifically, the portion of the drive end shaft in contact with the welding fixture yoke (Figure 76). The shaft is then treated as a simple beam in bending with circular cross-sectional area.

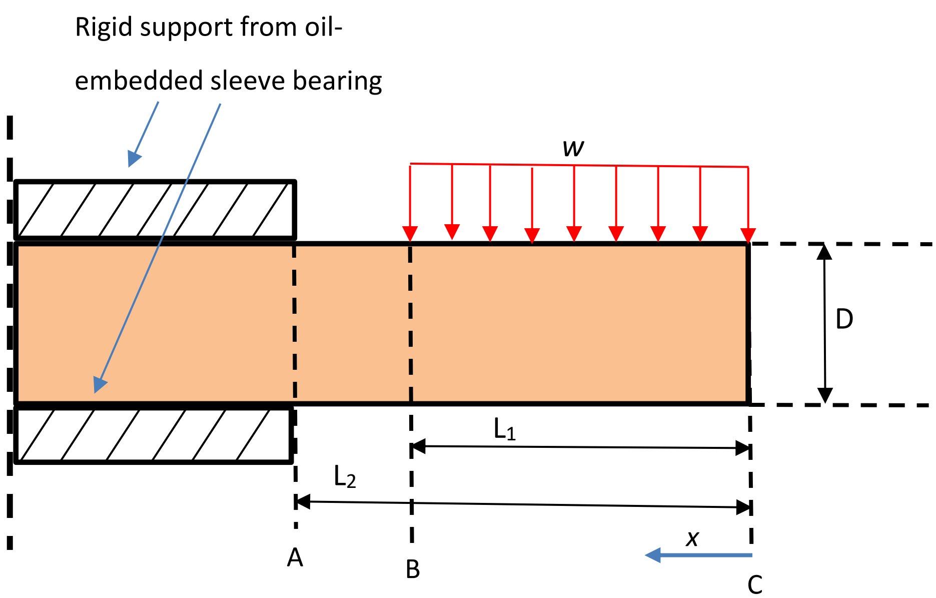


Figure 76: Drive End Shaft Stress Analysis with Distributed Load, w, from Welding Fixture Yoke

From Figure 76, distributed load *w* is applied on the drive end shaft for length of L_1 and the location of interest in the x-direction starts at the end of the drive end shaft, *C*. Table summarizes the variables shown in Figure 76.

TABLE V DEFINED VARIABLES OF Figure 76

Variable	Definition	Magnitude/Value [units]
W	Simplified distributed load from welding fixture	1,329.3 [lb/in]
D	Diameter of Shaft	2 [in]
L_1	Length of contact area between drive end shaft and welding fixture yoke	4.5138 [in]
L_2	Length from end of drive shaft to beginning of bearing	4.7638 [in]

From Table V, w is calculated from load *P* from the welding fixture that was determined in the assumption and dividing by L_1 shown in Eq. 3.2-1.

$$w = \frac{P}{L_1} \qquad \text{Eq. 3.2-1}$$

Where, $P = 6000\ [lb]$

From Figure 76, shear force and bending moment diagrams are obtained starting from *C* to *A*. From the shear force and bending moment diagrams, location on the shaft where max shear force and bending moment is found and average shear stress and max bending stress can be found in the drive end shaft.

First, reaction force and moment at location *A* is of the drive end shaft in Figure 76 is found. This is done with a free body diagram of the drive end shaft from *A* to *C* with reaction force R_{ay}, moment M_A, and distributed load *w* acting on shaft shown in Figure 77.

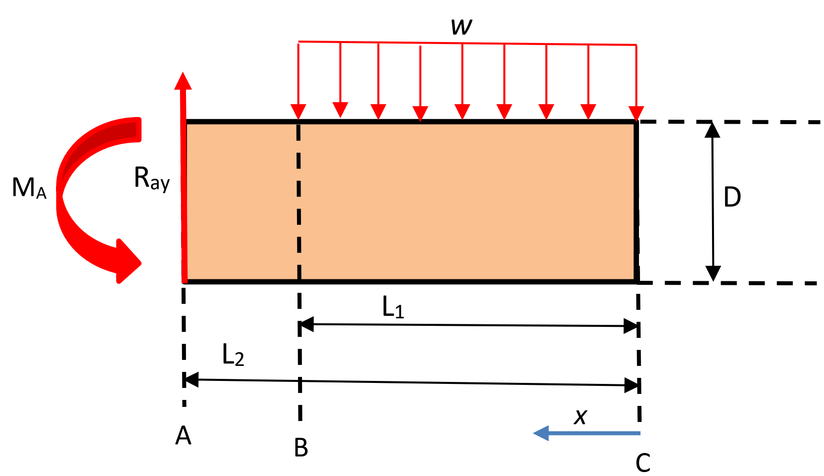


Figure 77: Free Body Diagram of Drive End Shaft from A to C

Summing the forces in the *y* direction in Figure 77, reaction force R_{ay} is found from Eq. 3.2-2. To find the reaction moment M_A at *A*, distributed load *w* is replaced with equivalent force load placed in the center of the distributed load *w*. Then setting sum of the moments at *A* and equal to zero, reaction moment M_A is then equal in magnitude to moment caused by the distributed load *w* (equation).

$$R_{ay} = wL_1$$ Eq. 3.2-2

Where,

$$R_{ay} = 6000\ [lb]$$

$$M_A = wL_1\left(L_2 - \frac{L_1}{2}\right)$$ Eq. 3.2-3

$$M_A = 15{,}042\ [lb \cdot in]$$

Where,

3.2.2.1.1. Shear Force, Bending Moment and Stresses of Drive End Shaft

Shear force and bending moments are now determined by cutting out a section of the drive end shaft starting from *C* and replacing with internal shear force *V* and bending moment *M* so that section of the drive end shaft remains stationary, which is shown in Figure 78. Shear force and bending moment can then be calculated and plotted as a function of *x* to make shear force diagrams.

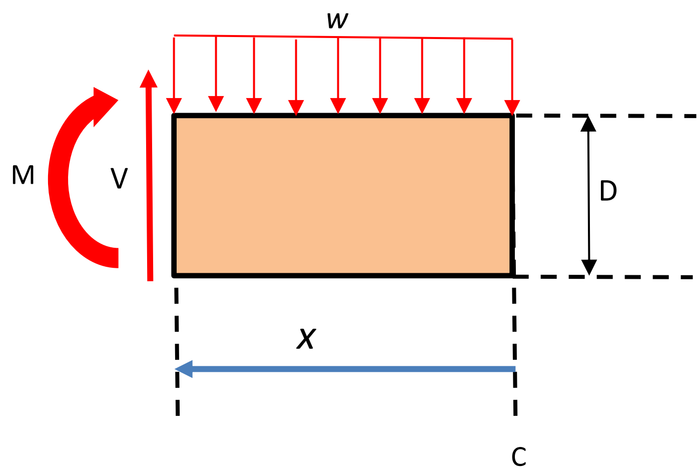


Figure 78: Shear Force and Bending Moment of Drive End Shaft

To calculated shear force in drive end shaft section under the distributed load *w*, sum of the forces in the *y* direction is done with respect to *x* (Eq. 3.2-4). To calculate the bending moment in the drive end shaft under the distributed load *w*, *w* is replaced with equivalent point load at the center of the distributed load with respect to *x*. The bending moment at *x*, then is the point load times the distance from x Eq. 3.2-5.

$$V = wx$$ Eq. 3.2-4

$$M = \frac{w}{x} \cdot \frac{1}{2} x = \frac{wx^2}{2}$$ Eq. 3.2-5

For section *A* to *B* of the drive end shaft (Figure 77), there is no load of the shaft so the internal shear force in this section is constant at the value of shear force calculated at *B*. For the bending moment in this section, bending moment with respect to *x* is in a constant slope. Shear force and bending moment diagrams are shown in Figure 79 and Figure 80.

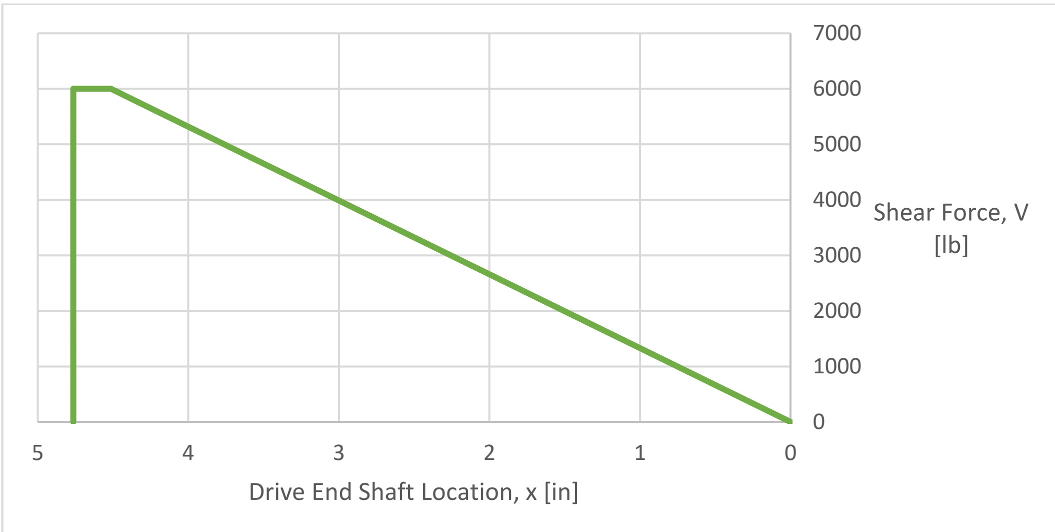


Figure 79: Shear Force Diagram of Drive End Shaft

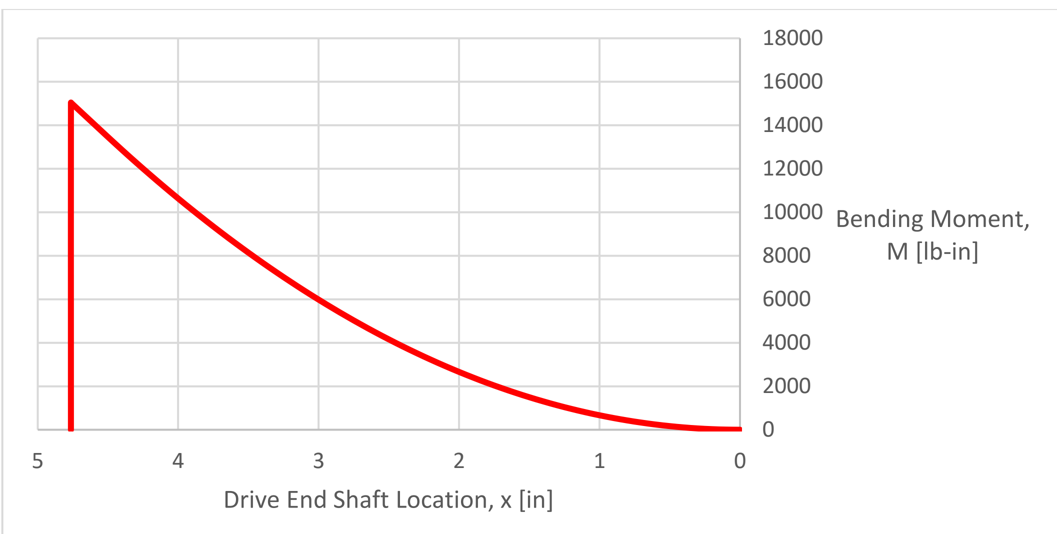


Figure 80: Bending Moment Diagram of Drive End Shaft

From Figure 79, maximum shear force in the drive end shaft is 6000 [lb] at the section *A* to *B*. Maximum bending moment in the drive end shaft is 15,042 [lb·in] located at *A* on the shaft from Figure 80 and Figure 76.

From these maximum values, the average shear stress and maximum bending stress can be calculated using Eq. 3.2-6, Eq. 3.2-7, and Eq. 3.2-8.

$$\tau_{avg} = \frac{V_{max}}{A_S} \quad \text{Eq. 3.2-6}$$

$$\sigma_{max} = \frac{|M_{max}|c}{I} \quad \text{Eq. 3.2-7}$$

Where *I* for circle is,

$$I = \frac{1}{4}\pi r^4 \quad \text{Eq. 3.2-8}$$

The values for variables are shown in Table VI.

TABLE VI. VARIABLES FOR STRESS ANALYSIS CALCULATIONS OF DRIVE END SHAFT

Variable	Definition	Magnitude/Value [unit]
V_{max}	Maximum shear stress in drive end shaft	6,000 [lb]
M_{max}	Maximum bending moment in drive end shaft	15,042 [lb·in]
A_S	Area of shearing, circular cross-section of drive end shaft	3.1416 [in^2]
c	The maximum distance from the neutral axis of the drive end shaft	1 [in]

The average shear stress and the maximum bending stress are summarized in Table VII.

TABLE VII. MAX STRESSES IN DRIVE END SHAFT

Stress in drive end shaft	Definition	Magnitude [psi]
τ_{avg}	Average shear stress	1,910
τ_{max}	Maximum shear stress	2,546
σ_{max}	Maximum bending Stress	19,152

The calculated average shear stress is not representative of the actual max shear stress in the drive end shaft. Maximum shear stress in the circular shaft can be determined using Eq. 3.2-9.

For circular beam shape:

$$\tau_{max} = \frac{4V_{max}}{3A_S} \quad \text{Eq. 3.2-9 [10]}$$

From Table VII,*TABLE VII* both the max shear stress and max bending stress are under the yield strength of the material used for the drive end shaft, 1045 cold drawn steel, yield strength of 77 [kpsi] [11] with a safety factor of 3.

3.2.2.1.2. Number of Cycles of Drive End Shaft

In determining the life cycle of the drive end shaft, the stress-life method from Shigley's Mechanical Engineering Design is used [12]. The assumption is made where the drive end shaft is a completely reversing simple loading case. Therefore, it is the following:

$$\sigma_{rev} = \sigma_{max} \quad \text{Eq. 3.2-10}$$

Where,

$$\sigma_{rev} = 19.2\ [kpsi]$$

The pristine endurance limit S_e' of 1045 cold drawn steel for the drive end shaft is determined using Eq. 3.2-11 and the minimum tensile strength S_{ut}.

$$S_e' = 0.5S_{ut} \quad \text{Eq. 3.2-11 [13]}$$

Where,

$$S_{ut} = 91\ [kpsi]\ [3]$$

Therefore,

$$S_e' = 45.5\ [kpsi]$$

Now the approximated actual endurance limit S_e of the drive end shaft is determined using the Marin equation (Eq. 3.2-12).

$$S_e = k_a k_b k_c k_d k_e k_f S_e' \quad \text{Eq. 3.2-12 [14]}$$

The modifying factors used to calculate the endurance limit are defined in Table VIII.

TABLE VIII. ENDURANCE LIMIT MODIFYING FACTORS

Modifying Factors	Definition
k_a	Surface condition modification factor
k_b	Size modification factor
k_c	Load modification factor
k_d	temperature modification factor
k_e	Reliability factor
k_f	Miscellaneous-effects modification factor

Surface condition of the drive end shaft is machined, and the modifying factor k_a is found using Eq. 3.2-13.

$$k_a = aS_{ut}^b \qquad \text{Eq. 3.2-13 [14]}$$

Where,

$$a = 2.70$$

$$b = -0.265 \qquad \text{for machined surface [15].}$$

The size factor of the drive end shaft at the critical location of max stress, *A* from Figure 77 subjected to bending and rotation is determined using Eq. 3.2-14.

$$k_b = 0.879d^{-0.107} \qquad \text{Eq. 3.2-14 [15]}$$

Where,

$$d = 2\ [in]$$

The load factor for bending is,

$$k_c = 1\ [16]$$

The A-Stand supports are used at room temperature inside the MacDon factory, therefore the temperature factor is,

$$k_d = 1\ [17]$$

Using a reliability of 99% for the standard deviation of the endurance limit, reliability factor is,

$$k_e = 0.814\ [18]$$

The miscellaneous-effects modification factor is not considered in the drive end shaft and is given a value of one. Table IX gives the summarized modifying factors for the Marin equation.

TABLE IX. CALCULATED MODIFYING FACTORS OF DRIVE END SHAFT FOR MARIN EQUATION

Modifying Factor
$\boldsymbol{k_a = 0.817}$
$\boldsymbol{k_b = 0.816}$
$\boldsymbol{k_c = 1}$
$\boldsymbol{k_d = 1}$
$\boldsymbol{k_e = 0.814}$
$\boldsymbol{k_f = 1}$

From Eq. 3.2-12, $S_e = 24.7\ [kpsi]$

The drive end shaft has no features at the critical location, *A* (Figure 77) where max stress is located. Therefore, there are no stress concentrations present at location *A* and no stress concentration factors need to be calculated to determine number of cycles for the drive end shaft.

To determine fatigue life of drive end shaft, constants *a* and *b* are calculated using Eq. 3.2-15 and Eq. 3.2-16.

$$a = \frac{(fS_{ut})^2}{S_e} \quad \text{Eq. 3.2-15 [19]}$$

$$b = -\frac{1}{3}\log\left(\frac{fS_{ut}}{S_e}\right) \quad \text{Eq. 3.2-16 [19]}$$

Where, $f \approx 0.86\ [4]$

Therefore,

$$a = 248.0$$

$$b = -0.167$$

With constants *a* and *b* determined, using equation xx, the number of cycles of the drive end shaft is calculated.

$$N = \left(\frac{\sigma_{rev}}{a}\right)^{\frac{1}{b}} \quad \text{Eq. 3.2-17 [19]}$$

Where, $N = 4.5 \times 10^6\ cycles$

From Shigley's textbook, cycle life of 10^6 cycles or more is considered as an infinite life for the mechanical component [20]. Therefore, the drive end shaft is assumed to have an infinite life span with a fatigue loading of three times the intended load of the welding fixture and accomplishes one of the clients needs in Table VI.

3.2.2.2. Stress Analysis of Idle End A-Stand Shaft

The idle end shaft is utilized to connect the welding fixture yoke with the A-Stand. The yoke is a tube that is assumed to apply a distributed surface load on the top cylindrical face of the shaft shown in Figure 81. In this section, bending stress and moment of the shaft will be determined while the shaft supporting the welding fixture.

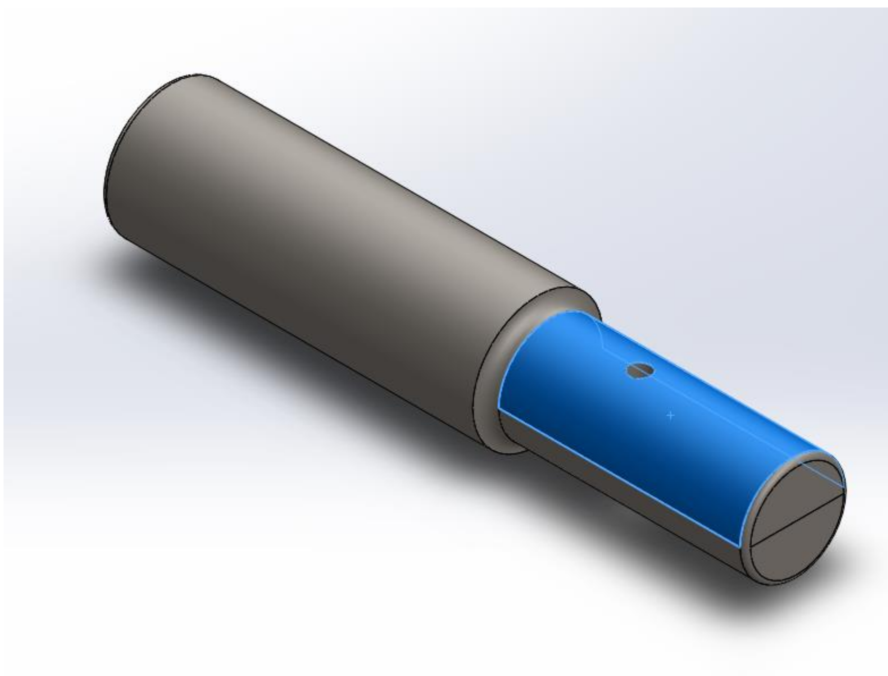


Figure 81: Idle End Shaft, Vertical Downwards Load is Placed on Highlighted Blue Surface

For the two-dimensional stress analysis, load from welding fixture yoke is simplified to a distributed load that is applied onto the idle end shaft. Specifically, the part of the shaft in contact with the welding fixture yoke which is indicated in Figure 82. The idle end shaft is then treated as a simple beam in bending with circular cross section.

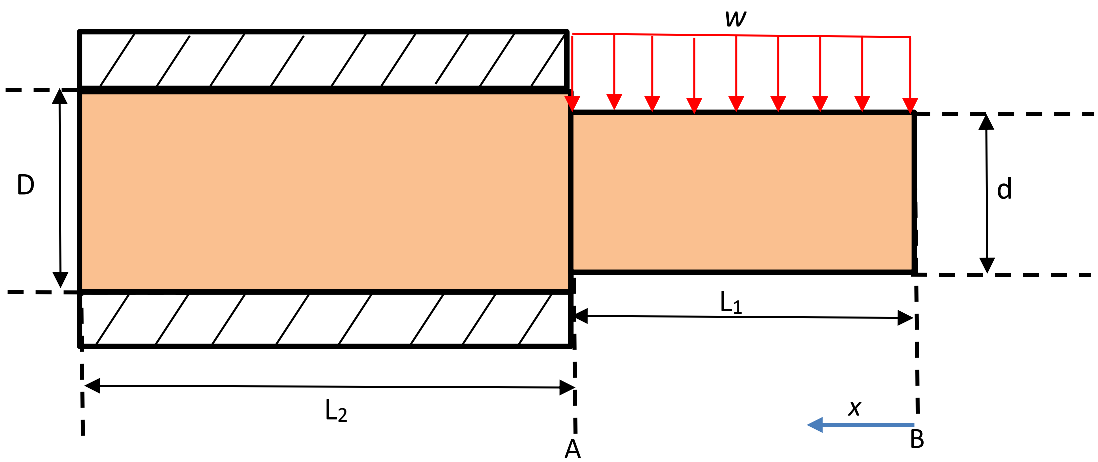


Figure 82: Idle End Shaft Stress Analysis with Distributed Load, w, from Welding Fixture Yoke

From Figure 82, distributed load w is applied on the idle end shaft for length of L_1 and the location of interest in the x-direction starts at the end of the idle end shaft, B. The variables showed in Figure 82 was summarized in Table X.

TABLE X. DEFINED VARIABLES FROM Figure 82

Variable	Definition	Magnitude (Unit)
W	Distributed load applied on the shaft with safety factor of 3.	1290.32 [lb/in]
D	Diameter of the shaft supporting the welding fixture.	2 [in]
D	Diameter of the shaft inside sleeve.	2.5 [in]
R	Fillet of the shaft	0.25 [in]
L_1	Length of the shaft supporting the welding fixture.	4.65 [in]
L_2	Length of the shaft inside sleeve.	7.06 [in]

From Table X, w is calculated from load P from the welding fixture that was determined in the assumption and dividing by L_1 show in Eq. 3.2-18. Therefore, the point load P is 6000 [lb].

$$w = \frac{P}{L_1} \qquad \text{Eq. 3.2-9}$$

From Figure 82, shear force and bending moment diagrams are obtained starting from B to A. from the shear bending moment diagrams, location of the shaft where maximum shear force and bending moment can be found and average shear stress and maximum bending stress can be found in the idle end shaft.

First, reaction force and moment at location A is found and indicated in Figure 83, where R_{ay} is the reaction force and M_A is the moment.

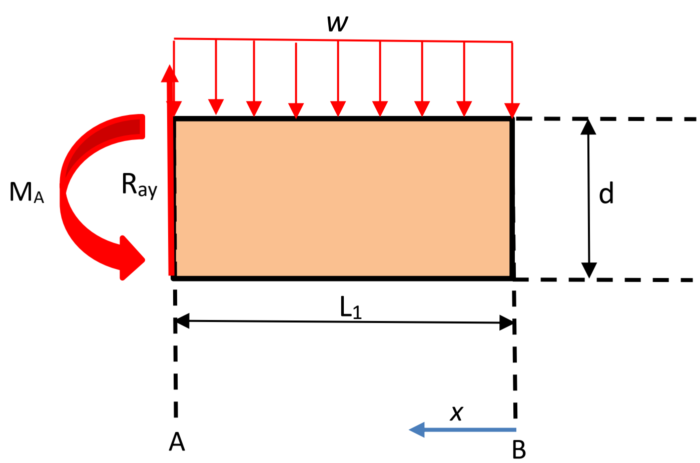


Figure 83: Free Body Diagram of Idle End Shaft from A to B

Summing all the forces in y-direction, the reaction force R_{ay} is found from Eq. 3.2-19. To find the reaction moment M_A at A, distributed load w is replaced with equivalent point load in the center of the distributed load w. Therefore, using moment balance equation, the reaction moment M_A is then equal in magnitude to moment caused by the distributed load w. Based on the Eq. 3.2-19, the reaction force is 6000 [lb]. And the reaction moment at location A is 13950 $[\mathrm{lb} \cdot \mathrm{in}]$.

$$R_{ay} = \mathrm{w}L_1 \qquad \text{Eq. 3.2-19}$$

$$M_A = \frac{\mathrm{w}{L_1}^2}{2} \qquad \text{Eq. 3.2-20}$$

3.2.2.2.1. Shear Force, Bending Moment and Stresses of Idle End Shaft

Shear force and bending moment are determined by cutting out the section of idle end shaft starting from B and replacing with the internal shear force V and the bending moment M, so that the section of the shaft remains stationary. The shear force and bending moment diagram can then be calculate and plotted as a function of x to make shear force and bending moment diagrams.

To calculate the shear force on idle end shaft under distributed load w. Force balance equation can be used. Moreover, to calculate the bending moment on the idle end shaft under distributed load w. The distributed load is replaced with equivalent point load at the center of the distributed load with respect to x. The values of the shear force and bending stress can be determined by Eq. 3.2-12 and 3.2-13.

$$V = \mathrm{wx} \qquad \text{Eq. 3.2-4}$$

$$M = \frac{\mathrm{wx}^2}{2} \qquad \text{Eq. 3.2-5}$$

Based on the results from previous equations, the shear force and bending moment diagrams are shown in Figure 84 and Figure 85.

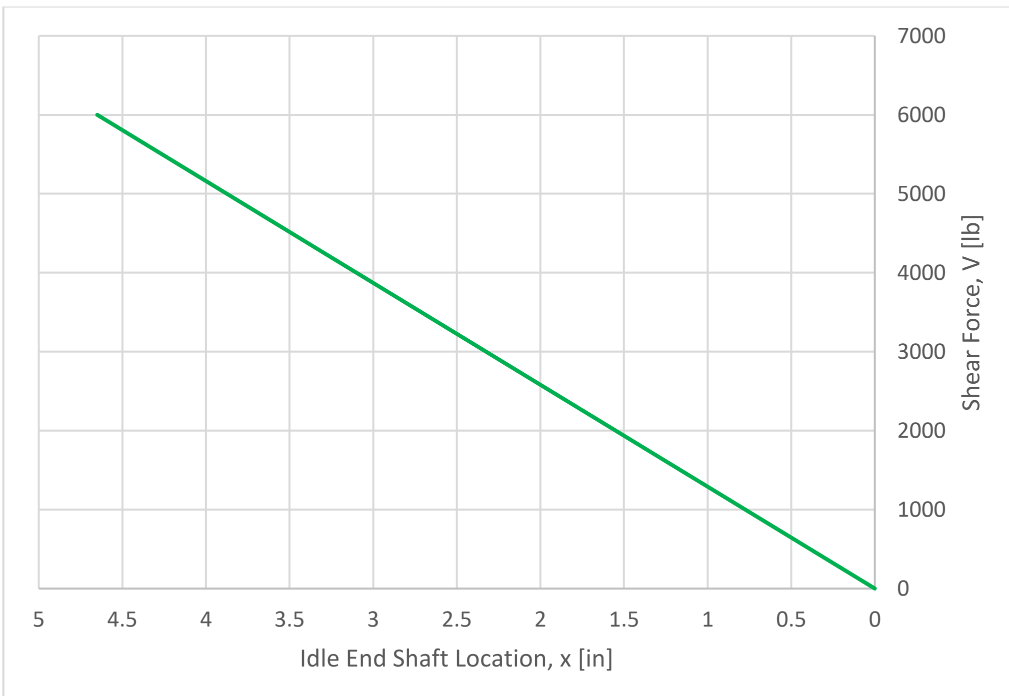


Figure 84: Shear Force Diagram of Idle End Shaft

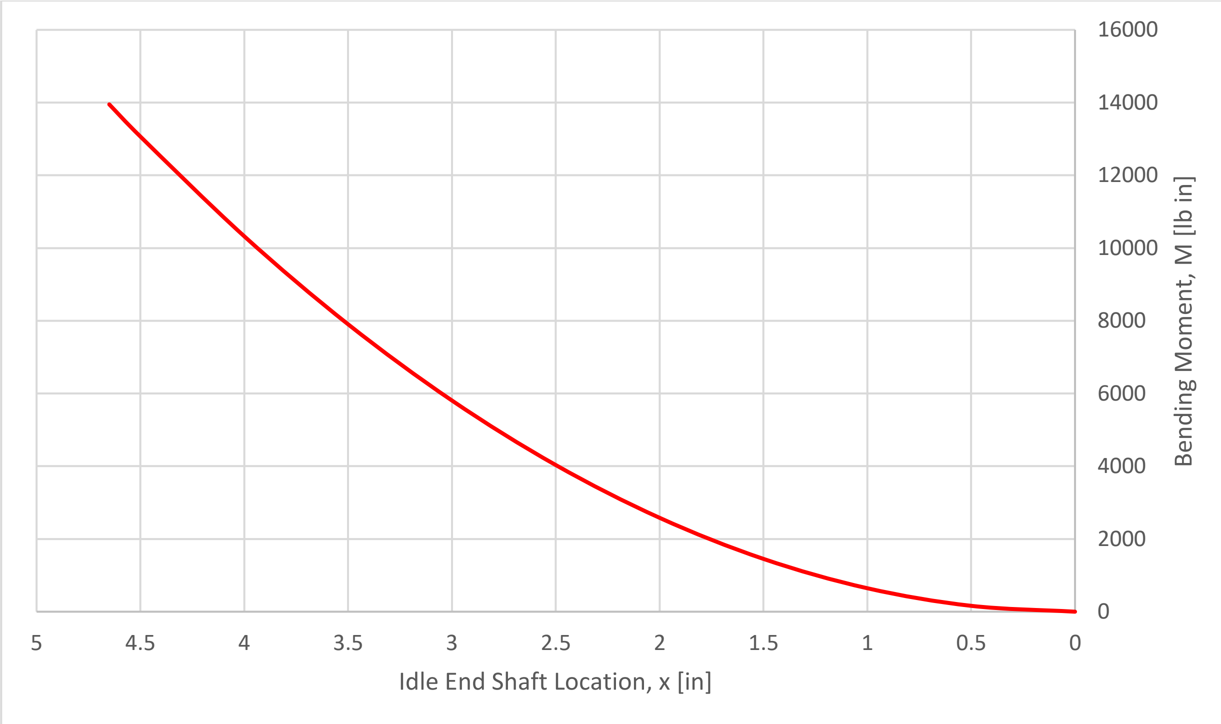


Figure 85: Bending Moment Diagram of Idle End Shaft

From Figure 84, the maximum shear force in the idle end shaft is 6000 [lb]. The maximum bending moment in the idle end shaft is 13,950 [lb · in] at location A of the shaft.

From the maximum values, the average shear stress and maximum bending stress can be calculated using Eq. 3.2-6, Eq. 3.2-7 and Eq. 3.2-8.

$$\tau_{avg} = \frac{V_{max}}{A_S} \quad \text{Eq. 3.2-6}$$

$$\sigma_{max} = \frac{|M_{max}|c}{I} \quad \text{Eq. 3.2-7}$$

Where *I* for circle is,

$$I = \frac{1}{4}\pi r^4 \quad \text{Eq. 3.2-8}$$

The values for the variable are shown in Table XI.

TABLE XI. VARIBALES FOR STRESS ANALYSIS CALCULATIONS OF IDLE END SHAFT

Variable	Definition	Magnitude/Value [unit]
V_{max}	Maximum shear stress in drive end shaft	6000 [lb]
M_{max}	Maximum bending moment in drive end shaft	13,950 [lb·in]
A_S	Area of shearing, circular cross-section of drive end shaft	3.1416 [in^2]
C	The maximum distance from the neutral axis of the drive end shaft	1 [in]

Therefore, the average shear stress and maximum bending stress are summarized in Table XII. The maximum shear stress in the idle end shaft can be calculated like the drive end shaft using Eq. 3.2-9.

TABLE XII. MAX STRESSES IN IDLE END SHAFT

Stress in drive end shaft	Definition	Magnitude [psi]
τ_{avg}	Average shear stress	1910
τ_{max}	Max shear stress	2544
σ_{max}	Maximum bending Stress	17,767

For the idle shaft, Steel C1045 was used and the yield strength is 77 [kpsi] [11]. From Table XII, both the maximum shear stress and maximum bending stress are under the yield strength of the material used for the idle end shaft. Therefore, the idle end shaft can support the load of the welding fixture with a safety factor of 3.

3.2.2.2.2. Stress Concentration of Idle End Shaft

The maximum stress in the idle end shaft is actual larger than the calculated max stress from Table XIII. This is because a stress concentration is present in the idle end shaft where the diameter changes from 2 [in] to 2.5 [in] (Figure 82). According to the dimension of the shaft found in Table XIII, the stress concentration factor can be found to be 1.55 using Figure 86.

TABLE XIII. IDLE END SHAFT STRESS CONCENTRATION LOCATION DIMENSIONS

Dimension	Length [in]
D	2.5
d	2
r	0.25

[redacted]

Figure 86: Chart for Theoretical Stress-Concentration Factor [21]

Therefore, the bending stress in account with stress concentration factor is calculated from Eq. 3.2-21.

$$\sigma_{max} = K_t \frac{M_{max} c}{I} \qquad \text{Eq. 3.2-21}$$

Where

$$\sigma_{max} = 27{,}531 \; [psi]$$

From factoring in the stress concentration present in the idle end shaft due to the increase in diameter, max stress is now 27.5 [kpsi]. This is still lower than the yield strength of steel C1045 (77 [kpsi]) and therefore shows idle end shaft can support the load from the welding fixture including a safety factor of 3.

3.2.2.2.3. Number of Cycles of Idle End Shaft

In determining the number of cycles in the idle end shaft, process used is the same as the drive end shaft section 3.2.2.1.2 which is the stress-life method from Shigley's [12]. The difference is the presence of stress concentration to the increasing radius feature of the idle end shaft. This difference will be explained in detail later in this subsection.

The idle end shaft is made from same 1045 cold drawn steel used in the drive end shaft. For this steel, the yield strength is 77 [kpsi] and the minimum tensile strength is 91 [kpsi] [11].

The endurance limit can be found same way as drive end according to Eq. 3.2-11 and Eq. 3.2-12.

$$S_e' = 0.5S_{ut}$$ Eq. 3.2-11 [13]

$$S_e = k_a k_b k_c k_d k_e k_f S_e'$$ Eq. 3.2-12

Where the modifying factors in Eq. 3.2-12 are summarized in Table VIII. The modifying factors can be determined by the equations in the following.

Surface factor, $$k_a = aS_{ut}^{\ b}$$ Eq. 3.2-13

Where, $$k_a = 0.817$$

Size factor, $$k_b = 0.879d^{-0.107}$$ Eq. 3.2-14

Where, $$k_b = 0.816$$

Reliability factor of 99%, $$k_e = 0.814$$

Therefore, the endurance limit can be determined by Eq. 3.2-12.

