DESIGN OF A TIEBACK ANCHOR SYSTEM

A Major Qualifying Project Report

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Submitted By:

Kelsie Lazaro

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Approved By:
Professor Leonard D. Albano

Abstract

Design analysis of multiple options for a through-bolt tieback anchor was proposed. The main objective of the project was to design an anchor with high constructability while also cost effective for production and sale by MIW Corporation. This objective was met through engineering drawings and structural analyses of multiple designs, and a multi-attribute analysis identified the most effective option. The project also included a detailed final design that met standards imposed by the Occupational Safety and Health Administration.

Capstone Design

The project focuses on developing a roof tieback anchor for MIW Corporation to produce and sell. Very few fabricators in the United States produce these items, and they are more commonly purchased and shipped from countries such as Canada. Recently MIW considered the possibility of selling their own within the Greater Boston area, which would be at lower cost than the Canadian systems due to the proximity of the company to its market.

Through-bolt tieback anchors are a safe and practical anchorage solution that is used for fall protection. They have an overall simple design which results in increased productivity for the manufacturer. Prior to producing these systems, the president of the company, George Malatos, wants to ensure he has a cost-effective design that complies with all related specifications. The project focuses on fulfilling these needs.

This project consisted of four phases: investigation of a benchmark design, creation of preliminary designs, analysis and evaluation of alternatives and selection of the best alternative, and preparation of a detailed design. The investigation of the benchmark involved back calculating the capacity of an existing design, creating a template that simplified the design of alternatives later in the project. Research was found through investigation of related engineering standards.

The first step in the creating the preliminary designs was to take into account the requests and design ideas of the client, MIW Corporation. Research was also completed to identify possible alternatives that could improve the design's sustainability and efficiency. Once all the information was compiled, five preliminary designs were generated. Different approaches were followed to determine the best design for the needs of the company, as well as the requirements for fall protection systems.

After the preliminary designs were defined, each alternative was analyzed and evaluated to identify the most efficient design. The designs were analyzed for constructability, sustainability, use flexibility, and cost efficiency. The best design was selected based on these four attributes.

The completion of this capstone design experience included the following realistic constraints: economic, health and safety, manufacturability, sustainability, and ethical. The cost

efficiency was analyzed using material take offs for each of the designs as well as considering production time. Cost factors include the building materials, complexity of fabrication (i.e. man hours for welding), and complexity of erecting.

Health and Safety is one the many engineering standards that were upheld throughout the duration of the project. Many of these standards are reflected by OSHA requirements. The main goal of the project was to design the anchor within Occupational Safety and Health Association's minimum design requirements for fall back systems in order to ensure safety of workers. Each design alternative was checked to confirm that it complies with all safety regulations.

The manufacturability of each design was considered for ease of construction, given the client's resources. The client's shop manager was consulted to review each of the designs to rate the difficulty of each of the connections as well as the bend in the ¾" bent bar of each design.

Sustainability in construction has increased its importance recently. The sustainability of the different materials used in the anchor designs were analyzed. Some factors analyzed included the protection against corrosion, resistance to fire and overall durability. Better sustainability also leads to lower maintenance costs.

The ASCE (American Society of Civil Engineers) Code of Ethics was also considered. The Code of Ethics was first adopted in 1914, and is the model for professional conduct for ASCE members. The four main principles of the Code of the Ethics assist engineers to uphold and advance the integrity, honor, and dignity of their engineering. While designing the roof anchor, the health, safety, and welfare of the possible users of the product were held in high regard.

Professional Licensure Statement

Professional Engineering (PE) licensure enforces standards that restrict practice to qualified individuals who have met specific qualifications through their education, work experience, and passing exams. This ensures a high quality of engineering work. Having a PE license shows the competence of an individual engineer. These standards are regulated by state in the United States.

Completing the requirements to become a licensed engineer is an extensive process. Obtaining a license is a high distinction that sets some engineers above the rest. It is not a requirement to become a licensed engineer; a non-certified engineer can work under supervision of one with a license. However, licensed engineers have access to more favorable employment opportunities, including business ownership. The licensing requirements begin with a completion of a bachelor's degree at an ABET-accredited engineering program. The next step is passing the Fundamentals of Engineering (FE) Exam to become an Engineer-in-Training (EIT). After a minimum of four years of acceptable work experience as an EIT under the supervision of a PE, the more specific Professional Engineering Exam can be taken. Passing the PE Exam along with the submission of an experience portfolio are the final steps to obtain the PE License.

Receiving PE licensure is a symbol of high qualification in the engineering industry. The achievement of becoming a PE means competence and safety to clients and the public, ability to take on greater responsibilities to an employer, and respect among co-workers and colleagues. Along with the ability to stamp and seal drawings, move up in their career, and perform consulting service, there are many responsibilities that licensed engineers have to follow, such as awareness of legal requirements, ethical conduct, continued education, and participation in professional organizations. Licensed engineers combine their skills to create high quality projects while upholding the health and safety of the public as one of their main responsibilities.

This project involves the analysis of roof anchor design alternatives. Once the design is chosen and completed, it will need to be approved by a professional engineer (PE). Achieving PE approval ensures the design is in compliance with all regulations. This maintains safety and fulfills the Massachusetts General Law that engineering work may be performed only by a Professional Engineer or under the direct supervision of a PE.

Acknowledgements

I would like to acknowledge a number of people. Without their contributions, I would not have been able to accomplish the goals of this project. These people include:

- ➢ First of all, my advisor, Professor Leonard Albano for his advice, patience and constant support throughout the project.
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Chapter One: Introduction

MIW Corporation has been fabricating and installing miscellaneous and ornamental metal since 1972. Originally concentrating on ornamental fences, gates, and rails, the company began to flourish with a number of projects in the Back Bay and Greater Boston Area in the 1970's.

In 1980, MIW began fabricating and installing more complex miscellaneous and ornamental steel after purchasing a small fabricating shop in Roslindale, MA. The company also started producing small to mid-size structural steel projects in 1990. This allowed MIW to expand their connections within the Boston Market and work on more complex projects.

In 2005, MIW became a member of the National Ornamental & Miscellaneous Metals Association (NOMMA) and the American Welding Society (AWS). These two memberships have allowed MIW to strengthen their networks, and gain numerous resources within their industry.

After purchasing a larger fabrication shop in Fall River, MA in 2007, the company has increased the number and types of equipment for the production of both miscellaneous and structural steel. Due to this expansion, the company also fabricates both stainless steel and aluminum products.

MIW became certified in steel fabrication by the American Institute of Steel Construction (AISC) in 2014. Participating in AISC's certification program shows the respect and safety MIW holds for its products and employees. Companies achieve a higher quality and value when certified by AISC.

MIW Corporation continues to look for ways to extend its market. One product they would like to begin producing is tieback anchors. Through-bolt tieback anchors are a permanent anchorage solution that is both safe and practical. They are used for fall protection and a wide range of suspended access uses. Some of these applications include window cleaning and exterior building maintenance.

The purpose of this project is to design an effective roof tieback system that meets the requirements of the Occupational Safety and Health Administration (OSHA) and The American National Standards Institute (ANSI) while still cost effective.

This report consists of seven chapters. Following this introduction, Chapter Two includes a background about fall back protection systems, the governing factors and design approaches taken in the design process. The third chapter provides a brief overview about the methodology of the project. Chapter Four explains the calculations and design process of the first, benchmark design. The fifth chapter includes each of the variations used in the alternatives and presents each of the designs. Chapter Six discusses the analysis of the alternative designs and explains the scoring processes used to give a value to the designs. The last chapter presents the final design and the future recommendations for the MIW Corporation.

Chapter Two: Background

The main goal of this project is to design a roof tieback system for MIW to fabricate, sell, and install. The goal was accomplished using methods to create an efficient alternative. This section addresses background information used to complete the project.

Fall Back Protection Systems

Through-bolt tieback anchors are a permanent anchorage solution that is both safe and practical. They are used for fall protection and a wide range of suspended access uses (Flexible Lifeline Systems, n.d.). Some of these applications include window cleaning and exterior building maintenance.

Figure 1: Roof tie-back anchor

The figure above is an example of a tie back anchor. It consists of a base plate, which is bolted to a beam on the roof; a metal pipe which has a tall enough height that it extends past roof decking, keeping the attachment point accessible after the roof is complete; and a top bent round bar, which a worker's lifeline is clipped to. OSHA requires the use of fall back protection when workers are doing specific tasks or suspended from minimum heights. Some of these tasks include exterior maintenance of buildings or window cleaning. The roof anchor provides safety protection from falls by clipping a rope descent system to the bent bar on the top of the permanent roof anchor (Selected OSHA Fall, 2015).

Governing Standards

OSHA is part of the United States Department of Labor, and it was created to assure safe and healthy working conditions for workers by setting and enforcing standards. OSHA works to provide training, outreach, education and assistance to improve safety in the workplace (About OSHA, n. d.).

OSHA regulates fall protection systems through certain criteria and practices. According to OSHA's *Regulations (Standards-29 CFR),* specifically OSHA 1926.502, anchors must be able to support at least 5000 pounds per person attached, or have a safety factor of two and used under the supervision of a qualified person. OSHA also limits the arresting force to a maximum of 1800 pounds or less, which is not governed by the anchor design but the user's weight and lifeline length. OSHA has specified a maximum arresting force, versus a minimum, to set largest force the lifeline and worker would experience in the case of a fall (Selected OSHA Fall, 2015). The American National Standards Institute (ANSI) focuses on strengthening the United States marketplace compared to the global economy while assuring the safety and health of consumers (About ANSI). ANSI has the same roof anchor standards as OSHA according to ANSI/ASSE Z359.0 of the American Society of Safety Engineer's ANSI/ASSE Z359 Fall Protection Code (Version 3.0)

Structural Design

A major part of this project is the structural analysis. The structural components that define the design affect the strength and efficiency of the anchor. Some of these components include the chosen materials, which affect strength and sustainability.

Benchmarked Design

The designs presented in this project are based off a roof anchor previously produced by MIW Corporation. The design was prepared by Olsen Engineers Inc. in October 2014.
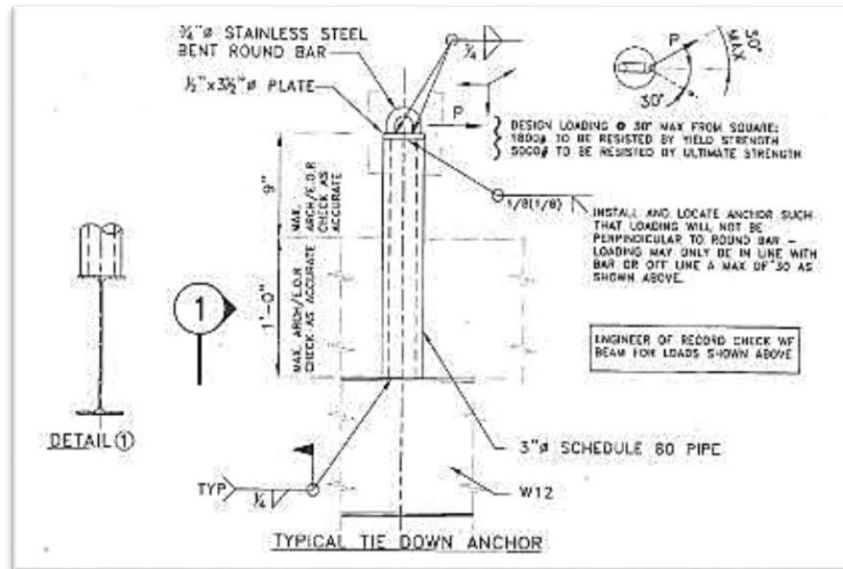
Figure 2: Tie-down Anchor designed by Olsen Engineers

This design, shown in Figure 2, consisted of a 1.75' tall 3" diameter schedule 80 pipe directly welded to a supporting beam. A 0.75" diameter stainless steel bent round bar was welded to a cap plate which was welded to the top of the pipe. Although none of the designs presented are identical to the original design, the design approach used by Olsen Engineers created the framework for the design process in this project.

Materials

Carbon steel is the lowest cost option but offers the least value for sustainability due to its susceptibility to rust. There are other metal options that do not have this problem. Stainless steel is protected against rust and corrosion, providing better sustainability. Stainless steel has a higher overall durability with resistance to fire damage, decreasing maintenance cost. Stainless steel also has a higher ultimate strength than carbon steel, shown in Table 1; however, it is much more expensive (Wenzel Metal Spinning, n.d.).

Table 1: Ultimate and Yield Strength of Carbon vs. Stainless Steel , values based on AISC Table 2-4

Material	Yield Strength	Ultimate Strength
ASTM A53 Grade B Carbon Steel	35 ksi	60 ksi
ASTM A240: 316 Stainless Steel	30 ksi	75 ksi

Another option is galvanized steel. Hot dipped galvanizing carbon steel has a small additional cost but gives the steel the protection it needs from corrosion with a layer of zinc covering all surfaces. However, welding materials that have already been galvanized can create a poisonous gas due to the reaction between the zinc and the copper (Wenzel Metal Spinning). The safety concerns to the welders and expense of safety precautions have to been taken into account when choosing or not choosing a design with galvanized members.

Sustainability

Leadership in Energy & Environmental Design (LEED) provides a framework for creating and maintaining green building designs through the design, construction and operation processes (About LEED, 2015). LEED applies to all building types such as residential, educational, retail, hospitality, healthcare, and existing buildings. Many construction projects strive to become LEED certified by fulfilling a list of criteria which involve achieving high performance in areas of human and environmental health.

One of the main goals of LEED is to reduce material waste. The addition of permanent roof anchors to a building is applying the idea of reusing materials for multiple purposes, versus using temporary supports each time a lifeline is needed.

Another way to keep material waste low is ordering the pipes and bent bars in readily available dimensions. The materials should be ordered in dimensions that can be cut down into the needed size with the least amount of waste.

Geometry

The geometry of the anchor design can greatly affect the strength. For a given applied load, a reduction in the height of the pipe cause lower moments and therefore stresses on the pipe. Although the reduction is beneficial, the pipe height has to be tall enough that it extends

past roof decking; keeping the attachment point accessible after the roof is complete. This is recommended to be a minimum of one foot.

A change in diameter or schedule of the pipe causes changes in the moment of inertia and area of the cross section, therefore also changing the stresses within the pipe. A change in the radius of the top curved beam affects the bending stresses throughout the curved member. These changes in the geometry also cause changes in the weight which affect the cost of the anchor.

Bending Stress of Curved Beam
The bending stress of a beam is equal to My/I when the beam is straight. When a member is curved, the neutral axis no longer passes through the centroid of the member. The figure below shows the dimensions of the values used in the calculation.
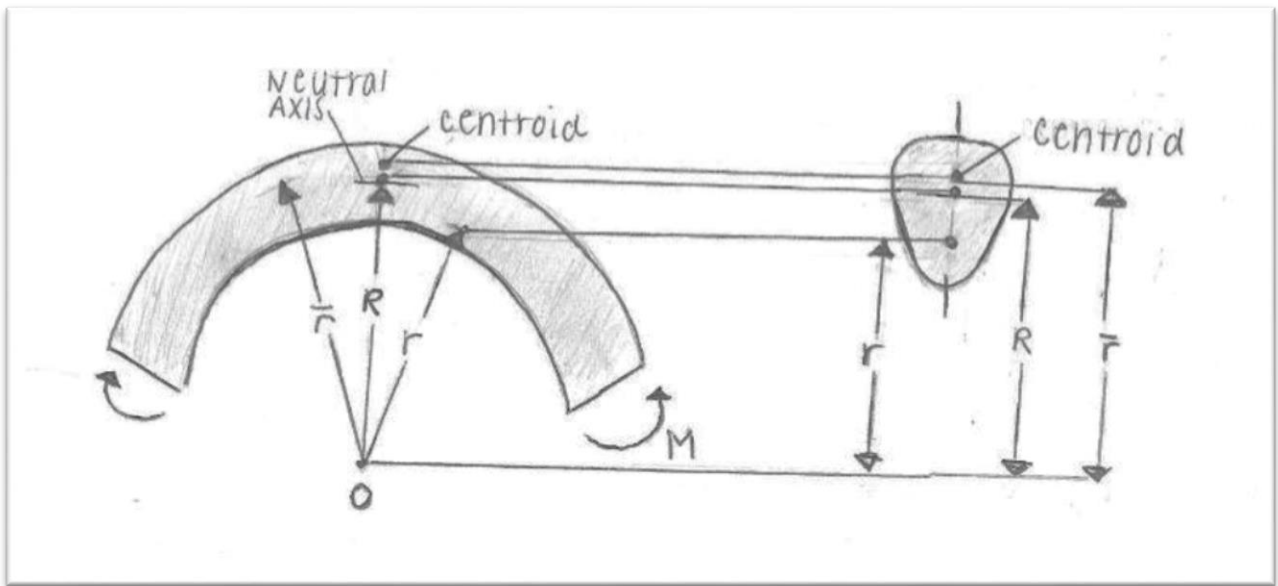
Figure 3: Three radii used in the bending stress calculation of a curved beam

The three radii from the center of curvature, O, are identified as $\bar{r}$, R, and r. The radius $\bar{r}$, is the distance from the center of curvature to the centroid of the member. R is the distance from O to the neutral axis of the bent member. Due to bending, different strains are caused at the top and bottom of the member, shifting the neutral axis from the centroid of the cross section. The

neutral axis is the axis in the member where no stress or strain is acting. The third radius, r, is the distance from the center of curvature to any arbitrary point the stress is being calculated at.

The equation used to calculate the location of the neutral axis is the area of the cross section over the integral of the area in respect to the radius, $R = \frac{A}{\int(\frac{dA}{r})}$. (Hibbeler, 2010).The integral can either be calculated by hand or looked up in a table of various geometries.

Once R has been found, the bending stress is simple to calculate. The equation of the bending stress in a curved member is $\sigma = \frac{M(R-r)}{Ar(\bar{r}-R)}$. The stress should be found at both the inside and outside of the beam to find which point is critical.

RISA3D

RISA3D is an engineering computer program used to analyze three-dimensional models and to draw designs (Risa3D, 2015). The program allows the user to design with many materials such as hot rolled steel, cold rolled steel, masonry, timber, concrete, etc., as well as many shapes like wide flange beams, hollow structural section columns, pipes, and so many more. Users also have the option of placing nodes in specific coordinates and creating their members to extend from one node to another. Figure 4 shows the top bent bar of the roof anchor drawn in RISA3D.
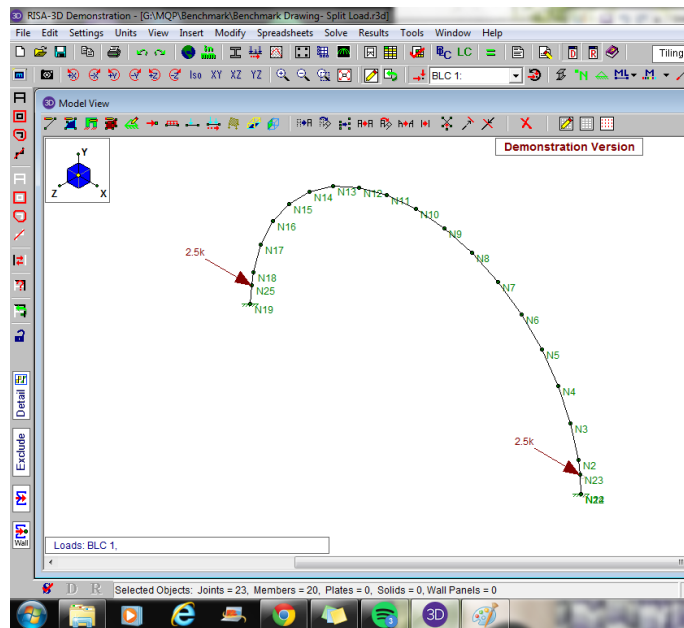

Figure 4: RISA3D drawing of top bent bar

Many load types can be applied to designs in the programs. These include nodal, point, moving, surface and distributed loads. Multiple load cases can be programmed to solve the design multiple times. The easy-to-use solver gives instant results for reactions, stresses and deflections, making calculations take significantly less time than calculating by hand, while providing code checks for the design.

Structural Capacity

While designing the anchor many checks and calculations were made to ensure structural integrity. The strength of the materials and welds were calculated to ensure they could withhold the minimum of strength of 5000 pounds, required by OSHA standards.

The two most common design philosophies for structural steel are Load and Resistance Factor Design (LRFD) and Allowable Stress Design (ASD). Until 1986, when AISC introduced LRFD specifications in their Steel Construction Manual, steel structures were solely built with the ASD approach. ASD uses a stress based strategy, keeping force levels below the member's yield by dividing the nominal strength by a factor larger than one, omega. The LRFD approach determines the required strength of members. This was done through the application of a strength reduction factor, phi. Phi is a factor, always less than one, that reduces the strength of members to ensure the designs can handle, at minimum, the calculated stresses.

Throughout this project, LRFD approach was used to check the strengths of the members in the anchor design. The value phi factors applied are found in codes and construction specifics governed by AISC (American Institution of Steel Construction). These values are also shown in Table 2.

Table 2: Table of Resistance Factors Used in LRFD Calculations

Strength Calculation	Resistance, Phi, Factor	Per AISC Reference
Axial Tension and Bending, Yield	$\Phi = 0.9$	AISC Section D2
Axial and Bending, Ultimate	$\Phi = 0.75$	AISC Section D2
Shear	$\Phi = 0.9$	AISC Section G1
Fillet Welds, across effective throat	$\Phi = 0.75$	AISC Section J2.4
Bolts	$\Phi = 0.75$	AISC Section J3.6
Block Shear Rupture	$\Phi = 0.75$	AISC Section J4.3

LRFD also uses load combination equations that assign a specific factor for each load type that are expressed in the equation. The only load consider in the design of the roof anchors was the 5000 pound ultimate load. Due to it being an "ultimate" load, it was assumed that the appropriate load factor is included within the value.

Chapter Three: Methodology

This section presents the overall methodology of the project. The project consisted of four major phases: benchmark calculations, preliminary designs, analysis of designs, and detailed design. A summary of the work completed for each phase can be found in Table 3; this section will provide an explanation of each phase.

Table 3: Brief explanation of the four phases of the project

Phase	Work Included for this Project
Preparation of Benchmark Calculation	Back calculating a precedent anchor design.
Creation of Design Alternatives	Multiple simple design alternatives, based on the needs of the sponsoring company and OSHA's regulations.
Analysis of Design Alternatives	Analysis of preliminary designs to identify the most effective.
Development of Detailed Design	More in-depth design of the chosen design from the analysis.

Preparation of Benchmark Calculations

Benchmark calculations of a precedent anchor design were done for the purpose of ensuring the analytical process and calculations used in this MQP project were performed properly and complied with current standards. This was completed by hand calculating the required strengths and dimensions to compare to the end values of the previous design. If the end values are similar the process is more than likely correct and can be used to investigate slightly varying designs.

These calculations included determining the internal forces and stresses acting on each of the design elements due to the yielding and ultimate loads of 1800 pounds and 5000 pounds. Using the calculated internal forces and stresses, the stainless steel SCH 80 pipe and ¾" bent bar were checked for minimum strength capacities according to their ASTM standard values.

