



ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)  
GRADO EN INGENIERÍA ELECTROMECÁNICA  
Especialidad Mecánica

**University of Michigan Steel Bridge**

Autor: Jorge Visedo Ceballos

Director: Jason McCormick

Madrid

Junio 2018



**AUTHORIZATION FOR DIGITALIZATION, STORAGE AND DISSEMINATION IN THE NETWORK OF END-OF-DEGREE PROJECTS, MASTER PROJECTS, DISSERTATIONS OR BACHILLERATO REPORTS**

***1. Declaration of authorship and accreditation thereof.***

The author Mr. /Ms. JORGE VISEDO CEBALLOS

**HEREBY DECLARES** that he/she owns the intellectual property rights regarding the piece of work:

that this is an original piece of work, and that he/she holds the status of author, in the sense granted by the Intellectual Property Law.

***2. Subject matter and purpose of this assignment.***

With the aim of disseminating the aforementioned piece of work as widely as possible using the University's Institutional Repository the author hereby **GRANTS** Comillas Pontifical University, on a royalty-free and non-exclusive basis, for the maximum legal term and with universal scope, the digitization, archiving, reproduction, distribution and public communication rights, including the right to make it electronically available, as described in the Intellectual Property Law. Transformation rights are assigned solely for the purposes described in a) of the following section.

***3. Transfer and access terms***

Without prejudice to the ownership of the work, which remains with its author, the transfer of rights covered by this license enables:

- a) Transform it in order to adapt it to any technology suitable for sharing it online, as well as including metadata to register the piece of work and include "watermarks" or any other security or protection system.
- b) Reproduce it in any digital medium in order to be included on an electronic database, including the right to reproduce and store the work on servers for the purposes of guaranteeing its security, maintaining it and preserving its format.
- c) Communicate it, by default, by means of an institutional open archive, which has open and cost-free online access.
- d) Any other way of access (restricted, embargoed, closed) shall be explicitly requested and requires that good cause be demonstrated.
- e) Assign these pieces of work a Creative Commons license by default.
- f) Assign these pieces of work a HANDLE (*persistent URL*). by default.

***4. Copyright.***

The author, as the owner of a piece of work, has the right to:

- a) Have his/her name clearly identified by the University as the author
- b) Communicate and publish the work in the version assigned and in other subsequent versions using any medium.
- c) Request that the work be withdrawn from the repository for just cause.
- d) Receive reliable communication of any claims third parties may make in relation to the work and, in particular, any claims relating to its intellectual property rights.

***5. Duties of the author.***

The author agrees to:

- a) Guarantee that the commitment undertaken by means of this official document does not infringe any third party rights, regardless of whether they relate to industrial or intellectual property or any other type.

- b) Guarantee that the content of the work does not infringe any third party honor, privacy or image rights.
- c) Take responsibility for all claims and liability, including compensation for any damages, which may be brought against the University by third parties who believe that their rights and interests have been infringed by the assignment.
- d) Take responsibility in the event that the institutions are found guilty of a rights infringement regarding the work subject to assignment.


**6. Institutional Repository purposes and functioning.**

The work shall be made available to the users so that they may use it in a fair and respectful way with regards to the copyright, according to the allowances given in the relevant legislation, and for study or research purposes, or any other legal use. With this aim in mind, the University undertakes the following duties and reserves the following powers:

- a) The University shall inform the archive users of the permitted uses; however, it shall not guarantee or take any responsibility for any other subsequent ways the work may be used by users, which are non-compliant with the legislation in force. Any subsequent use, beyond private copying, shall require the source to be cited and authorship to be recognized, as well as the guarantee not to use it to gain commercial profit or carry out any derivative works.
- b) The University shall not review the content of the works, which shall at all times fall under the exclusive responsibility of the author and it shall not be obligated to take part in lawsuits on behalf of the author in the event of any infringement of intellectual property rights deriving from storing and archiving the works. The author hereby waives any claim against the University due to any way the users may use the works that is not in keeping with the legislation in force.
- c) The University shall adopt the necessary measures to safeguard the work in the future.
- d) The University reserves the right to withdraw the work, after notifying the author, in sufficiently justified cases, or in the event of third party claims.

Madrid, on 13 of JUNE, 2018

**HEREBY ACCEPTS**

Signed 

Reasons for requesting the restricted, closed or embargoed access to the work in the Institution's Repository

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

.....*University of Michigan Steel Bridge*.....

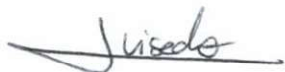
..... en

la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

curso académico ...*2017/2018*... es de mi autoría, original e inédito y

no ha sido presentado con anterioridad a otros efectos. El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido tomada

de otros documentos está debidamente referenciada.



*Jorge Visedo Ceballos*

Fdo.: (Nombre del alumno)

Fecha: *24/04/2018*

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO



*Jason P. McGonigle*

Fdo.: (Nombre del Director)

Fecha: *24/04/2018*





ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)  
GRADO EN INGENIERÍA ELECTROMECÁNICA  
Especialidad Mecánica

**University of Michigan Steel Bridge**

Autor: Jorge Visedo Ceballos

Director: Jason McCormick

Madrid

Junio 2018



# UNIVERSITY OF MICHIGAN STEEL BRIDGE

## TEAM

**Autor: Visedo Ceballos, Jorge.**

Director: McCormick, Jason P.

Entidad Colaboradora: University of Michigan

## **Resumen del proyecto**

Este proyecto abarca el trabajo en grupo realizado por un conjunto de alumnos interdisciplinar en la Universidad de Michigan, junto con un análisis crítico de las técnicas utilizadas. El objetivo del equipo SBT es construir un puente de acero, para la competición internacional “Steel Bridge Team”. Dicho puente debe tener unas dimensiones, y características estructurales básicas preestablecidas.

Las principales áreas para estudiar son el diseño y la fabricación del puente, dejando de lado el proceso de construcción, siendo esta área de mayor carácter deportivo-competitivo.

En el diseño se ha optado por un puente ligero y con pocas piezas, sin arcos superiores, para simplificar así su posterior construcción. Por otro lado, en la fabricación, todo ha sido construido en Acero, y los principales procesos de fabricación utilizados han sido arranque de material, fresadora en mayor medida y torno en menor. Como método de soldadura, se ha elegido soldadura TIG.



Puente montado en la Universidad de Michigan Oeste, para la competición regional.

Primeramente, se aborda la logística de la competición, tanto los requerimientos del puente como la organización que el equipo lleva durante el año académico para preparar el proyecto. Se propone abordar la enseñanza de las técnicas utilizadas por los miembros mas veteranos del equipo a aquellos más nuevos de manera mas organizada. También se presenta un programa de optimización para facilitar unas primeras pautas de diseño que consigan una máxima puntuación.

En cuanto al diseño se estudian algunos de los distintos modelos propuestos en el comienzo del curso, y se comparan resultados. Se estudian también las conexiones entre los miembros, y se proponen tanto nuevas conexiones más simples como una optimización de las conexiones ya usadas en años anteriores, para ello se simula el comportamiento de distintos diseños de conexiones bajo las mismas condiciones de carga y se comparan los

resultados. Finalmente se proponen unos porta-piezas modulares para el colque de las piezas en el proceso de soldadura.

En cuanto a la fabricación la Universidad de Michigan goza de unas instalaciones extraordinariamente buenas, que otorgan a los estudiantes una gran oportunidad para familiarizarse con los principales métodos de mecanizado y demás métodos de fabricación. En este trabajo se presentan los recursos utilizados y se observan algunos problemas que podrían surgir, y maneras de evitarlos.

# UNIVERSITY OF MICHIGAN STEEL BRIDGE

## TEAM

**Author: Visedo Ceballos, Jorge.**

Director: McCormick, Jason P.

Collaborating Entity: University of Michigan

### **Abstract of the project**

This project consists of the team work carried out by a set of interdisciplinary students in the University of Michigan, as well as a critical analysis of the used techniques. The objective of the STB is to build a steel bridge, for the international competition “Steel Bridge Team”. Said bridge must have some preestablished dimensions and basic structural characteristics.

The main areas to study are the design and fabrication of the bridge, leaving aside the construction process, which has more of a competitive sport like character.

For the design a light and simple bridge was chosen, without an overtruss, to later simplify its construction. On the other hand, on fabrication, everything has been built on steel, and the main fabrication process used have been machining, mainly on mill, but also on lathe. For welding, the TIG welding method was chosen.

In the design phase a light bridge with few pieces and without over truss was chosen to simplify its construction. On the other hand, in the manufacture, everything was built in steel, and the main manufacturing processes used consisted of material reduction, with the use of the lathe and the mill. TIG Welding was chosen as welding method due to its good mechanical properties and esthetic finish.



Mounted bridge in the University of West Michigan for the regional competition.

First, the paper addresses the logistics of the competition, both the requirements of the bridge and the organization of the team during the academic year to prepare the project. One of the proposals is to organize the teaching periods in which the most veteran members of the team show the youngest ones some of the technique they might. An optimization program is proposed to get to a first design that may achieve a maximum score.

In the design section some of the different models proposed at the beginning of the course are explored, and their results are compared. Another point that is studied is the connections issue. A first approach is to come up with new simpler connections that may result in a construction speed improvement. The other idea pursued is the optimization of the connections already used in previous years. For this the same simulation is carried out to compare the behavior of different designs of connections under the same Load conditions. Finally, a modular jig is proposed for the placing of the pieces in the welding process.

In terms of manufacturing, the University of Michigan has extremely good facilities, which give the students a great opportunity to become familiar with the main machining methods and other manufacturing methods. This paper presents the manufacturing resources used and shows some problems that could arise, and ways to avoid them.

## Acknowledgements

I would like to thank everyone in the Steel Bridge Team of the University of Michigan. They have been some great coworkers and have given me all the help I needed to work on this paper. Special thanks to Professor Jason McCormick, for tutoring me in this paper, and giving me the opportunity to participate.

Thanks also to both the universities I have attended, the University of Michigan and the Universidad Pontificia de Comillas.



*University of Michigan steel bridge team with the mounted bridge in the regional competition in Western Michigan University, April 2018*

# Document I

## Memory





# Index

<b>I. Memory</b>	<b>5</b>
1. Introduction	7
2. Requirements	9
2.1. Bridge Requirements	9
2.2. Organizational aspects	10
3. Design	12
3.1. Overall Bridge	12
3.2. Connections	13
3.3. Beam profiles	17
3.4. Jigs	18
4. Fabrication	21
4.1. Rough cutting	21
4.2. Lathe	22
4.3. Drill	23
4.4. Mill & CNC Mill	24
4.5. Other machines	24
4.6. Welding	26
4.7. Considerations	27
<b>II. Analysis</b>	<b>29</b>
1. Optimization program	31
2. Bridge	33
2.1. Basic model	33
2.2. Alternative with over truss	35
2.3. Final model	37

3. Connections	40
3.1. Simpler connections and 2018 connections	40
3.1.1. Axial load	40
3.1.2. Flexure	43
3.2. Optimization of dovetails.	44
3.2.1. Size	44
3.2.2. Depth	46
3.2.3. Gap	49
3.2.4. Angle	50
3.2.5. Round edges	51
3.2.6. Final optimal design	54
<b>III. Supplements</b>	<b>57</b>
1. Material	59
2. Load Cases	61
2.1. Competition	61
2.2. Simulation	62
3. Specs (bridge)	64
4. Results of the competition	65
5. Lists	66
5.1. List of figures	66
5.2. List of tables	69
5.3. List of formulas	69
6. Bibliography	70

# Part I

## Memory





# 1. Introduction

The Steel Bridge competition was started and sponsored in 1991 by the American Institute of Steel Construction (AISC). It is a yearly international competition held in the United States, in which different engineering universities from around the world face each other. First, regional competitions are held. After the regional competitions the universities that qualify from each region go to the national competition. This year's host university for the regional competition where University of Michigan competes was held at Western Michigan University in Kalamazoo, MI. The national competition will be at the University of Illinois at Urbana-Champaign in Champaign, IL.

The contest considers several categories:

- Display (aesthetics – appearance of bridge, technical poster, name on bridge)
- Construction speed (lowest time)
- Lightness (total weight of bridge, including weight from penalties)
- Stiffness (lowest aggregate deflection from 2 points)
- Construction Economy (considers number of builders, construction time, and other penalties)
- Structural Efficiency (considers weight, aggregate deflection, and other penalties)
- Overall Performance (sum of construction economy and structural efficiency)

The penalties arise from different restrictions that apply in the competition itself and represent would be accidents on a real-world construction site.

The team divides the project into three parts, first comes the design. In this first part, the general structure of the bridge is decided, working with different CAD systems and structural engineering programs for calculations

such as SolidWorks and RISA, the team decides the broad characteristics of the bridge, and then models it in detail.

After this comes fabrication, here the beam profiles from the design are turned into different parts that will make up the bridge itself. The major fabrication techniques used are, mill and lathe operations, steel cutting, and TIG welding.

Finally, the team practices construction. This part consists of practice to gain speed in the construction of the bridge for the competition day.

## 2. Requirements

### 2.1. Bridge Requirements

The details and requirements of the bridge for the competition change from year to year with more different aspects emphasized more than others in any given year. In response to these requirements, the bridge must change in a way that will maximize the overall score. This year's bridge has been designed following this idea of maximizing the score. The result has been a lighter, simpler and very fast building bridge, due to the higher importance of these areas in the upcoming competitions. This year's bridge does not have any over truss as it has in previous years, for this would greatly increase weight and damage the efficiency and the building speed which are very important areas this year.

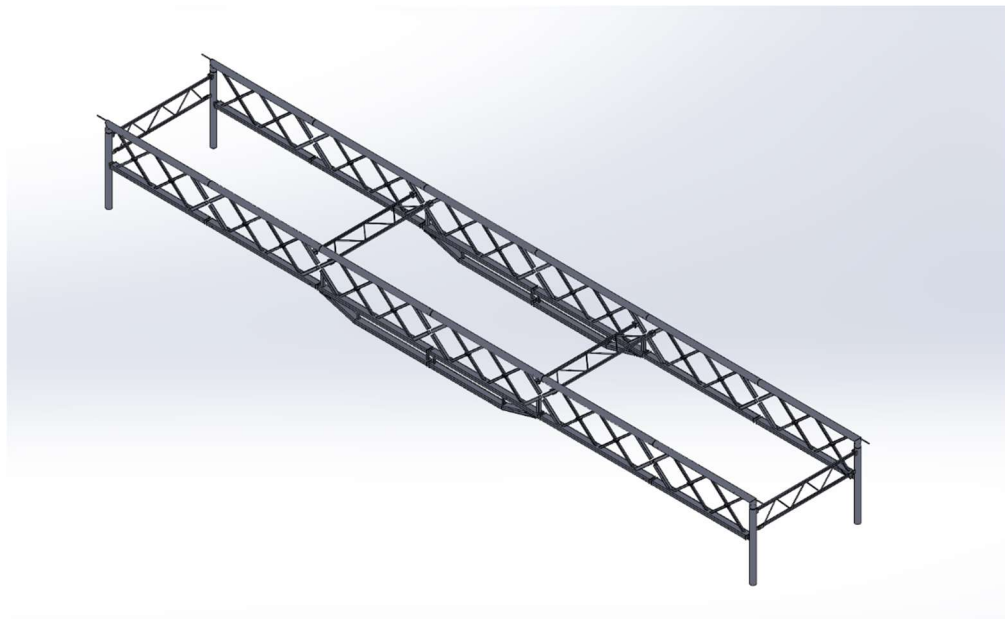


Figure 1: Isometric view of a CAD version of the bridge

In this paper, a more systemized analysis is suggested. To maximize points, a linear optimization program is proposed, leaving it as generic as

possible, so that year after year, the general constraints can be plugged in and an estimate of the optimal configuration can be obtained.

## **2.2 Organizational aspects**

In the design of the bridge, there have been several issues to address, including: connection design, beam profile design, and manufacturing processes to be used. In all of them, the team takes advantage of the experience gained through all the years the university has participated in this competition.

The team has access to all the information they need from previous years, but the great advantage comes from having team members who have several years' experience. These team members are the ones that lead the different areas and point out what the rest should be doing.

However, a more structured approach could be followed. After fabrication is finished, the workload on the team substantially decreases. With the beginning of the construction phase, the team members that are more focused on design and manufacturing can begin an apprenticeship phase. Although this is done, it is not conducted in the orderly fashion here proposed.

The main danger to the SBT is that the senior students leave without having a replacement to fill in their shoes the following years. This concern has been avoided by foreseeing this and trying to ensure there always is a replacement for the leaving seniors. However, some of the sectors of the team can suffer some years and find themselves having to learn how to do things that could have been taught by previous members of the team.

For instance, the welding sector usually consists of an experienced welder and an unexperienced welder one year, and only one welder the next. Alternating this way. For this important area, at least two welders should be in office every year, a more experienced one (at least one year of

practice) and an inexperienced one (at least 3 months of practice). This can be achieved with the apprenticeship program, which can take place in the Spring and summer term if people stay, or by the end of the winter semester or the beginning of the fall semester. Periods when the manufacturing phase is not active.

For design the same idea can be applied, teaching CAD design with Solid Works and RISA calculations. Also, the use of finite element analysis (FEA) should be considered, maybe sponsoring an ANSYS course for those interested. This will be a great asset to the team, being this kind of analysis is much more powerful than an ordinary CAD design or RISA analysis.

### 3. Design

#### 3.1. Overall Bridge

For the general design of the bridge, the teammates offered different alternatives with an approximation on what could be the benefit and overall score for that design. Then, all the ideas were reviewed, and the final bridge was designed from a mix of all the first designs (Fig. 2, 3, 4).

This is a very beneficial way of approaching a design because by looking at the different designs of your peers, you find ideas that had not crossed your mind prior. When taking the best ideas of all the different concepts, a superior final design will surely arise.

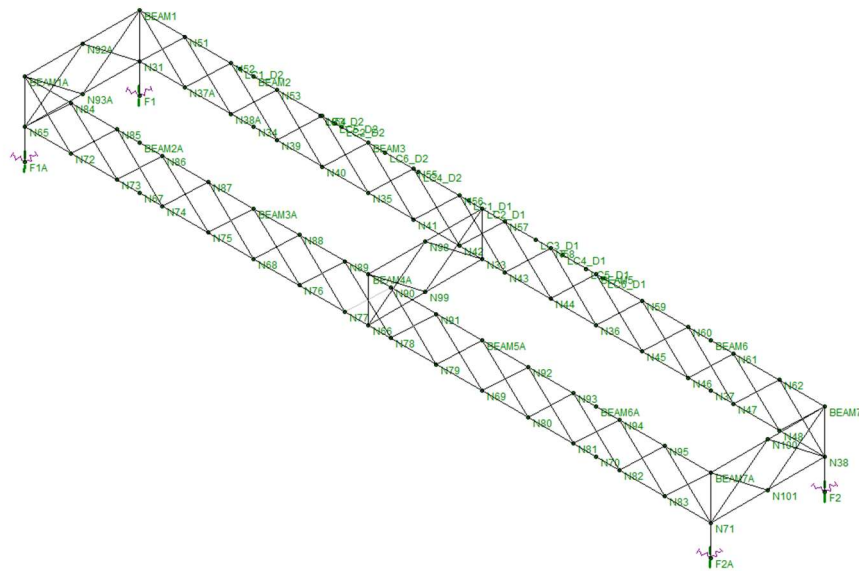


Figure 2: Basic design concept

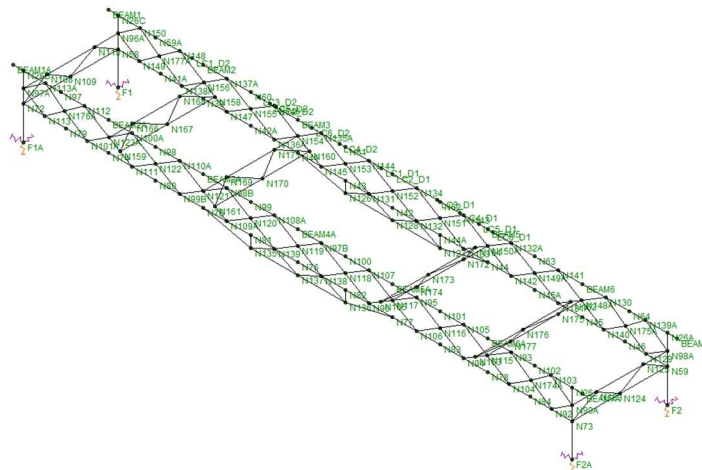


Figure 3: Intermediate design concept

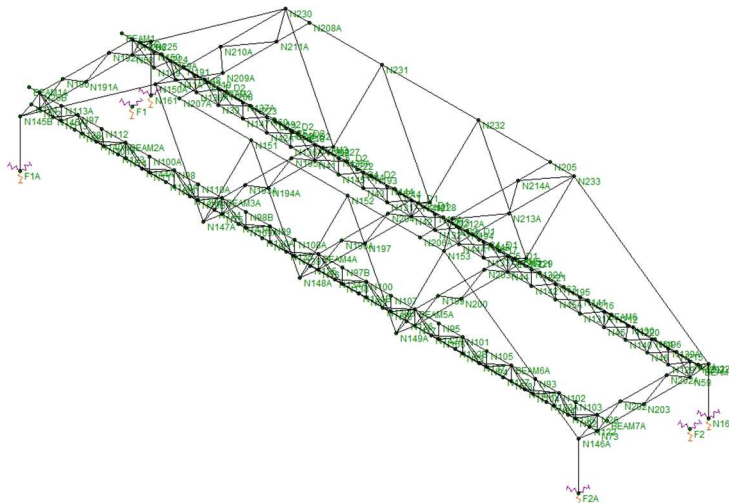


Figure 4: Over truss design concept

### 3.1. Connections

One of the main issues to be acknowledged for the design of the bridge are the connections to be used. There are several rules and considerations to take into account here. First, a nut and bolt must be used in every connection for safety reasons. Also, during the construction test, all parts must be carried by the operators one by one and mounted in an

orderly fashion, this prevents the parts from being too heavy or bulky, there is weight and size limit for parts too. So, fast mounting connections must be designed to fix all the parts which must be controlled in size and weight.

The solution was to come out with puzzle like connections that permitted fast mounting and have proven to work very well under the load specifications year after year, (Fig. 5, 6).

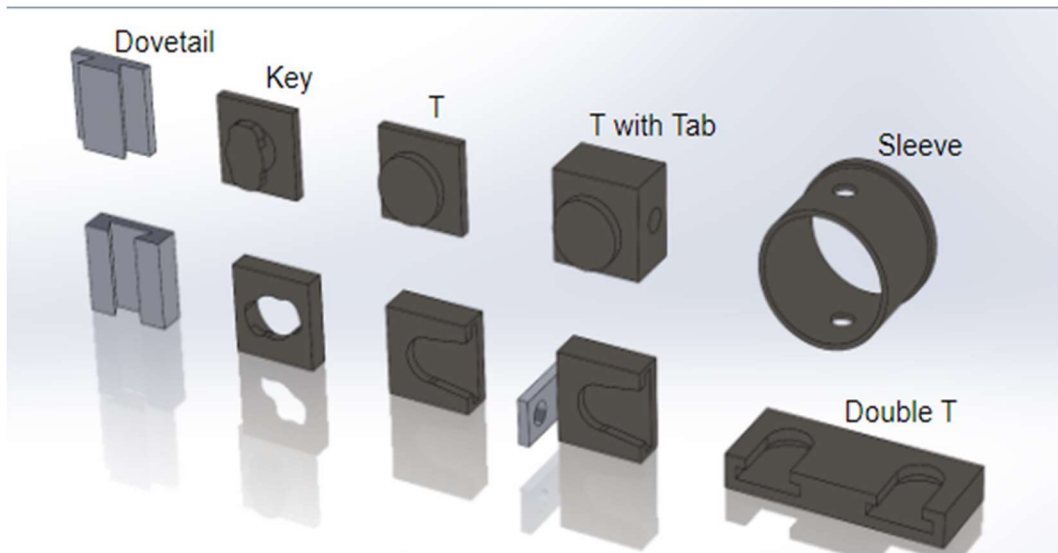


Figure 5: Connections Modeled with SolidWorks.

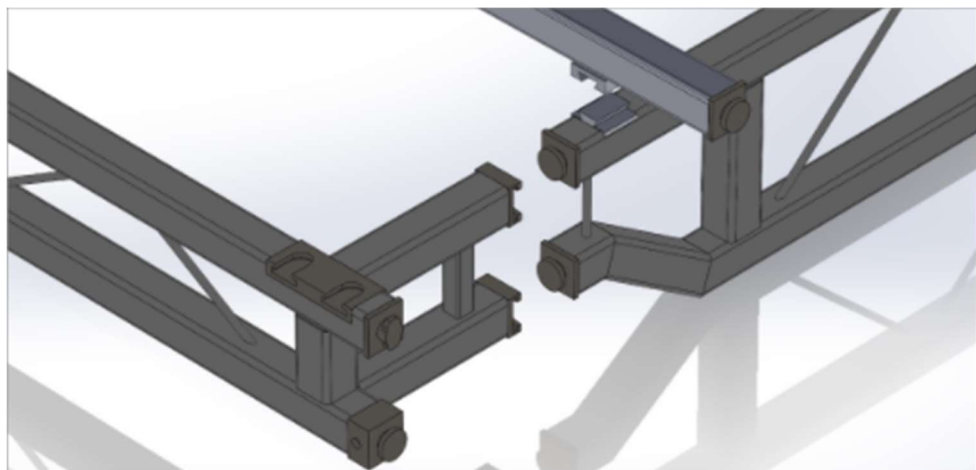
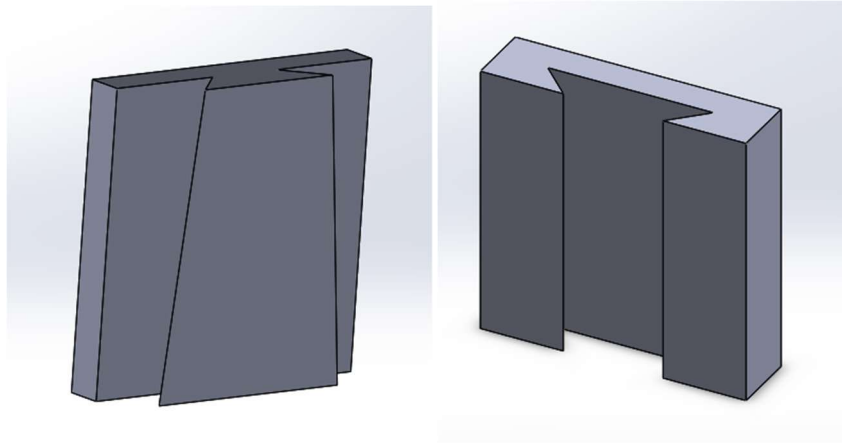


Figure 6: Connections and beams in solid works.