Where, $$S_e = 24.7\ [kpsi]$$

A Neuber Constant (a material constant) is calculated using Eq. 3.2-22. The value of the constant was calculated to be 0.07099 [$\sqrt{\text{in}}$].

$$\sqrt{a} = 0.246 - 3.08(10^{-3})S_{ut} + 1.51(10^{-5})S_{ut}^{\ 2} - 2.67(10^{-8})S_{ut}^{\ 3}$$ Eq. 3.2-22

$$K_f = 1 + \frac{K_t - 1}{1 + \sqrt{a/r}}$$ Eq. 3.2-23

Thus, the fatigue stress concentration can be determined by Eq. 3.2-23. The value was calculated to be 1.4060. The corresponding reversing bending stress is calculated by Eq. 3.2-24.

$$\sigma_{rev} = K_f \frac{Mc}{I}$$ Eq. 3.2-24

Where, $$\sigma_{rev} = 25.0\ [kpsi]$$

Two important constants will then be determined based on Eq. 3.2-25 and Eq. 3.2-26. Finally, the number of cycles on the idle end shaft is determined by Eq. 3.2-27 with fatigue strength fraction of 0.86 [19].

$$a = \frac{(f \cdot S_{ut})^2}{S_e} \quad \text{Eq. 3.2-25}$$

Where, $$a = 248.0$$

$$b = -\frac{1}{3} log \frac{f \cdot S_{ut}}{S_e} \quad \text{Eq. 3.2-26}$$

Where, $$b = -0.167$$

$$N = \left(\frac{\sigma_{rev}}{a}\right)^{1/b} \quad \text{Eq. 3.2-27}$$

Where, $$N = 927,119 \text{ cycles}$$

The number of cycles on the idle end shaft is in the high cycle life region described in Shigley's [20]. To make sure the idle end shaft lasts the intended life of 15 years required by the client, an approximation of the cycles a day is made so that cycles in 15 years can be determined. An assumption of 20-minute cycle time per workpiece on the welding fixture is made and one completed workpiece being one cycle. In 24-hours, the number of cycles is 72. In a five-day working week, the number of cycles is 360 cycles. In a year, 52 times 360 is 18,720 cycles. For 15 years, number of approximated cycles on the idle end shaft is 280,800 cycles. This is significantly lower than the cycles calculated for the idle end using the stress-life method. Therefore, idle end shaft successfully meets clients need in operating life.

3.2.2.3. Stress Analysis of Inboard Support Legs

The use of inboard support legs on both the drive end and the idle end A-Stands is required to prevent the A-Stands from falling over inward, towards the welding fixture as the fixture is lowered onto the A-Stands.

In this sub section, the cross-sectional area of the support legs is determined so that it can withstand the applied load from the welding fixture. The cross-sectional area of the support legs is determined by calculating analytically the force in the support leg due to the load from the welding fixture.

For this analysis, a beam with truss members acting as the support leg is used to simplify the analysis, which is illustrated in Figure 87 and Table XIV shows the legend for the A-Stand force analysis.

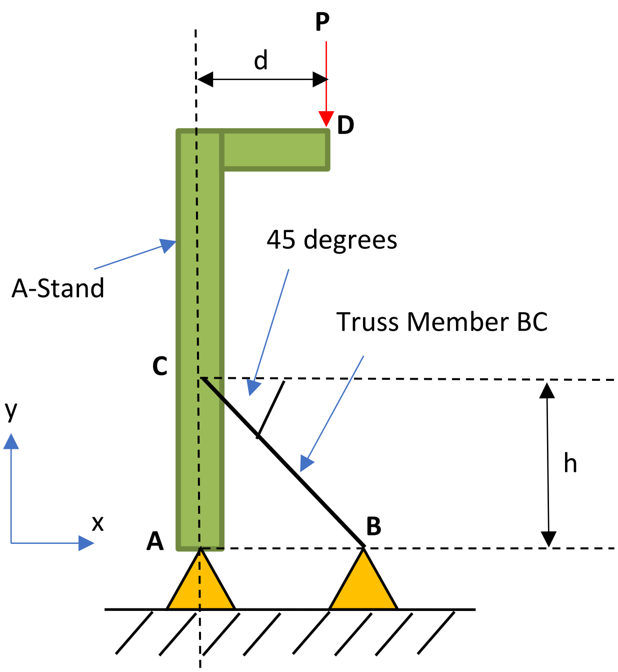


Figure 87: A-Stand Force Diagram

TABLE XIV. LEGEND FOR A-STAND FORCE ANALYSIS

Variable	Definition	Magnitude/Value [units]
P	Applied load from welding fixture multiplied by safety factor of 3.	6,000 [lb]
D	Horizontal distance from applied load P and y-axis intersecting points C and A.	10.7 [in]
H	Verticle distance from point C to B.	8 [in]

From Figure 87, the A-Stand and truss member *BC* are supported by hinged supports at points A and B. The hinged supports are used to simplify the analysis which eliminates possible moments at point A and B. The load P is applied at distance d from point A. From the stress analysis of the A-Stand shafts, the load P was a distributed load, but in this support leg analysis, the load P was made as a point load and set to the maximum distance that the shaft makes contact with the welding fixture yoke to observe the worst case scenario with the highest internal forces in the members of the structure. This means that the design will be over built to handle more than its intended load to ensure safety.

Since the member BC is a truss, its force must be along the same line of action as at the member and can only be in tension or compression represented as in Figure 88.

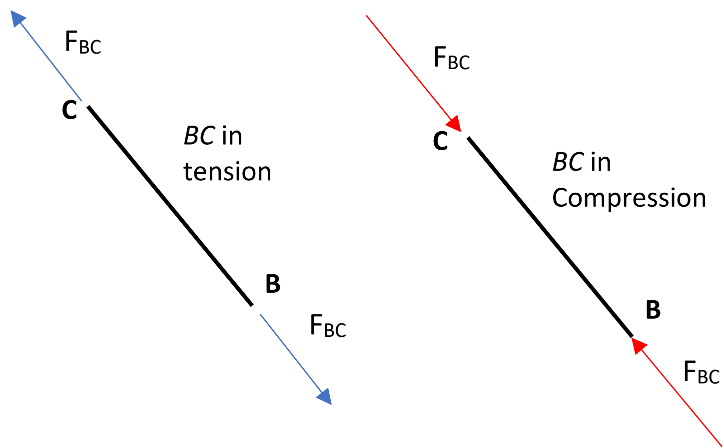


Figure 88: Truss Member BC, Force F_{BC} *shown in Tension and Compression*

To find the force F_{BC}, the following force and moment balance steps are taken:

1. Replace hinge supports at A and B with reaction forces in the x and y directions.
2. Generate system of equations by trying to solve for the unknown reaction forces at points A and B by analyzing total A-Stand Structure (A-Stand and truss BC a one rigid structure).
3. Generate system of equations by analyzing A-Stand and truss BC inidividually.
4. Solve for the unknown forces using the system of equations.

By replacing the hinged supports with reaction forces at A and B, we get the following reaction forces as shown in Figure 89.

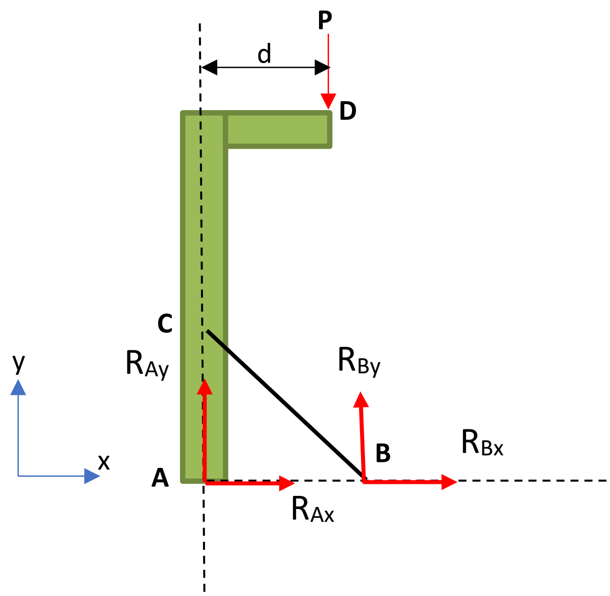


Figure 89: A-Stand with Reaction Forces

Detailed calculations for generating force and moment balance equations can be found in the Appendix C.1. Stress Calculations for the Support Leg. The following results of solving the unknowns; R_{Bx} and R_{By} are as follow:

$$|R_{Bx}| = |R_{By}| \quad \text{Eq. 3.2-28}$$

$$R_{By} = \frac{P\,d}{h} \quad \text{Eq. 3.2-29}$$

$$F_{BC} = \sqrt{2R_{By}{}^2} \quad \text{Eq. 3.2-30}$$

From Eq. 3.2-30, the force in truss BC was calculated to be 11,349 [lb] in compression. Since truss BC is in compression, buckling in truss BC must be taken into account.

3.2.2.3.1. Failure by Buckling From Compressive Load

Using Euler's Buckling Equation [5], the minimum critical moment of inertia I_{cr} of truss member BC is determined.

$$P_{cr} = \frac{\pi^2 E\, I_{cr}}{L^2} \quad \text{Eq. 3.2-31 [22]}$$

Where, $$P_{cr} = F_{BC}$$ Eq. 3.2-32

TABLE XV. DEFINED VARIABLES OF EULER'S BUCKLING EQUATION

Variable	Definition	Magnitude/Value [units]
P_{cr}	Critical compressive load that causes member to buckle.	11,349 [lb]
E	Young's modulus of elasticity of material used for member under compressive load.	29×10^6 [psi]
I_{cr}	Critical moment of inertia of member under compressive load.	Determined using Eq. 3.2-33 [in^4]
L	Length of the member under compressive load.	11.3 [in]

Substituting Eq. 3.2-32 in Eq. 3.2-31 and rearranging to solve for I_{cr}:

$$I_{cr} = \frac{F_{BC}L^2}{\pi^2 E}$$ Eq. 3.2-33

Where, $$I_{cr} = 5.063 \times 10^{-3}\ [in^4]$$

This moment of inertia is relatively small due to the large modulus of elasticity of the material used in member BC (1010 cold rolled steel, 29 x 10^6 [psi]). Therefore, it can be concluded that failure due to buckling of member BC, the inboard support leg is not likely compared to failure in the stress of the inboard support leg due to compressive load F_{BC}.

3.2.2.3.2. Failure by Normal Stress From Compression

The inboard support leg must now be checked for failure under the compressive load of F_{BC}. Normal stress in the support leg is set to the yield strength of the material used in the support leg. Minimum cross-sectional area of the support leg can than be determined using Eq. 3.2-34.

$$\sigma = \frac{F_{BC}}{A}$$ Eq. 3.2-34

Where, $$\sigma = \sigma_{yld}$$ Eq. 3.2-35

The minimum cross-sectional area *A* is calculated from Eq. 3.2-34 and solving for *A*, where σ_{yld} is 60,000 [psi] for 1010 cold rolled steel [23]. Minimum cross-sectional area required is 0.18915 [in^2].

Using 1010 cold rolled retangular tube steel supplied from metal supermarkets, the following cross-section is provided in Figure 90 with the dimension in Table XVI.

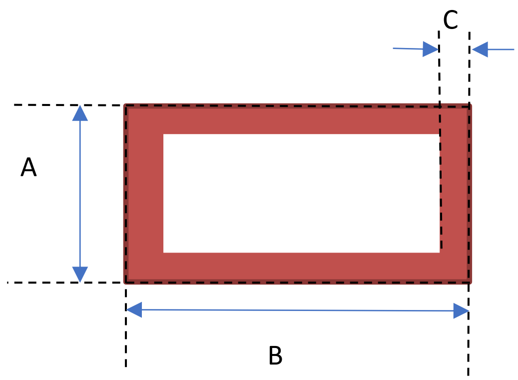


Figure 90: Cross-Sectional Area of Support Leg (Member BC)

TABLE XVI. DIMENSIONS OF CROSS-SECTION OF SUPPORT LEG (MEMBER BC)

Dimension	Length [in]
A	1.5
B	3
C	0.065

From Figure 90 and Table XVI, the cross-sectional area of the support leg is 0.2883 [in^2] which is larger than the required minimum cross-sectional area A (0.18915 [in^2]). Therefore, the support leg will not fail due to compressive load of F_{BC}.

Finally, checking the moment of inertia of the support leg using Eq. 3.2-36.

$$I = \frac{1}{12} bh^3 \qquad \text{Eq. 3.2-36}$$

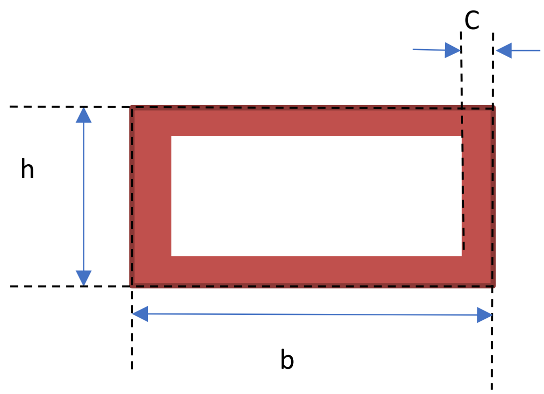


Figure 91: Cross-section of Support Leg for Moment of Inertia

TABLE XVII. DIMENSIONS OF CROSS-SECTION OF SUPPORT LEG FOR MOMENT OF INERTIA

Dimension	Length [in]
h	1.5
b	3
C	0.065

Since a hollow rectangular tube is used for the support leg, the moment of inertia of the support leg must be calculated by finding the moment of inertia of both the outer rectangle and inner rectangle in Figure 91. Then the actual moment of inertia of the support leg is calculated by subtracting the moment of inertia of inner rectangle from the moment of inertia of outer rectangle using the dimension given in Table XVII. The detailed calculation steps for this can be found in the Appendix C.3. Moment of inertia of the support leg is 0.1210 [in^4] which is larger than I_{cr} (5.063×10^{-3} [in^4]). Therefore, the support leg will not fail by buckling due to the compressive load of F_{BC}.

3.2.2.3.3. Final Results of Analytical Stress Analysis of Support Leg

The final calculated results are summarized in Table XVIII.

TABLE XVIII. FINAL RESULTS OF ANALYTICAL STRESS ANAYLSIS OF SUPPORT LEG

Variable	Definition	Magnitude [units]
F_{BC}	Compressive force in support leg	11,349 [lb]
I_{cr}	Critical moment of inertia of support leg	5.063×10^{-3} [in^4]
I_{actual}	Actual moment of inertia of support leg	0.1210 [in^4]
A_{min}	Minimum cross-sectional area of support leg	0.18915 [in^2]
A_{actual}	Actual cross-sectional area of support leg	0.2883 [in^2]

3.2.3. Preliminary FEA

In this section, the numerical results obtained from the finite element analysis (FEA) will be introduced to validate the accuracy of the analytical results in Section 3.2.2. by using both SolidWorks 2018/2019 and ANSYS. Material used in the FEA for both drive end and idle end shafts is 1045 cold drawn steel. The material properties provided by SolidWorks Version 2018/2019 was: 29.73 x 10^6 [psi] for modulus of elasticity, 0.29 for Poisson's Ratio, 90.65 [kpsi] for tensile strength, and 76.87 for yield strength.

3.2.3.1. Drive End

The numerical results for the drive end shaft are shown in this section. Drive end shaft was unable to converge due to boundary conditions applied.

3.2.3.1.1. Numerical Analysis from SolidWorks for Drive End Shaft

After building the model and applying boundary conditions to the shaft, the model will undergo static FEA analysis through SolidWorks. A convergence plot will be provided to find the converged maximum von-Mises stress if it exists.

The shaft will be analyzed in a static condition with a surface force load of 6,000 [lbs] applied onto the drive end shaft shown in Figure 92 with purple arrows. The direction of the force is normal to the top surface of the 2 [in] diameter shaft with 4.5138 [in] length. The sleeve bearing supporting the drive end shaft is simulated as fixed geometry in the y and z-direction for the 2 [in] diameter shaft with 4 [in] length. Finally, the end of the shaft is fixed in the x-direction which simulates the handle cover of the shaft. The boundary conditions and applied load of designed shaft are shown in Figure 92 as green vector arrows.

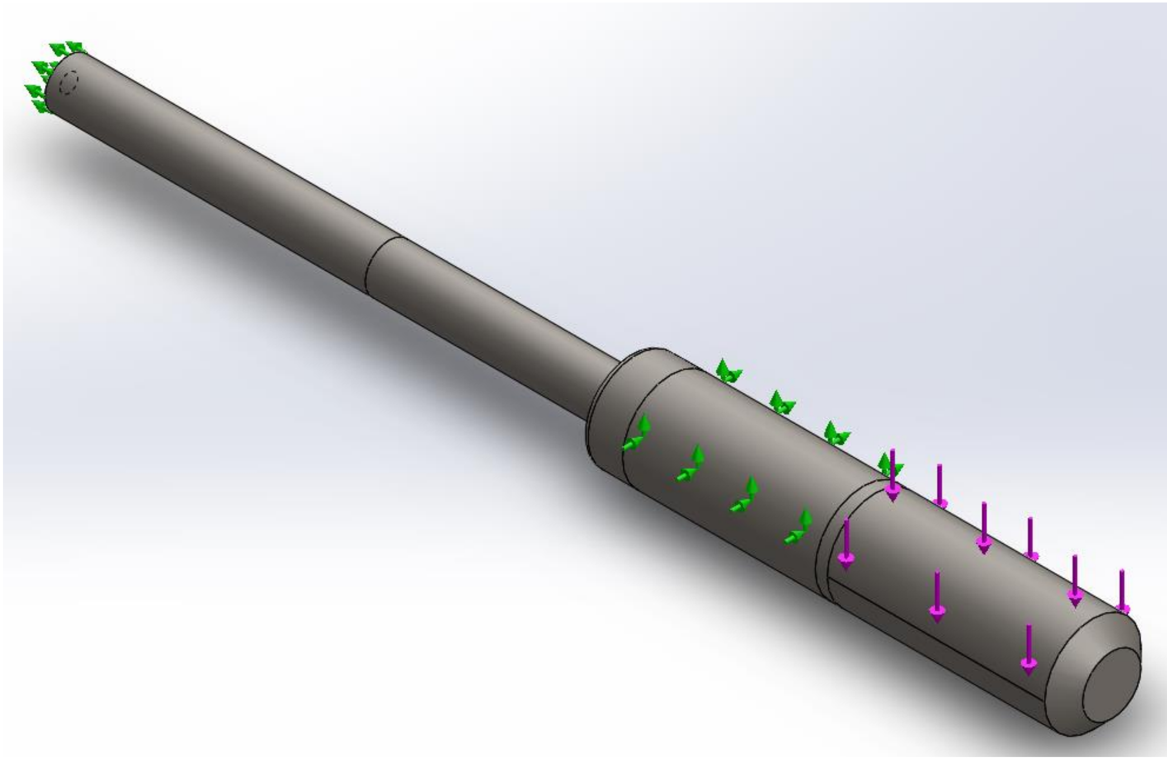


Figure 92: Boundary Conditions for the Drive End Shaft

From the results shown in Figure 93, maximum von-Mises was not able to converge and was increasing as mess was being refined to include more elements. The max stress was last calculated to be 37,480 [psi]. This exceeds the calculated max stress determined analytically in Section 3.2.2.1.1. The discrepancy can be explained by the discontinuity that occurs right where the drive end shaft begins to be fixed from the sleeve bearing.

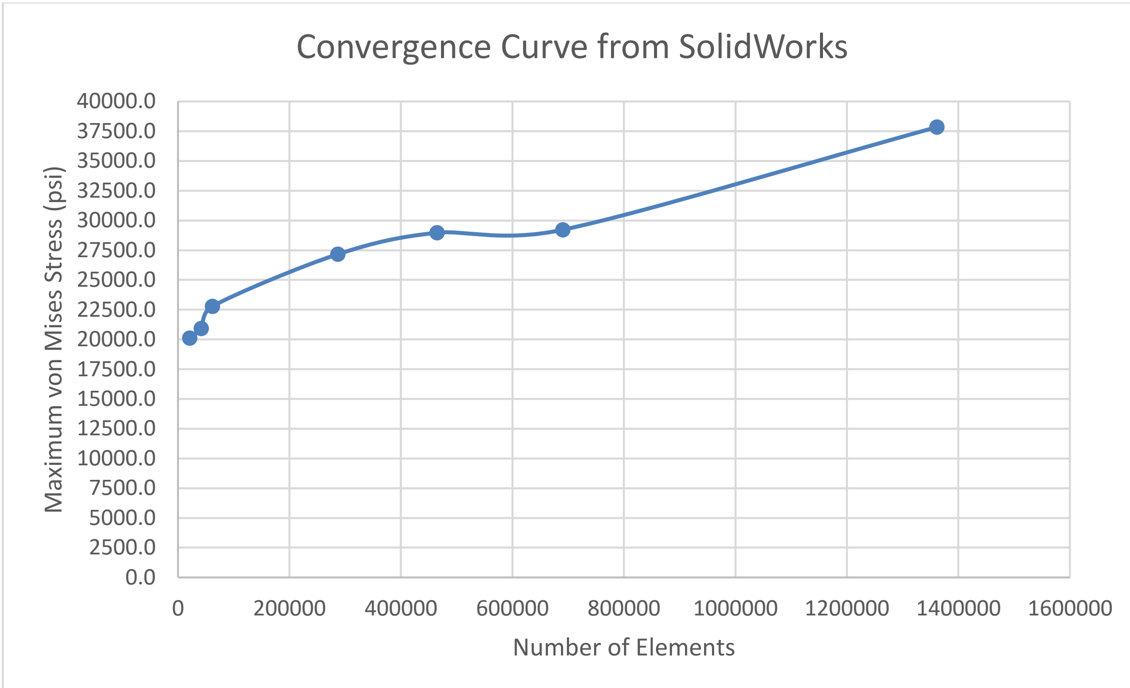


Figure 93: Convergence Plot from SolidWorks for the Drive End Shaft

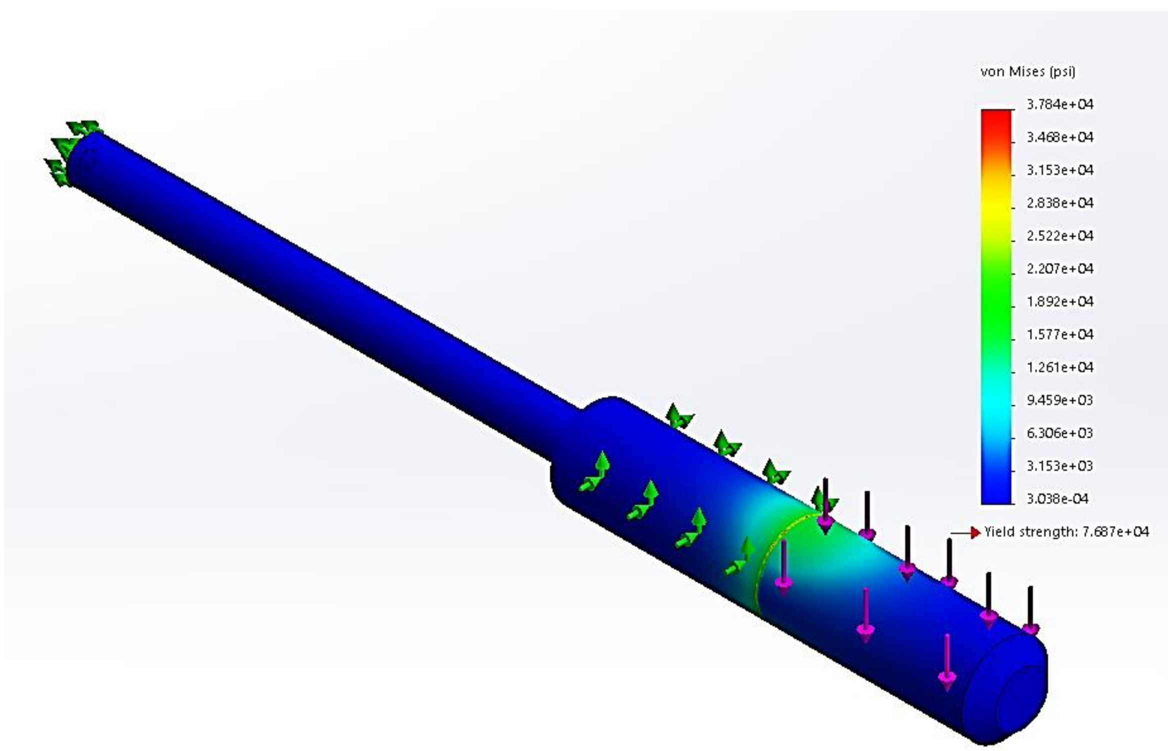


Figure 94: Preliminary FEA Result from SolidWorks for the Drive End Shaft

The final mesh conditions used for the last iteration of drive end shaft analysis is shown in Figure 95. This created a meshed model of the drive end shaft with 1,361,165 elements which can be seen in Figure 93.

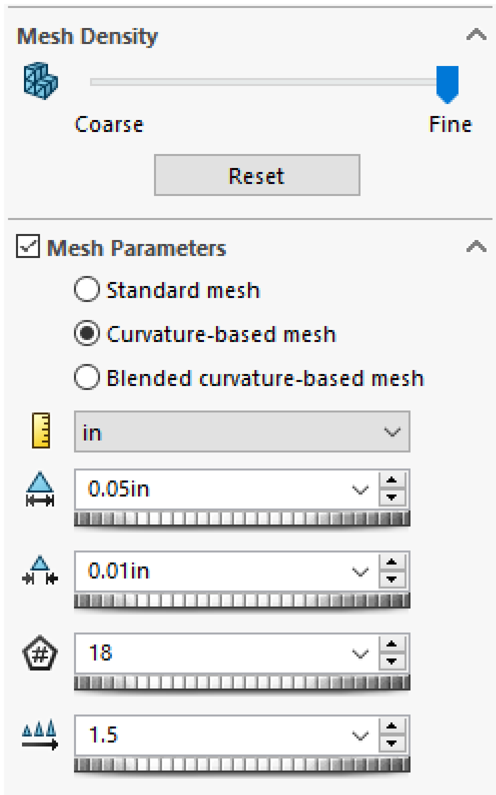


Figure 95: Final Mesh Condition for Final Iteration of Drive End Shaft

3.2.3.1.2. Numerical Analysis from ANSYS for Drive End Shaft

The designed drive end shaft had also been analyzed with different sizes of mesh in ANSYS. The convergence plot is indicated in Figure 96. The maximum von-Mises stress is 65228 psi which is indicated in Figure 97. Drive end shaft was also unable to converge most likely due to the applied boundary condition on the drive end shaft.

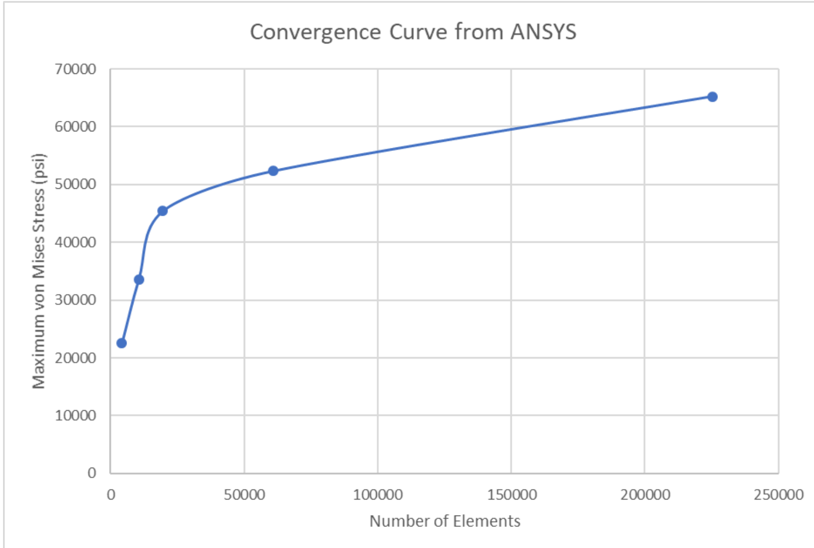


Figure 96: Convergence Plot from ANSYS for the Drive End Shaft

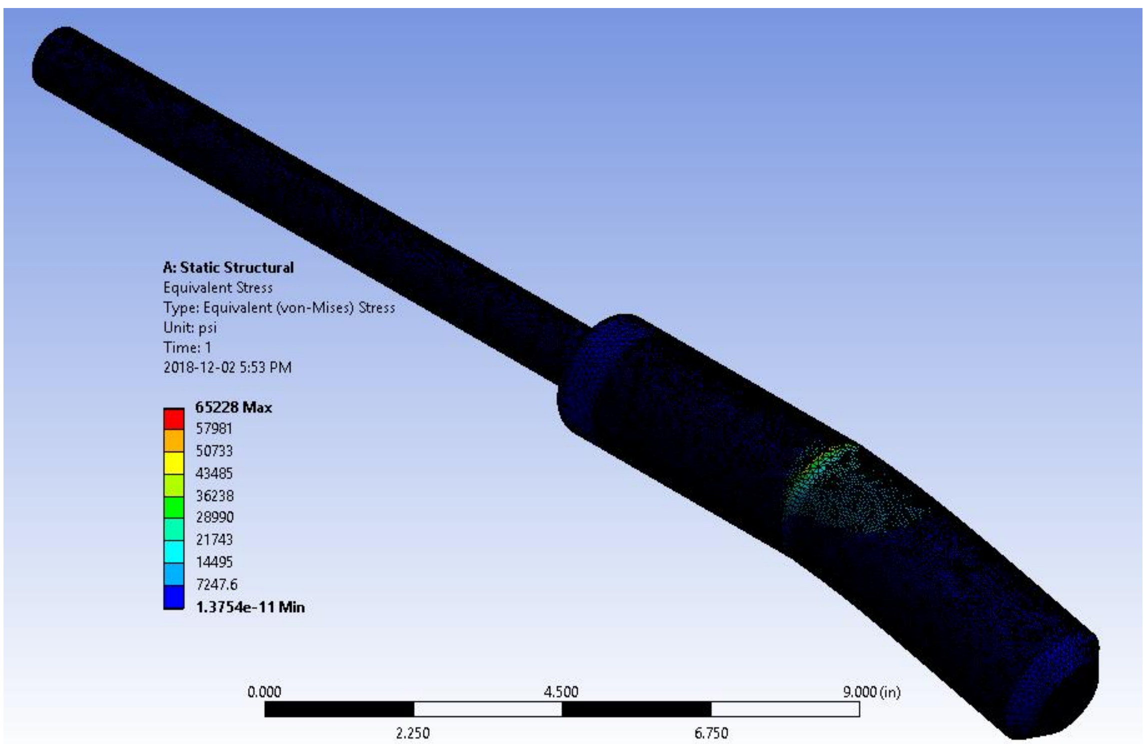


Figure 97: Preliminary FEA Result from ANSYS for the Drive End Shaft

Even though mesh was unable to converge and max stress was significantly higher than analytical results in Section 3.2.2.1.1, contour plots show in Figure 94 and Figure 97 show location of max stress which agrees with what is expected in analytical results.

3.2.3.2. Idle End

The numerical results for the idle end shaft are shown in this section. Results from FEA in both SolidWorks and ANSYS were able to converge.

3.2.3.2.1. Numerical Results from SolidWorks for Idle End Shaft

Recall that the shaft will be analyzed in a static condition like the drive end analysis. Surface load of 6,000 [lbs] is used and applied onto the surface of the idle end shaft shown in Figure 98 with purple arrows. The direction of the force is normal to the top surface of the 2 [in] diameter shaft with 5 [in] length. The 2.5 [in] shaft with 7.16 [in] length is considered as fixed geometry in the y and z-direction to simulated rigid support from the support tube of the idle end A-Stand. The back face of the idle end is fixed in the x-direction to simulate the handle cover which prevents movement in that direction. The boundary conditions of the designed shaft are shown in Figure 98 as green vector arrows.

.

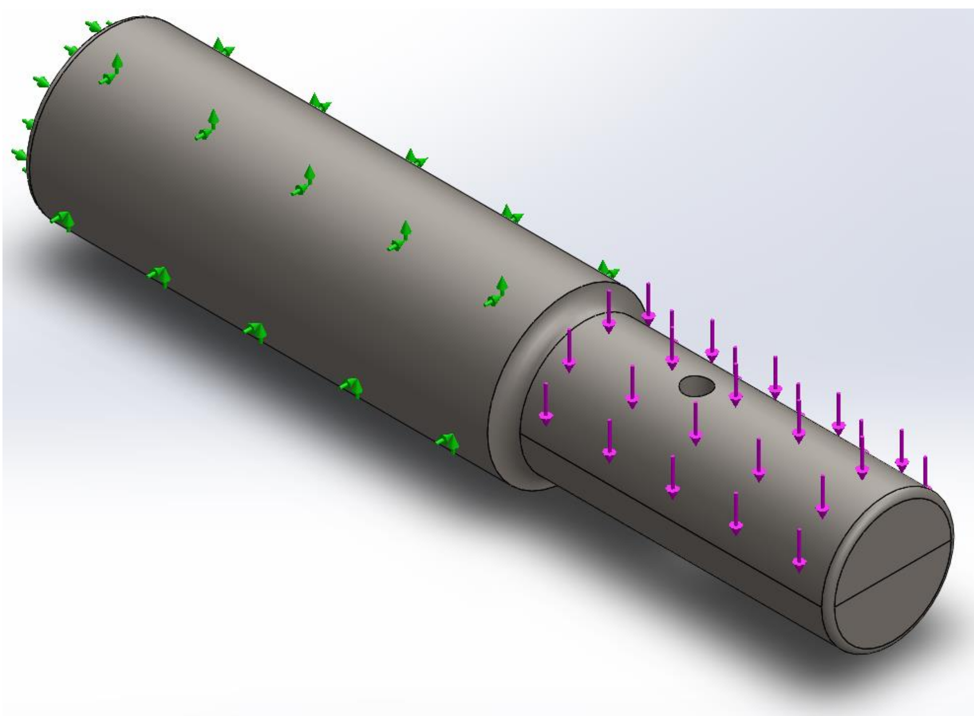


Figure 98: Boundary Conditions for the Idle End Shaft

After building the model of the designed shaft and applying boundary conditions to the shaft, the model can undergo static FEA analysis throughout SolidWorks. However, the model needs to be meshed. Since the mesh size will affect the final results, the results require convergence of the max von-Mises stress as mesh is made finer with more elements. The model will undergo few trials of stress analysis with different sizes of mesh elements. Therefore, a convergence plot of the maximum von-Mises stress over the number of elements will be created to find the converged maximum von-Mises stress if it exists.

The converged maximum von-Mises stress found will be compared with the allowable stress to see whether it satisfies the designated safety factor of 3. If the maximum von-Mises stress is below the allowable yield stress, the designed shaft can be considered feasible to hold the distributed load at static state.

The FEA analysis throughout ANSYS is similar as the analysis throughout in SolidWorks. A convergence plot will be provided to find the converged maximum von-Mises stress if it exists. For the final mesh conditions of the last iteration of the idle end, the same mesh conditions are used as the drive end shaft shown in Figure 95.

The designed shaft had been analyzed with different sizes of mesh in SolidWorks. The convergence plot is indicated in Figure 99. The maximum von-Mises stress is 29400 psi which is indicated in Figure 100.