The bent bar calculations included creating tables to determine the stresses at various locations around the bend. However, the structure of the bent bar was indeterminate which caused an approach of using virtual work for the analysis of a symmetric structure with an anti-symmetric loading.

Computer analysis in RISA3D was also used to calculate the stresses in the curved beam. This was used for comparison to check the hand calculated values to ensure accurate results. The hand calculated values and the computer analysis should not be expected to have identical results, because the computer results takes axial and shear deformation into account. The computer model also was not a perfectly curved shape. An difference of less than 20% between the two results is an acceptable difference. The shear force at the tip of the curve was found by the RISA3D program and hand calculations at 15 and 15.8 pounds, respectively, with an acceptable 5% error.

After the maximum stresses acting on the members were determined and checked against material limits, the weld lengths and strengths were calculated. The bottom of the pipe will be welded, using an all-around fillet weld, to a flange beam on the roof, or welded to a baseplate which can be bolted into a supporting beam. The E70 electrode weld had a minimum fillet of 1/4" due to the thickness of the pipe. However, a ¼" fillet weld was found not to be strong enough due to the shear stress the weld has to endure. It was determined that a minimum of 7/16" fillet weld would be needed to weld the pipe.

The weld of the bent bar to the sides of the pipe was checked using a fillet weld size of ¼" due to the thickness of the bent bars. The minimum required weld length for strength was calculated as 0.327" which is less than the minimum of four times the fillet size specified by AISC Table J2.4. Therefore, the minimum weld length is governed by four times the fillet size, or 1".

Creation of Design Alternatives

Creating alternative designs was the next step of the design process. The work done to complete the benchmark design was used as a template to create four, additional preliminary alternatives. The four main variations in the designs include adding a cap plate, a base plate, changing the material of the pipe, and changing the dimensions.

Adding a cap plate to the top of the pipe was one of the alternations in the designs. It distributes the stress from the bent bar around the entire edge of the pipe instead of in two small sections, but also causes an additional weld that was not included in the benchmark. The cap plate changes the weld types of the bent bar to the anchor from one–inch long fillet weld down

each side of the pipe to three all around welds. The cap plate also decreases the inside radius of the bent bar causing a slightly higher stress values on the outer radius of the bend while still being well under the limits.

The initial design included the base of the pipe welded to a roof. Due to the limitation that direct welding of the anchor is only possible on some metal roofs, an alternative of welding the pipe to a base plate and then bolting the plate into the roof was suggested. Designing the base plate required the calculation of the thickness for bending effects using assumed dimensions of the base plate. Then using the calculated thickness, the possible effects of prying, tension yield, tension rupture, and block shear rupture were investigated to determine the governing limit state for plate thickness.

The material of the pipe was also altered in the design. As mentioned in the background, different metal materials provide various pros and cons. Stainless steel offers protection against corrosion but it is more costly than carbon steel. Whereas carbon steel, the most common, lowest cost and most readily available of the choices, has lower ultimate strength than stainless steel but a higher yielding strength.

The dimensions of the anchor were altered by shortening the height of the pipe, changing the thickness of the pipe wall, or widening the radius. Widening the radius and thickening the wall gives the pipe a larger cross sectional area, strengthening the pipe against axial and bending stress failures. However it also gives the pipe a larger slenderness factor and weakens the pipe against failure due to buckling. Shortening the height on the other hand can decrease the maximum moment, therefore decreasing the bending stress in the pipe. These dimensions were changed relatively to the previously produced design, causing improvement without decreasing the constructability of the design.

The five designs, including the benchmark were created. Below is a table showing a brief explanation of the five designs.

Table 4: Brief design summary of alternatives

Design Number	Design Highlights
1 (Benchmark)	3" Diameter ASTM A316 Sch 80 Pipe, 1.75' 0.75" Diameter ASTM A316 Bent Bar Field Weld to Roof
2	3" Diameter ASTM A316 Sch 80 Pipe, 1.5' ASTM A316 Round PL 3.5" x 3/8" 0.75" Diameter ASTM A316 Bent Bar Field Weld to Roof
3	ASTM A53 Grade B 3" Diameter Sch 80 Pipe, 1.75' 0.75" Diameter ASTM A316 Bent Bar ASTM A316 Round PL 3.5" x 3/8" ASTM A316 Base PL 12" x 12" x 7/16"; Bolted to Roof
4	4" Diameter ASTM A316 Sch 80 Pipe, 1.5' 0.75" Diameter ASTM A316 Bent Bar Field Weld to Roof
5	3" Diameter ASTM A316 Sch 80 Pipe, 1.75' 0.75" Diameter ASTM A316 Bent Bar ASTM A316 Base PL 12" x 12" x 7/16"; Bolted to Roof

Analysis of Design Alternatives

Each of the alternative designs was analyzed to select the most efficient option considering the perspectives of sustainability, constructability, use flexibility, and cost. Each alternative was rated for its sustainability, constructability, and use flexibility with a score between one and four.

The sustainability of each design was assessed including protection against corrosion and overall durability. The leading differing factor in the five designs was the pipe material using both A316 stainless steel and ASTM A53 Grade B carbon steel. Stainless steel is protected against rust and corrosion, providing better sustainability as well as overall better durability with resistance to fire damage. ASTM A53 Grade B *c*arbon steel is the lowest cost option but offers a smaller value of sustainability due to its susceptibility to rust.

The constructability of the design considered ease of fabrication for MIW Corporation. The three sub-factors of constructability factors included component fabrication, assembly and field installation. Component fabrication includes the shop's limitations in bending the top bar of the anchor. Assembly factors were discussed with MIW's shop manager to compare the difficultly of the different welds. Some of the topics discussed included weld types or the

difficultly welding carbon and stainless steel together. The last constructability factor analyzed was the field installation process for the anchor. Bolting a baseplate to a roof is an easier process than field welding the anchor onto a high roof. The average of the three constructability subarea scores was the final constructability score.

The use flexibility of the design took into account the ability to use the anchor designs in various locations. For example, direct welding the anchor is only possible with some metal roofs. If the roof is constructed with concrete, the pipe cannot be welded directly to the roof. Bolting the anchors that were welded to base plates creates a more versatile alternative.

To balance the scoring values of the three attributes, a weighted scoring equation was used. To create proper weights for each of the three attributes, the attributes were all compared two at a time. It was found that sustainability was the most important of three, and constructability was more important than the use flexibility. In order to avoid disregarding use flexibility due to its score of zero, a nominal score of one was used, increasing each of the scores by one. The weight factors were used to create the final scoring equation of:

$$\text{Design Score} = \frac{\sum \left(\frac{3}{6} * Sustainability + \frac{2}{6} * Constructability + \frac{1}{6} * Use\ Flexibility\right)}{Cost} * 100$$

A cost analysis was completed for each design using take-offs. Cost estimates with the company's metal supplier were made to create the most accurate estimates available. A balance between use flexibility, sustainability, constructability and cost was desired. The cost comparisons of the different materials and dimensions of materials helped give a value for the different scores presented by the other three main attributes. The design decision balanced between all of the factors in the table. An equation dividing the attributes of the design by the cost was created to identify the best value solution.

Development of Detailed Design

In the results of the analysis, the best value solution was Design #3. However, the fifth design was a close second. Although Design #3 was chosen by the scoring, MIW Corporation expressed reservations about the welding the stainless steel and carbon steel together. It was expressed that stainless steel was the preferred material for all of the elements.

The final, recommended design is a variation of Design #5 by shortening the A316 stainless steel pipe to 1.5 feet, thereby reducing the maximum moment on the bottom on the pipe and lessening the fillet weld. The values of the stresses in the design were all recalculated and checked for proper strengths and specifications.

Shortening the height, while still keeping in mind minimum heights for the attachment to remain above the decking, also lessened the cost of the pipe, which is the most expensive member of the design. The efficiency of the design was rescored, and was calculated at higher than previous highest scorer.

Final AutoCAD drawings were created for the recommended design which can be viewed in Appendix S.

Chapter Four: Preparation of Benchmark Calculations

The first step in the design process was creating a benchmark design. Benchmarking is a process used to compare and base one's own designs and processes to industry's best practices. The purpose of making benchmark calculations was to ensure the analytical process and calculations used in this MQP project were performed properly and complied with current standards. If the required strengths and dimensions can be calculated with similar end values as the previous designs, the process is more than likely correct and can be used to investigate slightly varying designs.

A few previously designed anchors were researched and reviewed to create a design template for the synthesis and structural analysis of alternative designs. The chosen design for benchmarking consisted of a ASTM A316 3" diameter schedule 80 pipe with a height of 1.75 feet and ASTM A316 3/4" diameter bent round bar welded to the sides of the pipe with a bend radius of 1.75". This design can be seen in Figure 5 below.
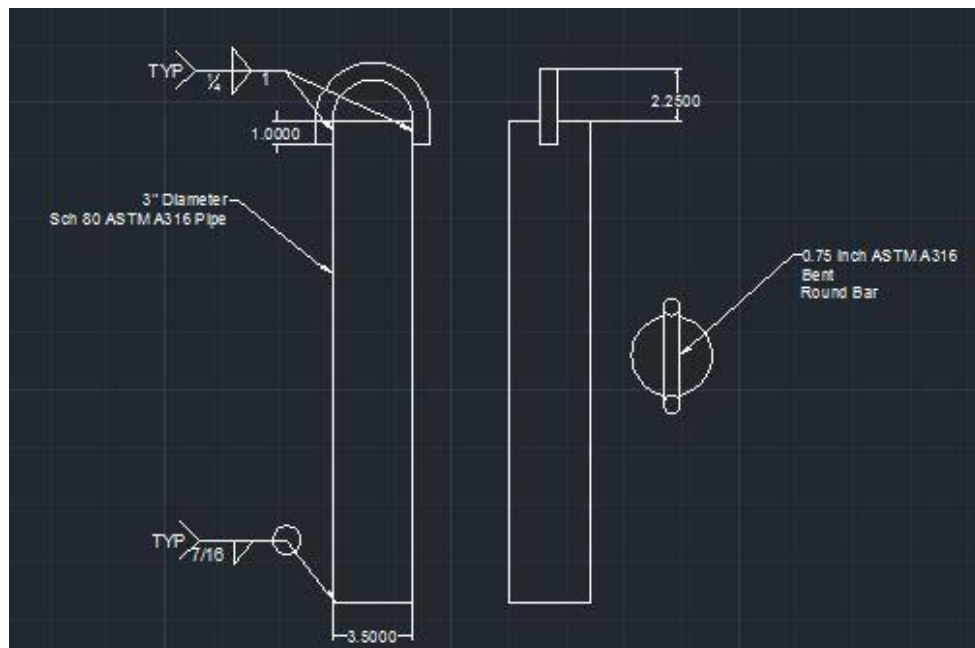

Figure 5: Benchmark Design Roof Tie-Down Anchor

The analytical calculations for this design can also be seen in Appendix C. These calculations included determining the internal forces and stresses acting on each of the design elements due to the yielding and ultimate loads. The ultimate load of 5000 pounds is governed by OSHA. Using these internal forces and stresses, the stainless steel SCH 80 pipe and ¾" bent bar were checked for minimum yielding and ultimate strength capacities according to their ASTM (American Society for Testing and Materials) standard values.

LRFD philosophy was used through the application of a strength reduction factor, phi, to ensure the designs can handle, at minimum, the calculated stresses. The value phi factors applied were found in codes and construction specifics governed by AISC.

The bent bar calculations included creating tables to determine the axial, bending and shear stresses at various locations around the bend. Stresses due to the 5000 pound ultimate load can be found in Table 5. Negative stress values represent the member being in tension.

Table 5: Stresses Acting on Round Bent Bar in Benchmark Design, based on applied 5000 lb force

Theta (degrees)	Axial Stress (psi)	Negative Bending Stress (psi)	Positive Bending Stress (psi)	Axial + Negative Bending (psi)	Axial + Positive Bending (psi)	Shear Stress (psi)
0	0.00	0.00	0.00	0.00	0.00	0.10
10	6.23	-169.96	224.99	-163.73	231.23	0.10
20	12.28	-334.76	443.15	-322.48	455.43	0.10
30	17.95	-489.39	647.84	-471.44	665.79	0.09
40	23.08	-629.15	832.84	-606.07	855.92	0.08
50	27.50	-749.79	992.54	-722.28	1020.05	0.07
60	31.09	-847.65	1122.09	-816.55	1153.18	0.05
70	33.74	-919.75	1217.53	-886.01	1251.27	0.03
80	35.36	-963.91	1275.99	-928.55	1311.35	0.02
85	213.12	-18280.00	24198.41	-18066.89	24411.53	5.72
90	35.90	0.00	0.00	35.90	35.90	5.73

[1] Negative stress represents the tension stresses.

The structure of the bent bar was indeterminate which caused an approach of using virtual work for the analysis of a symmetric structure with an anti-symmetric loading. One half of the bent bar was considered with a roller support located at the crown of the bent bar, which is at the axis of symmetry. Figure 6 below shows the force diagrams used to calculate the redundant shear force. Before the stresses could be calculated the shear force at the top of the arc was calculated using a unit load. Then "cuts" were made along the curve of the bar to calculate the shear and axial forces at different points due to the calculated shear force at the top. Figure 7 below shows the final results of the shear and reaction forces due to an applied force of 1800 pounds.
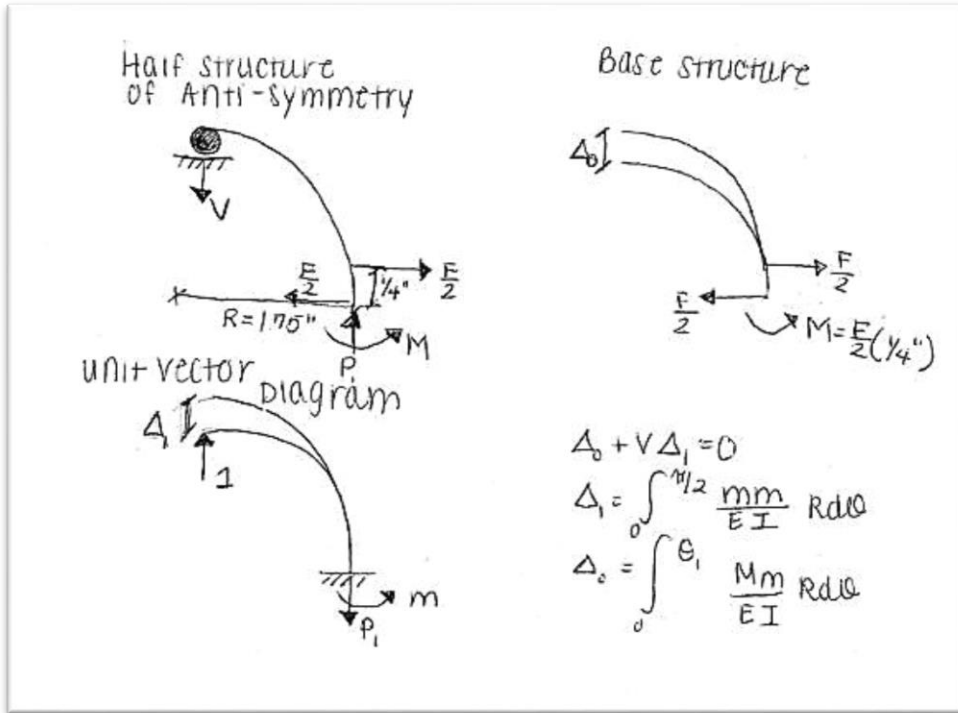
Figure 6: Force Diagrams of Virtual Work of a Half structure with Anti-Symmetric Boundary Condition
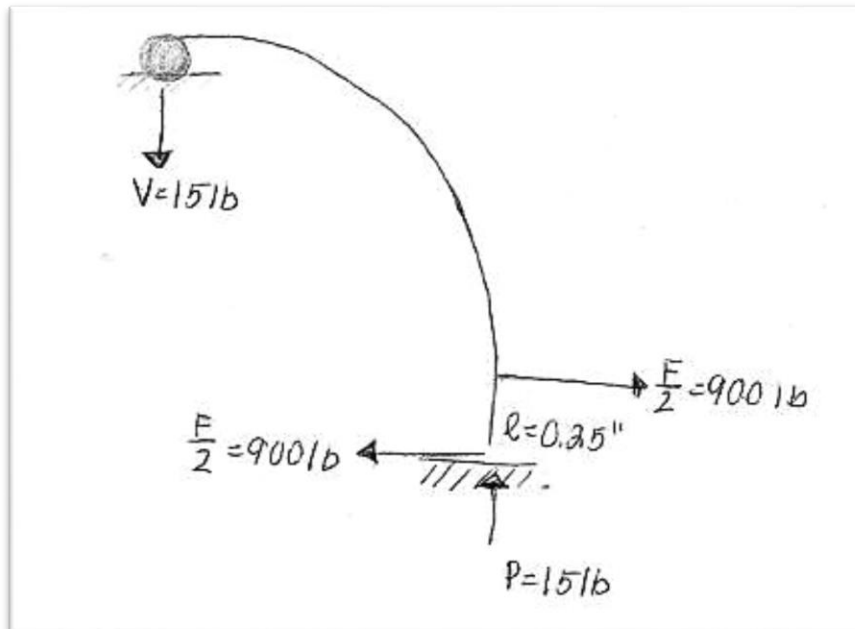

Figure 7: Final Results of Shear and Reaction Forces

From these found forces, the stresses in each element were calculated. The bending stress had to be calculated for a curved beam versus a typical straight beam in the bent bar. Refer to "Bending Stress of a Curved Beam" in the background for more information about bending stress in the curved members.

L...	Joint Label	X [k]	Y [k]	Z [k]	MX [k-ft]	MY [k-ft]	MZ [k-ft]
1	N1	-2.5	.016	NC	NC	NC	.585
1	N19	-2.5	-.016	NC	NC	NC	.585
1	Totals:	-5	0	0			
1	COG (ft):	NC	NC	NC			

Figure 8: Joint reaction results from computer analysis

Computer analysis in RISA3D was also used to calculate the stresses in the curved beam. This was used for comparison to check the hand calculated values to ensure accurate results. The computer results takes more shear deformation into account which causes slightly different results. The computer model also was not a perfectly curved shape. The model was digitized by 21 nodes about 10 degrees apart, which were all connected by individual members. The hand calculated values and the computer analysis should not be expected to have identical results. The shear force at the tip of the curve was found by the RISA3D program and hand calculations at 15 and 15.8 pounds, respectively, with an acceptable 5% error.

After the maximum stresses acting on the members were determined and checked against material limits, the weld lengths and strengths were calculated. These limiting equations and calculated values can be seen in Table 6 below. Throughout the calculations of the stresses the Load and Resistance Factor Design (LRFD) approach was used which determines the required strength of members. This was done through the application of a strength reduction factor, phi. Phi is a factor, always less than one, which reduces the strength of members to ensure the designs can handle, at minimum, the calculated stresses. The value phi factors applied were found in codes and construction specifics governed by AISC (American Institution of Steel Construction).

Table 6: Table of stress values and the corresponding limits calculated for the benchmark design

Pipe: Ultimate			Limits:
Axial Stress (ksi)	Bending Stress (ksi)	Axial + Bending (ksi)	Strength (ksi)
1.66	47.64	49.28	56.25 Φ = 0.75
Shear Stress (ksi)			Shear Strength (ksi)
1.66			40.5 Φ = 0.9
Pipe: Yield			
Axial Stress (ksi)	Bending Stress (ksi)	Axial + Bending (ksi)	Strength (ksi)
0.597	17.15	17.75	27 Φ = 0.9
Shear Stress (ksi)			Shear Strength (ksi)
0.597			16.2 Φ = 0.9
Bent Bar: Max Values			
Axial Stress (ksi)	Bending Stress (ksi)	Axial + Bending (ksi)	Strength (ksi)
0.213	24.198	24.411	37.5 Φ = 0.75
Shear Stress (ksi)			Shear Strength (ksi)
0.006			27 Φ = 0.9
Weld: Pipe to WF			
Ultimate Strength (ksi)			Weld Strength (ksi)
33.72			37.8 Φ = 0.75

     The bottom of the pipe will be welded to a flange beam on the roof, or welded to a baseplate which can be bolted into a supporting beam. The E70 electrode weld has an ultimate strength of 70 ksi and a minimum fillet size of 1/4" due to the thickness of the pipe according to AISC Table J2.4. The strength of the weld was calculated using the sum of the bending and axial stresses due to the ultimate load, and it was found that the ¼" fillet weld was not strong enough.

After multiple trail-and-error calculations, it was determined that a minimum of 7/16" fillet weld would be needed to weld the pipe to the supporting beam flange or baseplate.

Next the weld of the bent bar to the sides of the pipe was investigated. The minimum fillet weld size is ¼" due to the thickness of the bent bars, according to AISC Table J2.4. The minimum weld length was calculated using the strength per inch of weld. The minimum length was found to be 0.327" which is less than the minimum of four times the fillet size per AISC Specification section J2.2b. Therefore, the minimum weld length is governed by four times the fillet size, or 1".

Taking the time to understand a benchmark design assisted in the understanding of creating the alternative designs. It also helped to brainstorm the different concepts and criteria to consider while designing and then analyzing the alternative designs.

Chapter Five: Creation of Alternative Designs

Creating multiple preliminary designs was the next phase of the design process. Each design satisfies the constraints imposed by the needs of the sponsoring company, and they also follow the specifications for tieback anchors defined by the Occupational Safety and Health Administration (OSHA). In order to obtain the proper information about the specifications, background research was completed through OSHA, ANSI, and AISC (American Institute of Steel Construction).

The work done to complete the benchmark design was used as a template for the design and structural analysis of four other alternatives. Some of the variations in the designs include adding a cap plate, a base plate, changing the dimensions, and changing the material of the pipe.

As mentioned above, the work done on the benchmark design simplified the design process for the four other alternatives.

Cap Plate

One of the changes included adding a cap plate to the top of the pipe. It distributes the stress from the bent bar around the entire edge of the pipe instead of in two small sections. This causes an addition of a weld that was not included in the benchmark which also adds cost for the weld itself and the cap plate. The weld changes can be seen in the two figures below.

Figure 9: Bent Bar Connection with a Cap Plate	Figure 10: Bent Bar Connection without a Cap Plate
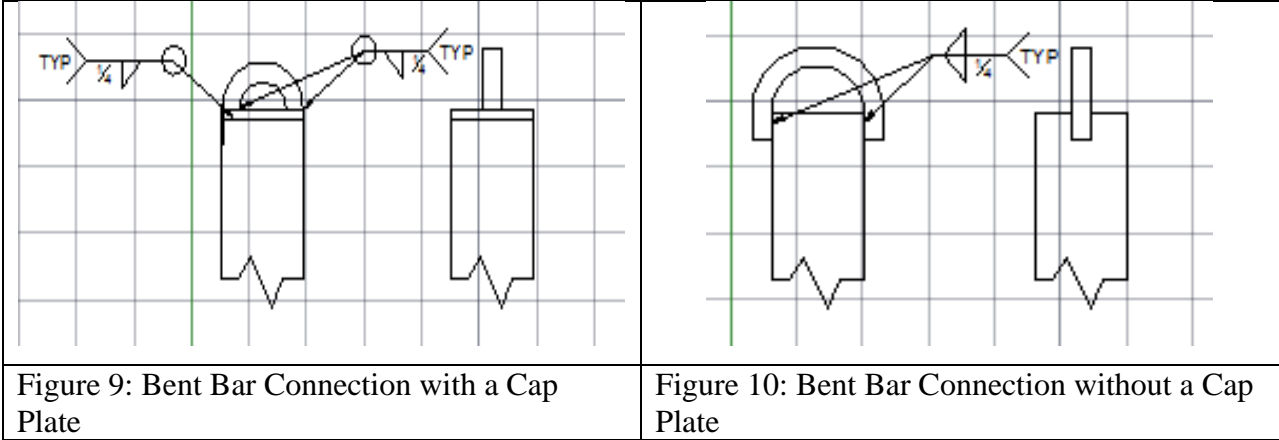
As shown in the two figures above, the cap plate changes the weld types of the bent bar to the anchor. Without the cap plate the bent bar is connected by a one -inch long fillet weld down each side of the pipe. With the cap plate, there are three all around welds. One to connect the cap plate to the pipe, and a second to connect the two ends of the bent bar to the cap plate.