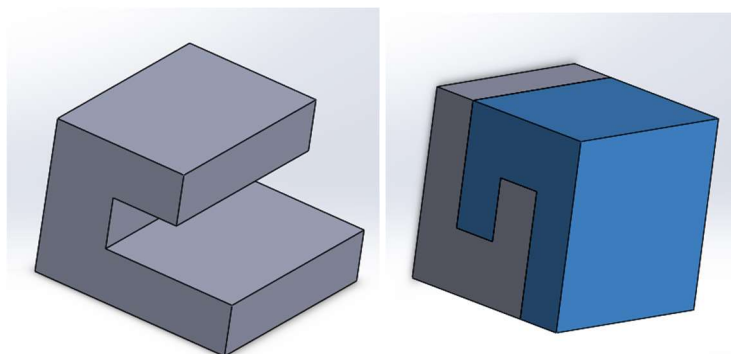
The connection that was mostly used this year was the “Dovetail”, (Fig. 7, 8). It is studied in this paper, showing some older versions of it, and considering ways to optimize it.



Figures 7 and 8: Male and Female 1x1'' tapered dovetail connections

An idea to consider is to make simpler connections so that the mounting can be faster (Fig. 9, 10). Also, this would reduce the use of the CNC mill, which requires special training.

As previously mentioned, a nut and bolt must be put in place in every connection for security reasons. However, in many of them it is structurally not necessary to put them in place and are only added to comply with the competition rules.



Figures 9 and 10: Alternative Square connection member, and assembly

It could be considered to take advantage of the rule of mandatory nut and bolt in every connection by increasing their structural presence (Fig. 11). As shown later this must be done with care, and a lot of trust is put into the bolts that are not manufactured by the team. A drawback to consider

here is that for bolts that take load, the tolerances must be tighter, maybe compromising construction time.

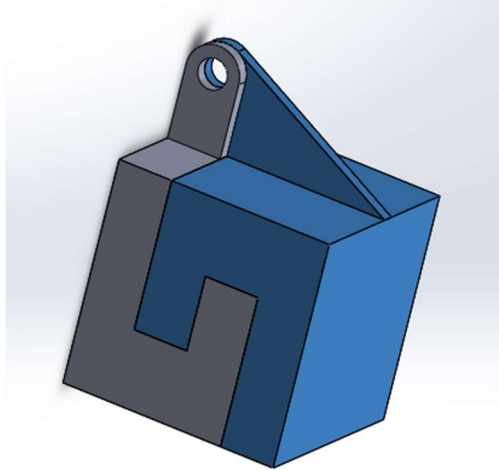


Figure 11: Full assembly of square connection with bolt

The bolt should be put on top or in the bottom, depending on where the highest tension forces will occur. However, further studies show that the position of the bolt may be vital to see where maximum tensions will occur.

Another problem that arose, was with the double connections like the double T, or two dovetails next to each other when one of them was not enough.

The risk when putting two connections next to each other is that even though in the model you can make a perfect fit, in the real world this is impossible. The tolerances achieved with machining are pretty good, but the mounting of the connections and the different parts can be complicated. This is, when mounting pieces together, the tolerances add up and the overall dimension of the piece might be considerably altered from what was expected. In addition to that, the welding process also changes the dimensions of the piece, so when you add it all together the dimensions

might have changed so much that the connections are either impossible to mount or difficult enough that they are a speed hazard.

This risk can be greatly minimized if instead of using two connections, one bigger connection is used, (Fig. 12) or a different type that can withstand more load is used.

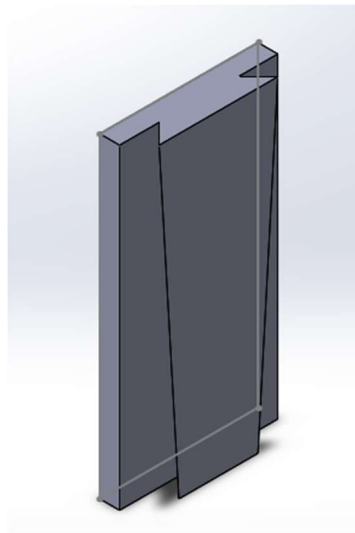


Figure 12: 1.25x2" dovetail, 2018

### 3.2. Beam Sections

Two different section shapes were chosen for the bridge, square and tubular beams. As a rule, the square profiles were more used where tension was the most critical force. On the other hand, tubular profiles were used where compression was more critical.

The square tubing was a better choice for the bottom of the bridge, where tensional forces would be important. Another good option would have been HEB or W profiles, however size and weight are an issue to consider. These types of beams are usually much bigger than those needed for the bridge.



Figure 13: Unused beams stored in Wilson Center

The bridge is also submitted to lateral loading, so it would not have been a good idea to use channel beams.

The tubular profile was chosen for compression because it responds better to buckling. Therefore, it has been used in the supports and in the top of the bridge.

Another important factor to consider is manufacturability. Here the clear winner is the square tubing beam because it is easier to handle, mount and alter than any of the other choices.

### **3.4. Jigs**

The jigs are the pieces used to hold the different parts of the bridge in the welding table, so that the welding can be performed effectively, accurately and securely. Also, some jigs had to be designed to hold parts in determined angles and positions for grinding and other processes, but these were not as vital.

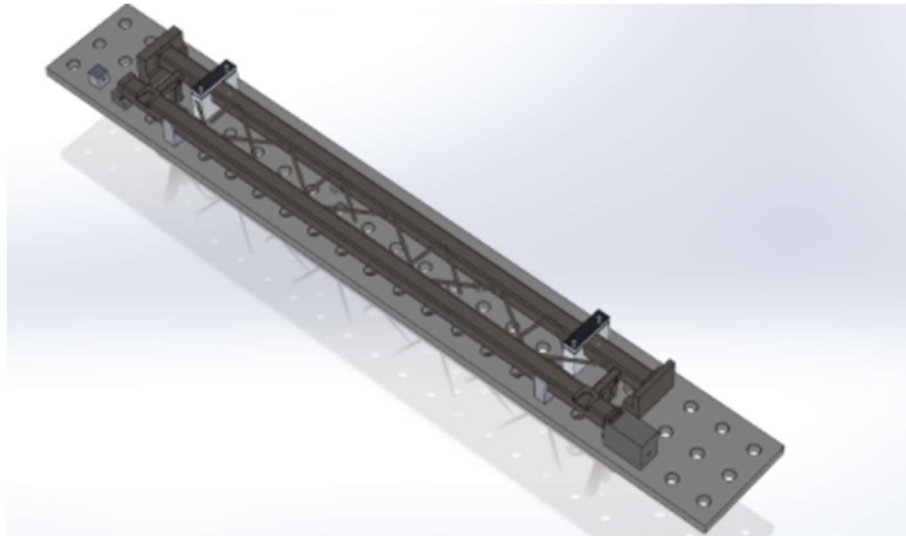
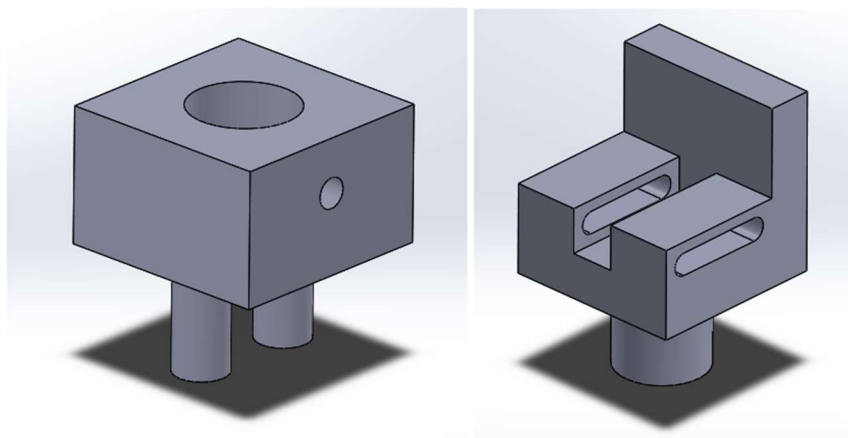


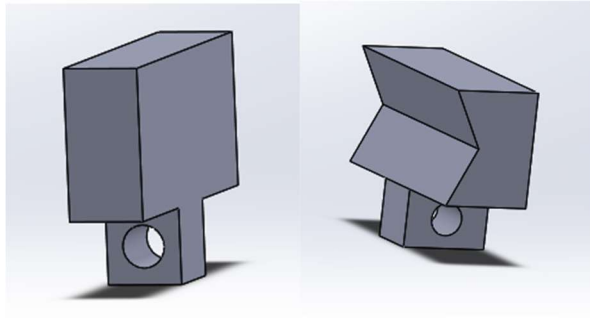
Figure 14: Example of jigs holding beam in the welding table, Solid Works

The main issue with the jigs is the fact that every part of the bridge requires a different position to be held in when welding it. Different jigs are needed for different pieces, different orientations, and different heights. The result is having to manufacture lots of jigs that may be used just once or a few times at best.

An idea is to go for modular jigs, that can accommodate different forms and sizes and can have different orientations, (Fig. 15-19).



Figures 15 and 16: Base and first part for modular jig



Figures 17 and 18: Second part for modular jig, for square and circular profiles

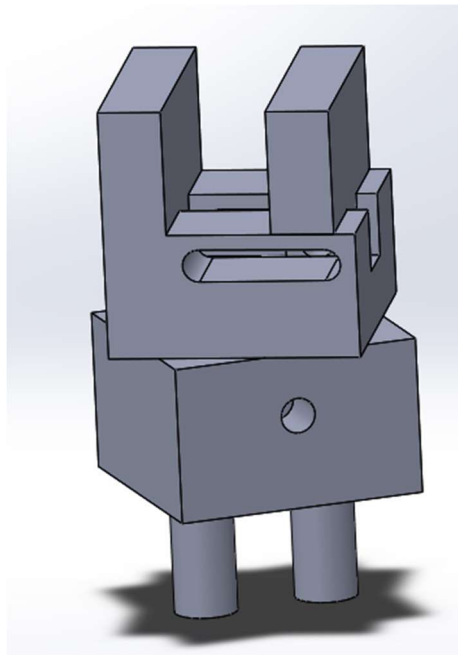


Figure 19: Modular jig mounted

With this type of solution, one could accommodate square or circular beams of different sizes, within some limits. The orientation of the piece is totally free and can be set with a set screw on the base. Finally, the height has a small tolerance in that the main part of the jig can be placed a bit higher with respect to the base and tightened there with the set screw.

## 4. Fabrication

The fabrication stage is one of the vital parts of the competition. The students get a chance to gain firsthand experience and understand the problems of taking a concept and making it happen.

During the manufacturing process, many problems arise that had not been thought of before. In a CAD model everything works perfectly, there are not any tolerance problems and roughness is not an issue. In reality however, the quality of the machined part is vital, and here the machining process and the person working on the part can make a big difference.

The raw stock bought is usually different section sizes of steel shapes for the bridge and aluminum for the jigs. The processes used to work the stock vary from rough cutting to CNC milling. Secondary processes used are also sand blasting, deburr with ceramic bits, or abrasive grinding wheels. The welding process used is TIG welding.

### 4.1. Rough cutting

This is a first process that is vital in the handling of the raw stock which comes in long, hardly workable beams. This type of machining leaves a terrible surface finish, so every cut must be over dimensioned by at least an eighth of an inch. This excess material is later machined to give a nice smooth surface finish with the mill.

For the first cuts, a Kalamazoo Industries abrasive cut off saw was used in the case of the steel beams and a Dake horizontal band saw was used for the aluminum stock. Posterior rough cuts can be made later with the Trade master vertical band saw.



Figures 20 and 21: Abrasive cut off saw and vertical band saw



Figure 22: Horizontal band saw

## 4.2. Lathe

The lathe was used to get the cylindrical parts needed. These are the sleeves in the round stock beams and the round connections. Also, some jigs had to be worked with this machine. The machine used is a Tormax Romi lathe.



Figure 23: Lathe

### 4.3. Drill

For drilling holes where precision was not an issue, the Clausing drill press was chosen over the mill, being this one was faster and easier to use.



Figure 24: Drill press

### 4.3. Mill and CNC Mill

The mill has been the most used machine. It is the most versatile to work with and can achieve a wide variety of different shapes. The mill was used in all different areas of the fabrication for beams, connections and jigs. The machine used is a Bridgeport mill series I.

When the complexity of the part could not be achieved with a conventional mill, the Bridgeport CNC mill was also available and has been also widely used.



Figures 25 and 26: Mill and CNC Mill

### 4.4. Other machines

Other machines used as mentioned before were a sand blaster, an automatic deburr machine with ceramic bits, and a series of abrasive grinding wheels.

The sand blasting is necessary to eliminate the coating that protects the steel parts for the welding process. This coating emits toxic gases when

heated that can be harmful when inhaled. It is also used to give a nice shiny finish to the bridge. The machine used was the Trinco Sandblaster.



Figure 27: Sandblaster

The deburring machine, the Vibra king 150SX Media Tumbler, is useful especially when dealing with numerous small parts.



Figure 28: Deburring machine

The abrasive grinding wheels were used to make angled edges in some steel parts due to the difficulty of doing this on a mill and the necessity of better precision and surface finish than that of a saw. The tungsten electrodes used in the welding also must be ground to keep them sharp.



Figures 29 and 30: Rusch machine & design abrasive belt tube and Pipe Notcher, and Wilton Disc Sander

#### 4.5. Welding

The welding process chosen for the bridge is TIG welding. This is due to several reasons, on the one hand the training offered at the university is for this type of welding, but a MIG welding machine is also available and the method does not differ too much.

The reason to prefer TIG is for the more elegant finish. Both methods give a sufficient weld strength, but MIG weld is much thicker and esthetically less appealing than a TIG weld.

This is a versatile welding process that can be used for different geometries and positions. SMAW welding is more adequate when in need of a portable welding machine to work in different locations. But the team has no need of this performing all the welding on the university premises. The same can be said about brazing, also this method of welding does not give as good mechanical properties as the electrode-based welds, achieving the weld at higher temperatures and melting the base metal.

For the TIG weld, the Miller Dynasty DX 300 was used with a sharp tip electrode fed with indirect current. The machine works in high frequency with a current of 50A.



Figure 31: TIG welding machine

#### **4.5. Considerations**

The manufacturing process is very well implemented in the team with a good division of labor between the teammates and clear a leadership structure.

Some ideas to consider are the ones mentioned before: control the number of welder in action each year by implementation of apprenticeship programs and reduction of the complex geometries that need CNC milling.

The CNC mill requires special training that only a few of the teammates have and can result in an excess of work for them and exclusion of some members from a portion of the work.



## Part II

# Analysis





# 1. Optimization program

For the optimization program proposed to maximize the points obtained in the competition, some sets and parameters must be defined.

Set of different categories:  $S$

In this case:

$$S = \{Display, Construction Time, Lightness, Stiffnes, Construction Economy, Structural Efficiency, Overall Performance\}$$

Formula 1: Set categories

All the categories will be referred to with their initials.

Parameters:

$V_i$  for all  $i \in S$  ; Value of category  $i$

$L_{ij}$  for all  $i \in S$  and all  $j \in S$  ; Maximum points for categories  $i$  and  $j$  together

Variables:

$X_i$  ; Score in category  $i$

Objective Function:

$$\text{Min} \sum_{\text{for all } i \in S} -V_i * X_i$$

Formula 2: Objective function

Constraints:

$$X_i + X_j \leq l_{ij} \text{ for all } i \in S \text{ } j \in S \text{ with } j \neq i$$

Formula 3: Constraints

The values for the parameters have to be deduced. For the values of each category, the weight with which each category is evaluated every year must be considered.

The maximum points for categories  $i$  and  $j$  together represent the compromise you make when scoring highly on category  $i$ , regarding category  $j$ . For example, if you want to score highly in Stiffness you are compromising something in weight. These parameters should be obtained with estimations based on the experience of the team in previous years.

This program can be solved with the simplex method and once points in each category are obtained, we can have a first idea of what the design of the bridge should be for that year.

## 2. Bridge

The main program used for the preliminary approaches of the design was RISA 3D. This program offers a simple first calculation of the member stresses and forces, so the main characteristics of the bridge can be decided.

As previously mentioned, many designs were considered and from all of them a final design was developed.

Some of the designs were quite different from the one the team finally chose, including over trusses and very different characteristics in general. The key ideas to consider here were deflection and stress experienced by members, mainly axial since the members act as trusses.

In the competition, one of six load cases is chosen at random. In the following images, only the load case that was chosen will be shown.

### 2.1. Basic model

This model shows the main design that was later followed. In all its simplicity, it captures the concept of a sturdy, fast mounting bridge the team wanted to go with, (Fig. 32).

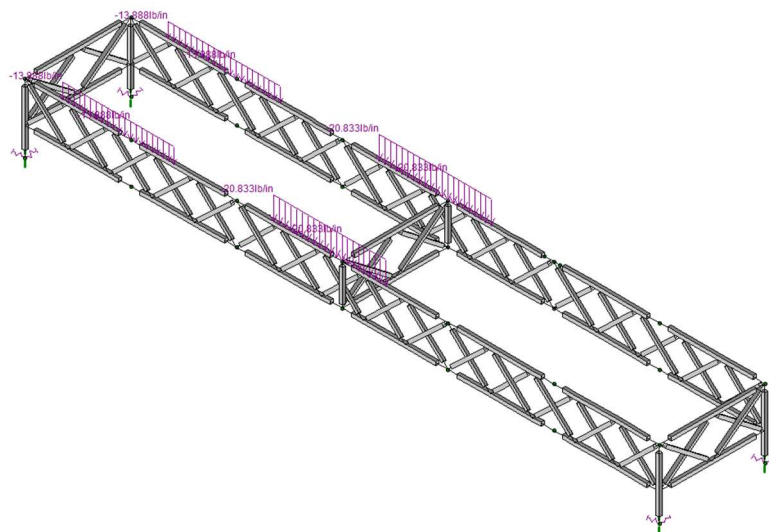


Figure 32: Basic Model, in RISA 3D under load case 1

The reactions that the bridge is subject to are F1 and F1A for the piers closer to the applied load and F2 and F2A for the piers farther away, (Table. 1).

	L...	Joint Label	X [lb]	Y [lb]	Z [lb]	MX [k-ft]	MY [k-ft]	MZ [k-ft]
1	1	F1	21.825	839.489	.071	0	0	0
2	1	F2	-21.825	459.39	.048	0	0	0
3	1	F1A	21.823	839.481	-.071	0	0	0
4	1	F2A	-21.823	459.381	-.048	0	0	0
5	1	Totals:	0	2597.741	0			
6	1	COG (in):	X: 72.027	Y: 21.753	Z: 17			

Table 1: Reactions for the Basic model

The most important load to study is the axial load, being the bridge is made of mainly truss members, (Fig. 33).

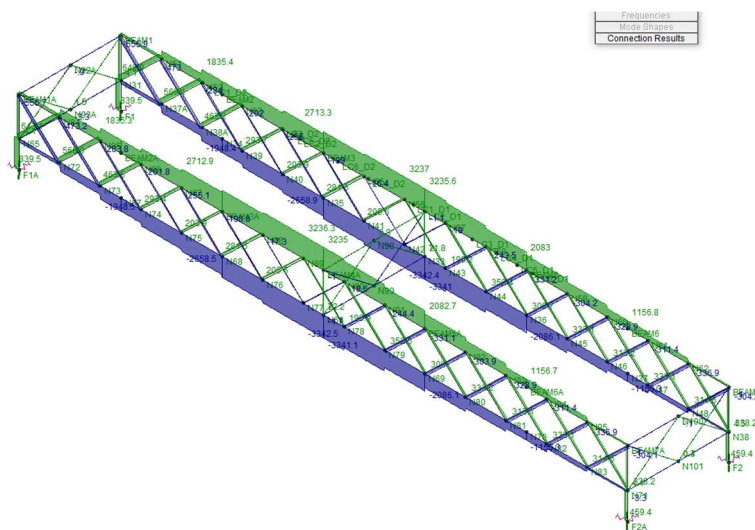


Figure 33: Axial load diagram for Basic model

In the diagram the most critical beams are the ones in the center, being subject to a maximum compression force of 3240 lb (14400N) on the top beams, and a maximum tension force of 3340 lb (14900 N).

Finally, the deflection under this load case for this model is shown, (Fig. 34):

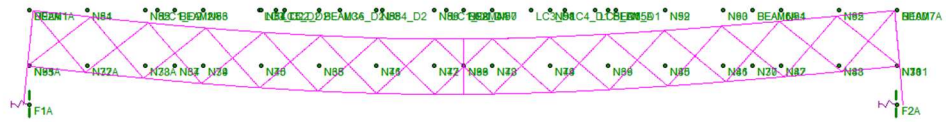


Figure 34: Deflection of the basic model under load case 1

The model had a maximum deflection in the middle of 0.67 in (17mm).

## 2.2. Alternative with over truss

The option of an over truss is certainly very appealing in terms of deflection, and even though it was not chosen it was indeed considered, (Fig. 35).

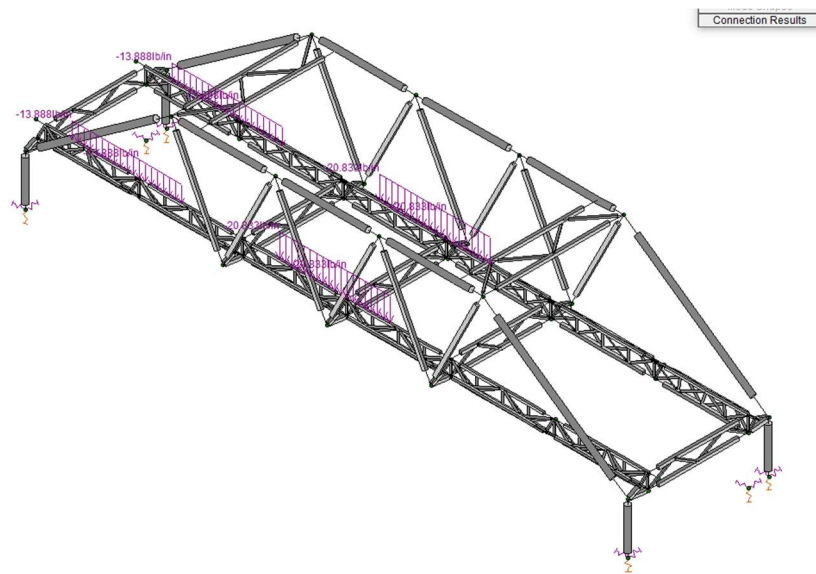


Figure 35: Over truss bridge under load case 1

Just in this render view of the bridge model it can be appreciated that the complexity of it and the number of members included would pose a serious problem regarding construction speed.

The reactions are similar to those encountered in the other models, (Table. 2).

	L...	Joint Label	X [lb]	Y [lb]	Z [lb]	MX [k-ft]	MY [k-ft]	MZ [k-ft]
1	1	F1	0	0	0	0	0	0
2	1	F2	0	0	0	0	0	0
3	1	F1A	46.611	856.418	-14.527	0	0	0
4	1	F2A	-46.61	462.47	-5.32	0	0	0
5	1	N161	46.61	856.419	14.527	0	0	0
6	1	N162	-46.611	462.481	5.32	0	0	0
7	1	Totals:	0	2637.788	0			
8	1	COG (in):	X: 68.931	Y: 21.002	Z: 16.375			

Table 2: Reactions of the over truss option

The axial loads to which this bridge is subject is considerably lower than the previous option (Fig. 36), this makes sense even intuitively since it has more members to share the load. This could make the bridge lighter even though it has more members.

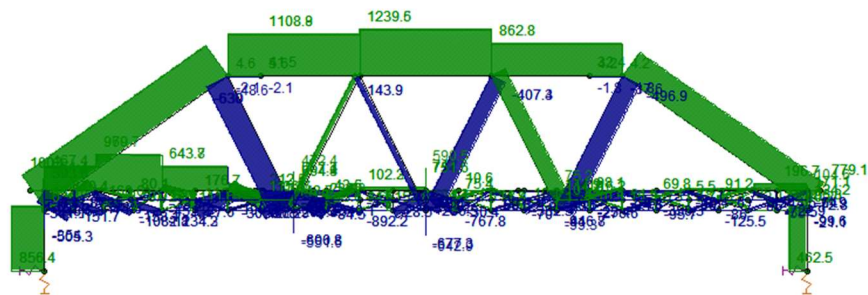


Figure 36: Axial load diagram for over truss model

Here the maximum load in compression, is 1240 lb (5510 N) and the maximum load in tension is a 630 lb (2800 N). Both values are much lower than in the other case.

The deflection diagram as shown next (Fig. 37), clearly proves the superior stiffness of an over truss bridge.

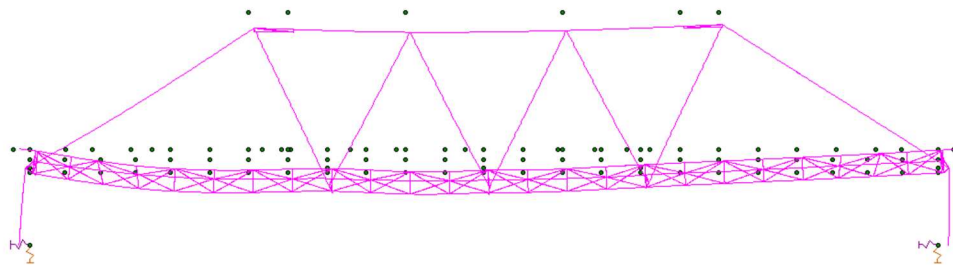


Figure 37: Deflection of the Over Truss bridge

The bridge model showed a maximum deflection directly below the left load of 0.22 in (5.6 mm).