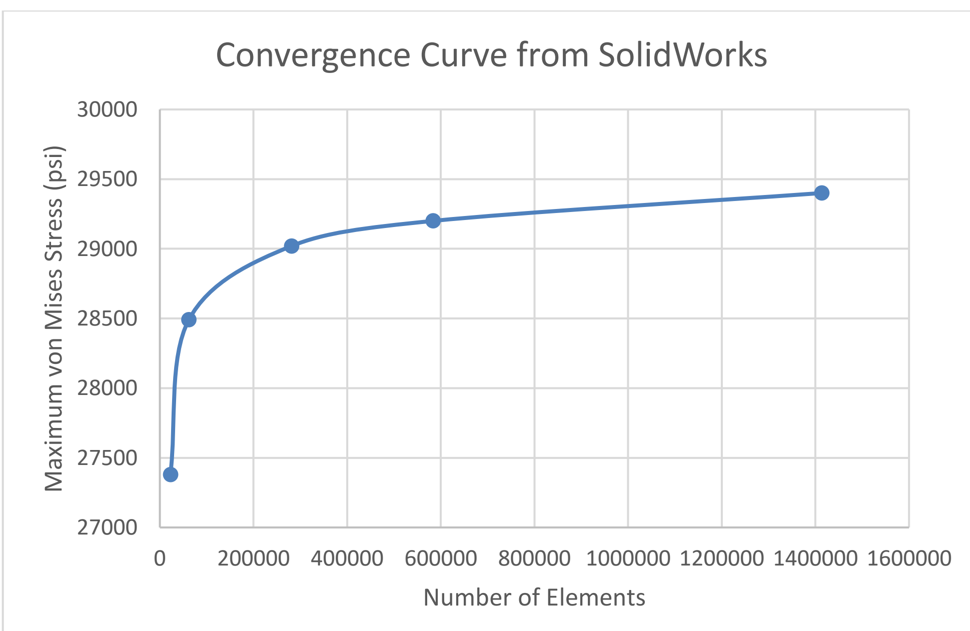


Figure 99: Convergence Plot from SolidWorks for the Idle End Shaft

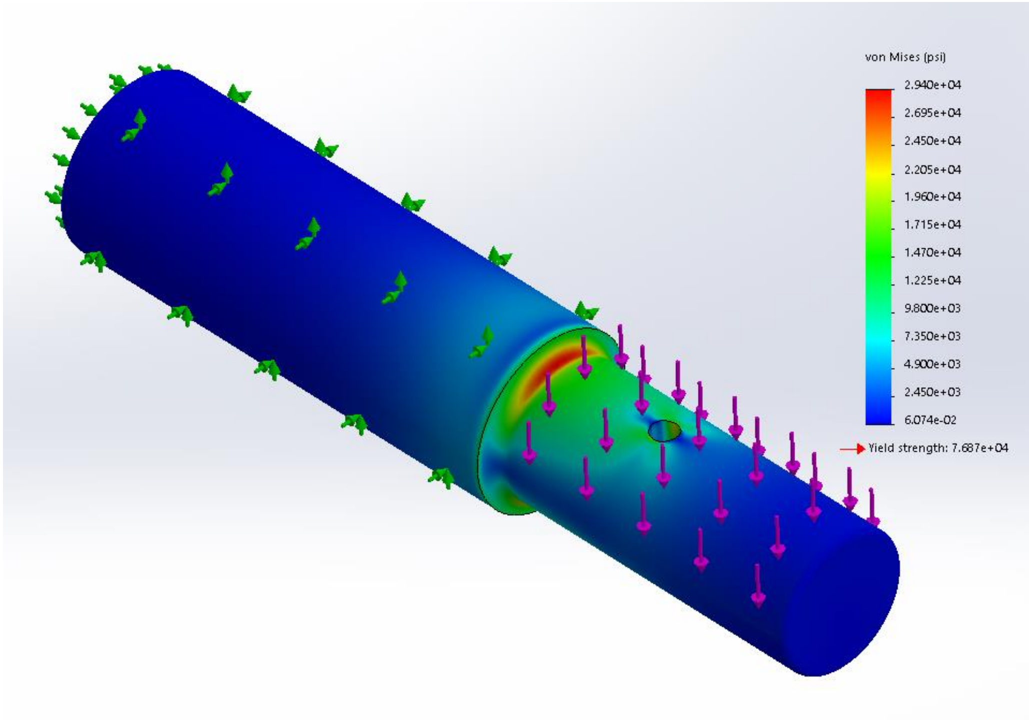


Figure 100: Preliminary FEA Result from SolidWorks for the Idle End Shaft

The results from SolidWorks FEA are similar with analytical results which is 27,531 [psi] in the location of the stress concentration. This shows that the applied boundary conditions are accurate and what the team expects.

3.2.3.2.2. Numerical Results from ANSYS for Idle End Shaft

The designed shaft had also been analyzed with different sizes of mesh in ANSYS. The convergence plot is indicated in Figure 101. The maximum von-Mises stress is 31680 psi which is indicated in Figure 102.

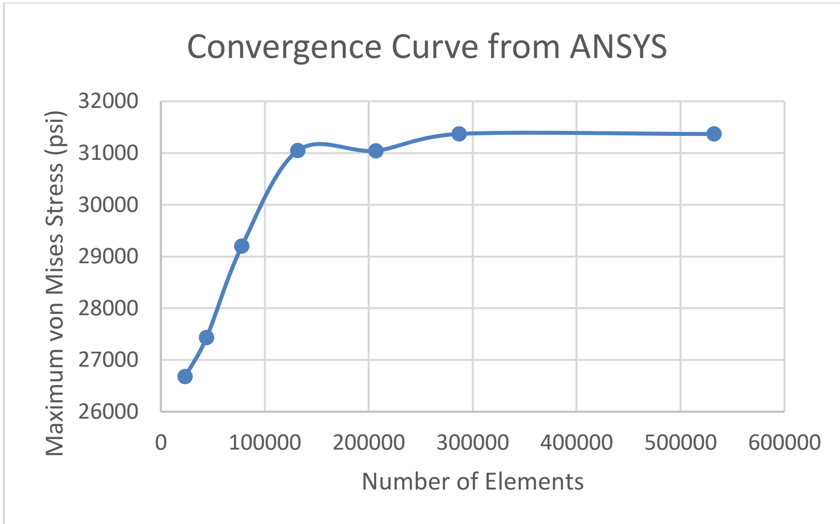


Figure 101: Convergence Plot from ANSYS for the Idle End Shaft

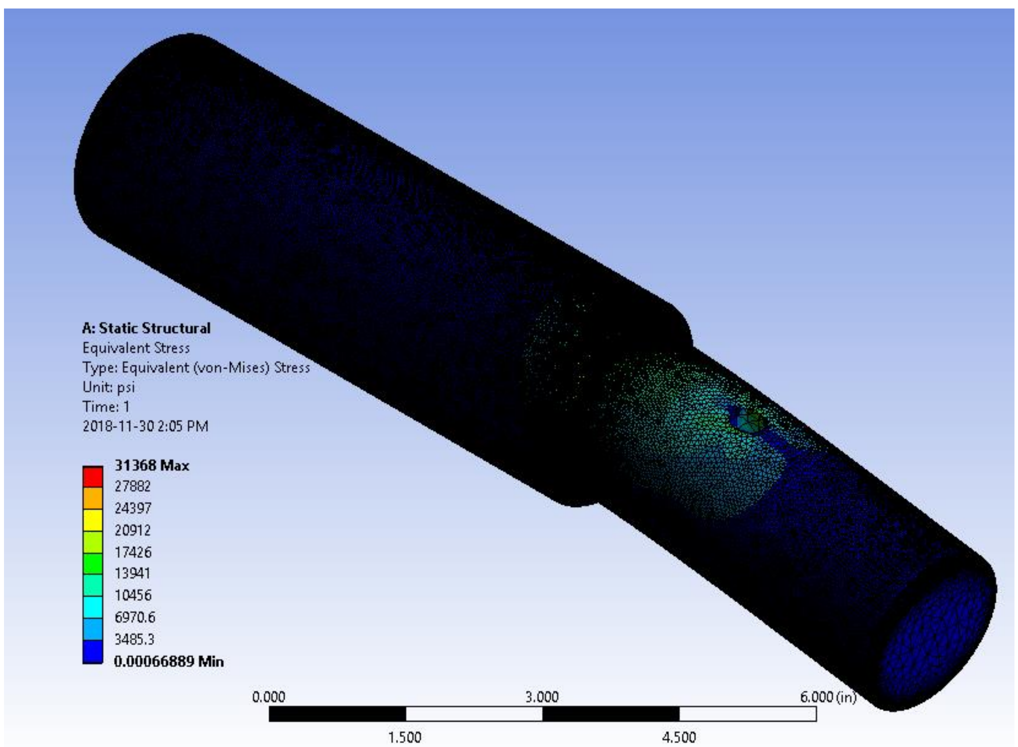


Figure 102: Preliminary FEA Result from ANSYS for the Idle End Shaft

The final maximum von-Mises stress in ANSYS FEA are similar to that of SolidWorks and the analytical results. This further supports results of analytical calculations of the idle end shaft.

3.3. Preliminary Cost Analysis

A preliminary cost analysis was performed to determine whether the final design is manufacturable within the budget. The raw materials used in the final design must be available from the client's stock material list or their designated material providers. The team chose McMaster Carr® and Metal Supermarket as the material providers because of their availability on the required materials. Since the price from the provider's website is in USD for McMaster Carr®, the total unit cost is later converted to CAD using a conversion rate of 1 USD is equal to 1.32 CAD.

A general rule of thumb for estimating manufacturing cost is two dollars per minute and the team estimated the required time of manufacturing depending on the size of the part and the complexity of manufacturing to estimate the final cost to produce a set of the final A-Stand.

The cost was analyzed separately for the drive end and the idle end since they have different features and geometry. Each component and their raw materials, and the estimated machining cost for the idle end and the drive end is shown in Table XIX and Table XX, respectively.

TABLE XIX: PRELIMINARY COST ANALYSIS FOR THE IDLE END ASSEMBLY

	Raw Material [P/N]	Material Cost [USD]	Required Machining	Unit Cost	Machining Cost [CAD]	Source
Shaft	C1045 Steel ASTM A108 [8920K79]	242.38 for 6ft	Drilling Turning Threading	34.45 USD	120	[24]
Sleeve	C1045 Steel ASTM A108 [8920K93]	577.82 for 6ft	Drilling Turning Cutting Boring	56.82 USD	200	[24]
Tabs	Low carbon steel sheet [6544K76]	90.61 for 12"x24"	Cutting	0.15 USD	60	[25]
Cup Layer	3" OD Acetal Rod [8497K493]	34.51 for 1ft	Turning Cutting Boring	7.19 USD	60	[26]
Handle	4130 Alloy steel [89955K779]	56.67 for 6ft	Cutting Welding	7.28 USD	60	[27]
Spacing	Low carbon bars [8910K817]	100.16 for 6ft	Cutting	6.61 USD	40	[28]
Back plate	Low carbon steel sheet [6544K78]	164.02 for 12"x24"	Cutting Threading	9.11 USD	50	[25]
Bearing	Oil-Embedded Bronze Sleeve Bearing [6391K689]	31.08 ea.	N/A	62.16 USD	N/A	[29]
Retaining Ring	Heavy Duty Spiral Internal Retaining Ring [92370A331]	7.51 ea.	N/A	15.02 USD	N/A	[30]
Locking Latch	Screw-on Turn Latch [1512N11]	11.39 ea.	N/A	22.78 USD	N/A	[31]
Screw	Grade 5 Steel Flanged Hex Head Screw [92979A257]	7.39 for 25	N/A	0.3 USD	N/A	[32]
Support Leg	C1010 Cold Worked Rectangular Tube	36.14 for 26"	Cutting	18.07 CAD	6	[33]
Support Leg Base	Low Carbon steel sheet [6544K36]	75.32 for 10"x10"	Cutting	37.66 USD	20	[25]
Support Leg Gusset	C1010 Cold Rolled Steel Plate [6544K29]	45.57 for 8"x8"	Cutting	23.16 USD	20	[25]
			Total [CAD]	391.72	636	
			Total [CAD]	1027.72		

TABLE XX: PRELIMINARY COST ANALYSIS FOR THE DRIVE END ASSEMBLY

	Raw Material at [P/N]	Material Cost [USD]	Required Machining	Unit Cost	Machining Cost [CAD]	Source
Shaft	C1045 Steel ASTM A108 [8920K75]	168.01 for 6ft	Turning Threading	41.13 USD	240	[24]
Flange hub cup	Low carbon steel round tube A513 [7767T93]	383.48 for 6ft	Cutting	13.32 USD	100	[24]
Flange hub wing	Low carbon steel bar [8910K959]	84.02 for 6ft	Drilling Milling	3.2 USD	40	[34]
Flange hub plate	Oversized S7 toll steel rod and disc [8453K34]	278.89 ea.	Turning Boring	70.25 USD	50	[35]
Gussets	Low carbon steel bar [8910K669]	70.49 for 6ft	Milling	5.38 USD	40	[34]
Flange key	oversized steel machine key stock [98830A630]	36.50 for 6ft	Milling Cutting	1.02 USD	40	[36]
Shaft sleeve	C1045 Steel ASTM A108 [8920K88]	392.26 for 6ft	Milling Boring Cutting Threading Turning	81.55 USD	120	[24]
Handle	4130 Alloy steel [89955K779]	56.67 for 6ft	Cutting Welding	7.28 USD	60	[27]
End cover	Low carbon steel sheet [6544K77]	134.82 for 12”x24”	Cutting Threading	9.60 USD	40	[25]
End spacer	Low carbon steel sheet [6544K77]	134.82 for 12”x24”	Cutting Threading	2.93 USD	40	[25]
Locating pins	Straight style ejector pins [93772A133]	15.28 ea.	Tapering Cutting	30.56 USD	40	[37]
Bearing	Oil-Embedded Bronze Sleeve Bearing [6391K28]	111.79 ea.	N/A	111.79 USD	N/A	[29]
Retaining Ring	Heavy Duty Spiral Internal Retaining Ring [92370A331]	7.51 ea.	N/A	15.02 USD	N/A	[30]
Locking Latch	Screw-on Turn Latch [1512N11]	11.39 ea.	N/A	22.78 USD	N/A	[31]
Bolt	Grade 5 Steel Flanged Hex Head Screw [92979A257]	7.39 for 25	N/A	0.3 USD	N/A	[32]
Screw	316 Stainless Steel Shoulder Screws [97345A619]	5.95 ea.	N/A	5.95 USD	N/A	[38]
Support Leg	C1010 Cold Worked Rectangular Tube	36.14 for 26”	Cutting	18.07 CAD	6	[33]

Support Leg Base	Low Carbon steel sheet [6544K36]	75.32 for 10”x10”	Cutting	37.66 USD	20	[25]
Support Leg Gusset	C1010 Cold Rolled Steel Plate [6544K29]	45.57 for 8”x8”	Cutting	23.16 USD	20	[25]
			Total [CAD]	655.47	856	
			Total [CAD]	1511.47		

From Table XIX and Table XX, the total cost of the final design is $2540 CAD in the components that are changed from the existing A-Stand design. To get the total cost for the entire A-Stands, the cost of the existing A-Stands is added onto the cost of the final design components that are changed from the existing A-Stand Design. The existing A-Stands cost $3000 CAD per pair. Therefore, total cost of the final A-Stand design is $5540 CAD which is under client’s budget of $8000 CAD.

3.4. Safety Validation

To validate the safety of the design, the standard operating procedure is explained in this section in detail. Also, preliminary failure modes and effects analysis (FMEA) for both the drive end and the idle end is presented.

3.4.1. Standard Operating Procedures

The detailed operating procedures of performing welding fixture changeover using the new A-Stand design are shown in the following section step by step with corresponding instructive illustrations.

1. Rotate the currently connected welding fixture to its original position.
2. Strap the welding fixture to the overhead gantry crane and lift the crane to eliminate the slack between the welding fixture and strap (make sure the strap is tight, but do not lift the A-stands).
3. Pull out the locking pin used on the idle end connection.

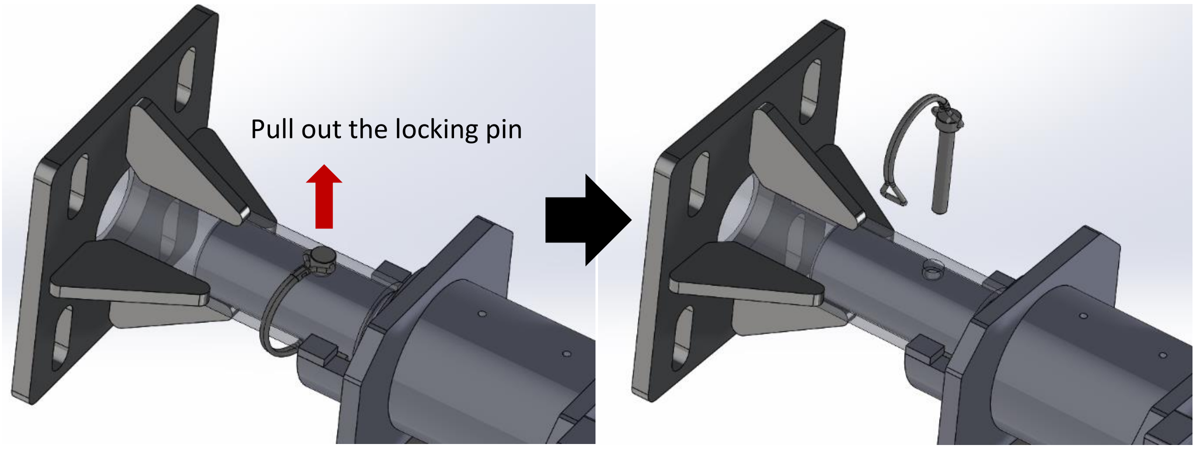


Figure 103: Operating Procedure for Welding Fixture Changeover, Pull Out Locking Pin, Idle End

4. Unlock the safety latches on both drive end and idle end.

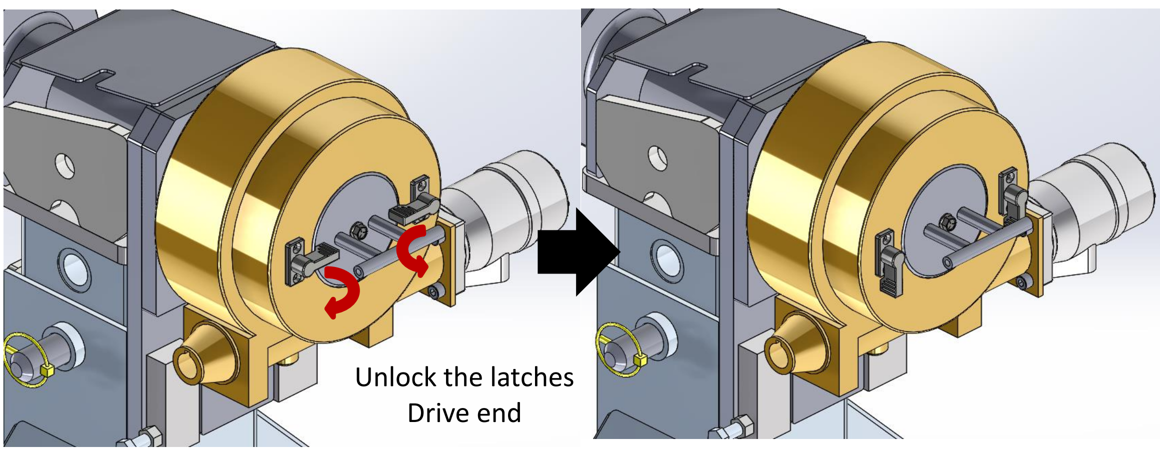


Figure 104: Operating Procedure for Welding Fixture Changeover, Unlock Safety Latches, Drive End

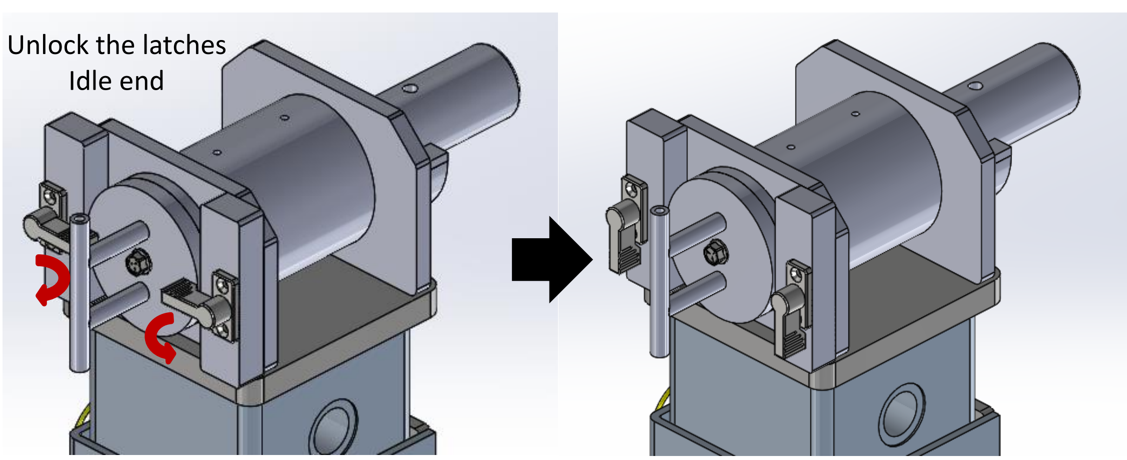


Figure 105: Operating Procedure for Welding Fixture Changeover, Unlock Safety Latches, Idle End

5. Pull the handles to retract the shafts of both drive end and idle end.

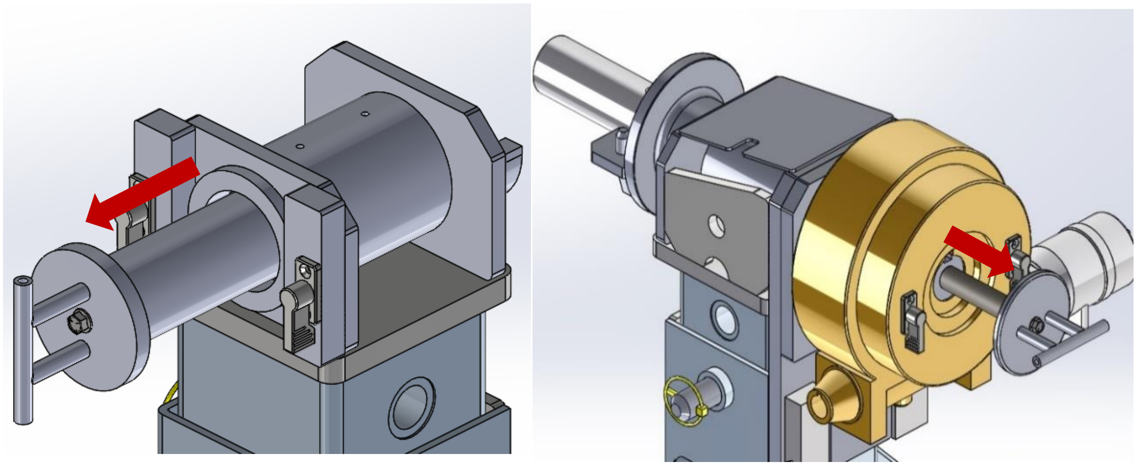


Figure 106: Operating Procedure for Welding Fixture Changeover, Retract shafts, Both Ends

6. Lift up and move away the welding fixture.
7. Bring in the new fixture, strap it to the crane, and lift it above the A-Stands.
8. Adjust the distance between the A-Stands to accommodate the length of the new welding fixture. If the new fixture is in the same length as the current one, keep the A-Stands in original places.
9. Lower the welding fixture using crane, and gently land it on the A-Stand shaft cups.

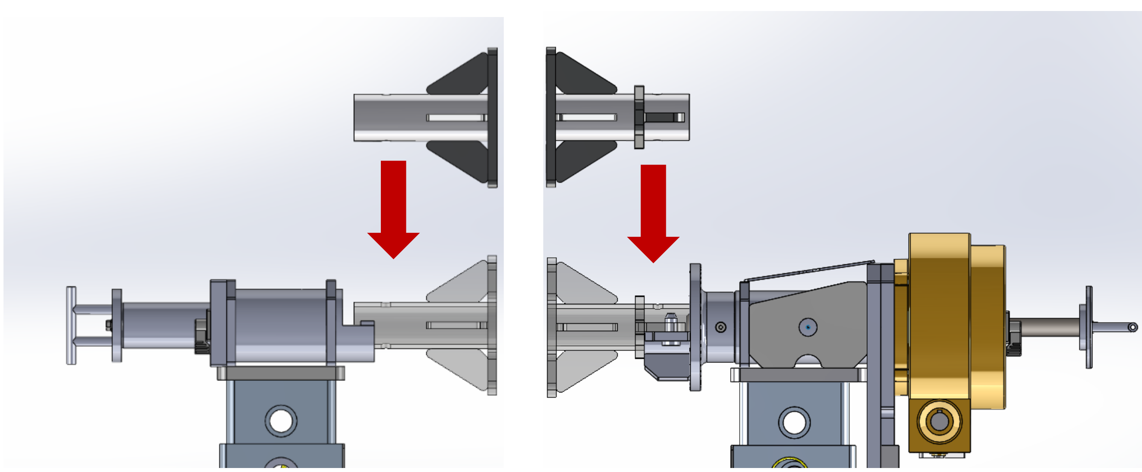


Figure 107: Operating Procedure for Welding Fixture Changeover, Land Welding Fixture on A-Stand Shaft

10. Push the handle to engage the shafts to the welding fixture yoke.

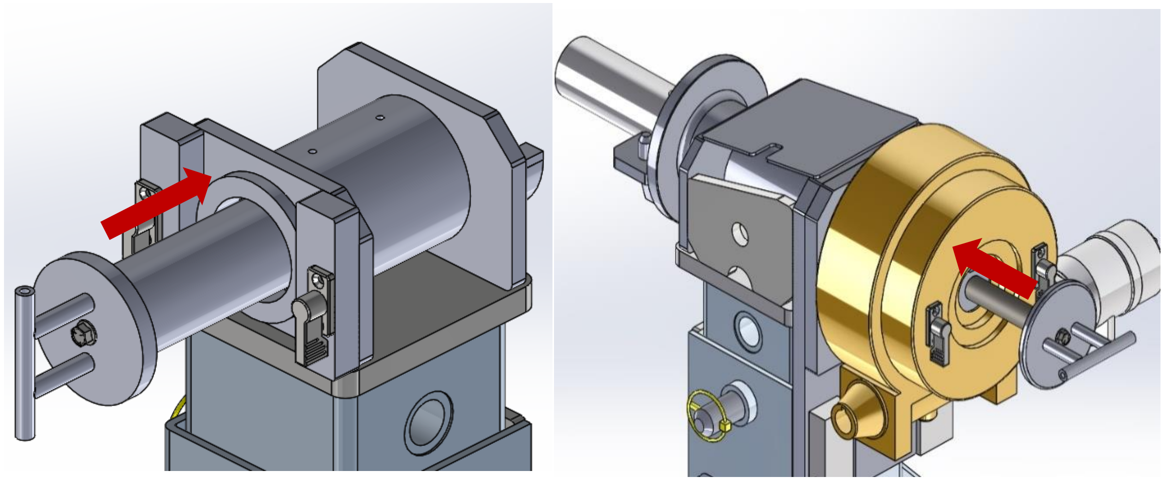


Figure 108: Operating Procedure for Welding Fixture Changeover, Push Shafts Back, Both Ends

11. Plug in the safety pin on the drive end connection.

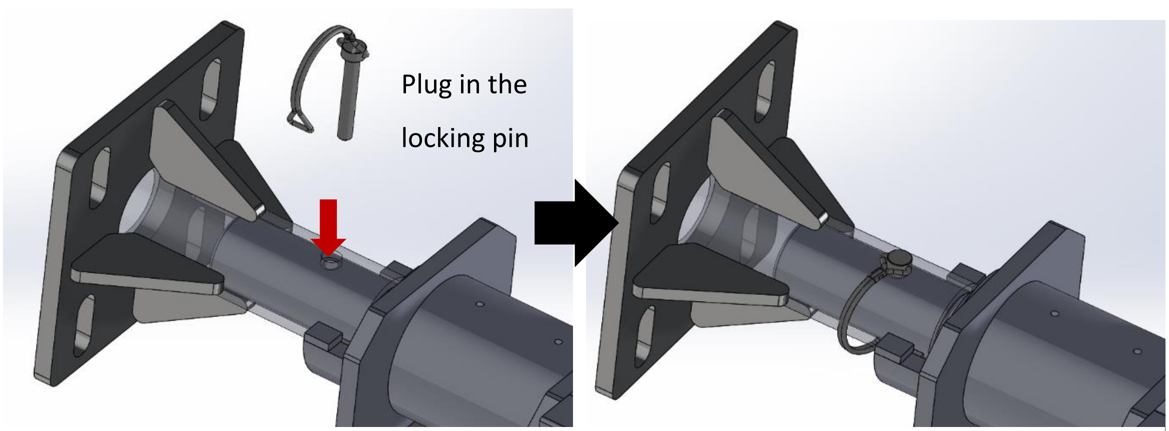


Figure 109: Operating Procedure for Welding Fixture Changeover, Plug in Locking Pin, Idle Ends

12. Lock up the safety latches.

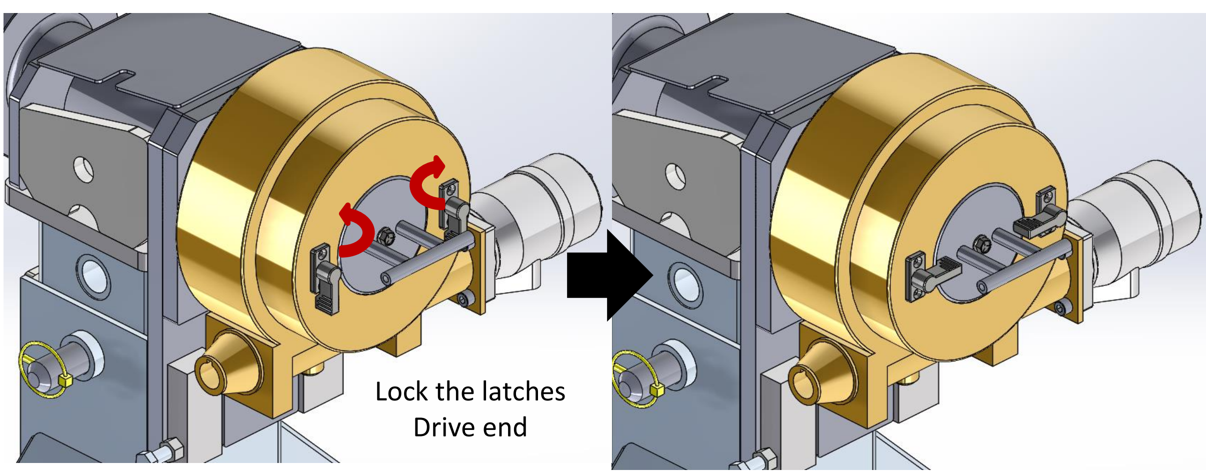


Figure 110: Operating Procedure for Welding Fixture Changeover, Lock Safety Latches, Drive End

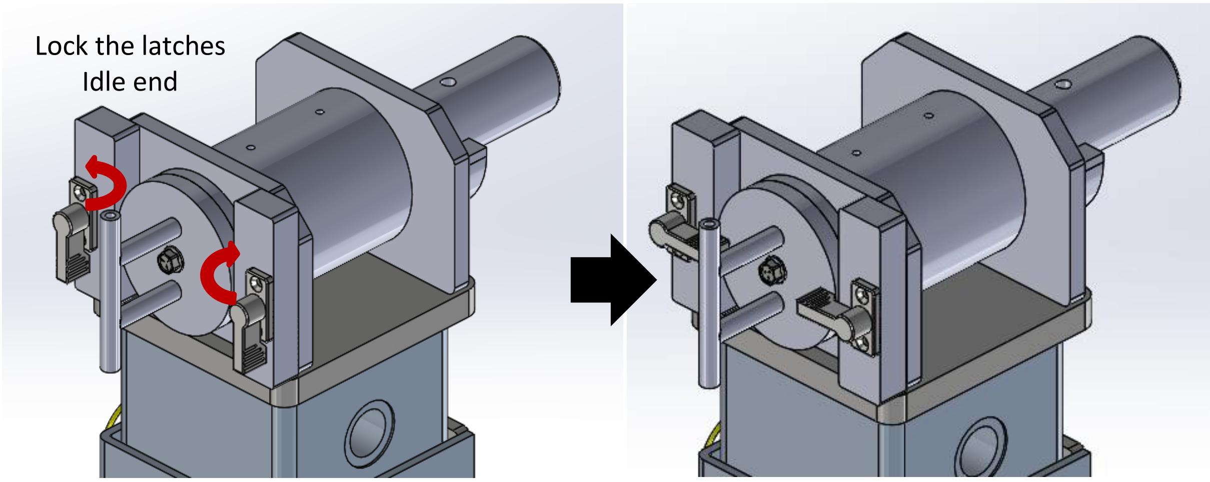


Figure 111: Operating Procedure for Welding Fixture Changeover, Lock Safety Latches, Idle End

13. Loose the strap. The welding fixture changeover complete.

3.4.2. Final Design Preliminary FMEA

A preliminary FMEA was used for both the idle end and the drive end to identify any potential failure modes that can occur in the final design. To initiate the failure modes analysis, the steps or inputs involved in the changeover process are identified. The three primary processes are: connecting welding fixture and shaft (in changeover), supporting the welding fixture (in operation), disconnecting welding fixture (in changeover).

Each failure mode is scored on a scale of one to ten on; severity, frequency of occurrence, and detection level. For the severity, a rating of one is when the failure is unnoticeable and does not affect the performance, and a rating of ten is if the failure can possibly injure people. For the frequency of occurrence, a rating of one is given if the failure only occurs once in a hundred year, and a rating of ten is if the failure occurs more than once a day. A rating of one is given for the detection level if the failure is obvious and easy to detect, and a rating of ten is given if the failure is not detectable.

Once all failure modes have scores for the three criteria mentioned above, the risk priority number (RPN) is calculated by multiplying the scores. Since RPN of one thousand is the highest number a failure mode can obtain, the team decided to provide action recommendations for the failure modes with RPN of higher than two hundred. If the failure mode’s RPN is lower than five hundred, it is assumed that they are not as severe, and the recommendation is to monitor them rather than taking any actions to prevent the failure. The preliminary FMEA for the final design can be found in Table XXI and Table XXII for the drive end and the idle end, respectively.