Initially the inside radius of the bent bar was welded to the outside of the pipe. When welded to the cap plate, the outside radius of the bent bar is at the end of the pipe, shortening the radius. This causes a slightly higher stress values at the outer radius while still being well under the limits.

Base Plate

The initial design considered the base of the pipe directly welded to a roof. Depending on the structure of the roof, this can be a strong and simple permanent solution. However this is only possible on some metal roofs. If the roof is constructed with concrete, the pipe cannot be welded directly to the roof. Alternatives include welding the pipe to a base plate, and then bolting the plate into the roof with anchor bolts.

Designing the base plate required the calculation of the thickness for bending using assumed dimensions of the base plate. The base plates of the anchor designs were also checked for the possibility of prying action (AISC 9-10). The effect of prying action happens only in bolted connection when a tensile force acts on a bolt (McCormac, 2011). The bolt's tension force is affected by the deformation of the thin plate being bolted down. When checking the minimum thickness of the plate to check its strength against prying action, a plate thickness was chosen so prying action did not have to be considered.

Then, using the calculated thickness, the in-plane effects of tension yield, tension rupture, and block shear rupture were investigated to determine the governing value of the three calculations.
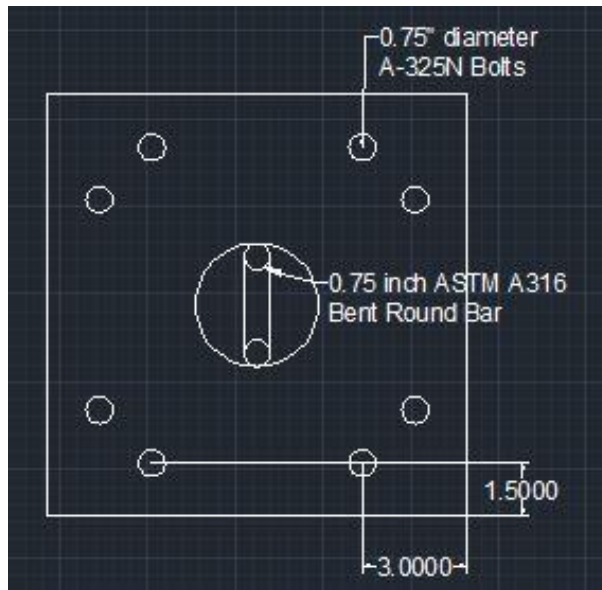
Figure 11: Drawing of the typical baseplate design and bolt placement

Next, the total permissible capacity of the base plate was found as the limit of the governing value between the tension yield, tension rupture, and block shear rupture to ensure baseplate is strong enough against the three common failure methods.

A-325N, the one of the most commonly used structural bolts, was chosen for the design. For this application, the bolt strength is governed by combined shear and tension (AISC J3.7). AISC equations J3-2 and J3-3b were used to calculate the available tensile strength subjected to combined tensile and shear of the bolts at 39.6 kips per bolt if four bolts are used. The required capacity was also checked to ensure it is less than the available capacity. Consideration has to be taken in deciding between constructability of field welding and bolting through a roof.

Pipe Material

Another alternative to the design was modifying the material of the pipe. As mentioned in the background, different metal materials provide various pros and cons. Stainless steel offers protection against corrosion but it is more costly than carbon steel.

Galvanizing is an alternative for corrosion protection with less added cost than stainless steel. However, the health concern with welding galvanized metal is not worth the corrosion protection unless the proper equipment is readily available to protect the welder from these dangers.

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Carbon steel, the most common and most readily available of the choices, has lower ultimate strength than stainless steel but a higher yielding strength. Carbon steel is also the least cost option for the initial cost, while also the least sustainable.
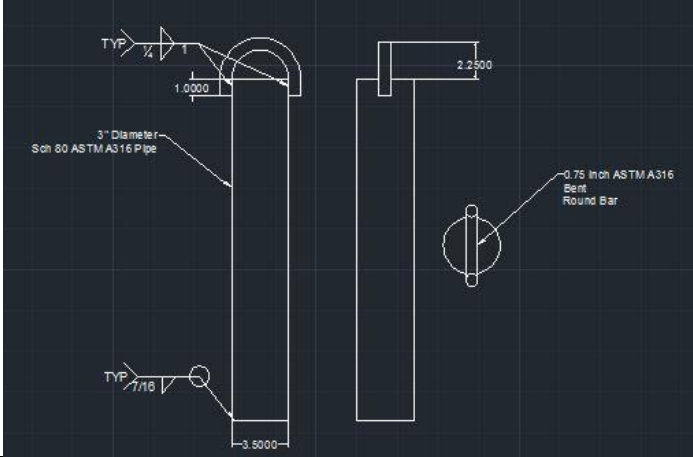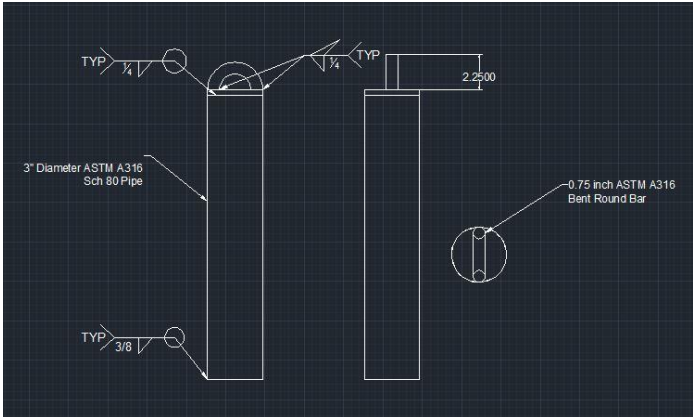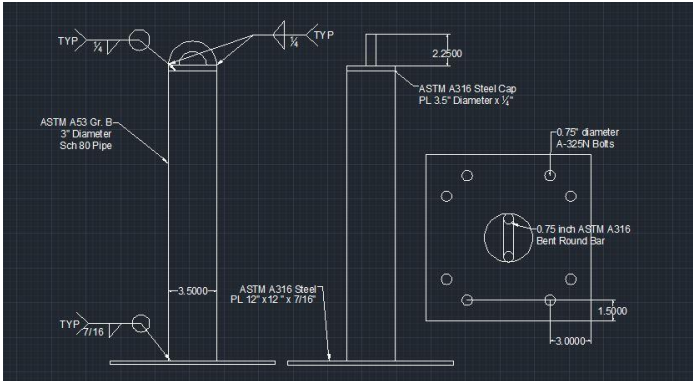
Dimensions of the Pipe

The dimensions of the anchor can be altered by shortening the height of the pipe, changing the thickness of the pipe or widening the radius. Widening the radius and thickening the wall can give the pipe a higher slenderness factor which may make the pipe more susceptible to buckling while the greater cross-sectional area strengthens the pipe against axial stresses. This also increases the weight per foot of the pipe and therefore the cost.

Shortening the height on the other hand can decrease the maximum moment, therefore decreasing the bending stress in the pipe. This also decreases the cost of the pipe, making the design more cost effective if the design can still handle all the stresses.

The five designs, including the benchmark were created. In Table 7 are drawings of each of the designs and design summaries.

Table 7: Design drawings and summaries of the five preliminary designs

Design Number	Design Highlights	Drawing
1 (Benchmark)	3" Diameter ASTM A316 Sch 80 Pipe, 1.75' 0.75" Diameter ASTM A316 Bent Bar Field Weld to Roof	
2	3" Diameter ASTM A316 Sch 80 Pipe, 1.5' ASTM A316 Round PL 3.5" x 3/8" 0.75" Diameter ASTM A316 Bent Bar Field Weld to Roof	
3	ASTM A53 Grade B 3" Diameter Sch 80 Pipe, 1.75' 0.75" Diameter ASTM A316 Bent Bar ASTM A316 Round PL 3.5" x 3/8" ASTM A316 Base PL 12" x 12" x 7/16"; Bolted to Roof	

4	4" Diameter ASTM A316 Sch 80 Pipe, 1.5' 0.75" Diameter ASTM A316 Bent Bar Field Weld to Roof	
5	3" Diameter ASTM A316 Sch 80 Pipe, 1.75' 0.75" Diameter ASTM A316 Bent Bar ASTM A316 Base PL 12" x 12" x 7/16 "; Bolted to Roof	

Below in Table 8, the summary of stresses and limiting strength values can be seen and compared. As shown in the table, most of the members and connections are overdesigned. The overdesign was a result of considering the constructability of the design immediately in the design process. The base design was Olsen Engineer's roof anchor which consisted of a 0.75" round bar and 3" diameter Sch 80 pipe with a height of 1.75 feet. Although the diameter of the pipe could have been reduced slightly, the bend radius would also decrease, therefore making the fabrication of the top, round bar more difficult.

Table 8: The design summary and stress values of the five preliminary designs

	Design #1 Benchmark	Design #2	Design #3	Design #4	Design #5	Limiting Equations
Bent Bar: Max Values						
Axial Stress (ksi)	0.213	0.467	0.467	0.403	0.213	$\frac{P}{A} \leq \Phi F_u$
Bending Stress (ksi)	24.198	26.911	26.911	27.189	24.198	$\frac{[M(R-r)]}{[Ar(r-R)]} \leq \Phi F_u$
Axial + Bending (ksi)	24.578	27.379	27.379	27.592	24.578	$\frac{[M(R-r)]}{[Ar(r-R)]} + \frac{P}{A} \leq \Phi F_u$
Strength (ksi)	*50*	*50*	*50*	*50*	*50*	
Shear Stress (ksi)	0.006	0.006	0.002	0.36	0.36	$\tau = \frac{VQ}{Scb} \leq 0.6\Phi F_u$
Shear Strength (ksi)	*30*	*30*	*30*	*30*	*30*	
Cap Plate: Ultimate						
Axial Stress (ksi)	x	0.744	0.744	x	X	$\frac{P}{A} \leq \Phi F_u$
Bending Stress (ksi)	x	0.52	0.52	x	X	$\frac{M}{S} \leq \Phi F_u$
Axial + Bending (ksi)	x	1.264	1.264	x	X	$\frac{M}{S} + \frac{P}{A} \leq \Phi F_u$
Strength (ksi)	*x*	*65*	*65*	*x*	*X*	
Shear Stress (ksi)	x	2.023	2.023	x	X	$\tau = \frac{VQ}{Scb} \leq 0.6\Phi F_u$
Shear Strength (ksi)	*x*	*39*	*39*	*x*	*X*	
Pipe: Ultimate						
Axial Stress (ksi)	1.64	1.651	1.64	1.5	1.64	$\frac{P}{A} \leq \Phi F_u$
Bending Stress (ksi)	47.64	40.9	47.64	27.14	47.64	$\frac{M}{S} \leq \Phi F_u$
Axial + Bending (ksi)	49.28	42.551	49.28	28.64	49.28	$\frac{M}{S} + \frac{P}{A} \leq \Phi F_u$
Ultimate Strength (ksi)	*75*	*75*	*60*	*75*	*75*	
Shear Stress (ksi)	1.66	1.65	1.66	0.66	1.65	$\tau = \frac{VQ}{Scb} \leq 0.6\Phi F_u$
Ultimate Shear Strength (ksi)	*45*	*45*	*35*	*45*	*45*	

Pipe: Yield						
Axial Stress (ksi)	0.6	0.6	0.6	0.539	0.6	$\frac{P}{A} \leq \Phi F_y$
Bending Stress (ksi)	17.15	14.7	17.15	9.76	17.15	$\frac{M}{S} \leq \Phi F_y$
Axial + Bending (ksi)	17.75	15.3	17.75	10.299	17.75	$\frac{M}{S} + \frac{P}{A} \leq \Phi F_y$
Yield Strength (ksi)	*30*	*30*	*36*	*30*	*30*	
Shear Stress (ksi)	0.596	0.596	0.596	0.239	0.596	$\tau = \frac{VQ}{Scb} \leq 0.6\Phi F_y$
Yield Shear Strength (ksi)	*30*	*18*	*21*	*18*	*30*	
Slenderness Ratio						
D/t	3.89	3.89	3.89	4.5	3.89	$\frac{D}{t} \leq \frac{0.07E}{Fy}$
0.07E/Fy	*65.3*	*65.3*	*57.17*	*65.3*	*65.3*	
Base Plate Capacity						
Tension Yield (kips)	x	x	236.25	x	236.25	$\Phi F_y(L * t)$
Tension Rupture (kips)	x	x	181.35	x	181.35	$\Phi F_u * Ae$
Block Shear Rupture (kips)	x	x	214.43	x	214.43	$F_u A_{nt} + 0.6F_u A_{nv} \leq F_u A_{nt} * 0.6F_y A_{gv}$
Total Permissible Capacity (kips)	x	x	181.35	x	181.35	
Bearing Capacity (kips)	x	x	307.1	x	307.1	$N* 2.4(\Phi d_b t F_u)$
Bolts						
Available Strength (ksi)	x	x	113.2	x	113.2	$1.3F_n{}'t$ $-\frac{F_{nt}}{\Phi F_{nv}} f_{rv} \leq F_{nt}$
Nominal Tensile Strength (ksi)	*x*	*x*	*90*	*x*	*90*	*Therefore 90 ksi governs*
Required Tensile Capacity (kips)	x	x	1.25	x	1.25	$f_{rv} \leq F_{nv}$
Available Tensile Strength (kips)	*x*	*x*	*39.6*	*x*	*39.6*	
Required Shear Capacity (kips)	x	x	1.25	x	1.25	$Rn \leq \Phi f_{rv}$
Available Shear Strength (kips)	*x*	*x*	*40.5*	*x*	*40.5*	

Weld: Pipe to Base Plate or WF						
Ultimate Stress (ksi)	33.72	34.52	33.72	33.44	33.72	$\dfrac{M}{S}+\dfrac{P}{A}$ $\leq \Phi * 0.6F_u$
Weld Strength (ksi)	*37.8*	*37.8*	*37.8*	*37.8*	*37.8*	

Limiting values are all shown in *italics*.

All calculations made for the five designs can be seen in the appendix. LRFD design was the approach taken in these calculations. However, because the 5000 pound load is considered an ultimate load, it is assumed the factor of safety is implicated in the load. The phi, or resistance, factors used in the calculations can be seen in Table 6.

Chapter Six: Analysis of Alternatives

Each alternative was analyzed to select the most efficient design. The perspectives of sustainability, constructability, use flexibility, and cost were all considered.

Evaluation Criteria

Sustainability in construction is growing in importance. Due to this, the sustainability of each design was rated. Sustainability factors considered included protection against corrosion and overall durability. The leading differing factor in the five designs was the pipe material. Four of the designs used stainless steel to protect was against rust and corrosion, providing better sustainability. It also has an overall better durability with resistance to fire damage than carbon steel, decreasing maintenance cost. ASTM A53 Grade B *c*arbon steel was used in one of the alternative designs. It is the lowest cost option but offers the lesser value for sustainability due to its susceptibility to rust.

The constructability of the design included the capabilities of MIW's shop to fabricate the design, as well as the ease of construction in the field. The constructability of the design was considered throughout the design of the anchor, taking into account the previously produced design. The three sub-factors of constructability included component fabrication, assembly and installation. In component fabrication, for example, the shop is limited to minimum radius the top bent bar can have. An example of an assembly difference is the type of weld used to attach the top bent bar to the anchor. Three of the designs use a 1" weld length down the side of the pipe, while the other two weld the ends of the pipe to a cap plate. According to the shop manager of MIW, Michael Walker, the weld to the side of the pipe is much easier for the shop; greater strength is also given by the larger weld area. Another assembly concern was welding carbon steel to stainless steel plates which requires a longer, more difficult welding process. The last constructability factor analyzed was the field installation process for ~~of~~ the anchor. Bolting a baseplate to a roof is an easier process for the field workers than bringing welding equipment up to the top of a building. The average of the three constructability subarea scores determined the final constructability score.

The use flexibility of each design was also considered during the analysis. Depending on the structure of the roof, the type of installation of the anchor may be limited. For example, directly welding the anchor is only possible with some metal roofs. If the roof is constructed with

concrete, the pipe cannot be welded directly to the roof. Bolting the anchors that were welded to base plates created an alternative that can be more versatile.

A cost analysis was completed for each design using take-offs. Cost estimates with Atlantic Stainless Steel, the company's metal supplier, were made to create the most accurate estimates available. A balance between use flexibility, sustainability, constructability and cost was desired. The cost comparisons of the different materials and dimensions of materials helped give a value for the different scores presented by the other three main attributes. The cost of each material can be seen in Table 9.

Table 9: Cost of materials used in anchor designs

Item	Cost
3" Sch 80 ASTM A316 Pipe (per foot)	$52.30
4" Sch 80 ASTM A316 Pipe (per foot)	$69.50
ASTM A316 0.75" Diameter Bent Bar (per inch)	$0.34
ASTM A316 Cap PL 3.5" OD x 1/4" (ea)	$2.63
ASTM A316 PL 12" x 12" x 7/16" (ea)	$2.88
3" Sch 80 ASTM A53 Grade B Pipe (per foot)	$23.84

Weighted Evaluation

The design decision will balance between all of the factors in the table. An equation of dividing the attributes of the design over the cost was created to give a monetary value to the other aspects of the design.

$$\text{Design Score} = \frac{\sum Attriutes}{Cost} = \frac{\sum(Sustainability + Constructability + Use\ Flexibility)}{Cost}$$

Recognizing that certain perfectives were more important than others, a weighted scoring equation was used. To create proper weights for each of the three attributes, the attributes were all compared two at a time. It was found that sustainability was the most important of the three, constructability was more important than the use flexibility, and use flexibility was not rated higher than either of the other two attributes.

Table 10: Scores of the three attributes from comparison and resulting weight factors

Attribute	Score from Weighting Comparison	Weight Factors
Sustainability	2	3/6
Constructability	1	2/6
Use Flexibility	0	1/6

In order to avoid disregarding use flexibility due to its score of zero, a nominal score of one was used, increasing each of the scores by one. The weight factors were used to create the final scoring equation of:

$$\text{Design Score} = \frac{\Sigma \left(\frac{3}{6} * Sustainability + \frac{2}{6} * Constructability + \frac{1}{6} * Use\ Flexibility \right)}{Cost} * 100$$

Evaluation of Alternatives

The first three were rated with a score between one and four, with four being the strongest score a design could receive in one area. The cost values were shown to identify the best value solution.

Using the scores shown in Table 11, the final scoring values were calculated. Table 12 below shows the finals scores of the five designs.

In the results shown in Table 12, Design #3 has the highest score followed by Design #5, #1, #2 and lastly #4. Although Design #3 had some of the lowest attribute scores, its low cost caused the design to have the highest value.

Table 11: The results of the five designs efficiency in sustainability, constructability, use flexibility and cost

	Design #1 Benchmark	Design #2	Design #3	Design #4	Design #5
Sustainability	**4.0**	**4.0**	**1.5**	**4.0**	**4.0**
Constructability	**2.7**	**2.0**	**2.2**	**2.7**	**3.7**
Component Fabrication	3.0	2.0	2.5	3.0	4.0
Assembly	3.0	2.0	1.0	3.0	4.0
Installation	2.0	2.0	3.0	2.0	3.0
Use Flexibility	**2.0**	**2.0**	**3.5**	**2.0**	**3.5**
Cost	$92.66	$94.89	$38.48	$105.65	$95.54

*Sustainability, Constructability, and Use Flexibility were scored from 1-4, with 4 being the strongest

Table 12: The final scores of the five preliminary designs

Weighted Scores	**Design #1**	**Design #2**	**Design #3**	**Design #4**	**Design #5**
Sustainability	2.0	2.0	0.8	2.0	2.0
Constructability	0.9	0.7	0.7	0.9	1.2
Use Flexibility	0.3	0.3	0.6	0.3	0.6
Weighted Sum of Attributes	**3.2**	**3.0**	**2.1**	**3.2**	**3.8**
Cost	$92.66	$94.89	$47.23	$105.65	$95.54
Final Score	**3.48**	**3.16**	**4.35**	**3.05**	**3.98**

Chapter Seven: Conclusions and Recommendations

Summary

This project focused on creating an efficient design of a roof tie-down anchor for the use of a lifeline system. The sponsoring company of this project has produced roof anchors in the past, but was recently in search of a more efficient design to eventually patent and produce in bulk.

The process to design an overall efficient design consisted of four phases: evaluation of a benchmark design, creation of alternatives, analysis of alternatives, and development of a final design. The overall goal of each of these phases was to design and select a sustainable, easily constructible, cost effective design that had use flexibility. Throughout all the design process, the strength of the anchor was ensured to be within the specifications of OSHA (Occupational Safety and Health Administration).