### 2.3. Final Model

The final model clearly follows the line of the basic model (Fig.38).

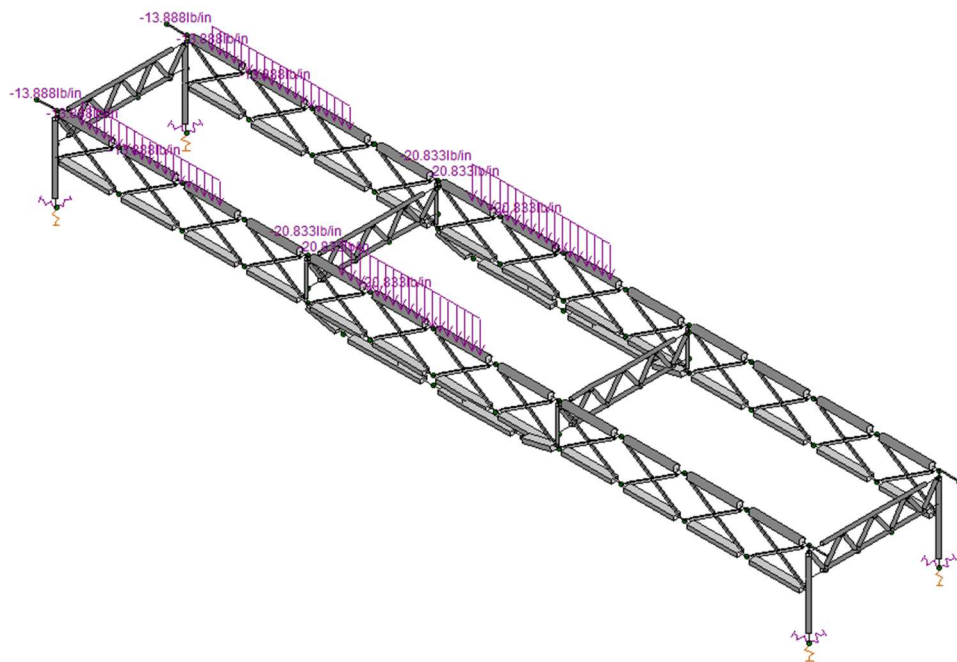


Figure 38: Final model for the bridge under load case 1

The most important addition here is the additional beam in the central bottom part of the bridge to help reduce deflection and stress.

The reactions are again similar, (Table. 3).

◀ ▶	L...	Joint Label	X [lb]	Y [lb]	Z [lb]	MX [lb-i...	MY [lb-i...	MZ [lb-i...
1	1	F1	9.03	871.598	.037	0	0	0
2	1	F2	-9.03	456.647	.023	0	0	0
3	1	F1A	9.03	871.597	-.037	0	0	0
4	1	F2A	-9.03	456.646	-.023	0	0	0
5	1	Totals:	0	2656.488	0			
6	1	COG (in):	X: 72.728	Y: 21.621	Z: 17			

Table 3: Reactions of final design

The axial load is also like the one in the basic model with the exception of the tension in the bottom of the bridge being lower due to the additional beam depth (Fig.39).

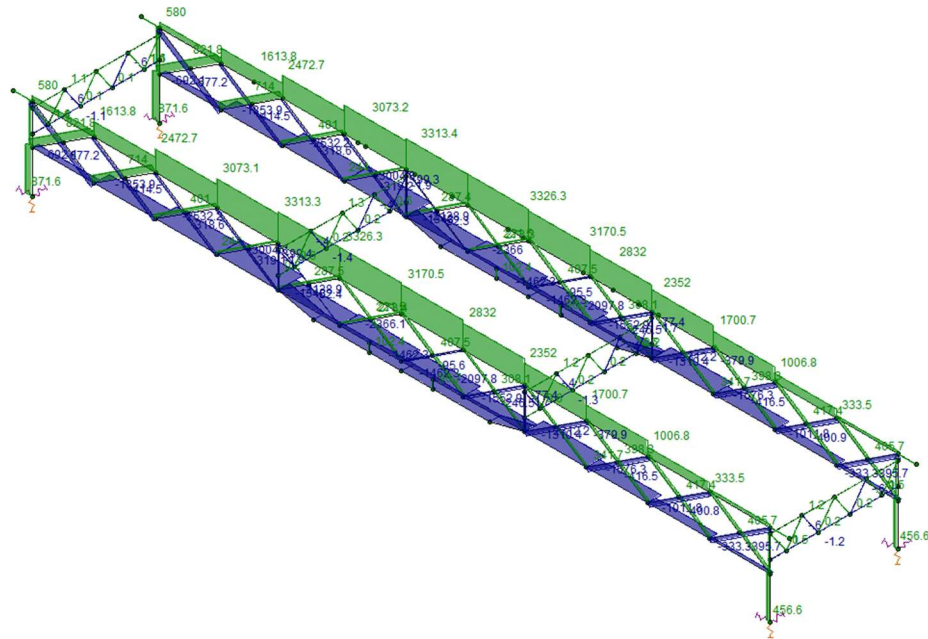


Figure 39: Axial load diagram for final design

Maximum load in compression is 3330 lb (14800 N) and of 3000 lb (13400 N) in tension.

Finally, the estimated deflection for this model is also very satisfactory (Fig.40), being closer to the over truss option than to the basic model.

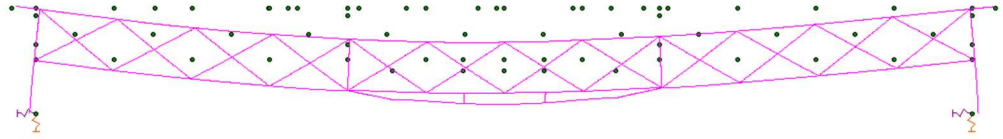


Figure 40: Deflection of final design under load case 1

The maximum deflection was 0.23 in (5.84 mm).

### 3. Connections

#### 3.1. Simpler connection and 2018 connections

Several ideas come to mind when thinking of the connections. It is clearly a vital part of the bridge, not only in regard to fast mounting, but also in the structural sense.

A balance must be sought here, if you go for more complex connections and tighter tolerances, you are sacrificing construction speed for structural sturdiness, and vice versa.

##### 3.1.1. Axial load

As mentioned before, the connection mainly used by the team, the “tapered dovetail” shows good results under axial load (Fig.41) and has the benefit that it can also withstand lateral loading.

The simulation carried out is just for comparative purposes, not to look for the breaking point of the connections.

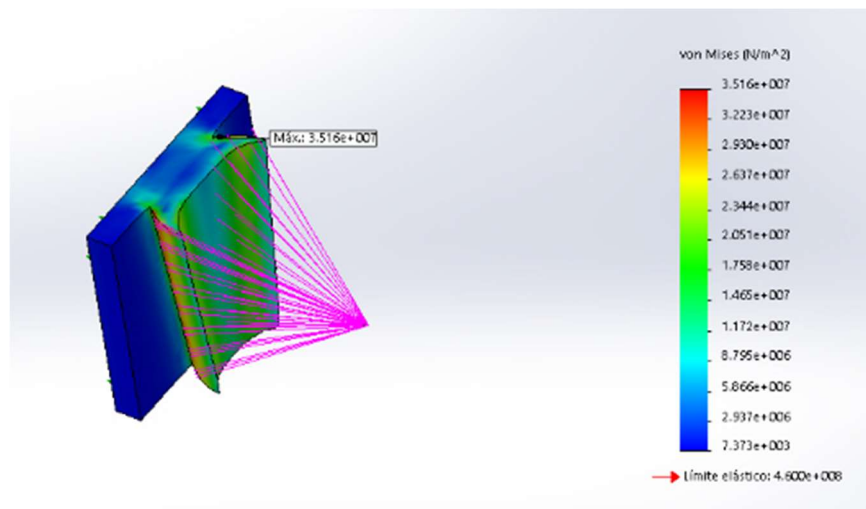
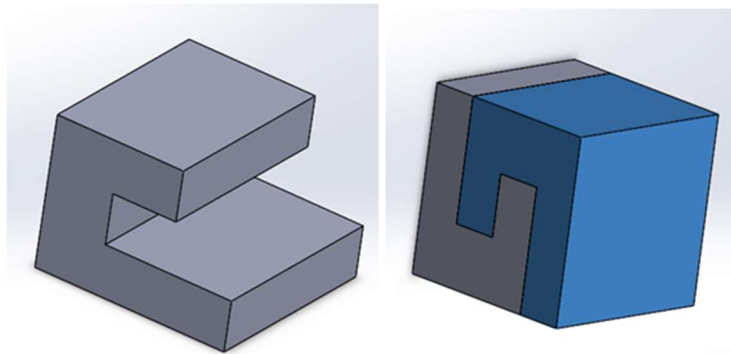


Figure 41: 1x1" Tapered dovetail under axial load case

The maximum stress in the tapered dovetail is 35 MPa (5 ksi). With this result, the other connections can be compared to see whether they are superior or similar in taking axial loading.

Here is an example of very simple connections, that works well in axial load (Fig.42-44).



Figures 42 and 43: Simple connection and assembly.

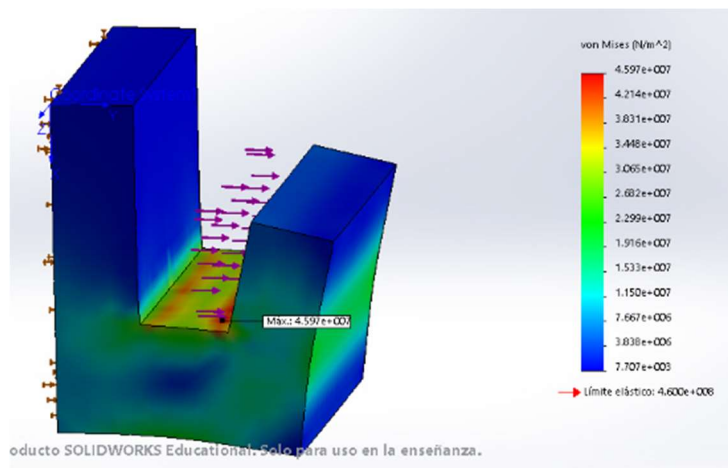


Figure 44: Simple connection under axial load case

The maximum stress is of 45.9 MPa (6.7 ksi), which is 24% higher than that of the dovetail connection. It is in the same order of magnitude, but the difference is to be considered.

Even trying to add a bolt to the simpler connection does not do the trick, if done without care, it can even be counterproductive, as shown next (Fig.45, 46).

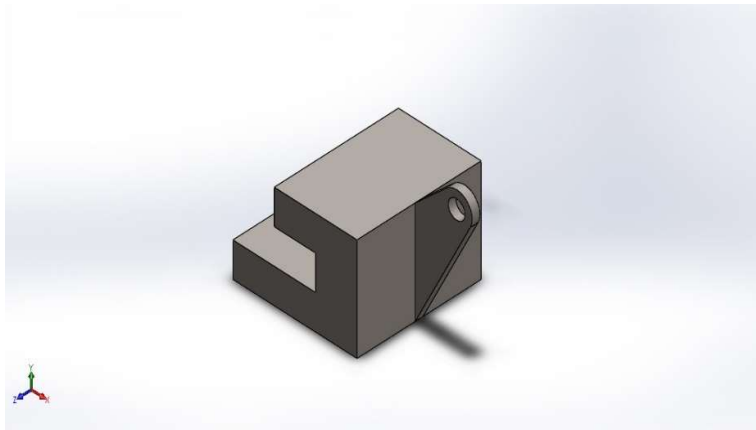


Figure 45: Simple connection with bolt structure

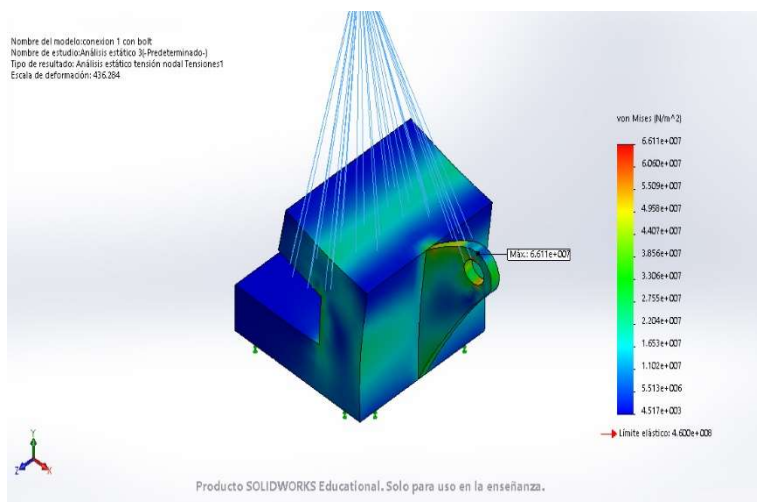


Figure 46: Simple connection with bolt under axial load case

Here the maximum tension stress is 66 MPa (9.6 ksi), which is even higher than the model without the bolt.

Other simpler connections used by the team do not require the same structural sturdiness.

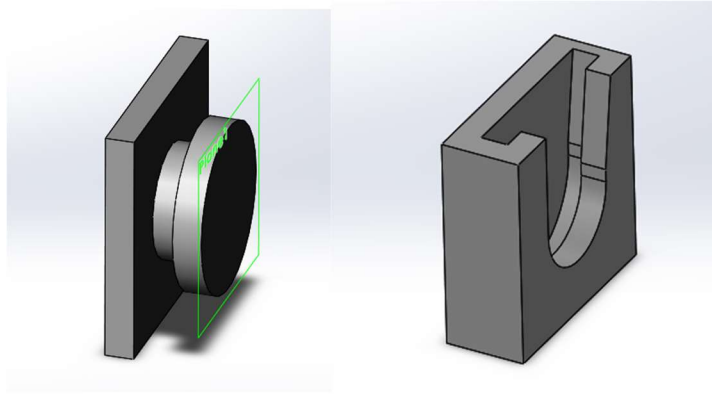


Figure 47 and 48: T connection male and female

This connection (Fig. 47, 48) has similar structural properties as the simpler one (Fig. 49) proposed but has the advantage of being able to take side load too.

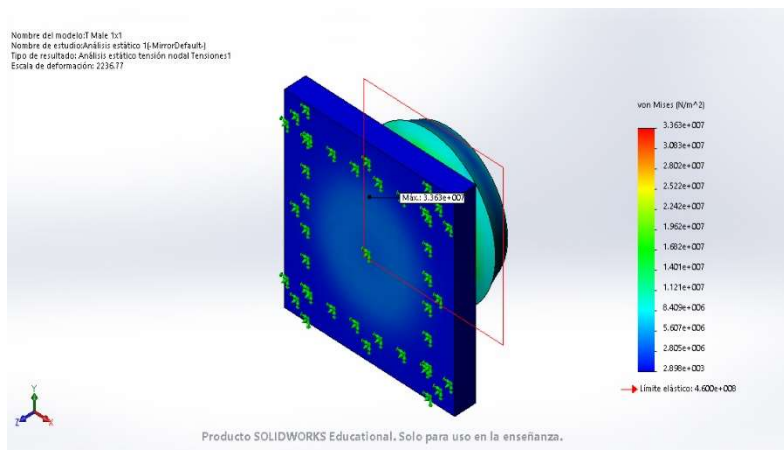


Figure 49: T connection under axial load case

The maximum stress is 34 MPa, which also provides very good results. The use of this connection in favor of the dovetail is decided in terms of mounting preferences. This connection can rotate whereas the dovetail cannot.

### 3.1.2. Flexure

Finally comparing results against flexural loads, the dovetail proves to be much superior to other alternatives (Fig. 50, 51). As a result, the dovetail is the most versatile and efficient connection.

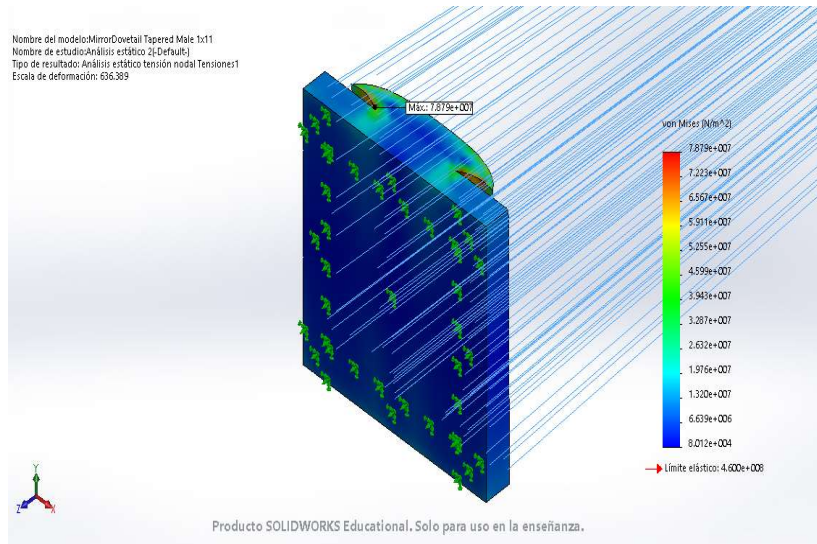


Figure 50: 1x1'' Tapered dovetail under flexion load case

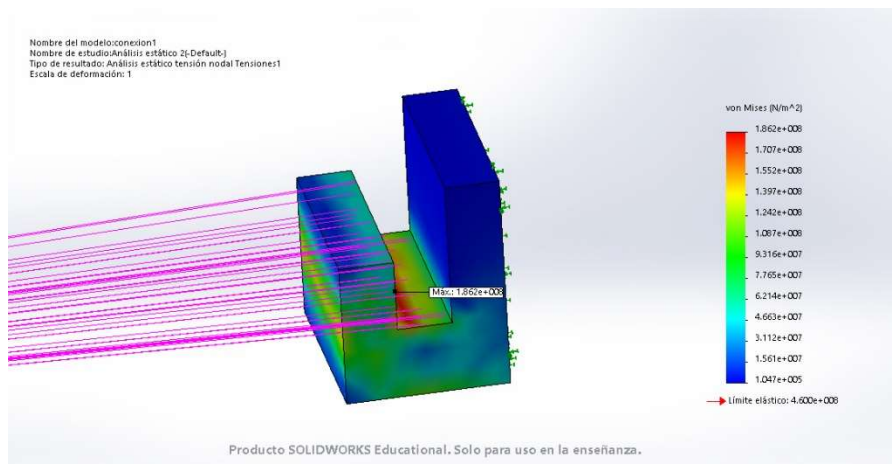


Figure 51: Simple connection under flexion load case

Here the dovetail is far superior with a maximum compression stress of 79 MPa (11.5 ksi), and even lower tension stress versus a maximum tension stress of 186 MPa (27 ksi) in the simpler connection.

Under this evidence and the fact that the dovetail is also used by many other universities with successful results in the competition, another approach to consider is to keep these ones, while trying to optimize them.

## 3.2. Optimization of dovetails.

### 3.2.1. Size

There are several ideas that can be addressed to make the dovetails more efficient. The first one is the size. As mentioned before, the option of having one sturdier connection instead of two normal ones is appealing in terms of simplicity and construction speed.

Examples of a different sized dovetail and its analysis is shown (Fig. 52-54).

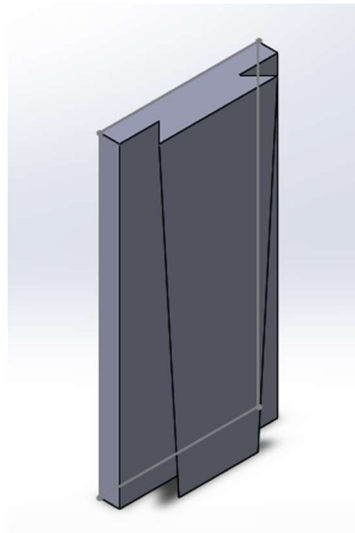


Figure 52: 1.25x2'' Tapered dovetail

Here is an image of a 1.25x2 in. dovetail, (31.75x50.8mm). Improvements are predicted here under axial load simply because there is more area to share it and under flexural load being the dovetail is deeper and wider.

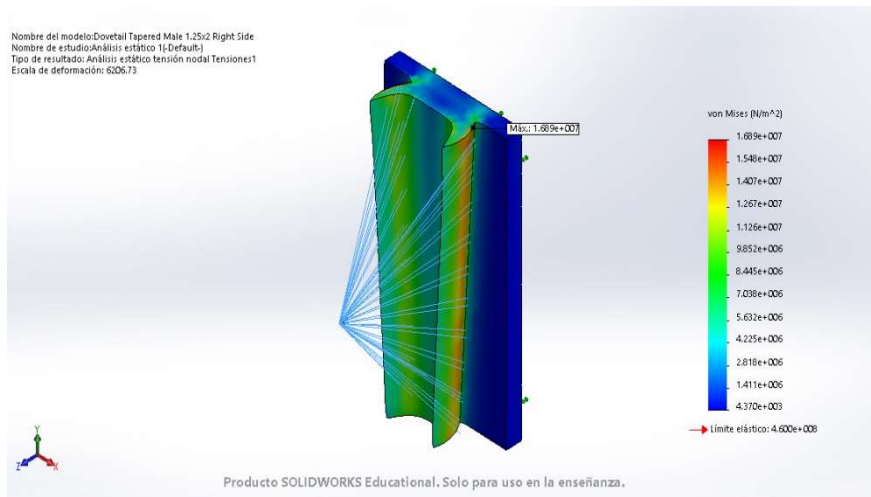


Figure 53: 1.25x2'' Tapered dovetail under axial load case

As expected the maximum tension stress in the axial conditions is of 17 MPa (2.5 ksi), about 50% lower than the 1x1in dovetail.

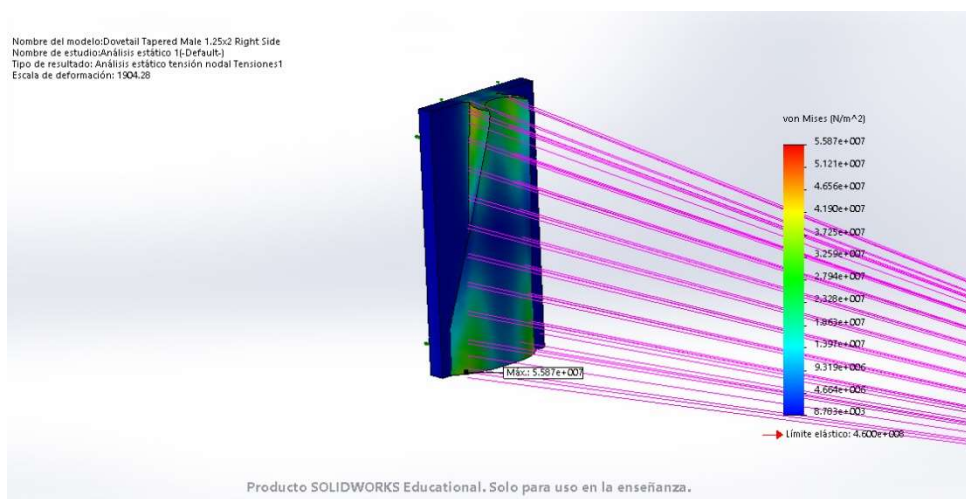


Figure 54: 1.25x2'' Tapered dovetail under flexion load case

The maximum compression stress is 56 MPa (8.12 ksi), about 30% lower than in the smaller version.

### 3.2.2. Depth

There are mainly three parameters to consider in the optimization of the dovetail: angle of the edge, alpha; the gap between the top and bottom, delta; and the depth of the dovetail, t (Fig. 55).

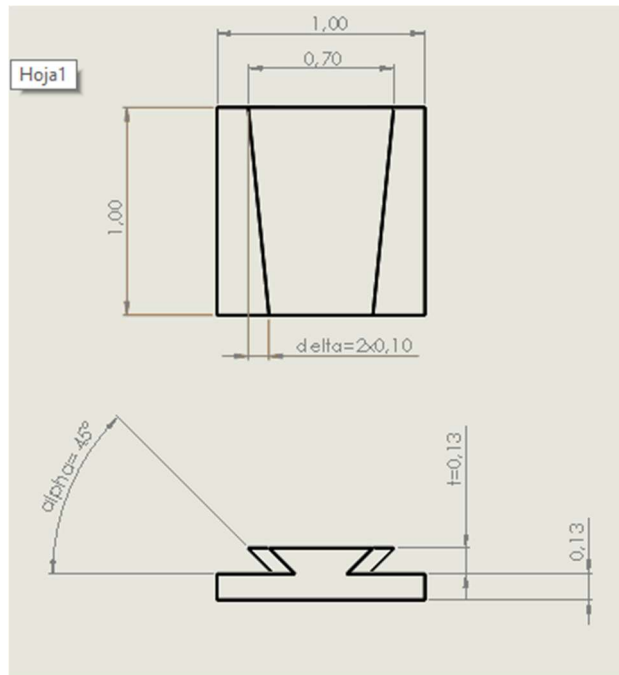


Figure 55: 1x1" tapered dovetail dimension sketch

Again, there are compromises to be made. The smaller alpha the more structurally sturdy, but if alpha is too small then the thickness of the edge might be too small, which defeats the purpose, risking a break there. Also, construction will be more difficult.

Here is an example of the piece with extra depth  $t$  of 0.16 in (4mm) (Fig. 56-58). The results are what was to be expected, higher surface equals higher axial load resistance.