TABLE XXI. PRELIMINARY FMEA FOR IDLE END

Process Step/Input (X)	Potential Failure Mode	Potential Effect	SEV	Potential Causes	FREQ	Current Controls	DET	RPN	Action Recommendations
In changeover: connecting welding fixture and shaft	Flange hub locating cup fails	No guide for aligning the shaft and fixture yoke.	8	Welding defects/failure	2	Maintenance	6	96	
				Equipment abuse: Drop the welding fixture on the cup without crane holding	4		7	224	Proper operator training
	Handle fails	No secure grip available. Hard to push the shaft.	3	Welding defects/failure	2	Maintenance	2	12	
	Bearings fail	Hard to push the shaft. Bearings wear out fast.	7	Improper lubricating	2	Lubricating/ replacement	2	28	
In operation: supporting the welding fixture	Locating pin of the flange fails	Insufficient connection between shaft and welding fixture. Not able to rotate welding fixture	8	Welding defects/failure	2	Maintenance/ replacement	6	96	
	Flange locating cup fails	Shaft has to withstand all the weight of the welding fixture. No connection between shaft and welding fixture. Not able to rotate welding fixture	8	Welding defects/failure	2	Maintenance	6	96	
	Key in the gearbox fails	Shaft does not rotate	8	Fatigue, Crack	2	Maintenance/ replacement	7	112	
	Key in the flange hub fails	Flange hub does not rotate with shaft, thereby fixture will not be rotated.	8	Fatigue, Crack	2	Maintenance/ replacement	7	112	
	Shaft housing fails	Welding fixture falls. Personal Injury. Equipment damage.	10	Fatigue, crack	1	Maintenance	2	20	
	Bearings fail	Hard to rotate the welding fixture. Bearings wear out fast.	7	Improper lubricating	2	Lubricating/ replacement	2	28	

	Shaft fails/deforms	Welding fixture falls. Welding fixture can not be rotated.	10	Fatigue, Equipment abuse	1	Maintenance/ replacement	2	20	
	Safety latches are unlock	Minor axial movement of the welding fixture.	5	Human error, latches fail	2	Maintenance/proper operator training	2	20	
In changeover: disconnecting welding fixture and shaft	Handle fails	No secure grip available. Hard to retract the shaft.	6	Welding defects/failure	2	Maintenance	2	24	
	Bearings fail	Hard to retract the shaft. Bearings wear out fast.	7	Improper lubricating	2	Lubricating/ replacement	2	28	

TABLE XXII. PRELIMINARY FMEA FOR DRIVE END

Process Step/Input (X)	Potential Failure Mode	Potential Effect	SEV	Potential Causes	FREQ	Current Controls	DET	RPN	Action Recommendations
In changeover: connecting welding fixture and shaft	Shaft housing cup fails	Damage to the housing. No yoke guide for aligning the shaft and fixture yoke.	8	Welding defects/failure	2	Maintenance	6	96	
				Equipment abuse: Drop the welding fixture on the cup without crane holding	4		7	224	Proper operator training
	Shaft and yoke do not align	Unable to connect the shaft and the fixture	7	Delrin® acetal resin layer wears out	4	Replacement	8	224	Replacement
	Absence of locking pin	No connection between shaft and welding fixture. Welding fixture falls.	9	Locking pin fails	2	Maintenance	6	108	
				Locking pin is not plugged in	2	Proper operator training	1	18	
	Handle fails	No secure grip available. Hard to push the shaft.	3	Welding defects/failure	2	Maintenance	2	12	
	Bearings fail	Hard to push the shaft. Bearings wear out fast.	7	Improper lubricating	2	Lubricating/replacement	2	28	

In operation: supporting the welding fixture	Shaft housing fails	Welding fixture falls. Personal Injury. Equipment damage.	10	Fatigue, crack	1	Maintenance	2	20	
	Bearings fail	Hard to rotate the welding fixture. Bearings wear out fast.	7	Improper lubricating	2	Lubricating/replacement	2	28	
	Shaft fails/deforms	Welding fixture falls. Welding fixture can not be rotated.	10	Fatigue, Equipment abuse	1	Maintenance/replacement	2	20	
	Safety latches are unlock	Minor axial movement of the welding fixture.	5	Human error, latches fail	2	Maintenance/proper operator training	2	20	
In changeover: disconnecting welding fixture and shaft	Handle fails	No secure grip available. Hard to retract the shaft.	6	Welding defects/failure	2	Maintenance	2	24	
	Bearings fail	Hard to retract the shaft. Bearings wear out fast.	7	Improper lubricating	2	Lubricating/replacement	2	28	
	Shaft leaves the housing	Shaft may fall to the ground. Damage to shaft.	8	Operator pulls the shaft all the way out of the housing	6	Proper operator training	6	288	Integrate an error-proof feature to prevent the shaft from pulling all the way out of the housing.
In transportation	Safety latches are unlock	Shaft falls	8	Human error. A-Stands are not moving in upright position	3	Proper operator training	3	72	

4. Recommendations

Current welding fixtures vary in length, they do not have standard length. This means that when performing welding fixture changeover, A-Stands still need to be moved to correct distance to match new welding fixture length. Moving A-Stands has not changed from existing way. That is using a forklift to pick up and move A-Stand to correct distance. The addition of casters and on A-Stands will allow A-Stands to be moved into place without requiring forklifts. This eliminates the forklift and drive as additional recourses and manpower which improves efficiency.

The retractable shaft mechanism allows for quick-changing of the welding fixtures. A-Stands can now remain stationary when the A-Stand shafts are retracted to disconnect from welding fixture yoke. Retractable shaft mechanism was designed for the hydraulic powered A-Stands. It is recommended to incorporate the idle end retractable shaft design to the manually powered A-Stands. This is because the hydraulic powered, idle end A-Stand is very similar to the manually powered A-Stands. This means, little to no changes are required to retrofit into existing manually powered A-Stands.

According to the final design FMEA, one of the failure modes is that the idle end shaft can be pulled all the way out of the shaft housing during the retraction. To prevent this, the team recommends to integrate a stopping mechanism into the idle end design. A deep-reach c-clamp can be utilized as a preventive tool. As shown in Figure 112, the clamp will be attached to the back of the idle end's head part.

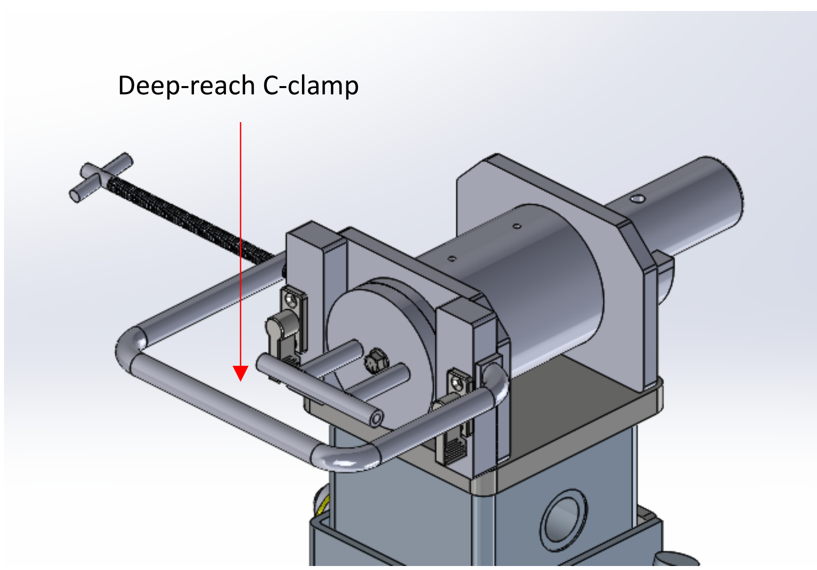


Figure 112: Final Idle End Design Integrated with a Preventive Deep-reach C-

The clamp is able to limit the maximum distance that the shaft can be retracted. Once the shaft is retracted to the position where the disc plate touches the clamp, the shaft will be blocked as shown in Figure 113. A c-clamp is economic, easy-to-use, requires minor maintenance, and it is also easy to assemble and remove. It is a quick and simple approach to prevent the idle end shaft being pulled out of the housing. The deep-reach c-clamp with an 8” opening and a 5 ¾” reach (Part#5119A18 from McMaster-Carr) is highly recommended, as its size fits the design very well.

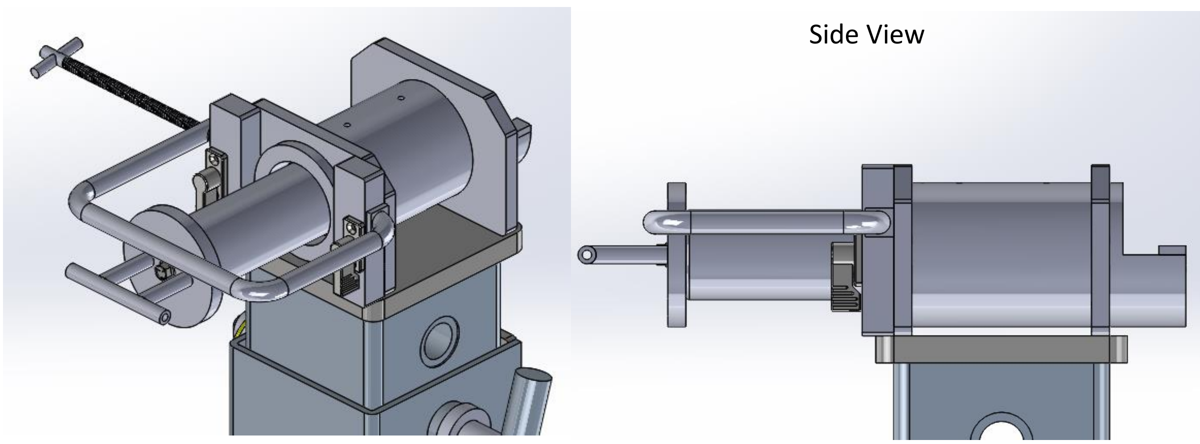


Figure 113: Shaft Reached Its Maximum Retraction Distance and Being Blocked by the C-clamp

5. Conclusion

A pair of quick change hydraulic powered A-Stands has been designed by the team, which meets the requirements from the client, MacDon Industries. The primary requirement of the client is to reduce the cycle time of welding fixture changeover from 45 minutes to 5 minutes. The final design features a retractable shaft mechanism which allows the A-Stand shafts to quickly connect to, and disconnect from, the welding fixture yokes. Thereby, welding fixtures can be easily lifted off, and lowered onto A-Stands, improving the welding fixture changeover process compared to the existing A-Stand design.

In the existing A-Stand design, the changeover process includes moving the entire A-Stand to couple to and decouple from welding fixture yoke. Such process requires using a forklift and is the most time-consuming process in the welding fixture changeover process. The retractable shaft design simplifies this process, thereby it significantly shortens the changeover time. The details of the final design's specifications and the target specifications are summarized in Table XXIII.

TABLE XXIII. FINAL DESIGN METRICS AND TARGETED METRICS TABLE

#	Metrics	Units	Ideal Values	Marginal Values	Final Design Values	Achieved (Yes/No)	Imp
1	Load capacity (a safety factor of 3 applied)	Ibs	12000	10200	12000	Yes	5
2	Manpower needed for the changeover	person	1	2	1	Yes	5
3	Equipment needed for the changeover	piece	1	2	2	Yes	5
4	Degree of retrofit on the existing bases	%	100%	50%	100%	Yes	3
5	Compatibility with existing fixture yoke	Yes/No	Yes	Yes	Yes	Yes	4
6	Compatibility with current power setup	Yes/No	Yes	Yes	Yes	Yes	5
7	Part lifecycle	years	15	13	>15	Yes	4
8	Changeover cycle time	min	5	10	5~10	Yes	5
9	Unit manufacturing cost (per A-Stand pair)	CAD $	8000	8000	5540	Yes	3
10	Simplicity of machining and tooling (per A-Stand pair)	hours	16	24	12.5	Yes	2
11	Size (footprint)	Inch x Inch	60×30	60×30	60×27 ¾	Yes	3

The final design was achieved by an iterative design process, which was built on the retractable shaft concept. The retractable shaft concept was selected as the most optimal approach to achieve a quick changeover. The performance of the critical components is verified through analytical stress analysis, stress-life analysis, and preliminary FEA. Standard operating procedure and failure modes and effects analysis were used as a preliminary safety analysis for the design. Preliminary drawings are provided for details of the final design components. The preliminary cost analysis was conducted for client's reference when weighting the benefits.

Recommendations were provided as the next plan of action to carry on the project. The team recommended to integrate casters to the final design A-Stand base to improve the A-Stand's mobility. It is also recommended to apply the retractable shaft mechanism to the manually powered A-Stands. In addition, a deep-reach c-clamp is recommended to be used as a stopping mechanism for the idle end.

Overall, the final design is successful in accomplishing client's design goals, while meeting their requirements. By implementing the proposed final design, client will be able to reduce the welding fixture changeover time to the target time. This will eliminate the bottleneck in the welding process and improve overall productivity of the welding stations.

6. References

[1] McMaster Carr. *Standard Sleeve Bearings* [Online]. Available: https://www.mcmaster.com/standard-sleeve-bearings [November 24, 2018].

[2] Engineering 360. *Bearings and Sleeve Bearings Information* [Online]. Available: https://www.globalspec.com/learnmore/mechanical_components/bearings_bushings/bushings_sleeve_bearings [November 24, 2018].

[3] Engineering 360. "Sleeve Bearings Information.jpg," in *Plain Bearings and Sleeve Bearings Information* [Online]. Available: https://www.globalspec.com/learnmore/mechanical_components/bearings_bushings/bushings_sleeve_bearings [November 24, 2018].

[4] DU PONT. Delrin – The high-performance acetal resin that global customers trust [Online]. Available: http://www.dupont.com/products-and-services/plastics-polymers-resins/thermoplastics/brands/delrin-acetal-resin.html?src=gg-kg_dpm-na-delrin_delrin-acetal&gclid=EAIaIQobChMIsMnxyKv73gIVkLbACh13DQY5EAAYASAAEgJ47PD_BwE [November 24, 2018]

[5] McMaster Carr. *316 Stainless Steel Shoulder Screw* [Online]. Available: https://www.mcmaster.com/97345a619 [November 28, 2018].

[6] McMaster Carr. *Oil Embedded Bronze Bearing* [Online]. Available: https://www.mcmaster.com/6391k689 [November 28, 2018].

[7] McMaster Carr. *Heavy Duty Spiral Internal Retaining Ring* [Online]. Available: https://www.mcmaster.com/92370a331 [November 28, 2018].

[8] McMaster Carr. *Screw-on Turn Latch* [Online]. Available: https://www.mcmaster.com/1512n11 [November 28, 2018].

[9] McMaster Carr. *Grade 5 Steel Flanged Hex Head Screw* [Online]. Available: https://www.mcmaster.com/92979a257 [November 28, 2018].

[10] R.G. Budynas, and J.K. Nisbett. *Shigley's Mechanical Engineering Design* 10th ed. New York: McGraw-Hill Education, 2015, pp. 110-111.

[11] R.G. Budynas, and J.K. Nisbett. *Shigley's Mechanical Engineering Design* 10th ed. New York: McGraw-Hill Education, 2015, pp. 1048.

[12] R.G. Budynas, and J.K. Nisbett. *Shigley's Mechanical Engineering Design* 10th ed. New York: McGraw-Hill Education, 2015, pp. 282-284.

[13] R.G. Budynas, and J.K. Nisbett. *Shigley's Mechanical Engineering Design* 10th ed. New York: McGraw-Hill Education, 2015, pp. 290.

[14] R.G. Budynas, and J.K. Nisbett. *Shigley's Mechanical Engineering Design* 10th ed. New York: McGraw-Hill Education, 2015, pp. 295.

[15] R.G. Budynas, and J.K. Nisbett. *Shigley's Mechanical Engineering Design* 10th ed. New York: McGraw-Hill Education, 2015, pp. 296.

[16] R.G. Budynas, and J.K. Nisbett. *Shigley's Mechanical Engineering Design* 10th ed. New York: McGraw-Hill Education, 2015, pp. 298.

[17] R.G. Budynas, and J.K. Nisbett. *Shigley's Mechanical Engineering Design* 10th ed. New York: McGraw-Hill Education, 2015, pp. 299.

[18] R.G. Budynas, and J.K. Nisbett. *Shigley's Mechanical Engineering Design* 10th ed. New York: McGraw-Hill Education, 2015, pp. 301.

[19] R.G. Budynas, and J.K. Nisbett. *Shigley's Mechanical Engineering Design* 10th ed. New York: McGraw-Hill Education, 2015, pp. 293.

[20] R.G. Budynas, and J.K. Nisbett. *Shigley's Mechanical Engineering Design* 10th ed. New York: McGraw-Hill Education, 2015, pp. 282.

[21] R.G. Budynas, and J.K. Nisbett. "Round shaft with shoulder fillet in bending," in Charts of Theoretical Stress-Concentration Factors, in *Shigley's Mechanical Engineering Design* 10th ed. New York: McGraw-Hill Education, 2015, pp. 1036.

[22] F. P. Beer, E. RJ. Jr, J.T. DeWolf, and D.F. Mazurek, Mechanics of Materials. 2 Penn Plaza, New York: McGraw-Hill Education, 2015, pp. 695.

[23] Metal Supermarkets. (2018). *Cold Rolled Steel C1010* [Online]. Available: https://www.metalsupermarkets.com/metals/cold-rolled-steel/cold-rolled-steel-c1010/. [November 28, 2018].

[24] McMaster Carr. *Carbon Steel* [Online]. Available: https://www.mcmaster.com/catalog/124/3801 [November 25, 2018].

[25] McMaster Carr. *Carbon Steel* [Online]. Available: https://www.mcmaster.com/catalog/124/3799 [November 25, 2018].

[26] McMaster Carr. *Acetal* [Online]. Available: https://www.mcmaster.com/catalog/124/3722 [November 25, 2018].

[27] McMaster Carr. *Alloy Steel* [Online]. Available: https://www.mcmaster.com/catalog/124/3818 [November 25, 2018].

[28] McMaster Carr. *Carbon Steel* [Online]. Available: https://www.mcmaster.com/catalog/124/3796 [November 25, 2018].

[29] McMaster Carr. *Sleeve Bearings* [Online]. Available: https://www.mcmaster.com/catalog/124/1210 [November 25, 2018].

[30] McMaster Carr. *Retaining Rings* [Online]. Available: https://www.mcmaster.com/catalog/124/3380 [November 25, 2018].

[31] McMaster Carr. *Cam and Compression Latches & Locks* [Online]. Available: https://www.mcmaster.com/catalog/124/2982 [November 25, 2018].

[32] McMaster Carr. *Hex Head Screws* [Online]. Available: https://www.mcmaster.com/catalog/124/3237 [November 25, 2018].

[33] Metal Supermarkets. (2018). Cold Rolled Rectangular Tube [Online]. Available: https://www.metalsupermarkets.com/metals/cold-rolled-steel/cold-rolled-steel-rectangular-tube-crew/ [November 27, 2018].

[34] McMaster Carr. *Carbon Steel* [Online]. Available: https://www.mcmaster.com/catalog/124/3795 [November 25, 2018].

[35] McMaster Carr. *Tool Steel* [Online]. Available: https://www.mcmaster.com/catalog/124/3830 [November 25, 2018].

[36] McMaster Carr. *Clevis Pins* [Online]. Available: https://www.mcmaster.com/catalog/124/3458 [November 25, 2018].

[37] McMaster Carr. *Precision & L-Shaped Pins* [Online]. Available: https://www.mcmaster.com/catalog/124/3442 [November 25, 2018].

[38] McMaster Carr. *Shoulder Screws* [Online]. Available: https://www.mcmaster.com/catalog/124/3171 [November 25, 2018].

Appendix

Table of Contents

Appendix A: Concept Development

A.1. Concept Generation

In this section, the concept generation is presented in detail. Firstly, the current A-Stand design is described. With a good understanding of the current design, preliminary concepts are generated from internal group brainstorming and external researching. Four different preliminary concepts will be introduced in section A.1.1., the namely A-Stand cup design, supporting frame design, casters design, and a base with slit design. Then a screening for preliminary concepts is performed to determine the best concept approach for the project objective. According to a list of important selection criteria, the cup design is taken for further concept development. With the client's feedback and group discussion, the team decide to not be limited within the cup design, but in general redesign the coupling action behind it. Three further expanded concepts for coupling method are then presented in detail.

A.1.1. Preliminary Concept Generation

This section will show the team's preliminary concept generation process prior to the further concept generation process.

A.1.1.1. Concept #1: A-Stand Cup Design

The A-Stand shaft is split into two cups that encase the welding fixture yoke which consists of bottom half and top half cup. The bottom half cup is one with the A-Stand shaft that runs through the head of the A-Stand. The top half cup is separate. The bottom half and top half cups are fastened together with welding fixture yoke using bolts and nuts. Two bolts run though bottom half cup, welding fixture yoke, and top half cup which can be seen in Figure A1.

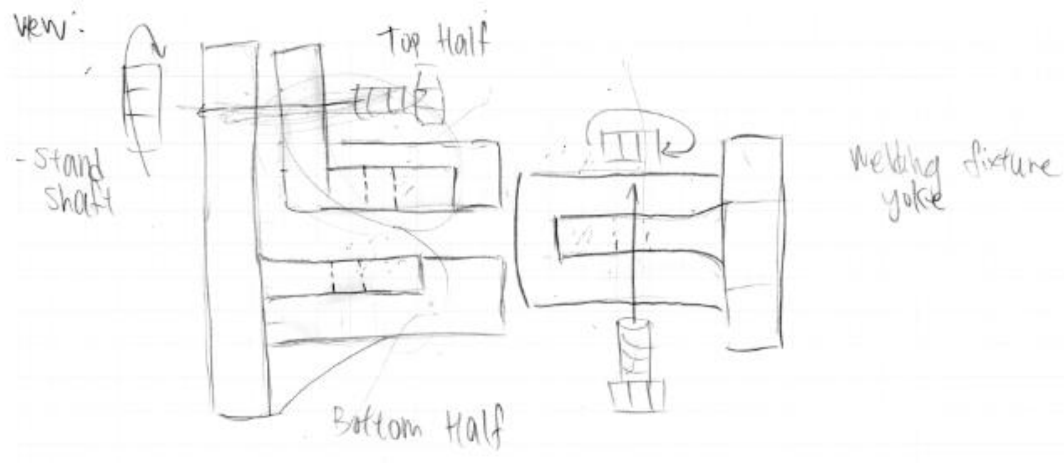


Figure A1: Illustrated Side View of A-Stand Cup Design

This cup design improves the welding fixture changeover process by eliminating the process of sliding the A-Stand in and out of welding fixture yoke in the current design. When the welding fixture is removed from the A-Stand, the cup design allows the welding fixture to be lifted off the A-Stands instead of sliding the entire A-Stand outward to disconnect the A-Stand Shaft from the welding fixture yoke in the current A-Stand design. When installing the required welding fixture, the welding fixture can be lowered onto the bottom half cup of the A-Stand, then the top half cup is placed on top of the welding fixture yoke and the bottom half cup. The coupled assembly can then be fastened with the required bolts and nuts. This eliminates the need of pushing the whole A-Stand in towards the welding fixture to get the A-Stand Shaft into welding fixture yoke which is time consuming, and requires a forklift or crane due to the heavy weight of the A-Stands.

Safety concerns arise if nuts are not torqued securely; causing loose connection, or a bolt and nut was forgotten during the fastening process of the A-Stand cups. Also, with the number of bolts and nuts used in this design, they can be dropped or misplaced, requiring additional time in the changeover process. The top half cup can be dropped on the floor, causing damage to the part and not being able to securely hold the welding fixture yoke.

A.1.1.2. Concept #2: Supporting Frame

In the supporting frame concept, a frame is used to connect the A-Stands together which allows the welding fixture to be set down on the supporting frame. The objective of the supporting frame is to reduce the use of manpower and equipment and be easy to use. This is done by allowing the welding fixture to be lifted off the support frame and switched out for another welding fixture which is simply lowered onto support frame. This eliminates the need to slide A-Stands in and out of the welding fixture yoke. This concept was inspired by the welding fixture frame shown in Figure A2 and patent CN202278353U [1], which consists of a welding fixture frame that is commonly used.

[redacted]

Figure A2: Welding Fixture Bed Frame [2]

The design contains an additional truss frame under the current welding fixture. The top view of the frame is illustrated in Figure A3. The new truss frame will be connected to the shaft on both A-Stands instead of the welding fixture, and the welding fixture will be put on top of the frame. Mechanical clamping elements, or bolt holes, will be designed at the edge of the frame. While changing the welding fixture, the clamping elements or bolts can be easily operated to engage or disengage. On one of the A-Stands, a hydraulic handle will be built, so the welding fixture can freely rotate off the ground with the frame.

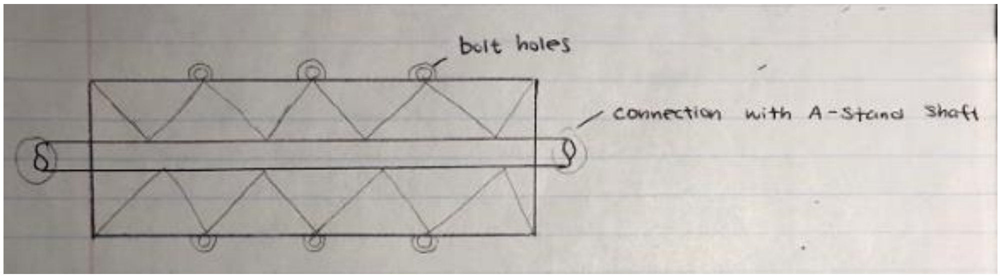


Figure A3: Illustrated Top View of the Bed Frame

The side frame is another concept using A-Stands. The major objective of the side frame is easy to use which consequently reduces the changeover time. This concept is inspired by Figure A4. In this concept, some parts may need to be redesigned.

Figure A4: Welding Fixture Side Frame [3]

The design contains additional shafts and flat boards to attach onto the current structure. The concept is to redesign the connection part on the A-Stands. Also, to extend the shaft on welding fixtures so that it can be fixed on the side boards. By changing the connection part, the welding fixture does not need to be connected to the A-Stand. Instead, the welding fixture will be simply lifted off by opening the handcuffs on the side boards. The handcuff connections will have tolerance, so that the welding fixture can freely rotate off the ground. In this case, the manpower and equipment will be reduced. Moreover, the gearbox can still be put at the same position as before to rotate the welding fixture.

A.1.1.3. Concept #3: A-Stands with Casters

A caster is a wheeled device mounted to an object that helps for easy rolling movement of the object [4]. Casters are used in a wide range of applications, from small furniture to massive industrial equipment. Their sizes and capacities vary, depending on their use. Heavy duty casters are able to withstand weight up to 100,000 pounds [4]. An example of the caster’s application in the automotive industry is shown in Figure A5, where a worker is moving a heavy chassis stand with casters.

Figure A5: Example of Caster's Application in Automotive Industry [5]

There are primary two types of casters; rigid casters and swivel casters. Rigid casters only allow for movement in one direction, normally forwards or backwards. Swivel casters allow for movement in all horizontal directions. They normally have one or two sets of raceways that allow for a 360-degree swivel under load [4]. Features like locks or brakes are usually added to casters to prevent them from rotating and swiveling when needed.

Kingpin casters and kingpinless casters are two typical types of swivel casters. A Kingpin caster is a traditional swivel caster that consists of 6 components: a top plate, a kingpin, a lower race, a lower bearing, an upper race, and an upper bearing. The kingpin is generally a bolt or a rivet, which is used to hold all the other five components together. A schematic of the kingpin caster is shown in Figure A6. Being the only joining element in a caster, the kingpin absorbs a lot of forces when in use. When the caster is being abused, the forces can cause the kingpin to shear and lead to catastrophic failure. Towing and shock loading are two primary causes of caster failure [6].

[redacted]

Figure A6: Schematic of a Kingpin Caster[7]

Compared to the kingpin casters, kingpinless casters are more durable, and thus, more desired in heavy industrial applications. The kingpinless caster has a simpler structure, and it uses a forged race instead of separated lower and upper races [6]. Such a design eliminates the need for a kingpin as well as any failure can be caused by a kingpin. Therefore, kingpinless casters will be preferred for the application in this project. A schematic of a kingpinless caster is shown in Figure A7.

[redacted]

Figure A7: Schematic of a Kingpinless Caster [8]

In this project, the use of casters will significantly increase the mobility of the A-Stands, and thus, ease the changeover process. With the casters installed, the heavy A-Stands can be easily moved by one person instead of using a forklift. In addition, better mobility eases the process of aligning the stand with the fixture during changeover. As a result, the changeover cycle time will be brought down.

One of the concepts is to use heavy duty locking swivel casters on the A-Stands. Casters will be installed at the bottom of the stand bases. Once stands are pushed and connected to the welding fixture, casters will be locked in place. This eliminates the need for a forklift, but the casters will need to withstand the entire weight of a pair of A-Stands and a welding fixture all the time.

Another concept generated is to use retractable casters. Casters will only be used during changeover, and they will be retracted once the changeover is finished. Therefore, the casters do not have to withstand the weight of both stands and welding fixture but only the weight of one stand.

After researching, several existing designs have inspired the team, including patent GB2206859A [9], which consists of common pool tables with casters. The examples of two existing designs of workbench with retractable casters are shown in Figure A8.

[redacted]

Figure A8: Examples of Existing Designs of a (a) Car Jack [10] and a (b) Hydraulic [11] Retractable Casters

The designs both use jacks to retract the casters. The jacks are installed in a frame, connecting the fixed frame roof and the moveable frame floor. Casters are installed at the bottom of the moveable frame floor. When the table is lifted by the jack, the casters will come in contact with the floor, allowing A-Stand to move freely. When the table is lowered, the casters will be retracted, and the workbench's feet will stand on the ground to keep the workbench still.

According to the existing designs, three different configurations are developed and shown in Figure A9, Figure A10, and Figure A11.

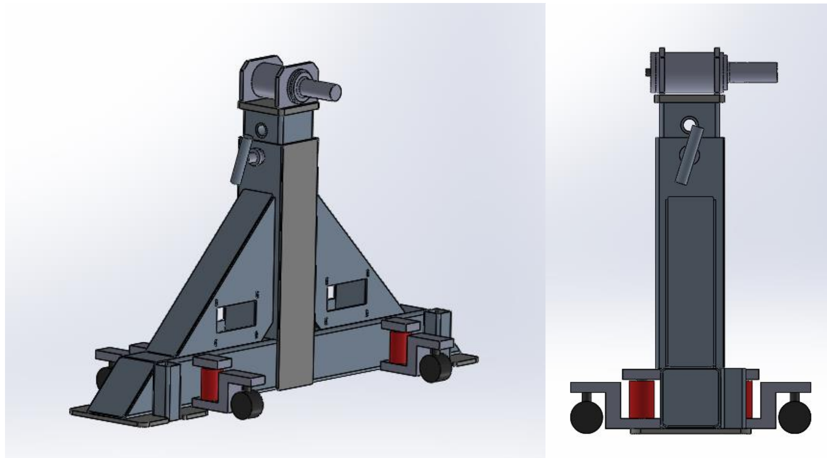


Figure A9: Retractable Caster Concept Configuration #1

As shown in Figure A9, the first configuration has 4 retractable caster kits installed on both sides of the stand. Each kit consists of a bottle jack, a locking swivel caster and a frame. The reason for using the bottle jack in the design is that it is the best type of jack used for short vertical lifts [12]. Four casters arranged in such a systematic way provide balance to the stand.

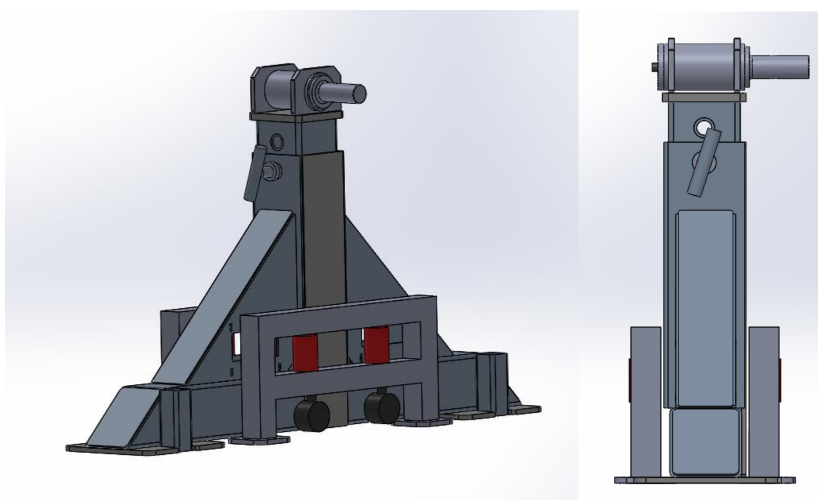


Figure A10: Retractable Caster Concept Configuration #2

As shown in Figure A10, the second configuration has two retractable caster frames attached on both sides of the stand. The frame has a similar structure to the existing designs shown in Figure A8. Similar to the second configuration, the third configuration, Figure A11, has the same retractable caster frame. But the frame is built in to the stand instead of being attached at both sides. This configuration has a smaller footprint, and thus will be beneficial to storing. However, with a narrow base, the A-Stand is likely to tip over when being moved.

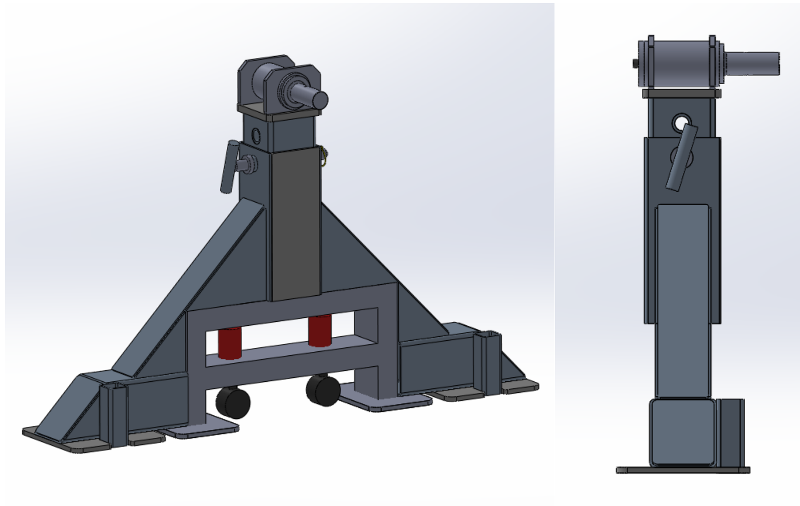


Figure A11: Retractable Caster Concept Configuration #3

A.1.1.4. Concept #4: A Slit Cut-out on A-Stand Base

The current A-Stand design requires the user to pull out the entire A-Stand assembly from the yoke of the welding fixture while the beam is still locked onto the A-Stand base, as shown in Figure A12. This process repositions the A-Stand assembly which makes the users re-position to align with the welding fixture yoke. It also makes the user struggle when disconnecting from the welding fixture because the neck is still locked into the heavy A-Stand base.

Figure A12: Disconnecting the A-Stand from the Welding Fixture

This problem can be resolved by cutting a slit on the A-Stand base, then the neck can be easily removed, and the user does not need to struggle with the weight of the entire A-Stand assembly. The user will remove the locking pin that locks the neck to the base, then simply disconnect the head from the yoke of the welding fixture. This design is safer for the user since they do not need to kick or pull the whole weight of the assembly.

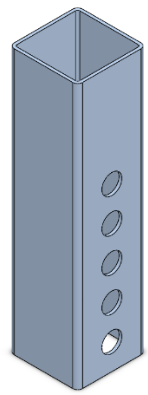


Figure A13: Current Neck

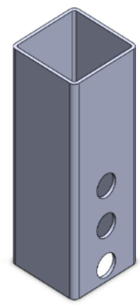


Figure A14: New Neck

The current neck shown in Figure A13 goes almost all the way to the bottom of the base shown in Figure A15, and the holes allow the users to adjust the height of the neck. The current frame has five different adjustable height, but it is observed that not all of them are used. The length of the frame then can be reduced and only leave the necessary amount of locking holes as shown in Figure A14. This length is just enough for the frame to be removed without interfering with the support legs of the base. The slit is cut out from the existing base as shown in Figure A16, and the length is slightly longer than the new frame for easy removal.