In the results of the analysis, the highest scoring design was Design #3. Design #5 was a close second. Although Design #3 was chosen by the scoring, there were reservations by MIW Corporation about welding the stainless steel and carbon steel together. It was expressed that stainless steel was the preferred material for all of the components.
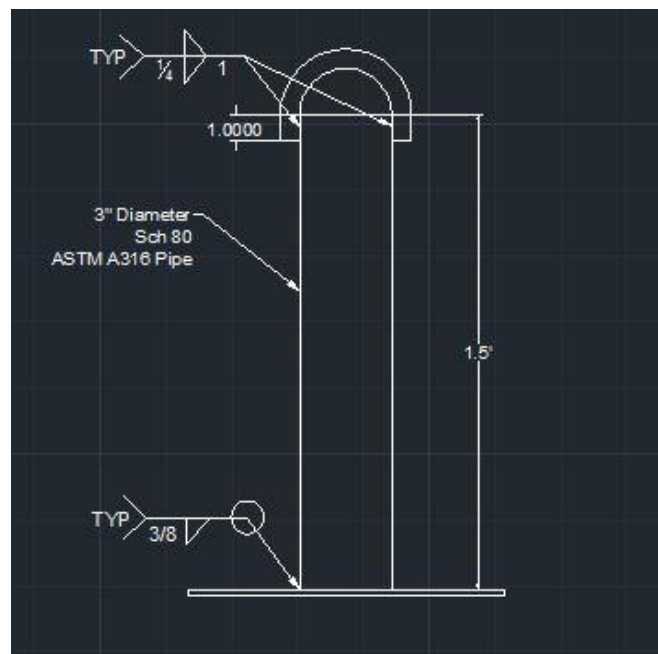
Figure 12: Recommended Design of Roof Tie-Down Anchor
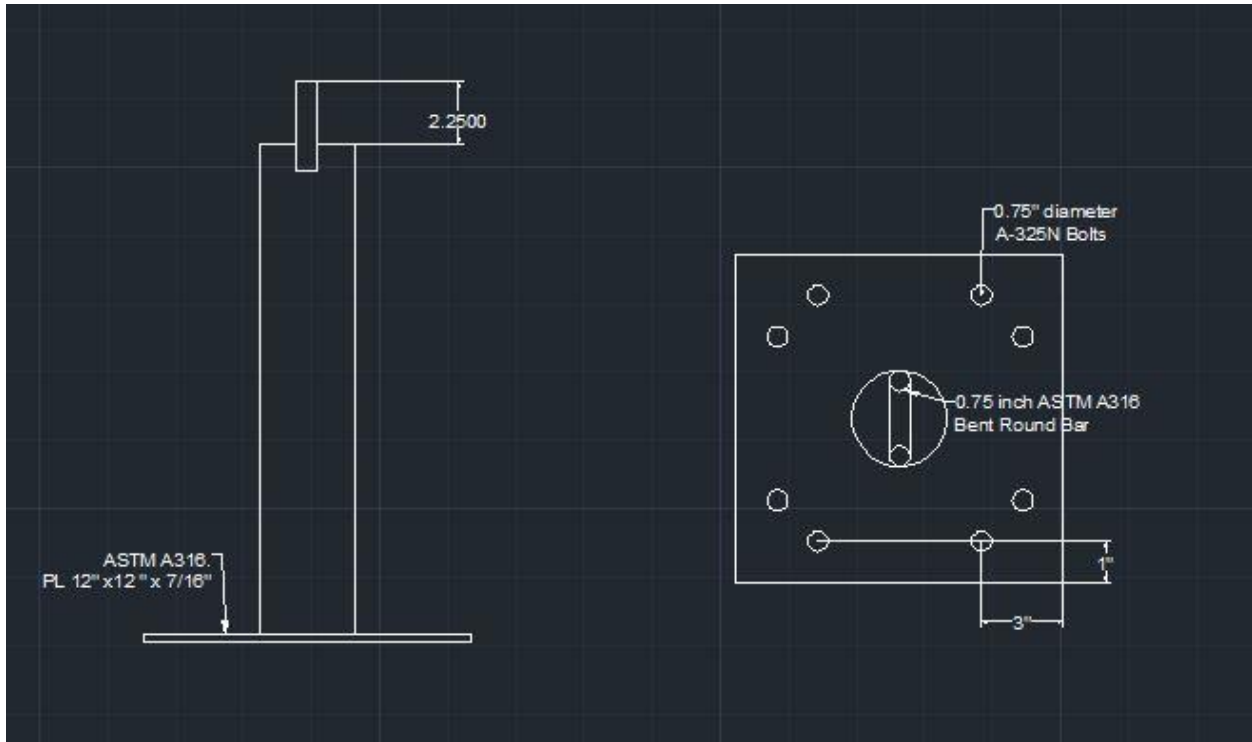
Figure 13: Recommended Design of Roof Tie-Down Anchor

The final, recommended design is a variation of Design #5, shown in Figure 13. Shortening the ASTM A316 stainless steel pipe to 1.5 feet, reduced the maximum moment on the bottom on the pipe, lessening the fillet weld. The original dimension of 1.75', although taller than necessary, was used because it was the dimension of MIW's previously produced design. The pipe height only has to be tall enough to extend past roof decking; keeping the attachment point accessible after the roof is complete.

The values of the stresses in the design were all recalculated and can be seen in the appendix. Table 12 shows the final values of the stresses and strengths, as well as their limiting values.

Table 13: Table of stress values and the corresponding limits calculated for the final design

Bent Bar: Max Values			Limits:
Axial Stress (ksi)	**Bending Stress (ksi)**	**Axial + Bending (ksi)**	**Strength (ksi)**
0.213	24.198	24.412	37.5 $\Phi = 0.75$
Shear Stress (ksi)			**Flexural Shear Strength (ksi)**
0.006			27 $\Phi = 0.9$
Pipe: Ultimate			Limits:
Axial Stress (ksi)	**Bending Stress (ksi)**	**Axial + Bending (ksi)**	**Strength (ksi)**
1.66	40.89	42.55	52.5 $\Phi = 0.75$
Shear Stress (ksi)			**Flexural Shear Strength (ksi)**
1.65			45.4 $\Phi = 0.9$
Pipe: Yield			
Axial Stress (ksi)	**Bending Stress (ksi)**	**Axial + Bending (ksi)**	**Strength (ksi)**
0.597	14.72	15.32	27 $\Phi = 0.9$
Shear Stress (ksi)			**Flexural Shear Strength (ksi)**
0.596			16.2 $\Phi = 0.9$
Slenderness Ratio			
D/t			**0.07E/Fy**
3.89			65.3

Base Plate Capacity			
Tension Yield (kips)	**Tension Rupture (kips)**	**Block Shear Rupture (kips)**	**Bearing Capacity (kips)**
236.25	*181.35 (Total Permissible Capacity)*	214.43	307.1 $\Phi = 0.75$
Bolts			
Available Strength (ksi)			**Nominal Tensile Strength (ksi)** *Upperlimit*
113.2			90
Required Capacity (kips)			**Available Tensile Strength (kips)**
1.25			29.7 $\Phi = 0.75$
Required Shear Capacity (kips)			**Available Shear Capacity (kips)**
1.25			30.4 $\Phi = 0.75$

Shortening the height also lessened the cost of the pipe, which is the most expensive member of the design. The efficiency of the design was rescored, and was calculated at higher than previous highest scorer. The new scoring chart can be seen in Table 14 below.

Table 14: Final scores including the recommended design

Weighted Scores	**Design #1**	**Design #2**	**Design #3**	**Design #4**	**Design #5**	**Recommended Design**
Sustainability	2.0	2.0	0.8	2.0	2.0	2
Constructability	0.9	0.7	0.7	0.9	1.2	1.2
Use Flexibility	0.3	0.3	0.6	0.3	0.6	0.6
Weighted Sum of Attributes	**3.2**	**3.0**	**2.1**	**3.2**	**3.8**	**3.8**
Cost	$92.66	$94.89	$47.23	$105.65	$95.54	$82.47
Final Score	**3.48**	**3.16**	**4.35**	**3.05**	**3.98**	**4.61**

Conclusion

The final design recommended achieved all of the project objectives. Overall, this project met the needs of MIW Corporation and provided a simple and efficient alternative for MIW Corporation to produce that considered the sustainability, constructability, use flexibility and cost of the design. The anchor was designed to fulfill the requirements imposed by OSHA 1926.502 as well as ANSI A10.32-2004.

Through the investigation of various designs and their analysis, the recommended design is believed to be the most efficient of the designs. It is recommended that final design and supporting calculations are reviewed and stamped by a licensed engineer then patented for production and sale by MIW Corporation in the future.

Once produced, regulations require annual inspection of anchors by a qualified person and recorded in the Building Façade Maintenance Equipment log book.

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Appendices

Appendices A: Project Proposal

Project No. LDA-1506

DESIGN OF A TIEBACK ANCHOR SYSTEM

FOR MIW CORPORATION

A Proposal for a Major Qualifying Project by

_____

Kelsie Lazaro

Date: May 29, 2015

Approved:

_____

Professor Leonard D. Albano 122

Abstract

Design analysis of multiple options for a through-bolt tieback anchor is proposed. The main objective of the project is to design an anchor with high constructability while also cost effective for the production and sale for MIW Corporation. This objective will be met through the engineering drawings and structural analyses of multiple designs, and a multi-attribute analysis to choose the most effective option. The project will also include a detailed final design including OSHA standards.

Table of Contents

Introduction and Problem Statement

MIW Corporation has been fabricating and installing miscellaneous and ornamental metal since 1972. Originally concentrating on ornamental fences, gates, and rails, the company began to flourish with the number of projects in the Back Bay and Greater Boston Area in the 1970's.

In 1980, MIW began fabricating and installing more complex miscellaneous and ornamental steel after purchasing a small fabricating shop in Roslindale, MA. The company also started producing small to mid-size structural steel projects in 1990. This allowed MIW to expand their connections within the Boston Market and work on more complex projects.

In 2005, MIW became a member of the National Ornamental & Miscellaneous Metals Association (NOMMA) and the American Welding Society (AWS). These two certifications have allowed MIW to strengthen their networks, and gain numerous resources within their industry.

After purchasing a larger fabrication shop in Fall River, MA (2007), the company has increased the number and types of equipment for the production of both miscellaneous and structural steel. Due to this expansion, the company also fabricates both stainless steel and aluminum products.

MIW became certified in steel fabrication by the American Institute of Steel Construction (AISC) in 2014. Following the AISC specification and codes shows the respect and safety MIW holds for its products and employees. Companies achieve a higher quality and value when certified by AISC.

MIW Corporation, a booming company, continues to look for ways to extend their market. One product they would like to begin producing is tieback anchors. Through-bolt tieback anchors are a permanent anchorage solution that is both safe and practical. They are used for fall protection and a wide range of suspended access uses. Some of these applications include window cleaning and exterior building maintenance.

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The figure above is example of a tie back anchor. It consists of a base plate, which bolts into the roof; a metal post; and a top bent round bar, which the lifeline is clipped to.

Fall back systems are regulated by OSHA (Occupational Safety and Health Association) and ANSI (American National Standard Institute). Some of these standards include and a minimum ultimate strength and maximum arresting force.

The purpose of this project is to design an effective roof tieback system for the required loads by OSHA, while still cost effective.

Scope of Work

The main goal of this project is to design a roof tieback system for MIW to fabricate, sell, and erect. The goal will be accomplished by creating multiple designs through calculations and computer drafting. Included in these designs will be the considerations of the needs of the sponsoring company, MIW Corporation. These designs will include weld types and different metal materials such as stainless steel and steels of different schedules and dimensions. Engineering drawings and design calculations will be made for each design.

Each design will be analyzed using the engineering drawings, design calculations and considering costs of the different materials used. These designs will be evaluated to identify the most effective alternative while keeping production costs low. The chosen design will be pursued in detail to prepare for production by MIW Corporation.

Capstone Design

The project focuses on developing a roof tieback anchor for MIW Corporation to produce and sell. Very few fabricators in the United States produce these, and they are more commonly purchased and shipped from countries such as Canada. Recently MIW considered the possibility of selling their own within the Greater Boston area, which would be at lower cost than the Canadian systems due to the proximity of the company.

Through-bolt tieback anchors are a safe and practical anchorage solution that is used for fall protection. They have an overall simple design which results in increased productivity for the manufacturer. Prior to producing these systems, the president of the company, George Malatos, wants to ensure he has a cost effective design and complies with all related specifications. The project focuses on fulfilling these needs.

This project consists of four phases: creation of preliminary designs, analysis of designs, preparation of a detailed design, and certification of design. The first step in the creating the preliminary designs is researching related engineering standards. The requests and design ideas for the MIW must also be considered in the design. Interviews with both the company president and the senior project manager will be conducted. Once all the information is compiled the design can be started. Different approaches will be taken to find the best design for the needs of the companies, as well as the requirements of fall protection systems.

After all of the designs have been completed, the analysis of the design can begin to find the most efficient design. These designs will be analyzed for constructability and cost of materials. A design will be selected based on the ease of construction, engineering standards, and cost efficiency.

The cost efficiency will be analyzed using material take offs of each of the designs and well as considering production time. Cost comparisons will be performed to determine the most cost efficient of the designs. Cost factors include the building materials, complexity of fabrication (i.e. man hours for welding), complexity of erecting.

Health and Safety is one the many engineering standards that will be upheld throughout the duration of the project. Many of these standards are reflected by OSHA requirements. The ASCE (American Society of Civil Engineers) Code of Ethics is also considered. While designing

the roof anchor, the health, safety, and welfare of the possible users of the product will be held in high regard.

In addition, the main goal of the project will be design the anchor within Occupational Safety and Health Association's minimum design requirements of fall back systems in ensure safety of workers who use them. The design will be continuously checked that it complies with all safety regulations.

Once the design has been complete, it will need to be approved by a professional engineer (PE). Achieving PE licensure ensures the design is in compliance will all regulations. This maintains safety and decreases the chance of structural failure of the design.

Methodology

As outlined in the scope of work, the project will consist of four major phases: preliminary designs, analysis of designs, detailed design, certification of design. A summary of the work to be completed for each phase can be found in the table below; this section will provide an explanation of each phase.

Phase	Work Included for this Project
Creation of Preliminary Designs	Multiple simple designs applying the needs of the sponsoring company and OSHA's regulations.
Analysis of Designs	Analysis of preliminary designs to find the most effective.
Preparation of Detailed Design	More in depth design of the chosen design from the analysis.

Creation of Preliminary Designs

Creating multiple preliminary designs will be the first objective of the design process. Each design will apply the constraints due to the needs of the sponsoring company. In order to include the needs and ideas of the company, interviews will be completed with the company's president, George Malatos, and senior project manager, Jon Manuel. Mr. Malatos and Manuel can also share insight on the preferences of fall back system preferences for their erectors.

In addition, preliminary designs will be proposed while staying within the specifications of tieback anchors. The organizations that regulate fall protection systems include Occupational

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Safety and Health Administration (OSHA). In order to obtain the proper information about the specifications, background research will be completed through the OSHA and AISC (American Institute of Steel Construction).

Different design methods will include: differences in the type and amount of welding, different types of metals, changes in heights and thicknesses of the materials. Each design will have its own calculations written out and AutoCAD drawing to show the design visually.

Analysis of Designs

Each design will be analyzed for factors such as constructability and cost of materials. The constructability of the design includes the capabilities of MIW's shop to construct the design, therefore the ease of construction. For example, the shop is limited to minimum radius the top bent bar can have. Another constructability factor is following specifications with AISC and OSHA. Each design will be analyzed to ensure it follows the specifications that apply to its design.

A cost analysis will be completed for each design using take-offs. Cost estimates will be made using the sponsoring company's metal supplier to create the most accurate estimates available. The cost comparisons of the different materials and dimensions of materials will help determine the most efficient design. Stronger metals will also have a higher cost. A balance between strength and cost is desired. The final report will contain a table of each design's cost of the design.

The design decision will balance the cost and constructability to find the overall most efficient of the designs.

Preparation of Detailed Design

Once one design has been chosen, the preliminary design will be presented to MIW. Interviews with the president and senior project manager will completed again to collect more suggestions on the design. After this, final calculations will be made and more detailed drawings will be created in AutoCAD. Throughout the entire design process, it will be continuously checked that it complies with all regulations with OSHA.

Deliverables

This project will produce a number of deliverables at its final completion. The main deliverable will be the completed MQP Report which includes background research, methodology of the project, and supporting information for all decisions and conclusions made.

Other deliverables correlate with each phase of the methodology. First includes calculations and AutoCAD drawings of each preliminary design. The second includes an explanation of the analysis and decision of choosing a single design. The last deliverable includes the detailed design of final roof anchor system.

Conclusion

The scope of work for this project is extensive considering the time frame. However it will provide a great learning opportunity in both design and professionalism. The main challenge of this project is keeping the costs to fabricate the anchor low when OSHA has very high specification for fall protection system.

The next challenge will be approving the design for fabrication. The sponsoring company does not have a licensed engineer. External sources will be used to certifying the product. The final challenge will be having the design stamped by a licensed engineer.

Schedule

The work in this project will be completed in three segments over the course of one term. The first phase will include the project proposal and a recording the needs and other consideration from the sponsoring company. This segment will be completed by the end May. The second segment will include the design and analysis of the preliminary anchor designs. This will be completed by the end of June. Also completed by the end of June will be a first submittal of the final report. The MQP report will be written continuously throughout the project, and the final report will be submitted at the end of the term. The final segment will include the detailed design of the selected alternative. The final segment will be completed by the end of E-term – the final completion of the project.

The flow chart below shows flow of work throughout the project:
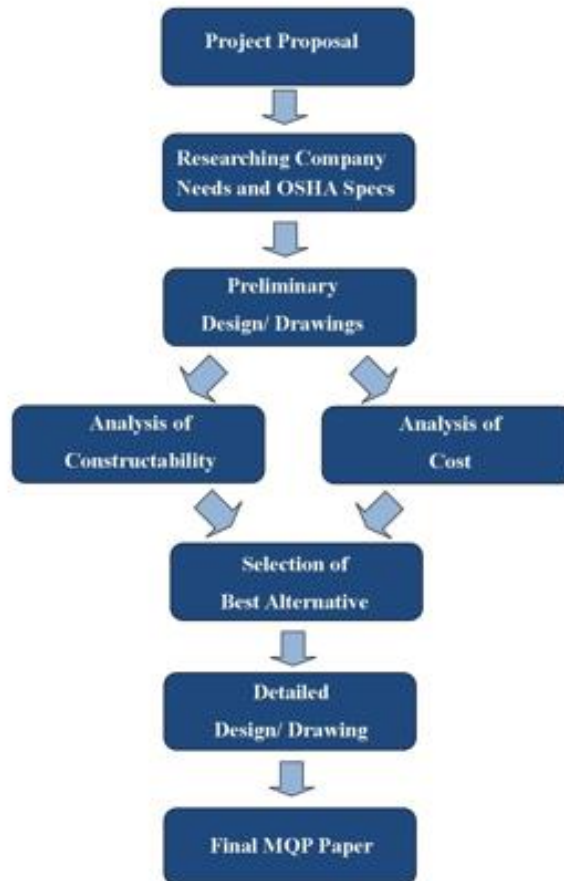
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Appendix B: AutoCAD Drawing of Benchmark Design
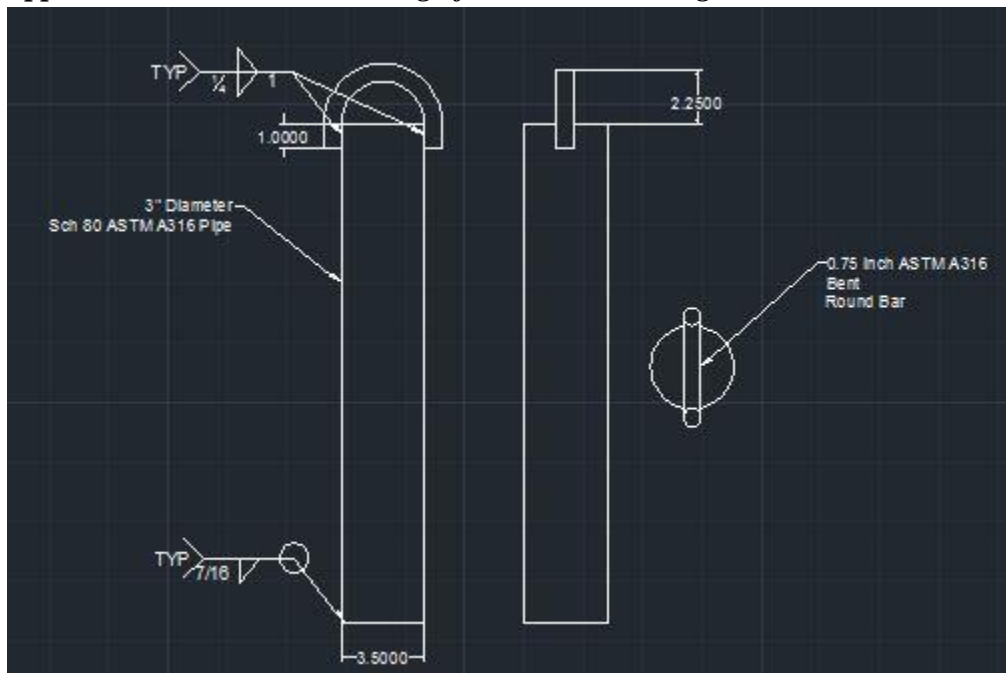
Appendix C: Hand Calculations of Benchmark Design

BENCHMARK ultimate strength of pipe 1.
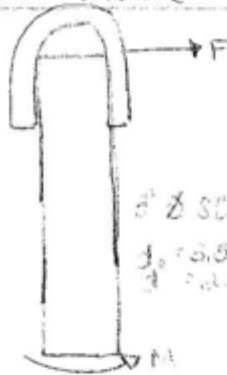
PIPE
$P_{max} = 5^k$
$M_{max} = P_{max} X = (5^k)(1.75" - 0.25") = 8.35$

$S = 0.0982(d_o^4 - d_i^4) = a.a3$ in

$A = \pi(\frac{d}{2})^2 - \pi(\frac{d_i}{2})^2 =$

$f = \frac{M}{S} + \frac{P}{A} = \frac{8.85^{14}(12")}{2.23in^3} + \frac{5^k}{3.16in^2} = 49.28$ KSI

$\sigma = \frac{M}{S} = \frac{8854 ft\ lb(12")}{2.23in^3} = 47644.3 = 47.64$ KSI < 70 KSI

$\tau = \frac{VQ}{SCb} = \frac{(5000lb)(1.508in^3)(1.68u)}{(2.23in^3)(1.09in)(3u)} = 1.658$ KSI $< 0.6(70) = 42$ KSI

Yield strength of pipe
$P = 1800\ lb = 1.8^k$
$M = (1800lb)(1.75' + 0.2') = 3187.5\ lb.ft = 3.188^{k.ft}$
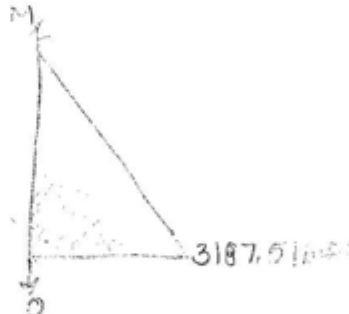
$S_{pipe} = 2.23in^3$
$A_{pipe} = 3.16in^2$

$\sigma = \frac{M}{S} = \frac{3187.5\ ft\ lb(12")}{2.23in^3} = 17152.47 = 17.15$ KSI < 30 KSI ✓

$C_1 = 0.743in$ from center
$C_2 = 0.619"$

$\bar{C} = \frac{C_1A_1 - C_2A_2}{A_1 - A_2} = \frac{(0.743)\pi(\frac{d_o}{2}^2) - (0.619)\pi(\frac{2.34}{2})}{\frac{\pi}{4}(2.5^2 - 2.4^2)} = 1.03$ in

$A_Q = \frac{A_{pipe}}{2} = 1.08in^2$

$Q = A\bar{C} = (1.08in^2)(1.03in) = 1.55$ in³

$\tau = \frac{VQ}{SCb} = \frac{(1800)(1.55)}{(2.23)(1.09)(2)} = < 0.6(30$ KSI) $= 18$ KSI ✓

$f_b = \frac{M}{S} + \frac{P}{A} = 3187\frac{lb.ft}{}(\frac{1k}{1000lb})(12") = 25$ KSI ✓

