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MECH 4860 – ENGINEERING DESIGN
FINAL DESIGN REPORT

TEAM #18: Quad Core Power

HYDROELECTRIC TURBINE – DISTRIBUTOR FALL ARREST ANCHOR SYSTEM DESIGN

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Dear Dr. Labossiere:

Enclosed you will find the Final Design Report for the Fall Arrest System Design project.

The report begins by outlining current methods used for anchoring fall arrest equipment and the issues with these methods. Next, project objectives and scope are discussed, followed by customer needs, constraints and limitations, and target specifications. The introduction section of the report ends with an explanation of the team's design process which describes how the final design was obtained. The final design report continues with a detailed description of the team's final design including the design features, major components and the safety analysis performed on the design. The design section of the report concludes with assembly and operation instructions as well as cost analysis for the design. Lastly, the team summarizes the project and gives recommendations for the project moving forward. Several appendices are attached to the end of the report detailing the team's concept selection process as well as detailed calculations and the team's final engineering drawings.

This project was a valuable learning experience which the team has greatly benefitted from. We are grateful to have had the opportunity to take part in this company sponsored project. Thank you for your time and please contact us if you have questions or concerns about the information presented in this report.

Yours truly,

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Executive Summary

currently faces an issue regarding the fall protection of workers conducting routine maintenance work on turbine runners and liners. Currently, two methods of fall arrest anchor systems are used by the workers during maintenance work. First, an anchor strap is wrapped and secured around the bottom of wicket gates or stay vanes, both located at foot level. Second, a cable is wrapped around the circular perimeter of the stay vanes, above head level. Depending on the method used, workers can connect their fall arrest lanyards either to the anchor of the strap, or the cable wrapped around the stay vanes to use as an anchor point. Current fall arrest anchor methods are undesirable as these are not engineered solutions and poses safety risks to workers such as trip hazards and increased potential free-fall distance. has asked that an engineered fall arrest anchor device be designed to reduce worker's free-fall distance and improve their safety.

After examining the client's requests, the team identified the most important needs to be reduction of free-fall distance, easy and safe installation and disassembly, minimized number of components, lightweight, and ability to fit through the scroll hatch opening which is 30” by 24”. The team created target specifications and metrics for each of these needs during the problem definition phase of the project.

During the second phase of the project, the team broke down the fall arrest anchor system design into three main sections. The three sections included anchor type, ability to fix the anchor onto the fall arrest anchor system, and fixture method of the fall arrest anchor system to the existing structures. A total of 13 concepts were generated using the three sections and these concepts were presented to the client. Following client evaluation, the team was requested to further explore a clamp style design for the fall arrest anchor system. The 13 concepts were compared to current fall arrest anchor methods and screened using criteria developed by the team with input from the client. These criteria included safety, compatibility, performance, design mobility, worker mobility, ease of use and manufacturability. Seven concepts passed the initial concept screening with one concept set as a reference to which the rest of the designs were compared to. The remaining design post screening were scored using the same criteria while also considering the client's interest in the clamp style design. The team chose a dual clamp fall arrest anchor device as the final design.

During the final design phase, the team analyzed their fall arrest anchor system design using both hand calculations and finite element analysis (FEA). The design was optimized to ensure the target specifications were met. The final anchor system design meets all of the client's needs that were determined during the first phase of the project. The new design reduced worker's free fall distance by 5.83 ft, a 42% reduction when compared with current anchoring method. The team's anchor system design is easy and safe to install and disassemble, with a setup time of 15 minutes. In addition, the anchor device uses hollow tubes as the main structure which makes the design lightweight, and an overall design mass of 35.37 kg. The team researched material and manufacturing costs to perform an in-depth cost analysis for our design. The total cost to implement the design came in at $1931.47, which is less than half the given budget of $5000.

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1. Introduction

This report is centered around Quad Core Power's fall arrest anchor system design for Throughout the report, information on the project definition and our design methodology will be provided, as well as a description and analysis of our final anchor system design. The introduction section of our report will begin with some background on and our project, followed by an explanation of the problem statement. Next, the objectives, deliverables and scope of the project will be discussed, along with the customer needs, target specifications and the project's constraints and limitations. Finally, the team's design methodology will be explained which finishes off the introductory section of the report.

1.1 Company and Project Background

is the main power supplier for the province of . Most of the power they supply is hydroelectric power [1]. The company has 15 hydroelectric power generating stations, 2 thermal generating stations, and 4 remote diesel generating stations which generate all the power needed for our province. Each of the hydroelectric generating stations house several turbine generators. In order to keep these turbine generators functioning properly, routine maintenance must be done regularly on turbine runners and liners. The workers performing maintenance work on the turbines have a risk of falling since they are working from the bottom ring of the turbine. Figure 1 illustrates the fall potential for workers on a side view diagram of a generation station.

[redacted]

Figure 1. Worker fall potential shown on side view of generating station [2]

Currently, [redacted] has two methods which are used as fall arrest anchor systems. The first method involves wrapping a strap around the bottom of one of the wicket gates as shown in Figure 3 The company's second approach entails wrapping wire rope around the stay vanes as demonstrated in Figure 3. However, neither of these methods are ideal since they are both located at the worker's foot level and result in a rather large free fall distance for the workers.

[redacted]

Figure 2. Stay vanes [2]

[redacted]

Figure 3. Wicket gate [2]

1.2 Problem Statement

The main problem that faces is their lack of an engineered fall arrest anchor device for workers performing turbine maintenance work. The two current methods used for anchoring fall arrest equipment create tripping hazards for the workers since they are located at foot level. In addition, these methods produce large free fall distances for employees. The two main fall potential locations that are of concern is the fall from bottom ring platform to the water in the draft tube area with fall distance of 17.4 ft, and between bottom ring platform and bottom of scroll case with fall potential of 9 ft. The company needs an engineered fall arrest anchor system which will improve worker safety and reduce their fall distance.

1.3 Project Objectives

The primary objective of this project was to design a fall arrest anchor device or system for personnel working from the bottom ring of a vertical axis hydroelectric turbine distributor in order to reduce the worker's fall potential. The anchor device must improve employee safety and decrease fall distance. Our design must also not alter or modify existing structures, be easy to install, and fit through an oval opening of 30" by 24". The team was required to create a lightweight design that minimized the number of components. Team Quad Core Power was given a budget of $5000 which the anchor system design needed to stay under. The project must be completed by Wednesday, December 4, 2019.

1.4 Design Scope

As part of the scope of this project, our team will be designing a fall arrest anchor system for employees working on the bottom ring of a hydroelectric turbine distributor. The system shall comply with Workplace Safety and Health Act and Regulation, CSA standard Z569.16-15 design of active fall-protection system, and any applicable standards that may be discovered later on [3, 4]. The "Fall Protection" chapter discusses two systems which are guardrail systems and fall protection systems. However, guardrail systems are not part of the scope of this project. There are several types of fall protection systems including travel restraint systems, fall arrest systems, safety nets and other fall protection systems [3]. This project only involves the design of a fall arrest anchor system. Fall arrest equipment such as the lifeline, lanyard, full body harnesses and shock absorbers will not be included as part of our design, but will be mentioned as to how to equip to the design.

The anchor system is the secure point of a lifeline or lanyard. The design shall include the structure of the anchor, anchor's strength, stability, location of the anchor and the method to install the anchor. The scope of this project will also include the design of a temporary fixed support system since the fall arrest anchor system cannot damage existing structures and must disassemble after use. The temporary fixed support system without a shock absorber must be capable of supporting a static force at least 8 kN as per Workplace Safety and Health Act and Regulation and CSA standard Z569.16-15 design of active fall-protection systems [3, 4]. Additionally, the strength, stability, location and the method to install the temporary fixed support system must be considered as part of this project. The anchor system is to be designed for workers who are conducting work from the bottom ring of the turbine, meaning the fall potential distance considered is from the bottom ring to the runner support beam or maintenance platform and from the bottom ring to the scroll case floor. Figure 4 illustrates the fall potential from the bottom ring to the maintenance platform.

[redacted]

Figure 4. Fall potential from current fall arrest anchor methods [2]

1.5 Customer Needs

After visiting the headquarters and generating station in September to gather information, our team created a summary of the client's needs shown in TABLE I during the project definition phase of the project. The client needs and importance rankings were reviewed and confirmed by our client at

TABLE I. CUSTOMER NEEDS [2]

#	Client Needs	Importance
1	Follow safety regulations to ensure worker safety	5
2	Keep the existing components or structures	5
3	Reduce free fall distance compared to existing methods	5
4	Lightweight and small size	3
5	Easy to install and disassemble	4
6	Low cost	2

1.6 Target Specifications

Target specifications are based on the customer needs identified in the section 1.5. To establish the target specifications, metrics and their importance, ratings have selected. Multiple metrics are required in order to satisfy every customer need. TABLE II shows the teams chosen metrics and their ideal values and were reviewed and confirmed by our client at

TABLE II. CUSTOMER NEEDS METRICS AND TARGET SPECIFICATIONS [3] [5]

Metric #	Need #s	Metrics	Importance	Units	Acceptable range	Target
1	1	Minimum anchor static load	5	kN	> 8	> 10
2	1	Maximum fall arrest force	5	kN	< 8	< 8
3	1	Maximum free fall distance	5	m	< 1.2	< 1
4	1, 4	Inhibit worker mobility	5	Yes/No	No	No
5	2	Not alter components or existing structure	5	Yes/No	Yes	Yes

6	3	The distance between anchor point to bottom ring level	5	m	> 1	> 2
7	4	Maximum weight per component	3	lbs	< 40	30
8	4	Maximum size per component	3	inch	< 30 x 24	20 x 15
9	4	Number of components of the device	4	unit	> 1	< 20
10	5	Time to install or disassemble design	4	minutes	< 30	10
11	6	Materials & Manufacturing cost	2	CAD$	< 5000	< 2500

Note: Importance range for TABLE III is between 1-5 (importance level from low to high)

1.7 Design Methodology

Once the team had finished developing the project definition, the concept generation and selection process was able to begin. Each team member developed a minimum of three design concepts. In total, 13 potential anchor system designs were generated. The team then screened all of these concepts using two main categories: ability to attach the anchor to the temporary fixed support and ability to attach the temporary fixed support to existing structures.

The initial screening process allowed the team to narrow down the number of concepts considered from 13 to 3. Following the initial screening process, an in-depth concept scoring process was conducted using the two previously mentioned categories. Therefore, the team chose to combine features from both design concepts to create the best possible anchor system design. More information on the team's concept generation process can be found in Appendix C.

2. Final Design

In this section, a final overview of the fall arrest anchor system is conducted including the details of individual subassemblies as well as a description of the design features. During the concept generation and selection phase of the project, the device was designed to be used on both stay vanes and wicket gates. The geometry of the wicket gates generally stays constant for all turbine generators at the generating station while the geometry of the stay vanes tends to differ. In addition, the wicket gates are closer to the fall potential range than the stay vanes which means that workers are more likely to fall when working around the wicket gates. Therefore, due to time and technology constraints, the final design is limited to focus on the wicket gates.

2.1 Overview of Design

A dual clamp fall arrest device has was selected as the final design. This design is an improvement based on previous concepts shown in Appendix C. There were certain problems the team needed to consider with these design concepts. Some of these considerations were how to apply force to the clamp arm, unreasonable geometry of the clamp arm and inappropriate anchor point. The final design solved these problems effectively. Each of the following design details are discussed in detail later in the report. First, the device uses a self-lock nut and threaded method to apply force to the clamp arm. Next, the device uses a sign side clamp tighten method. This design reduces the employee's workload significantly and reduces the risk of injury. Lastly, this device used a swivel anchor located at the midpoint of the device. The swivel anchor effectively distributes the force evenly across all contact surfaces. The fall arrest anchor device is intended to be installed on the wicket gate as shown in Figure 5 and Figure 6. The location of this device is flexible along the vertical axis of the side face of the wicket gate and can be adjusted by workers.

[redacted]

Figure 5. Front view of final assembly with wicket gate

[redacted]

Figure 6. Back of final assembly with wicket gate

Due to the rotation of the wicket gate, workers may work from either side of the wicket gate. Therefore, the fall arrest anchor device has been designed to be axisymmetric. The fall arrest anchor device can be used from either side of the wicket gate as demonstrated in Figure 7.

[redacted]

Figure 7. Installation of final assembly in opposite orientation

The final assembly of fall arrest anchor device consists of two main steel hollow tubes with an outer radius of 1.18 inches, an inner radius of 0.75 inches, anchor board, two clamp arms and six rubber mats.

The two main stainless-steel hollow tubes are connected by two mid-support circular rods as shown in Figure 8. The total mass of the device is 39 pounds. Material, weight and size details for each component can be found in Appendix B. The major components of the design are further explained in a later section of the report.

[redacted]

Figure 8. Final assembly consisting main components

2.2 Final Design and Customer Needs

This section explains how the features of the fall arrest anchor device satisfy the customer needs. The customer needs include reduced free fall distance, no alterations or damage to existing structures, lightweight, minimized number of components, and easy and safe installation for workers. In addition, this section shows the team's calculations and FEA to prove that the device complies with safety regulations.

2.2.1 Design Safety and Regulations

The first customer need established by the client was for the fall arrest anchor system design to meet safety regulations to ensure worker safety. After research and review of applicable design regulations and standards, including the Health and Workplace Safety Act and CSA standard Z569.16-15 for design of active fall-protection systems, the design requirements that must be met for a temporary fixed, rigid anchor fall arrest system were summarized in TABLE III [3, 4]. The design requirements were utilized to design the fall arrest anchor system.

TABLE III. DESIGN SAFETY REGULATIONS AND REQUIREMENTS

Regulations and standards design requirements
1. Support a static force of at least 8 kN [3, 4]
2. Fall arrest system does not subject user to a peak dynamic fall arrest force greater than 8 kN [3, 4]
3. Ensure maximum free fall distance does not exceed maximum free fall permitted by the system [4]
4. Minimum clearance between the foot of worker suspended from a fully extended lanyard is 0.6 m [4]

As per the first design requirement in TABLE III, temporary fixed support systems are required to be capable of supporting a static load of 8 kN [3, 4]. A static loading analysis was performed on a

[redacted]

schematic of the initial clamping design to determine required frictional forces on the clamp arms to support the 8 kN load. As the nuts on the threaded rods are tightened, the nuts exert a force on the frictional material used to support the design on the wicket gates. The minimum allowable static load of 8 kN was used for the analysis, with four reaction forces, at each corner of the design frame. An assumption made for ease of analysis is that the four vertical forces are equal in magnitude, as seen in Figure 9.

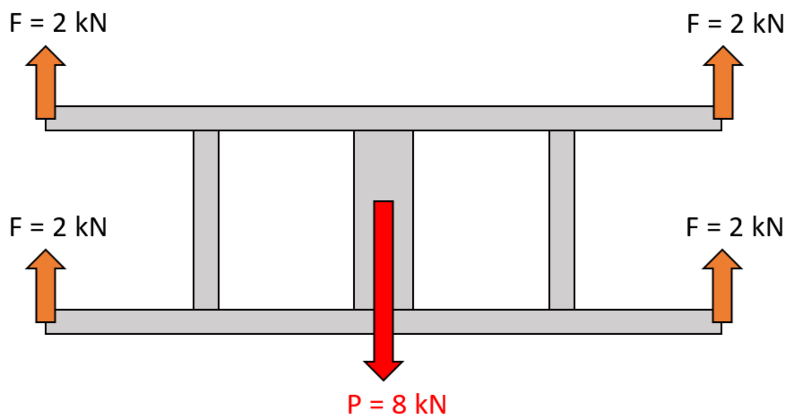


Figure 9. Overall free body diagram of design frame

Next, taking the sum of forces in the free body diagram and using force equilibrium equation, Equation 1, the magnitudes of the vertical frictional forces were determined.

$$+\uparrow \sum F_y = 0 \qquad \text{Equation 1}$$

$$4F - 8 = 0 \rightarrow F = 2\ \text{kN}$$

The vertical force at each of the corner of the design's frame, is known as the frictional force Ff, and was determined to be 2 kN. A frictional force at each corner of the design is required to sufficiently fix the design onto the structure during both loading and non-loading scenarios. The total frictional force must be greater than the applied load, to ensure prevention of vertical motion. Frictional force is dependent on the magnitude of a normal force, N, and static coefficient of friction of a surface, μS, as shown in Equation 2 [6].

$$F_f = \mu_s N \qquad \text{Equation 2}$$

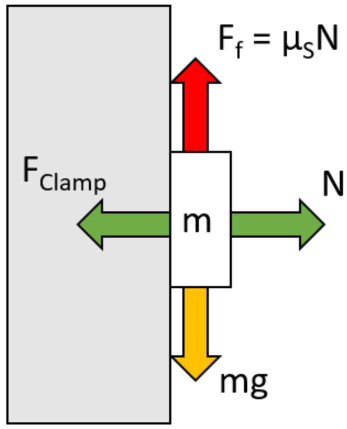


Figure 10. Free body diagram of clamping material

The normal force is the corresponding and opposite force to the clamping force, F_{clamp}, generated by the elongation of a rod as a direct result of the number of turns of a nut and thread pitch, p. For this analysis, the weight of the design is the product of the mass and gravitational acceleration, mg, was deemed to be negligible as it is significantly smaller than the applied load. Taking the force balance in the vertical direction in Equation 3, an expression for clamping force can be determined.

$$+\uparrow \sum F_y = 0 \rightarrow F_f - mg = 0 \qquad \text{Equation 3}$$

$$\mu_s N - mg = 0$$

$$N = \frac{mg}{\mu_s}$$

$$F_{clamp} = \frac{mg}{\mu_s} \qquad \text{Equation 4}$$

Displacement, δ, can be determined using Equation 5 [7].

$$\delta = \frac{FL}{AE} \qquad \text{Equation 5}$$

Where F is the internal force, L is length of material, A is cross-sectional area, and E is the material's young's modulus.