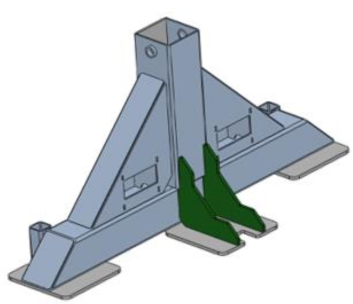


Figure A15: Current Base

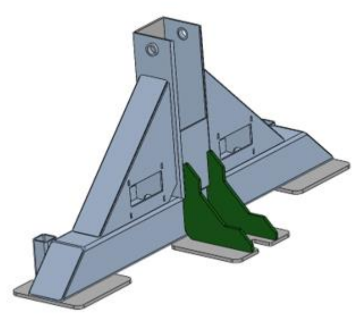


Figure A16: New Base

An illustration of the current process is shown in Figure A17 and an illustration of the new process is shown in Figure A18.

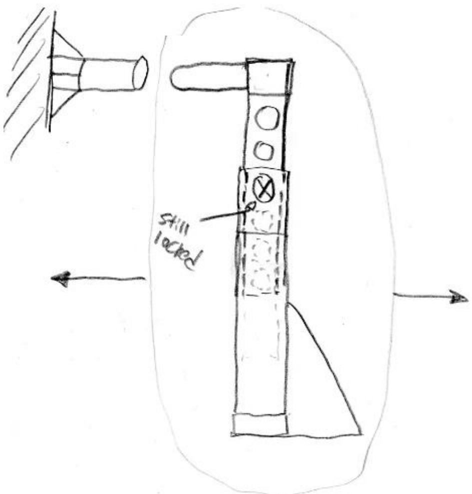


Figure A17: Illustration of the Current Process

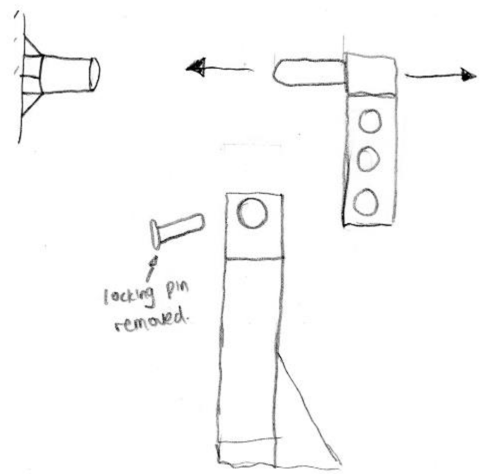


Figure A18: Illustration of the New Process

A.1.2. Preliminary Concept Screening

Preliminary concepts are screened with the client's feedback of each preliminary concept to ensure the chosen concept satisfies the client's needs and objectives while integrating good ideas from other concepts. The four main concept approaches are as follows:

- Redesign of the A-Stand shaft and welding fixture yoke coupling action with the cup design that eliminates the process of sliding the entire A-Stand
- Connecting A-Stands together using supporting the frame design that allows the welding fixture to be placed on top of eliminating process of moving A-Stands during changeover
- Use of casters on the A-Stand to improve mobility of the A-Stand which eliminates the need for forklifts or cranes during changeover
- Redesign of the A-Stand frame to have a cut-out slit so only a portion of the A-Stand needs to be moved during changeover

The A-Stand shaft cup design eliminates the difficult process of sliding the A-Stand Shaft in and out of welding fixture yoke. This redesign of the coupling action between A-Stands and welding fixtures is what the client is looking for to improve changeover time. However, problems with this design is safety of using bolts and nuts to fasten the top and bottom halves of the A-

Stand cup. A bolt could be forgotten, or a nut installed loosely during changeover could cause the welding fixture to fall off the A-Stand causing a major safety issue. The client suggested to have mistake-proof designs for locking the top and bottom portion of the A-Stand cup so that there is no way to forget a step. Also, loose components are easily lost and damaged if dropped on the floor. The client suggested to design a component where all parts are connected together.

Issues with using the supporting frame to attach the A-Stands together ruins the versatility of free-standing A-Stand pairs to accommodate any length of welding fixture jigs. Also storing A-Stands will become difficult and take too much room due to the large foot print of bed the frame. This is a problem at MacDon because of limited space.

Using casters of A-Stands to improve mobility is not what the client was looking for due to the following reasons. A-Stands are already narrow, therefore adding casters and pushing the A-Stand has a high chance of instability which would cause A-Stands to tip over. It will still be hard to align the A-Stand shaft with the welding fixture yoke due to the floor not being level. Using step down casters are highly unlikely due to the weight of the A-Stands (591 lbs). The factory floor is bumpy and dirty which is not ideal for casters, causing rough movements which introduces instability. However, casters would improve the changeover process eliminating the need of a forklift when moving A-Stands to the right length of the welding fixture to be used and aligning with welding fixture yoke. Therefore, casters can be the next design step after solving the coupling action between the A-Stand and the welding fixture yoke.

A problem with the slit cut-out design is that it introduces a pivot point that could cause the top half of A-Stands to tip inward, and causing the welding fixture to fall down. Introducing additional mechanical locking means adding to complexity of design. Moving the top half of the A-Stands is still heavy due to the weight of the gearbox (approximately 230 lbs), requiring a crane.

The four concepts are screened against each other using the caster design as a reference.

TABLE AI. CONCEPTS VARIABLE LEGEND

Concept Variable	Concept Design
REF.	Casters
A	Shaft Cup
B	Slit Cut-out
C	Supporting Frame

TABLE AII. PRELIMINARY CONCEPTS SCREENING MATRIX

Selection Criteria	Concept Variants			
	A	B	C	REF.
Ease of Use	+	-	+	0
Mobility	-	-	-	0
Storing	0	0	-	0
Compatibility	-	-	-	0
Cost	+	0	-	0
Ease of Manufacturing	+	+	0	0
Maintenance	+	-	0	0
Durability	-	0	+	0
Pluses	4	1	2	
Same	1	3	2	
Minuses	3	4	4	
Net	1	-3	-2	
Rank	1	3	2	
Continue?	Yes	No	No	

From Table AI, the A-Stand cup design was the best design concept. However, from client feedback, the design should not be limited to just the cup design, but in general, redesign of the coupling action between the A-Stands and the welding fixture.

A.1.3. Further Concept Generation on Coupling Action

A.1.3.1. Concept #1: A-Stand Clamping Shaft Design

This A-Stand clamp design is refined from the preliminary cup design. From the client feedback during preliminary concept screening, redesign in coupling action was ruled to be the desired design approach. Problems with preliminary cup design was safety of using bolts and nuts to secure top and bottom half cups of the A-Stand. A bolt can be forgotten or nut not tightened during changeover, causing the welding fixture to fall during operation. Also, the concern of loose components during changeover process would cause likelihood of losing them and damaging them if dropped on the floor.

This A-Stand Cup design addresses the first issue by using a spring-loaded pin to allow for automatic locking without using fasteners, shown in Figure A19. The spring-loaded latch mechanism can be dissembled to allow for easy maintenance and replacement of parts.

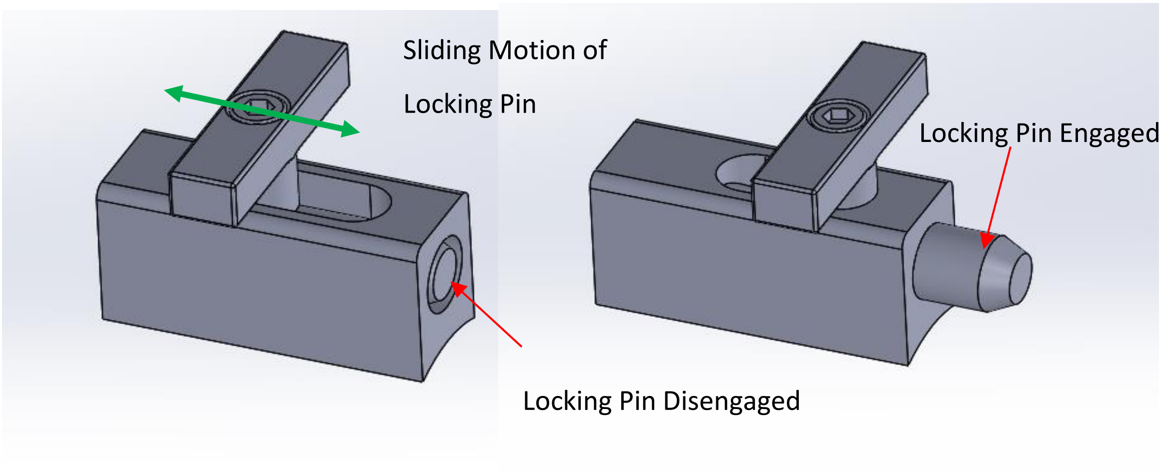


Figure A19: Locking Pin Mechanism

For the second issue of separate components, a locking mechanism is contained within the top half cup so no loose bolts and nuts are present during changeover. The bottom and top half are now connected by a hinge which allows the top half to clamp down on welding fixture yoke and lock with the bottom half, as shown in Figure A20 and Figure A21

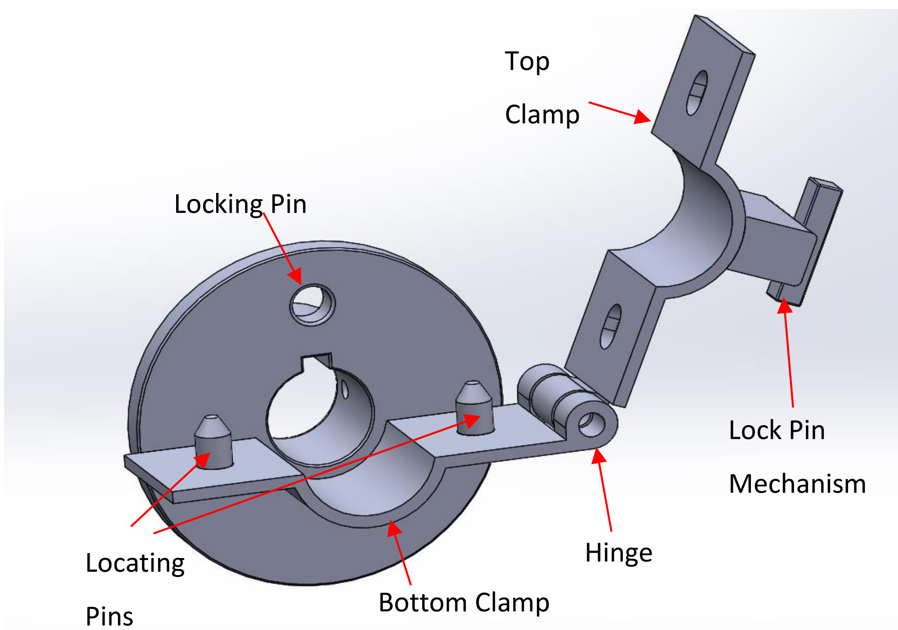


Figure A20: A-Stand Clamping Shaft Opened (Front View)

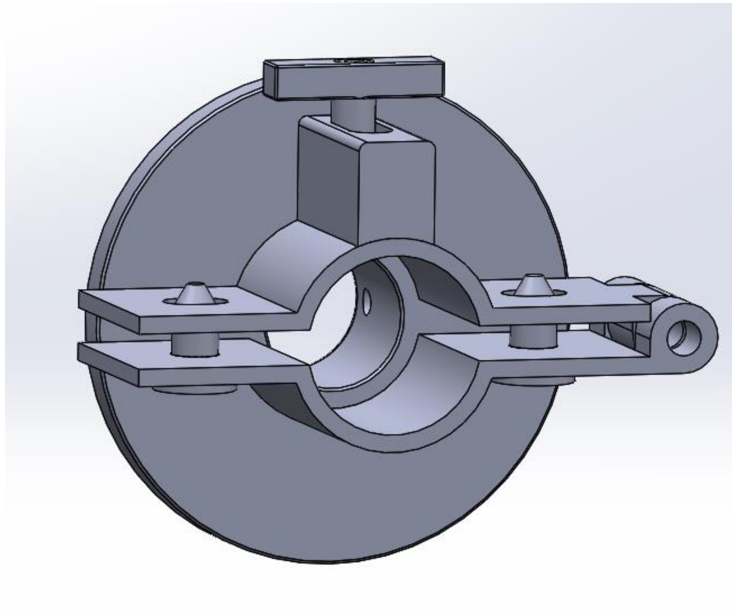


Figure A21: A-Stand Clamping Shaft Closed (Front View)

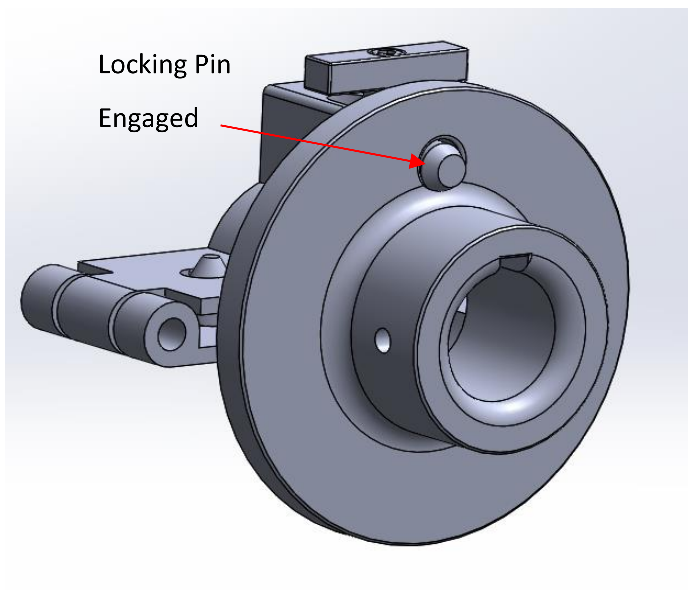


Figure A22: A-Stand Shaft Closed (Back View)

Figure A22 shows the back view connected to the A-Stand and shows the locking pin engaged.

Problems with this design are the strength of the locking pin when supporting the weight of the welding fixture. In this case, two locking pins may be needed to double up the strength and prevent shearing of the pin. Also, the chance of bending or fracture of the bottom and top cups due to the thinness of the cups is present. Extra reinforcements may be required to prevent bending or fracturing of the cups, such as adding gusset plates around the cups.

A.1.3.2. Concept #2: Sleeve Design

This design is more focusing on the coupling action between the A-Stand and the yoke. The current procedure requires one of the A-Stands to move to disconnect the fixture from the welding fixture yoke. The sleeve design is inspired by a multi stage telescopic cylinder shown in Figure A23. Instead of hydraulic or pneumatic powered telescopic cylinders, the sleeve design consists of multiple layers of hollow shaft that slide in and out from the welding fixture to connect or disconnect with the shaft from the A-Stand base. The first stage is welded to the base of the existing yoke, and the last stage is when the sleeves are fully engaged. This way the users are not required to move either the welding fixture or the A-Stand to disconnect them.

[redacted]

Figure A23: Telescopic Double Acting Cylinder (3 stage)[13]

The sleeve design also requires a way to lock them in place together. If the sleeve design is simply slid to connect the fixture and the shaft, there are chances of them loosening while working. This risk can be prevented by adding brackets on each end of the sleeve so the earlier stage shaft can hold the next shaft, which also informs the user once each sleeve is fully engaged because they will not be able to pull.

It is also important to make sure the sleeves are securely connected to the shaft. It can be done by using multiple pins on each sleeve, and the user manually locks and unlocks every time they need to. However, to prevent the users from forgetting to lock the pins, it is highly desired to allow the sleeves to lock automatically.

To allow the sleeves to securely lock automatically, a spring-loaded detent can be added on the shaft where the bracket on the last stage of the sleeve sits. Once the last stage is fully engaged, the spring-loaded detent will sit right behind of the bracket and securely lock the sleeve on the shaft. Figure A24 shows a cross-sectional view of when the sleeves are engaged, and Figure A25 shows the cross-sectional view of when the sleeves and the shaft are not connected. It can be seen that neither the welding fixture nor the A-Stand has moved during this process.

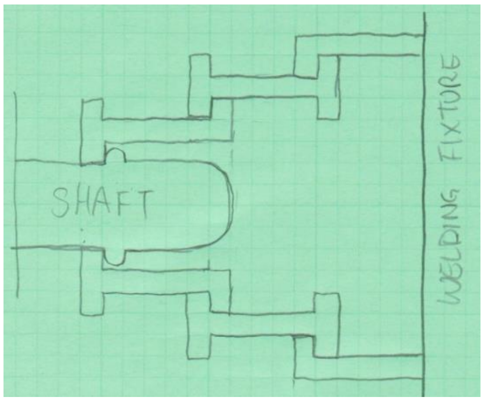


Figure A24: Sleeves Engaged (Cross-Sectional View)

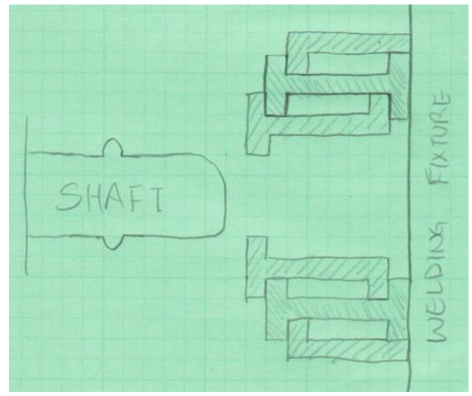


Figure A25: Sleeves Disengaged (Cross-Sectional View)

To better aid with the sleeve design, a 3D CAD model was created. Figure A26 shows the sleeve design when it is engaged and disengaged, respectively. Figure A27 shows the side view of when it is engaged and disengaged, respectively.

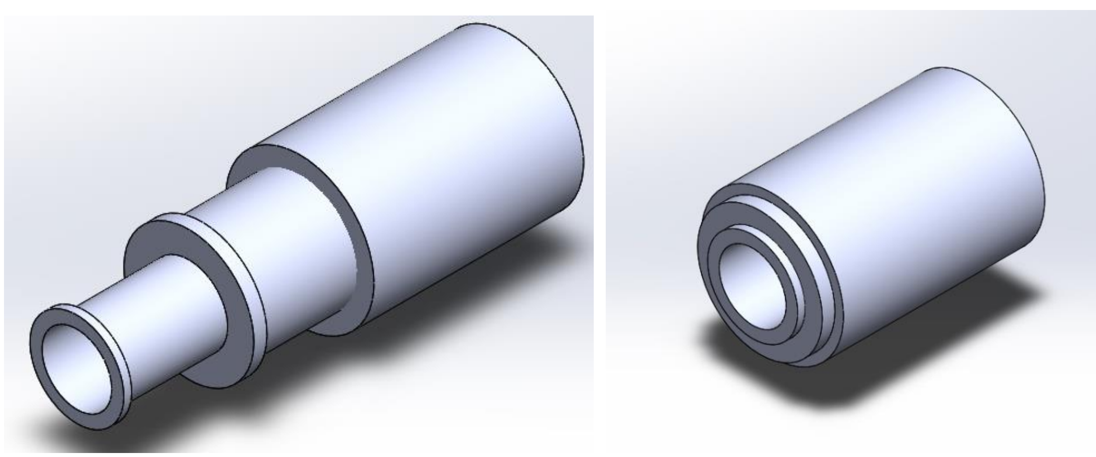


Figure A26: Sleeves Engaging and Disengaging

Figure A27: Sleeves Engaging and Disengaging (Side View)

A.1.3.3. Concept #3: Retractable Shaft Design

This design is to ease the changeover process using a retractable shaft. As presented in Figure A28, the design concept consists of three primary sections: a stand head, a back support and a yoke guide. This concept is to be applied on the idle end stand only. The drive end stand has a gearbox and a more complicated inner structure of its head, thus applying this concept to the drive end is not feasible.

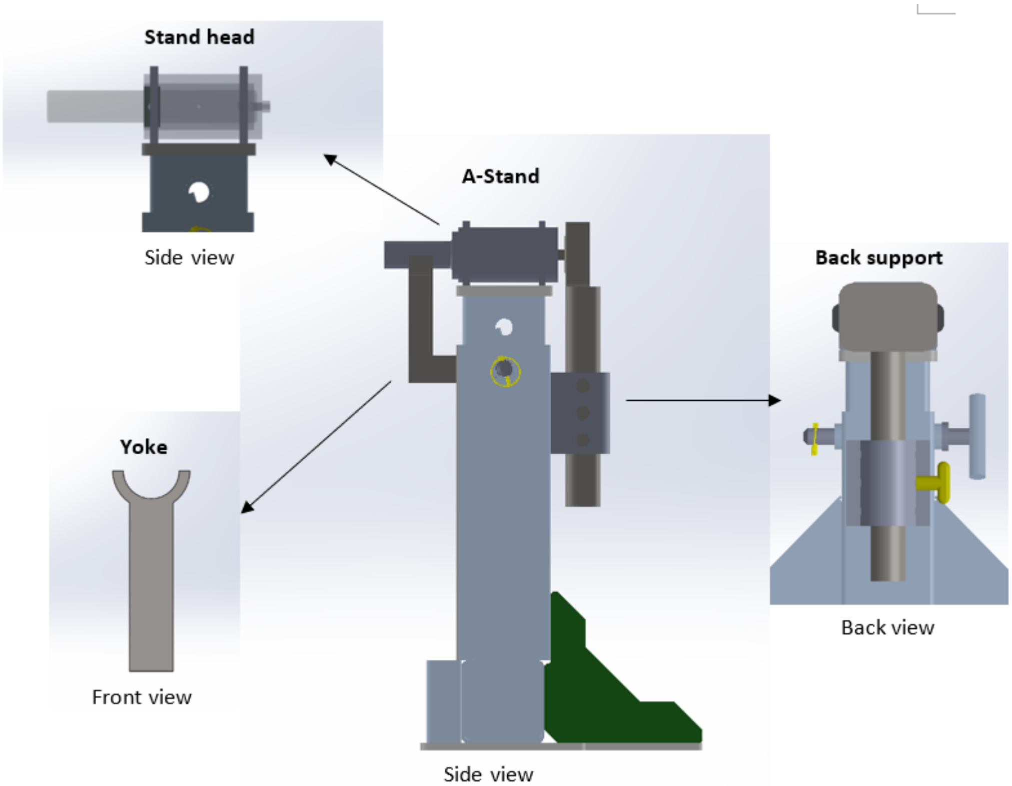


Figure A28: Presentation of retractable shaft design

The retracting feature is primarily developed on the stand head part. As shown in Figure A29, the stand head consists of a solid shaft, a ball bearing, an outer housing, an inner housing, a lid and a bolt. Two hollow shafts are used as inner and outer housings. A ball bearing is used to connecting the shaft and the inner housing. The shaft is connected to a circular lid using a bolt, and the lid has the same diameter as the outer housing. Such a structure is quite similar to that of the existing design. The only difference is that the existing design has a disc plate mounted on the shaft at the ball bearing side, which prevents sliding motion along the shaft axis.

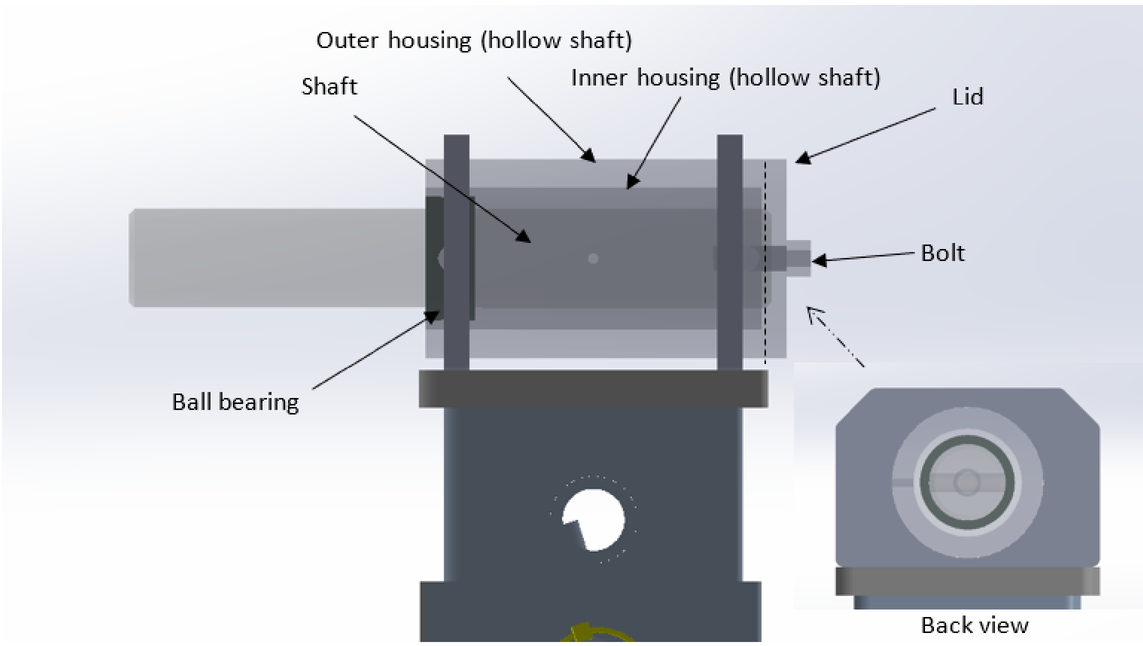


Figure A29: Details of Stand Head Design

This design allows the shaft to slide in the outer housing by eliminating the disc plate in the existing design. Therefore, the shaft can be retracted when a fixture changeover is required. The retracting motion is shown in Figure A30.

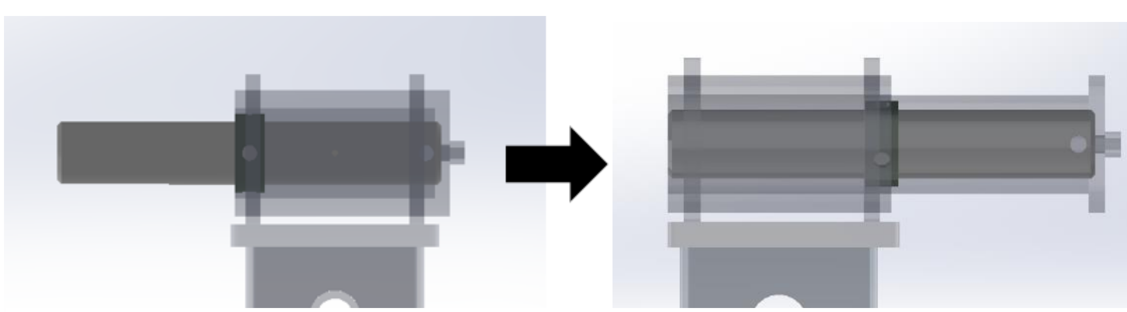


Figure A30: Retracting Motion of Retractable Shaft Design

Such retracting motion simplifies the coupling and decoupling between the shaft and the fixture yoke. Instead of struggling to in pull the A-Stand out of the fixture yoke, the operator can easily decouple the connection by retracting the shaft when switching out the welding fixture. When switching in a new fixture, the operator can simply insert the shaft into the fixture yoke instead of using a forklift to carry the stand and walk it into the yoke.

In addition, a yoke guide is designed to ease the aligning process during changeover. The yoke guide is aligned up with the shaft. As long as the yoke is placed on the guide, the operators can accurately slide the shaft into the yoke. A close view of the fixture yoke stands on the yoke guide coupling with the shaft is shown in Figure A31. The fixture yoke is shown transparent in the figure.

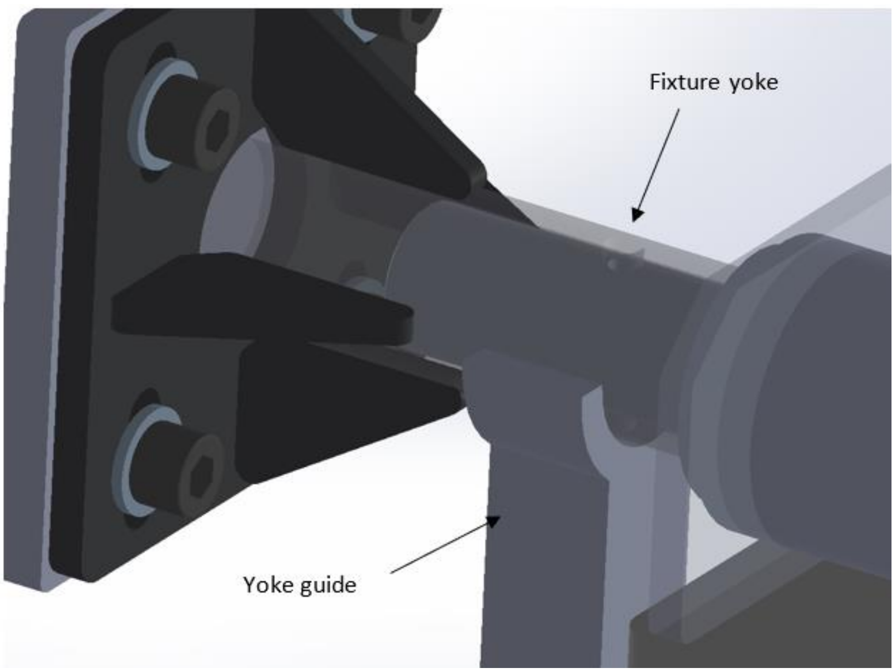


Figure A31: The Coupling of Fixture Yoke and Shaft with the Yoke Guide

When the shaft is in a rotating motion, it is possible that it can slide axially in the housing. The lid mounted at one end will prevent the shaft from moving towards the welding fixture, but not move away from it. Thus, a back support is added to the stand to provide extra holding. The details of the back-support kit are shown in Figure A32. It consists of a quick release spring pull pin, a tube housing and a back support. Instead of a normal insert pin, a pull pin will be installed on the housing to eliminate the number of loose parts in this design.

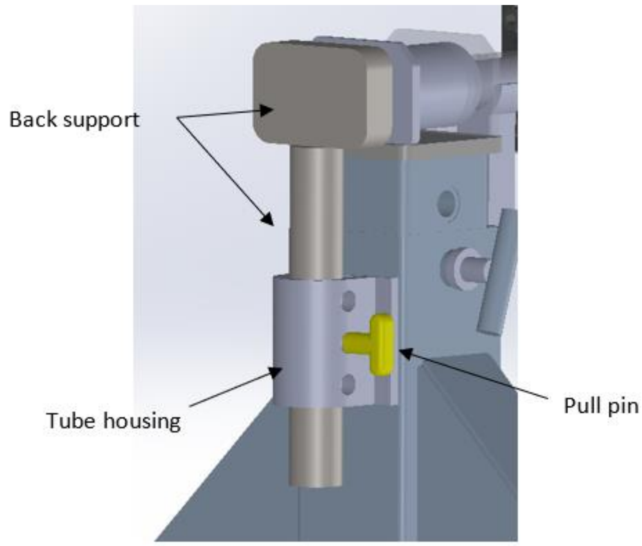


Figure A32: Details of Back Support

The back support is a rigid support piece welded on the top of a tube. The back support can be lifted or lowered by adjusting the tube. It will be retracted downwards when the shaft needs to be pulled out and lifted back in place to prevent the shaft from sliding. The retracting motion is presented in Figure A33.

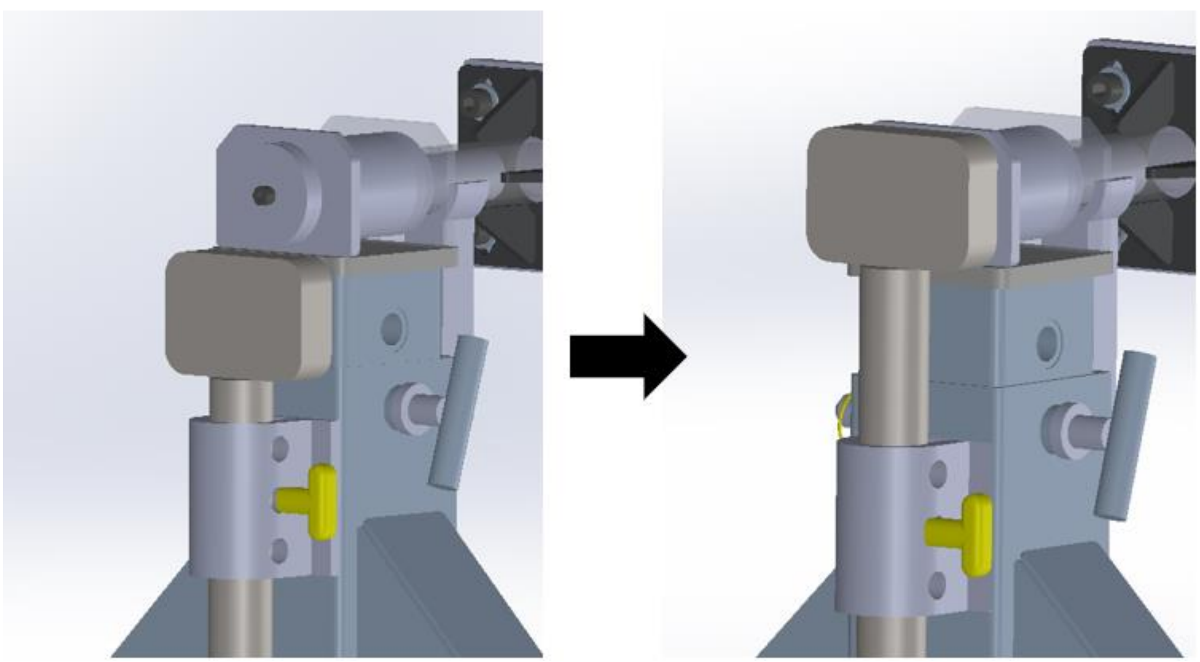


Figure A33: Retractable Back Support

A.2. Concept Analysis and Selections

In this section, the three concepts from the previous section were evaluated and selected according to a list of selection criteria. A selection weighting matrix is presented first to weigh each criterion based on their importance and relevance to the design. Then a weighted scoring matrix is utilized to make the final selection. The retractable shaft design is selected for further development, and a refinement is performed at the end of this section.

A.2.1. Selection Weighting Matrix

The selection weighting matrix is presented in Table AIII, and the details of each criterion will be defined, followed by the table.

TABLE AIII. SELECTION WEIGHTING MATRIX

Selection Criteria		Ease of Use	Amount of Loose Parts	Safety, Mistake Proofing	Compatibility with Existing Design	Cost	Ease of Manufacturing	Ease of Maintenance	Durability
	ID	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Ease of Use	**A**		B	C	A	A	A	A	A
Amount of Loose Parts	**B**			C	B	B	B	B	B
Safety, Mistake Proofing	**C**				C	C	C	C	C
Compatibility with Existing Design	**D**					D	D	D	H
Cost	**E**						F	E	H
Ease of Manufacturing	**F**							G	H
Ease of Maintenance	**G**								H
Durability	**H**								
Customer Need ID		**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Occurrence		4	5	6	3	1	1	1	3
Calculated Weight (%)		14.29	17.86	21.43	10.71	3.57	3.57	3.57	10.71

Ease of use (A):

This criterion is defined by the operation of the changeover process from beginning to end. The coupling action design is easy to use if the number of steps is low and fast. This enables a fast changeover time which is this project's main objective. Also important in this criterion is the difficulty when connecting A-Stands to the welding fixture. The current A-Stand design requires the entire A-Stand to be pulled away from the welding fixture to disconnect the A-Stand Shaft from the welding fixture yoke; and when connecting the A-Stand to the welding fixture yoke, the entire A-Stand must be aligned and pushed toward the welding fixture so that the A-Stand Shaft slides into the welding fixture yoke. This process requires additional resources, such as a forklift or crane, due to the heavy weight of the A-Stands making the process difficult and time consuming. The design will rank high in this criterion if it is able to eliminate the need of the forklift and the difficult task of aligning the A-Stand shaft being slid into the welding fixture yoke.