$r = 2.5"$ $\eta = 0.85$

$P = 2500 \text{ lb}$

$M = Ph - Pr\sin\theta$ $\qquad I = 2.3 \text{ in}^4$

$m = -r\cos\theta$

$\theta_1 = 5.74° = 0.1002 \text{ rads}$

$$\Delta_o = \int_0^{\theta_1} \frac{(Ph - Pr\sin\theta)(-r\cos\theta)\, r\, d\theta}{EI}$$

$$\int \frac{Pr^3\sin\theta\cos\theta - Phr^2\cos\theta}{EI}\, d\theta$$

$$= -\frac{Pr^3\sin^2\theta}{2EI} - \frac{Phr^2\sin\theta}{EI}\, \Big|_0^{0.1002}$$

$$= = -\frac{Pr^2}{2EI}\left(r\sin^2\theta - 2h\sin\theta\right)\Big|_0^{0.1002}$$

$$\Delta_o = -3.033\times10^{-6} \text{ inches}$$

$$\delta = \int_0^{\pi/2} \frac{(-r\cos\theta)^2}{EI}\, r\, d\theta$$

$$= \int \frac{r^2\cos^2\theta \cdot r}{EI}\, d\theta$$

$$= \frac{r^3}{EI}\int \cos^2\theta\, d\theta$$

$$= \frac{r^3}{EI}\left(\frac{\theta + \sin\theta\cos\theta}{2}\right)\Big|_0^{\pi/2}$$

$$= \frac{r^3}{2EI}\left(\theta + \sin\theta\cos\theta\right)\Big|_0^{\pi/2}$$

$$\delta = 1.91\times10^{-7} \text{ inches}$$

$$V = -\frac{\Delta_o}{\delta} = -\frac{(-3.033\times10^{-6}) \text{ inches}}{1.91\times10^{-7} \text{ inches}} = 15.88$$

$V = 62.98$ lb

$\ell = R\sin\theta$
  ex. $\ell(\theta=0) = 2.5$ in $(\sin 10°) = 0.43$ in
$P(axial) = V\sin\theta$
  ex. $P(\theta=10°) = 62.98$ lb $[\sin 10°] = 10.94$ lb
$V(shear) = V\cos\theta$
  ex. $V(\theta=10°) = 62.98$ lb $[\cos 10°] = 62.02$ lb
$Mom(in) = V\ell (lb \cdot in)$
  ex. $M(\theta=10°) = 62.98$ lb$(0.43$ in$) = 27.34$ lb·in

@ 85°
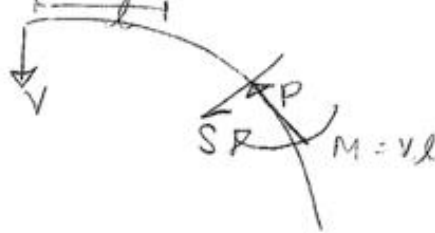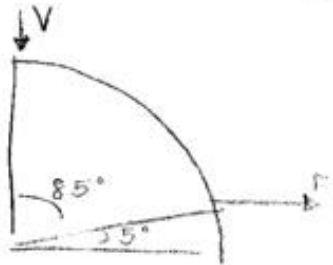
$M = V\ell + \frac{1}{2} f \cdot f - \frac{0.85°}{\sin 6.218}$)
  $= 741.45$ lb·in
$V(shear) = V\sin(5°) \cdot \sin(5°) = 902.00$
$P = V\cos(5°) + \frac{1}{2}\sin(5°) = 141.18$ lb

$I_x = \frac{\pi R^4}{4} = \frac{\pi(1.75)^4}{4} = 7.366$ in^4

$\bar{y} = \frac{4d}{6\pi} = \frac{4(0.75)}{6\pi} = 0.159"$

$t = 0.75"$

$Q = A\bar{y} = \frac{\pi(0.75)^2}{2}(0.159") = 0.035$ in^3

$\frac{VQ}{It} = 0.00634V$

ex.
$\tau = \frac{VQ}{It} (\theta=10°) = \frac{(62.98 \ lb)(0.035 \ in^3)}{7.366 \ in^4 (0.75)}$

$A = \pi c^2 = 0.4418$ in^2
$\bar{r} = 1.75" + \frac{0.75}{2} = 2.125"$

$\int \frac{dA}{r} = 2\pi(\bar{r} - \sqrt{\bar{r}^2 - c^2})$
  $= 2\pi(2.125 - \sqrt{2.125^2 - 0.375^2})$
  $= 0.2095$ in

$R = \frac{A}{\int \frac{dA}{r}} = \frac{0.4418 \ in^2}{0.2095 \ in} = 2.1088$ in

r c inside $= 1.75"$
r c outside $= 2.5"$
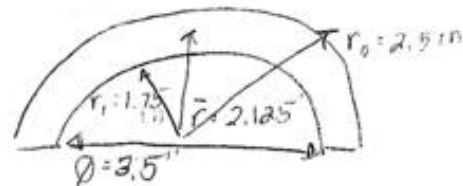
$\sigma = \frac{M(R-r)}{A_1(\bar{r}-R)}$

@inside
$\sigma = \frac{M(2.1088-1.75)}{0.4418(1.75)(2.125-2.1088 \ in)} = 0.7109M$

@outside
$\sigma = \frac{M(2.1088-2.5)}{(0.4418)(2.5)(2.125-2.1088)} = 21.803M$

weld calculation:

$F_{EXX} = 70$ ksi (table 9-1)

ASD $\Omega = 2.70$ for stainless steel
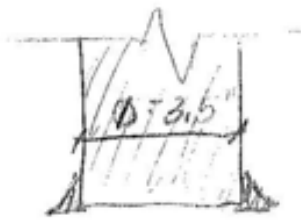
weld

weld circumference = $\pi(3.5) = 11$ in

$\phi = 3.5"$

Pipe to WF or base plate

$F_y = 70$ ksi

$S_{weld} = \frac{\pi}{4}(d_{pipe})^2 = 3.28\ in^3$

$A_{weld} = \pi\left(\frac{d_{pipe}}{4}\right) = $

3.94

$P_{MAX} = 5\ k$

$M_{MAX} = 5\ k(1.75 + 0.25") = 8.85\ ^{ik}$

$f_{weld\ ultima}\left[\left(\frac{M_{MAX}}{S_{weld}}\right) + \left(\frac{P_{MAX}}{A_{weld}}\right)\right] = 32.72\ ksi < (0.6)(0.9)(70) = 37.8\ ksi$ ✓

Bent Bar + Prop? Weld calculations

$\emptyset = 3.5"$

$r = 2.25"$
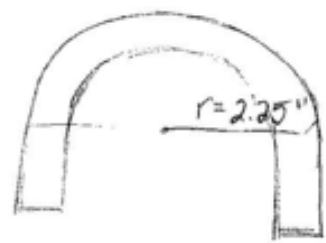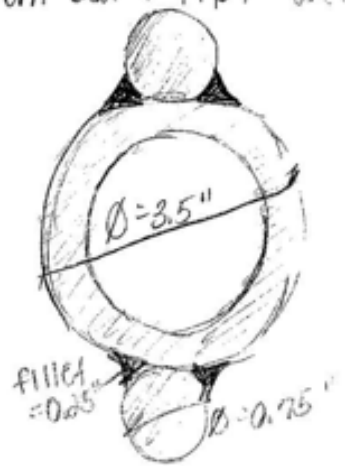
fillet = 0.25
$\emptyset = 0.75"$

Thinner thickness = 0.46"
Min fillet = 1/4" (Table J2.4)

Max fillet = 0.9375"

weld capacity
$t_e = 0.707a = 0.707(0.6875") = 0.486"$

$R_n = 0.6 F_{xx} t_e = 0.6(70)(0.486") = 20.412 k/in$

$\phi R_n = 0.75(20.412) = 15.3 \ k/in$

weld strength

$L_w = \dfrac{5 \ k}{15.3 \ in} = 0.327" < 4("¼") = 1"$

weld strong

Appendix D: RISA 3D Results of Forces in Bent Bar in Benchmark Design

3D Joint Reactions

L...	Joint Label	X [k]	Y [k]	Z [k]	MX [k-ft]	MY [k-ft]	MZ [k-ft]
1	N1	-2.5	.016	NC	NC	NC	.585
1	N19	-2.5	-.016	NC	NC	NC	.585
1	Totals:	-5	0	0			
1	COG (ft):	NC	NC	NC			

Appendix E: Preliminary Sketches

1.25'
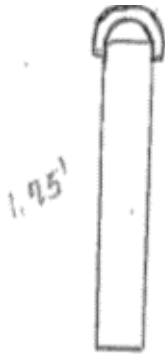
Design #1:
· Stainless steel
· Welded to roof
· No cap plate

1.5'
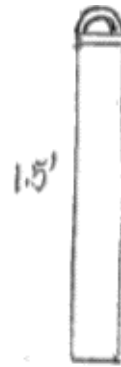
Design #2:
· stainless steel
· welded to roof
· "cap plate

1.75'
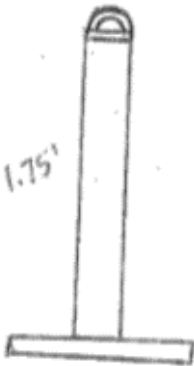
Design #3:
· carbon steel
· base plate
· bolted to roof
· cap plate

4"⌀
1.5'

Design #4:
· S.S. steel
· welded to roof
· No cap plate

1.75'
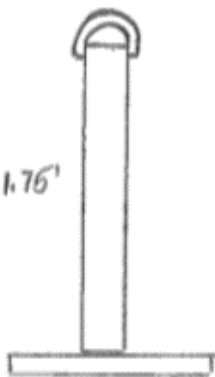
Design #5:
· Stainless steel
· base plate
· bolted to roof
· No cap plate

Design #2

3"∅ Sch 80
$d_o = 3.5"$
$d_i = 2.9"$

Pipe - Ultimate Strength

$P_{max} = 5^k$
$L = 1.5' + 0.25" = 1.52'$
$M_{max} = 5^k(1.52') = 7.6^{ik}$
$S_{pipe} = 0.098a \left(\frac{d_o^4 - d_i^4}{d_o} \right) = 2.28 \, in^3$
$A_{pipe} = \pi \left[\left(\frac{d_o}{2} \right)^2 - \left(\frac{d_i}{2} \right)^2 \right] = 3.0 \, in^2$

$\sigma = \frac{M}{S} = \frac{7.6^{ik}(12"/)}{2.28 \, in^3} = 40.9 \, KSI < 70 \, KSI$

$f_b = \frac{M}{S} + \frac{P}{A} = 40.9 \, KSI + \frac{5^k}{3.05 \, in^2} = 42.54 \, KSI < 70$

$c = 0.743 \quad \text{from Statics}$

$= \frac{\bar{y} \cdot A_1}{A_o - A_1} = \frac{0.743(3.5") - (0.6154)(2.9")}{3.5" - 2.9"} = 1.03 \, in$

$A_Q = \frac{Area}{2} = \frac{3.05}{2} = 1.508 \, in^2$
$Q = A\bar{c} = (1.508)(1.03) = 1.55 \, in^3$

$\tau = \frac{VQ}{Scb} = \frac{(5006 \, lb)(1.55 \, in^3)}{(2.28 \, in^4)(1.95 \, in)(1.2)} = 1654.9 \, psi = 1.65 \, KSI < (0.6)(70) = 42 \, KSI \checkmark$

Yield Strength

1800 lb

$P = 1800 \, lb = 1.8^k$
$M = 1800(1.52') = 2736^{ik}$
$\sigma = \frac{M}{S} = \frac{2736^{ik}(12")}{2.28 \, in^3} = 14.7$

$\tau = \frac{VQ}{Scb} = \frac{(1800 \, lb)(1.55 \, in^3)}{(2.28 \, in^4)(1.95 \, in)(1.2)} = 596 \, psi = 0.599 \, KSI < (0.6)30 = 18 \checkmark$

$f_b = \frac{M}{S} + \frac{P}{A} = 14.7 + \frac{1.8^k}{3.05 \, in^2} = 15.3 \, KSI < 30 \, KSI \checkmark$

Weld Calculations
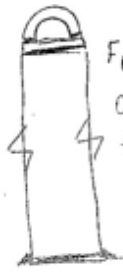
$F_{EXX} = 70 \, KSI$

$d_{bar} = 0.75"$

fillet $= 3/8"$

Pipe to WF

$d_{weld} = d_{bar} + fillet + \sqrt{2} = 4.03"$

$S_{weld} = \pi \left(\dfrac{d_{weld}^4 - d_{pipe}^4}{32 \cdot d_{weld}} \right) = 2.77 \, in^3$

$A_{weld} = \dfrac{\pi}{4} (d_{weld}^2 - d_{pipe}^2) = 3.15 \, in^2$

$D_{MAX} = 5^K \qquad M_{MAX} = 7.6^{1K}$

$f_{ultimate} = \left[\dfrac{M_{MAX}}{S_{weld}} + \dfrac{P_{MAX}}{A_{weld}} \right]$

$= 24,622 \quad 0.6(0.9)(70) = 37.8 \checkmark$

Cap Plate to Pipe

R $3.5 \emptyset \times 3/8"$

3" $\emptyset$ sch pipe — weld all around
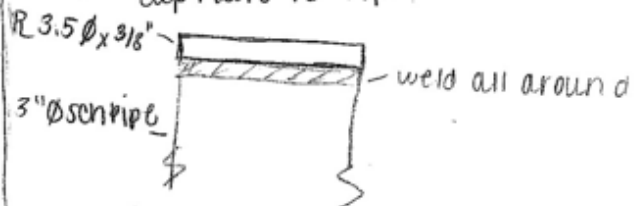
$d_{weld} = d_{bolt} + fillet + \sqrt{2} = 2.85"$

$S_{weld} = \pi \left(\dfrac{d_{weld}^4 - d_{pipe}^4}{32 \cdot d_{weld}} \right) = 1.795 \, in^3$

$A_{weld} = \dfrac{\pi}{4} (d_{weld}^2 - d_{pipe}^2) = 2.04 \, in^4$

$P = 5^K \qquad M_{MAX} = 0.26^{1K}$

$f_{weld\,ultimate} = \dfrac{0.26^{1K}}{1.795 \, in^3} + \dfrac{5^K}{2.04 \, in^4}$

$= 4.19 \, KSI < 37.8 \, KSI \checkmark$

$r = 1.75$ $\eta = 0.09$ $I = 0.6836 \, \text{in}^4$

$P = 2500 \, \text{lb}$

$M = Ph - Pr\sin\theta$

$m = -r\cos\theta$

$\theta_1 = 8.21° = 0.143 \text{ rads}$

$$\Delta_0 = \int_0^{\theta_1} \frac{(Ph - Pr\sin\theta)(-r\cos\theta)\, r\,d\theta}{EI}$$

$$\int \frac{Pr^3\sin\theta\cos\theta - Phr^2\cos\theta}{EI}\, d\theta$$

$$= \left. -\frac{Pr^3\sin^2\theta}{2EI} - \frac{Phr^2\sin\theta}{EI} \right|_0^{0.143}$$

$$= = \left. -\frac{Pr^2}{2EI}\left(r\sin^2\theta - 2h\sin\theta\right) \right|_0^{0.143}$$

$\Delta_0 = 0.0714 \times 10^{-4} \text{ inches}$

$$\delta = \int_0^{\pi/2} \frac{(-r\cos\theta)^2}{EI}\, r\,d\theta$$

$$= \int \frac{r^2\cos^2\theta \cdot r}{EI}\, d\theta$$

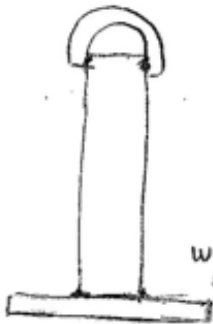$$= \frac{r^3}{EI}\int\cos^2\theta\, d\theta$$

$$= \left. \frac{r^3}{EI}\left(\frac{\theta + \sin\theta\cos\theta}{2}\right) \right|_0^{\pi/2}$$

$$= \left. \frac{r^3}{2EI}(\theta + \sin\theta\cos\theta) \right|_0^{\pi/2}$$

$\delta = 2.199 \times 10^{-7} \text{ inches}$

$$V = \frac{\Delta_0}{\delta} = \frac{0.0714 \times 10^{-4} \text{ inches}}{2.199 \times 10^{-7} \text{ inches}} = 82.47 \text{ pounds}$$

Cap plate

A992 steel

$F_y = 50$ KSI

$F_u = 65$ KSI

assume $= 3/8"$
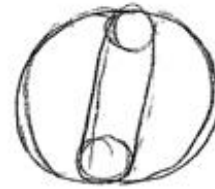
$\text{Area}_{cap} = \dfrac{\pi (3.5)^2}{4} = 9.62 \text{ in}^2$

$P_{Max} = 5^k$

$M_{Max} = 5^k (5/8" + 1/4") = 3.125^{"k}$

$S_{cap} = \dfrac{\pi R^3}{4} = \dfrac{\pi d^3}{32} = \dfrac{\pi (3.5")^3}{32} = 4.2 \text{ in}^3$

$f_b = \dfrac{M}{S} + \dfrac{P}{A} = \dfrac{3.125^{"k}}{4.2 \text{ in}^3} + \dfrac{5^k}{9.62 \text{ in}^2} = 1.264$ KSI < 65 KSI ✓

$\tau = \dfrac{VQ}{S_{cb}} = \dfrac{(5000 \text{ lb})(3.57 \text{ in}^3)}{(4.2 \text{ in}^3)(1.75 \text{ in})(1 \text{ in})} = 2.023$ KSI $< 70(0.6) = 42$ KSI ✓

$Q = A\bar{C} = \dfrac{9.62 \text{ in}^2}{2}(0.743 \text{ in}) = 3.57 \text{ in}^3$

$P_L = 3.5" \varnothing \times 3/8"$

Weld calculation

Bent bar to cap plate

$D_{bar} = 0.75"$

fillet $= 0.25"$

$d_{weld} = d_{bar} + \text{fillet}\sqrt{2} = 1.104 \text{ in}^3$

$S_{weld} = \pi \dfrac{d_{weld}^4 - d_{bar}^4}{32 \cdot d_{weld}} = 0.104 \text{ in}^3$

$A_{weld} = \pi \dfrac{d_{weld}^2 - d_{bar}^2}{4} = 0.515 \text{ in}^2$

$P = 5^k$

$M = 5^k (0.25") = 1.25^{"k}$

$f_{weld} = \dfrac{M}{S} + \dfrac{P}{A}$

$= \dfrac{1.25^{"k}}{0.104 \text{ in}^3} + \dfrac{5^k}{0.515 \text{ in}^2} = 21.73$ KSI < 70 KSI ✓

Design #3

$F_Y = 36 \, ksi$
$F_u = 60 \, ksi$

A36
3"Ø Sch80
pipe
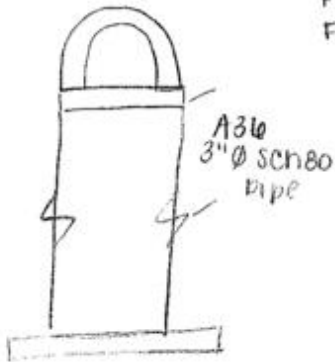
Pipe Ultimate strength
$P_{Max} = 5^K$
$M_{Max} = (1.75' + 0.25'')(5^K) = 8.85^{ik}$
$L = 1.75' + 0.25'' = 1.77'$

$S_{pipe} = 0.0982 \left(\dfrac{d_o^{u} \cdot d_i^{u}}{d_o} \right) = 2.23 \, in^3$

$A_{pipe} = \pi \left[\left(\dfrac{d_o}{2} \right)^2 - \left(\dfrac{d_i}{2} \right)^2 \right] = 3.016 \, in^2$

$\sigma = \dfrac{M}{S} = \dfrac{8.85^{ik}(12"/_1)}{2.23 \, in^3} = 47.64 \, ksi < 60 \, ksi$ ✓

$f_b = \dfrac{M}{S} + \dfrac{P}{A} = 47.64 + \dfrac{5^K}{3.016 \, in^2} = 49.26 \, ksi < 60 \, ksi$ ✓

$C_o = 0.743 \, from \, center$
$C_i = 0.0154$

$C = \dfrac{C_o \, A_o - C_i \, A_i}{A_o - A_i} = \dfrac{0.743(3.5)^2 - 0.0154(2.9)^2}{3.5^2 - 2.9^2} = 1.63 \, in$

$A_o = \dfrac{area}{2} = \dfrac{3.016}{2} = 1.508 \, in^2$

$Q = A\bar{c} = 1.508 \, in^2 (1.03 \, in) = 1.55 \, in^3$

$\tau = \dfrac{VQ}{Scb} = \dfrac{(5000 \, lb)(1.55 \, in^3)}{(2.23 \, in^3)(1.75 \, in)(1.2)} = 1654.9 \, psi = 1.655 \, ksi < 60(0.6) = 36 \, ksi$ ✓

Yield strength

M
1800 lb
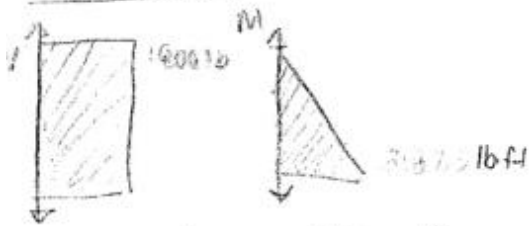
$P = 1800 \, lb = 1.8^K$
$M = 1800 \, lb (1.77') = 3187.5 \, lb \cdot ft = 3.188^{ik}$

$\sigma = \dfrac{M}{S} = \dfrac{3.188^{ik}(12"/_1)}{2.23 \, in^2} = 17.15 \, ksi < 36 \, ksi$

$\tau = \dfrac{VQ}{Scb} = \dfrac{(1800 \, lb)(1.55 \, in^3)}{(2.23 \, in^3)(1.75 \, in)(1.2)} = 595.77 \, psi = 0.596 \, ksi < 36(0.6) = 22 \, ksi$ ✓

$f_b = \dfrac{M}{S} + \dfrac{P}{A} = 17.15 \, ksi + \dfrac{1.8^K}{3.016 \, in^2} = 17.75 \, ksi < 36 \, ksi$ ✓

Cap plate

A992 steel

$F_y = 50$ KSI

$F_u = 65$ KSI

assume = 3/8"

$Area_{cap} = \dfrac{\pi(3.5)^2}{4} = 9.62 \, in^2$

$P_{max} = 5^k$

$M_{Max} = 5^k \left(\frac{5}{8}" + \frac{1}{4}"\right) = 8.125 \, "k$

$S_{cap} = \dfrac{\pi R^3}{4} = \dfrac{\pi \phi^3}{32} = \dfrac{\pi(3.5")^3}{32} = 4.21 \, in^3$

$f_b = \dfrac{M}{S} + \dfrac{P}{A} = \dfrac{3.125 \, "k}{4.21 \, in^3} + \dfrac{5^k}{9.62 \, in^2} = 1.264$ KSI < 65KSI ✓

$\tau = \dfrac{VQ}{Scb} = \dfrac{(5000 \, lb)(3.57 \, in^3)}{(4.21 \, in^3)(1.75 \, in)(1.21 \, in)} = 2.023$ KSI < 70 KSI $(0.6) = 42$ KSI ✓

$Q = AC = \dfrac{9.62 \, in^2}{2}(0.743 \, in) = 3.57 \, in^3$

$P_L = 3.5" \phi \times 3/8"$

Weld calculation

Bent Bar to Cap plate

$\phi_{Bar} = 0.75"$

$fillet = 0.25"$

$d_{weld} = d_{bar} + fillet\sqrt{2} = 1.104 \, in^3$

$S_{weld} = \pi \dfrac{d_{weld}^4 - d_{bar}^4}{32 \, d_{weld}} = 0.1041 \, in^3$

$A_{weld} = \pi \dfrac{d_{weld}^2 - d_{bar}^2}{4} = 0.515 \, in^2$

$P = 5^k$

$M = 5^k(0.25") = 1.25 \, "k$

$f_{weld} = \dfrac{M}{S} + \dfrac{P}{A}$

$= \dfrac{1.25 \, "k}{0.1041 \, in^3} + \dfrac{5^k}{0.515 \, in^2} = 21.73$ KSI < 70