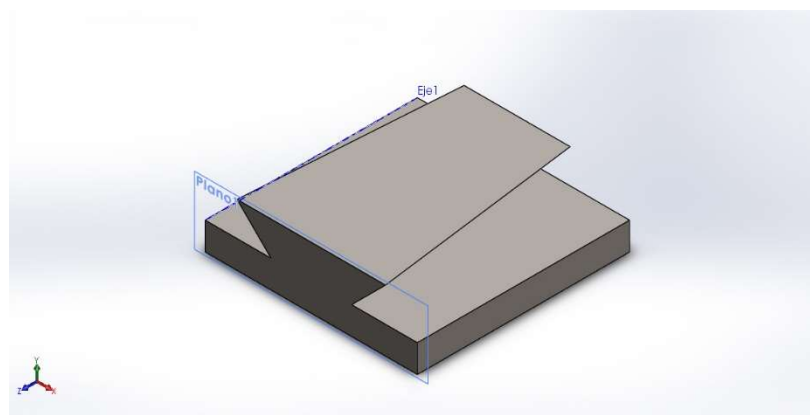


Figure 56: 1x1" tapered dovetail extra depth

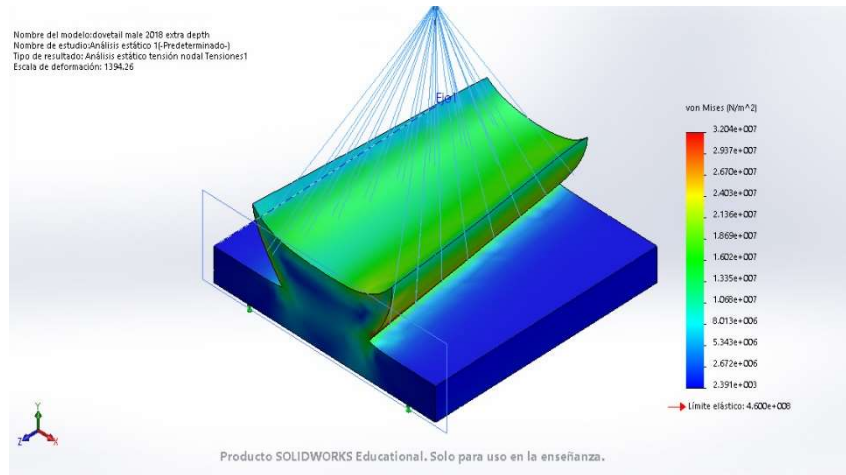


Figure 57: 1x1" tapered dovetail extra depth under axial load case

The maximum tension stress is 32 MPa (4.64 ksi). The improvement is not too significant, a mere 8.5% reduction in the maximum pressure. However, every improvement is to be considered. Danger with making the depth too big is to risk fracture when contact with the base of the connection, "a" is too little (Fig. 56).

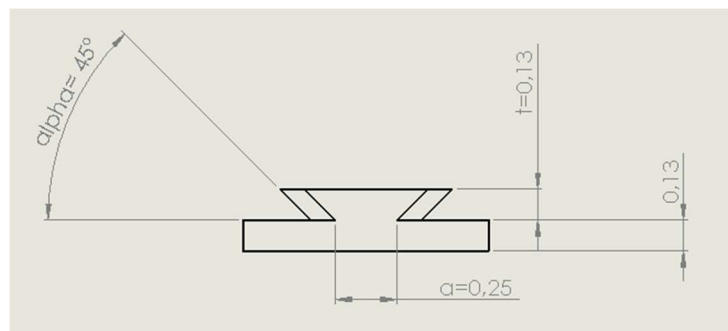


Figure 58: 1x1" tapered dovetail dimension sketch

As foreseen, lower depth results in less area and less resistance to axial load (Fig. 59).

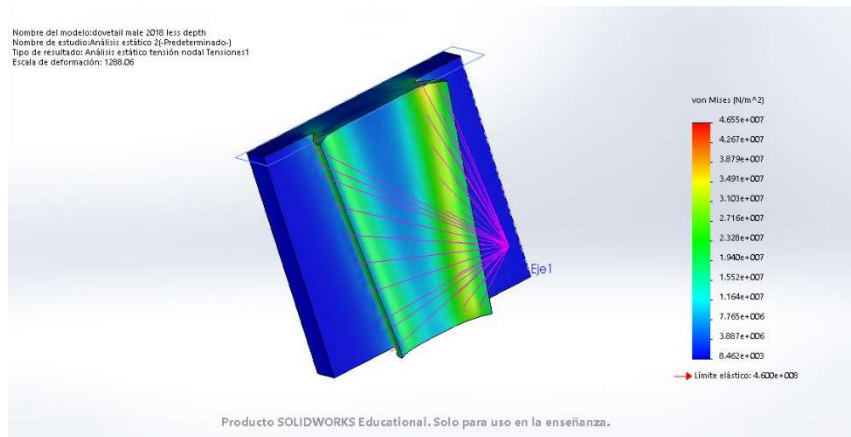


Figure 59: 1x1" tapered dovetail low depth under axial load case

The maximum tension with a depth of 0.1 in. (2.5mm) would be 47 MPa (6.8 ksi), which is quite high in comparison with the other alternatives.

### 3.2.3. Gap

The gap in the dovetail is added for mounting purposes. As shown below (Fig. 60), the team has used dovetails without a gap in previous years.

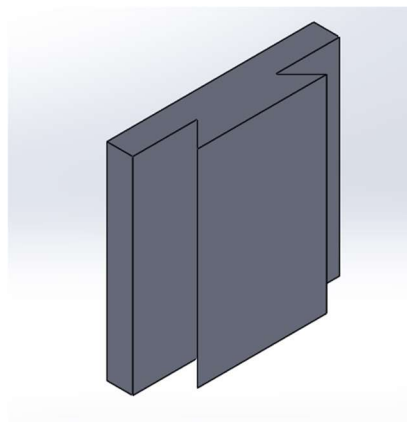


Figure 60: 1x1" dovetail

This configuration offers good results under axial load (Fig. 61) but can give trouble because it cannot take vertical loading. In terms of mounting, using a gap helps by being able to just hammer the male part into the female part without going too far.

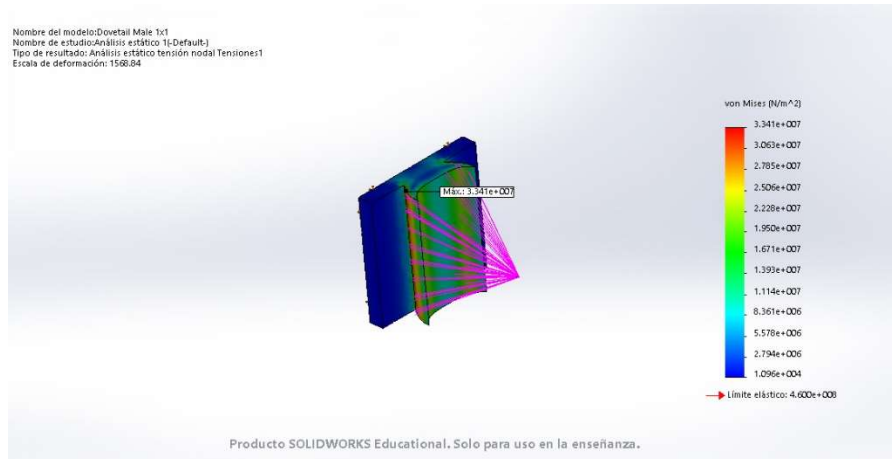


Figure 61: 1x1" dovetail under axial load case

In the image above, the maximum stress experienced by the dovetail is of 33.4 MPa (4.8 ksi), about a 4.5% better performance than the dovetail used this year, but with the mentioned drawbacks.

If the gap is to be included, it is important to try to minimize it in order to be the closest possible to this configuration.

### 3.2.4. Angle

The angle of the dovetail proves to be very important. Different angles have been used in other years in combination with other different configurations.

However, a design just with a variation in angle is shown here for comparison purposes (Fig. 62).

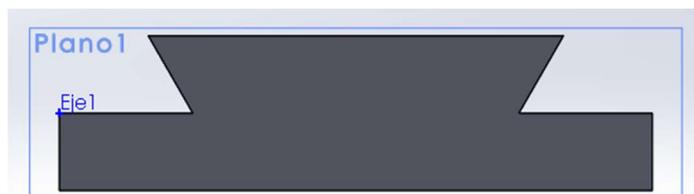


Figure 62: 1x1" Tapered dovetail higher angle

The angle for this connection is 60° which is shown next to be a very beneficial option (Fig.63).

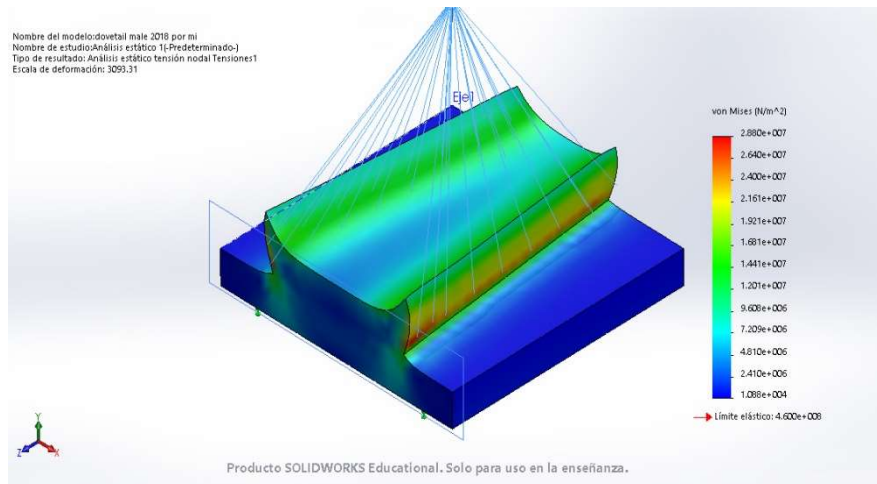


Figure 63: 1x1" Tapered dovetail higher angle under axial load case

With this angle, the maximum tension stress experienced by the dovetail is of 28.8 MPa (4.17 ksi). This stress is an improvement of almost 18% with respect to the dovetail used this year. Increasing the angle too much can be tricky though, the connection might end up slipping out. 60° is a safe option, this finding is proved by it having been used in previous years.

### 3.2.5. Round edges

A final consideration to consider is to make rounder geometries. This is generally preferred in industry because sharp edges are areas of concentration of stress and they can more easily fail by fracture.

Some round geometries have been used in the past (Fig. 64-65).

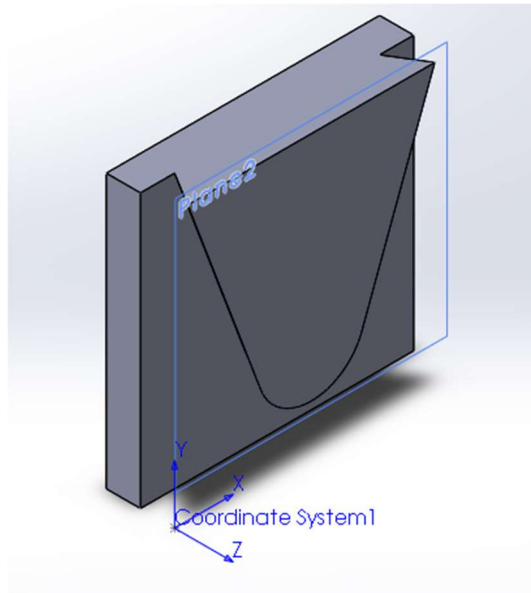


Figure 64: 1x1" Dovetail with round end

However, the results for these are not as satisfactory with a maximum tension stress of 55 MPa (8 ksi). This result shows that this configuration is worse than the one used this year.

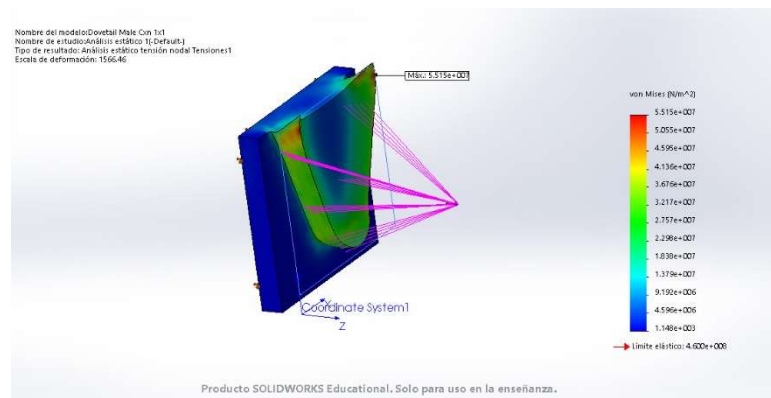


Figure 65: 1x1" Dovetail with round end under axial load case

Nevertheless, this idea is not to be dismissed and by just rounding up the edges of the existing dovetail (Fig. 66), benefits can be obtained.

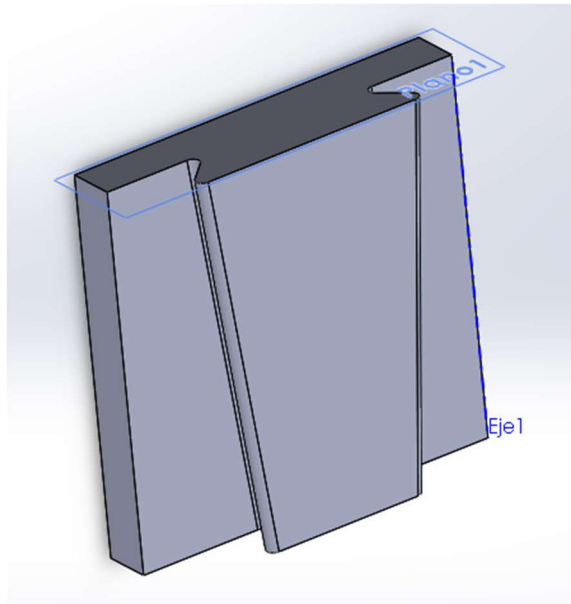


Figure 66: 1x1" Dovetail with round edges

The improvement in tension resistance is not too great (Fig. 67). The maximum tension stress is about the same as that with a sharp corner, 34.7MPa (5 ksi).

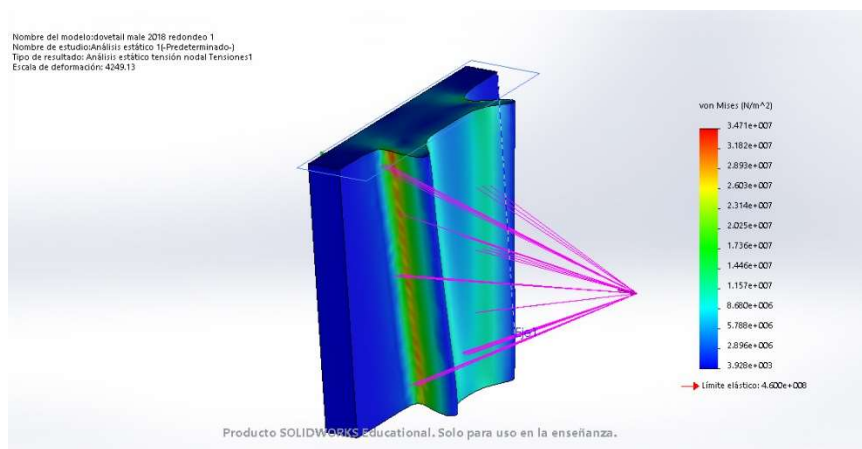


Figure 67: 1x1" Dovetail with round edges under axial load case

The improvement in risk of failure by fracture without having to increase the risk of failure by plastic deformation makes this design alteration appealing. In addition to that, having round edges is beneficial in construction. Finally, in term of security, the dovetails used by the team are quite sharp and the risk of cuts is reduced with this configuration.

### 3.2.6. Final optimal design

A final design for a dovetail is here considered mixing all the beneficial factors considered before (Fig.68-70).

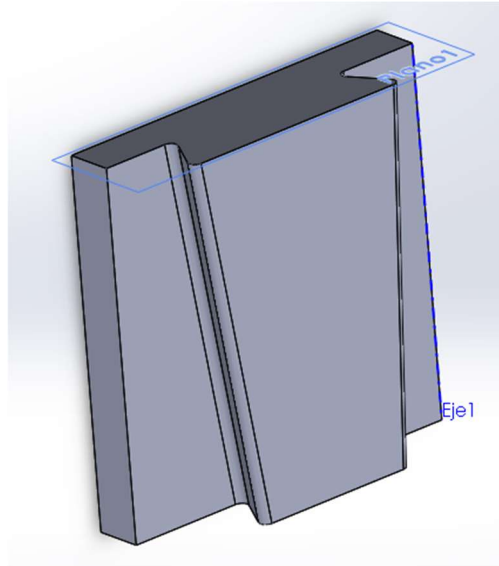


Figure 68: 1x1" Dovetail, final design

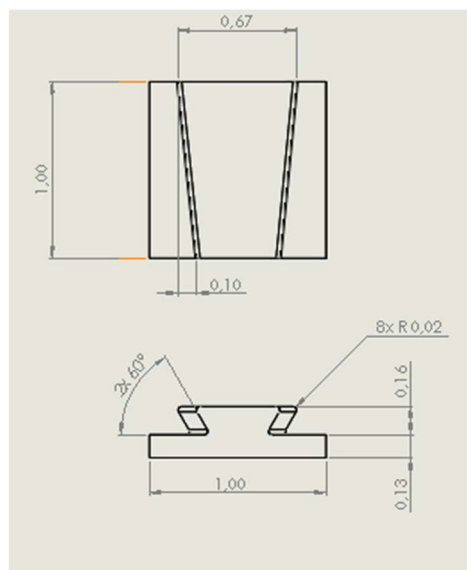


Figure 69: 1x1" Dovetail, final design dimension sketch

The results under axial load for the final dovetail are very satisfactory. The maximum tension stress is of 26.4 MPa (3.8 ksi), a 25% improvement from the one used by the team this year.

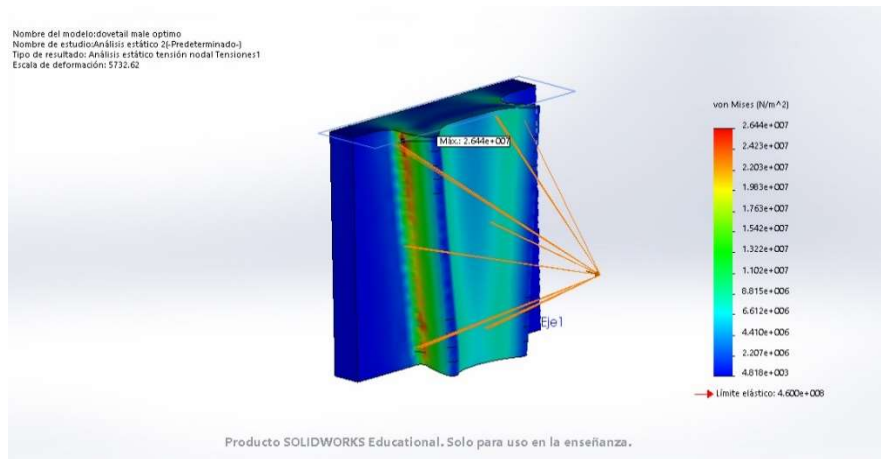


Figure 70: 1x1" Dovetail, final design under axial load case

This improvement in mechanical properties can be translated in looser tolerances, which results in smoother connections and in faster mounting.



# Part III

## Supplements





## 1. Material

The material used is AISI 4130 Alloy steel or 25CrMo4 by ISO standards. This low carbon steel allows good manufacturability and is easy to weld. The Chromium and Molybdenum improve its mechanical properties. To improve ductility and machinability, the alloy is also annealed at 850°C.

Element	Content (%)
Iron, Fe	97.03 – 98.22
Chromium, Cr	0.80 – 1.10
Manganese, Mn	0.40 – 0.60
Carbon, C	0.280 – 0.330
Silicon, Si	0.15 – 0.30
Molybdenum, Mo	0.15 – 0.25
Sulfur, S	0.040
Phosphorous, P	0.035

Table 4: Chemical composition of AISI 4130 Alloy steel

Properties	Metric	Imperial
Density	7.85 g/cm <sup>3</sup>	0.284 lb/in <sup>3</sup>
Melting point	1432°C	2610°F

Table 5: Physical properties of AISI 4130 Alloy steel

<b>Properties</b>	<b>Metric Imperial</b>	
Tensile strength, ultimate	560 MPa	81200 psi
Tensile strength, yield	460 MPa	66700 psi
Modulus of elasticity	190- 210 GPa	27557- 30458 ksi
Bulk modulus (Typical for steel)	140 GPa	20300 ksi
Shear modulus (Typical for steel)	80 GPa	11600 ksi
Poissons ratio	0.27- 0.30	0.27-0.30
Elongation at break (in 50 mm)	21.50%	21.50%
Reduction of area	59.6	59.60%
Hardness, Brinell	217	217
Hardness, Knoop (Converted from Brinell hardness)	240	240
Hardness, Rockwell B (Converted from Brinell hardness)	95	95
Hardness, Rockwell C (Converted from Brinell hardness, value below normal HRC range, for comparison purposes only.)	17	17
Hardness, Vickers (Converted from Brinell hardness)	228	228

Table 6: Mechanical properties of AISI 4130 Alloy steel

## 2. Load Cases

### 2.1. Competition

As mentioned, one of six load cases is chosen at random for the competition. The load case chosen this year is load case 1, but the bridge was tested with all the load case scenarios. For design and analysis, the team chooses to go for the load case that gives the worse overall results.

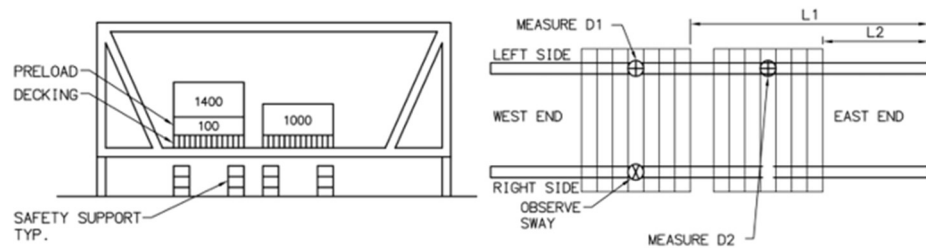


Figure 71: Vertical load test plan

Here are all the load case scenarios are modeled in RISA 3D (Fig. 72-77).

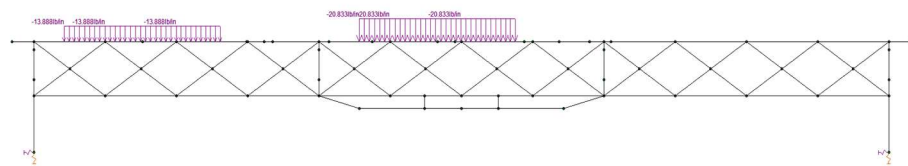


Figure 72: Load case 1

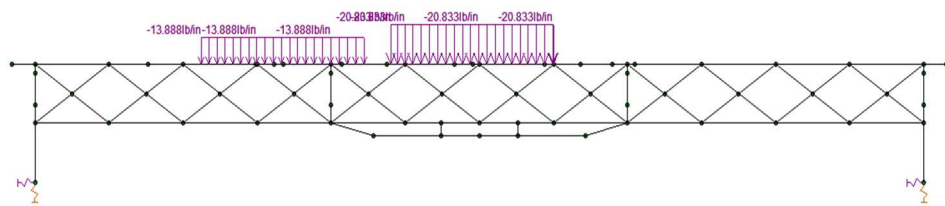


Figure 73: Load case 2

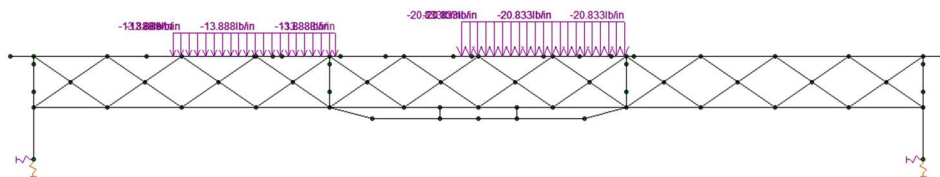


Figure 74: Load case 3

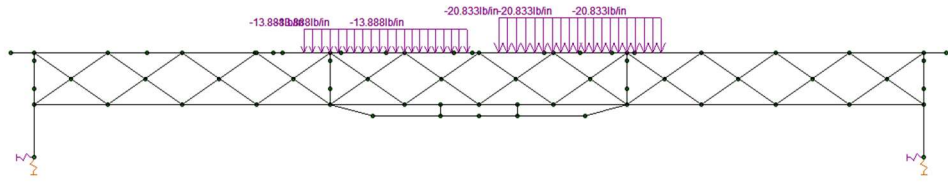


Figure 75: Load case 4

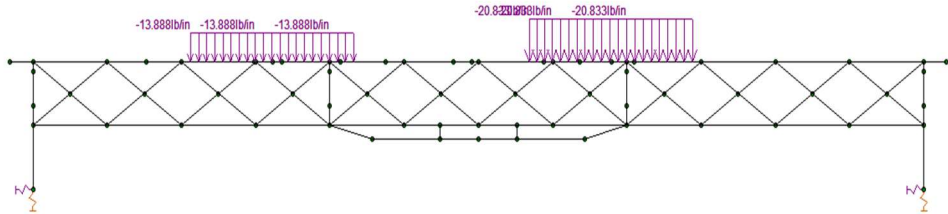


Figure 76: Load case 5

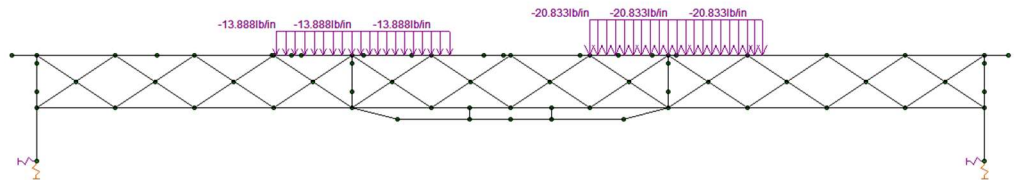


Figure 77: Load case 6

The bridge also must withstand a lateral load test of 50 lbs. (222.4N), while a load of 75 lbs. (333.6N) is vertically applied (Fig. 78).

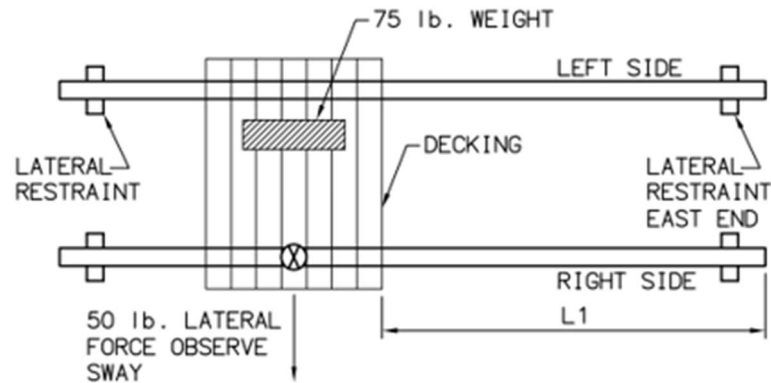


Figure 78: Lateral load test plan

## 2.2. Simulation

In the comparison of the different connections, two main load cases were used, one for axial loading and one for flexural loading.