When the bolts are tightened to generate a clamping force, the bolts on the main frame will elongate and the rubber frictional material will be compressed, as shown in Figure 11.

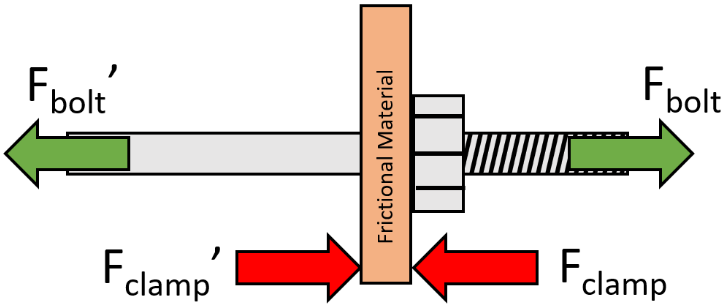


Figure 11. Free body diagram of bolt, nut and frictional material

The displacement equations for bolts and frictional rubber material are shown in Equation 6 and Equation 7 below. Note, the force exerted on the bolt, F_{bolt}, is equal and in the opposite direction of the clamping force. Similarly, F_{bolt} is also equal to the force exerted on the rubber friction material F_{rubber}.

$$\delta_{bolt} = \frac{F_{bolt} L_{bolt}}{A_{bolt} E_{bolt}} \qquad \text{Equation 6}$$

$$\delta_{rubber} = \frac{F_{rubber} L_{rubber}}{A_{rubber} E_{rubber}} \qquad \text{Equation 7}$$

The displacement of the bolt with respect to the frictional rubber material is governed by the Equation 8. This displacement is determined by the number of rotations and thread pitch of the bolt.

$$\delta_{bolt/rubber} = \delta_{bolt} - \delta_{rubber} \qquad \text{Equation 8}$$

Alternatively, the displacement of the bolt with respect to rubber frictional material can be calculated using the number of turns of a nut and pitch, as seen in Equation 9 [7].

$$\delta_{bolt/rubber} = (\#\text{ of nut turns}) \cdot (\text{pitch}) \qquad \text{Equation 9}$$

With the aid of generated computer model of the design, the length and cross-sectional area of frictional rubber material was predetermined and sized accordingly to cover the arching clamp arms on the leading and trailing edge of the wicket gates. The magnitude of F_{bolt} can be determined by equating equations 6 and 7 and using number of turns as 8.15 and pitch as 0.00254 meters.

$$(\#\text{ of nut turns}) \cdot (\text{pitch}) = \delta_{bolt} - \delta_{rubber}$$

$$(\#\text{ of nut turns}) \cdot (\text{pitch}) = \frac{F_{bolt} L_{bolt}}{A_{bolt} E_{bolt}} - \frac{F_{bolt} L_{rubber}}{A_{rubber} E_{rubber}}$$

$$0.0207 = (3.73 \cdot 10^{-8}) \cdot \mathrm{F_{bolt}} \cdot -(8.38 \cdot 10^{-6}) \cdot \mathrm{F_{bolt}}$$

$$\mathrm{F_{bolt}} = \mathrm{F}_{clamp} = 2483.411\ \mathrm{N}$$

Using Equation 2, and static coefficient friction value of 0.84, the frictional force is determined as

$$\mathrm{F_f} = \mu_s \mathrm{N} = \mu_s \mathrm{F_{clamp}}$$

$$\mathrm{F_f} = 2135.733\ \mathrm{N}$$

From the force analysis, 8.15 rotations of the self-locking nuts with a pitch of 0.00254 m, generate a frictional force of approximately 2135.733 N at each of the four clamp arms of the design, exceeding the 8 kN applied loading scenario. Based on the static analysis, the fall arrest anchor system can be safely supported on the wicket gates under an 8 kN load.

The second design requirement in Table 4 is for the maximum fall arrest force (MAF) to be less than 8 kN. The MAF on a user is generally controlled by the magnitude of free fall distance (FFD) and the energy absorbing lanyard (EAL) utilized. One method to ensure the MAF experienced by users is to limit the FFD. To get a better understanding of the FFD, the fall potential areas in the workspace should be understood. As mentioned earlier in the report, two fall potential areas exist when performing routine maintenance at the bottom ring area of a hydroelectric turbine distributor. The first area is located at the edge of the bottom ring platform with the fall potential into the water within draft tube area, located approximately 17.5 feet below bottom ring. The second fall potential area also exists at the bottom ring platform with the fall potential towards the bottom of the scroll case, located 9 ft. below bottom ring. In the event of a fall, the falling worker will be exposed to a free fall distance before the activation of the energy absorption portion of the fall protection equipment which decelerates the fall rate of the worker. During activation of the energy absorbing portion of the EAL, the worker's body and fall protection system will be exposed to a MAF. By minimizing the FFD of a user, the EAL has less energy to dissipate upon activation as demonstrated in Equation 10.

$$Potential\ Energy\ (PE) = mgh \qquad \text{Equation 10}$$

Potential energy is the product of the mass of falling object m, height or vertical distance of object h, and g is gravitational constant [8]. The PE is equivalent to the kinetic energy (KE) right before the activation of the EAL, and can be determined using Equation 11 [9].

$$Kinetic\ Energy\ (KE) = \frac{1}{2}mv^2 \qquad \text{Equation 11}$$

For a general straight-line collision scenario, the average impact force is determined using Equation 12 [9].

$$F_{impact} = \frac{\Delta KE}{D} \qquad \text{Equation 12}$$

As seen in the potential and kinetic energy relationship shown in Equation 10 and Equation 11, it's clear that minimization of FFD reduces the PE and KE and in turn minimizes the force of impact which is equivalent to the MAF.

A second method for ensuring the MAF felt by users is less than 8 kN is through proper selection of the EAL. Energy absorbing lanyards are rated for specific user weights and limits the MAF experienced by users. For instance, an E4-rated EAL is designed for reducing user MAF to 4 kN for max user mass of 115 kg, whereas an E6-rated EAL is designed for reducing user MAF to 6 kN, for a max user mass of 140 kg [10]. Usage of E4 or E6 rated EALs is one way to ensure the MAF experienced by users is less than 8 kN. It is important to note that higher rated EALs increase the fall arrest distance and must be sized accordingly to prevent contact with surface and falling user [4]. In the end, combination of minimization of FFD and proper selection of EAL will ensure MAF experienced by users is less than 8 kN.

The third design requirement in Table IV, is to ensure the FFD of system does not exceed the maximum free fall permitted by the fall arrest anchor system. First, the FFD for the current and new fall arrest anchor system must be determined. The current setup for workers to anchor to the wicket gate involves wrapping an anchor strap around the bottom of the wicket gate and connecting their retractable web lanyards equipped with an energy absorber connected to their full body harnesses, to the anchor on the anchor strap. The current method is undesirable since the FFD is quite large due to anchor point being located below foot level exposing workers to large MAFs. With the new fall arrest anchor system, an anchor strap is no longer needed and only requires use of a web retracting lanyard. Furthermore, the new fall arrest anchor system design can be mounted on the wicket gate at a higher elevation than the current method. With a clear understanding of the current and new fall arrest anchor setup, the FFD can be determined. As per CSA standard Z259.16-15, design of active fall-protection systems, FFD for rigid anchors is determined to be the sum of the length of the lanyard (L_Y) and vertical distance from D-ring of a full body harness to the anchor point (H_D) [4]. Free fall distance can be calculated using Equation 13 below.

$$\text{Free Fall Distance (FFD)} = H_D + L_Y \qquad \text{Equation 13}$$

For proper comparison of FFD between current and new methods, the client provided measurements of anchor strap and web retractable lanyards currently used by workers for fall protection while performing maintenance in the bottom ring area [5, 10]. The same retractable web lanyard will be used for a fair comparison for free fall distances. Fall protection equipment dimensions and free fall distance comparison are shown in TABLE IV.

TABLE IV. FREE FALL DISTANCE COMPARISON

Current Method		New Method	
Parameters	Dimensions	Parameters	Dimensions
Anchor Strap Length (ft)	6	Anchor Strap Length (ft)	N/A
Height of D-ring from Anchor Point (ft)	5.83	Height of D-ring from Anchor Point (ft)	0
Self-Retracting Lanyard Length (ft)	8	Self-Retracting Lanyard Length (ft)	8
Free Fall Distance (ft)	13.83	Free Fall Distance (ft)	8
Free Fall Distance (m)	4.216	Free Fall Distance (m)	2.440

As seen in TABLE IV, with the new anchor system design, FFD was reduced by 5.83 ft resulting in a 42% FFD reduction.

With FFD determined for the new fall arrest anchor system design, the maximum permittable fall distance by the system, h_{max}, was determined using Equation 14, as per CSA standard Z259.16-15, design of active fall-protection systems [4].

$$h_{max} = \left(\frac{1000 \cdot F_{avg}}{m \cdot g}\right) \cdot X_{max} \quad \text{Equation 14}$$

Where F_{avg} is the average arresting force for an EAL, m is mass of user, g is gravitational acceleration, and X_{max} is the max extension of the energy absorber.

The model of the EAL typically used by workers in the bottom ring area for fall protection was provided by the client, and the specifications were retrieved online. The specifications of the exact model of the EAL provided by the client was not available online, instead a green colored, E6 rated variant of the same model and same length was used to determine h_{max}. A worker mass of 140 kg was used to simulate a heavy loading scenario for the EAL. Shown in are the specifications used to determine h_{max}.

TABLE V. MAX PERMITTABLE FALL DISTANCE

Parameter	**Magnitude**
Average arrest force, F_{avg} (kN) [3, 4]	3.25
Mass of worker, m (kg)	140

Max extension of energy absorber, X_{max} (m) [10]	2.24
Gravitational acceleration, g (m/s^2)	9.81
Maximum permittable fall distance,h_{max} (m)	3.06

The free fall distance of the new fall arrest anchor system design is 2.44 m, and is less than the max permittable fall distance of 3.06 m, satisfying the third design requirement in TABLE III.

For the fourth design requirement in TABLE III, the minimum clearance allowed for a rigid anchor system between the foot of worker suspended from a fully arrested lanyard and the ground is 0.6 m [4]. To satisfy the 0.6 m clearance requirement, the maximum arrested extension of the EAL must be less than the total fall distance. For the purpose of this analysis, the total fall distance used was the largest change in elevation in the work space, which is from the bottom ring platform to the water in the draft tube, with a change in elevation of 5.32 m. The manufacturer, Safety Direct Ltd., literature value for the maximum arrested extension of the green, E6 rated variant of the EAL is 4.18 m [10]. The difference between the maximum arrested extension and total fall distance is 1.14 m, which is greater than the 0.6 m minimum clearance requirement, thus satisfying the fourth design requirement in TABLE III.

Four metrics are related to the design's safety and compliance with safety regulations. The client placed the highest important on these metrics which include design minimum anchor static load, maximum fall arrest force, maximum free fall distance, and inhibit worker mobility.

For the first metric, the fall arrest anchor system was to be designed for a minimum anchor static load of 8 kN. The target value for this metric was 10 kN, however, the current system is only designed to support only 8.5 kN. The target metric of 10 kN was not met, however, the minimum anchor static load is still within the acceptable range of greater than 8 kN. It is important to note that although the target metric was not met, the anchor system design fulfilled several of the design safety standards and requirements from the Health and Workplace Safety Act and CSA standard Z569.16-15 for design of active fall-protection systems, as specified in TABLE III.

For the second metric, the maximum fall arrest force of the design was specified be to less than 8 kN. As discussed in the design safety and regulation section of the report, utilization of an E4 or E6 rated energy absorbing lanyard in combination with minimization of free fall distance, will ensure a maximum arrest force less than 8 kN. With the utilization of blue colored E6 rated web retracting lanyard from, Safety Direct Ltd., the maximum arrest force is limited to a max value of 3.25 kN [10]. The max fall arrest value of 3.25 kN is less than the target metric of 8 kN, thus meeting the metric requirement and ensures user safety.

For the third metric, the maximum free fall distance was designed to be limited to 1 m. The target value for this metric was to limit the maximum free fall distance to less than 1 m. The original purpose of this metric was to determine whether or not the free fall distance for the system had decreased. After review of the target metric value and use of the free fall distance definition of CSA standard Z569.16-15 for design of active fall-protection systems, governed by Equation 13, this target metric value was deemed to be inaccurate. Using Equation 13 with D-ring height from anchor point of 5.83 ft. and web retractable lanyard length of 8 ft, the current free fall distance was actually 13.83 ft or 4.2 m. Utilization of the same free fall distance equation with the new anchor design and same retractable web lanyard length, resulted in a new free fall distance of 8 ft or 2.44 m. Clearly, the free fall distance for the new anchor design decreased by 5.83 ft or 1.76 m, thus meeting the original intent of the metric. In the end, the original intent of this metric was met as free fall distance was decreased, and the range and target metric values should be re-defined.

For the fourth metric, the design was not supposed to limit worker mobility in the work area. With regards to current method for anchoring to the wicket gate, the worker mobility is limited to a single wicket gate. With the new design, this worker mobility also holds true, as the fall arrest anchor system is still mounted on a single wicket gate. The mobility of workers within the vicinity of the new anchor system design has improved when compared to current methods, due to the elimination of the anchor strap at foot level and no longer presents tripping hazards. Overall, the new fall arrest anchor system design improved worker mobility, and thus meeting the fourth metric.

[redacted]

Figure 12. Improvement of new fall arrest anchor system

2.2.2 No Damage to the Existing Structures

The fixture method used to fix the fall arrest device to the wicket gate is by clamping onto the wicket gate. This ensures the device can fix on the wicket gate temporarily without any damage to the wicket gate. As part of the design, the clamp arms have been separated by a relatively soft material since the entire device is made from metal. The usage of the rubber mat in the fall arrest anchor device provides a smooth and soft surface at the contact surface between the device and the wicket gate. The use of rubber mats prevents the direct connection between the steel and the wicket gate which would create a significant frictional force in this case. The rubber mat can also increase the contact area which leads to a reduction of frictional force that is generated. There are six pieces of rubber mats in total on the device which is shown in Figure 13. The rubber mats can be fixed to the device using super glue

[redacted]

Figure 13. Implementation of rubber mat on system

Regarding in terms of safety consideration, rubber pads with grooves along the middle of one side will be fixed onto the middle surface, leading and trailing edges of a wicket gate through use of an adhesive. The adhesive will be used to join the groove surface of the rubber to the cylindrical frame of the design. The rubber pad is equipped along the inside surface of the arching clamp arms on leading edge, trailing edges, and along the curved middle section of the main frame rods. The rubber surface increases the grip and overall clamping force of the fall arrest anchor system design on the wicket gates through increased contact area and an increased coefficient of friction between surfaces. The grip and clamping force of the design is critical to ensure worker and equipment safety especially in the event of fall arrest loading scenario. The rubber pads also provide protection to the wicket gate surfaces from getting damaged through contact with the metallic surface of the design during usage. Incorporation of rubber grip pads into the design addresses safety and compatibility with existing structures client needs.