$r = 1.75$ $n = 0.89$ $I = 0.6836 \text{ in}^4$
$P = 256 \text{ lb}$

$M = Ph - Pr\sin\theta$

$m = -r\cos\theta$

$\theta_1 = 8.21° = 0.143 \text{ rads}$

$$\Delta_o = \int_0^{\theta_1} \frac{(Ph - Pr\sin\theta)(-r\cos\theta)\, r\, d\theta}{EI}$$

$$\int \frac{Pr^3\sin\theta\cos\theta - Phr^2\cos\theta}{EI}\, d\theta$$

$$= \frac{-Pr^3\sin^2\theta}{2EI} - \frac{Phr^2\sin\theta}{EI}\ \Big|_0^{0.143}$$

$$= = \frac{-Pr^2}{2EI}\left(r\sin^2\theta - 2h\sin\theta\right)\ \Big|_0^{0.143}$$

$\Delta_o = 0.0714 \times 10^{-4} \text{ inches}$

$$\delta = \int_0^{\pi/2} \frac{(-r\cos\theta)^2}{EI}\, r\, d\theta$$

$$= \int \frac{r^2\cos^2\theta\ r}{EI}\, d\theta$$

$$= \frac{r^3}{EI}\int \cos^2\theta\, d\theta$$

$$= \frac{r^3}{EI}\left(\frac{\theta + \sin\theta\cos\theta}{2}\right)\ \Big|^{\pi/2}$$

$$= \frac{r^3}{2EI}\left(\theta + \sin\theta\cos\theta\right)\ \Big|_0^{\pi/2}$$

$\delta = 2.199 \times 10^{-7} \text{ inches}$

$$V = \frac{\Delta_o}{\delta} = \frac{0.0714 \times 10^{-4}\text{ inches}}{2.199 \times 10^{-7}\text{ inches}} = 82.47 \text{ pounds}$$

Weld calculations (design #5)

weld circumference
$= \pi(3.5\,in) = 11\,in$

$F_{EXX} = 70\ KSi$ (Table 9-1)
$d_{bar} = 0.75"$
$d_{fillet} = \cancel{0.25"}\ 7/10"$
$d_{pipe} = 3.5"$

Pipe to Base Plate

$F_u = 70\ KSi$

$d_{weld} = d_{pipe} + fillet\sqrt{2}$
$= 3.5 + (7/10)\sqrt{2} = 4.12"$

$S_{weld} = \pi\left(\dfrac{d_{weld}^4 - d_{pipe}^4}{32 \times d_{weld}}\right)$

$= \pi\left(\dfrac{4.12^2 - 3.5^2}{32(4.12)}\right) = 2.277\ in^3$

$A_{weld} = \dfrac{\pi(d_{weld}^2 - d_{pipe}^2)}{4}$

$= \dfrac{\pi}{4}(4.12^2 - 3.5^2) = 3.71\ in^2$

$P_{max} = 5^k$
$M_{max} = 8.85'^k$

$f_{weld\ ultimate} = \dfrac{(8.85'^k)(12"/')}{2.277\ in^3}\quad \dfrac{5^k}{3.71\ in^2}$

$= 33.72\ KSi < 0.6(0.9)(70) = 37.8\ KSi$ ✓

ID = 2.4"
OD = 3.5"
Fillet = 0.25"
$\emptyset = 0.75"$
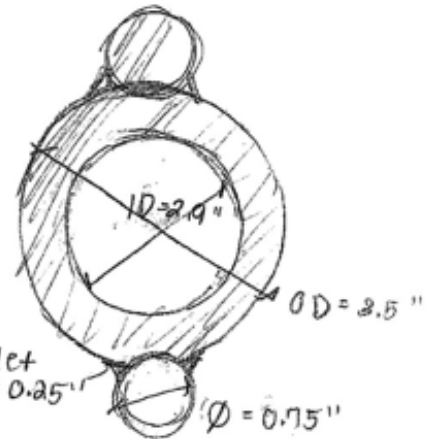
Thinner Thickness $= 0.75"$
Min Fillet $= 0.25"$
Max Fillet $= 0.75"\ 7/16" = 0.6875"$

Weld capacity

$t_e = 0.707a = 0.707(0.6875") = 0.486$

$R_n = 0.6 F_{xx}\, t_e = 0.6(70)(0.486) = 20.41\ K/in$

$\emptyset R_n = 0.75(20.412\ K/in) = 15.3\ K/in$

$L_w = \dfrac{5^k}{15.3\ K/in} = 0.327" < 4(1/4") = 1'$

$\therefore L_w = 1"$

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Base Plate

$m=1.5"$
$n=1.5"$
$\ell=1.5"$

$b=3"$

$12"$

$\delta = 6"$

$m=1.5"$

$P_L \ 12" \times 12 \times 1/4$

$t \geq \ell \sqrt{\dfrac{2 P_u}{0.9 F_y B N}}$

$t \geq 1.5" \sqrt{\dfrac{2(5 \cdot y)}{(0.9)(50 \ ksi)(12)(12)}}$
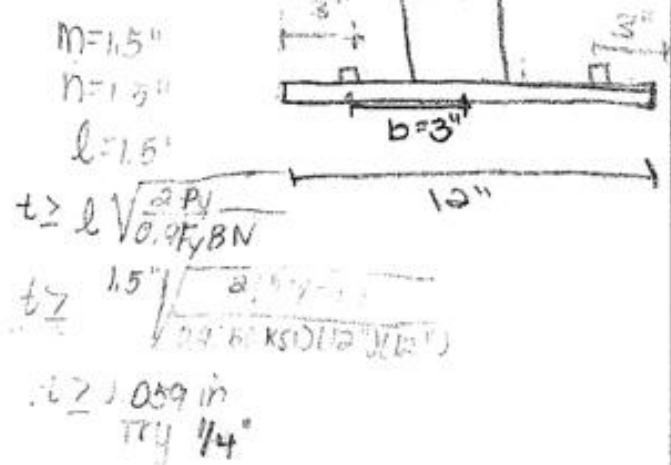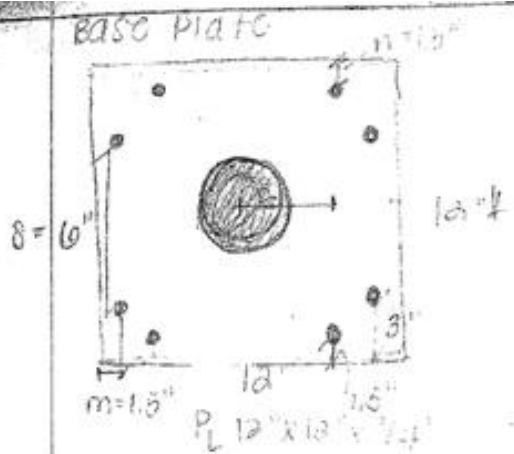
$t \geq 1.089 \ in$
Try $1/4"$

Prying action

$t_{min} = \sqrt{\dfrac{4 T \ell'}{\phi \rho F_u}} = \sqrt{\dfrac{4(0.625^k)(2.625")}{(0.9)(2.25")(50 \ ksi)}} = 0.254" \leq 7/16" ✓$

$T = \dfrac{5^k}{8 \ bolts} = 0.625^k$

$b' = \left(3" - \dfrac{0.75}{2}\right) = 2.625"$

$F < S = 10"$
$\quad < 8(b') = 2.625(.5) = 5.25'$

$T \leq (0.9)(4)(F_u \cdot 50)(t = 7/16")^2 (\rho = 2.25)$ over $2(b = .5")$

$T = 0.625^k \leq 3.22^k ✓$

$t_{min} = \sqrt{\dfrac{4(0.625) \quad b' = 2.625}{(\phi=0.9)(F_y=50 \ ksi)[1+(\delta=0.024)(1)]}} = 0.377 < 7/16" ✓$

$\delta = 1 - \dfrac{(d' = 3/16 + 1/16)}{\rho = 5.25"} = 0.024$

$B = \dfrac{1}{\rho}\left(\dfrac{\beta}{T} - 1\right) = \dfrac{1}{3.23}\left(\dfrac{17.89^k}{0.625^k} - 1\right) = 8.55 \geq 1 \quad \therefore \alpha' = 1$

$\rho = \dfrac{b'}{a'} = \dfrac{2.625"}{(3/4 + 1/16) + 0.75 = 0.8135} = 3.23$

$B = (54 \ ksi)(\phi = 0.75)(A_b' = \dfrac{\pi}{4}(0.75)^2) = 17.89^k$

$t_{min} = 0.377" < 7/16" ✓$

Prying action does not need to be considered

Base Plate

$$t \geq l \sqrt{\frac{2 P_u}{0.9 F_y BN}}$$

$$t \geq 4.25" \sqrt{\frac{2(5^K/FT)}{0.9(50 KSI)(12")(12}}$$

$t \geq 0.167"$

Try $t = 7/16"$

P_L 12" × 12" × 7/16"

Tension Yield

1. $T_u \leq (\phi = 0.9)(50 KSI)(12" × 7/16) = 236.25^K$

Tension Rupture

$A_e = (7/16)(12" - 4(3/4" + 1/8")) = 3.72 in^2$

$T_u \leq (\phi = 0.75)(F_u = 65 KSI)(A_e = 3.72 in^2) = 181.35^K$

Block Shear Rupture

$R_n = F_u A_{nt} + 0.6 F_u A_{nv} \leq F_u A_{nt} + 0.6 F_y A_{gv}$

$A_{nt} = [(12" - 5") - 8(\frac{1}{2})(3/4" + 1/8")] (7/16") = 1.53 in^2$

$F_u A_{nt} = (F_u = 65 KSI)(A_{nt} = 1.53 in^2) = 99.53^K$

$A_{nv} = 2[(12 - 1.5") - 7"(3/4" + 1/8")](t = 7/16") = 3.83 in^2$

$0.6 F_y A_{nv} = 0.6(50 KSI)(3.83 in^2) = 114.9^K$

$A_{gv} = 2(12 - 1.5")(t = 7/16") = 9.19 in^2$

$0.6 F_y A_{gv} = 0.6(50 KSI)(9.19 in^2) = 256^K$

$99.53^K + 114.9^K \leq 99.53^K + 256^K$

$\boxed{214.43^K} \leq 355.53^K$

A - 325 N Bolts

$\phi R_n = (\phi = 0.75)(F_n = 54 KSI)(A_b = \frac{\pi}{4}(.75)^2) = 17.89^K/Bolts$

8 Bolts = 4(17.89) = 143.14^K

Edge = $(\phi = 0.75)(1.2)(L_c = 1.5")(t = 7/16")(F_u = 65 KSI) = 38.4^K$

Upper Bound = $(\phi = 0.75)(2.4)(d_b = 0.75)(t = 7/16")(F_u = 65 KSI) = 38.44^K/Bolt$

Total Permissible Capacity = $(38.44")(8 bolts) = 307.1^K \geq .214.4^K$ ✓

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Appendix H: Hand Calculations of Design #4

Design # 4
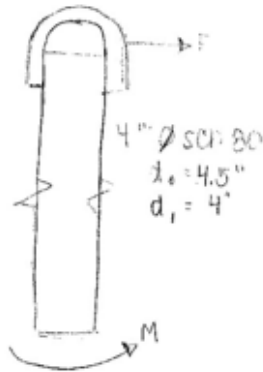
Pipe

$P_{max} = 5^k$

$M_{max} = (1.5' + 0.25")(5^k) = 7.6^{"k}$

$S_{pipe} = 0.0982 \left(\dfrac{d_o^4 - d_i^4}{d_o} \right) = 3.362 \text{ in}^3$

$A_{pipe} = \pi \left(\dfrac{4.5}{2} \right)^2 - \pi \left(\dfrac{4}{2} \right)^2 = 3.337 \text{ in}^2$

$f_b = \dfrac{M}{S} + \dfrac{P}{A} = \dfrac{7.6^{"k}(12"/)}{3.362 \text{ in}^3} + \dfrac{5^k}{3.337 \text{ in}^2} = 28.64 \text{ KSI} < 70 \text{ KS}$

$\sigma = \dfrac{M}{S} = \dfrac{7.6^{"k}(12"/)}{3.362} = 27.14 \text{ KSI} < 70 \text{ KS}$ ✓

$\tau = \dfrac{VQ}{Scb} = \dfrac{(5000 \text{ lb})(2.259 \text{ in}^3)}{(3.362 \text{ in}^3)(2.25 \text{ in})(2.25 \text{ in})} = 663.6 \text{ psi} = 0.66 \text{ KSI} < 0.6(70 \text{ KSI}) = 42 \text{ KSI}$

Yield strength of Pipe

$P = 1800 \text{ lb} = 1.8^k$

$M = (1800 \text{ lb})(1.95 + 0.25") = 2.736^{"k}$

$\sigma_{yield} = \dfrac{M}{S} = \dfrac{2.736^{"k}(12"/)}{3.362 \text{ in}^3} = 9.76 \text{ KSI} < 30 \text{ KSI}$ ✓

$V \uparrow \quad 1800 \text{ lb}$

M
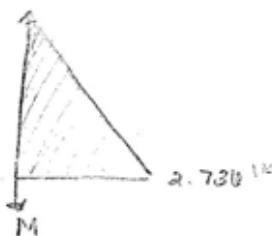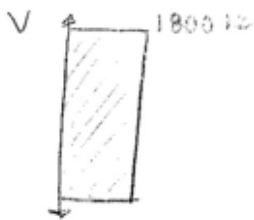
$2.736^{"k}$

$A = 3.337 \text{ in}^2, \ 1.669 \text{ in}^2$

$C_o = \dfrac{4r}{3\pi} = \dfrac{4(\frac{4.5}{2})}{3\pi} = 0.955 \text{ in}$

$C_i = \dfrac{4r}{3\pi} = \dfrac{4(\frac{4}{2})}{3\pi} = 0.849 \text{ in}$

$\bar{C} = \dfrac{C_o A_o - C_i A_i}{A_o - A_i} = \dfrac{\frac{2}{\pi} \left[(0.955)(4.5)^2 - 3.3 \cdots (4^2) \right]}{\frac{\pi}{4}(4.5^2 - 4^2)}$

$= 1.354 \text{ in}$

$Q = A\bar{C} = (1.669 \text{ in}^2)(1.354) = 2.259$

$\tau = \dfrac{VQ}{Scb} = \dfrac{(1800)(2.259 \text{ in}^3)}{(3.362 \text{ in}^3)(2.25)(2.25)} = 238.9 \text{ psi} = 0.239 \text{ KSI} < 0.6(30 \text{ KSI}) = 18 \text{ KSI}$ ✓

$f_b = \dfrac{M}{S} + \dfrac{P}{A} = \dfrac{2.736^{"k}(12"/)}{3.362 \text{ in}^3} + \dfrac{1.8^k}{3.337 \text{ in}^2} = 10.299 \text{ KSI} < 30 \text{ KSI}$ ✓

$P = 2500 \, lb$

$I = 4.24 in^4$

$h = 0.25"$

$r = 3"$

$M = Ph - Prsin\theta$

$m = -r\cos\theta$

$\theta_1 = 0.0834 \, rads = 4.78°$

$$\Delta_o = \int_o^{\theta_1} \frac{(Ph - Prsin\theta)(-rcos\theta)}{EI} \, rd\theta$$

$$\int \frac{Pr^3 sin\theta cos\theta - Phr^2 cos\theta}{EI} \, d\theta$$

$$= \left. -\frac{Pr^3 sin^2\theta}{2EI} - \frac{Phr^2 sin\theta}{EI} \right|_0^{0.0834}$$

$$= = \left. -\frac{Pr^2}{2EI}(rsin^2\theta - 2hsin\theta) \right|_0^{0.0834}$$

$\Delta_o = 1.97 \times 10^{-6} \, inches$

$$\delta = \int_o^{\pi/2} \frac{(-rcos\theta)^2}{EI} \, rd\theta$$

$$= \int \frac{r^2 cos^2\theta \, r}{EI} \, d\theta$$

$$= \frac{r^3}{EI} \int cos^2\theta \, d\theta$$

$$= \left. \frac{r^3}{EI} \left(\frac{\theta + sin\theta cos\theta}{2} \right) \right|_0^{\pi/2}$$

$$= \left. \frac{r^3}{2EI} (\theta + sin\theta cos\theta) \right|_0^{\pi/2}$$

$\delta = 3.57 \times 10^{-7} \, inches$

$$V = \frac{\Delta_o}{\delta} = \frac{1.97 \times 10^{-6} \, inches}{3.57 \times 10^{-7} \, inches} = 5.51 \, pounds$$

Weld calculations (Design #4)   - Ø=4.5in, No cap plate
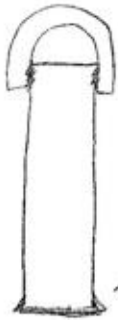
F_{exx} = 70 KSI (Table 9-1)
d_{bar} = 0.75"
d_{fillet} = 0.25"
d_{pipe} = 4.5"

weld cir
= π(4.5)
= 14.14in

Ø = 4.5"
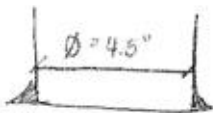
Pipe to WF or base plate
F_u = 70 KSI
d_{weld} = d_{pipe} + fillet·$\sqrt{2}$
= 4.5 + 0.25$\sqrt{2}$ = 4.85 in

S_{weld} = $\frac{\pi(d_{weld}^4 - d_{pipe}^4)}{32 \cdot d_{weld}}$

= $\frac{\pi(4.85^4 - 4.5^4)}{32(4.85)}$ = 2.8990 in³

A_{weld} = $\frac{\pi(d_{weld}^2 - d_{pipe}^2)}{4}$

= $\frac{\pi(4.85^2 - 4.5^2)}{4}$ = 2.57 in²

P_{max} = 1.8ᵏ
M_{max} = 1.8ᵏ(1.5' + 0.25") = 2.74 in·k

OD = 4.5"
ID = 4"
Fillet = 0.25"
Ø = 0.75"
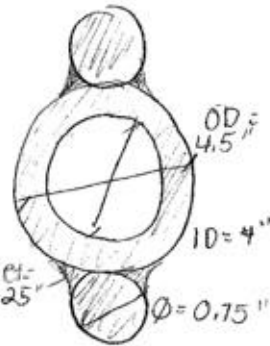
Thinner thickness = 0.75"
Min Fillet = 1/4"
Max Fillet = 0.75 - 1/16" = 0.6875"

Weld Capacity -
t_e = 0.707a = 0.707(0.6875") = 0.486"

R_n = 0.6$F_{xx}t_e$ = (0.6)(70KSI)(0.486) = 20.42 k/in
$ΦR_n$ = 0.75(20.42 k/in) = 15.3 k/in
weld strength

L_w = $\frac{5^k}{15.3 k/in}$ = 0.327" < 4(1/4") = 1"

weld length = 1"

$f_{weld\ ultimate}$ $\left(\frac{(7.01^k)(12")}{2.8990 in^3}\right)$ + $\left(\frac{5^k}{2.57 in^2}\right)$ =
= 33.44 KSI < 0.6(0.9)(70) = 37.8 KSI ✓

85

Design #5

Pipe - Ultimate strength

$P_{max} = (1.75' + 0.25'')(5'') = 8.85^{ik}$

M_{max}

$L = 1.75' + 0.25'' = 1.77'$

$S_{pipe} = 0.0982 \left(\dfrac{d_o^4 \cdot d_i^4}{d_o} \right) = 2.23 \, in^3$

$A_{pipe} = \pi \left[\left(\dfrac{d_o}{2} \right)^2 - \left(\dfrac{d_i}{2} \right)^2 \right] = 3.016 \, in^2$

$\sigma = \dfrac{M}{S} = \dfrac{8.85^{ik} (12/1)}{2.23 \, in^3} = 47644.84 \, psi = 47.64 \, KSI < 70 \, KSI \checkmark$

3" Ø SCH 80
$d_o = 3.5''$
$d_i = 2.9''$

$f_b = \dfrac{M}{S} + \dfrac{P}{A} = 47.64 \, KSI + \dfrac{5^{ik}}{3.016 \, in^2} = 49.28 \, KSI < 70 \, KSI \checkmark$

$\tau = \dfrac{VQ}{S c b} = \dfrac{(5000 \, lb)(1.55 \, in^3)}{(2.23 \, in^3)(1.75 \, in)(12)} = 1654.9 \, psi = 1.65 \, KSI < 70 \, KSI (0.6) = 42 \, KSI \checkmark$

Yield strength
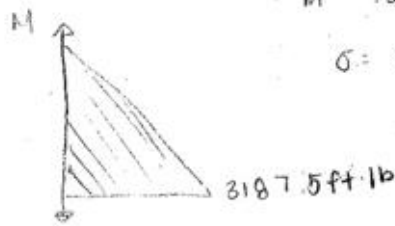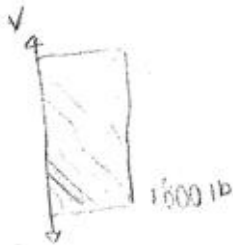
$P = 1800 \, lb = 1.8^k$

$M = 1800 \, lb (1.77') = 3187.5 \, ft \cdot lb = 3188^{ik}$

$\sigma = \dfrac{M}{S} = \dfrac{3187.5 \, ft \cdot lb (12/1)}{2.23 \, in^2} = 17152.47 \, psi = 17.15 \, KSI < 30 \, KSI \checkmark$

1800 lb

3187.5 ft·lb
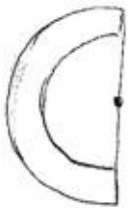
$C_o = 0.743 \, in$ from center
$C_1 = 0.6154$

$\bar{C} = \dfrac{C_o A_o - C_1 A_1}{A_o - A_1} = \dfrac{0.743 (3.5^2) - (0.6154)(2.9^2)}{3.5^2 - 2.9^2} = 1.03 \, in$

$A_\emptyset = \dfrac{Area}{2} = \dfrac{3.016}{2} = 1.508 \, in$

$Q = A\bar{C} = (1.508 \, in^2)(1.03 \, in) = 1.55 \, in^3$

$\tau = \dfrac{VQ}{S c b} = \dfrac{(1800 \, lb)(1.55 \, in^3)}{(2.23 \, in^3)(1.75 \, in)(1.2)} = 596 \, psi = 0.590 \, KSI < 30 \, KSI (0.6) = 18 \, KSI \checkmark$

$f_b = \dfrac{M}{S} + \dfrac{P}{A} = 17.15 \, KSI + \dfrac{1.8^k}{3.016 \, in^2} = 17.75 \, KSI < 30 \, KSI \checkmark$