The one for axial load consisted of an axial load of 1000 N (224.8 lbs) applied in the middle of the piece at a distance of 1 in. This was done using the remote mass tool in solid works with direct force transfer (Fig. 79).

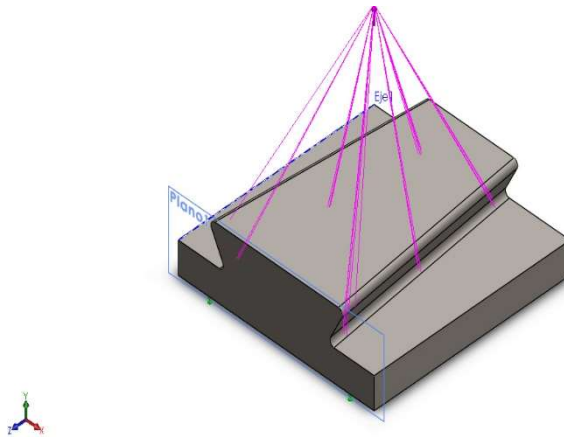


Figure 79: Axial load case in 1x1" dovetail final design

The flexural simulation consisted of a centered remote mass with direct transfer of 100 N (22.4 lbs) at a distance of 11.8 in (300mm) (Fig. 80).

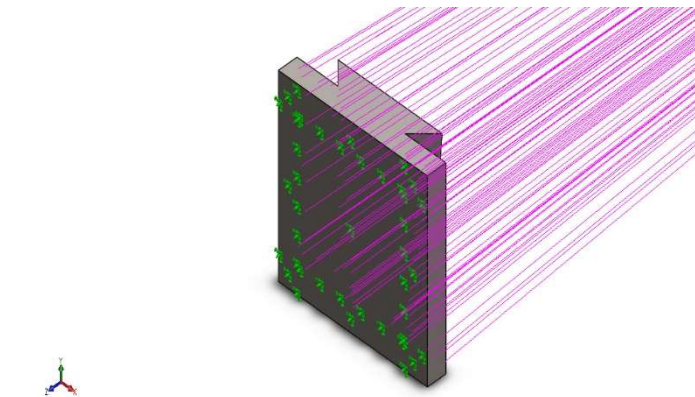


Figure 80: Flexion load case in 1x1" tapered dovetail

### **3. Specs (bridge)**

The results of the bridge tested in the lab are an aggregate deflection of 0.793 in (20.14 mm) and an overall weight of 161 lb (73 kg).

In the competition, the University of Michigan came in first at the regional competition with a total weight of 162 lbs (73.5 kg), an aggregate deflection of 0.53 in (13.5 mm), and a construction time of 3 minutes and 48 seconds.

#### 4. Results of competition

In the regional competition the University of Michigan came out first, winning all categories except for stiffness and structural efficiency.



Figure 81: University of Michigan construction team

In the national competition, the university of Michigan was thirteenth overall. More particularly, the team came out first in aesthetics, fourth in lightness, sixth in construction economy, and eighth in construction speed.

## 5. Lists

### 5.1. List of figures

<b>Number</b>	<b>Name</b>	<b>Page</b>
Figure 1	Isometric view of a CAD version of the bridge	9
Figure 2	Basic Design Concept	12
Figure 3	Intermediate design concept	13
Figure 4	Over truss design concept	13
Figure 5	Connections Modeled with SolidWorks	14
Figure 6	Connections and beams in SolidWorks	14
Figure 7	Male 1x1" tapered dovetail connection	15
Figure 8	Female 1x1" tapered dovetail connection	15
Figure 9	Alternative Square connection member	15
Figure 10	Alternative Square connection assembly	15
Figure 11	Full assembly o square connection with bolt	16
Figure 12	1,25x2" dovetail, 2018	17
Figure 13	Unused beams stored in Wilson Center	18
Figure 14	Example of jigs holding beam in th welding table, Solid Works	19
Figure 15	Base for modular jig	19
Figure 16	First part for modular jig	19
Figure 17	Second part for modular jig, square profile	20
Figure 18	Second part for modular jig, circular profile	20
Figure 19	Modular jig mounted	20
Figure 20	Abrasive cut off saw	22
Figure 21	Vertical Band saw	22
Figure 22	Horizontal Band saw	22
Figure 23	Lathe	23

Figure 24	Drill press	23
Figure 25	Mill	24
Figure 26	CNC mill	24
Figure 27	Sandblaster	25
Figure 28	Deburring machine	25
Figure 29	Rush machine & design abrasive belt tube and pipe	26
Figure 30	Wilton disc sander	26
Figure 31	TIG welding machine	27
Figure 32	Basic model, in RISA 3D under load case 1	33
Figure 33	Axial load diagram for basic model	34
Figure 34	Deflection of the basic model under load case 1	35
Figure 35	Over truss bridge under load case 1	35
Figure 36	Axial load diagram for over truss model	36
Figure 37	Deflection of the over truss bridge	37
Figure 38	Final model for the bridge under load case 1	37
Figure 39	Axial load diagram for the final design	38
Figure 40	Deflection of final design under load case 1	39
Figure 41	Tapered dovetail under axial load case	40
Figure 42	Simple connection	41
Figure 43	Simple assembly	41
Figure 44	Simple connection under axial load case	41
Figure 45	Simple connection with bolt structure	42

Figure 46	Simple connection with bolt under axial load case	42
Figure 47	T connection male	43
Figure 48	T connection female	43
Figure 49	T connection under axial load case	43
Figure 50	1x1" Tapered dovetail under flexion load case	44
Figure 51	Simple connection under flexion load case	44
Figure 52	1.25x2" Tapered dovetail	45
Figure 53	1.25x2" Tapered dovetail under axial load case	46
Figure 54	1.25x2" Tapered dovetail under flexion load case	46
Figure 55	1x1" tapered dovetail dimension sketch	47
Figure 56	1x1" tapered dovetail extra depth	47
Figure 57	1x1" tapered dovetail extra depth under axial load case	48
Figure 58	1x1" tapered dovetail dimension sketch	48
Figure 59	1x1" tapered dovetail low depth under axial load case	49
Figure 60	1x1" dovetail	49
Figure 61	1x1" dovetail under axial load case	50
Figure 62	1x1" Tapered dovetail higher angle	50
Figure 63	1x1" Tapered dovetail higher angle under axial load case	51
Figure 64	1x1" Dovetail with round end	52
Figure 65	1x1" Dovetail with round end under axial load case	52
Figure 66	1x1" Dovetail with round edges	53
Figure 67	1x1" Dovetail with round edges under axial load case	53
Figure 68	1x1" Dovetail, final design	54
Figure 69	1x1" Dovetail, final design dimension sketch	54
Figure 70	1x1" Dovetail, final design under axial load case	55
Figure 71	Vertical load test plan	61
Figure 72	Load case 1	61
Figure 73	Load case 2	61
Figure 74	Load case 3	61
Figure 75	Load case 4	62
Figure 76	Load case 5	62
Figure 77	Load case 6	62
Figure 78	Lateral load test plan	62
Figure 79	Axial load case in 1x1" dovetail final design	63
Figure 80	Flexion load case in 1x1" tapered dovetail.	63
Figure 81	University of Michigan construction team	64

## 5.2. List of tables

	<b>Name</b>	<b>Page</b>
Table 1	Reactions for the basic model	34
Table 2	Reactions for the over truss option	36
Table 3	Reactions of final design	38
Table 4	Chemical composition of AISI 4130 Alloy steel	59
Table 5	Physical properties of AISI 4130 Alloy steel	56
Table 6	Mechanical properties of AISI 4130 Alloy steel	60

## 5.3. List of formulas

	<b>Name</b>	<b>Page</b>
Formula 1	Set categories	31
Formula 2	Objective function	31
Formula 3	Constraints	31

## 7. Bibliography

1. Aisc.org. (2018). Student Steel Bridge Competition | American Institute of Steel Construction. [online] Available at: <https://www.aisc.org/education/university-programs/student-steel-bridge-competition/>
2. Help.solidworks.com. (2018). 2014 Ayuda de SOLIDWORKS - Criterio de máxima tensión de von Mises. [online] Available at: [http://help.solidworks.com/2014/spanish/solidworks/cworks/r\\_Maximum\\_von\\_Mises\\_Stress\\_Criterion.htm](http://help.solidworks.com/2014/spanish/solidworks/cworks/r_Maximum_von_Mises_Stress_Criterion.htm)
3. Hibbeler, R. (2012). Structural analysis. Boston: Prentice Hall.
4. Cat.calc\_est\_2\_im.efn.uncor.edu. (2018). [online] Available at: [http://www.cat.calc\\_est\\_2\\_im.efn.uncor.edu/wp-content/uploads/2013/10/Cap-02\\_CRITERIOS-DE-FALLA\\_31-a-52\\_v5.pdf](http://www.cat.calc_est_2_im.efn.uncor.edu/wp-content/uploads/2013/10/Cap-02_CRITERIOS-DE-FALLA_31-a-52_v5.pdf)
5. AZoM.com. (2018). AISI 4130 Alloy Steel (UNS G41300). [online] Available at: <https://www.azom.com/article.aspx?ArticleID=6742>
6. Teamprojects.engin.umich.edu. (2018). Machines - Wilson Student Team Project Center. [online] Available at: <http://teamprojects.engin.umich.edu/machines/>

# Document II

## Engineering Drawings





## 1. Drawings list

1. Alternative square connection
2. Alternative square jig
3. T connection
4. Final dovetail
5. Blue beam 1 bottom
6. Blue beam 1 top
7. Blue beam 5 bottom
8. Blue beam 5 top
9. Blue beam 4 bottom
10. Blue beam 4 top
11. Blue beam Depth 1
12. Blue pier 0
13. Cross bracing

## Comments

The team has organized the bridge in a way that it has two axes of symmetry one longitudinal and one transversal. Longitudinally, both sides of the bridge are mirrored, one side is named blue side and the other maize side (colors of the University of Michigan).

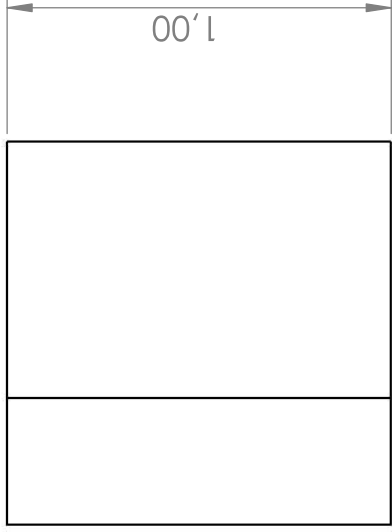
The pieces are also numbered from 0 to 7. The piers are either pier 0 or pier 7. The beams are numbered 1 through 6, and the depth beams that go in the bottom 1 through 2.

To avoid repeating drawings, only one quarter of the drawings of the bridge are shown here.

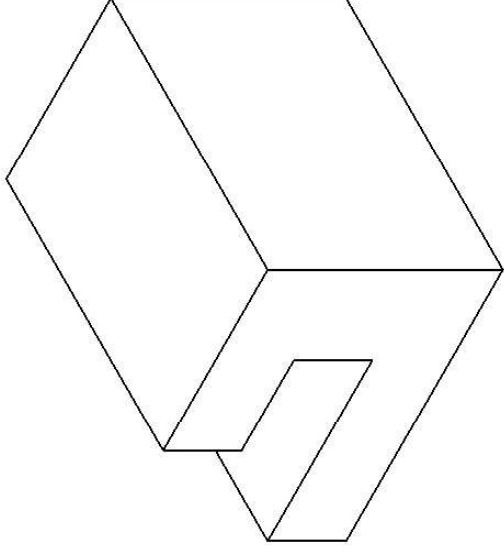
2

1

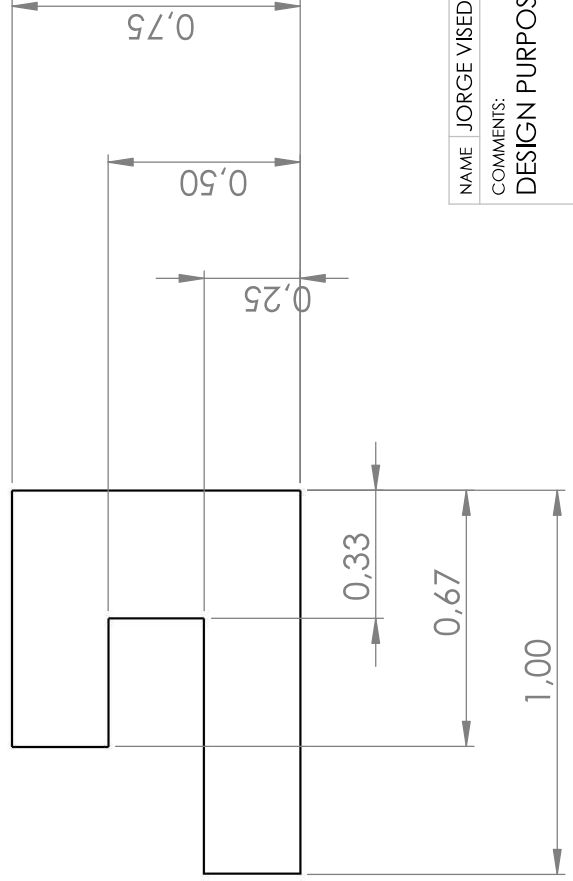
B



B



A



A

NAME | JORGE VISEDO

DATE | 06/06/2018

COMMENTS:  
DESIGN PURPOSES

DWG. NO.

ALT SQUARE CONNECTION

SCALE: 2:1 QUANTITY: N/A SHEET 1 OF 1

1

2

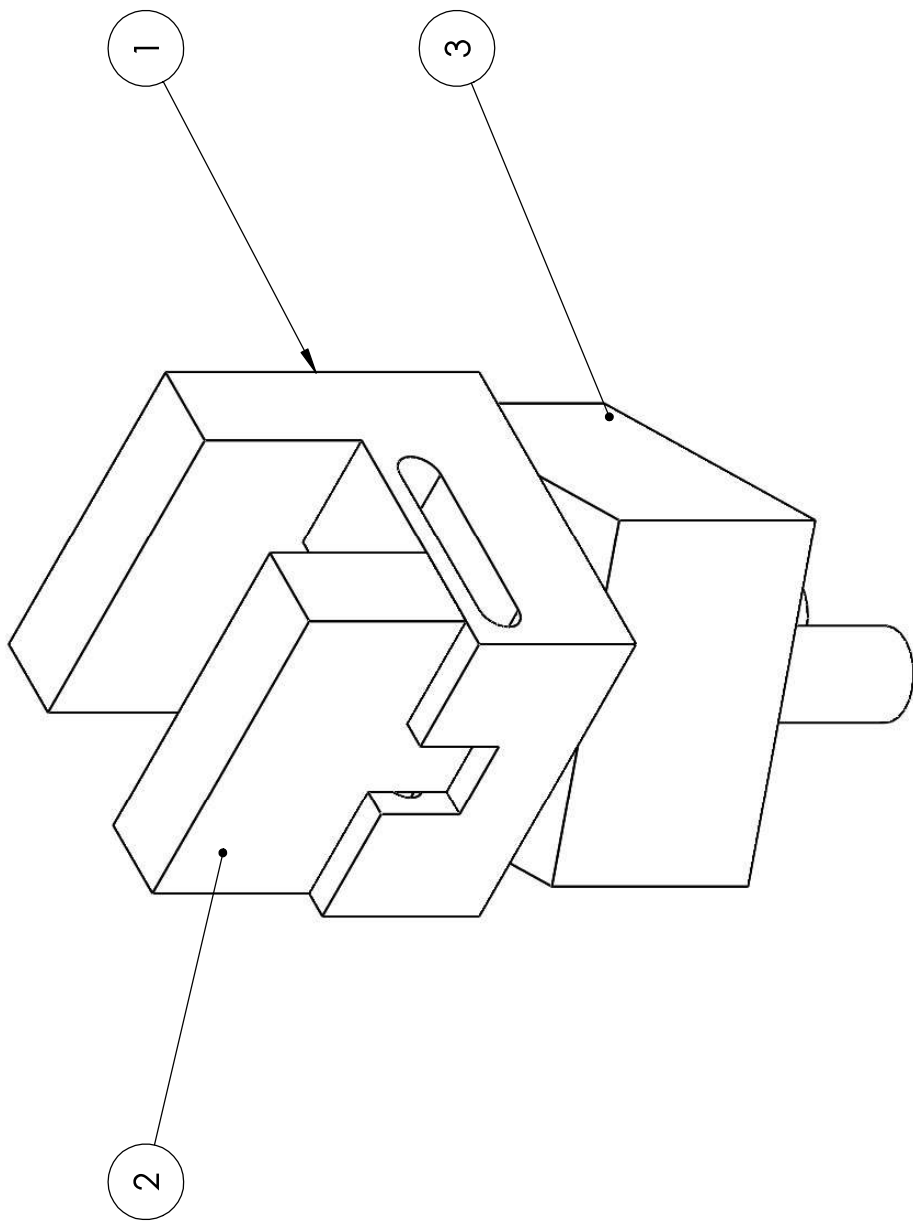
1

B

B

A

A



NAME | JORGE VISEDO

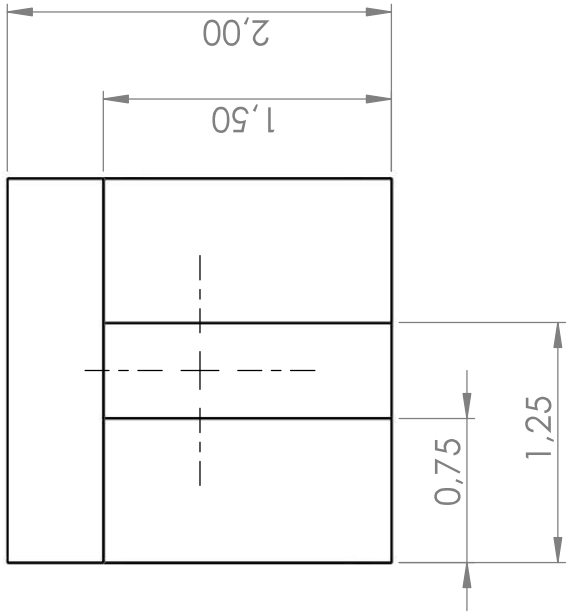
DATE | 06/06/2018

COMMENTS:  
DESIGN PURPOSES

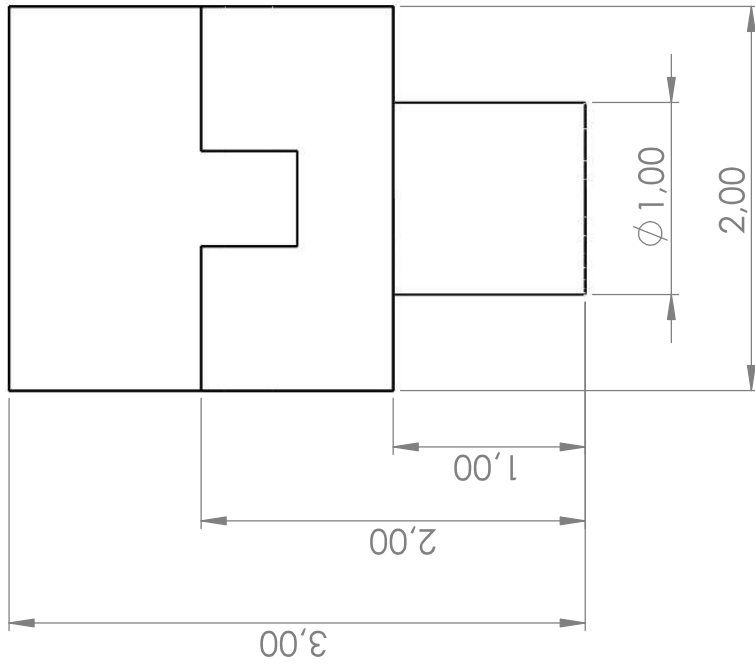
DWG. NO.

**ALT SQUARE JIG**

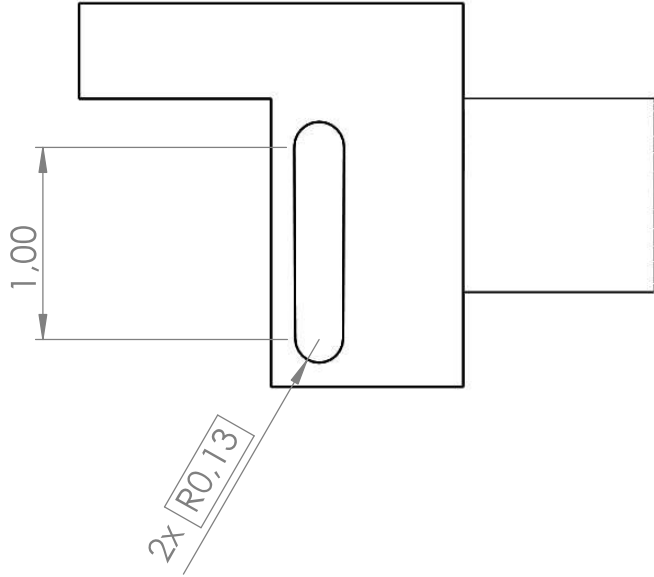
SCALE: 1:1 | QUANTITY: N/A | SHEET 1 OF 4



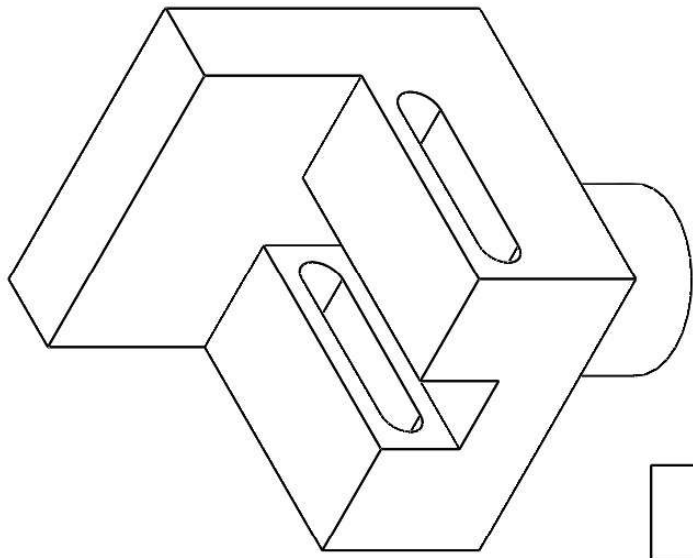
B



A



A



B

DATE 06/06/2018

NAME XXXXXXXX

DWG. NO.

COMMENTS:

# ALT SQUARE JIG

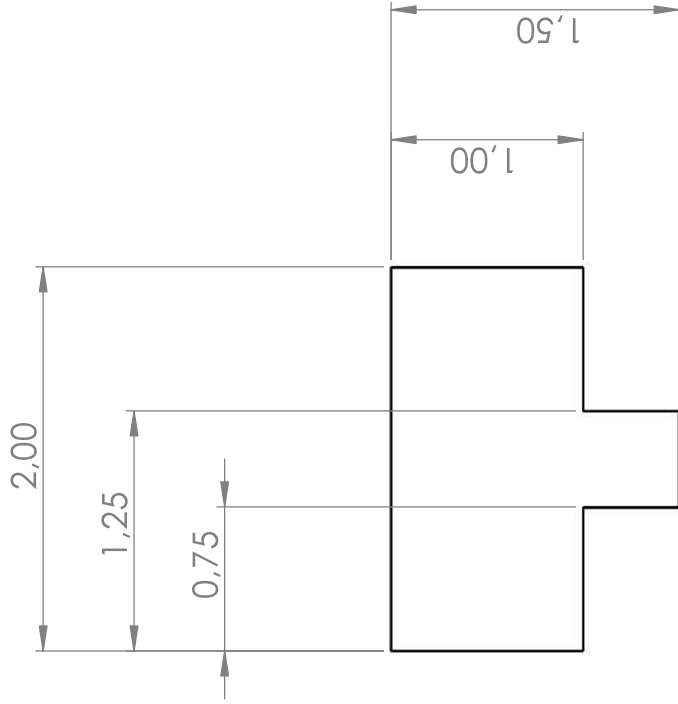
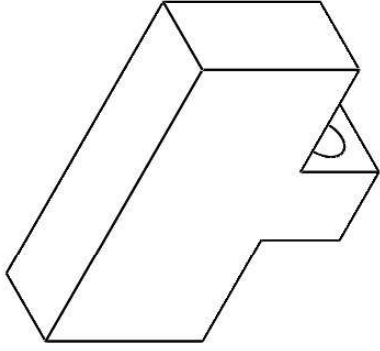
SCALE: 1:1 QUANTITY: N/A SHEET 2 OF 4

B

B

A

A



$\phi 0,28$

NAME

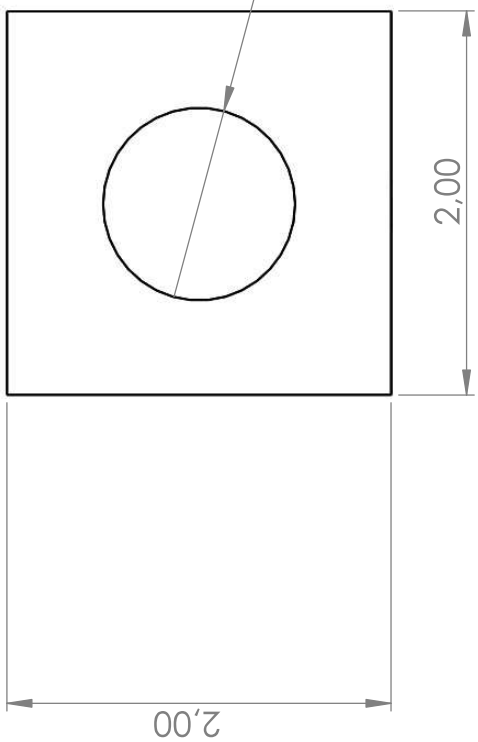
DATE 06/06/2018

COMMENTS:

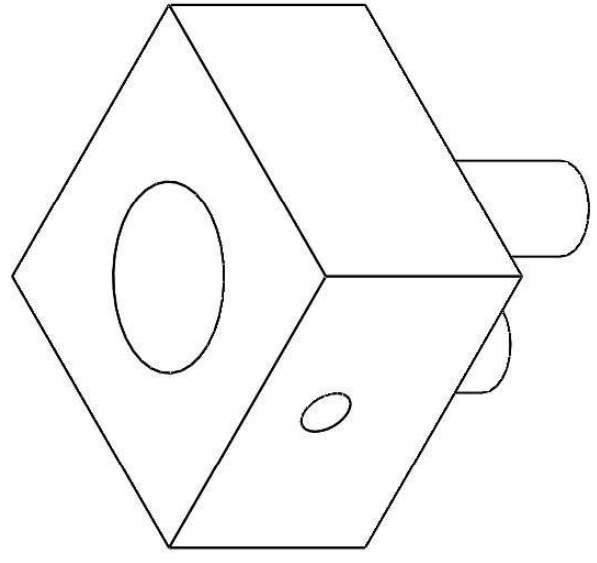
DWG. NO.