[redacted]

Figure 14. Wicket gate – leading edge rubber grip

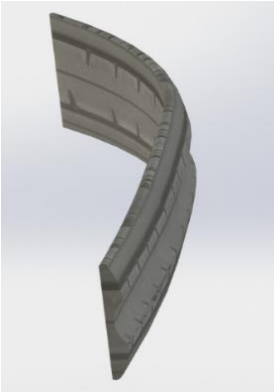


Figure 15. Wicket gate – middle rubber grip

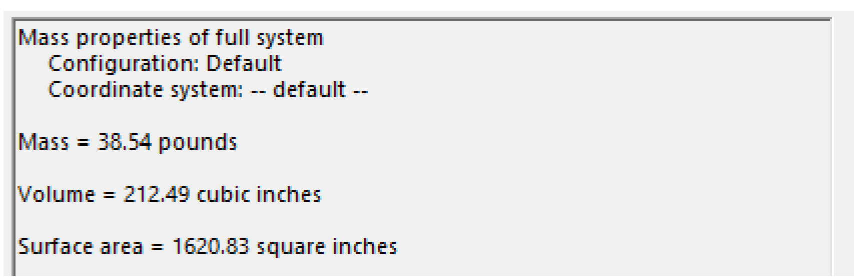
Figure 16. Wicket gate – trailing edge rubber grip

2.2.3 Light Weight and Small Size

According to the weight of different components, the maximum weight for a single component is the weight of the top frame and the bottom frame which each weighs 8.55 lbs. The target specifications state that the maximum weight per component should be 30 lbs. The maximum weight of the designed component is significantly less than the targeted value which means our design meets the metric #7. In addition, the total weight of the entire structural design is 38.54 lbs,, as shown in Figure 18, which is 61.46% lighter than the total maximum weight value of 100 lbs.

[redacted]

Figure 17. Weight of each component of design


Mass properties of full system
Configuration: Default
Coordinate system: -- default --

Mass = 38.54 pounds

Volume = 212.49 cubic inches

Surface area = 1620.83 square inches

Figure 18. Total weight of whole structural design

The main body frame of the fall arrest anchor system design consists of two hollow cylindrical rods, which are shown by yellow rods in Figure 19 and Figure 20. The frame has two parts, a top and a bottom hollow rod that is bent into the shape of a wicket gate. Each rod has two holes and a groove drilled in for the insertion of the main frame connector rods and an anchor mounting plate, respectively. Together, the top and bottom rods act as the foundation of the design as all other parts connect to these structures. The main frame geometry was selected to be a cylindrical rod to accommodate the complex shape of the wicket gate consisting of multiple curves, which could present complications for linear frame geometries. Furthermore, the cylindrical rod shape of the frame is small compared to a linear geometric frame and can be further hollowed out, addressing client's size and weight constraints for the design. The overall design has a total weight of 38.54 lbs, approximately 61.46 % lighter than the total weight limit constraint of 100 lbs.

[redacted]

Since workers need to carry the device through a narrow space, the device must fit through an oval opening of 30 X 24 inch. To meet this need, the device is designed to be detachable. The size of the largest component which is the yellow clamp frame can fit through an opening of 10 X 2 inch. The targeted maximum size per component is 20 x 15 and the maximum size of our design is much smaller than the targeted value which means that the targeted requirement has been met. In order to make the device lighter, hollow tubes are used as the main structure show in Figure 24. When comparing between a solid tube and a hollow tube, the hollow tube has the benefit of being lightweight as well as a greater bending resistance than the solid tube referring to the second moment of area calculation found in the Appendix A.

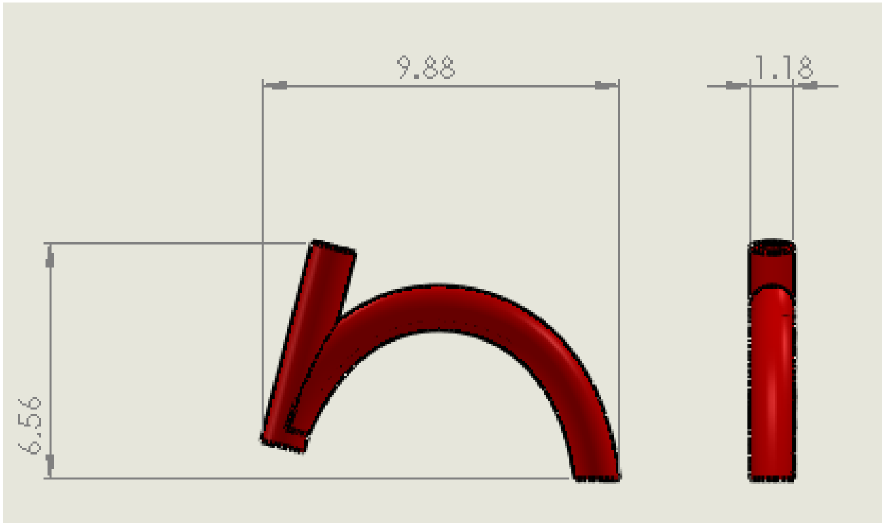


Figure 21. Dimension of the arced clamp arm

[redacted]

Figure 22.Dimension of the cylindrical hollow rods

[redacted]

Figure 23. Dimension of the final assembly

[redacted]

Figure 24. Implementation of hollow tubes on system

2.2.4 Easy and Safe to Set Up

One of the important features of the fall arrest anchor device is the ease and safety of the installation of the device onto the wicket gate. Regarding the number of components for the device, the final design has 16 components in total. According to our table of customer needs, metrics, and target specifications, the targeted total number of components for the device is less than 20. The team's design meets this requirement. Due to the wicket gate's leading edge and trailing edge shown in Figure 25 and Figure 26, the trailing edge of the wicket gate is close to the fall potential area which is not suitable for employees to work. Compared to trailing edge of the wicket gate, the leading edge of the wicket gate is far from the fall potential area which means it is safer for workers to perform work on this side of the wicket gate. The fall arrest anchor device uses a single side fastening method for this reason, which means that workers only need to set up the device on one side of the wicket gate. The installation of the fall arrest device involves assembling the clamp arms and two main hollow steel tubes using self-locking nuts to make them tighten together. Regarding the safety consideration of installation, the only tool required to install the device is a screwdriver which reduces the amount of risks present during installation. The approximate time needed to install the device is 15 minutes or less. The target specifications specify a target assembly time between 10 and 30 minutes. As 15 minutes is within this range, the team has met this specification. More information on the specific operation process will be discussed in a later section of the report.

[redacted]

Figure 25. Leading edge of wicket gate

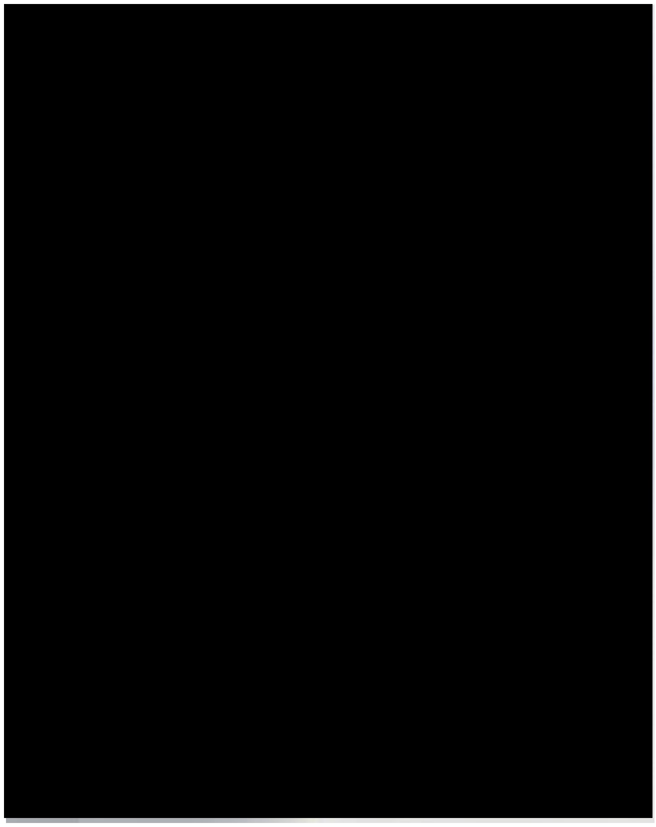


Figure 26. Trailing edge of wicket gate

[redacted]

Figure 27. Installation Operation of fall arrest anchor system

2.3 Major Components of Design

[redacted]

Figure 28. Dual threaded – frame connector rods

Threaded connector rods, as shown in Figure 28, are utilized to connect the top and bottom frames of the design and connect the clamping arms to design frame. The material for vertical dual threaded rods is 52100 alloy steel. The horizontal threaded rods welded onto the frames are constructed with 6061 aluminum. The threaded ends of the connector rods are inserted through drilled holes on the cylindrical rod frame and fastened with nuts to connect the top and bottom frames of the design. Self-locking nuts are used for fastening when attaching the arched clamping arms to the main body frame of the design using the connector rods. The implementation of the connector rods provides an easy to build yet sturdy connection method for the top and bottom rod frames of the design, and allows for a dual clamp design which is a design feature that the client had requested for the final design. The connector rod utilized in the design is relatively small and lightweight, easy to install and disassemble, and available for purchase online helping reduce design cost due to less manufacturing required for the design. The inclusion of the frame connector rods addresses the small and lightweight, easy to install and disassemble, and low-cost customer needs for the design.

[redacted]

Figure 29. Self-lock nut

[redacted]

Figure 30. Resistance to loosening diagram for nuts [11]

Self-locking nuts are utilized for fastening the clamp arms of the fall arrest anchor system design around the wicket gate. The self-locking nuts utilized in the design are made of steel. Two self-locking nuts are utilized in the design, one nut each for top and bottom frames. Tightening the nuts causes the extension of the threaded rods and rod frames and result in the component being in a state of tension, increasing the device grip and clamp force around the wicket gate. Due to safety concerns regarding potential loosening of regular nuts in a fall arrest load event, nuts with high resistance to loosening are preferred. Self-locking nuts were included into the design since they are relatively small in size, improve the overall safety of the design by having high resistance to loosening, easy to install, and readily available online decreasing the design cost as through reduction of parts that have to be manufactured. The incorporation of self-locking nuts into the addresses the design safety, small size and lightweight, easy to install and disassemble, and low-cost client needs for the design.

[redacted]

Figure 31. Arched clamp arms

The arched clamp arms assist in the distribution of the required clamping force to secure and fix the device onto the wicket gates. A hollow cylindrical straight piece in the arched clamp arm allows for easy insertion of the threaded end of the clamp arm connector rods. Attached to the hollow straight piece is an arched, hollow, cylindrical piece, which is slightly larger in radius and bent to the shape of the leading edge of the wicket gate. The arched clamp arms are constructed using alloy steel. The design utilizes two clamp arms to evenly distribute the clamping force onto the wicket gates, resulting in a dual clamp design which was a design feature requested by the client for the final design. After the threaded ends of the clamp arm connector rods have been inserted through the clamp arms, a self-locking nut is threaded onto both rods and tightened to increase the grip of the clamp arms on the wicket gate surface and distribute the clamping force. The dual clamp design is a safer design option than a single clamp design due to the additional grip provided by the second arm, as well as increased safety provided by the secondary arm should the other arm malfunction. The arched shape of the clamp arms makes it readily compatible with wicket gates, while also being easy to install and disassemble due to only a self-locking nut being required to fasten the arms onto the frame of the design. Since the clamp arms can be easily loosened and re-tightened, the device can be freely adjusted vertically along the wicket gate, to decrease potential free fall distance for connected workers. The use of the arched clamp arms addresses design safety, easy to install and disassemble, and reduced free fall distance client needs for the design.

[redacted]

Figure 32. Swivel hoist ring anchor

For the device anchor point, a swivel hoist ring anchor sourced online from William Hackett was utilized [12]. The hoist ring anchor was manufactured with forged alloy steel and designed using safety factors, tested for applications with applied loads ranging from 0.5 to 16.9 tonnes [12]. The specific hoise anchor for the design has a load limit of 1.25 tonnes, equivalent to 12.5 kN, and the maximum fall arrest load of 8 kN falls well within this range. With regards to anchor motion, the anchor can rotate 360^o at the base, and has a maximum pivot range of 180^o [12], allowing anchored workers to move freely and perform maintenance work as required. The hoist rings are readily available for purchase online, and reduces the manufacturing required for the overall design. The anchor is fastened to a steel metal plate using a socket head screw. The steel plate is inserted into the grooves during assembly of the frame and is secured in place once the vertical frame connector rods have been tightened.

2.4 Operations to Install Design on Wicket Gate

The entire fall arrest device consists of eleven components including six Extra-Wide lock nuts, one thin locknut, and one Socket Head Screw bolt. These parts are standard parts and therefore have no special requirements for tools. Based on safety considerations, the entire assembly and set up process should involve at least two workers. The first worker assembles the main structure at a safe location. The installation steps are shown as below. Once the installation of the main structure is complete, a worker can start to set up the device on the wicket gate.

Steps to install the design on the wicket gate:

Step#1: The first step is the assembly of the anchor point. Workers must put the bolt into the hole of the swivel anchor and install it with the red mid board shown in Figure 33. Workers don’t need to worry about the direction since the geometry of the mid board is symmetric. The recommended torque for tightening is 70 lb/ft. The time taken in this process is estimated at 1 minute.

[redacted]

Figure 33. Operation of installing anchor point

Step#2: The second step is the main structure assembly. Workers must install the anchor assembly into the slot and two rods into the hole at both the top and bottom frames. Next, attach bolts to the rods with lock nut. Make sure the anchor ring faces out as shown in Figure 33. The recommend torque for tightening is 70 lb/ft. The time taken in this process is estimated at 5 minutes.

After the main structure assembly workers can set up the device to the wicket gate. The design itself allows worker to set up the device within a safe range. But just in case the workers had a safety measure. For example, temporarily use the previous method. There are three major steps to set up the main structure on the wicket gate. Recommend two workers to do the operation. The steps of installation are present as below.

Steps to install final assembly on the wicket gate:

Step #1: One worker should hold the main structure to the wicket gate as shown in Figure 34. Workers need to make sure the trailing edge of the device mates to the trailing edge of the wicket gate. Workers don't have to be too close to the fall potential edge. The design is long enough to allow the worker to stand at a safe range to operate. This step will take approximately 1 minute to complete.

Figure 34. Operation of attaching main frame on the wicket gate

Step #2: Another worker is responsible for installing the clamp arm shown in Figure 35. Worker can either install the top clamp arm or bottom clamp arm. At the same time put self-lock nut on and hand tighten until the clamp arm touches the leading edge of the wicket gate. Since the worker is at a relatively safe location, this worker will be responsible for the next step. This process takes 2 minutes to finish.

[redacted]

Figure 35. Operation of installing clamp arm

Step #3: The last step is tightening the self-lock nut until the right edge of the clamp arm reaches the red line shown in Figure 36. Before tightening, make sure the device is horizontal and we recommend tightening the top clamp arm first. Once the clamp arms of the device are tight with the wicket gate, the worker can pull down on the device to test it to it is tight enough. If not, check that the device is horizontal. Make sure the contact surface fully touches then tighten again.

[redacted]

Figure 36. Operation of installing clamp arm on the main frame using self-lock nut

If the operation is smooth, the whole process will not take more than 15 minutes. If there is a fall occur, the device needs to be checked and reset. First, check to see if the clamp is loose. Workers can see from the scale shown in Figure 36 whether the clamp arms are loose. If there are signs of loosening, the worker needs to completely loosen the self-lock. Check to see if there is damage to the nut (replace the self- lock if necessary) and repeat the installation steps one to three. Secondly, check to see if the main structure has been deformed. For example, check if the mid board, main clamp frame is deformed or loose. Lastly, the worker should check the rubber mat. If there are obvious cracks on the rubber mat surface or deformation of the rubber, the rubber mat should be replaced.

2.5 Cost Analysis

This following section describes the total cost of manufacturing the final design assembly. The cost analysis is divided into two parts: fabrication parts and purchased parts. This analysis has been compiled into a table.

2.5.1 Fabrication Parts Cost Analysis

The TABLE VI breaks down all of the sourced components used in the final design. Parts are sorted by sheet number, quality, description, material used for parts, size of the parts and the price from the sources. For the majority of the fabricated parts, such as hollow cylindrical rod, arched clamp arm and mid plate, these are manufactured by manufacturing suppliers. The team treats the cost analysis of the manufacturing process as an estimated higher price scenario. However, some of the bigger companies such as would have long-term suppliers for manufacturing devices which can offer lower manufacturing price to reduce the whole cost by around 30% to 40%. Lastly, it should be noted that the rubber mats used in the design have different sizes which are required to be manufactured separately.

TABLE VI. BILL OF MATERIAL OF FABRICATION PARTS

Item	Quality	Description	Made From	Size
1	2	Hollow Cylindrical Rod	Alloy Steel	48x8.38x1.18 in^3
2	2	Arced Clamp Arm	Alloy Steel	6.56x9.88x1.18in^3
3	2	Rubber mat	Rubber (60 A Belt)	18 in^2 with 7.67-inch Arc Length
4	2	Rubber mat	Rubber (60 A Belt)	56.18 in^2 with 26.9-inch Arc Length
5	2	Rubber mat	Rubber (60 A Belt)	20.94 in^2 with 9.14-inch Arc Length
6	1	Mid plate	Rubber (60 A Belt)	11.7” × 3.02”

2.5.2 Purchased Parts Cost Analysis

The TABLE below illustrates the purchased parts of the structural assembly. The parts are sorted by sheet number, quality, description, material used for parts, size of the parts and the price from the sources. Most of the purchased parts are obtained from the vendor McMASTER CARR where could get some parts with a discounted price in order to cut the total purchased cost down by approximately 25%.