Amount of Loose Parts (B):

Having loose parts in the design during welding fixture changeover is not desired. Loose parts can be misplaced and lost, dropped on the floor and damaged, and create inefficiency in the change-over process. Therefore, the design ranks high in this criterion if little to no loose parts are present when change over occurs.

Safety, Mistake Proofing (C):

Safety is the top importance at MacDon. Injuries caused by poor design are unacceptable, therefore all new designs are required to pass a safety audit. The design must have safety built in, such as mistake proofing. This can be done by not allowing the process to continue without completing the prior step. In the case of welding fixture change over, if the design requires fastening of bolts and nuts to secure the welding fixture onto the A-Stands, the design might fail the safety audit because the chance to miss fastening step of bolt or nut. The design ranks high in safety if there is little to no chance of forgetting steps that could cause a failure in supporting the welding fixture during the welding process. This can lead to serious injury if welding fixtures fall off the A-Stands, as welding fixtures can weigh up to 4000 lbs.

Compatibility with Existing Design (D):

Compatibility with the existing design is beneficial to the client. As less changes are made to current A-Stands and welding fixture yoke design, reduction in the amount of manufacturing new components allows the client to reuse most of the current supply. This significantly reduces the cost of project.

Cost (E):

Cost is a concern for the client as $8000 budget per pair of A-Stands is set. If the new design costs too much to create, it will not be worth the investment to the client.

Ease of Manufacturing (F):

The design must be able to be manufactured to be successful. The easier manufacturing becomes, the cost of the design is reduced as there is no need for expensive machining equipment and processes. Also, difficult manufacturing techniques are not favourable and should be reduced as much as possible. An example is welding, as this process can cause warpage and cause parts to not fit if tight tolerances are required. Welding is also a time-consuming process.

Ease of Maintenance (G):

The design must be easy to maintain in order to reduce as much downtime as possible to keep productivity high. If maintenance is difficult and/or often, non-valve added time will decrease productivity. Replacement of worn parts is ideal and not expensive.

Durability (H):

The design must be durable to withstand daily operation and abuse, and has a long-life span. Having a long life cycle of the A-Stand and its components is desired to save as much money for MacDon as possible.

A.2.2. Weighted Scoring Matrix

In this section, the three concept designs presented in Section A.1.4. (1: A-Stand Clamping Shaft Design, 2: Sleeve Design, and 3: Retractable Shaft Design) were compared to each other and scored in each of the weighted selection criteria from Section A.2.1. on a scale of one to five

(Table AIV*TABLE AIV*). The selection weighted scoring matrix is presented in Table AV and the justifications on the scoring of each concept with respective design criteria are defined after.

TABLE AIV. RATING KEY FOR WEIGHTED SCORING MATRIX

Rating	Performance
5	Best
4	Excellent
3	Good
2	Acceptable
1	Poor

TABLE AV. WEIGHTED SCORING MATRIX

		Concepts					
		A A-Stand Clamping Shaft		B Sleeve		C Retractable Shaft	
Selection Criteria	Weight	Rating	Weight Score	Rating	Weight Score	Rating	Weight Score
Ease of Use	14.29%	4	0.5716	3	0.4287	3	0.4287
Amount of Loose Parts	17.86%	5	0.893	5	0.893	5	0.893
Safety, Mistake Proofing	21.43%	3	0.6429	3	0.6429	4	0.8572
Compatibility with Existing Design	10.71%	4	0.4284	4	0.4284	3	0.3213
Cost	3.57%	3	0.1071	3	0.1071	3	0.1071
Ease of Manufacturing	3.57%	2	0.0714	3	0.1071	3	0.1071
Ease of Maintenance	3.57%	4	0.1428	2	0.0714	3	0.1071
Durability	10.71%	3	0.3213	2	0.2142	4	0.4284
Total Score		3.1785		2.8928		3.2499	
Rank		2		3		1	
Continue?		No		No		Develop	

From Table AV, the retractable shaft design ranked highest with score of 3.2499. Therefore, retractable shaft was determined as the most optimal design concept.

Justification for the ratings of each concept design in each of the selection criteria are presented below. Justification is sorted into sections by the selection criteria, and each design is represented by letters A, B, and C for the clamp design, sleeve design, and retractable shaft design, respectively.

Ease of use:

A. The clamp design is the easiest to use of the three because the welding fixture only needs to be lifted off and lowered onto the A-Stand bottom clamps when changeover is performed. The clamps are easy to lock in place because of a hinge connecting the top and bottom clamp and auto locking pin. Therefore, having a rating of 4.
B. The sleeve design received a rating of 3. It is quite easy since it only requires simple sliding motion and has a feature that automatically locks between the A-Stand and the welding fixture. However, since there are multiple stages in the sliding sleeve, it can cause problems once one of the stages get stuck and the user might have to struggle to fully engage each sleeve if the A-Stands and welding fixture are not perfectly aligned.
C. The retractable shaft concept allows for a sliding motion of the shaft, which eases the coupling process during changeover, eliminating the need to move the entire A-Stand to disconnect from welding fixture. The design of a quick release pull pin and the yoke guide also simplify the changeover process and provide better operator ergonomics. Difficulty is still present if the welding fixture and the A-Stand are not aligned, giving it a rating of 3.

Amount of loose parts:

All three designs have no loose parts; thus, they received a rating of 5.

Safety, Mistake Proofing:

A. The clamp design integrates a self-locking pin to ensure the top cannot be forgotten to be locked into the bottom half of the cup cannot. A spring-loaded pin goes into the A-Stand shaft once dropped in place. However, the strength of locking pin might not be feasible to support the load of the welding fixture. Therefore, a rating of 3 was given.
B. For the safety criterion, the sleeve design received a rating of 3. As shown in the above section, this design has multiple sleeves that the user has to slide on or off of the shaft. During this process, there is a chance that the user might pinch their hands in between each stage. Also, if the spring-loaded detent fails to engage, the user might not have

noticed this incident, which can cause the sleeves to disengage from the shaft due to cyclic loading.

C. The potential failure point is at the back support. The support can fail due to shear stress induced by the axial force. However, the back support is not likely to experience critical load when in use. According to the functionality of the A-Stands, the major force will be acting on the shaft in the vertical direction but not the axial direction. The back support is strong enough to withstand minimal axial stresses. The shaft strength has been proven to withstand a welding fixture load with the current design, giving it a rating of 4.

Compatibility with Existing Design:

A. The only component that changes from the A-Stand is the shaft end that attaches to the welding fixture yoke. Therefore, the majority of A-Stand can be reused, reducing the amount of manufacturing; while the existing welding fixture yoke can be reused. Therefore, this design ranks excellent at 4.
B. The sleeves will be built on the base of the existing yoke which is already compatible with the existing welding fixture. Also, the last stage of the sleeve will fit to the shaft from the A-Stand, so this design received rating of 4 for the compatibility with the original design criterion.
C. The retractable shaft design is built on the existing A-Stands. The structure of the stand head is simply modified based on the existing head structure. The other components in the design are just add-on parts, which will not be compatible with the A-Stand base. Therefore, it has given a rating of 3.

Cost:

A. Only a portion of the A-Stand shaft is changed, the cost of material is low because little material is used. However, manufacturing components can take a lot of time due to the amount of welding required. This gives it a rating of 3.
B. The cost is determined based on the number of parts that needs to be manufactured. The base of the yoke attached to the welding fixture is reused, but the sleeves must be manufactured. It can be difficult to manufacture these parts, so this design was given a rating of 3 for the cost criterion.

C. Besides the cost of manufacturing additional add-on parts, no significant cost is required in the design. Therefore, the design was given a rating of 3.

Ease of Manufacturing:

A. Manufacturing the clamp design will be difficult. This is because a lot of parts are welded together, which can lead to distortion and cause the welding fixture yoke not to fit with the clamping parts, giving it a rating of 2.
B. The sleeve design requires multiple hollow shafts that require very low tolerances. The sleeves are relatively smaller, thinner, and have brackets which make this design quite difficult to manufacture, so it received rating of 3 for ease of manufacturing.
C. The design requires minimal modification on the shaft, and re-manufacturing is not required. The add-on components will need to be manufactured. The manufacturing of the add-on components will not be complicated due to the simplicity of their structure, giving it a rating of 3.

Ease of Maintenance:

A. The parts in the locking pin mechanism can be disassembled, and it is easy to replace broken components giving a high ranking of 4 for this criterion.
B. Since the sleeves are a one-piece design, this design seems like it does not require much maintenance. However, if a mid-stage or the first stage goes wrong, the whole sleeve assembly will have to be taken out from the welding fixture to be fixed. It also can be difficult due to its thickness, so the sleeve design received a rating of 2 for ease of maintenance.
C. Due to the friction induced by the sliding motion, the interface between inner and outer housings will experience wear. Lubricating can be frequent, giving a rating of 3.

Durability:

A. The clamp design has a chance of failure around the welds. Because a lot of pieces are welded together in this design, durability is not the best. To improve its durability, thicker and more gussets are needed around the top and bottom cups of the A-Stand clamp, giving a rating of 3.

B. The thickness of the sleeve design can cause cracking in the weld between the base and the first stage sleeve due to cyclic loading and the weight of the welding fixture. Also, since it is relatively not easy to maintain, the sleeve design was given a rating of 2 for the durability.
C. The design is built on the existing shaft structure. According to the performance of the existing design, and the solid shaft is durable. The add-on parts will not experience significant force when in use. Therefore, this design received 4.

A.2.3. Concept Selection and Refinement

Based on the weighting matrix presented, the retractable shaft design concept is selected for further development. The selected concept has strong performance on safety, durability and ease of manufacturing. Most importantly, the design's key component, shaft retains to be the existing shaft. Therefore, the strength of the shaft is already validated from performance of the existing design.

An issue with the generated retractable shaft concept is the friction at the interface of the inner and outer housings during the sliding motion. The use of a linear-motion bearing was inspired by researching the patent database and the team found US3398999A [14]; which can be beneficial in reducing the friction, allowing a smooth sliding motion, thereby ease the maintenance and improve the design's durability. A linear-motion bearing is a bearing that provides one-direction free motion [15]. Linear-motion ball bearings are the most commonly used type of linear-motion bearing, providing smooth motion along the axial direction. An example of a linear-motion ball bearing is illustrated in Figure A34. A linear-motion ball bearing generally consists of ball elements, a retainer, an outer cylinder (housing), a side ring [16]. The steel ball elements are the key components that provide the linear motion in the bearing, and they are held by a retainer. The retainer is secured inside the outer cylinder with a side ring. The linear-motion ball bearing will enable the retractable shaft a smooth sliding motion with very low friction. One of the advantages of the ball bearing is that it uses a round shaft structure for the guiding axis, which is compatible with the generated retractable shaft concept. The linear-motion ball bearings are also available in a wide variety of shapes and installation methods, which increases the design's flexibility and ease of manufacturing [16].

[redacted]

Figure A34: (a) Linear-Motion Ball Bearing [17], and (b) Illustration of the Linear-Motion Ball Bearing [18]

The linear-motion ball bearing will be placed between the inner housing and the outer housing, as shown in Figure A35.

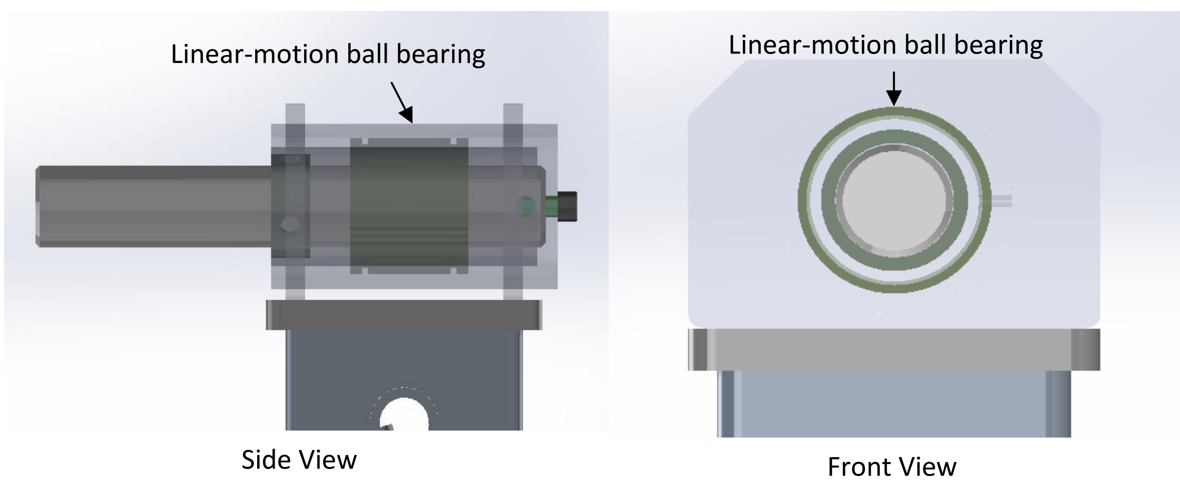


Figure A35: Retractable Shaft Design with Linear-motion Ball Bearing

Therefore, the retractable shaft now allows for smooth action for both rotating and sliding as illustrated in Figure A36.

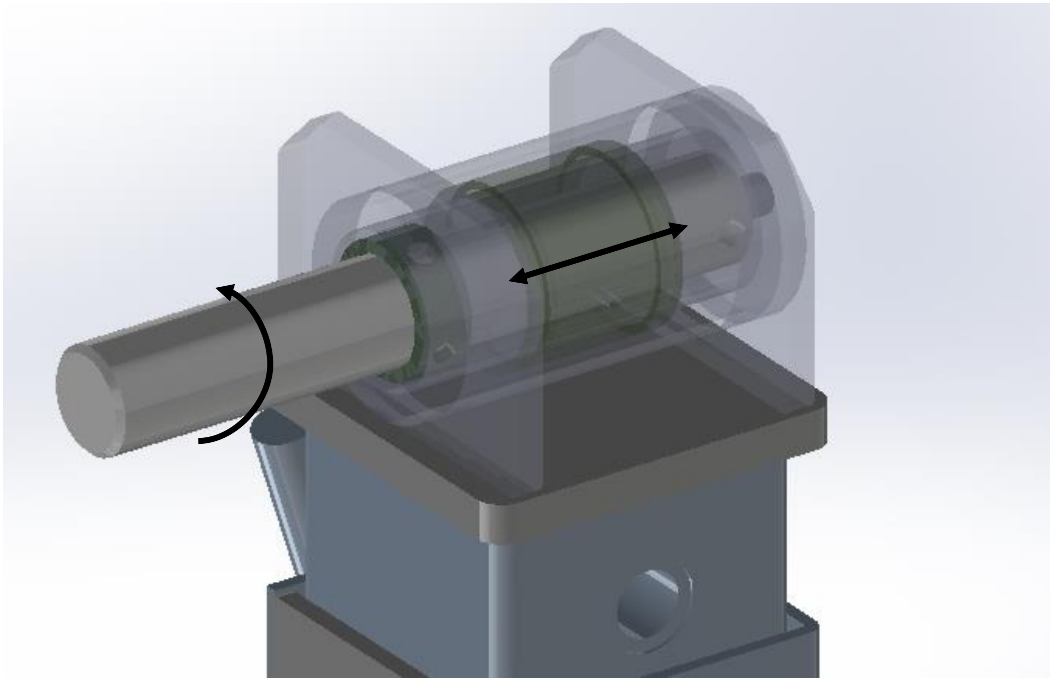


Figure A36: Sliding and Rotating Motion

Appendix B: Design Optimization

B.1. Preliminary FMEA for Iterated Designs

A preliminary FMEA was performed on both the drive end and the idle end of the A-Stands to further develop the design.

To initiate the failure modes analysis, the steps or inputs involved in the changeover process are identified. The three primary process steps are: connecting the shaft and the fixture, while in use of the assembly, disconnecting the shaft and the fixture. Then potential failure modes in the steps were identified and investigated.

Once possible failure modes are identified, each of them is ranked based on their severity, frequency of occurrence, and detection level. The ranking is on a scale of one to ten. For severity, one being not noticeable failure, and ten being a failure that involve damage or hazard for personal injury. For frequency of occurrence, a rating of one is for an unlikely mode, and a rating of ten is for a failure mode that is almost inevitable and would occur multiple times a day. For detection level, a rating of one is given if the failure is obvious and easy to detect or prevent; a rating of ten is given if the failure cannot or will not be detected or prevented. The risk priority number (RPN) is calculated by multiplying the three criteria. For the failure modes have a RPN over five hundred, further design development will be performed to address them.

Since the drive end and the idle end have different structures and features, FMEA were performed separately on them. The preliminary FMEA for the drive end is shown in Table BI and the one for the idle end is shown in Table BII.

TABLE BI. PRELIMINARY DRIVE END FMEA ITERATION

Process Step/Input (X)	Potential Failure Mode	Potential Effect	SEV	Potential Causes	FREQ	Current Controls	DET	RPN	Action Recommendations
Connecting fixture and shaft	Fixture yoke breaks and fails	Injury, Fixture falls	10	Welded connection fails, Loose bolts	2	Tighten the bolts every once in a while	6	120	
	Cup/Guide fails	Shaft has to withstand all the weight, reduced torque	6	-Welded connection fails -Fixture gets dropped on the cup/guide	2	Maintenance	6	72	
	Shaft and yoke do not align	Unable to connect the shaft and the fixture	6	Tolerance	2	Maintenance	9	108	
	A-Stand base tips over	Injury, Damaged parts, Fixture falls	10	Not enough support	10	Support legs	10	1000	Additional support legs
	Locating pins fail	Less secure connection	6	Welded connection fails	3	Maintenance	6	108	
While in use	Key fails	Shaft does not rotate	6	Fatigue, Crack	4	Maintenance	7	168	

	Sleeve/Housing fails	Injury, Damaged parts, Fixture falls	8	Fatigue, Crack	5	Maintenance	10	400	
	Cup/Guide experiences wear	Cup/Guide fails, shaft and yoke do not align	6	Friction	10	Maintenance	9	540	Use anti-wear material
Disconnecting fixture and shaft	Handle breaks	Unable to retract the shaft	6	Welded connection fails	3	Maintenance	6	108	
	Shaft gets stuck inside	Unable to retract the shaft	6	Deformed shaft, Contaminated grease	1	Maintenance	10	60	
	Grease gets exposed	Contaminated grease	7	Grease catches dirt	10	Training	9	630	Use oil impregnated bearing
		Makes a mess	6	Grease overflows	9	Maintenance	10	540	
		Catches on fire	10	Grease overflows	6	Maintenance	10	600	

TABLE BII. PRELIMINARY IDLE END FMEA ITERATION

Process Step/Input (X)	Potential Failure Mode	Potential Effect	SEV	Potential Causes	FREQ	Current Controls	DET	RPN	Action Recommendations
Connecting fixture and shaft	Fixture yoke fails	Injury, Fixture falls	10	Welded connection fails, Loose bolts	2	-Tighten the bolts every once in a while -Maintenance	6	120	
	Cup/Guide fails	Shaft has to withstand all the weight, reduced torque	6	-Welded connection fails -Fixture gets dropped on the cup/guide	2	Maintenance	6	72	
	Shaft and yoke do not align	Unable to connect the shaft and the fixture	6	Tolerance	2	Maintenance	9	108	
	A-Stand base tips over	Injury, Damaged parts, Fixture falls	10	Not enough support	10	Support legs	10	1000	Additional support legs
	Locating pins fail	Less secure connection	6	Welded connection fails	3	Maintenance	6	108	
While in use	Sleeve/Housing fails	Injury, Damaged parts, Fixture falls	8	Fatigue, Crack	5	Maintenance	10	400	

	Cup/Guide experiences wear	Cup/Guide fails, shaft and yoke do not align	6	Friction	10	Maintenance	9	540	Use anti-wear material
Disconnecting fixture and shaft	Handle breaks	Unable to retract the shaft	6	Welded connection fails	3	Maintenance	6	108	
	Shaft gets stuck inside	Unable to retract the shaft	6	Deformed shaft, Contaminated grease	1	Maintenance	10	60	
	Grease gets exposed	Contaminated grease	7	Grease catches dirt	10	Training	9	630	Use oil impregnated bearing
		Makes a mess	6	Grease overflows	9	Maintenance	10	540	
		Catches on fire	10	Grease overflows	6	Training, Maintenance	10	600	
Transporting	User forgets to lock the latch	Shaft falls and gets damaged	10	Human error	5	Training	4	200	

Appendix C: Stress Calculations

C.1. Stress Calculations for the Support Leg

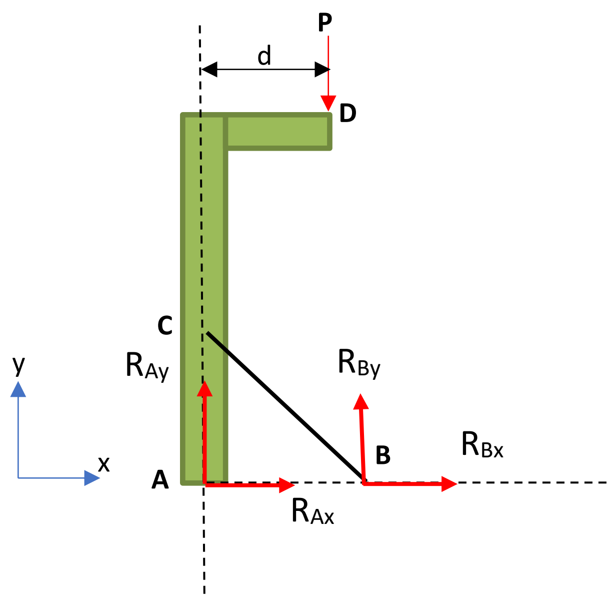


Figure C1: A-Stand Freebody Diagram

Moment Balance Equation at A:

$$\sum M_A = R_{By} \cdot h - P \cdot d = 0$$

$$R_{By} = \frac{P \cdot d}{h} = 8025\ lb$$

Vertical Force Balance Equation:

$$\sum F_y = R_{Ay} + R_{By} - P = 0$$

$$R_{Ay} = P - R_{By} = -2025\ lb$$

Horizontal Force Balance Equation:

$$\sum F_x = R_{Ax} + R_{Bx} = 0$$

$$R_{Ax} = -R_{Bx}$$

For Truss BC:

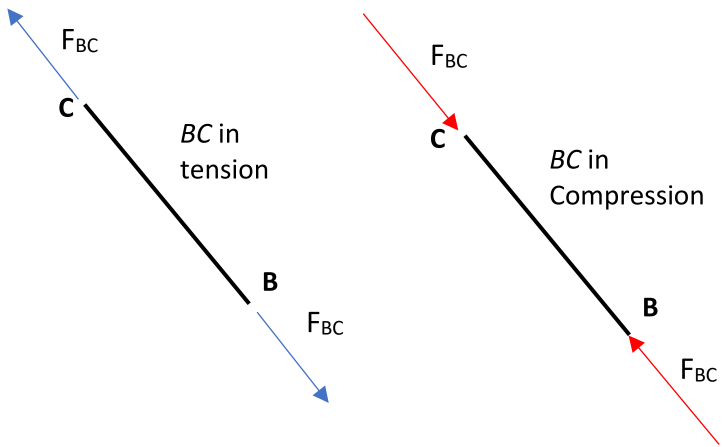


Figure C2: Truss Member BC, Force F_{BC} *shown in Tension and Compression*

$$F_{BC} = \sqrt{{R_{Bx}}^2 + {R_{By}}^2}$$

$$|R_{By}| = |R_{Bx}|$$

$$F_{BC} = \sqrt{2{R_{By}}^2} = \sqrt{2(\frac{P \cdot d}{h})^2} = 11349\ lb\ (compression)$$

Appendix D: Preliminary Engineering Drawings

In this section, preliminary engineering drawings for both the drive end and the idle end of the final design will be presented. The drawings are only produced for the parts that the existing design does not have. The drawings are in imperial units and since the tolerances were not specified, the drawings do not include specific tolerance limit. Note that the preliminary drawings are not for construction.

D.1 Preliminary Drawings for the Drive End

The preliminary engineering drawings for the new parts that requires machining on the drive end of the final design will be presented in this section.