# ALT SQUARE JIG

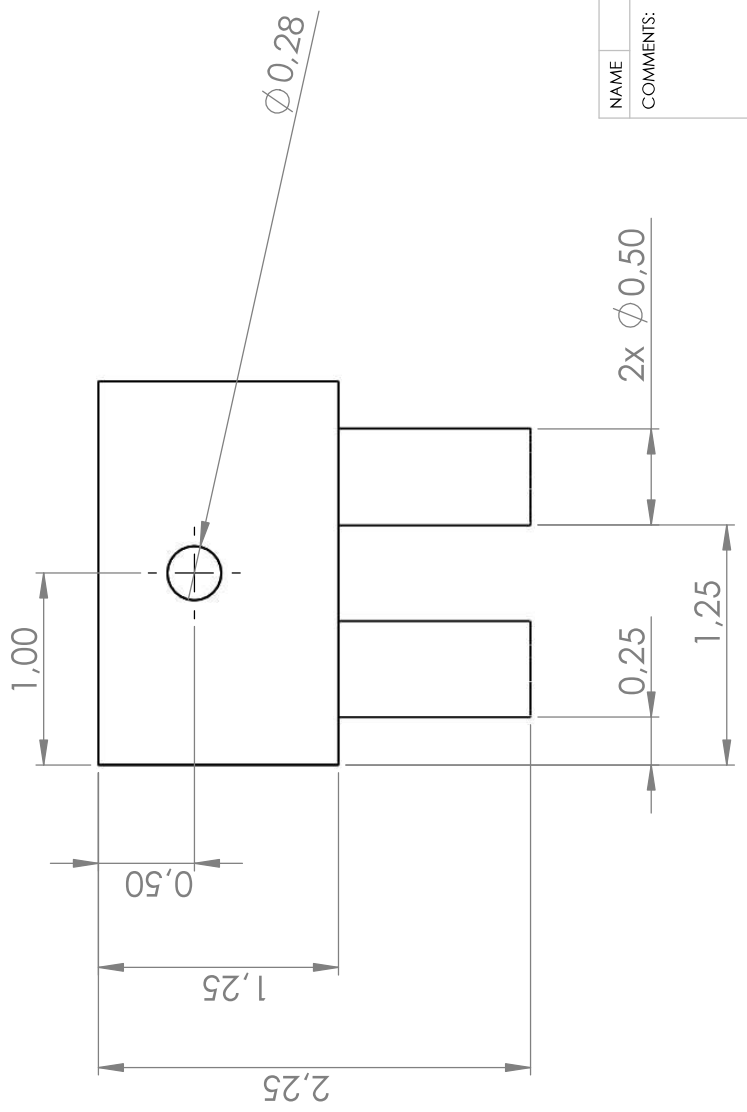
SCALE: 1:1 QUANTITY: N/A SHEET 3 OF 4



B



B



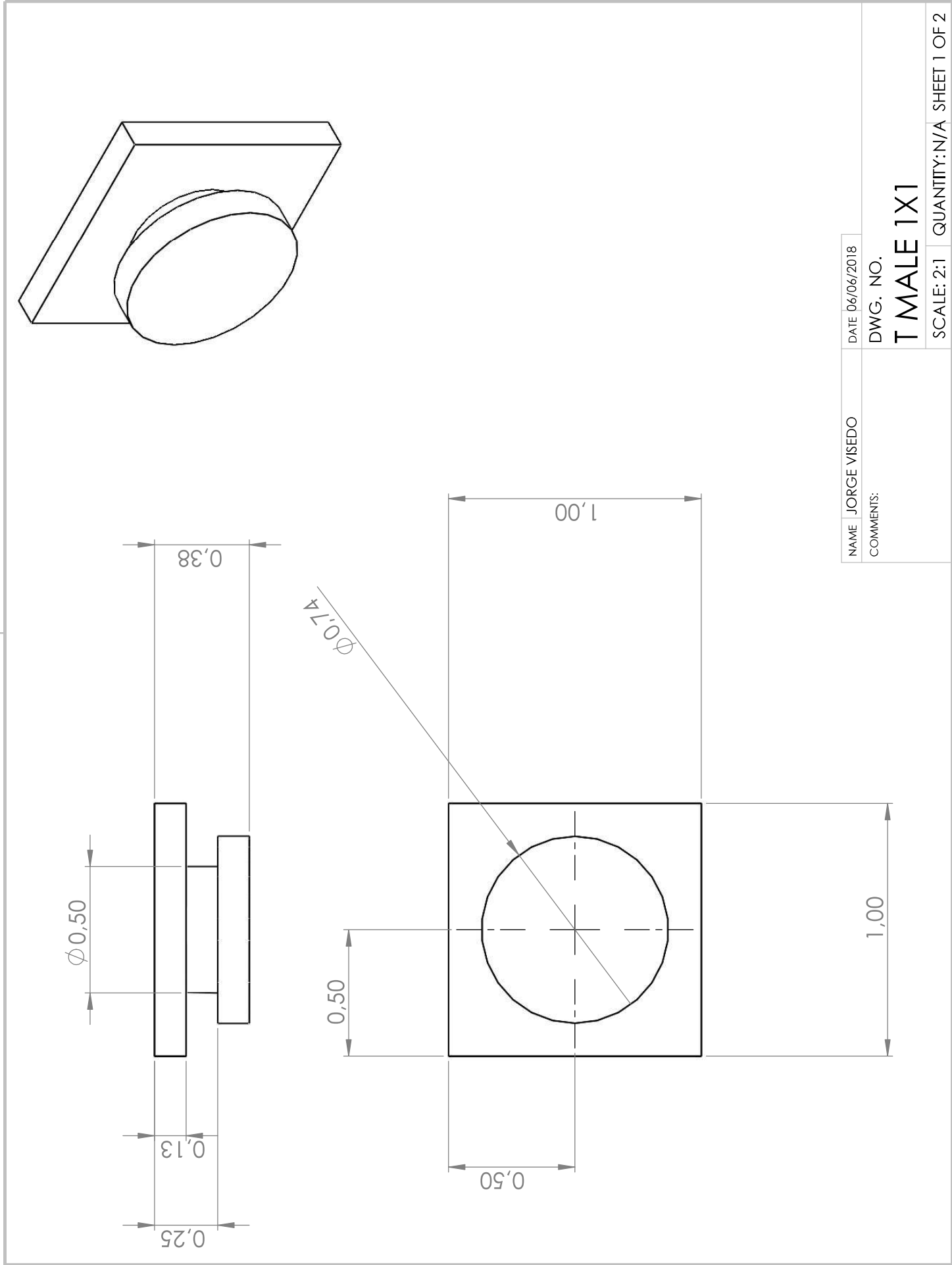
A

A

NAME	DATE 06/06/2018
COMMENTS:	DWG. NO.
<b>ALT SQUARE JIG</b>	
SCALE: 1:1	QUANTITY:
SHEET 4 OF 4	

2

1



B

A

B

A

NAME | JORGE VIEGO

DATE | 06/06/2018

COMMENTS:

DWG. NO.

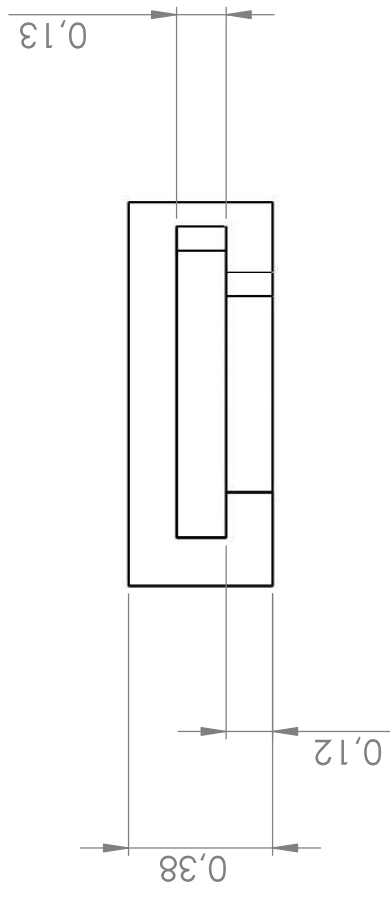
**T MALE 1X1**

SCALE: 2:1

QUANTITY: N/A SHEET 1 OF 2

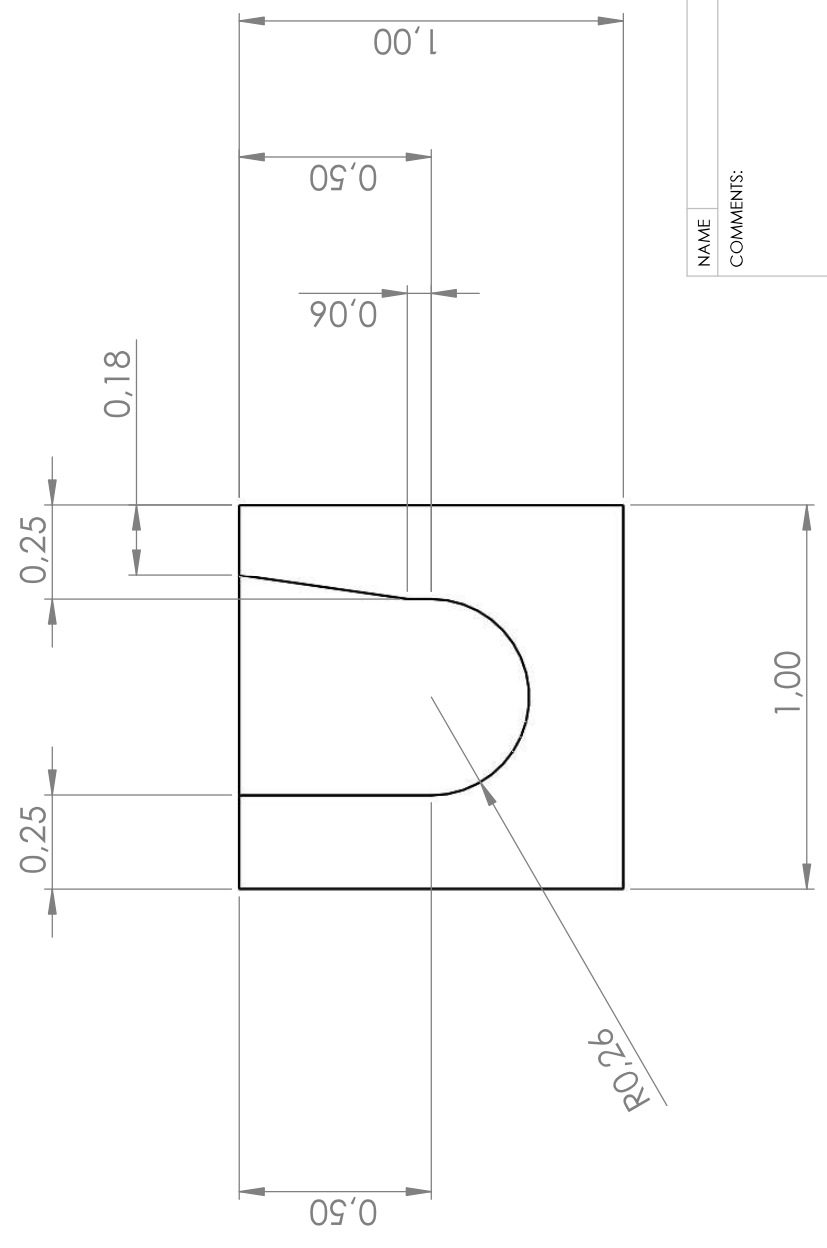
2

1



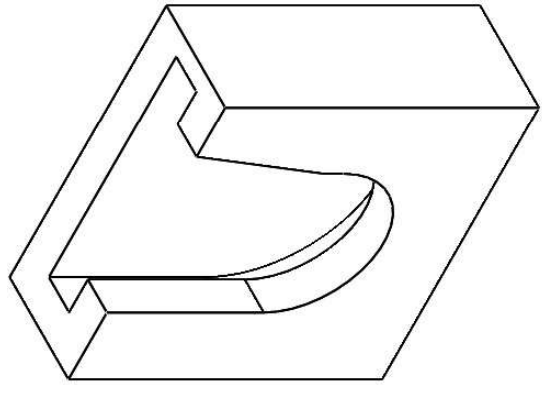
B

B



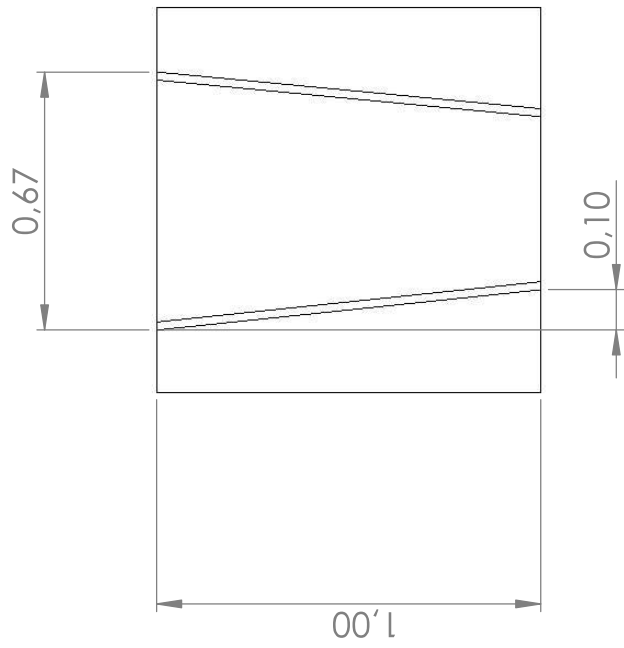
A

A

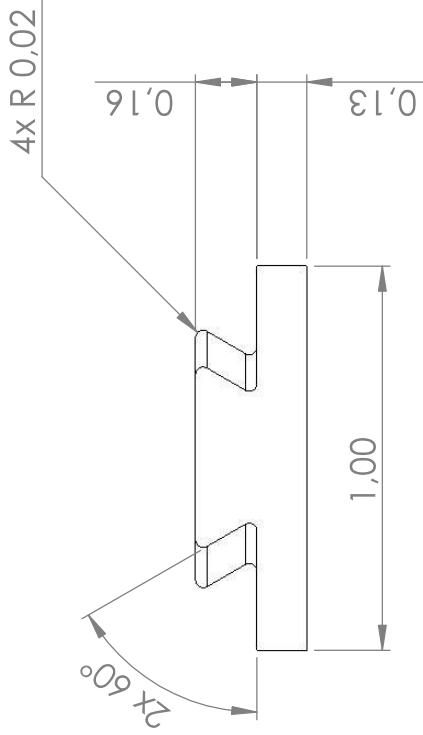


NAME	DATE 06/06/2018
COMMENTS:	DWG. NO.
<b>T FEMALE 1X1</b>	
SCALE: 2:1	QUANTITY: N/A SHEET 2 OF 2

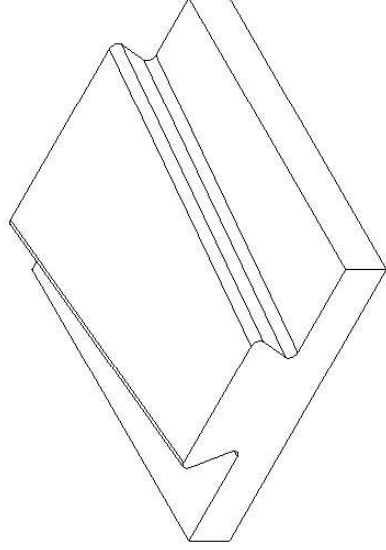
2



B



A



B

A

NAME: JORGE VISEDO DATE: 06/06/2018

COMMENTS: FOR DESIGN PURPOSES DWG. NO.

# DOVETAIL MALE FINAL

SCALE: 2:1 QUANTITY: SHEET 1 OF 1

1

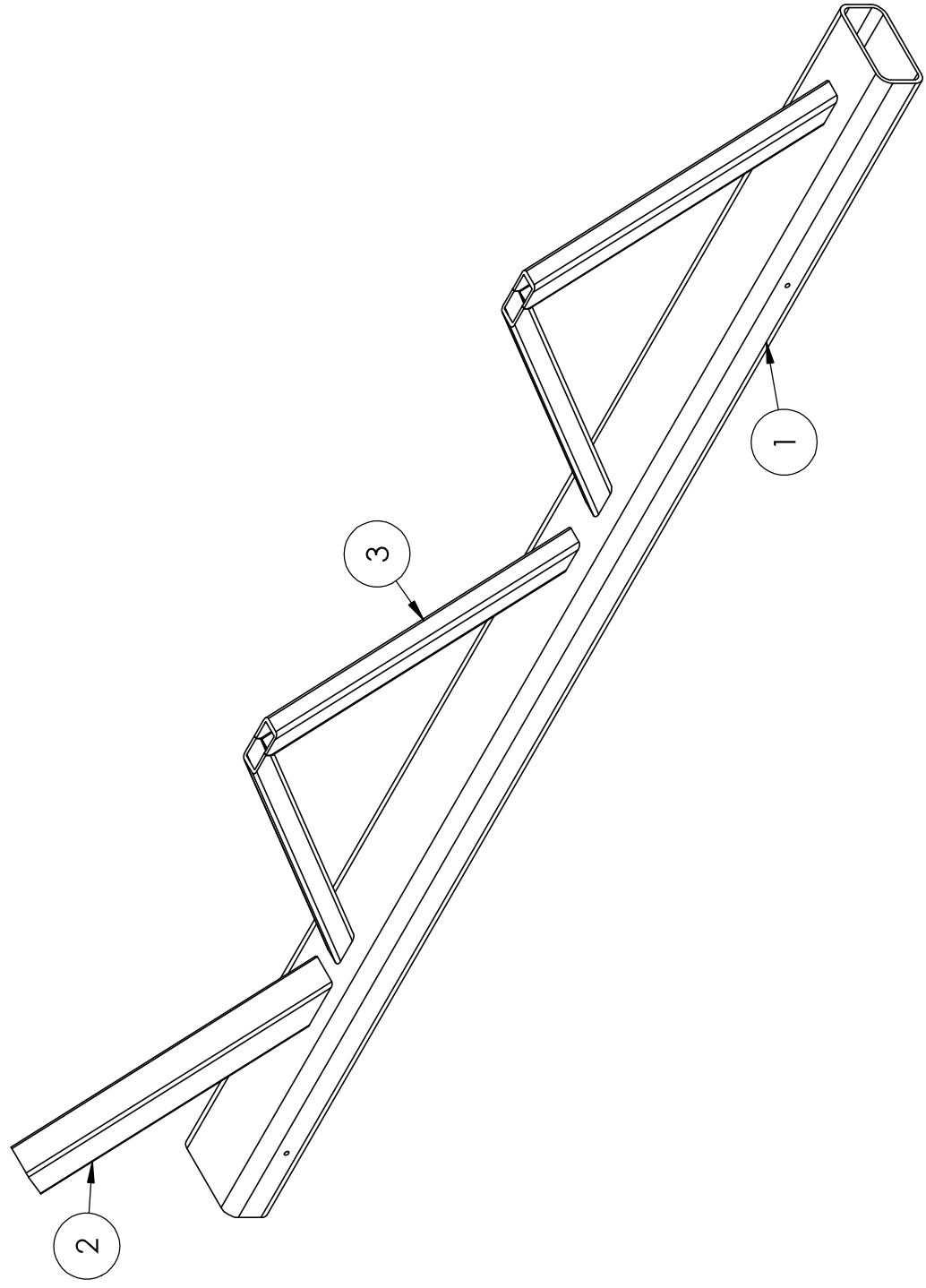
2

B

A

B

A



NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	

**SAME AS MAIZE  
BEAM 1 BOTTOM**

DWG. NO.	
BLUE BEAM 1 BOTTOM	
SCALE: 1:3	QUANTITY: 1
SHEET 1 OF 5	

1

2

1

B

B

ITEM NO.	QTY.	DESCRIPTION	LENGTH
1	1	Rectangular Tube 1x2x0.083	28.75
2	1	Square Tube 0.75x0.75x0.035	6.48
3	4	Square Tube 0.50x0.50x0.065	6.81

A

A

NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	

DWG. NO.

BLUE BEAM 1 BOTTOM

SCALE: N/A QUANTITY: 1 SHEET 2 OF 5

1

1

2

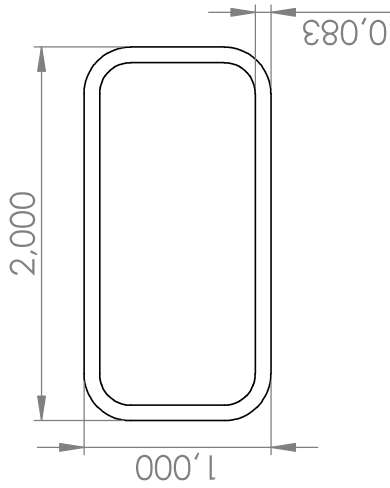
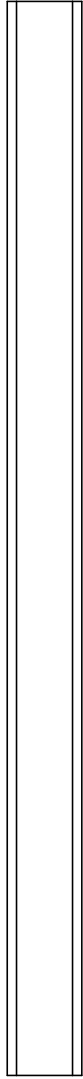
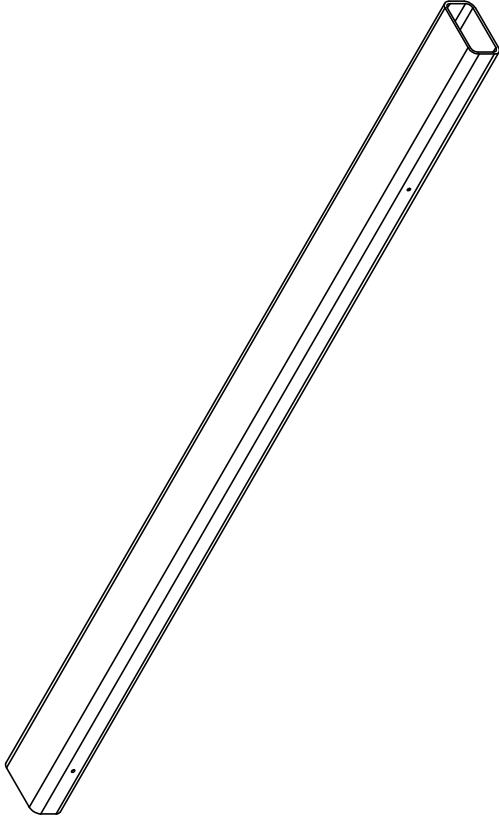
1

B

B

A

A



NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	LASER CUT PIECE A

DWG. NO.	BLUE BEAM 1 BOTTOM
SCALE: 1:5	QUANTITY: 1
SHEET 3 OF 5	

1

2

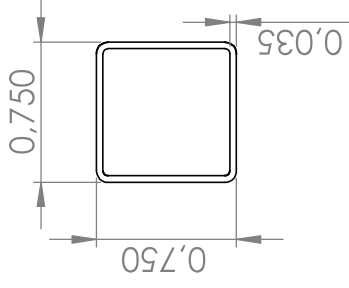
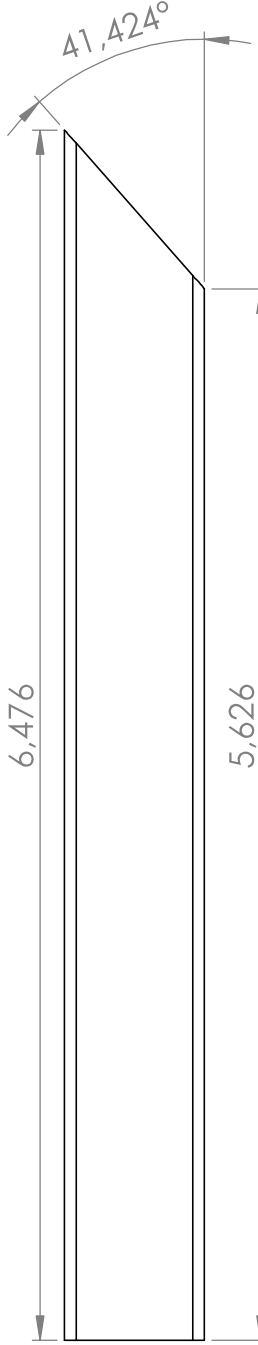
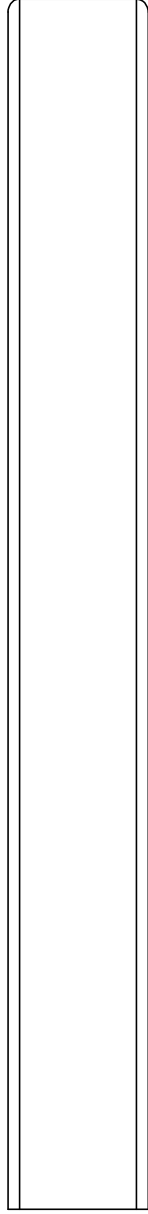
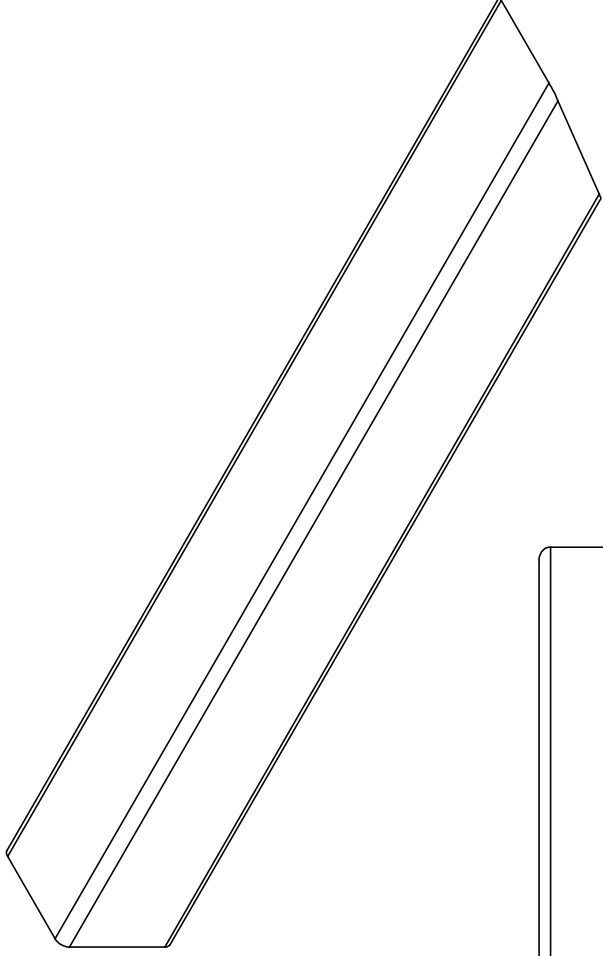
1