TABLE VII. BILL OF MATERIAL OF PURCHASED PARTS

Item	Quality	Description	Made From	Size	Manufacturer (or Dist.)	Price ($)/ per unit
1	2	Connecting Rod	6061 Aluminum	3/4”-10 Thread - 24” Length	McMASTER-CARR	34.39
2	2	Extra-Wide Steel-Insert Locknut	Steel	¾”-10 Thread Size	McMASTER-CARR	6.98
3	2	Threaded Linear Motion Shaft	52100 Alloy Steel	3/4" Diameter-14” Length	McMASTER-CARR	71.84
4	4	Extra-Wide Steel-Insert Locknut	Steel	1/2"-13 Thread Size	McMASTER-CARR	4.71
5	1	Black-Oxide Alloy Steel Socket Head Screw	Black-Oxide Alloy Steel	3/4"-16 Thread Size-2 ¾” Length	McMASTER-CARR	4.66
6	1	High-Strength Steel Thin Nylon-Insert Locknut	Zinc-Plated Steel	3/4”- 16 Thread Size	McMASTER-CARR	2.50
7	1	Swivel Hoist Ring- type 203 metric thread with alloy steel washer	Forged alloy steel, quenched and tempered	M8 * 1.25	RS Industrial Services	79.05
					Total Cost ($)	331.47

2.5.3 Manufacturing and Assembly Cost

For the manufacturing and assembly cost, since there is no information about operational processes such as grinding, turning, milling, sawing, welding as well as the material handling costs, the team set up an approximate labor wage at $30.00 USD per hour. Based on this scenario, the team estimates the whole manufacturing process should be within 5 working days assuming 8 working hours per day. Also, such overhead rate should also be included into analysis with $10 USD per hour and some other machine cost are taken into consideration as shown in the table below.

TABLE VIII. COST SUMMARY OF MANUFACTURING AND ASSEMBLY

Total Manufacturing Hour (hrs)	40
Labor Rate ($USD/hr)	$30.00
Total Manufacturing Labor Cost ($USD)	$1200.00
Overhead Labor Rate ($USD/hr)	$10
Total Overhead Labor Cost	$400.00
Total Manufacturing and Assembly Cost	$1600.00

2.5.4 Summary of Design Cost

The table below shows the summary of the fabricated parts, purchased parts as well as manufacturing and assembly costs. As indicated in the table, 17.16% accounts for the cost of purchased parts and 82.84% is taken by the manufacturing cost. It shows that most of the design cost accounted from the manufacturing and assembly cost.

TABLE IX. SUMMARY OF DESIGN COST

Cost Item	Cost ($)	% of the Design Cost
Total Purchased Parts Costs	331.47	17.16
Total Manufacturing and Assembly Costs	1600	82.84
Total Whole Design Cost	1931.47	100

3. Project Summary and Recommendation

requires an engineered anchor device or system to anchor their workers fall arrest equipment when performing turbine maintenance work. The current methods used by company employees now result in large free-fall distances and create tripping hazards for the workers. The purpose of the anchor device is to reduce the free-fall distance for employees and allow them to perform maintenance work without inhibiting movement. The anchor system should also be easy to install and disassemble while adhering to all safety standards set by the province of . The client has also requested that the design be light weight and keep all existing structures with no alterations. The team has been given a budget of $5000 to stay within for our design.

The team's design process followed a three-phase approach as taught in our Engineering Design course. The three phases included Problem Definition (Phase 1), Concept Generation and Selection (Phase 2), and Final Design (Phase 3). Each phase was completed in a detailed fashion following the client's needs and specifications.

During the first phase of the project, the team worked with the client to define the problem and understand the customer needs. Each customer need was analyzed to create target specifications and metrics to measure them by. The scope and objectives of the project were also defined during this phase, as well as constraints and limitations for the project. In addition, the team identified the project deliverables and created a project schedule including internal deadlines, project milestones, a work breakdown structure and a Gantt chart.

The second phase of the project was started by performing research on fall arrest anchor system types. After completing our research, the team begun generating potential concepts for our final design. Each team member came up with a minimum of three concepts, which resulted in a total of 13 design concepts. Following the completion of our concept generation, the team performed an in-depth concept screening and scoring process which led us to our final design.

The team began the final phase of the project by performing hand calculations and finite element analysis (FEA) to analyze the stresses in our final design which was selected at the end of the previous phase. Phase 3 of the project primarily involved optimizing our final design to ensure it was the best possible design for our client. A thorough cost analysis was also executed during this phase of the project. Once the analysis of the design was complete, the team created the final technical engineering drawings and bill of materials for the client.

The project was successfully completed as the team's final fall-arrest anchor device design meets all of the client's needs and specifications. The total cost of the final design is $1931.47, which includes the cost of all purchased parts as well as manufacturing and assembly costs. The specifications of the team's final design comply with the customer needs and target specifications which were set during phase 1 of the project. The final fall arrest anchor design reduces the worker's free-fall distance by 60 inches and will not inhibit their movement. Furthermore, the final design is easy and safe to install or disassemble and will not alter any of the existing structures. Lastly, the team has created a design that is lightweight and small which will allow the device components to fit through the scroll hatch opening.

Moving forward, the team recommends the following to the client. All engineering drawings and analysis are to be considered as preliminary since none of the team members are Professional Engineers. Therefore, the team recommends that all technical drawings, hand calculations and finite element analysis be reviewed by the client or another certified Professional Engineer prior to continuing with the production of the design.

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Appendix A: Moment of Inertia Calculation

In this section, the comparison of the bending resistance between the solid round rod and hollow round tube is present. The moment inertia of a shape as a property of a cross section can be used to predict the resistance to bending. Two key components to determine the deflection of a structure are the load applied and its geometry of the cross section. The relationship between the moment inertia and the resistance to bending is directly proportional.

The formulas for the moment inertia for solid and hollow round tubes are

$$I_s = \frac{\pi d^4}{64} \text{(for solid round rod)}$$

$$I_h = \frac{\pi(d^4 - d_i^4)}{64} \text{ (for hollow round tube)}$$

Where $d = outer\ diameter$, $di = inner\ diameter$.

The assumption on this calculation is that both rod and tube are made of the same material. The outer diameter is 1.17 inches and the inner diameter is 0.8 inches.

Solid Rod:

$$Area\ A_s = \pi(\frac{d}{2})^2 = \pi(\frac{1.17\ inch}{2})^2 = 1.075\ in^2$$

$$Moment\ of\ inertia\ I_s = \frac{\pi d^4}{64} = \frac{\pi(1.17)^4}{64} = 0.09198\ in^2$$

Hollow Tube:

$$Area\ A_h = \pi(\frac{d}{2})^2 - \pi\left(\frac{d_i}{2}\right)^2 = \pi\left(\frac{1.17\ inch}{2}\right)^2 - \pi\left(\frac{0.8\ inch}{2}\right)^2 = 0.5725\ in^2$$

$$Moment\ of\ inertia\ I_h = \frac{\pi(d^4 - d_i^4)}{64} = \frac{\pi(1.17^4 - 0.8^4)}{64} = 0.07188\ in^2$$

So, comparing moment of inertia for the hollow tube and solid rod:

$$\frac{I_h}{I_s} = \frac{0.07188}{0.09198} = 0.7815$$

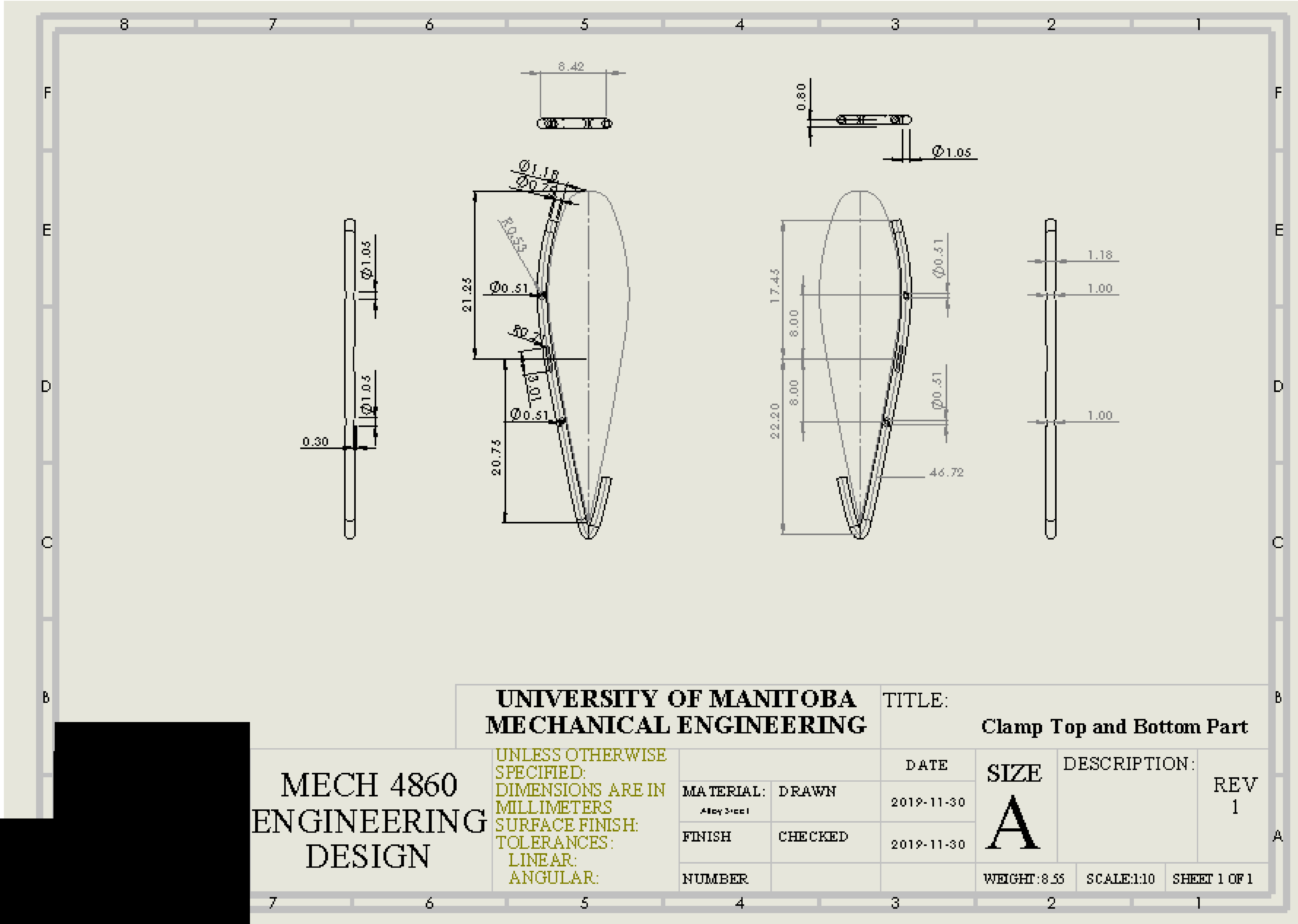
$$\frac{A_h}{A_s} = \frac{0.5725}{1.075} = 0.5326$$

Therefore, the moment of inertia of hollow tube is approximately 78% of that of solid rod but the cross- sectional area of hollow tube which is directly relevant to the weight is only 53% of the solid rod indicating that for the same cross-sectional area, hollow tube obtains higher ability to resist bending.

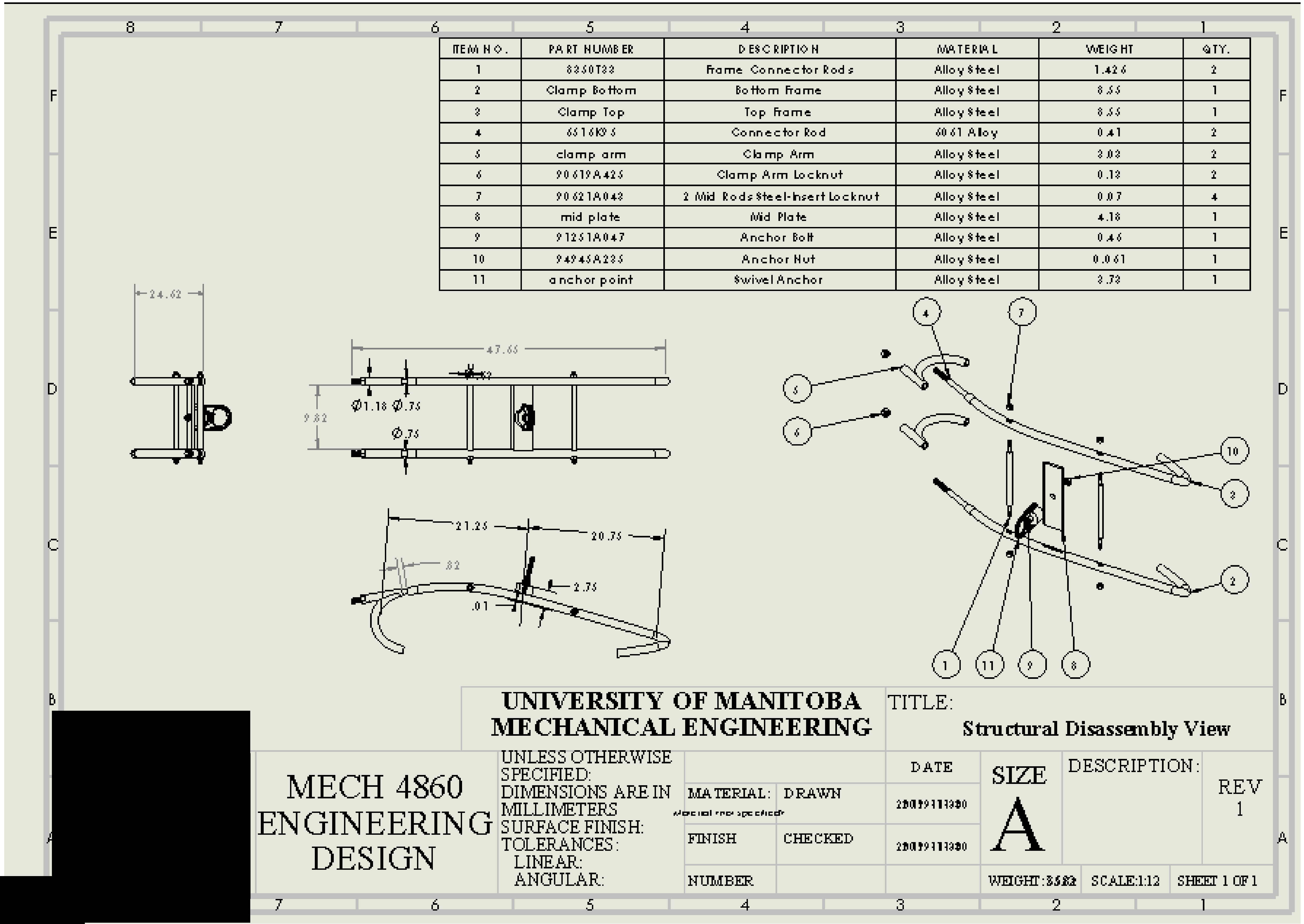
Appendix B: Final Design Technical Engineering Drawings

The following section contains the preliminary engineering drawings of final design and the figure xx is the final assembly drawing of the team's design. Before moving forward to the manufacturing process, these engineering drawing should be reviewed and signed by the head of manufacturing department.