$r = 2.5"$ $\eta = 0.89$

$P = 2500 \, lb$

$M = Ph - Pr\sin\theta$ $I = 2.3 \, in^4$

$m = -r\cos\theta$

$\theta_1 = 5.74° = 0.1002 \, rads$

$$\Delta_o = \int_0^{\theta_1} \frac{(Ph - Pr\sin\theta)(-r\cos\theta)\, r\,d\theta}{EI}$$

$$\int \frac{Pr^3\sin\theta\cos\theta - Phr^2\cos\theta}{EI}\, d\theta$$

$$= -\frac{Pr^3\sin^2\theta}{2EI} - \frac{Phr^2\sin\theta}{EI} \Big|_0^{0.1002}$$

$$= = -\frac{Pr^2}{2EI}\left(r\sin^2\theta - 2h\sin\theta\right)\Big|_0^{0.1002}$$

$\Delta_o = -3.033\times10^{-6} \text{ inches}$

$$\delta = \int_0^{\pi/2} \frac{(-r\cos\theta)^2}{EI}\, r\,d\theta$$

$$= \int \frac{r^2\cos^2\theta \cdot r}{EI}\, d\theta$$

$$= \frac{r^3}{EI}\int\cos^2\theta\, d\theta$$

$$= \frac{r^3}{EI}\left(\frac{\theta + \sin\theta\cos\theta}{2}\right)\Big|_0^{\pi/2}$$

$$= \frac{r^3}{2EI}(\theta + \sin\theta\cos\theta)\Big|_0^{\pi/2}$$

$\delta = 1.91\times10^{-7} \text{ inches}$

$$V = -\frac{\Delta_o}{\delta} = -\frac{(-3.033\times10^{-6}) \text{ inches}}{1.91\times10^{-7} \text{ inches}} = 15.88$$

weld calculations (Design #5)

weld circumference
$= \pi(3.5\text{ in}) = 11\text{ in}$

$F_{Exx} = 70$ KSI (Table 9-1)
$d_{bolt} = 0.75"$
$d_{fillet} = 0.25\ 7/10"$
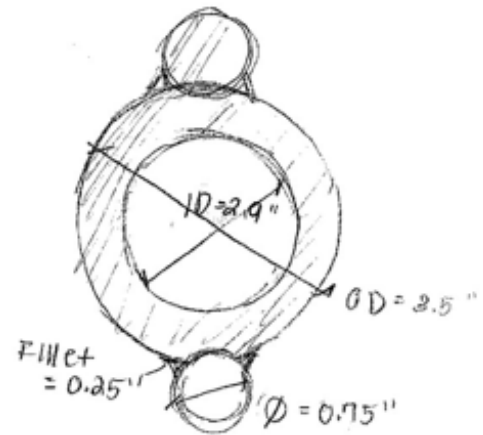$d_{pipe} = 3.5"$

Pipe to Base Plate

$F_u = 70$ KSI

$d_{weld} = d_{pipe} + fillet\sqrt{2}$
$= 3.5 + (7/10)\sqrt{2} = 4.12"$

$S_{weld} = \pi\left(\dfrac{d_{weld}^4 - d_{pipe}^4}{32 \times d_{weld}}\right)$
$= \pi\left(\dfrac{4.12^2 - 3.5^2}{32(4.12)}\right) = 2.277"^3$

$A_{weld} = \dfrac{\pi(d_{weld}^2 - d_{pipe}^2)}{4}$
$= \dfrac{\pi}{4}(4.12^2 - 3.5^2) = 3.71\text{ in}^2$

$P_{max} = 5^k$
$M_{max} = 8.85^{1k}$

Thinner Thickness $= 0.75"$
Min Fillet $= 0.25"$
Max Fillet $= 0.75" - 1/16" = 0.6875"$

weld capacity
$t_e = 0.707a = 0.707(0.6875") = 0.486"$
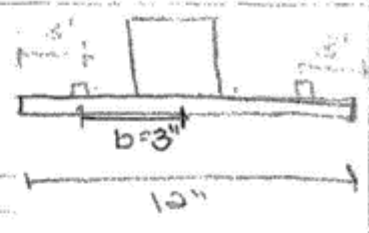$R_n = 0.6 F_{xx} t_e = 0.6(70)(0.486) = 20.412\ ^{k/in}$
$\phi R_n = 0.75(20.412\ ^{k/in}) = 15.3\ ^{k/in}$
$L_w = \dfrac{5^k}{15.3\ ^{k/in}} = 0.327" < 4(1/4") = 1"$
$\therefore L_w = 1"$

$f_{weld\ ultimate} = \dfrac{(8.85\cdot 12")}{2.277\text{ in}^3} - \dfrac{5^k}{3.71\text{ in}^2}$
$= 33.78\text{ KSI} < 0.6(0.9)(70) = 37.8\text{ KSI}$ ✓

Base Plate

$m = 1.5"$
$n = ?$
$\ell = 15$

$b = 3"$

$t \geq \ell \sqrt{\dfrac{2 P_u}{0.9 F_y B N}}$

$8 = 6"$

$12"$

$15" \sqrt{\dfrac{2}{50 \text{ ksi} \cdot 8}}$

$\geq 0.09 \text{ in}$

try $1/4"$

$m = 1.5"$

Prying action

$t_{min} = \sqrt{\dfrac{4 T b'}{\phi p F_u}} = \sqrt{\dfrac{4(3.66^k)(2.625")}{(0.9)(2.25)(50 \text{ ksi})}} \quad 0.854" \leq 7/16"$ ✓

$T = \dfrac{5^k}{8 \text{ bolts}} = 0.625^k$

$b' = (3" - 3.25") = 2.625"$

$p < s = 10'$
$< 2(b') = 5.26" = 5.25'$

$T \leq (0.9 \quad \quad (t = 7/16")^2 \quad \phi$
$a = b = 5")$

$T = 0.625^k \leq 3.22^k$ ✓

$t_{min} = \sqrt{\dfrac{\quad \quad 2.625}{\quad 1 + (5 + 2.024) \quad}} = 0.377 < 7/16"$ ✓

$\delta = 1 - \dfrac{d'}{p} = \dfrac{13/16}{5.25} = 0.024$

$p = 5.25"$

$\beta = \dfrac{1}{\rho} \left(\dfrac{T}{t} \right) = \dfrac{1}{3.23} \left(\dfrac{17.89^k}{0.625} - 1 \right) = 8.55 \geq 1 \quad \& \quad \alpha' = 1$

$\rho = \dfrac{2.625"}{(3/4 + 7/16) + 0.75} = 3.23$

$\beta = (54 \text{ ksi})(\phi = 0.75)(A_b = \dfrac{\pi}{4}(0.75")^2) = 17.89^k$

$\delta_{min} = 0.377" < 7/16"$ ✓

Prying action does not need to be considered

Base Plate

$$t \geq \ell \sqrt{\frac{2 P_u}{0.9 F_y BN}}$$

$$t \geq 4.25'' \sqrt{\frac{2(5^K/FT)}{0.9(50KSi)(12'')(12}}$$

$$t \geq 0.167''$$

Try $t = 7/16''$

PL $12'' \times 12'' \times 7/16''$

Tension Yield

1. $T_u \leq (\phi = 0.9)(50 KSi)(12'' \times 7/16'') = 236.25^K$

Tension Rupture

$A_e = (7/16)(12'' - 4(3/4'' + 1/8'')) = 3.72 in^2$

$T_u \leq (\phi = 0.75)(F_u = 65 KSi)(A_e = 3.72 in^2) = 181.35^K$

Block Shear Rupture

$R_n = F_u A_{nt} + 0.6 F_u A_{nv} \leq F_u A_{nt} + 0.6 F_y A_{gv}$

$A_{nt} = \left[(12'' - 5'') - 8(\frac{1}{2})(3/4'' + 1/8'')\right](7/16'') = 1.53 in^2$

$F_u A_{nt} = (F_u = 65 KSi)(A_{nt} = 1.53 in^2) = 99.53^K$

$A_{nv} = 2\left[(12 - 1.5'') - 7''(3/4'' + 1/8'')\right](t = 7/16'') = 3.83 in^2$

$0.6 F_y A_{nv} = 0.6(50 KSi)(3.83 in^2) = 114.9^K$

$A_{gv} = 2(12 - 1.5'')(t = 7/16'') = 9.19 in^2$

$0.6 F_y A_{gv} = 0.6(50 KSi)(9.19 in^2) = 256^K$

$99.53^K + 114.9^K \leq 99.53^K + 256^K$

$\boxed{214.433^K} \leq 355.53^K$

A - 325 N Bolts

$\phi R_n = (\phi = 0.75)(F_n = 54 KSi)(A_b = \frac{\pi}{4}(.75)^2) = 17.89^K/Bolts$

8 Bolts $= 4(17.89) = 143.14^K$

Edge $= (\phi = 0.75)(1.2)(L_c = 1.5'')(t = 7/16'')(F_u = 65 KSi) = 38.4^K$

Upper Bound $= (\phi = 0.75)(2.4)(d_b = 0.75)(t = 7/16'')(F_u = 65 KSi) = 38.44^K/Bolt$

Total Permissible Capacity $= (38.44'')(8 bolts) = 307.1^K \geq .214.4^K$ ✓

Appendix J: Stress Values in Bent Bar for Design #2

| Theta (degrees)	Axial Stress (psi)	Negative Bending Stress (psi)	Positive Bending Stress (psi)	Axial + Negative Bending (psi)	Axial + Positive Bending (psi)	Shear Stress (psi)
0	0.00	0.00	0.00	0.00	0.00	0.21
10	12.75	-355.95	546.42	-343.20	559.17	0.20
20	25.11	-701.08	1076.24	-675.97	1101.35	0.19
30	36.71	-1024.91	1573.36	-988.21	1610.06	0.18
40	47.19	-1317.60	2022.67	-1270.41	2069.86	0.16
50	56.24	-1570.26	2410.52	-1514.02	2466.76	0.13
60	63.58	-1775.20	2725.13	-1711.62	2788.71	0.10
70	68.99	-1926.21	2956.94	-1857.22	3025.93	0.07
80	72.30	-2018.68	3098.91	-1946.39	3171.21	0.04
85	250.49	-17530.74	26911.65	-17280.25	27162.13	5.73
90	73.41	0.00	0.00	73.41	73.41	5.73

Appendix K: Stress Values in Bent Bar for Design #3

| Theta (degrees)	Axial Stress (psi)	Negative Bending Stress (psi)	Positive Bending Stress (psi)	Axial + Negative Bending (psi)	Axial + Positive Bending (psi)	Shear Stress (psi)
0	0.00	0.00	0.00	0.00	0.00	0.08
10	12.75	-355.95	546.42	-343.20	559.17	0.07
20	25.11	-701.08	1076.24	-675.97	1101.35	0.07
30	36.71	-1024.91	1573.36	-988.21	1610.06	0.07
40	47.19	-1317.60	2022.67	-1270.41	2069.86	0.06
50	56.24	-1570.26	2410.52	-1514.02	2466.76	0.05
60	63.58	-1775.20	2725.13	-1711.62	2788.71	0.04
70	68.99	-1926.21	2956.94	-1857.22	3025.93	0.03
80	72.30	-2018.68	3098.91	-1946.39	3171.21	0.01
85	250.49	-17530.74	26911.65	-17280.25	27162.13	2.10
90	73.41	0.00	0.00	73.41	73.41	2.10

Appendix L: Stress Values in Bent Bar for Design #4

Theta (degrees)	Axial Stress (psi)	Negative Bending Stress (psi)	Positive Bending Stress (psi)	Axial + Negative Bending (psi)	Axial + Positive Bending (psi)	Shear Stress (psi)
0	0.00	0.00	0.00	0.00	0.00	0.00
10	2.16	-70.77	93.68	-68.60	95.84	0.00
20	4.26	-139.39	184.51	-135.13	188.77	0.00
30	6.23	-203.77	269.74	-197.54	275.97	0.00
40	8.01	-261.96	346.77	-253.95	354.78	0.00
50	9.54	-312.19	413.27	-302.65	422.81	0.00
60	10.79	-352.94	467.21	-342.15	477.99	0.00
70	11.71	-382.96	506.95	-371.25	518.65	0.00
80	12.27	-401.35	531.29	-389.08	543.56	0.00
85	189.76	-20539.09	27188.90	-20349.32	27378.66	0.36
90	12.46	0.00	0.00	12.46	12.46	0.36

Appendix M: Stress Values in Bent Bar for Design #5

| Theta (degrees)	Axial Stress (psi)	Negative Bending Stress (psi)	Positive Bending Stress (psi)	Axial + Negative Bending (psi)	Axial + Positive Bending (psi)	Shear Stress (psi)
0	0.00	0.00	0.00	0.00	0.00	0.01
10	6.23	-169.96	224.99	-163.73	231.23	0.01
20	12.28	-334.76	443.15	-322.48	455.43	0.01
30	17.95	-489.39	647.84	-471.44	665.79	0.01
40	23.08	-629.15	832.84	-606.07	855.92	0.00
50	27.50	-749.79	992.54	-722.28	1020.05	0.00
60	31.09	-847.65	1122.09	-816.55	1153.18	0.00
70	33.74	-919.75	1217.53	-886.01	1251.27	0.00
80	35.36	-963.91	1275.99	-928.55	1311.35	0.00
85	213.12	-18280.00	24198.41	-18066.89	24411.53	0.36
90	35.90	0.00	0.00	35.90	35.90	0.36

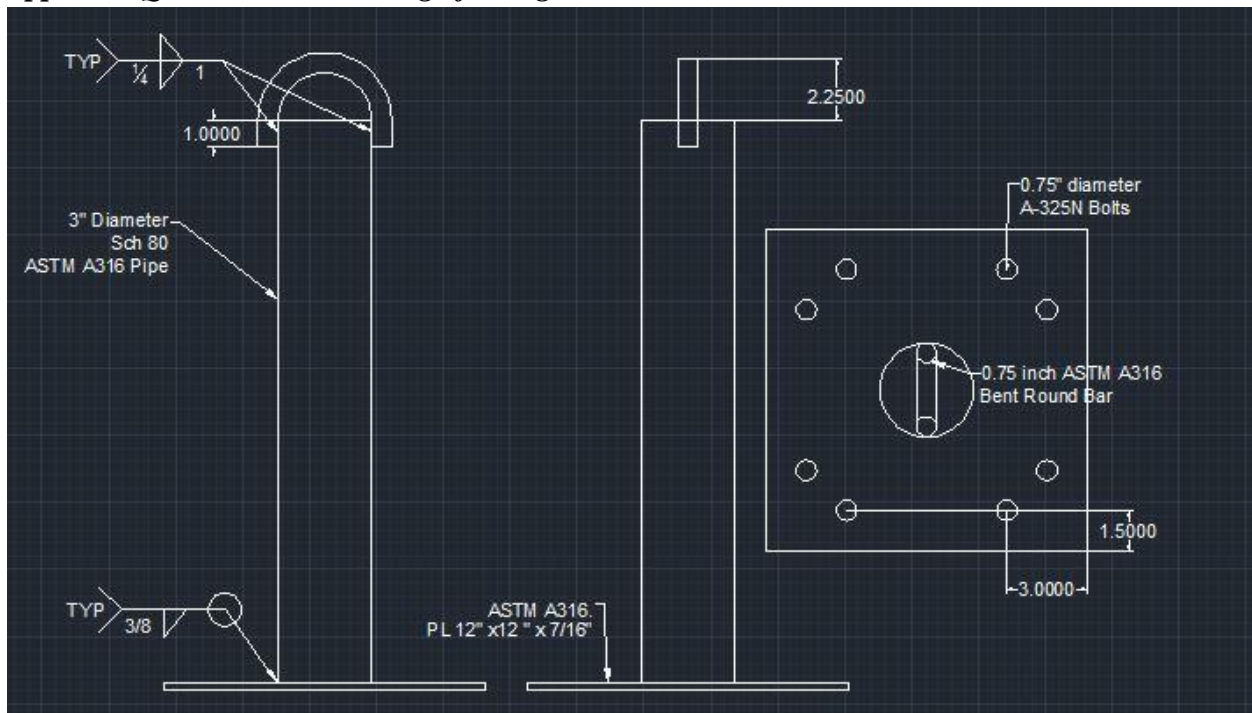*Appendix N: AutoCAD Drawing of Design #2*
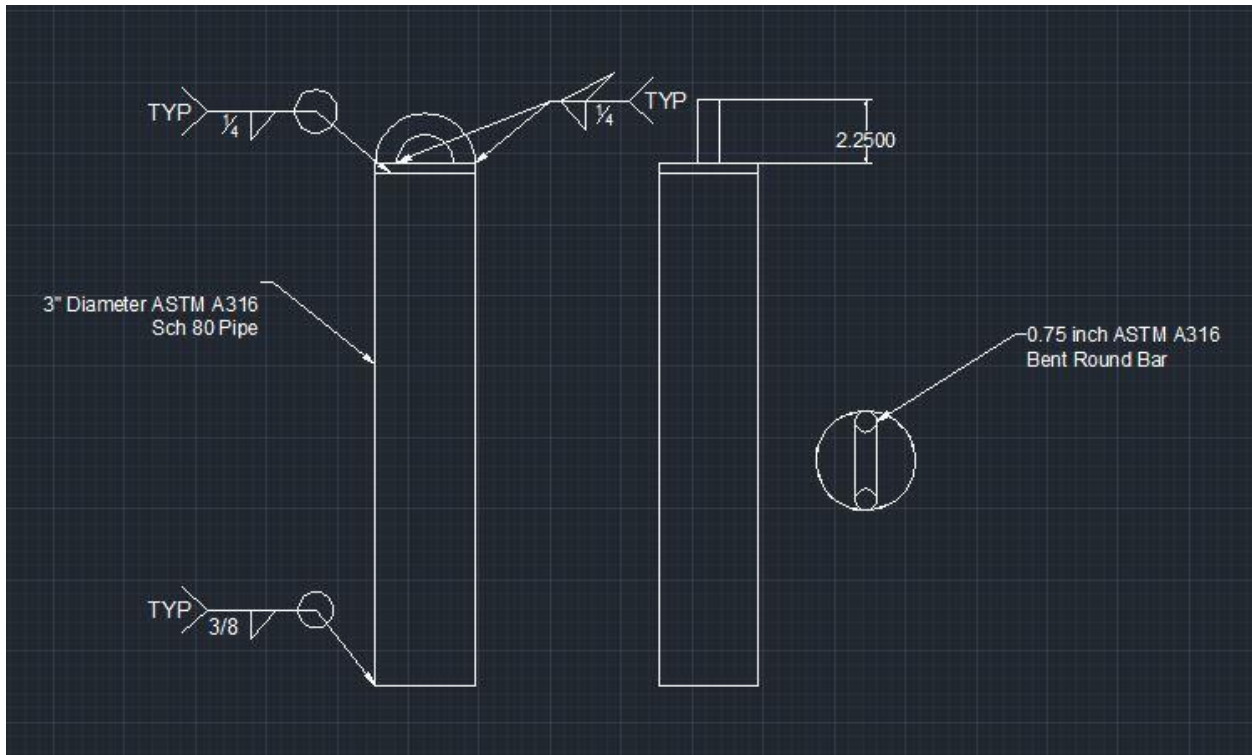
Appendix O: AutoCAD Drawing of Design #3
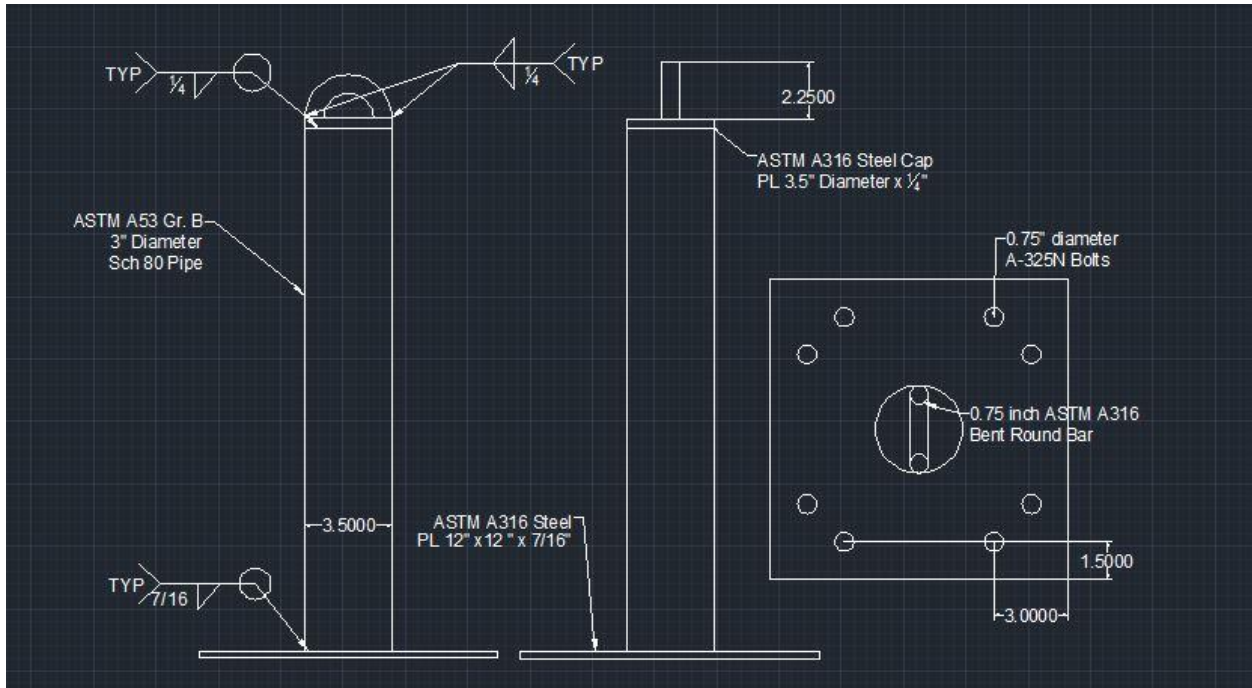
Appendix P: AutoCAD Drawing of Design #4
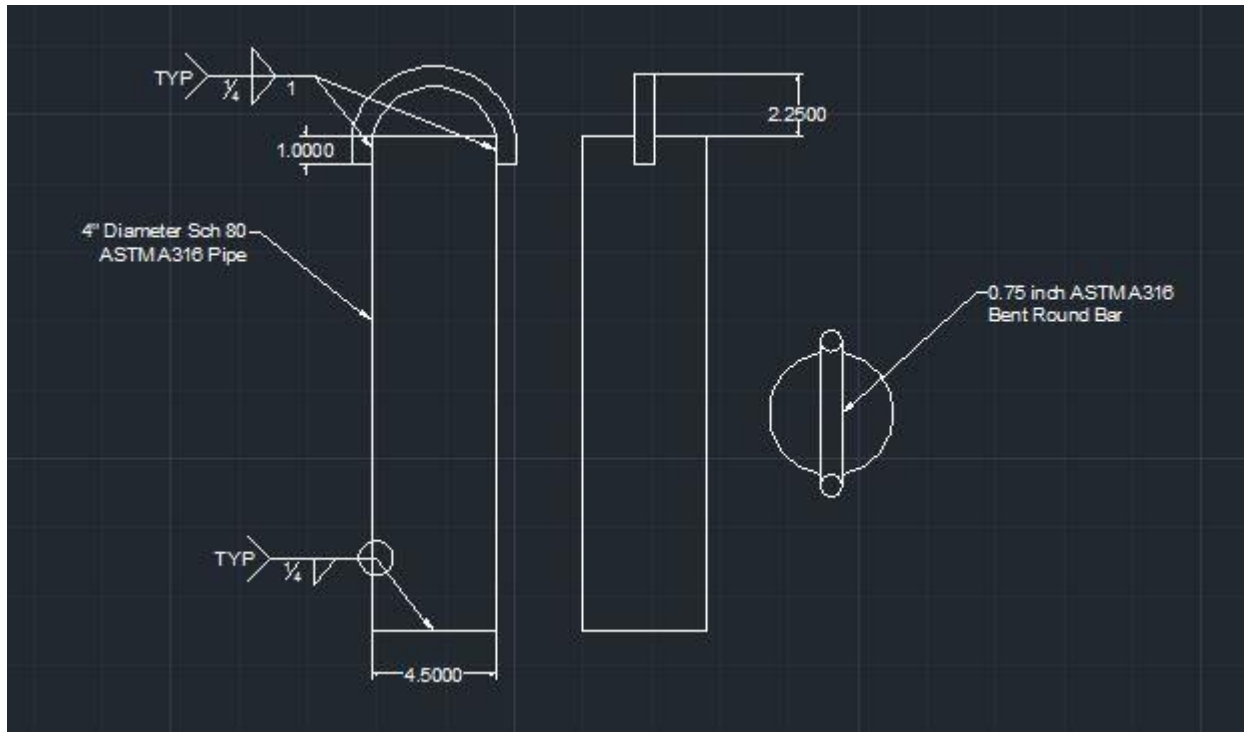
Appendix Q: AutoCAD Drawing of Design #5