B

B

A

A



NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	

DWG. NO.	
BLUE BEAM 1 BOTTOM	
SCALE: 1:1	QUANTITY: 1
	SHEET 4 OF 5

GRINDER

1

2

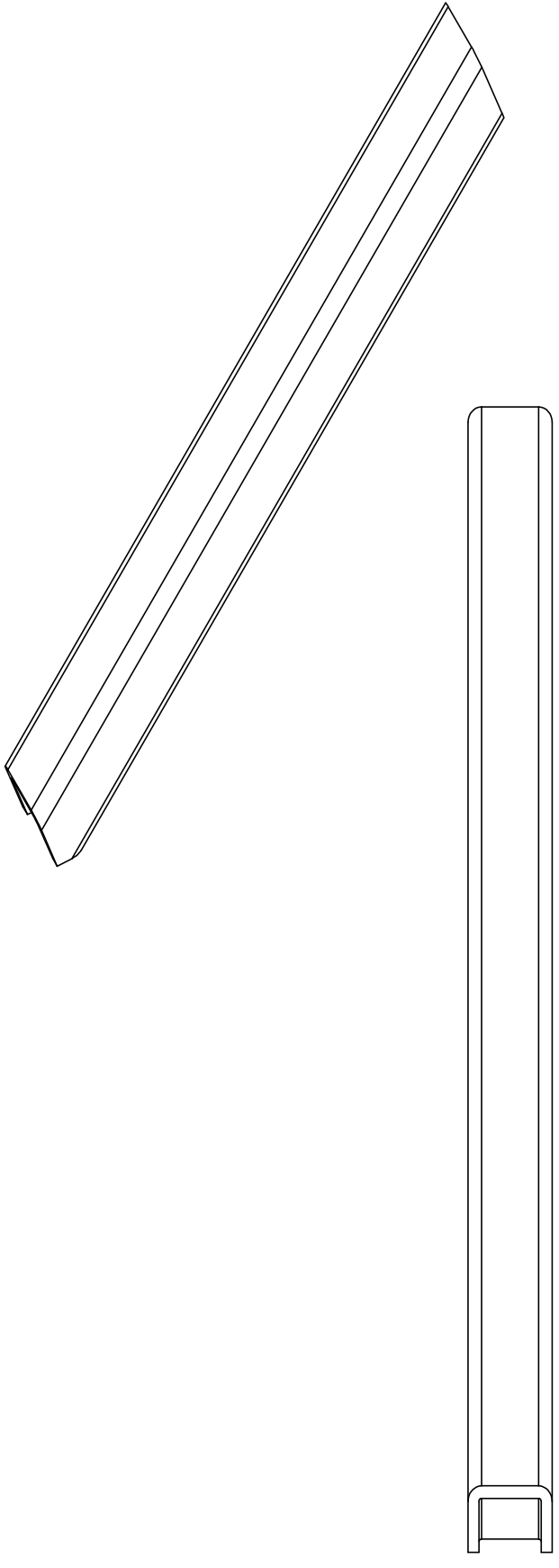
1

B

B

A

A



41,424°

6,810

48,576°

6,243

41,424°

0,500

0,500

0,065

NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	

GRINDER

DWG. NO.

BLUE BEAM 1 BOTTOM

SCALE: 1:1 QUANTITY: 4

SHEET 5 OF 5

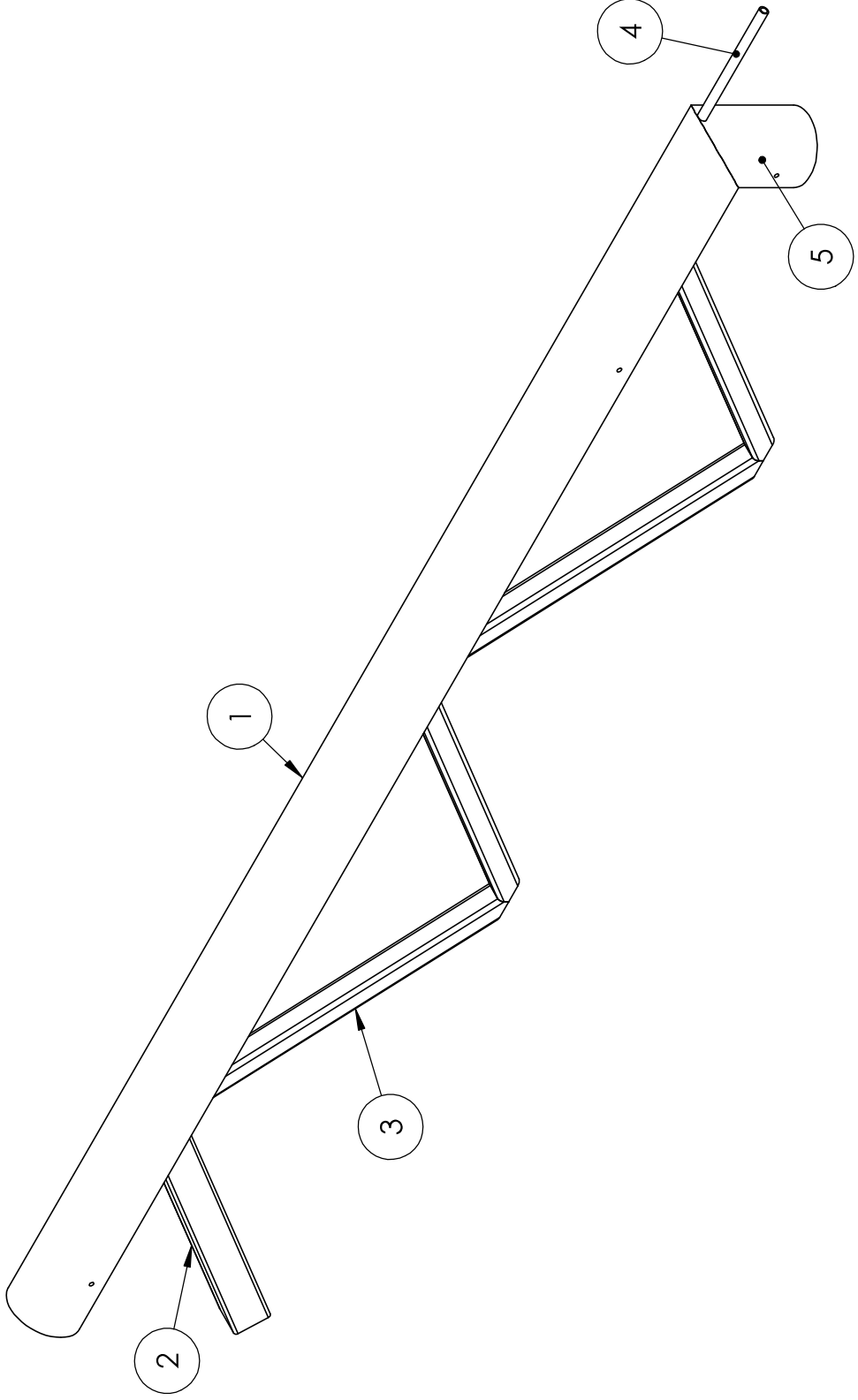
1

1

2

B

A



B

A

NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	SAME AS MAIZE BEAM 1 TOP

DWG. NO.	BLUE BEAM 1 TOP
SCALE: 1:3	QUANTITY: 1
SHEET 1 OF 7	

1

B

B

ITEM NO.	QTY.	DESCRIPTION	LENGTH
1	1	PIPE, SCH 40, 1,5000 DIA.	30.62
2	1	TUBE, SQUARE ,75 X ,75 X ,035	6.2155
3	4	Square Tube 0.50x0.50x0.065	6.6554
4	1	PIPE, SCH 40, ,1875 DIA.	2.7559
5	1	PIPE, SCH 40, 1,5000 DIA.	2.5

A

A

NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	

DWG. NO.  
BLUE BEAM 1 TOP

SCALE: N/A QUANTITY: 1 SHEET 2 OF 7

2

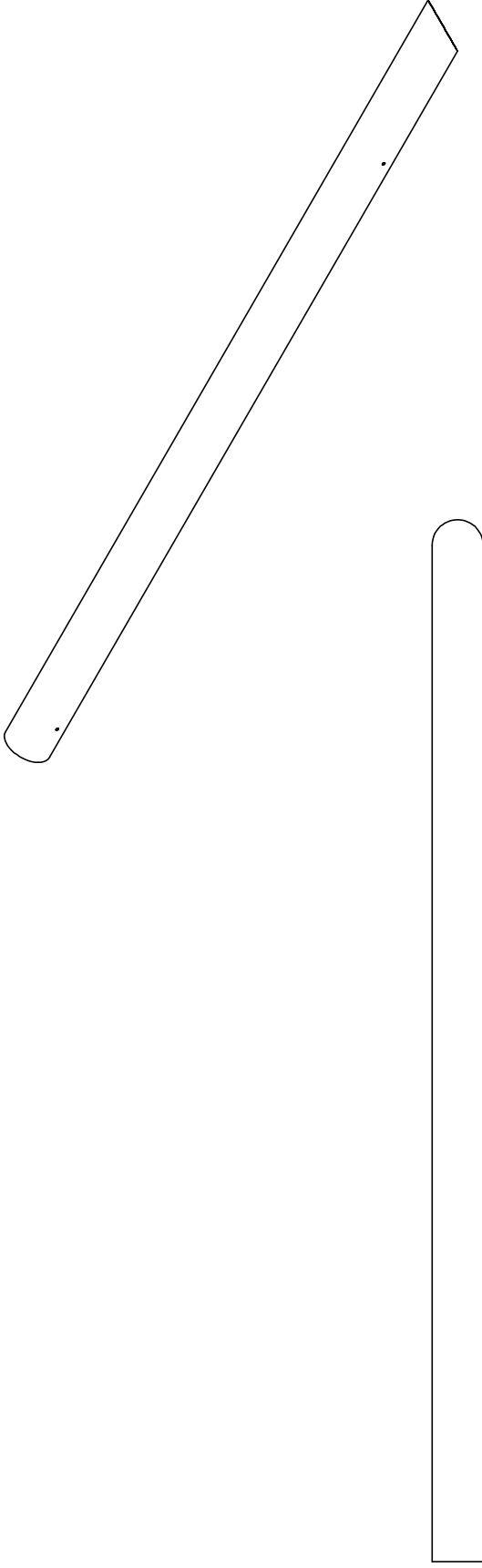
1

B

B

A

A



2 x  $\phi$  3/32 THRU

0,750

30,620

1,370

24,870

29,120

45°

$\phi$  1,500

0,065

NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	LASER CUT PIECE E

DWG. NO.  
BLUE BEAM 1 TOP

SCALE: 1:5 QUANTITY: 1 SHEET 3 OF 7

1

2

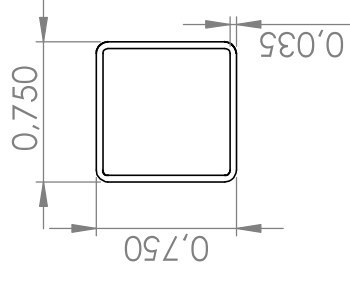
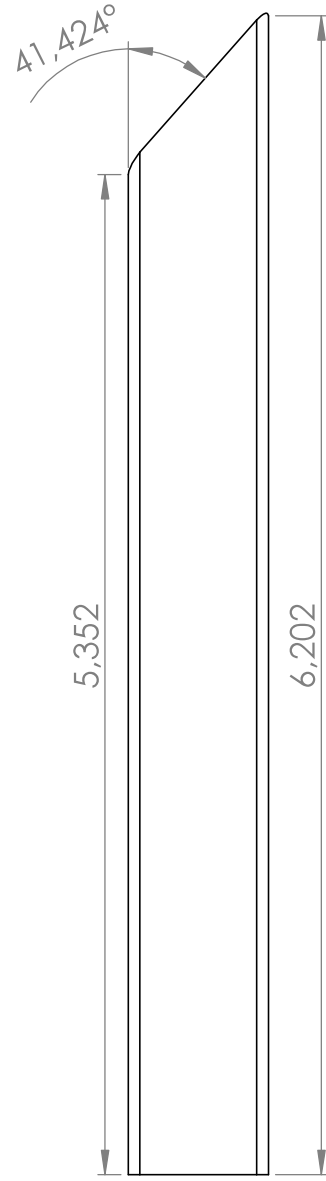
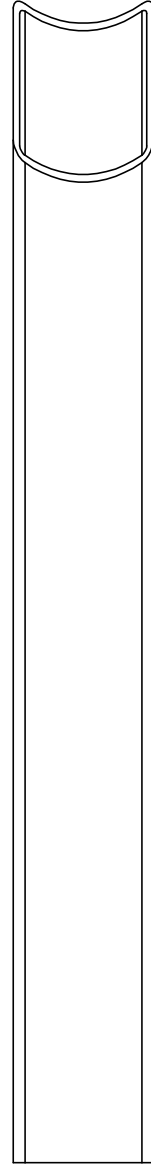
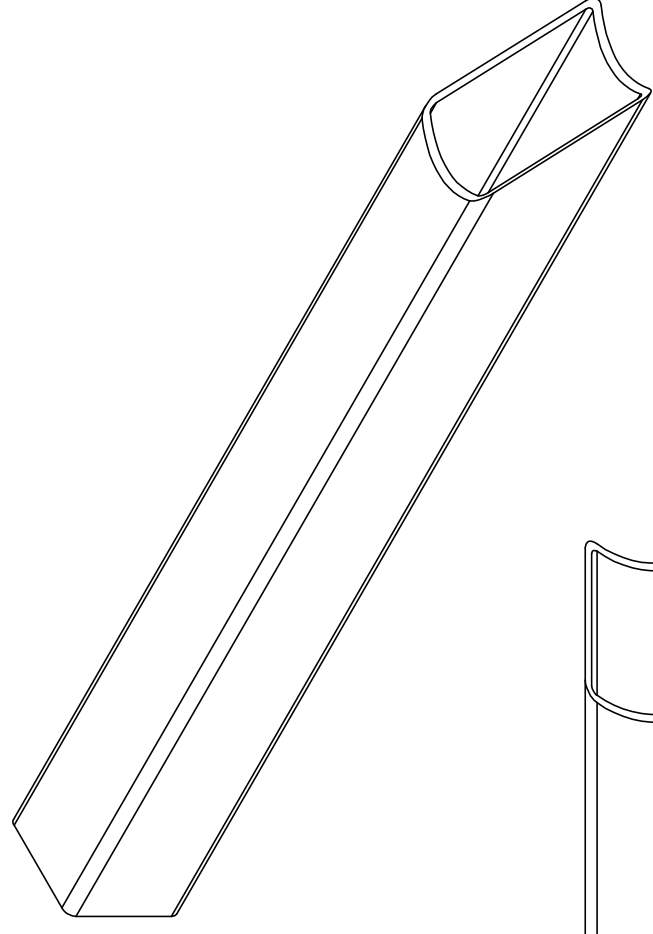
1

B

B

A

A



NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	GRINDER 1.5 TUBE NOTCH

DWG. NO.  
BLUE BEAM 1 TOP

SCALE: 1:1    QUANTITY: 1    SHEET 4 OF 7

1

2

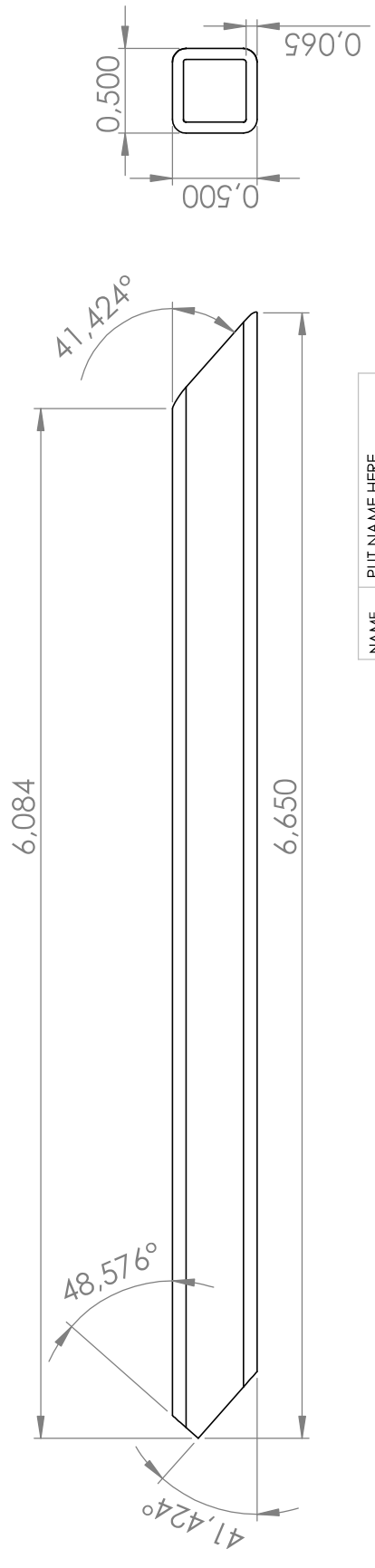
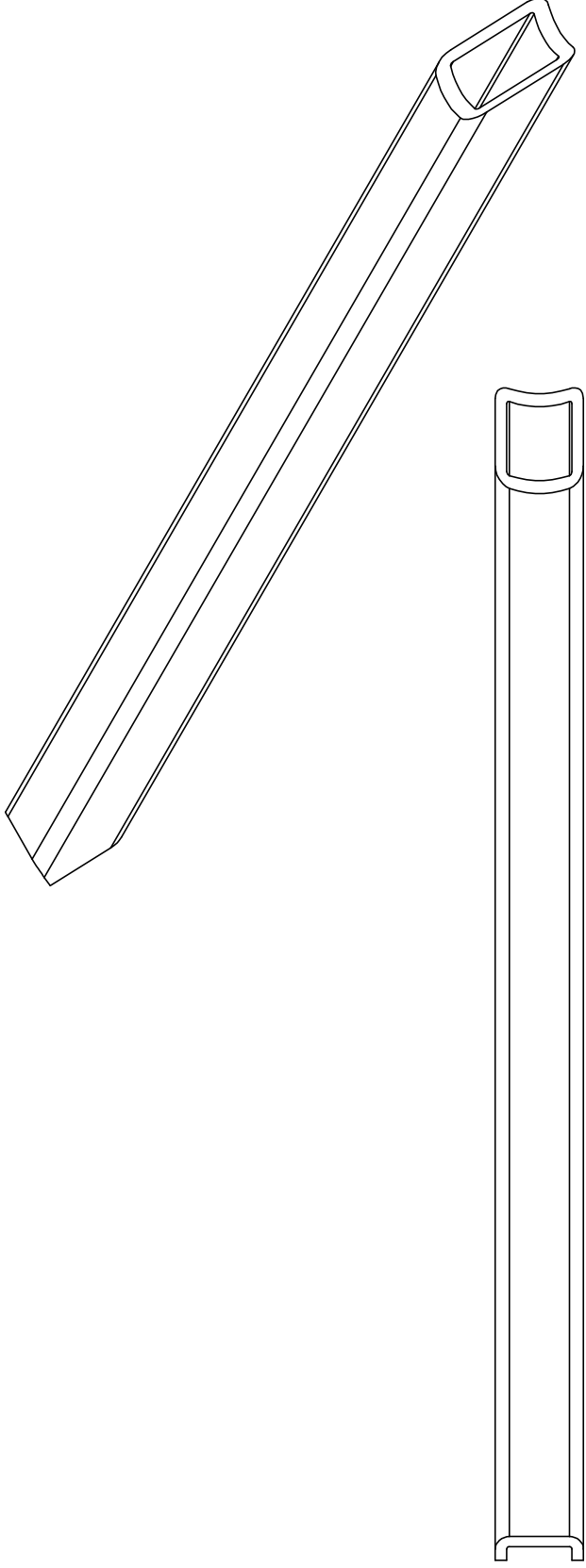
1

B

B

A

A



NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	GRINDER 1.5 TUBE NOTCH

DWG. NO.	BLUE BEAM 1 TOP
SCALE: 1:1	QUANTITY: 4
SHEET 5 OF 7	

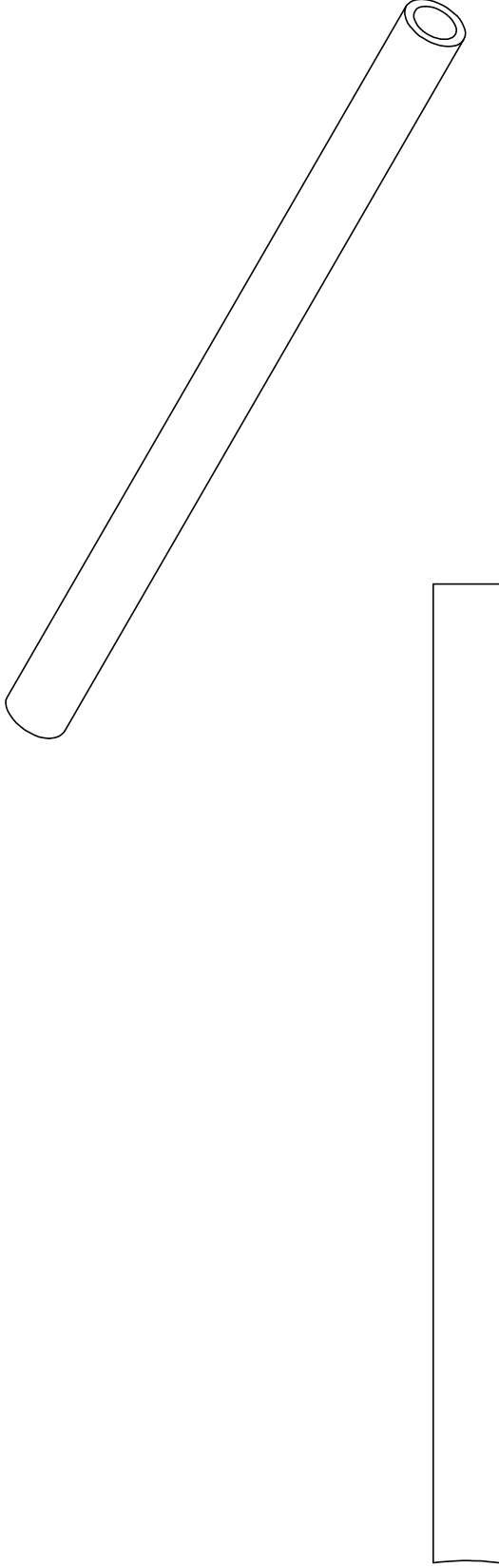
1

2

1

B

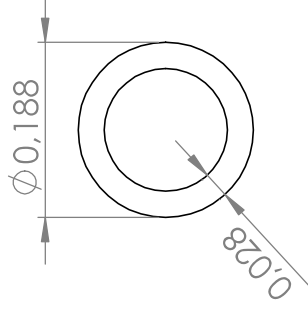
B



2,750

A

A



NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	1.5 TUBE NOTCH

DWG. NO.  
BLUE BEAM 1 TOP

SCALE: 2:1    QUANTITY: 1    SHEET 6 OF 7

1

2

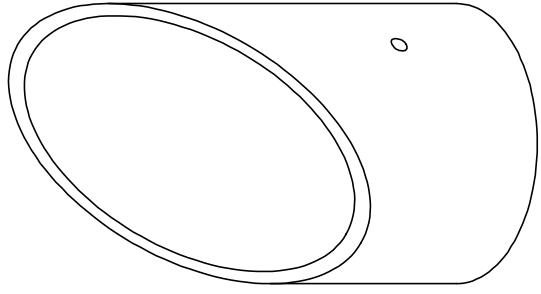
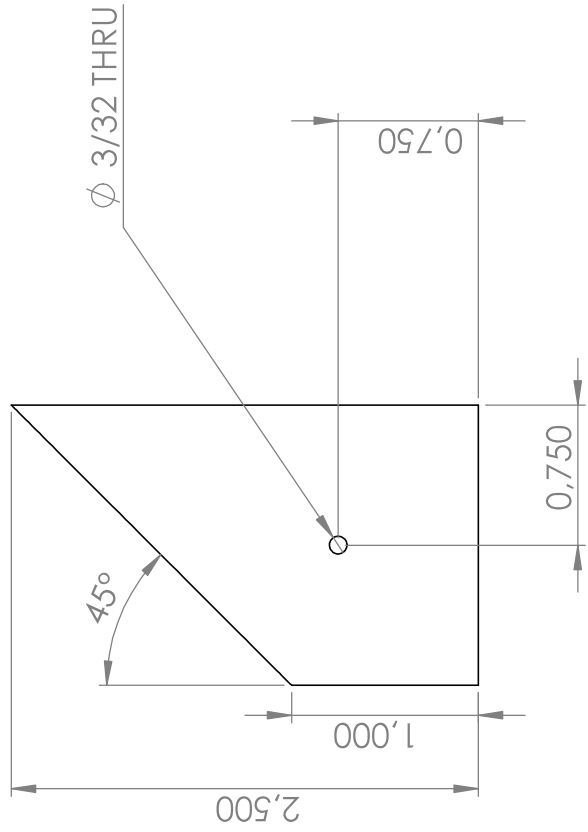
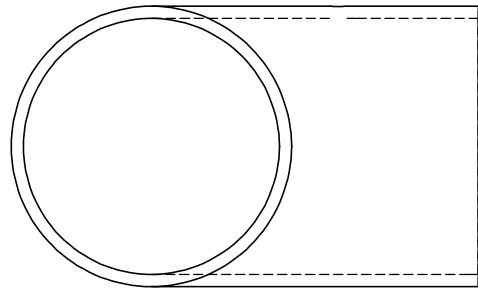
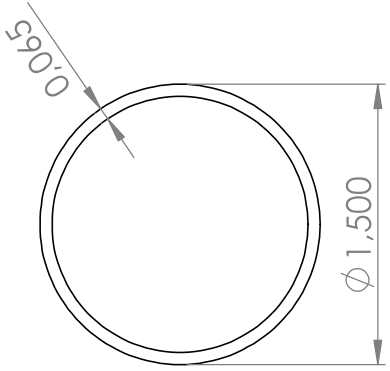
1