[redacted]

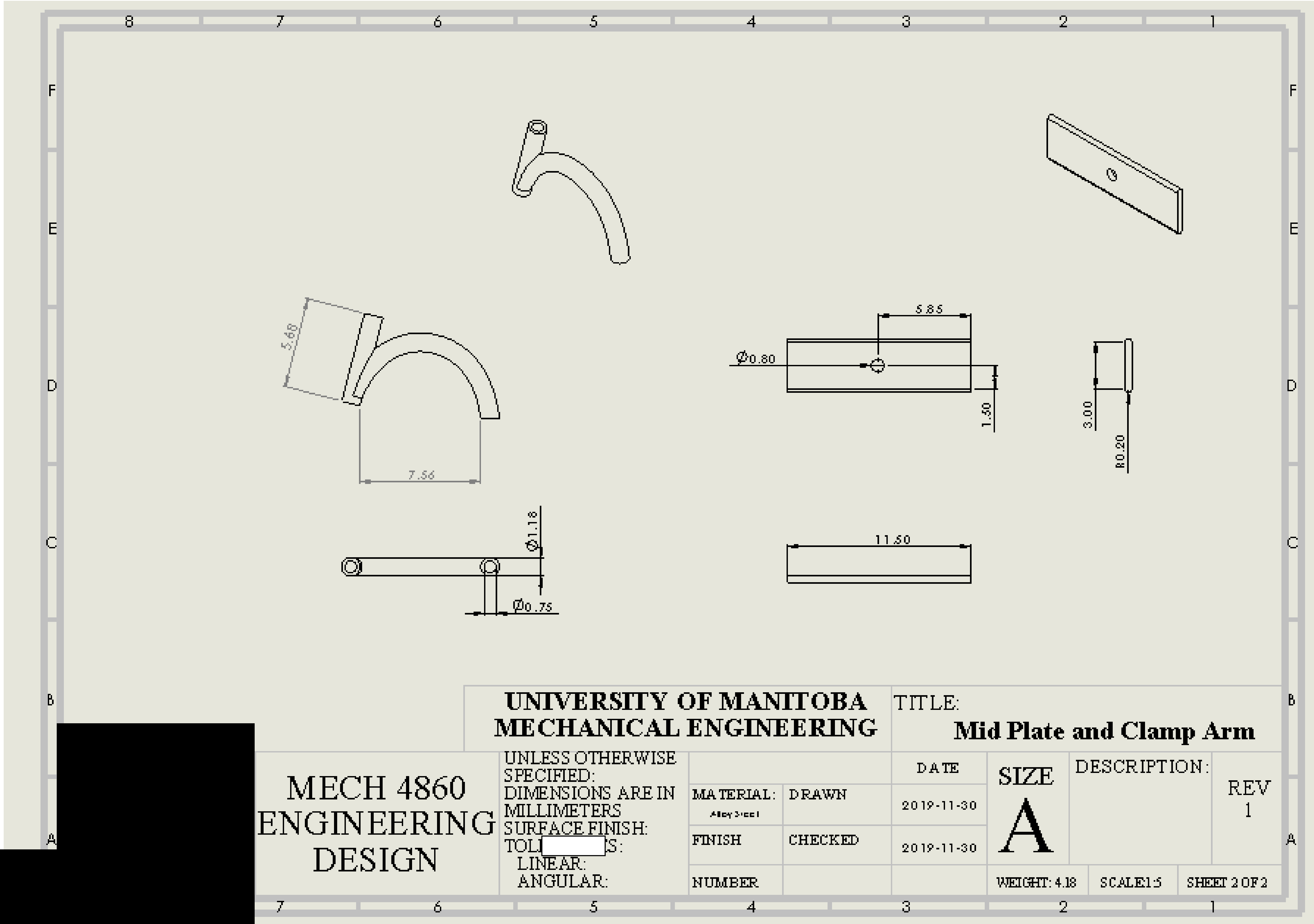

8.42
0.80
Ø1.05
Ø1.18
Ø0.72
R0.53
21.25
Ø0.51
Ø0.72
3.01
Ø0.51
20.75
Ø1.05
Ø1.05
0.30
17.45
8.00
8.00
22.20
Ø0.51
Ø0.51
46.72
1.18
1.00
1.00
UNIVERSITY OF MANITOBA
MECHANICAL ENGINEERING
TITLE:
Clamp Top and Bottom Part
MECH 4860
ENGINEERING
DESIGN
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
DATE
MATERIAL:
Alloy Steel
DRAWN
2019-11-30
FINISH
CHECKED
2019-11-30
NUMBER
SIZE
A
DESCRIPTION:
REV
1
WEIGHT: 8.55
SCALE:1:10
SHEET 1 OF 1

[redacted]



ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	WEIGHT	QTY.
1	8350T33	Frame Connector Rods	Alloy Steel	1.426	2
2	Clamp Bottom	Bottom Frame	Alloy Steel	8.55	1
3	Clamp Top	Top Frame	Alloy Steel	8.55	1
4	6516K95	Connector Rod	6061 Alloy	0.41	2
5	clamp arm	Clamp Arm	Alloy Steel	3.03	2
6	90619A425	Clamp Arm Locknut	Alloy Steel	0.13	2
7	90621A043	2 Mid Rods Steel-Insert Locknut	Alloy Steel	0.07	4
8	mid plate	Mid Plate	Alloy Steel	4.18	1
9	91251A047	Anchor Bolt	Alloy Steel	0.46	1
10	94945A235	Anchor Nut	Alloy Steel	0.061	1
11	anchor point	Swivel Anchor	Alloy Steel	3.73	1

[redacted]


5.85
Ø0.80
1.50
3.00
R0.20
5.68
7.56
Ø1.18
Ø0.75
11.50
UNIVERSITY OF MANITOBA
MECHANICAL ENGINEERING
TITLE:
Mid Plate and Clamp Arm
MECH 4860
ENGINEERING
DESIGN
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
LINEAR:
ANGULAR:
DATE
MATERIAL:
Alloy Steel
DRAWN
2019-11-30
FINISH
CHECKED
2019-11-30
NUMBER
SIZE
A
DESCRIPTION:
REV
1
WEIGHT: 4.18
SCALE1:5
SHEET 2 OF 2

[redacted]

Appendix C: Concept Generation and Selection Process

1. Research of Anchor Structure and Anchor Point

The following sections describe the research of anchor structure as a major component of the whole system and based on the research, optimization and adaption on the final design. Also, the research of anchor point outlines the advantages and disadvantages of different shapes in order to aid in the process of concept generation.

1.1 Research of Anchor Structure

The fixture method of temporary fall arrest system is primarily a component of a personal fall arrest system which can be used for positioning the worker, restricting the travelling of workers and keeping workers under safe working environment. After researching different methods, the three most common methods and their advantages are as follows.

[redacted]

A sliding beam anchor is an anchor connector designed to move along the structure as a component of the attached personal fall arrest system. It provides complete mobility and the anchor can effortlessly slide across the beam eliminating the contact between metal and metal without using any pin or chain. The advantage of this method is the locking mechanism which protects the anchor from accidental disengagement.

[redacted]

The freestanding counterweight anchor, which can be regarded as a single anchor point system, is one of the most common fixture methods for a temporary fall arrest device. The tie-off point can be attached with lifelines or a lanyard. The whole structure is simply placed on the working surface of the bottom ring. The advantage to this method is that it is simple, fast and efficient in installation and disassembly.

[redacted]

Another method is the beam trolley which is a type of moveable anchorage connector used to support the worker. The anti-friction bearings at the top the structure connect with the horizontal bar through two components welded on the bar. At the middle of the horizontal bar, the anchor point is attached with a strip on the horizontal bar. The advantage to this method is that the beam trolley can be positioned anywhere on the wicket gate to provide mobility for the worker while also having the capability to be fitted at a specific location by workers.

1.2 Research of Anchor Point

Asymmetric D shape anchor, also called modified D carabiners, have similar features as the regular D shape anchor point while it has slightly smaller size at one end which leads to reduction on weight. The asymmetric shape having larger gate openings than that of regular D shape which makes worker clipping easier. However, this shape is more expensive than other shapes and not as strong as the regular D shape.

[redacted]

Pear shape carabiners with large gate openings which allows easier attachment of ropes and gear. The advantages of this pear-shape carabiner are easy to use as a result of large opening gate and specifically designed for the security of belaying and rappelling while it is heavier and weaker than other shapes.

[redacted]

Oval carabiners having smooth, uniform top and bottom curves to restrict load shifting is not as strong as other shapes. One of the advantages is the ability to hold more gears while it has smaller gate opening and not as strong as other shapes.

[redacted]

2. Concept Generation

Concept generation process involves brainstorming of alternative concept to meet the target specifications of the project. At the beginning of concept generation, every member of the team was tasked to come up with a minimum of three different concept with the terms of anchor structure and anchor point in the aspect of location and attachment method. The outcome of this concept generation process is a total number of 13 concepts of structural design. The detailed description of each concept is presented as below.

Concept A

This concept utilizes a clamp style design for securing the fall arrest anchor system onto stay vanes and wicket gates. The design utilizes a U-shaped anchor, and is fixed onto the main frame by bolt, nut, washer assembly. Two L-shaped arms act as clamps and are lined on the interior with a plastic to allow for extra grip on existing structures. In addition, the L-shaped arms have a hollow square opening on the body to allow for horizontal movement along the main support bar. There are two circular holes near the bottom of the L-shaped arms to allow for insertion of a threaded rod with a lever on one end and bolt on the opposite as an additional securing method. The clamp width can be adjusted using the drilled holes on the main frame and is secured by locking pins.

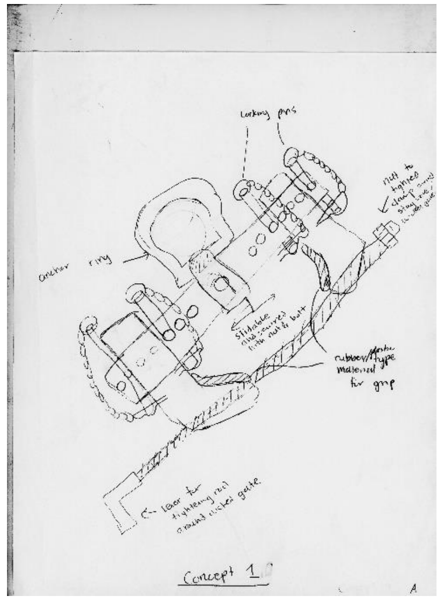


Figure 43. Concept A

Concept B

This concept uses a counter-weight design for securing the fall arrest anchor system on the bottom ring floor. The design uses a threaded rod with a circular anchor. The anchor is threaded into the pole, that is also threaded onto the main base plate. Each of the three base plate legs is drilled to allow for insertion of a bolt onto which weights can be stacked and secured by a nut. The base plate is lined with a plastic on the bottom, to allow for extra grip to the bottom rip floor.

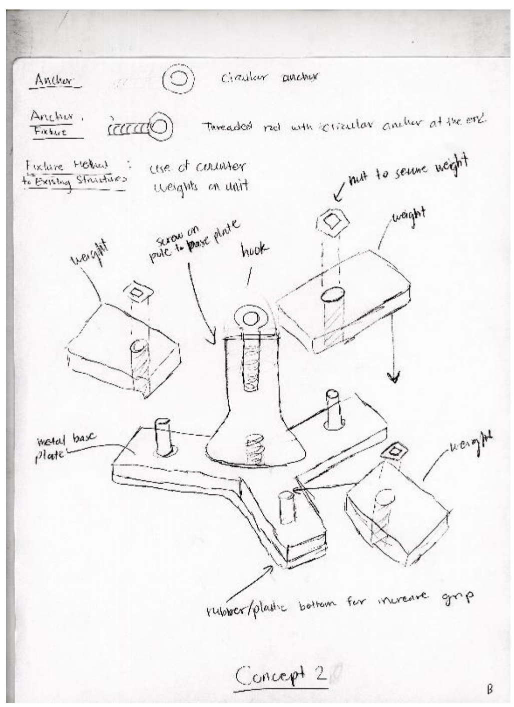


Figure 44. Concept B

Concept C

Similar to the first design, this design utilizes a clamp style design for securing the fall arrest anchor system onto the wicket gates or stay vanes. The design uses a D-shaped anchor and is secured onto the main body frame by bolt, nut washer assembly. The design uses C-shaped arms that can slide on the main body frame horizontally. The C-shaped arms are lined with a plastic on the inside to allow for extra grip, and the arm width can be adjusted using locking pins.

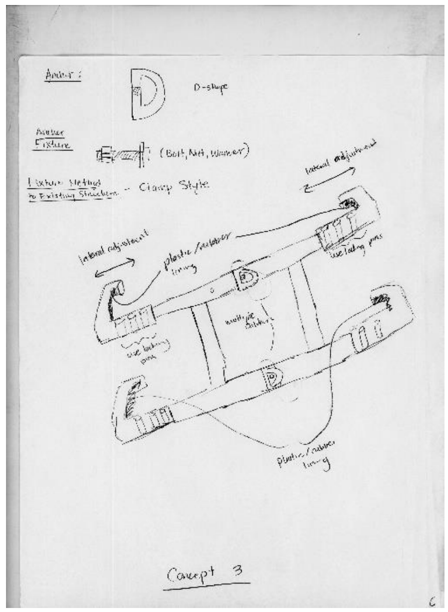


Figure 45. Concept C

Concept D

This concept is characterized by use of the circular track above head-level, as an anchor point. As shown in Figure 46, the detachable track is bolted to the temporary fixed support. A trolley anchor device can slide along the track. The type of the anchor utilized in this design is a D-shaped anchor and is bolted onto the trolley anchor device. The free moving rollers in the design allow for smooth travel around the work area while always remaining tied off. The method to fix the temporary fixed support involves using a clamp arm structure to clamp the stay vanes or wicket gates shown in Figure 47. Using an adjustable plunger, the two structures are connected then fixed with a bolt.

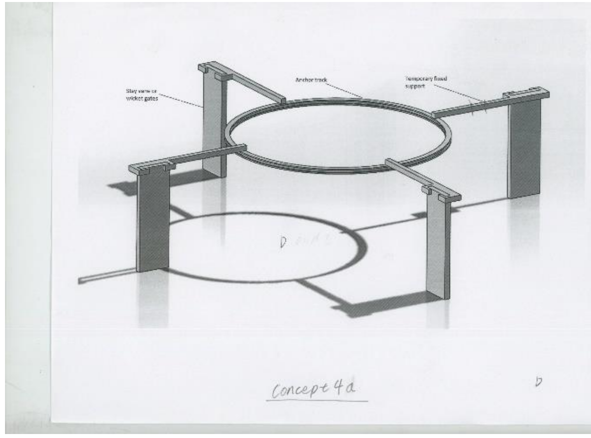


Figure 46. Concept D (a)

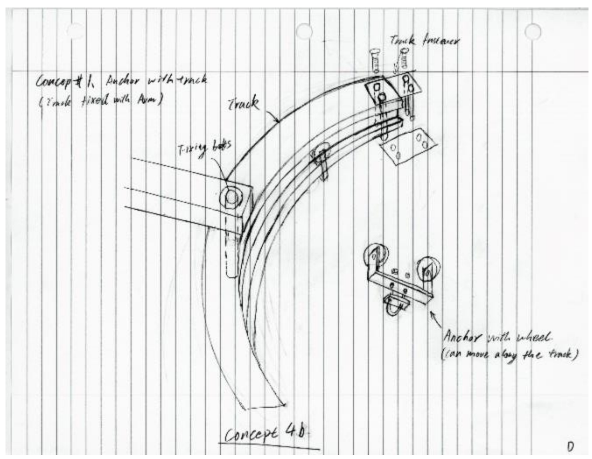


Figure 47. Concept D (b)

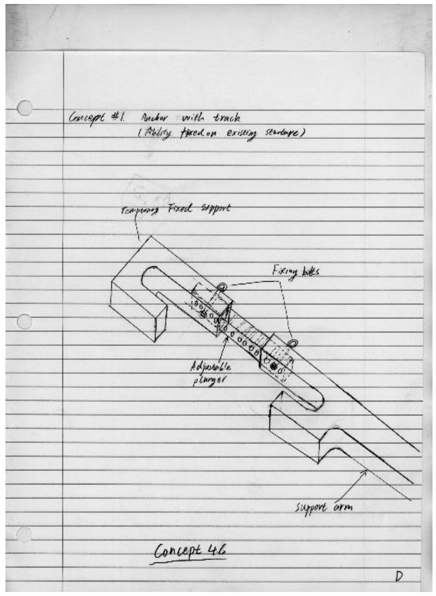


Figure 48. Concept D (c)

Concept E

The special feature of this concept is that the position of the anchor can be adjusted. This device can be installed on any two or more stay vanes and wicket gates. This design is connected to other designs through use of a common overhead lifeline. The worker can adjust the position of the anchor connector to change the activity range. The type of the anchor utilized in this design is a D-shaped anchor which is bolted onto the connector. The method used to fix the temporary fixed support is by using a clamp arm structure to clamp to the stay vanes or wicket gates shown in Figure 49. The adjustable inter-pluggable is used to connect the two structures then fixed with a bolt.