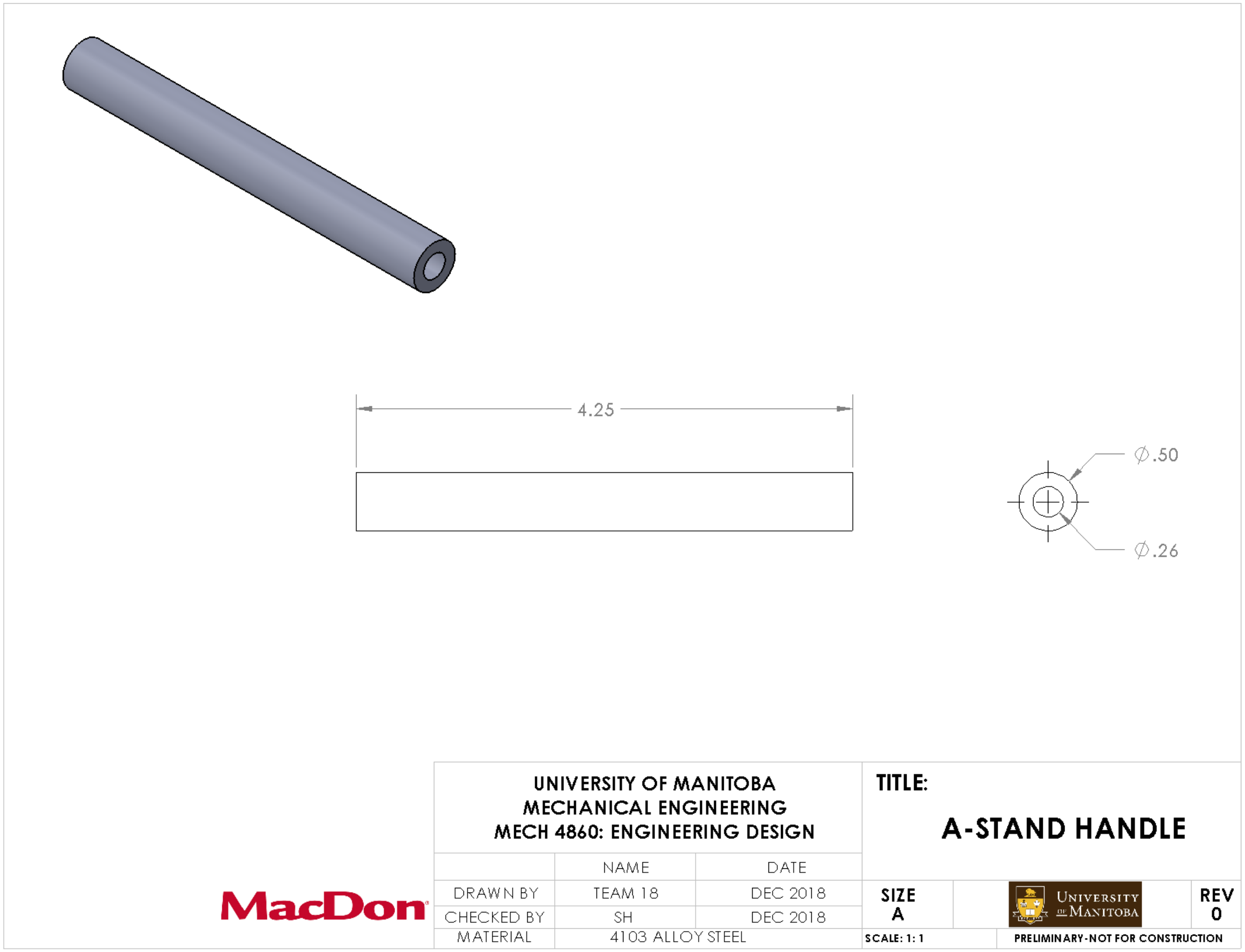


Figure D1: Preliminary Drawing for the A-Stand Handle

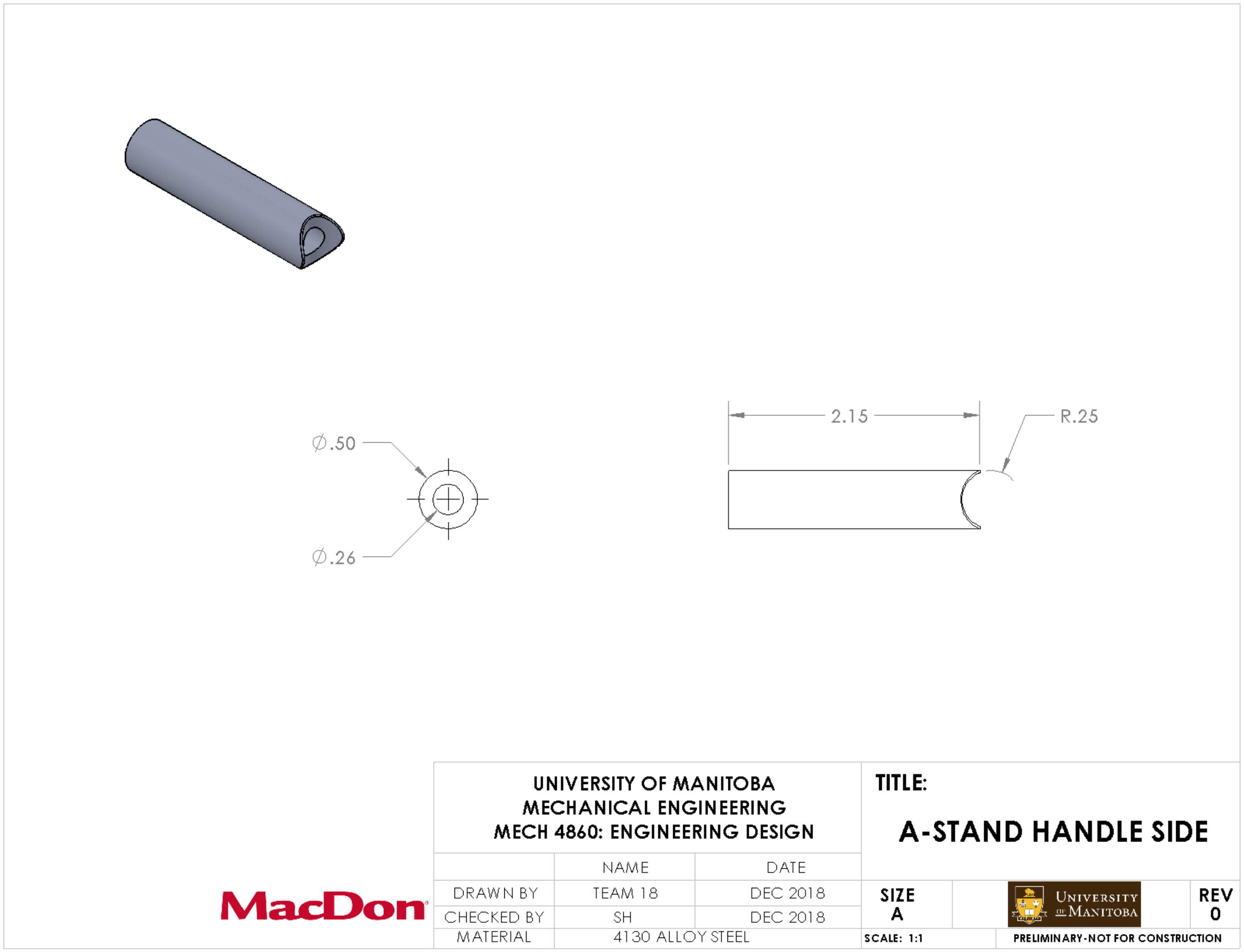


Figure D2:Preliminary Drawing for the A-Stand Side Handle

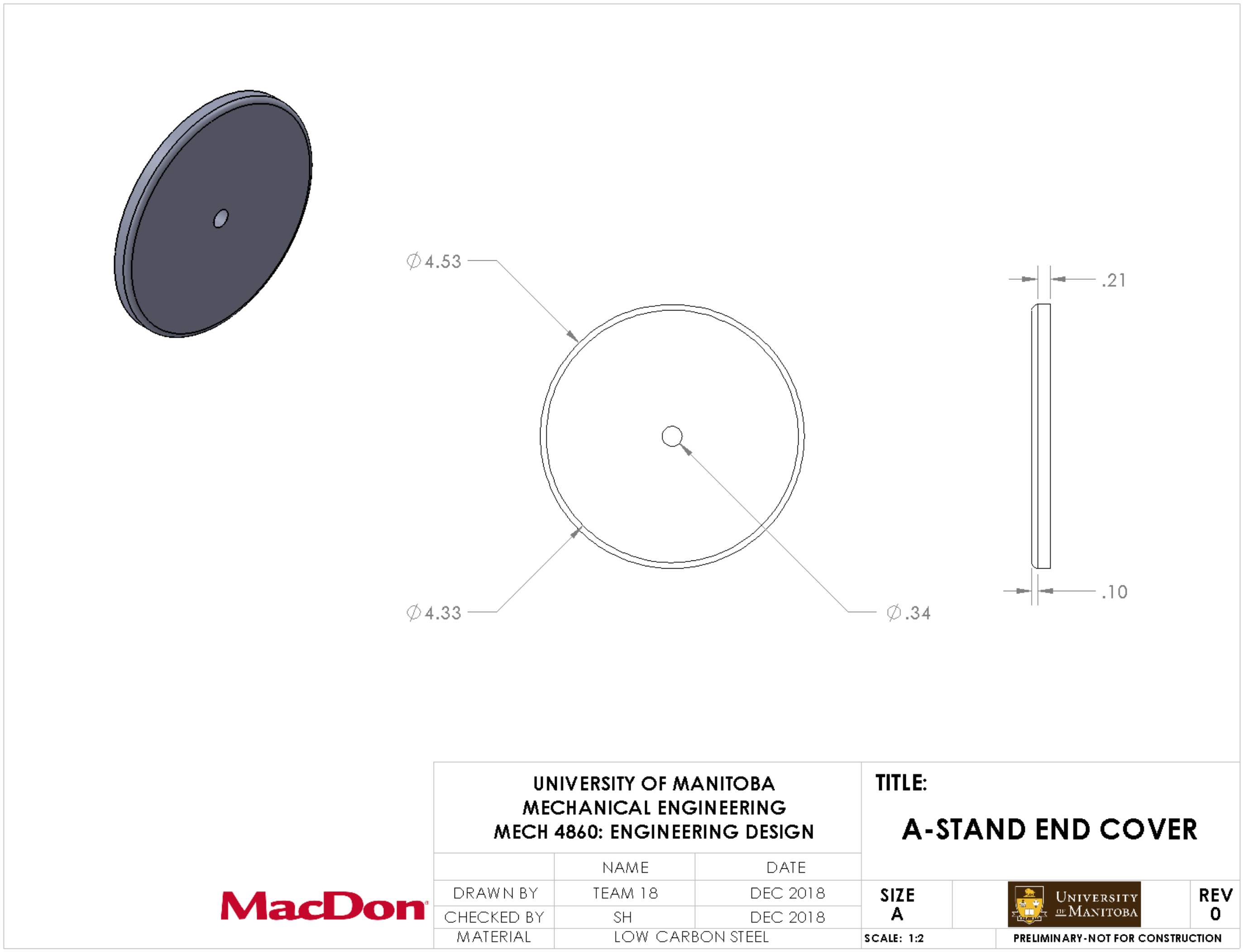


Figure D3: Preliminary Drawing for the A-Stand End Cover

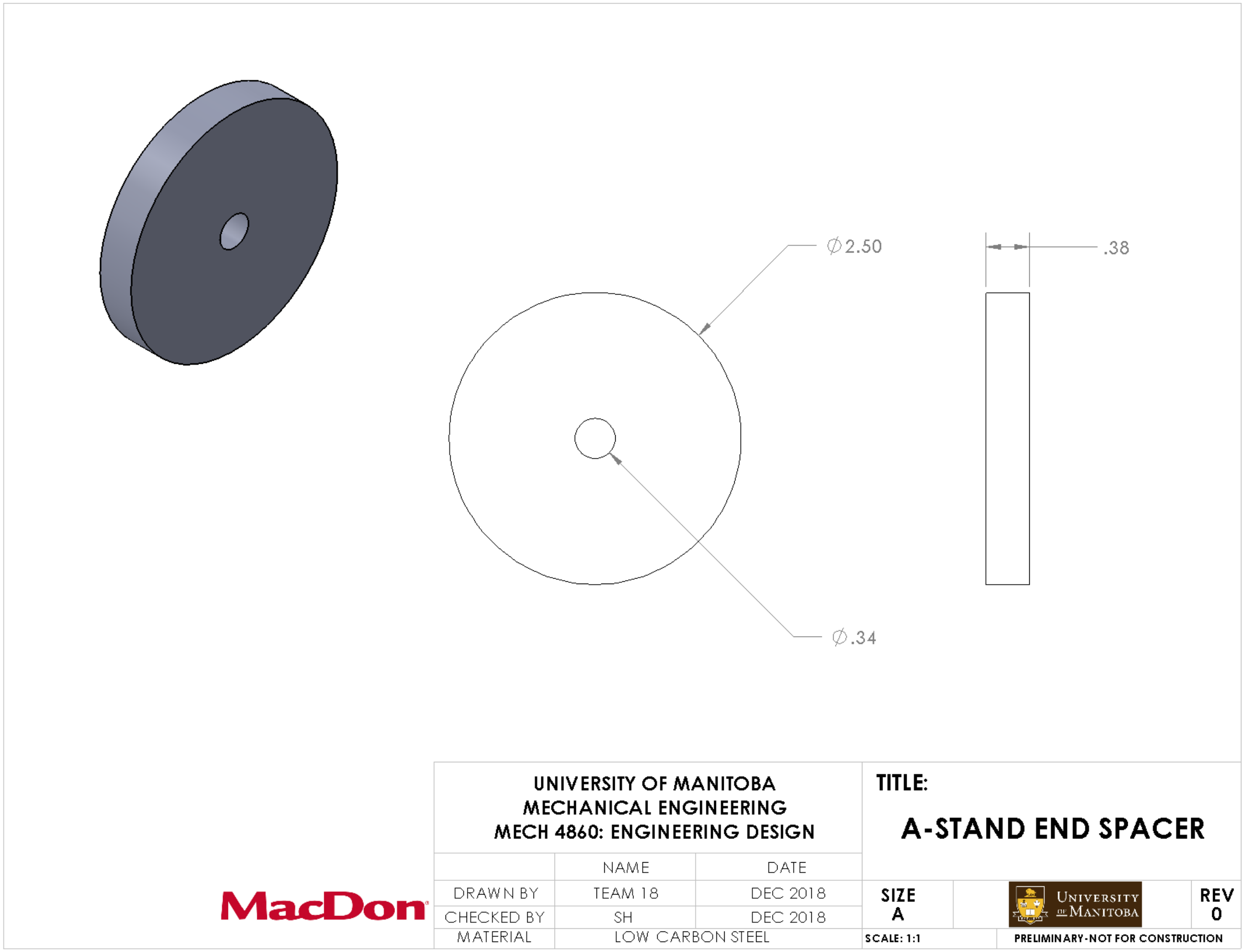


Figure D4: Preliminary Drawing for the A-Stand End Spacer

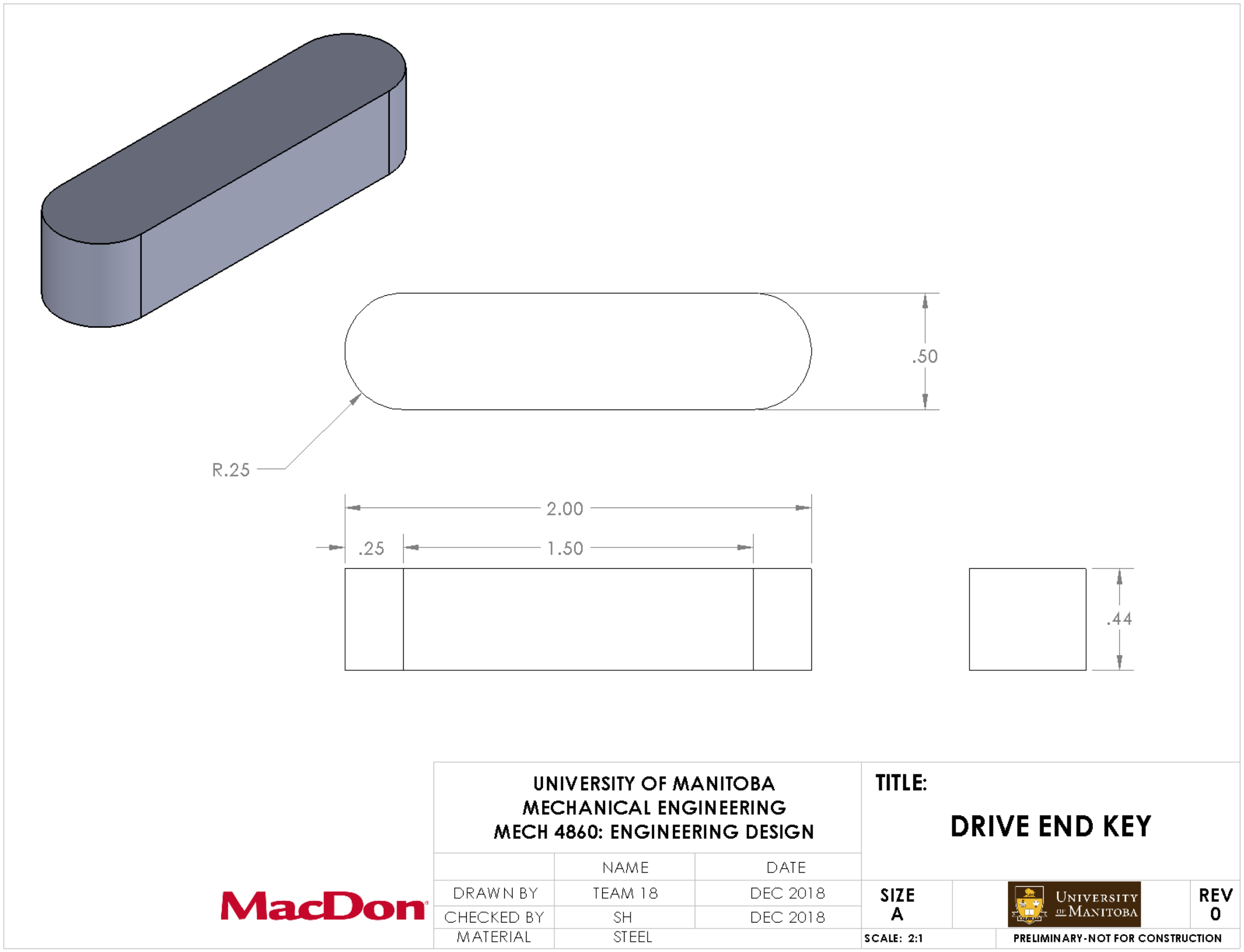


Figure D5: Preliminary Drawing for the Drive End Key

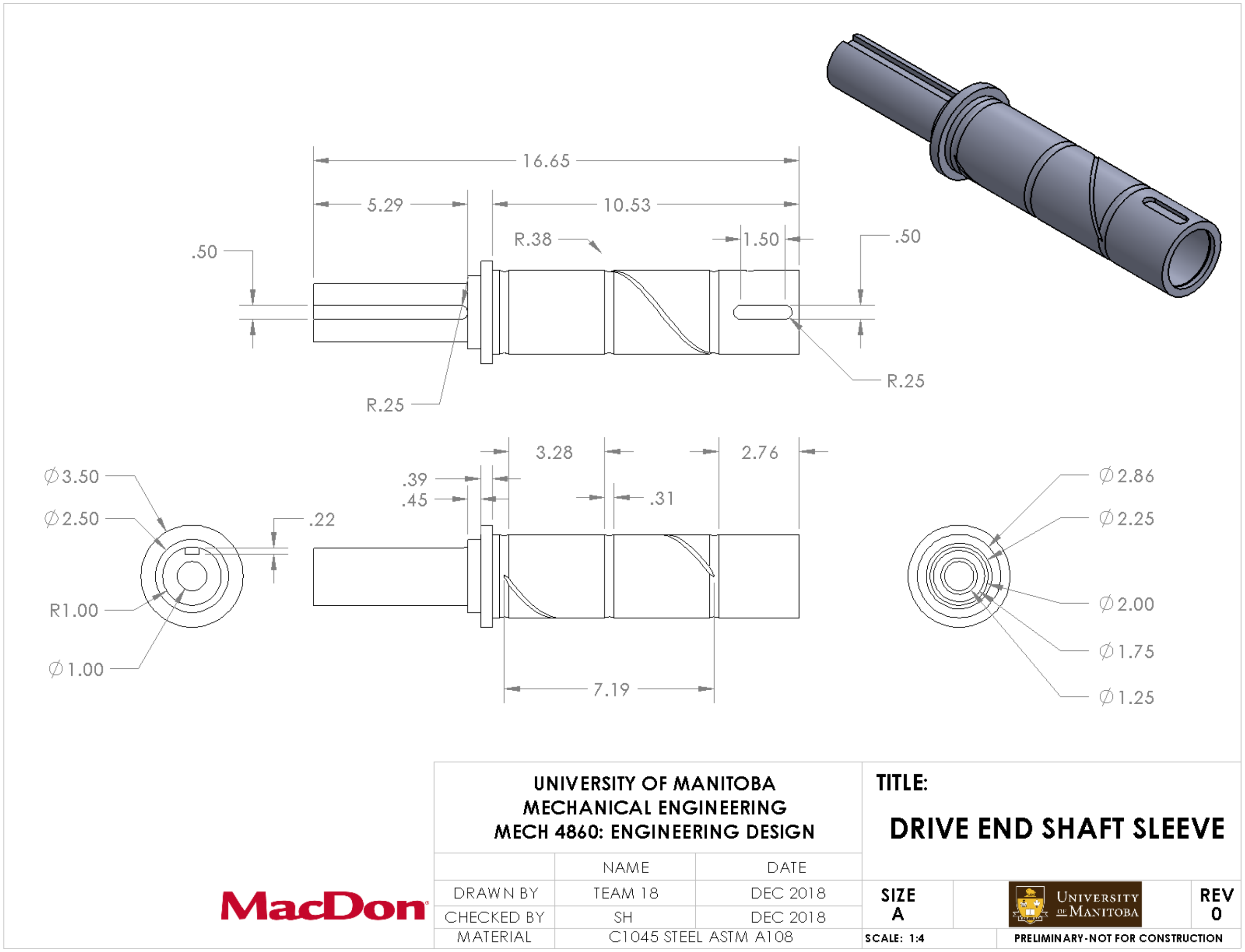


Figure D6: Preliminary Drawing for the Drive End Shaft Sleeve

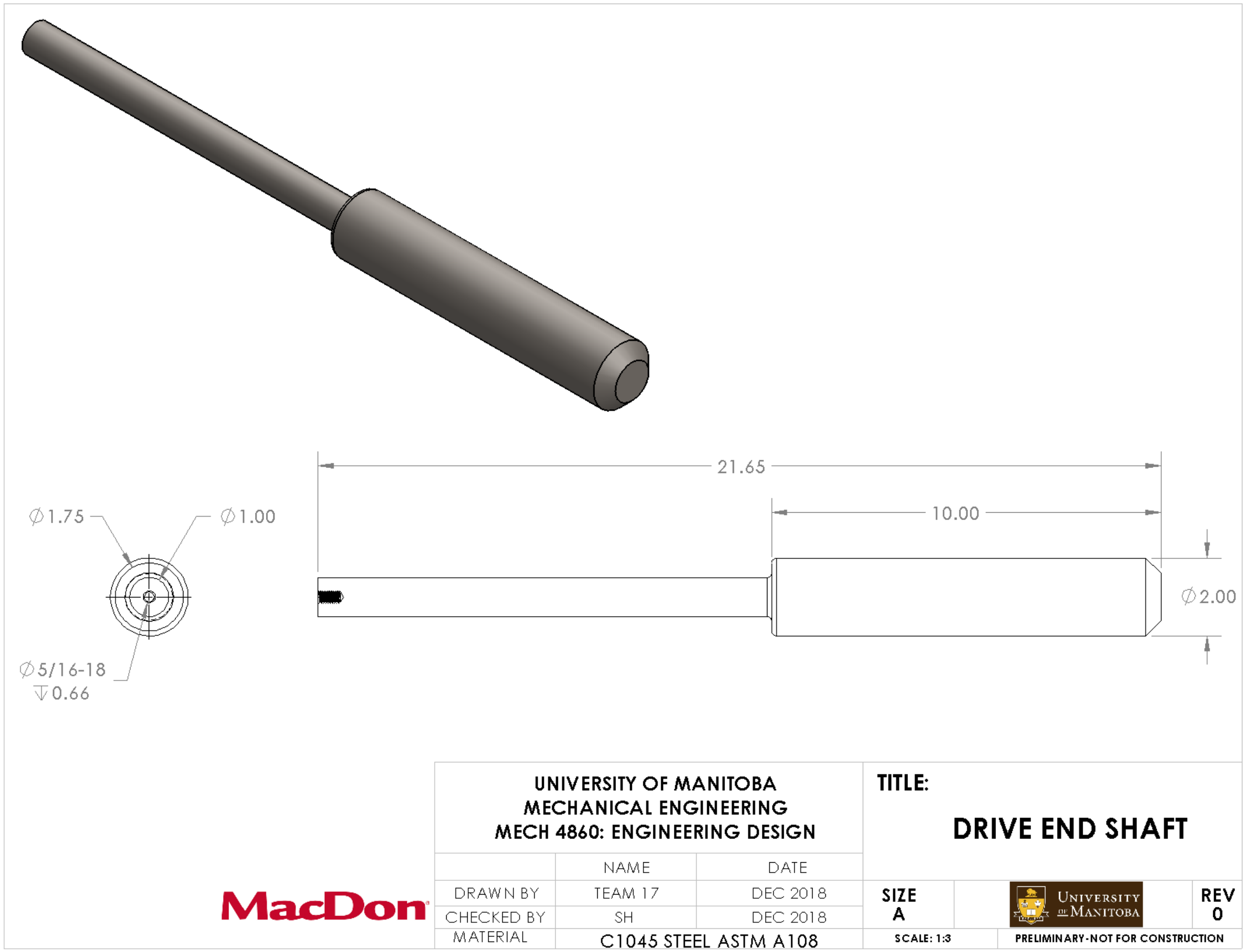


Figure D7: Preliminary Drawing for the Drive End Shaft

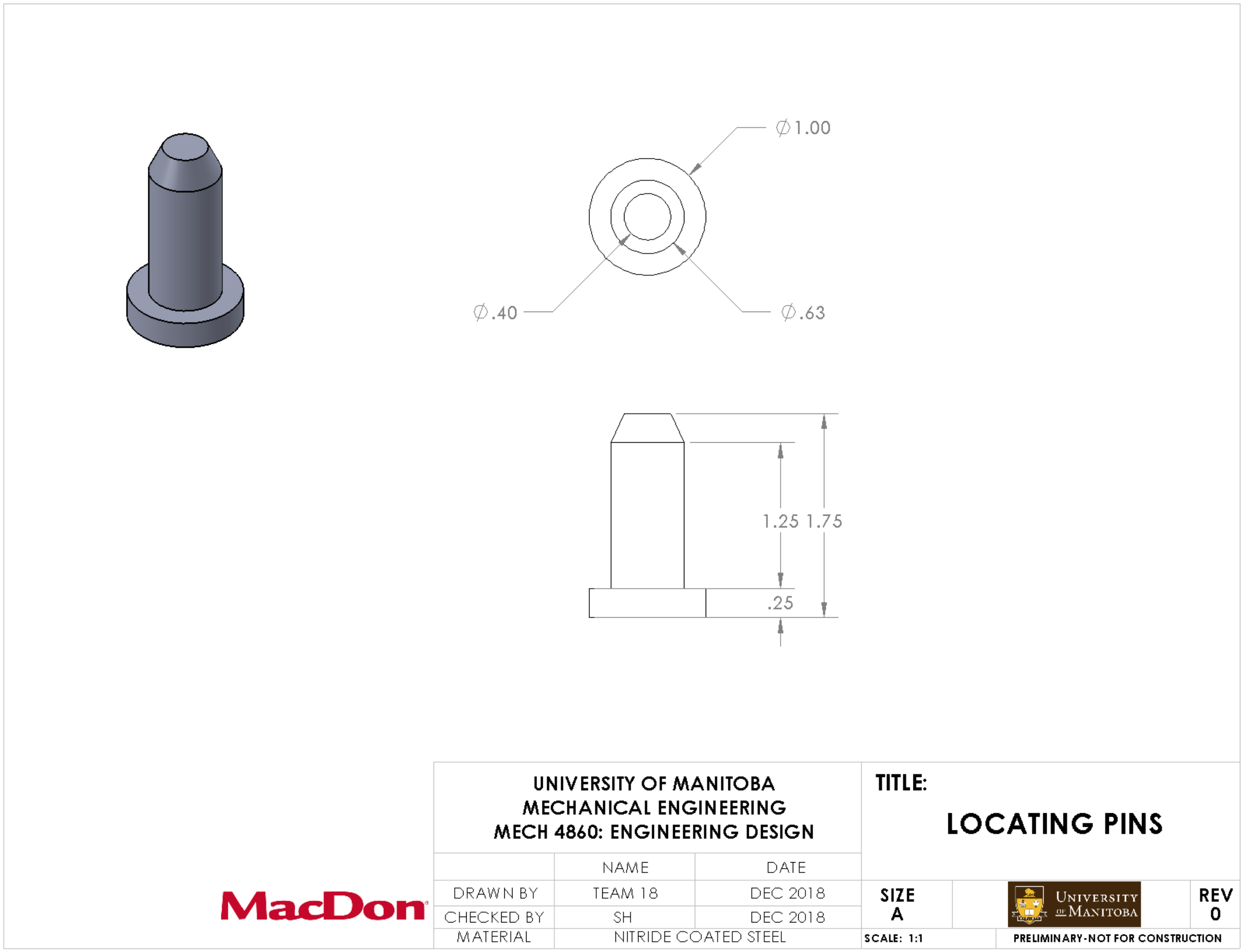


Figure D8: Preliminary Drawing for the Locating Pins

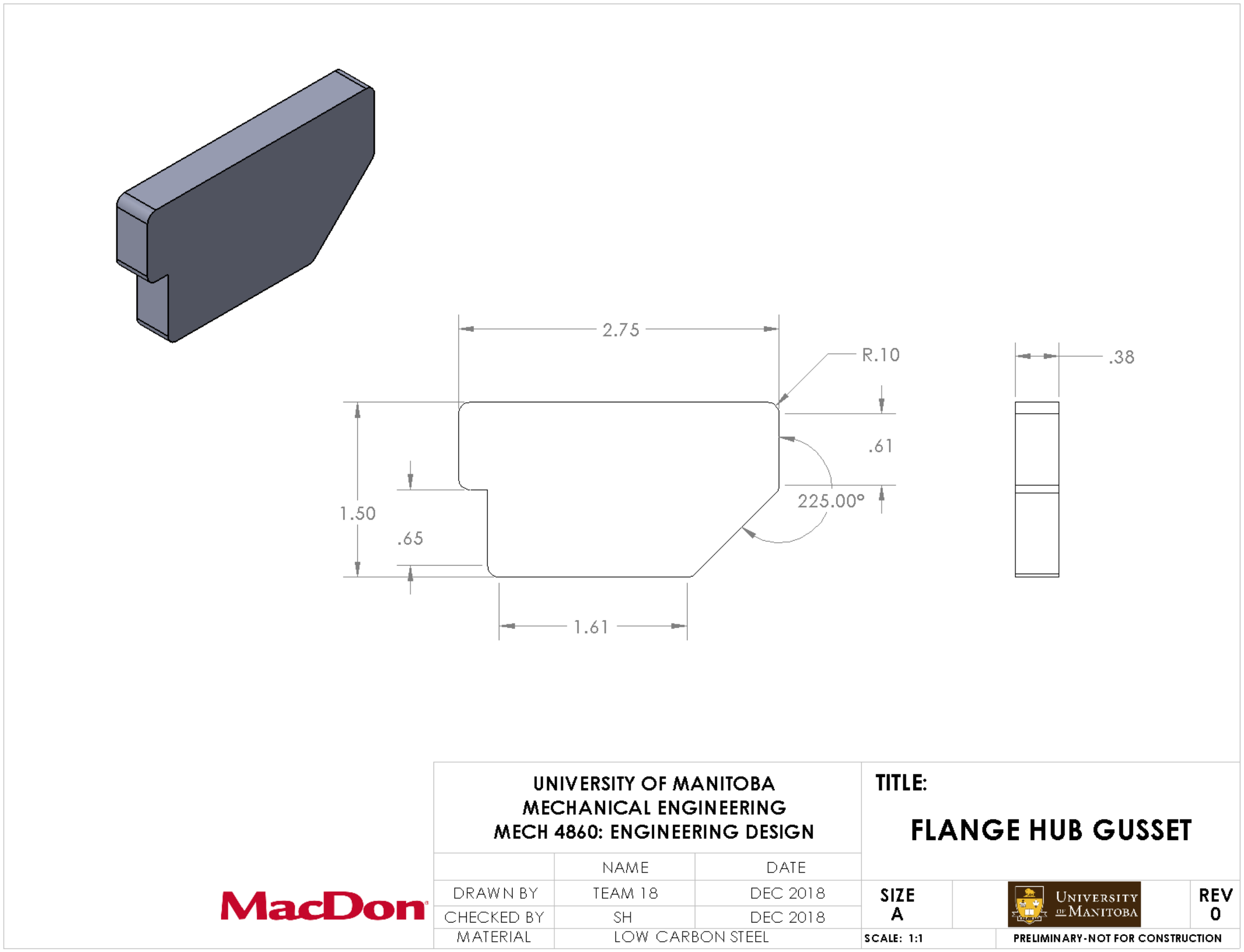
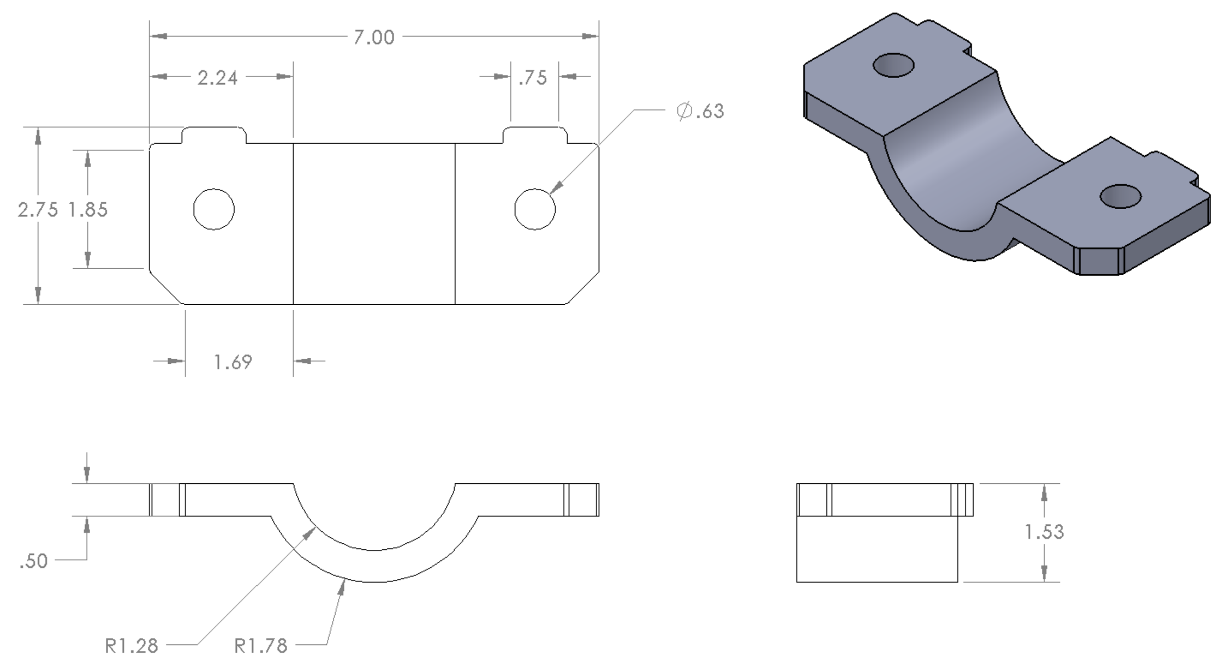


Figure D9: Preliminary Drawing for the Flange Hub Gusset



MacDon

UNIVERSITY OF MANITOBA MECHANICAL ENGINEERING MECH 4860: ENGINEERING DESIGN			TITLE: FLANGE HUB CUP		
	NAME	DATE			
DRAWN BY	TEAM 18	DEC 2018	SIZE A	UNIVERSITY OF MANITOBA	REV 0
CHECKED BY	SH	DEC 2018			
MATERIAL	LOW CARBON STEEL		SCALE: 1:2	PRELIMINARY-NOT FOR CONSTRUCTION	

Figure D10: Preliminary Drawing for the Flange Hub Cup

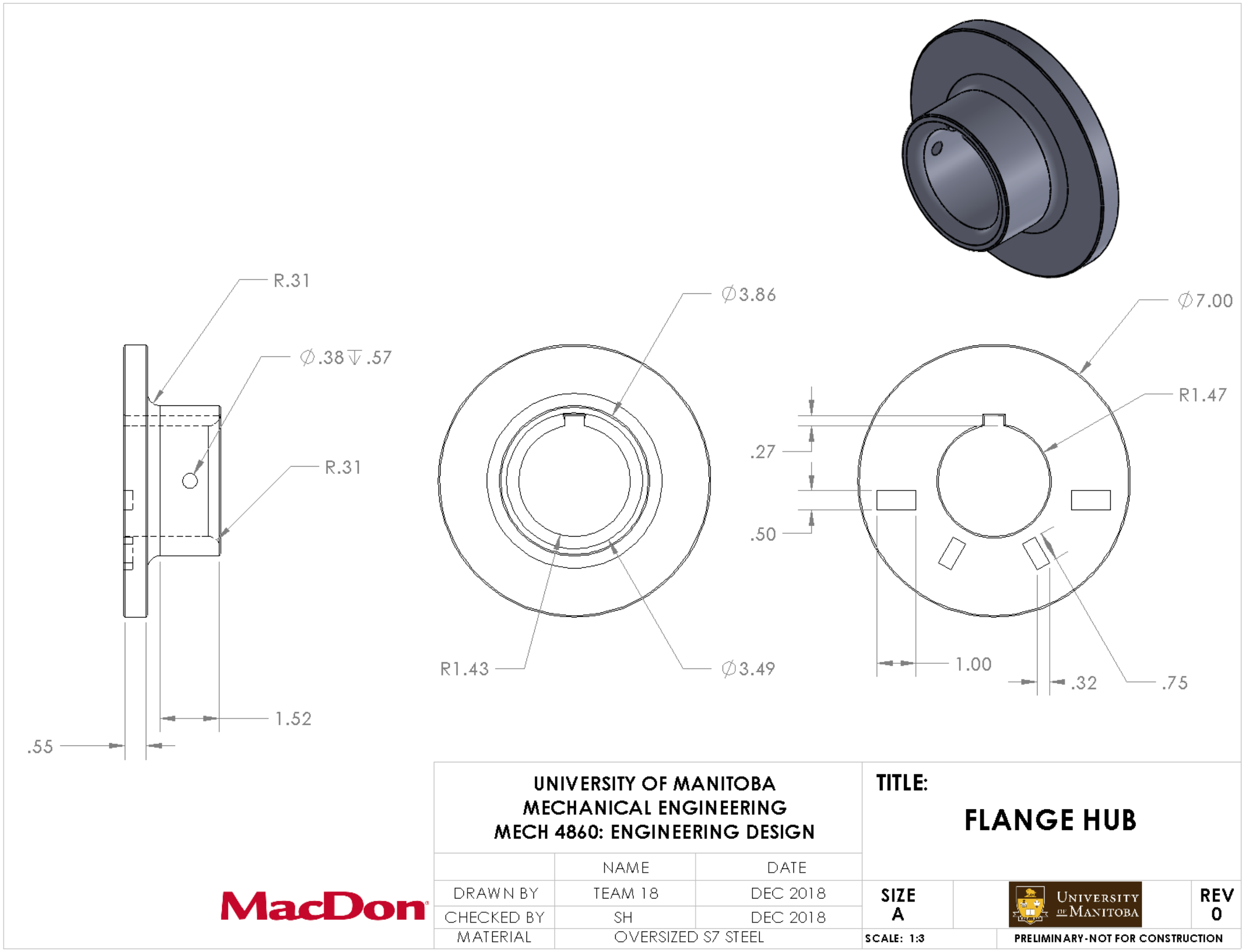


Figure D11: Preliminary Drawing for the Flange Hub

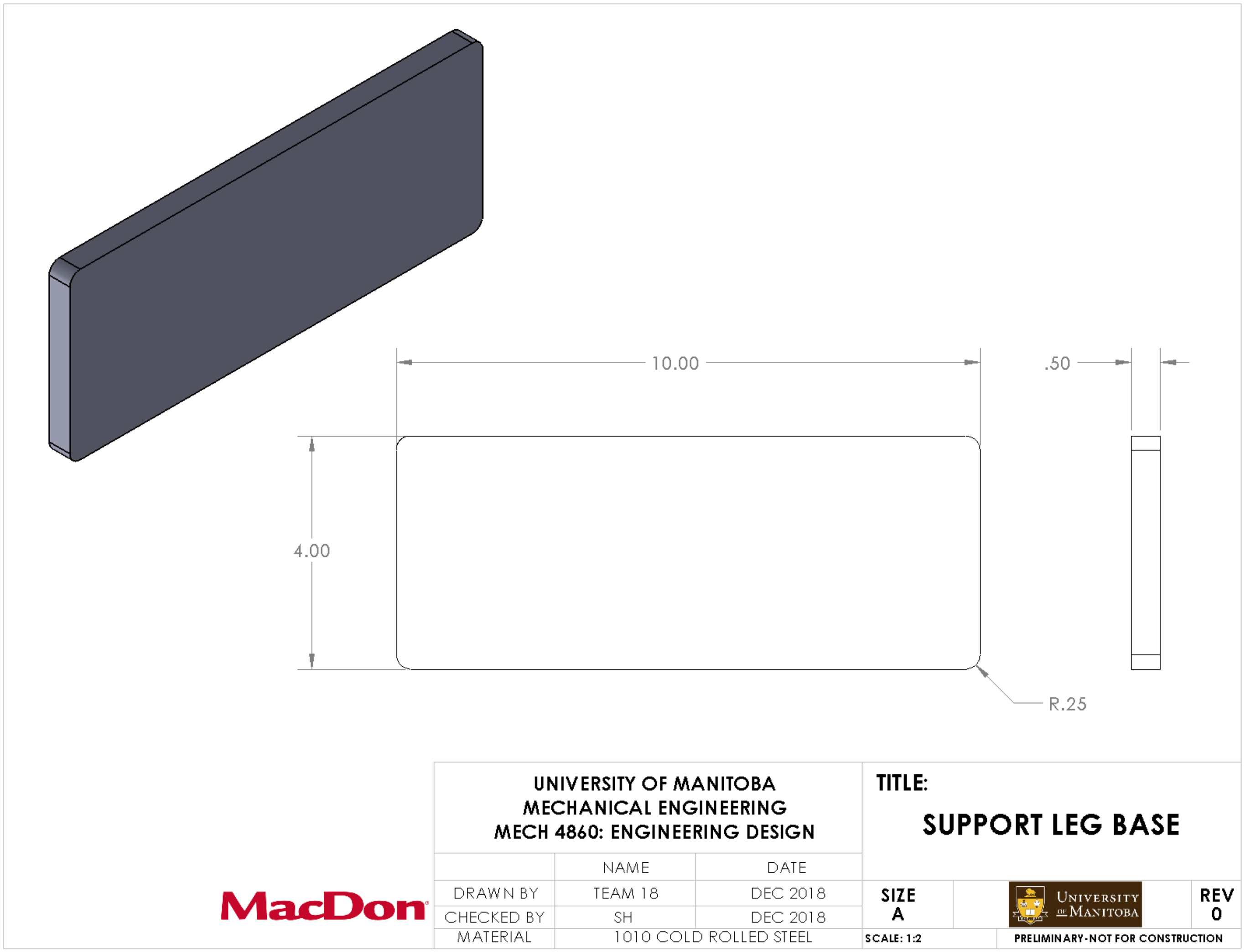


Figure D12: Preliminary Drawing for the Support Leg Base

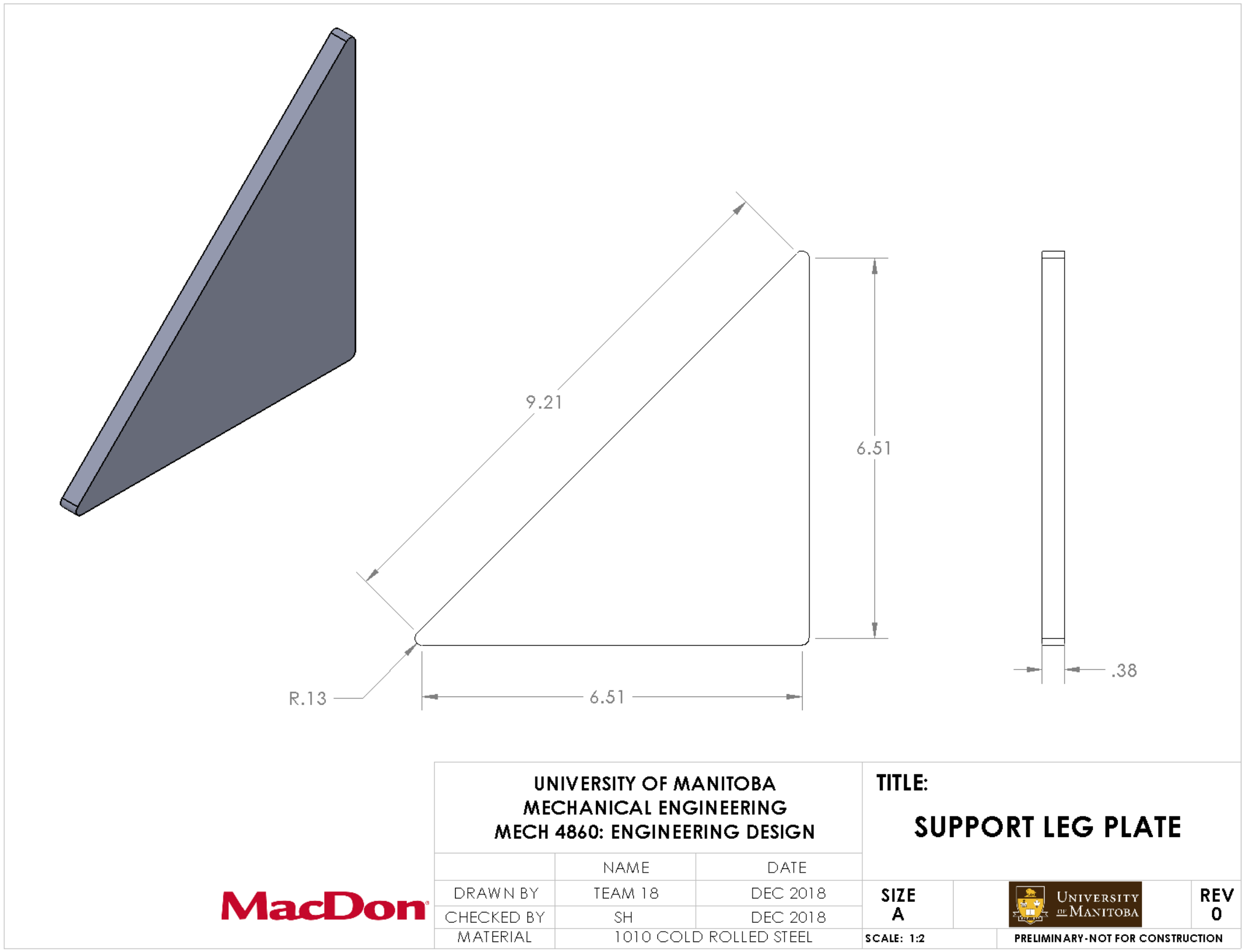


Figure D13: Preliminary Drawing for the Support Leg Plate

D.2 Preliminary Drawings for the Idle End

The preliminary engineering drawings for the new parts that requires machining on the idle end of the final design will be presented in this section.