Appendix R: Atlantic Stainless Steel Estimate

Atlantic Stainless Co., Inc.
140 John Dietsch Sq
North Attleboro, MA 02763
Phone: (800) 876-2700 Fax: (508) 699-8311
Website: www.atlanticstainless.com

July 16, 2015
3:17:28PM
Page 1 of 2

Quotation No. 44992

Bill To	M I W Corporation (Malatos Iron)	Ship To	M I W Corporation (Malatos Iron)
	1205 Bay Street		1205 Bay Street
	Fall River, MA 02724		Fall River, MA 02724
			Phone: 617-438-5350
		ATTN:	Kevin White

Customer P.O. #:
Contract:
Sales 1: Phil Roundtree
Terms: CIA

Quote Date: 07/16/2015
F.O.B.: Pick up/Will Call
Sales 2: Warren Fischer

Due Date: 07/16/2015
Ship Via: Will Call

Pcs	Description	Width	Length	Weight	Price	UM	Extension	Tax
1	3 SCH 80S (.300) STAINLESS STEEL PIPE-WELDED 316L Polished #4		240"	205	$52.30	F	$1,046.00	T
1	4 SCH 80S (.337) STAINLESS STEEL PIPE-WELDED 316L Polished #4 180 grit 1 week		240"	300	$69.50	F	$1,390.00	T
1	3/4 STAINLESS STEEL ROUND BAR 316/L not polished		144"	16	$2.67	P	$48.06	T
1	1/4 STAINLESS STEEL PLATE 316/L HiDef Plasma Cut Disc 3-1/2" Od Mill Finish			2	$5.25	E	$5.25	T
1	1/2 STAINLESS STEEL PLATE 316/L HiDef Plasma Cut 12" x 12" Mill Finish			25	$72.00	E	$72.00	T

	Total Weight			550		
		Subtotal Non taxable				$0.00
		Subtotal taxable				$2,561.31
		Massachusetts: 6.25%				$160.09
		Total				$2,721.40

Appendix S: AutoCAD Drawings of Recommended Design
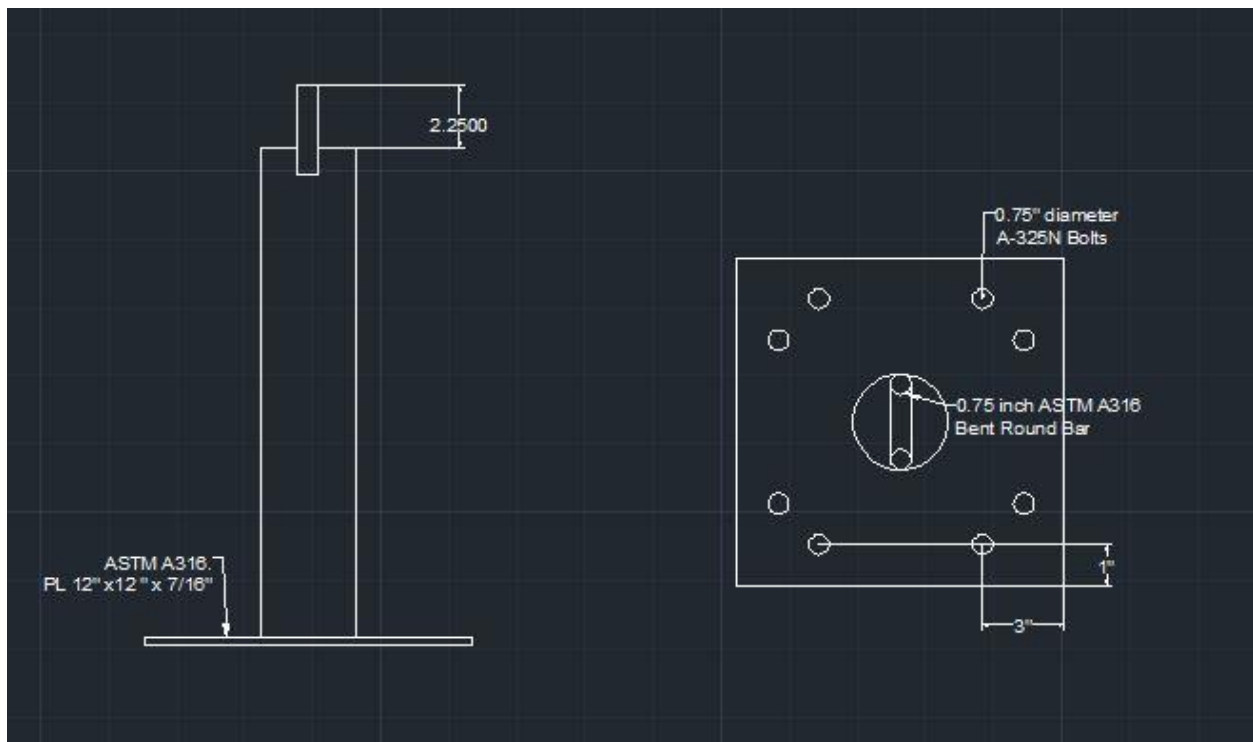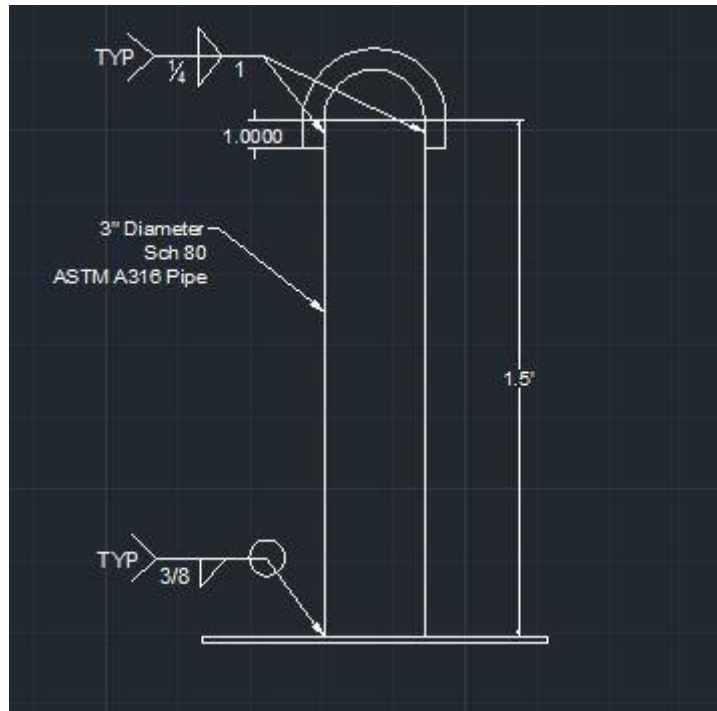
Appendix T: Hand Calculations of Recommended Design

Final Design
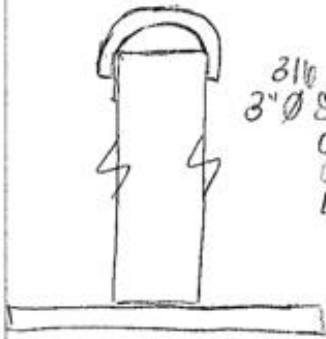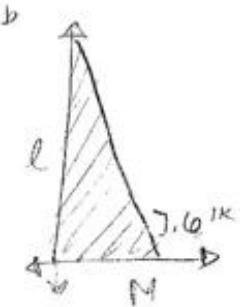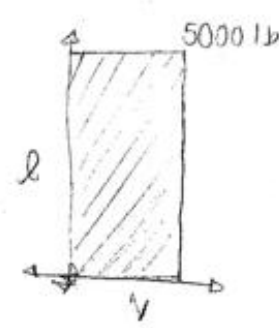
Pipe Ultimate Strength

$P_{max} = 5^k$

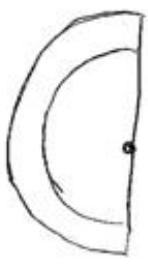$L = 1.5' + 0.25'' = 1.52'$

$M_{Max} = 5^k(1.52') = 7.6^{1k}$

$S_{pipe} = 0.0982\left(\dfrac{d_o^4 - d_i^4}{d_o}\right) = 2.23\ in^3$

$A_{pipe} = \dfrac{\pi}{4}(d_o^2 - d_i^2) = 3.016\ in^2$

$\sigma = \dfrac{M_{Max}}{S_{pipe}} = \dfrac{7.6^{1k}(12'')}{2.23\ in^2} = 40.89\ KSI < 75\ KSI \checkmark$

$\dfrac{P}{A} = \dfrac{5^k}{3.016\ in^2} = 1.66\ KSI < 75\ KSI \checkmark$

$f_b = \dfrac{M}{S} + \dfrac{P}{A} = 40.89 + 1.66 = 42.55\ KSI < 75\ KSI \checkmark$

$C_o = 0.743\ in\ from\ center$

$C_i = 0.6154\ in$

$\bar{C} = \dfrac{C_o A_o - C_i A_i}{A_o - A_i} = \dfrac{0.743(3.5^2) - 0.6154(2.9)^2}{3.5^2 - 2.9^2} = 1.03\ in$

$A_Q = \dfrac{Area}{2} = \dfrac{3.016}{2} = 1.508\ in^2$

$Q = A\bar{C} = (1.508\ in^2)(1.03\ in) 1.55\ in^3$

$\tau = \dfrac{VQ}{SCb} = \dfrac{(5000\ lb)(1.55\ in^3)}{(2.23\ in^3)(1.751\ in)(1.2)}$

$= 1654.9\ psi = 1.65\ KSI < 0.6(75\ KSI) = 45\ KSI \checkmark$

Yield Strength - Pipe
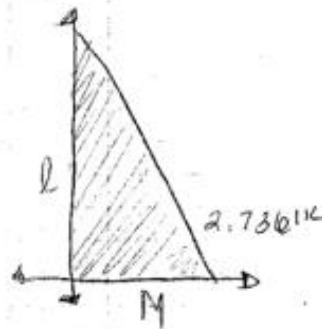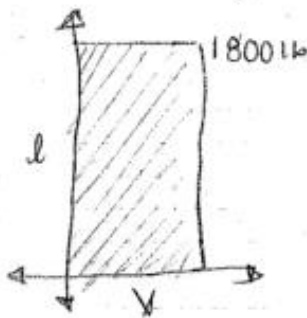
$P = 1800\ lb$

$M = 1800\ lb\,(1.52') = 2.736^{1K}$

$\sigma = \dfrac{M}{S} = \dfrac{2.736^{1K}(12"/_1)}{2.23\,in^3} = 14.72\ KSI < 30\ KSI$ ✓

$\dfrac{P}{A} = \dfrac{1.8^K}{3.016^K} = 0.597\ KSI < 30\ KSI$ ✓

$f_b = \dfrac{M}{S} + \dfrac{P}{A} = 14.72 + 0.597 = 15.32\ KSI < 30\ KSI$

$T = \dfrac{VQ}{SCb} = \dfrac{(1800\,lb)(1.55\,in^3)}{(2.23\,in^3)(1.75\,in)(1.2)} = 596\ psi = 0.596\ KSI < 0.6\,(30\,KSI) = 18\ KSI$ ✓

Bent Bar Hand Calculations

$r = 2.5''$

$M = Ph - Pr\sin\theta$

$m = -r\cos\theta$

$I = 2.3 in^4$

$h = 0.25 in$

$P = 2500 lb$

$\theta = 5.74° = 0.1002 \text{ rads}$

$$\Delta_o = \int_0^\theta \frac{(Ph - Pr\sin\theta)(-r\cos\theta) \, r d\theta}{EI}$$

$$\int \frac{Pr^2\sin\theta\cos\theta - Phr\cos\theta}{EI} \, d\theta$$

$$= -\frac{Pr^3\sin^2\theta}{2EI} - \frac{Phr^2\sin\theta}{EI} \Big|_0^{0.1002}$$

$$= = -\frac{Pr^2}{2EI}\left(r\sin^2\theta - 2h\sin\theta\right) \Big|_0^{0.1002}$$

$$\Delta_o = -3.083 \times 10^{-6} \text{ inches}$$

$$\delta = \int_0^{\pi/2} \frac{(-r\cos\theta)^2 \, r d\theta}{EI}$$

$$= \int \frac{r^2\cos^2\theta \, r}{EI} \, d\theta$$
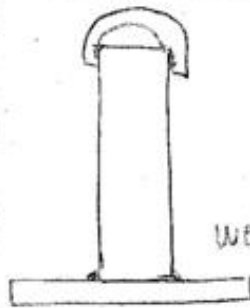
$$= \frac{r^3}{EI} \int \cos^2\theta \, d\theta$$

$$= \frac{r^3}{EI}\left(\frac{\theta + \sin\theta\cos\theta}{2}\right) \Big|_0^{\pi/2}$$

$$= \frac{r^3}{2EI}(\theta + \sin\theta\cos\theta) \Big|_0^{\pi/2}$$

$$\delta = 1.91 \times 10^{-7} \text{ inches}$$

$$V = -\frac{\Delta_o}{\delta} = \frac{-(-3.083 \times 10^{-6}) \text{ inches}}{1.91 \times 10^{-7} \text{ inches}} = 15.88 \text{ pounds}$$

Weld Calculations

$F_{EXX} = 70$ KSI (Table 9-1)
$d_{bar} = 0.75"$
$d_{fillet} = 3/8"$
$d_{pipe} = 3.5"$

weld circumference
$= 3.5$ in $(\pi) = 11$ in

Pipe to Base Plate

$d_{weld} = d_{bar} + fillet \sqrt{2}$
$= 3.5" + 3/8" \sqrt{2} = 4.03"$

$S_{weld} = \dfrac{\pi}{32} \times \dfrac{d_{weld}^4 - d_{pipe}^4}{d_{weld}} = 2.77 in^3$

$A_{weld} = \dfrac{\pi}{4} (d_{weld}^2 - d_{pipe}^2) = 3.131 in^2$

$P_{max} = 5^k$

$M_{max} = 7.6^{ik}$

$f_{weld} = \dfrac{7.6^{ik}(12"/_1)}{2.77 in^3} + \dfrac{5^k}{3.131 in^2} =$

$= 34.52$ KSI $< 0.6 (\phi = 0.9)(70$ KSI$) = 37.8$ KSI ✓
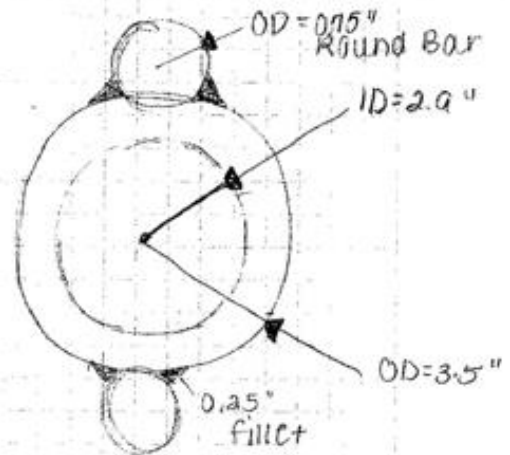
Round Bar to Pipe

OD = 0.75" Round Bar
ID = 2.0"
OD = 3.5"
0.25" fillet

Thinner Thickness = 0.75"
Min Fillet = 0.25"
Max Fillet = 0.75" − 1/16" = 0.6875"

weld capacity
$t_e = 0.707a = 0.707(0.6875")$
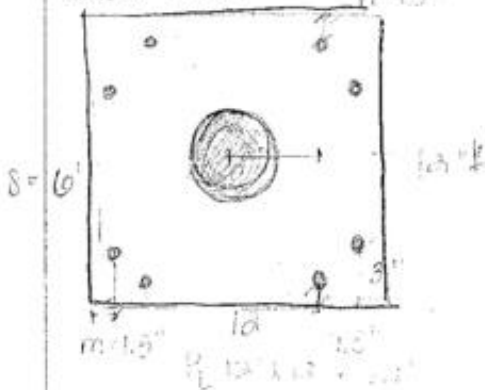$= 0.486"$

$R_n = 0.6 F_{xx} t_e = 0.6(70)(0.486)$
$= 20.412$ k/in

$\phi R_n = 0.75(20.412$ k/in$) = 15.3$ k/in

$L_w = \dfrac{5^k}{15.3 k/in} = 0.327" < 4(1/4") = 1"$

$\therefore \underline{L_w = 1"}$

Baseplate

$m = 1.5"$
$n = 1.5"$
$\ell = 1.5$

$b = 3"$

$12"$

$s = 6'$

$m = 1.5"$

$t \geq \ell \sqrt{\dfrac{2P_l}{0.9 F_y BN}}$

$t \geq 1.5 \sqrt{\dfrac{2(5^k/_{FT})}{0.9(50\,KSI)(12")(12")}}$

$t \geq 0.059"$

Try $7/16"$

Prying action

$t_{min} = \sqrt{\dfrac{4Tb'}{\phi_l F_y}} = \sqrt{\dfrac{4(0.625^k)(2.625")}{(0.9)(2.25")(50\,KSI)}} = 0.254" \leq 7/16" \checkmark$
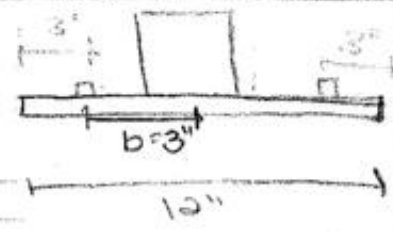
$T = \dfrac{5^k}{8\ bolts} = 0.625^k$

$b' = (3" - 2.??) = 2.625'$

$p < s = 10'$
$< 2(b) = 2(2.625) = 5.25'$

$T \leq \dfrac{(0.9 = \phi\ (F_y = 50\,KSI\ (t = 7/16")^2\ (p = 5.25")}{2\cdot b' = 6"}$

$T: 0.625^k \leq 3.22^k \checkmark$

$t_{min} = \sqrt{\dfrac{p' \cdot 2.625}{[1+(\delta - 0.024)\ ]}} = 0.377 < 7/16" \checkmark$

$1 - \left(\dfrac{d' = 3/4 + 1/8}{p = 5.25}\right) = 0.024$

$B\ \dfrac{1}{p}\left(\dfrac{2}{?} - 1\right) = \dfrac{1}{3.23}\left(\dfrac{17.89^k}{0.625^k} - 1\right) = 8.55 \geq 1\ \therefore\ \alpha' = 1$

$\dfrac{2.625"}{(3/4 + 1/16)} + 0.75 = ?$ 3.23

$B = (54\,KSI)(\phi = 0.75)(A_b = \tfrac{\pi}{4}(0.??)^2) = 17.89^k$

$t_{min} = 0.377" < 7/16" \checkmark$

Prying action does not need to be considered

Bolts

1. Tension Yield
$$Tu = \leq (\phi = 0.9)(50 ksi)(12'' \times 7/16'') = 236.25^k$$

2. Tension Rupture
$$A_e = (7/16)(12'' - 4(3/4'' + 1/8'')) = 3.72 in^2$$
$$Tu = \leq (\phi = 0.75)(F_u = 65 ksi)(A_e = 3.72 in^2) = 181.35^k$$

3. Block Rupture
$$R_n = F_u A_{nt} + 0.6 F_u A_{nv} \leq F_u A_{nt} + 0.6 F_y A_{gv}$$
$$A_{nt} = [(12'' - 5'') - 8(1/2)(3/4'' + 1/8'')](7/16'') = 1.53 in^2$$
$$F_u A_{nt} = (F_u = 65 ksi)(A_{nt} = 1.53 in^2) = 99.53^k$$

$$A_{nv} = 2[(12 - 1.5'') - 7''(3/4'' + 1/8'')](t = 7/16'') = 3.86 in^2$$
$$0.6 F_y A_{nv} = 0.6(50 ksi)(3.82 in^2) = 114.9^k$$
$$A_{gv} = 2(12 - 1.5)''(t = 7/16'') = 9.19 in^2$$
$$0.6 F_y A_{gv} = 0.6(50 ksi)(9.19 in^2) = 250^k$$
$$99.53^k + 114.9^k \leq 99.53^k + 250^k$$
$$\boxed{214.43^k} \leq 355.53^k$$

A325-N Bolts
$$\phi R_n = (\phi = 0.75)(F_n = 54 ksi)(A_b = \frac{\pi}{4}(0.75)^2) = 17.89^k/bolt$$
$$8 \text{ Bolts} = 4(17.89^k) = 143.14^k$$
Edge $= (\phi = 0.75)(1.2)(L_c = 1.5'')(t = 7/16'')(F_u = 65 ksi) = 38.4^k$
upper bound $= (\phi = 0.75)(2.4)(d_b = 0.75)(t = 7/16'')(F_u = 65 ksi) = 38.44^k/bolt$
Total permissable capacity $= (38.44^k)(8 \text{ bolts}) =$
$$= 307.1^k \geq 214.4^k \checkmark$$

Appendix U: Stress Values in Bent Bar for Recommended Design

Theta (degrees)	Axial Stress (psi)	Negative Bending Stress (psi)	Positive Bending Stress (psi)	Axial + Negative Bending (psi)	Axial + Positive Bending (psi)	Shear Stress (psi)
0	0.00	0.00	0.00	0.00	0.00	0.10
10	6.23	-169.96	224.99	-163.73	231.23	0.10
20	12.28	-334.76	443.15	-322.48	455.43	0.10
30	17.95	-489.39	647.84	-471.44	665.79	0.09
40	23.08	-629.15	832.84	-606.07	855.92	0.08
50	27.50	-749.79	992.54	-722.28	1020.05	0.07
60	31.09	-847.65	1122.09	-816.55	1153.18	0.05
70	33.74	-919.75	1217.53	-886.01	1251.27	0.03
80	35.36	-963.91	1275.99	-928.55	1311.35	0.02
85	213.12	-18280.00	24198.41	-18066.89	24411.53	5.72
90	35.90	0.00	0.00	35.90	35.90	5.73