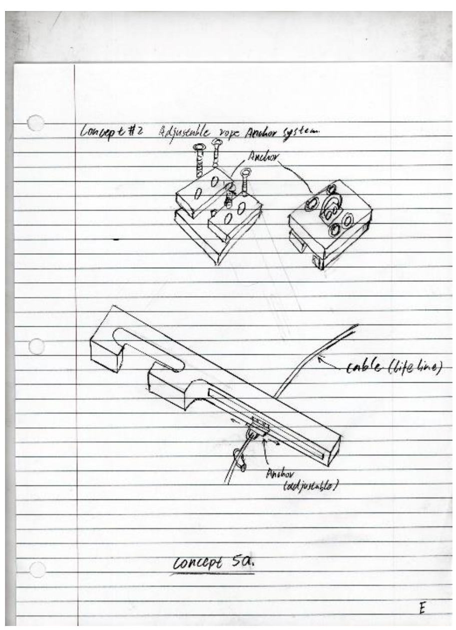


Figure 49. Concept E (a)

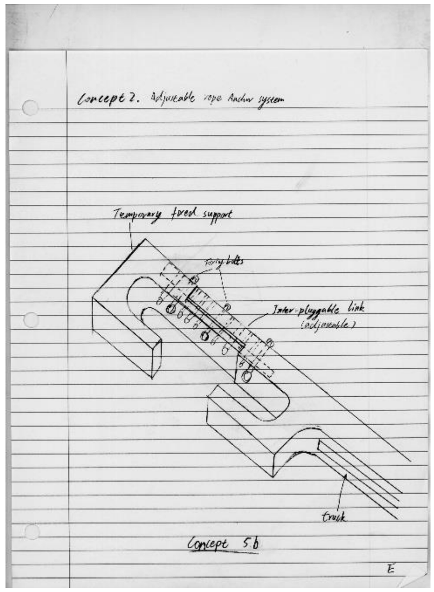


Figure 50. Concept E (b)

Concept F

This concept is meant to be fixed on the stay vanes or wicket gates. This concept has two major characteristics. First, the design is easy to install. It must only be adjusted to the required size and then it can be clipped on the stay vanes or wicket gates as shown in Figure 51. Second, the design is and fixed by bolt.

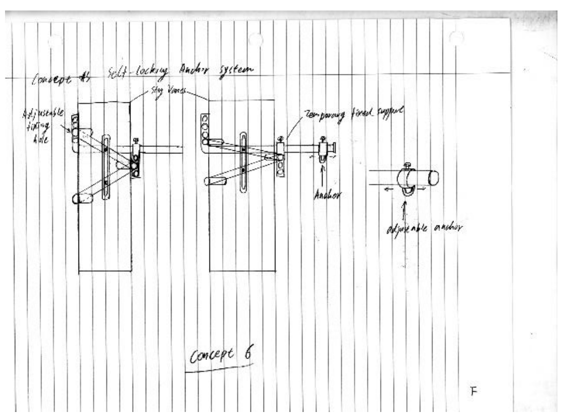


Figure 51. Concept F

Concept G

This concept involves using padded handle tie down straps to hold the device on the stay vanes or wicket gates. The straps must be wrapped around the stay vanes or wicket gates and the ratchet strap must be tightened. There are two D-bolt forged anchors bolted on the temporary fixed plate at different heights.

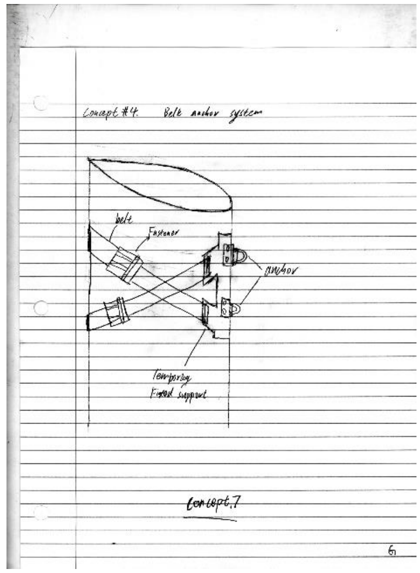


Figure 52. Concept G

Concept H

This concept involves three pipe sections stacked together with a D-ring attached to each pipe section. The pipe sections are anchored by a weighted plate.

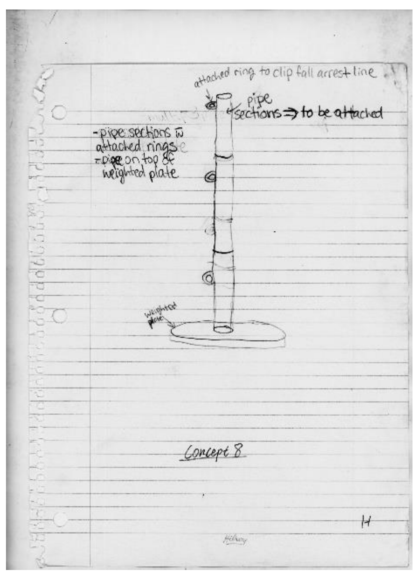


Figure 53. Concept H

Concept I

This concept involves a plate that can be attached to a stay vane or wicket gate using the attached vice mechanism. A D-ring is attached to the front side of the plate for fall arrest equipment to clip onto wicket gate or stay vane.

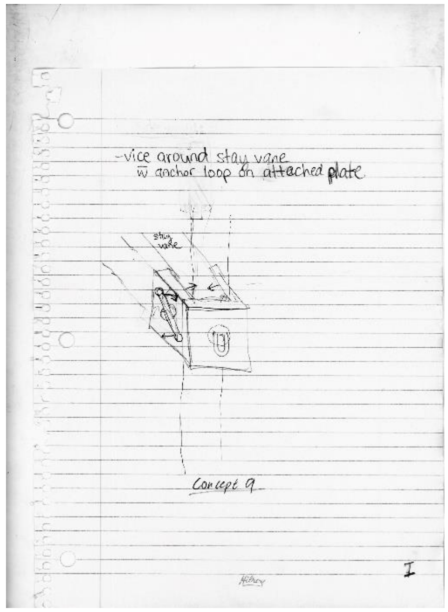


Figure 54. Concept I

Concept J

This concept involves a beam with vices at either end which would attach to and run between 2 wicket gates. A D-ring is attached to the bottom of the beam for fall arrest equipment to clip onto wicket gate or stay vane.

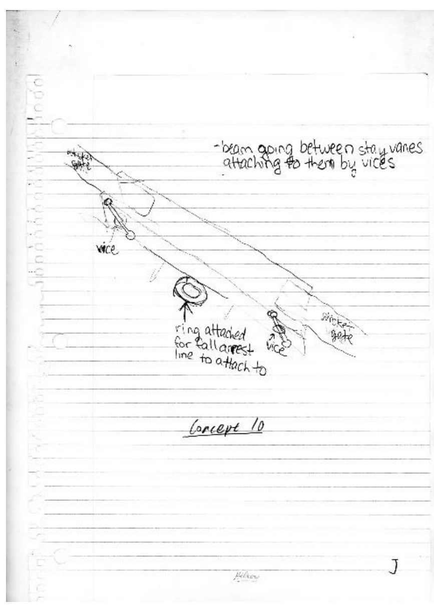


Figure 55. Concept J

Concept K

This concept contains a water tank which is empty before installation and input water when installation. The top of the tank is a rotation responsive engagement device which is locked when the worker pulls the rope attached on the ring.

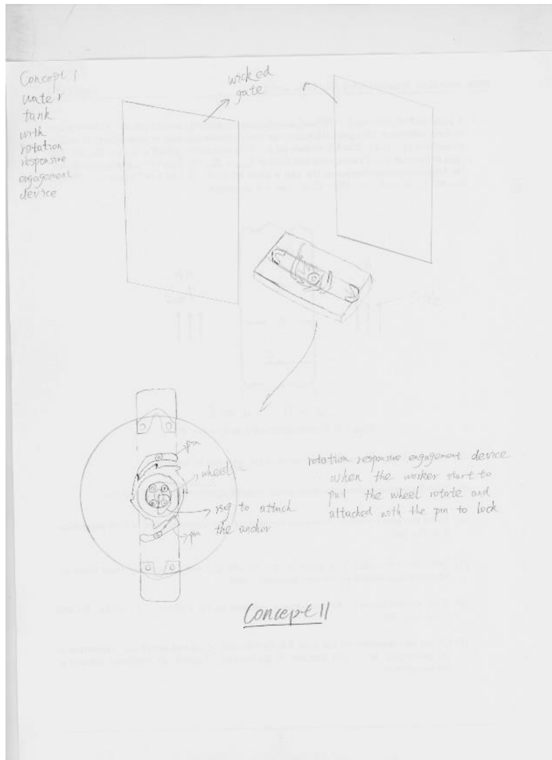


Figure 56. Concept K

Concept L

This concept contains an anchor structure inserted at the back-bottom location of wicked gates with a mounting flange provided with an anchor mounting bracket fixing on it.

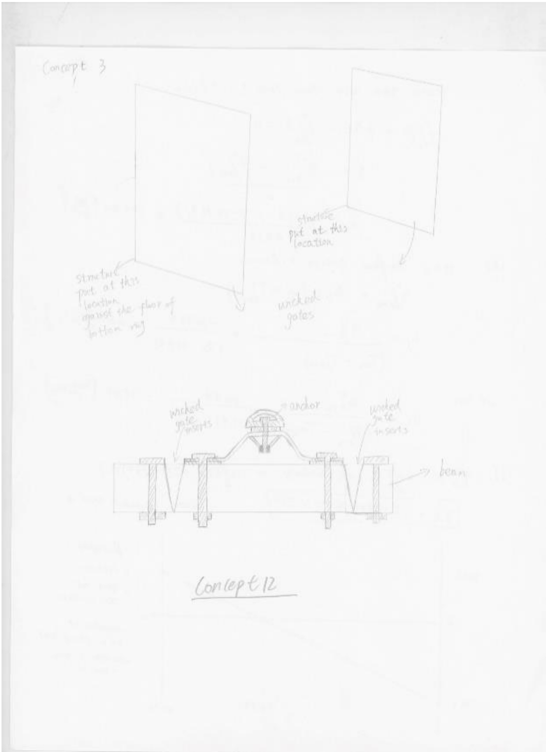


Figure 57. Concept L

Concept M

This concept contains an anchor structure This concept is a vacuum anchor fall arrest system which is attached on the wicked gates with a tie structure connecting two ropes from two vacuum device. The air should be vacuumed before using this system to ensure the safety of the worker.

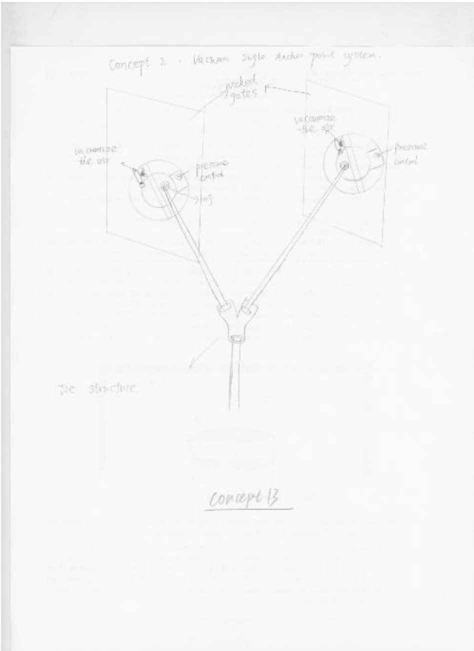


Figure 58. Concept M

3. Concept Selection Criteria

The team first re-analyzed the customer needs, design constraints, and metrics to develop appropriate concept screening criteria for the generated concepts. The criteria and definition are shown in TABLE X.

TABLE X. CONCEPT SCREENING SELECTION CRITERIA AND DEFINITION

Selection Criteria	Definition
Safety	This criterion focuses at the overall safeness of the design, geometry, fixture methods, and if the design introduces any risks to workers.
Compatibility	This criterion looks at the compatibility of the conceptual design with the existing structures in the work space such as the bottom ring floor, wicket gates, and stay vanes.
Performance	This criterion compares the concept regarding to performance to reduce the free fall distance against current methods.
Design Mobility	This criterion investigates the mobility and portability of the design and the individual components through analysis of size, weight, and number of components.
Worker Mobility	This criterion assesses the impact of the conceptual design on the mobility and work performance of workers in the work space.
Ease of Use	This criterion analyzes the ease of use of the conceptual design through analysis of overall effort required to construct the design, number of components and tools utilized, and assembly and disassembly times.
Manufacturability	This criterion assesses the manufacturability of the design based on complexity of design geometry, additional processing requirements, and cost to manufacture.

4. Concept Screening

The purpose of this section is to eliminate concepts which are not acceptable or meeting the target specification involving comparing concepts based on several criteria. Besides, concept scoring is conducting based on the same criteria with a weighted percentage according to importance to each criterion. The outcome of this section is to decide the concept to develop further.

4.1 Temporary Fixed Support to Current Structure Design

The concept screening for this section will be focused on the method to setup temporary fixed support to existing structures based on the criteria in. There are thirteen concepts have been selected for this concept screening, and finally three concepts can continue to develop. The screening matrix for the concept is show in TABLE XI. The three concepts will be described in this section.

TABLE XI. METHOD OF FIXTURE FOR CONCEPTS TO EXISTING STRUCTURES SCREENING MATRIX

	CONCEPT VARIANTS													
Selection Criteria	Ref	A	B	C	D	E	F	G	H	I	J	K	L	M
Safety	0	+	-	+	+	+	+	+	-	-	-	-	-	-
Compatibility	0	+	-	+	+	+	+	+	-	+	-	-	-	-
Performance	0	+	0	+	+	+	+	+	0	+	+	0	+	+
Design mobility	0	-	-	-	-	-	-	0	-	-	-	-	0	-
Worker Mobility	0	+	-	+	-	-	-	+	-	+	-	-	-	-
Ease of use	0	-	-	-	-	-	-	0	-	0	-	-	0	0
Manufacturability	0	-	-	-	-	-	-	0	-	-	-	-	0	-
PLUSES	0	4	0	4	3	3	3	4	0	3	1	0	1	1
SAMES	7	0	1	0	0	0	0	1	1	0	0	1	1	0
MINUSES	0	3	4	3	4	4	4	0	6	3	6	6	3	5
NET	0	1	-4	1	-1	-1	-1	4	-6	0	-5	-6	-2	-4
CONTINUE?		yes	no	yes	no	no	no	yes	no	no	no	no	no	no

<u>Concept A:</u>

Compared with current method, this concept has advantages in aspects of safety, compatibility, performance and mobility of worker. The first is safety, the conceptual design uses two L-shaped arms to clamp both edges of the stay vane or wicket gate as show in Figure 2 and Figure 3 to generate friction which can achieve the requirement of fixing. This concept has a tightening rod around the wicket gate which can increase the friction between the device and the stay vane or the wicket gate which tremendously improves the safety of the device. Secondly, with respect to the aspect of compatibility and performance, this concept obtains better scoring than the current method. The L-shaped arms have a hollow square opening on the body to allow for horizontal movement along the main support bar. In this case, the device can be applied on both stay vane and wicket gates. And the device can set up higher position than the current method due to the ability of adjustment of the device which is easier to reduce the free fall distance as a result of improvement of the performance. Due to small size of the design, it doesn't inhibit the mobility of workers. Furthermore, worker can adjust the height of the device according to the area of work. However, this concept is much heavier and more complicated compared with the current method. And the time of installation should be longer than that of current method regarding to the different components needs to manufacture. From the manufacturability this concept is not as good as the current method as the involvement of some mechanical technology. But in general, this concept can be continued to develop through this concept screening.

Concept C:

Considered with respect to safety, this concept includes two clamping structure with increasing contact area between the device and the stay vane or wicked gate rather than using one structure containing two L-shaped arms where the static friction increases to prevent the device from sliding off. This leads to the better safety performance. The design using C-shaped arms instead of L-shaped can also increase the contact area. Then, this concept also contains improvement in compatibility and performance. The utilization of D-shaped anchor which is fixed onto structure as it decreases the degree of freedom of fixture than the current method as of the rope application. Based on the small size of the design, it doesn't inhibit the worker's mobility. Furthermore, worker can adjust the height of the device according to the requirement of workplace. However, this concept is also considered to be heavier and more mechanical components than the current method which takes more time to set up. For the manufacturability, this concept with more components is more difficult to manufacture than the current method. Generally, this concept can be continued to develop through the concept screening section.

Concept G:

For safety, this concept using the padded handle tie down straps twines around the wicked gate or stay vane where the static friction is increased due to the increase of contact area between the device and the wicked gate or stay vane. The device becomes more stable as the value of static friction gets closer to the gravity force value. As the conceptual design only contains belt and fastener with temporary fixed support, the device is considered as more compatible and better performance due to the reduction of free fall distance with the implementation of the D-shaped anchor and adjustment of the position of device. The device is treated as portable device as of the small size design which does not influence the mobility of worker. For manufacturability, this concept is simple and similar structure as current method. To summarize, concept G can be carried on next stage of discussion in the concept screening section.

4.2 Anchor Fixture Method to Temporary Fixed Support Design

To narrow down the number of concepts, a concept screening matrix is introduced as shown in the Table below. The score "better than" (+)," same as" (0) and "worse than" (-) is distributed in each cell in the matrix based on rate of concept against the reference concept. The total rating is summed with corresponding rank order to determine the concept to develop further.