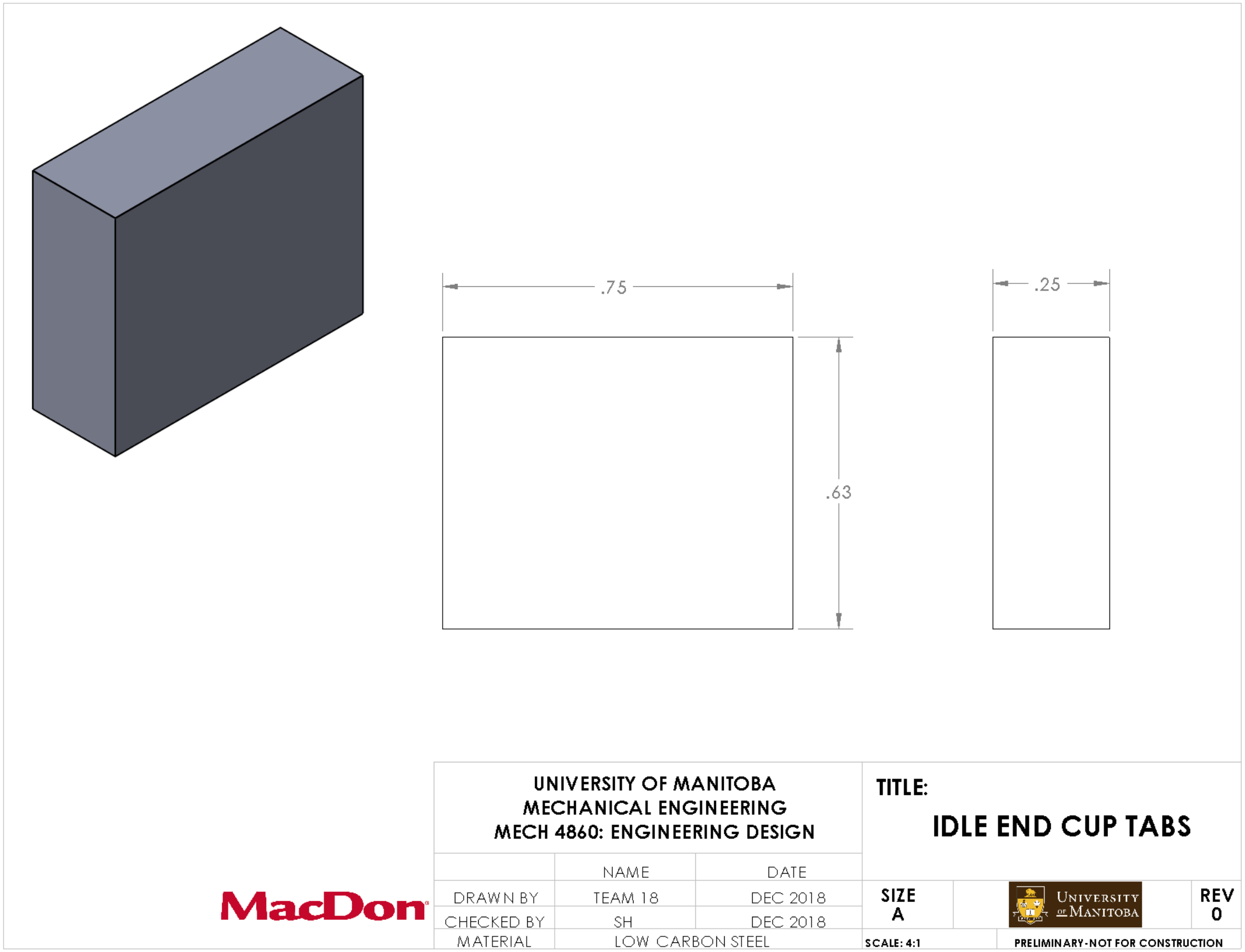


Figure D14: Preliminary Drawing for the Idle End Cup Tabs

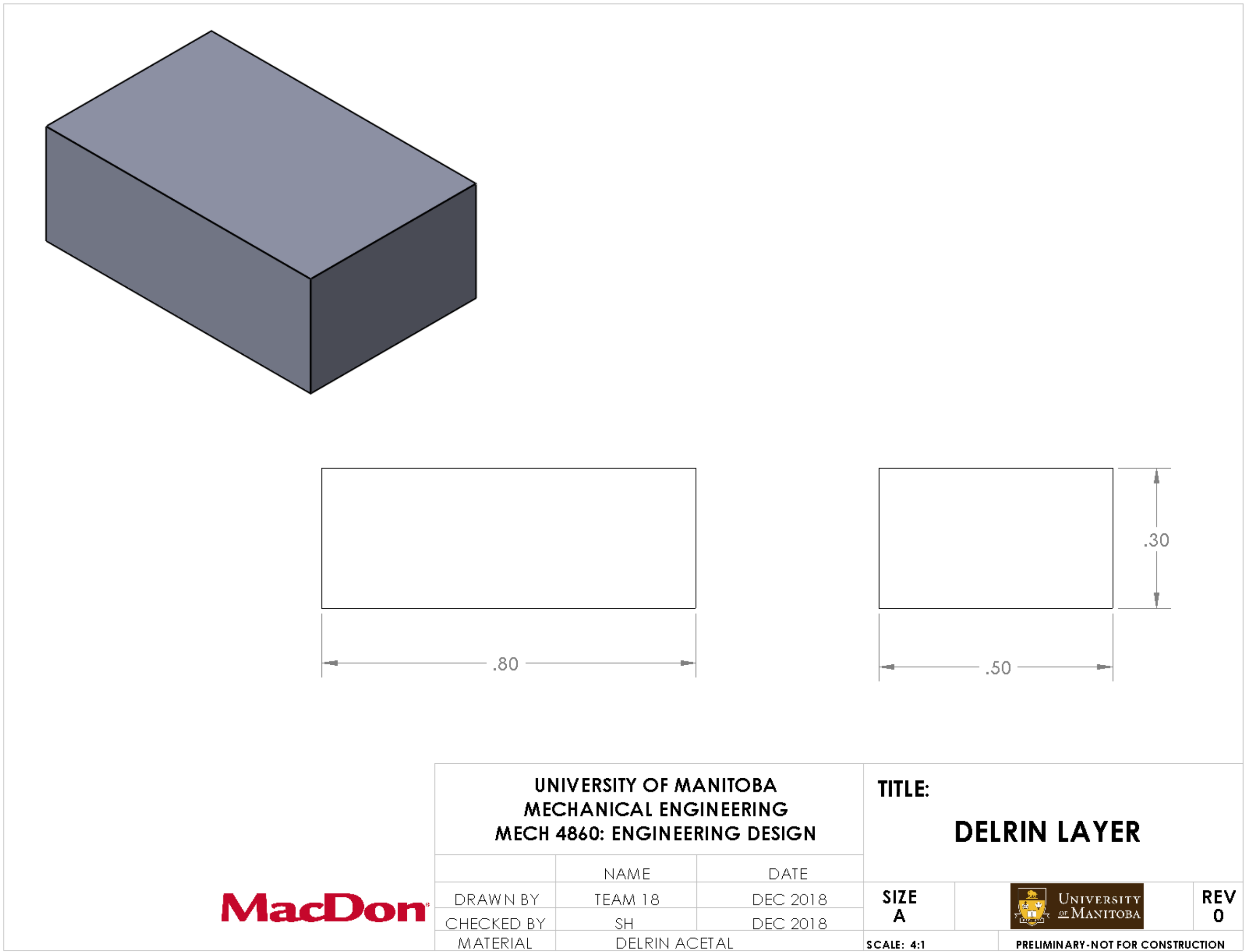


Figure D15: Preliminary Drawing for the Delrin Layer

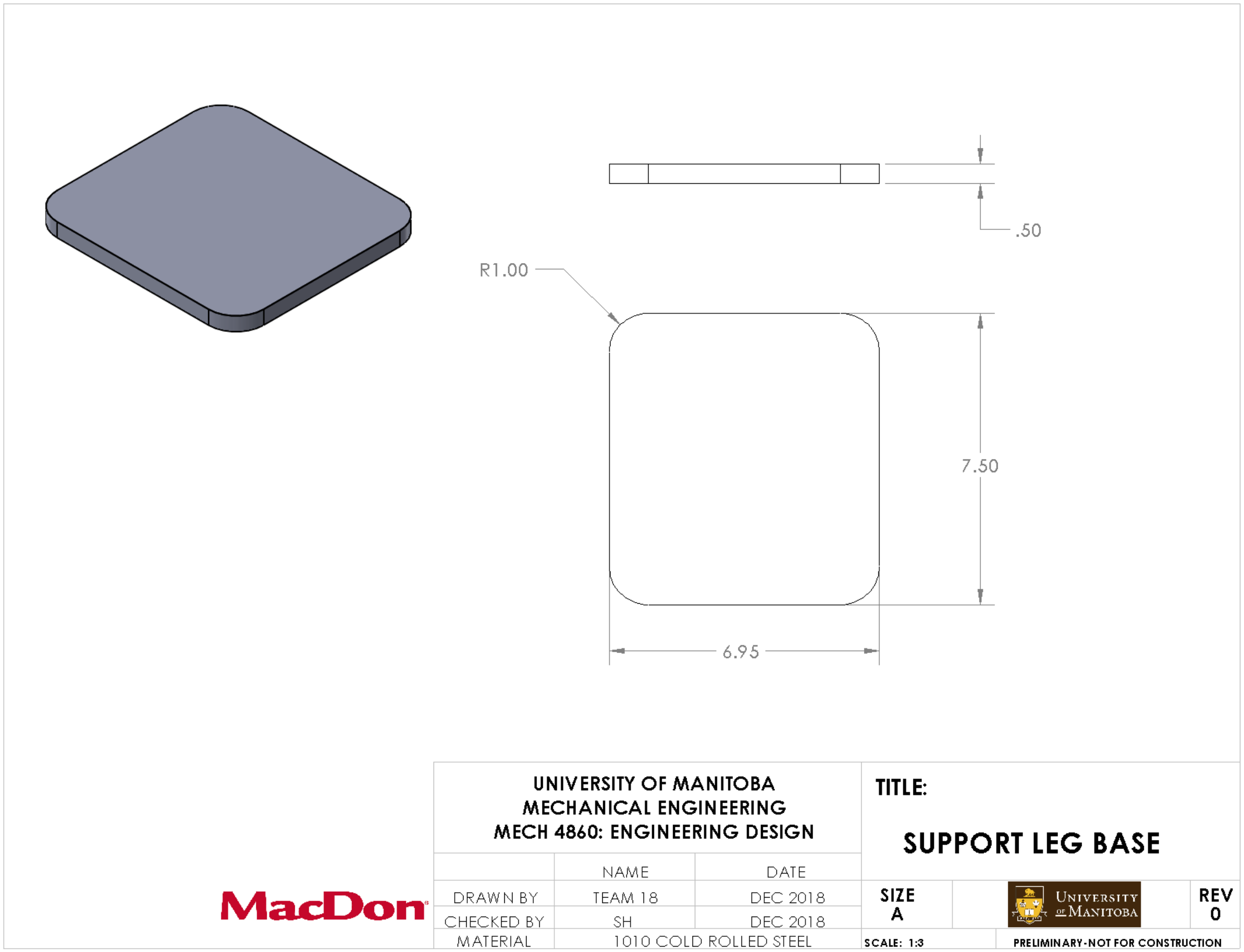


Figure D16: Preliminary Drawing for the Support Leg Base

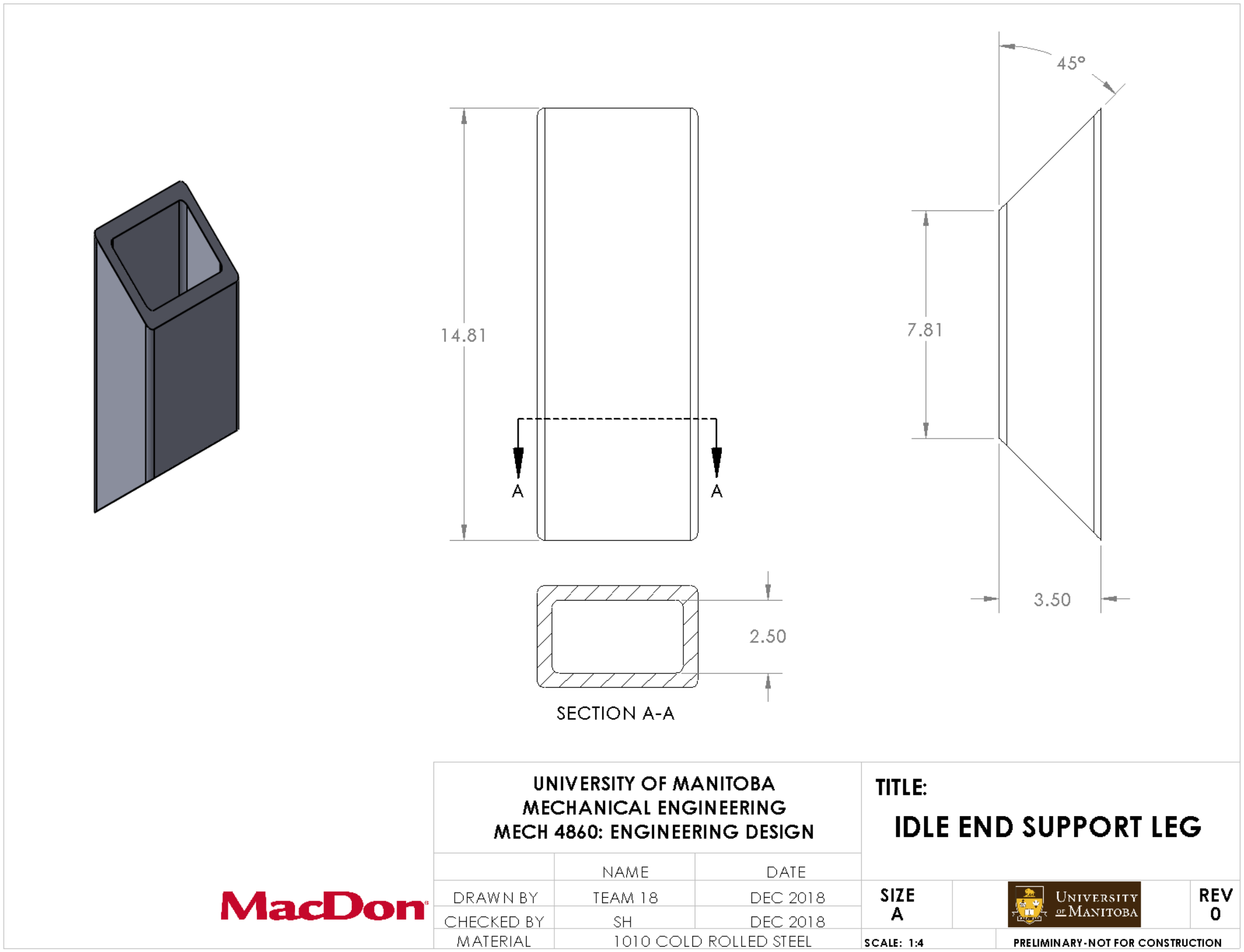


Figure D17: Preliminary Drawing for the Support Leg

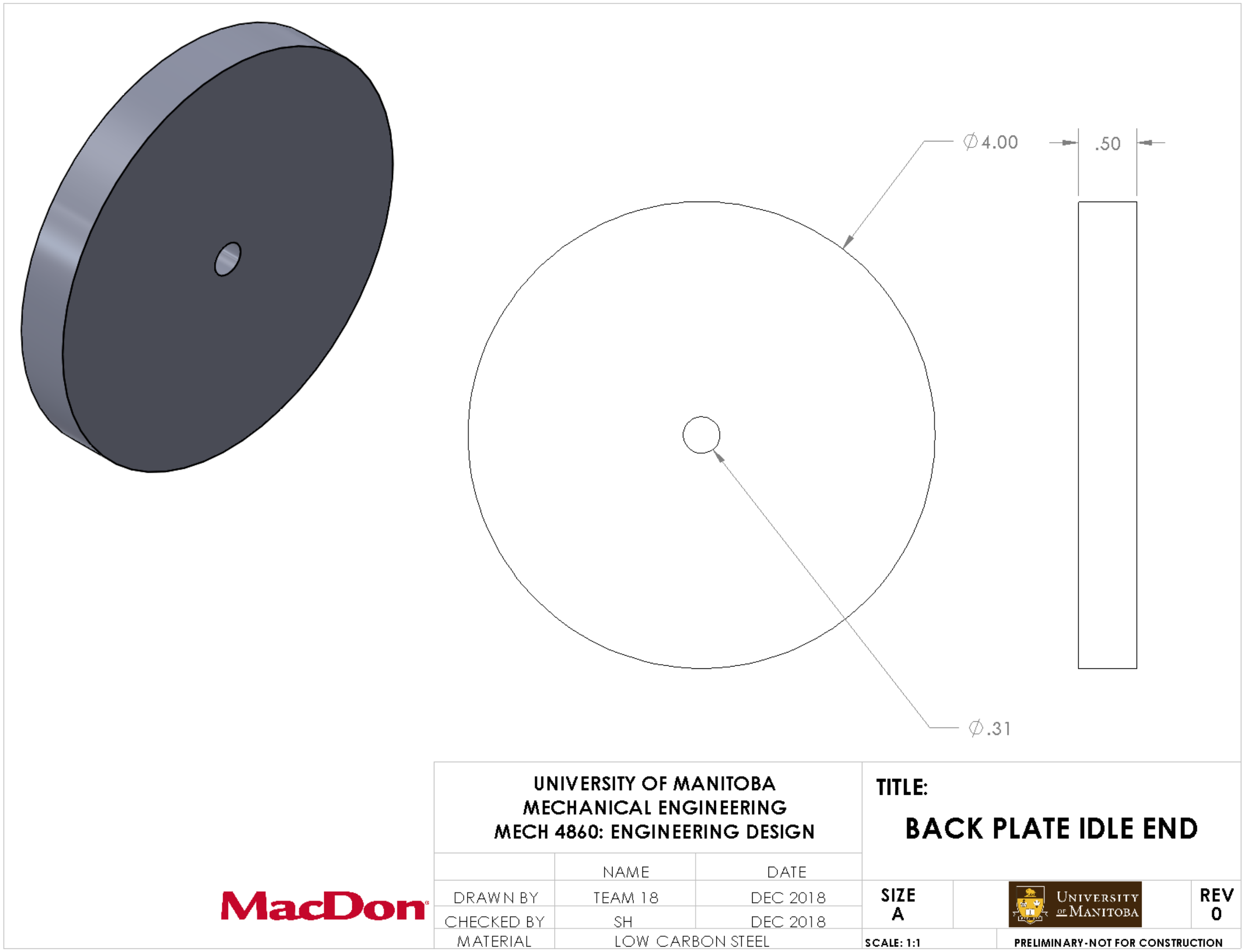


Figure D18: Preliminary Drawing for the Idle End Back Plate

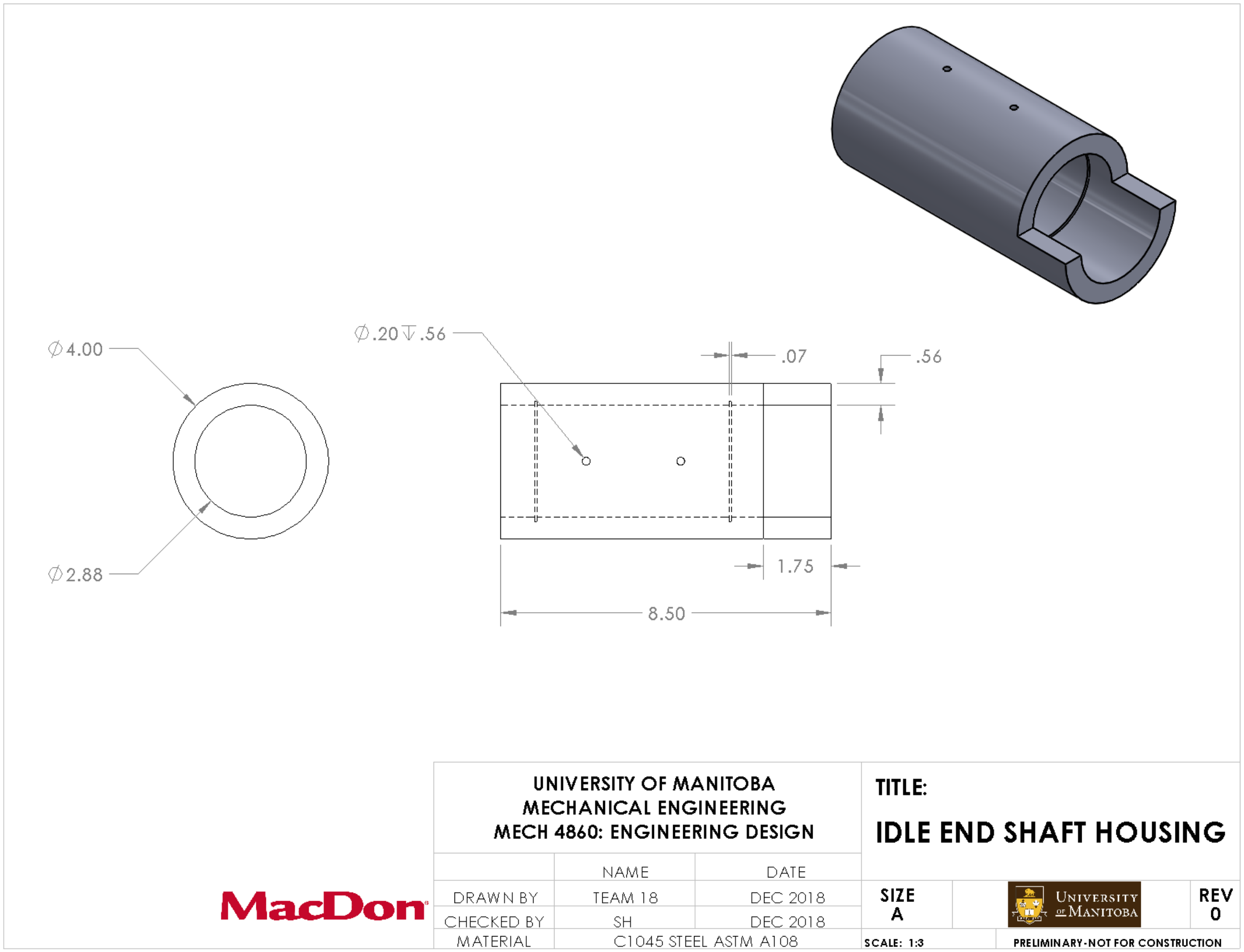


Figure D19: Preliminary Drawing for the Idle End Shaft Housing

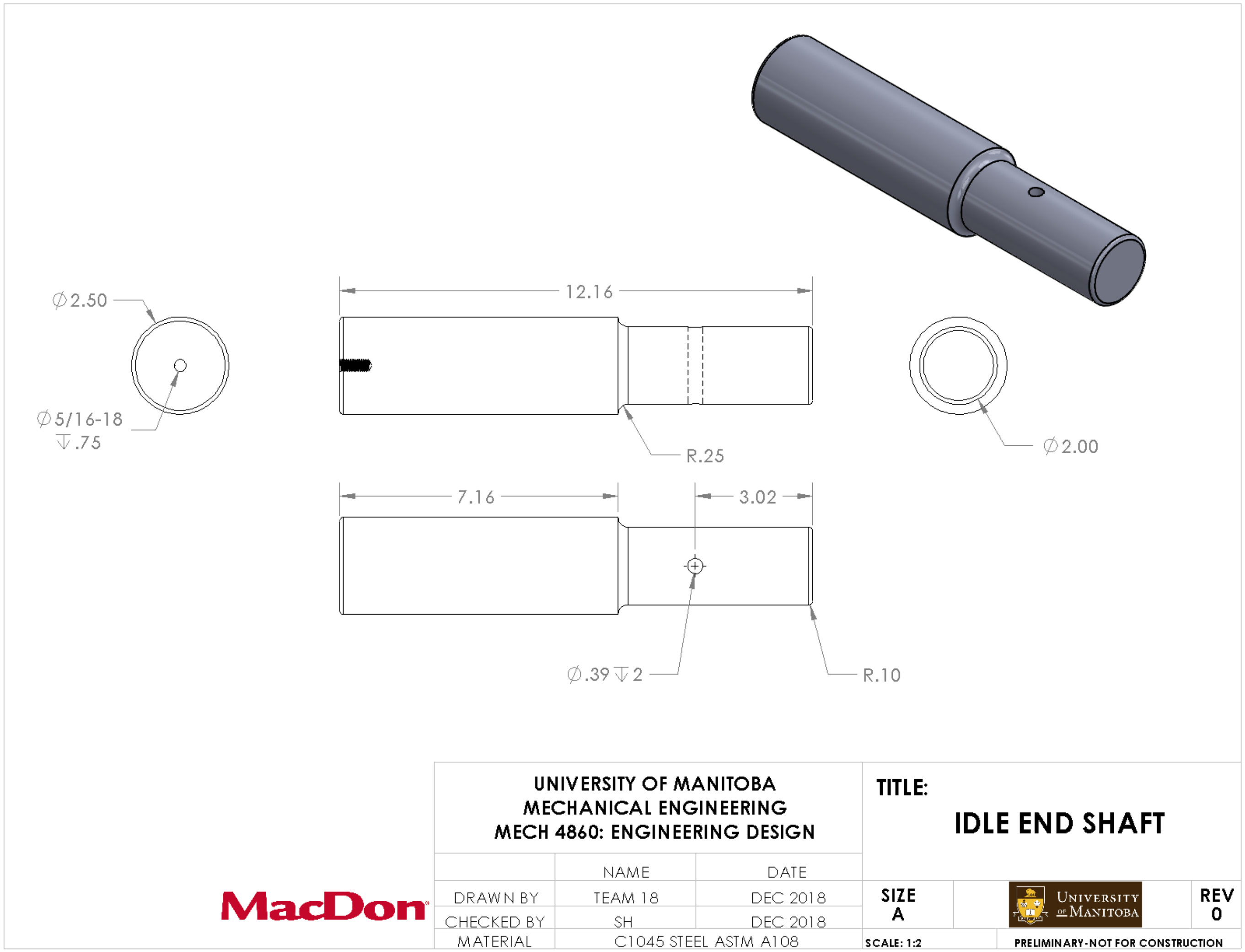


Figure D20: Preliminary Drawing for the Idle End Shaft

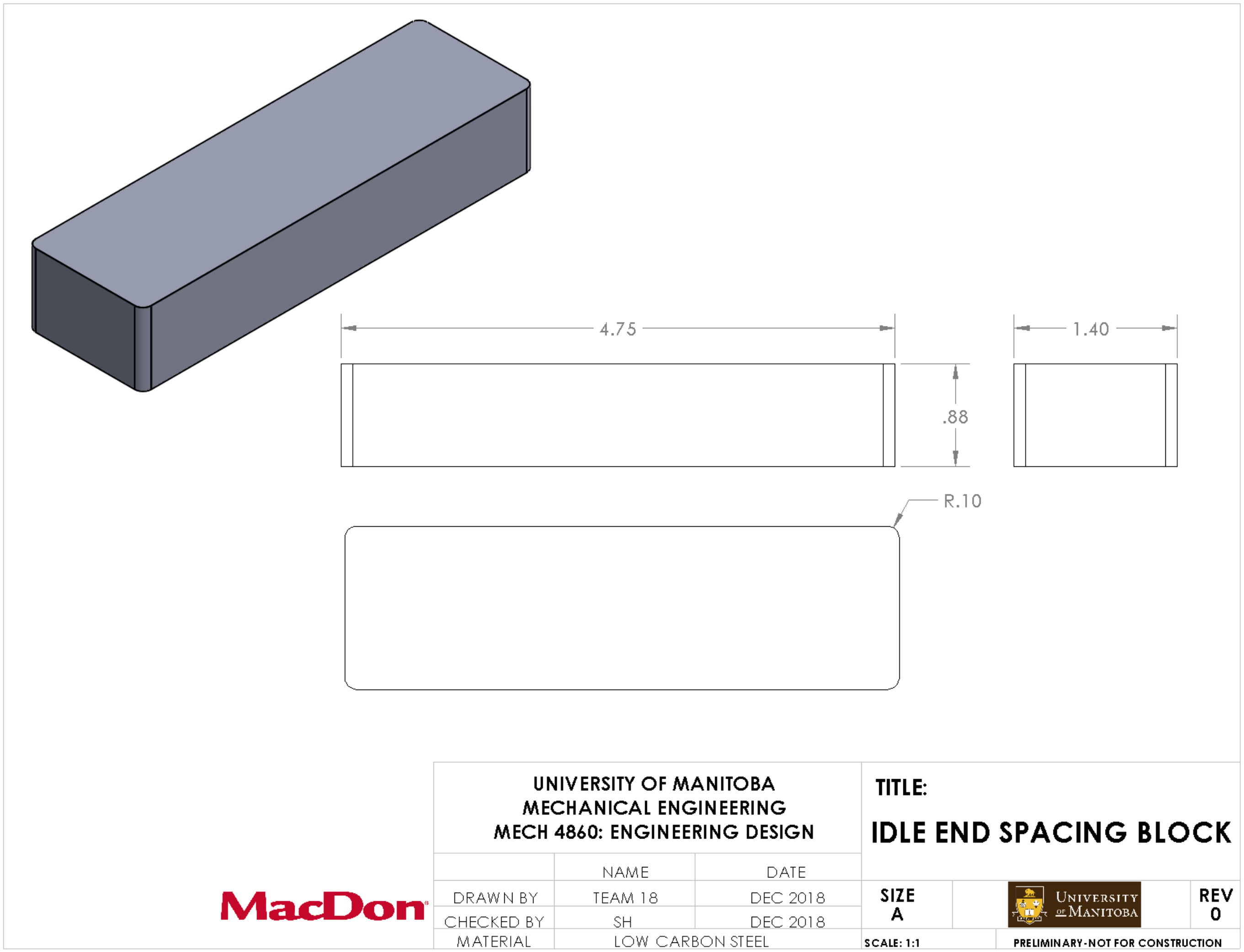


Figure D21: Preliminary Drawing for the Idle End Spacing Block

Appendix E: References

[1] Frame welding fixture capable of quickly turning over, by Zhensen Shou. (2012, June 20). CN Patent CN202278353U [Online]. Available: https://patents.google.com/patent/CN202278353U/en [October 25, 2018]

[2] thefabricator.com. (2015, August 17). "Frame-Welding-Fixture.jpg", in *What to look for in railing and frame welding fixtures* [Online]. Available: https:// www.thefabricator.com/article/shopmanagement/what-to-look-for-in-railing-and-frame-welding-fixtures. [October 20, 2018].

[3] SUPERIOR CONCEPTS, INC. " mig-weld-clamping-fixture.jpg", in *Designs - Welding* [Online]. Available: http://superiorconceptsinc.com/designs5431.html?gallery=10. [October 20, 2018].

[4] "Caster", in *Wikipedia, the Free Encyclopedia* [Online], September 25, 2018. Available: https://en.wikipedia.org/wiki/Caster. [October 21, 2018]

[5] Caster Connection. (2018, August 22). "Push-Pull-Caster-Wheels.jpg" in *How to choose casters by application, environment, and floor surface.* [Online]. Available: https://casterconnection.com/choose-casters-application-environment-floor-surface/. [October 21, 2018]

[6] Conveyer & Caster Equipment for Industry. *Technical Article: Why Kingpinless Swivel Casters* [Online]. Available: https://www.cc-efi.com/technical-library/why-kingpinless-swivel-casters. [October 21, 2018]

[7] Conveyer & Caster Equipment for Industry. "Kingpin.png", in *Technical Article: Why Kingpinless Swivel Casters* [Online]. Available: https://www.cc-efi.com/technical-library/why-kingpinless-swivel-casters. [October 21, 2018]

[8] Conveyer & Caster Equipment for Industry. "Kingpinless.png", in *Technical Article: Why Kingpinless Swivel Casters* [Online]. Available: https://www.cc-efi.com/technical-library/why-kingpinless-swivel-casters. [October 21, 2018]

[9] Pool table lifting device, by Barry Christopher Davies. (1989, January 11). UK Patent GB2206859A [Online]. Available: https://patents.google.com/patent/GB2206859A/en?oq=GB2206859a [October 25, 2018]

[10] Welding Design & Fabrication. (2011, October 28). " Existing Design of Retractable Caster.jpg", in *Welding Table* [Online]. Available: https://weldingweb.com/showthread.php?61973-Welding-Table&highlight=bender. [October 21, 2018]

[11] Pinterest. "Garage-Workbench-Workbench-Plans.jpg", in *Discover ideas about Garage Tools* [Online]. Available: https://www.pinterest.ca/pin/289708188505190334/?lp=true. [October 21, 2018]

[12] "Jack (device)", in *Wikipedia, the Free Encyclopedia* [Online], June 28, 2018. Available: https://en.wikipedia.org/wiki/Jack_(device). [October 21, 2018].

[13] RIG NIT CALICUT, "Multistage-Telescopic-Cylinders.png", in *Tutorial 3: Cylinder* [Online]. Available: http://www.rignitc.com/pneumatics-tutorial-3/. [October 21, 2018]

[14] Linear motion ball bearing assembly, by Robert M Halvorsen. (1968, August 27). US3398999A [Online]. Available: https://patents.google.com/patent/US3398999A/en?oq=3398999

[15] "Linear-motion bearing," in Wikipedia, the Free Encyclopedia [Online], March 2, 2017. Available: https://en.wikipedia.org/wiki/Linear-motion_bearing [October 25, 2018]

[16] Motion control tips editor. (2011, October 4). What are Linear Bearings [Online]. Available: https://www.motioncontroltips.com/linear-motion-bearings/

[17] MOTION CONTROL TIPS. (2011, October 4). “linear-motion-bearing.jpg,” in What are Linear Bearings [Online]. Available: https://www.motioncontroltips.com/linear-motion-bearings/

[18] ISOTECH, inc. (2018, February 14). “slide-bushing-diagram.gif” in FIVE REASONS FOR USING A SLIDE BUSHING IN LINEAR MOTION APPLICATIONS [Online]. Available: https://www.isotechinc.com/slide-bushing-in-linear-motion-applications/