TABLE XII. METHOD OF FIXTURE FOR ANCHOR ON FALL ARREST ANCHOR DESIGN SYSTEM

	CONCEPT VARIANTS													
Selection Criteria		A	B	C	D	E	F	G	H	I	J	K	L	M
Safety	0	+	+	+	+	+	+	0	+	+	+	+	0	+
Performance	0	+	+	+	+	+	+	+	0	0	0	+	0	0
Design Mobility	0	-	0	+	-	-	-	+	-	-	-	-	-	0
Worker Mobility	0	0	0	0	+	+	0	0	0	0	0	0	0	0
Ease of Use	0	+	0	+	-	+	+	+	-	-	-	-	-	+
Manufacturability	0	-	0	-	-	-	-	-	0	0	0	-	-	0
PLUSES	0	3	2	4	3	4	3	3	2	2	2	2	0	2
SAMES	4	1	4	1	0	0	1	2	3	3	3	1	4	4
MINUSES	0	2	0	1	3	2	2	1	2	2	2	3	3	0
NET	0	1	2	3	0	2	1	2	0	0	0	-1	-3	2
CONTINUE?		yes	yes	yes	no	yes	yes	yes	no	no	no	no	no	yes

Seven concepts have been chosen to move forward in our selection process for this category. The table above outlines how these concepts have been selected to progress. Each concept has been found to be better overall than current methods. The concepts moving forward are Concepts A, B, C, E, F, G, and M.

From the concepts selected to move ahead, all of the concepts but G have improved safety over current methods, where concept G is as safe as the current methods. For performance, all of the chosen concepts except M have better performance while M performs as well as current methods. Concepts A, E, and F have less design mobility; however, concepts C and G have improved design mobility and design concepts B and M are as mobile as current methods. Worker mobility remains the same as current methods for all concepts except E which has better worker mobility. All of the concepts moving forward are easier to use than current methods with the exception of concept B which is as easy to use as the current methods. Manufacturability is unfortunately lower in all continuing concepts except for concepts B and G which are as easy to manufacture as the current methods.

4.3 Anchor Design

In order to help reduce the manufacturing time and costs, the team investigated possible D and U-shaped anchors available for purchase from current manufacturers. Some of the D-shaped anchor types found were D-ring anchor plates, D-ring bolt anchors and D-ring anchor straps. Two of the companies the team investigated for pricing were Acklands Grainger and Fastenal.

5. Concept Scoring

This section outlined the methodology used to finalize the design for the aspect in temporary fixed support to the current method and the anchor fixture method.

A Weighted decision matrix was introduced to determine the relative importance of each criteria corresponding to two aspects in this section. Each criterion was placed at the left and the top side of the tables with the intersecting rows and columns. The intersecting cells represents the comparison between two criteria based on the level of importance. The rank among each criterion can be listed as the outcome in this stage of analysis.

5.1 Concept Scoring for Temporary Fixed Support to Current Method

Criteria for the concept scoring conducted by comparing the temporary fixed support with the current method were determined according to customer needs. The results of the weighted decision matrix are shown in. The safety is our first priority and performance are alongside it. The following table is design mobility and ease of use. The worker mobility and manufacturability take the less weight.

TABLE XIII. CONCEPT SCORING FOR TEMPORARY FIXED SUPPORT TO CURRENT METHOD CRITERIA WEIGHTS

		Safety	Compatibility	Performance	Design Mobility	Worker Mobility	Ease of Use	Manufacturability
	Criteria	A	B	C	D	E	F	G
A	Safety		A	A	A	A	A	A
B	Compatibility			C	B	E	F	G
C	Performance				C	C	C	C
D	Design Mobility					F	E	D
E	Worker Mobility						F	E
F	Ease of Use							F
G	Manufacturability							
	Total Hits	5	1	5	3	2	3	1
	Weightings	0.25	0.05	0.25	0.15	0.1	0.15	0.05

TABLE XIV. CONCEPT SCORING FOR TEMPORARY FIXED SUPPORT TO CURRENT METHOD

		Concept					
		Concept A		Concept C		Concept G	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Safety	0.25	0.333333	0.0833333	0.666667	0.166667	0	0
Compatibility	0.05	0.333333	0.0166667	0	0	0.666667	0.033333
Performance	0.25	0.333333	0.0833333	0.666667	0.166667	0	0
Design Mobility	0.15	0.333333	0.05	0	0	0.666667	0.1
Worker Mobility	0.1	0	0	0.666667	0.066667	0.333333	0.033333
Ease of Use	0.15	0.333333	0.05	0	0	0.666667	0.1
Manufacturability	0.05	0.333333	0.0166667	0	0	0.666667	0.033333
Total Score		0.3		0.4		0.3	
Rank		2		2		1	
Continue?		No		Yes		No	

5.2 Concept Scoring for Anchor Fixture Method

As shown in the table above, our six criteria used for evaluating our concepts will be safety, performance, design mobility, worker mobility, ease of use, and manufacturability. Safety has been decided to be our most important criteria and therefore has been given a weighting of 0.333333. Performance and design mobility came second with a weighting of 0.2, followed by ease of use which had a weighting of 0.13333. Finally, worker mobility and manufacturability had the lowest weighting which was 0.066667.

TABLE XV. CONCEPT SCORING FOR ANCHOR FIXTURE METHOD CRITERIA WEIGHTS

		Safety	Performance	Design mobility	Worker Mobility	Ease of use	Manufacturability
	Criteria	A	B	C	D	E	F
A	Safety		A	A	A	A	A
B	Performance			B	B	B	F
C	Design mobility				C	C	C
D	Worker Mobility					E	D
E	Ease of use						E
F	Manufacturability						
	Total Hits	5	3	3	1	2	1
	Weightings	0.333333	0.2	0.2	0.066667	0.133333	0.066667

Table XVI. CONCEPT SCORING FOR ANCHOR FIXTURE METHOD

		Concept													
		Concept A		Concept B		Concept C		Concept E		Concept F		Concept G		Concept M	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Safety	0.333333	0.095238	0.031746	0.047619	0.015873	0.190476	0.063492	0.285714	0.095238	0.047619	0.015873	0.285714	0.095238	0.047619	0.015873
Performance	0.2	0.142857	0.028571	0.047619	0.009524	0.190476	0.038095	0.190476	0.038095	0.190476	0.038095	0.190476	0.038095	0.047619	0.009524
Design mobility	0.2	0.095238	0.019048	0.285714	0.057143	0.238095	0.047619	0.047619	0.009524	0.142857	0.028571	0.190476	0.038095	0	0
Worker Mobility	0.066667	0.190476	0.012698	0.047619	0.003175	0.047619	0.003175	0.238095	0.015873	0.285714	0.019048	0.047619	0.003175	0.142857	0.009524
Ease of Use	0.133333	0.1	0.013333	0.3	0.04	0.25	0.033333	0.05	0.006667	0.15	0.02	0.15	0.02	0	0
Manufacturability	0.066667	0.095238	0.006349	0.142857	0.009524	0.285714	0.019048	0	0	0.190476	0.012698	0.238095	0.015873	0.047619	0.003175
	Total Score	0.111746032		0.135238095		0.204761905		0.165396825		0.134285714		0.21047619		0.038095238	
	Rank	6		4		2		3		5		1		7	
	Continue?	No		No		No		No		No		Yes		No	

The table above displays our evaluation of the team's design concepts for the anchor fixture method. Concepts E & G have been given the best score for the safety criteria. Since safety has been chosen to be the heaviest weighted criteria, this score will count for the biggest portion of the total score of each concept. Concepts C, E, F, and G have the best performance score, while concept B scored the best for design mobility. By our concept scoring for anchor fixture methods, concept G has been chosen to advance in our selection process.

5.3 Final Concept to Develop Further

The goal of concept selection above is to develop the best concept. Through the concept screening and concept scoring base on the concept criteria. The final concept for the fall arrest anchor device is concept C which is the dual clamp and bar show in Figure 59. The ideal of this final concept is combined ideal from three concept. Through the concept scoring the method for fixing the temporary fixed support to the existing structure in concept C which is the dual clamp would worker better. And for anchor fixture method concept G which using the multiple bolts fixture. For the anchor the D-shape fixed anchor would be better. The subsection is the detail of the developed concept.

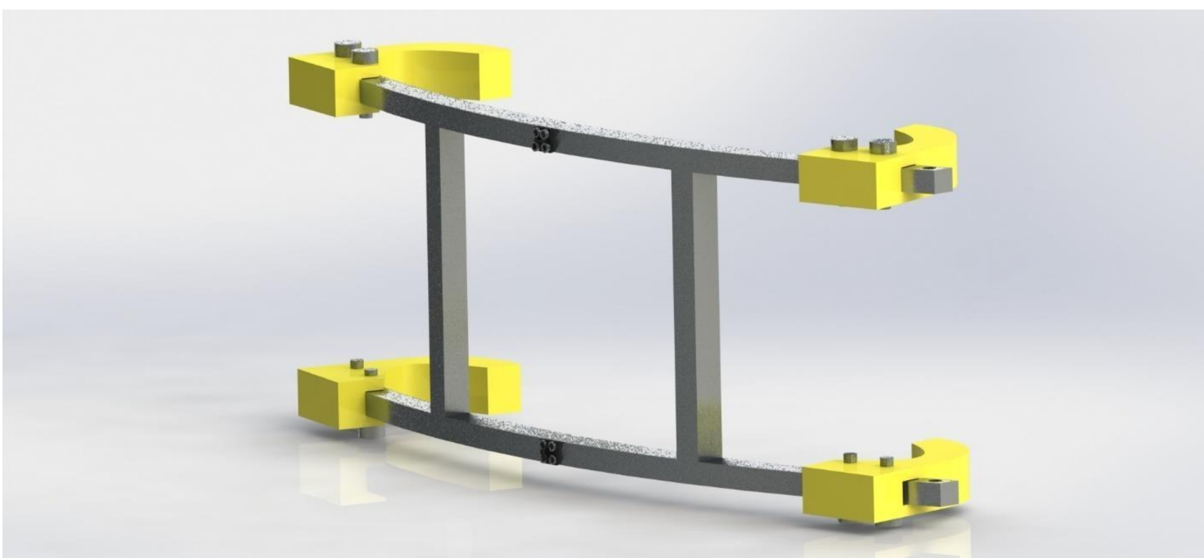


Figure 59. Final concept-dual clamp and bar

The fixture method for the final concept design is using 4 clamp arms to fix the device on the stay vane or wicket gate shown in Figure 60. This image is simulated the turbine distributor and the location of the stay vanes or wicket gate. The specific situation has some error with the actual situation. The main purpose is showing the method to fix the device to the stay vanes or wicket gate. The overall view is shown in Figure 61. The flat ring structure is the bottom ring level and the multiple vertical structure is the wicket gate. Since stay vanes is also the vertical structure and located behind the wicket gate this model does not show.

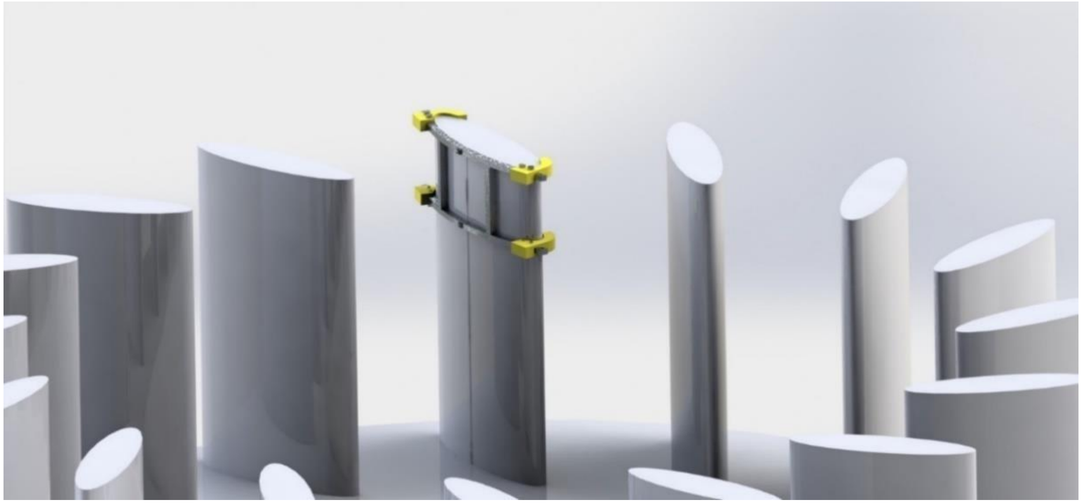


Figure 60. Fixture method for final concept

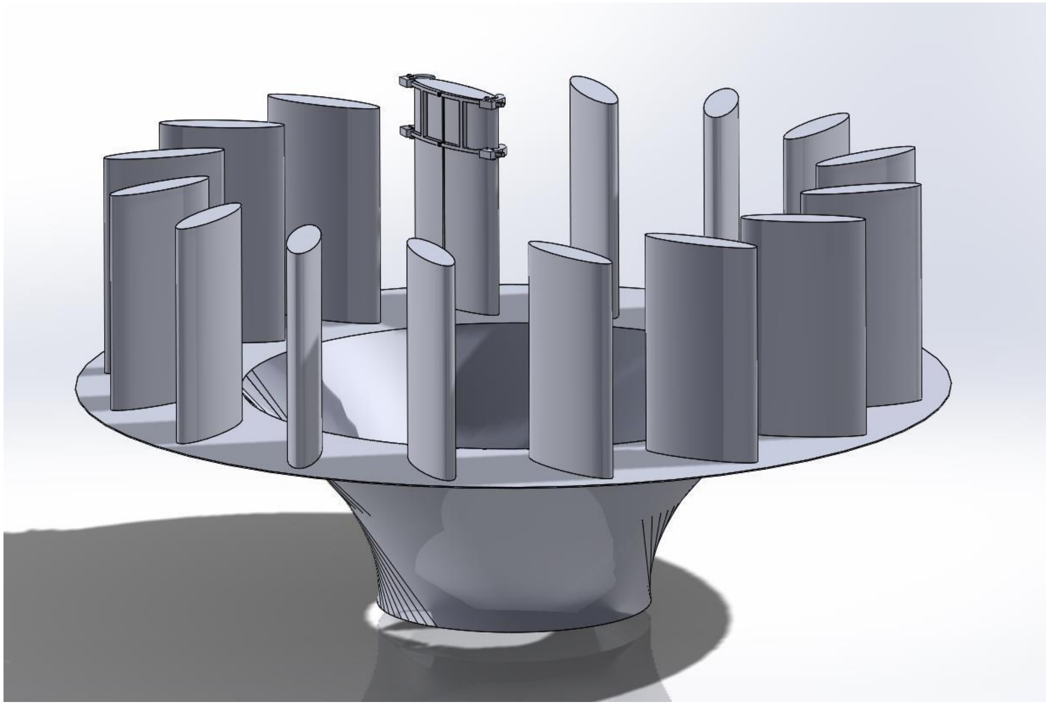


Figure 61. Overall view of the turbine distributor

It can be clearly seen from the Figure 60 and Figure 61 indicating that the fall arrest device can set up at the top of the wicket gate. In this case, the final concept reduced the free fall distance compared to existing methods show in Figure 62. The green arrow is the improved free fall distance and red arrow is the current free fall distance. The free fall distance has decreased significantly.

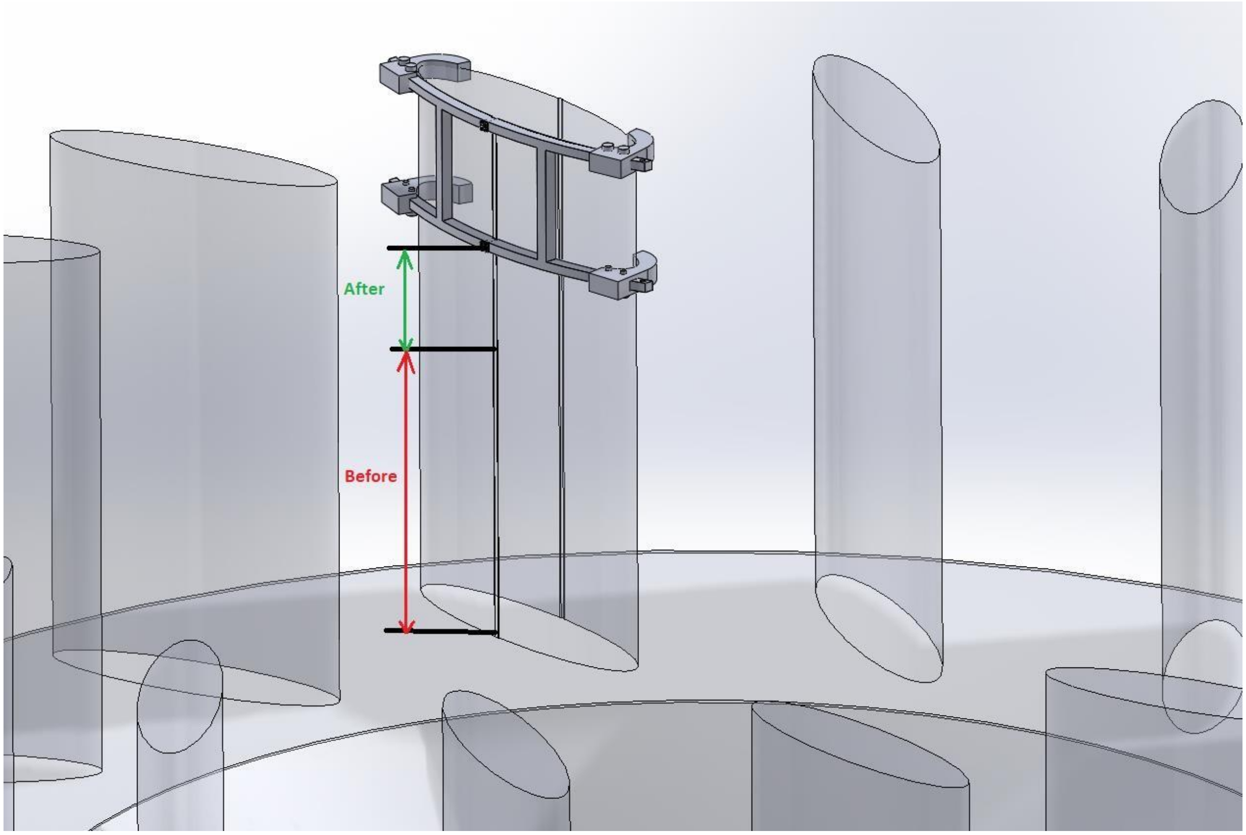


Figure 62. Final concept compared with the current method

In order to make the device safer, we changed the shape of the clamp arm show in Figure 63. The edge of the wicket gate can just fit in the internal shape of the clamp show in Figure 65 and connect the clamp arm and main bar by using the locking pin. It can improve the safety by increase the friction. The multiple hole on the dual bar allowed the worker adjust the width and fit with either stay vanes and wicket gate. By using the lock pin worker can quick and safe to set up and disassemble with minimal tools. However, during the manufacturing process it is hard to set up a fine adjustment between available locking pin holes and before put the lock pin in it is hard to generate the clamping load. In the next phase we will develop clamp arm fixture method by using the sawtooth bar similar to the sliding beam anchor show in.

[redacted]

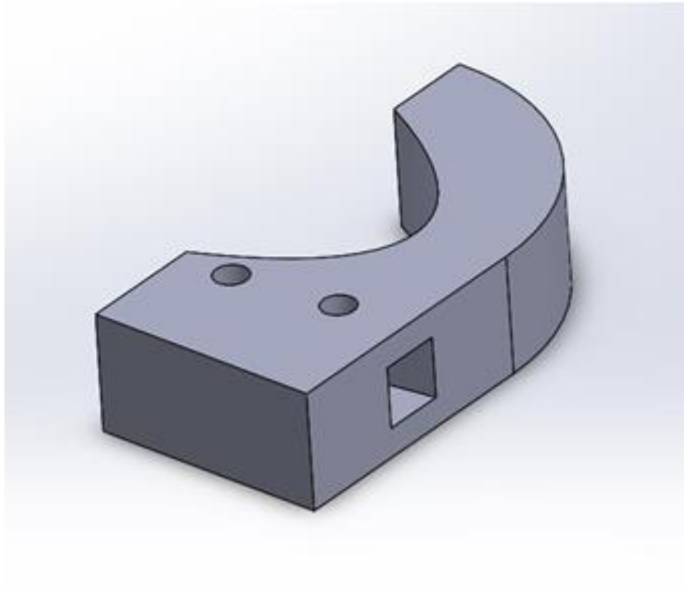


Figure 63. Initial clamp arm design

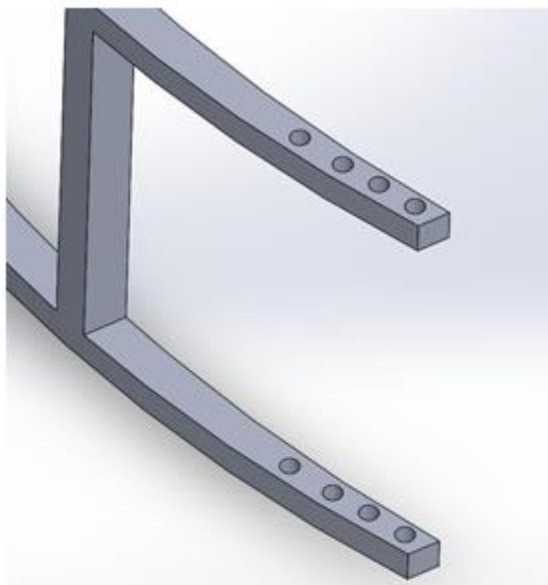


Figure 64. Fixture holes

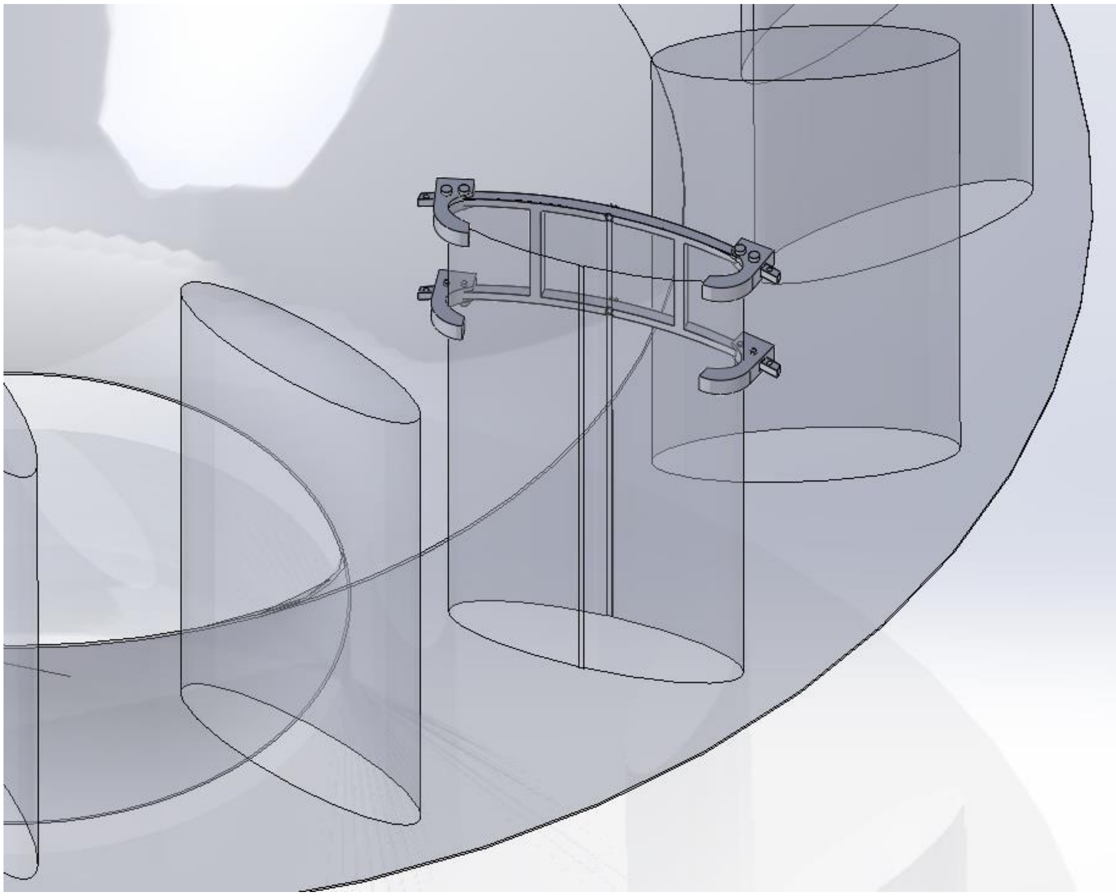


Figure 65. Device fitting around the wicket gate

Regarding to the anchor fixture method to temporary fixed support and anchor design, the ideal for the anchor fixture method is from concept G which is using bolt to fix the anchor. For this case, we did some optimization. Instead of using two bolts we use four bolts square anchor show in Figure 66. The advantage is that the corresponding adjustment under different loading conditions can be made by the workers show in Figure 67 and Figure 68.

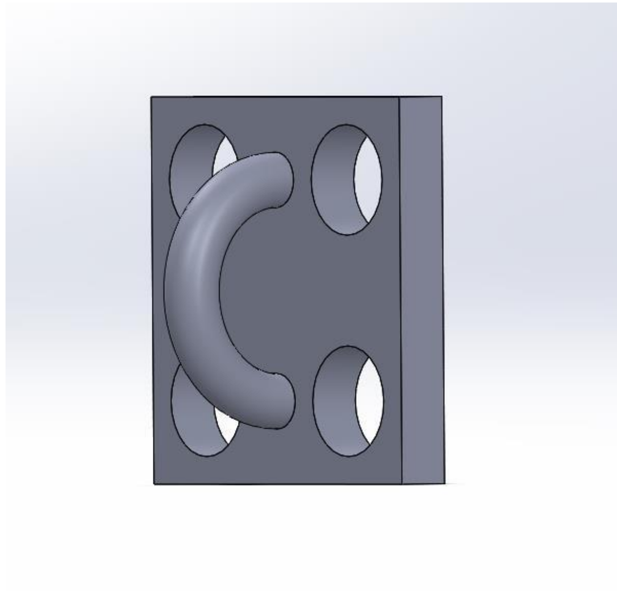


Figure 66. Square anchor

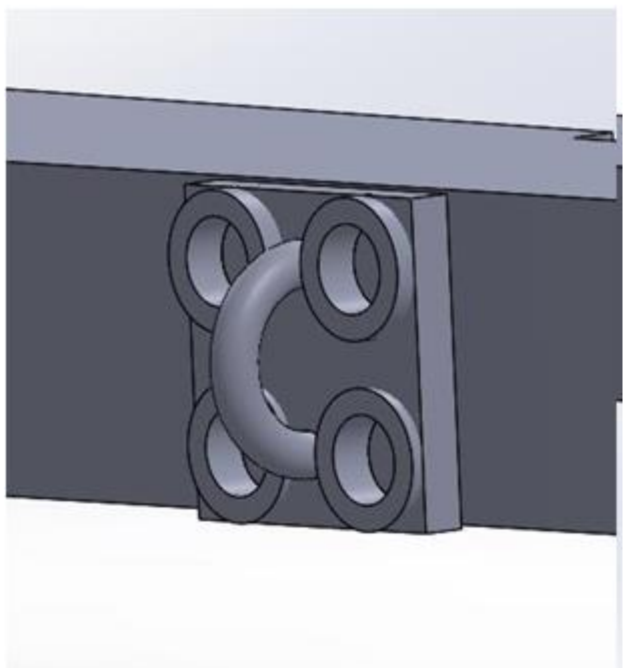


Figure 67. Vertical anchor

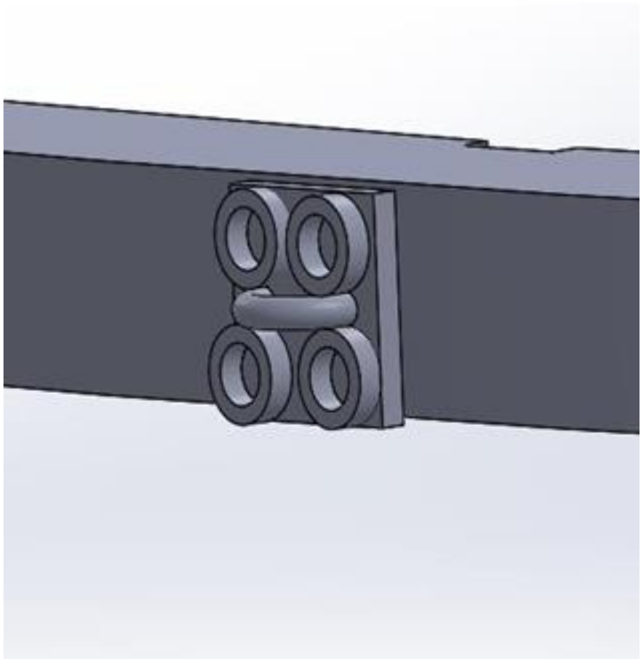


Figure 68. Horizontal anchor

Appendix D: Criteria Rating for Each Criterion on Different Consideration

Temporary Fixed Support

Safety Concept	Concept A	Concept C	Concept G
Concept A		C	A
Concept C			C
Concept G			
Total Hits	1	2	0
Weightings	0.333333	0.666667	0

Design Mobility Concept	Concept A	Concept C	Concept G
Concept A		A	G
Concept C			G
Concept G			
Total Hits	1	0	2
Weightings	0.333333	0	0.666667

Manufacturability Concept	Concept A	Concept C	Concept G
Concept A		A	G
Concept C			G
Concept G			
Total Hits	1	0	2
Weightings	0.333333	0	0.666667

Compatibility Concept	Concept A	Concept C	Concept G
Concept A		A	G
Concept C			G
Concept G			
Total Hits	1	0	2
Weightings	0.333333	0	0.666667

Worker Mobility Concept	Concept A	Concept C	Concept G
Concept A		C	G
Concept C			C
Concept G			
Total Hits	0	2	1
Weightings	0	0.666667	0.333333

Performance Concept	Concept A	Concept C	Concept G
Concept A		C	A
Concept C			C
Concept G			
Total Hits	1	2	0
Weightings	0.333333	0.666667	0

Ease of Use Concept	Concept A	Concept C	Concept G
Concept A		A	G
Concept C			G
Concept G			
Total Hits	1	0	2
Weightings	0.333333	0	0.666667

Anchor Fixed Method

Safety Concept	Concept A	Concept B	Concept C	Concept E	Concept F	Concept G	Concept M
Concept A		A	C	E	A	G	M
Concept B			C	E	B	G	G
Concept C				E	C	G	C
Concept E					E	E	E
Concept F						G	F
Concept G							G
Concept M							
Total Hits	2	1	4	6	1	6	1
Weightings	0.095238	0.047619	0.190476	0.285714	0.047619	0.285714	0.047619

Performance Concept	Concept A	Concept B	Concept C	Concept E	Concept F	Concept G	Concept M
Concept A		A	C	E	A	G	A
Concept B			C	E	F	G	B
Concept C				C	F	C	M
Concept E					F	E	E
Concept F						G	F
Concept G							G
Concept M							
Total Hits	3	1	4	4	4	4	1
Weightings	0.142857	0.047619	0.190476	0.190476	0.190476	0.190476	0.047619

Design mobility Concept	Concept A	Concept B	Concept C	Concept E	Concept F	Concept G	Concept M
Concept A		B	C	A	F	G	A
Concept B			B	B	B	B	B
Concept C				C	C	C	C
Concept E					F	G	E
Concept F						G	F
Concept G							G
Concept M							
Total Hits	2	6	5	1	3	4	0
Weightings	0.095238	0.285714	0.238095	0.047619	0.142857	0.190476	0

Worker Mobility Concept	Concept A	Concept B	Concept C	Concept E	Concept F	Concept G	Concept M
Concept A		A	A	E	F	A	A
Concept B			C	E	F	B	M
Concept C				E	F	G	M
Concept E					F	E	E
Concept F						F	F
Concept G							M
Concept M							
Total Hits	4	1	1	5	6	1	3
Weightings	0.190476	0.047619	0.047619	0.238095	0.285714	0.047619	0.142857

Ease of use Concept	Concept A	Concept B	Concept C	Concept E	Concept F	Concept G	Concept M
Concept A		B	C	A	F	G	A
Concept B			B	B	B	B	B
Concept C				C	C	C	C
Concept E					F	D	E
Concept F						G	F
Concept G							G
Concept M							
Total Hits	2	6	5	1	3	3	0
Weightings	0.1	0.3	0.25	0.05	0.15	0.15	0

Manufacturability Concept	Concept A	Concept B	Concept C	Concept E	Concept F	Concept G	Concept M
Concept A		B	C	A	F	G	A
Concept B			C	B	F	G	B
Concept C				C	C	C	C
Concept E					F	G	M
Concept F						G	F
Concept G							G
Concept M							
Total Hits	2	3	6	0	4	5	1
Weightings	0.095238	0.142857	0.285714	0	0.190476	0.238095	0.047619