B

B

A

A



NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	LASER CUT PIECE D
DWG. NO. BLUE BEAM 1 TOP	

SCALE: 1:1    QUANTITY: 1    SHEET 7 OF 7

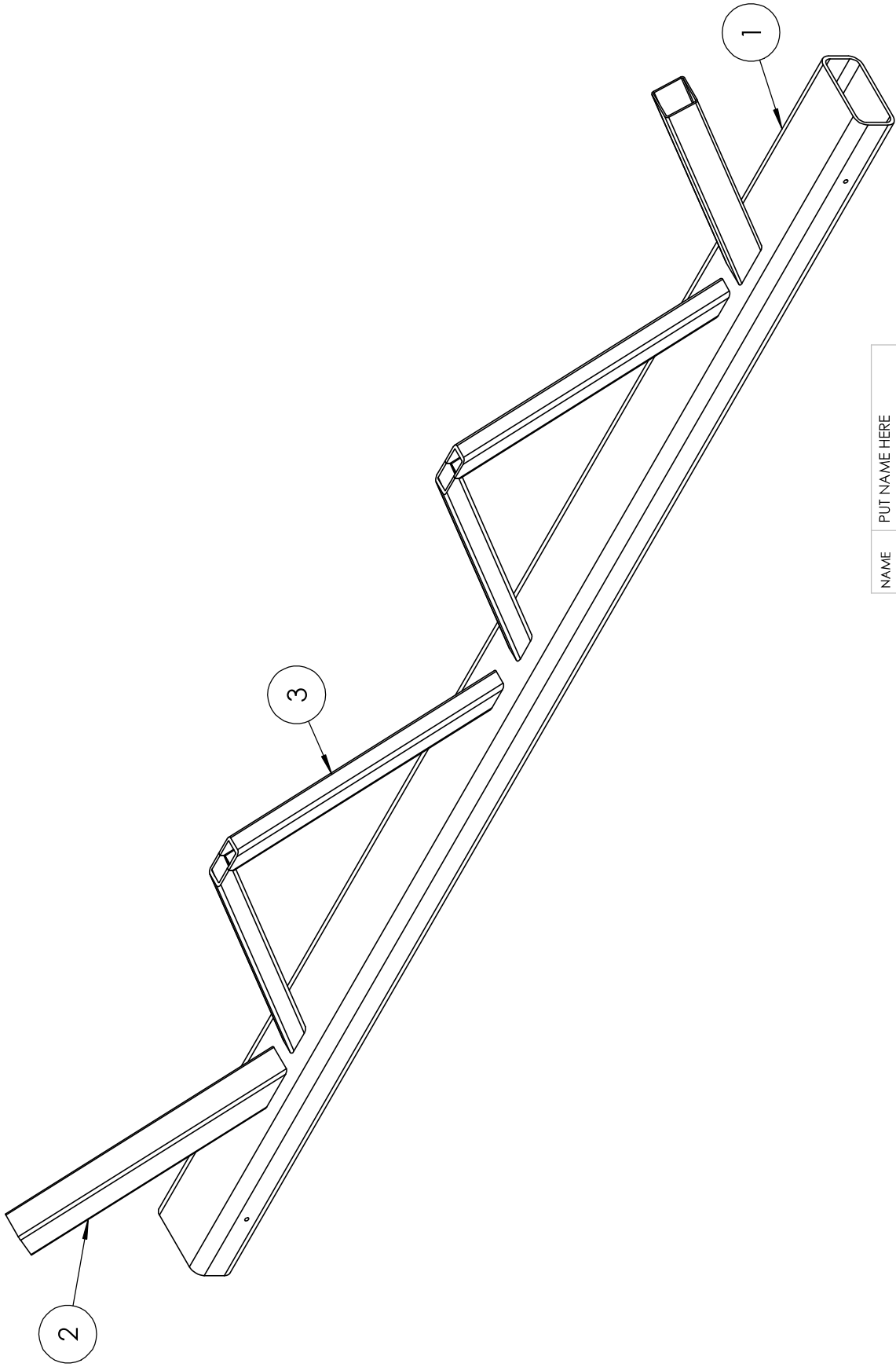
1

1

2

B

A



B

A

NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	SAME AS MAIZE BEAM 5 BOTTOM

DWG. NO.	BLUE BEAM 5 BOTTOM
----------	--------------------

SCALE: 1:3	QUANTITY: 1	SHEET 1 OF 5
------------	-------------	--------------

1

2

1

B

B

ITEM NO.	QTY.	DESCRIPTION	LENGTH
1	1	Rectangular Tube 1x2x0.083	33.25
2	2	Square Tube 0.75x0.75x0.035	6.48
3	4	Square Tube 0.5x0.5x0.065	6.81

A

A

NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	

DWG. NO.

# BLUE BEAM 5 BOTTOM

SCALE: 1:10 QUANTITY: SHEET 2 OF 5

1

1

2

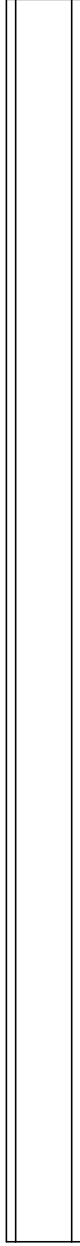
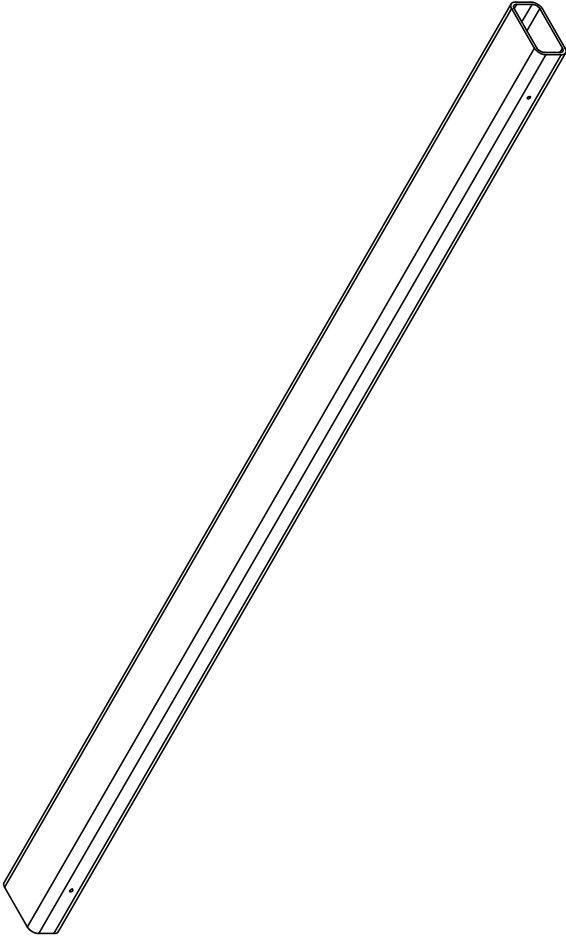
1

B

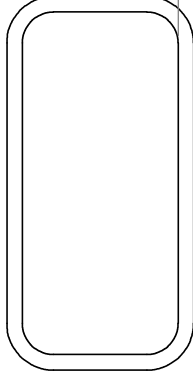
B

A

A



33,254



0,083

NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	LASER CUT PIECE B

DWG. NO.  
**BLUE BEAM 5 BOTTOM**

SCALE: 1:5    QUANTITY: 1    SHEET 3 OF 5

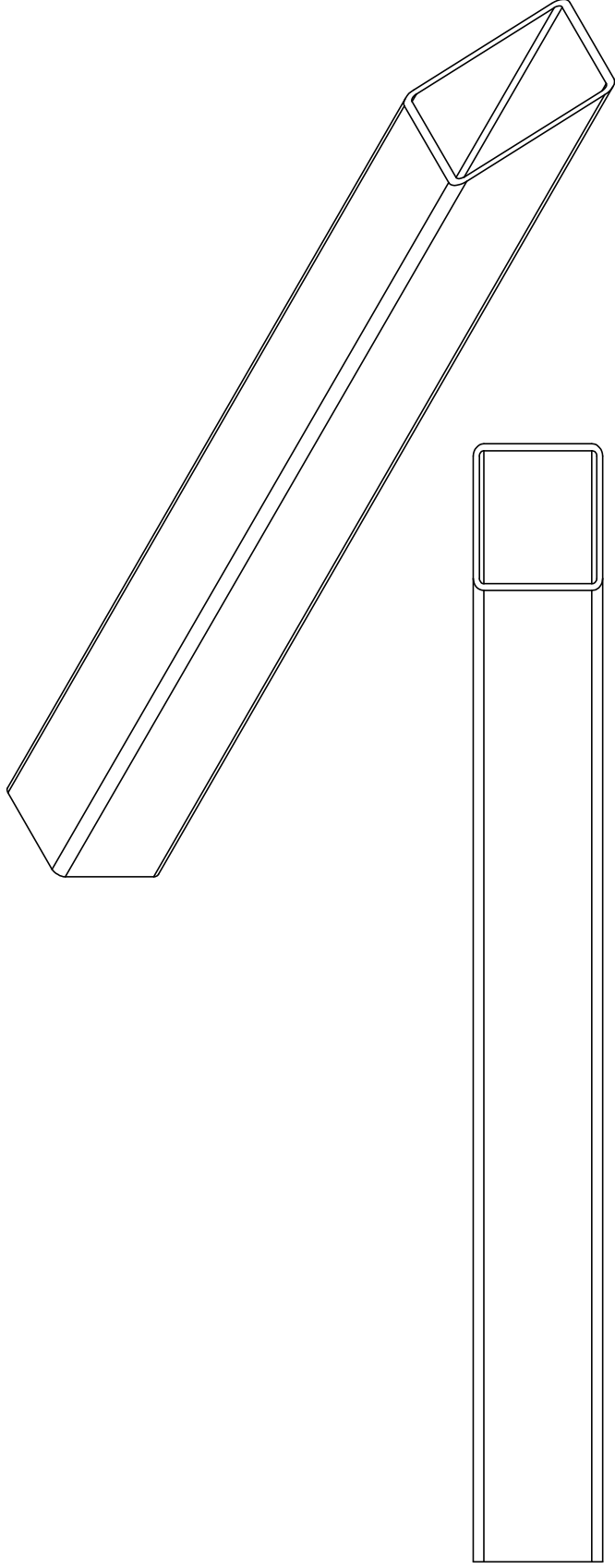
1

2

1

B

B

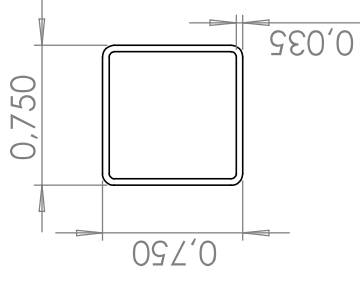


A

A

5,626

6,476



NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	

GRINDER

DWG. NO.  
BLUE BEAM 5 BOTTOM

SCALE: 1:1    QUANTITY: 2    SHEET 4 OF 5

1

1

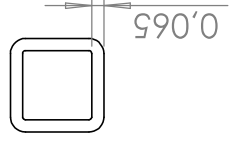
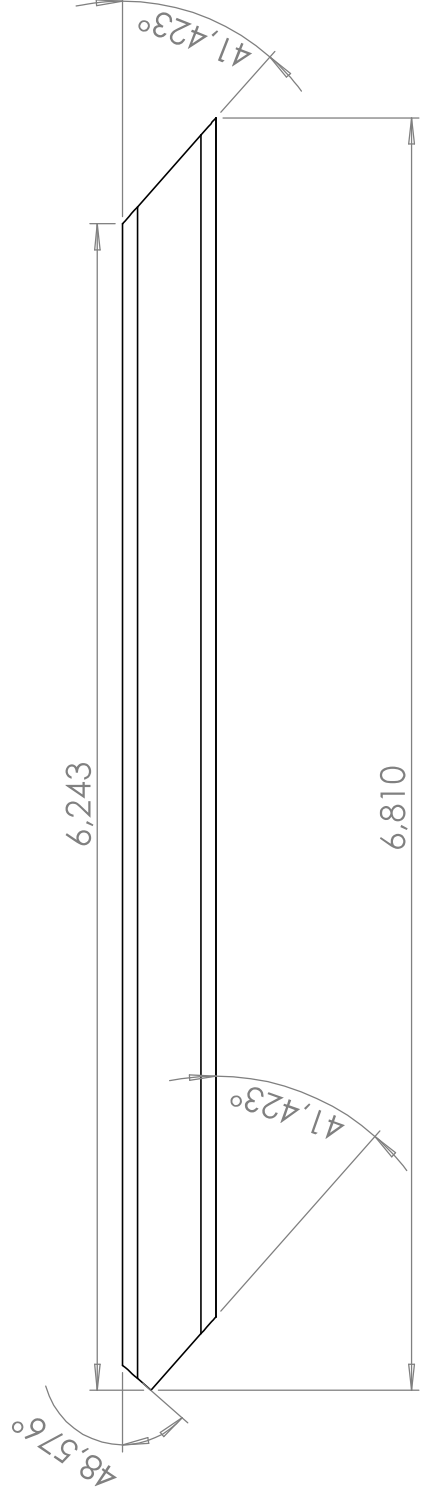
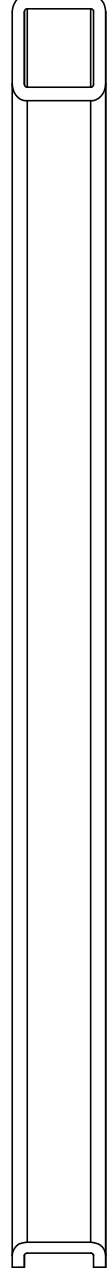
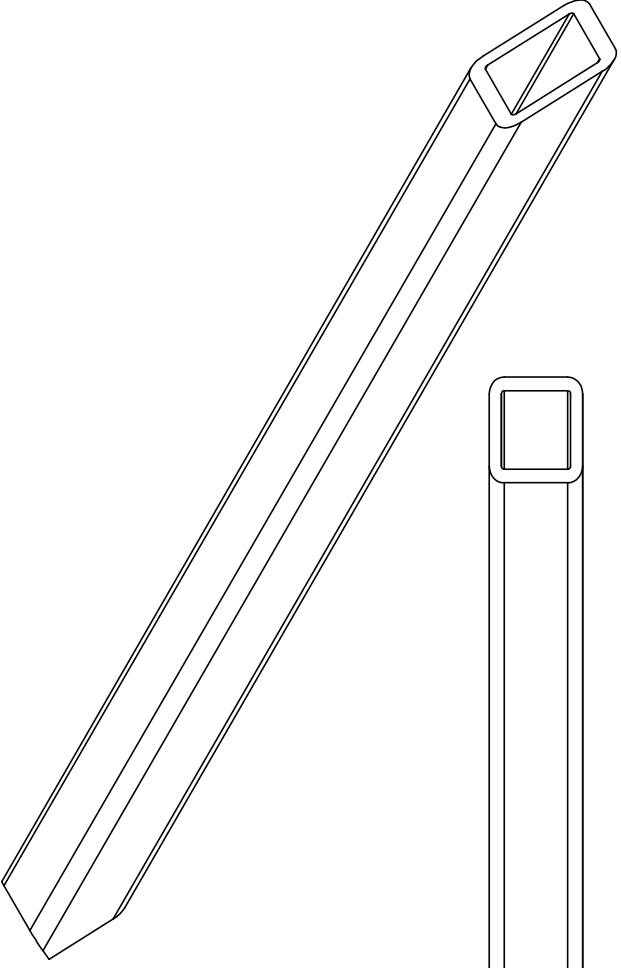
2

B

A

B

A



NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	GRINDER

DWG. NO.  
BLUE BEAM 5 BOTTOM

SCALE: 1:1    QUANTITY: 4    SHEET 5 OF 5

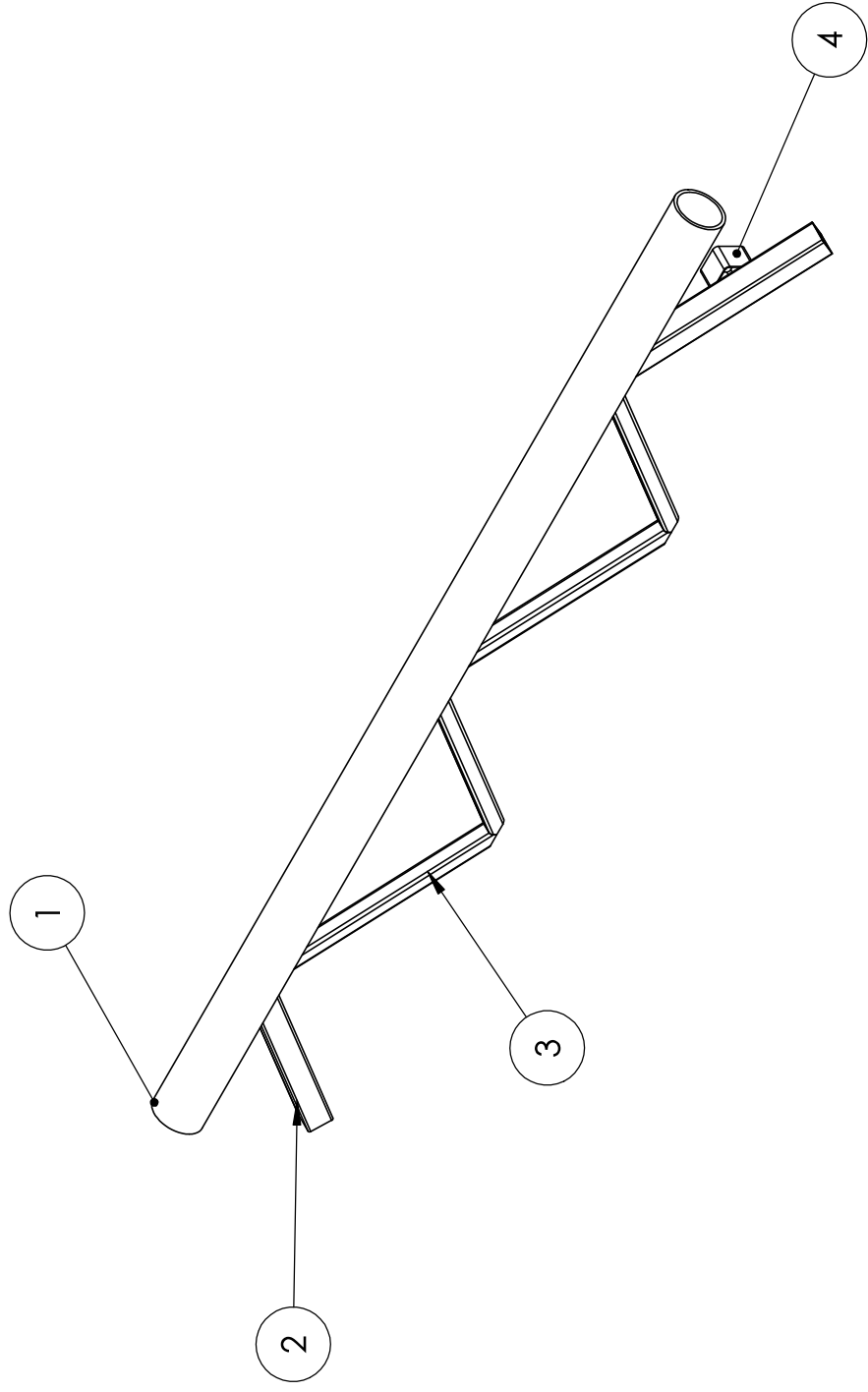
1

1

2

B

A



B

A

NAME | JORGE VIEUDO

DATE | 05/06/2018

COMMENTS:

DWG. NO.

# BLUE BEAM 5 TOP

SCALE: 1:5 QUANTITY:

SHEET 1 OF 6

B

B

ITEM NO	QTY.	DESCRIPTION	LENGTH
1	1	PIPE 1.5X0.095	33.870
2	2	SQ BEAM 0.75X0.035	6.202
3	4	SQ BEAM 0.5X0.035	6.65
4	1	SQ BEAM 1X0.035	0.75

A

A

NAME DATE 05/06/2018

COMMENTS: DWG. NO.

**BLUE BEAM 5 TOP**

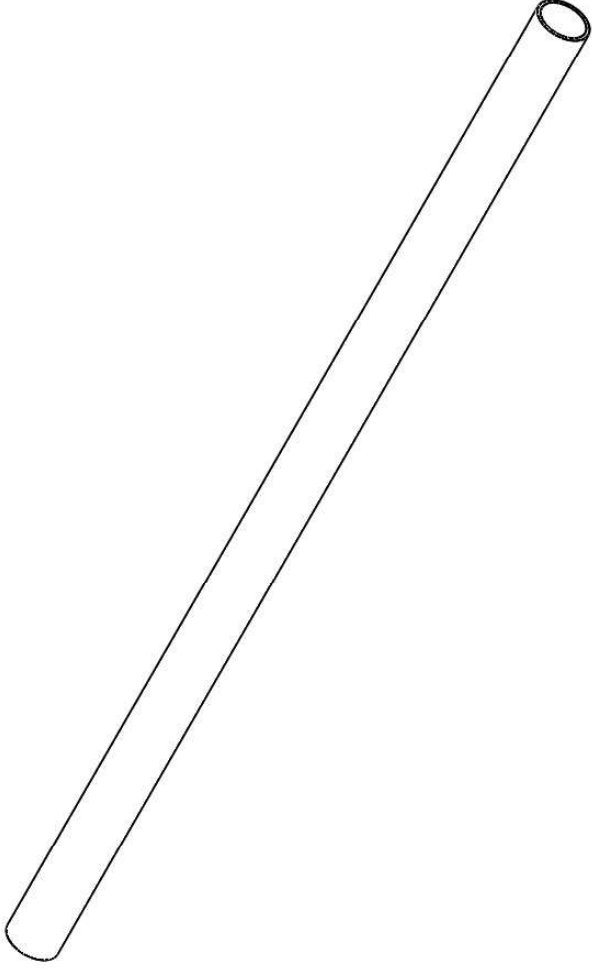
SCALE: N/A QUANTITY: SHEET 2 OF 6

2

1

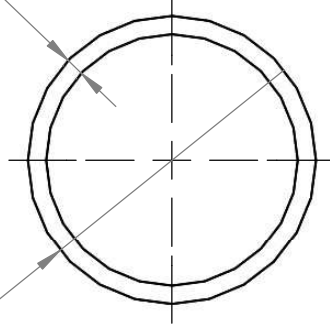
B

B



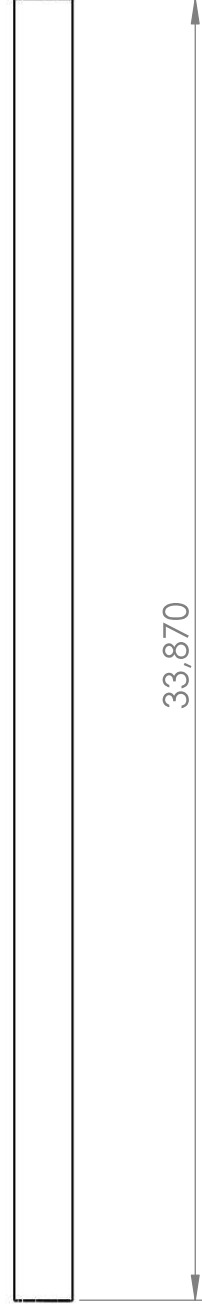
$\varnothing 1.500$

0.095



A

A



33.870

NAME

DATE 05/06/2018

COMMENTS:

DWG. NO.

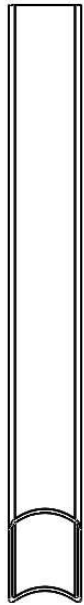
**BLUE BEAM 5 TOP**

SCALE: 1:5 QUANTITY: 1

SHEET 3 OF 6

2

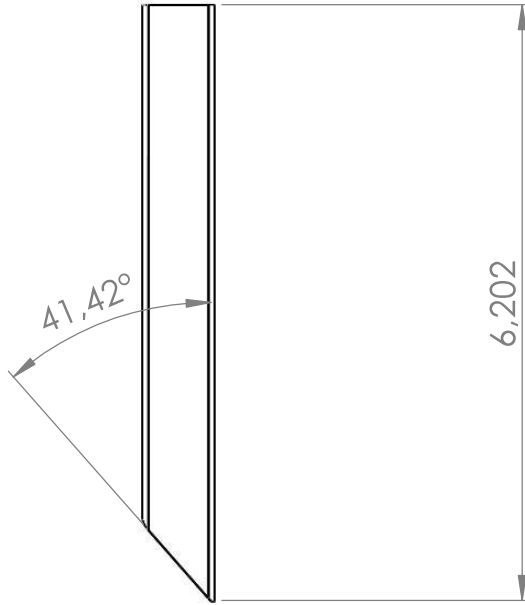
1



$R0,750$

B

B

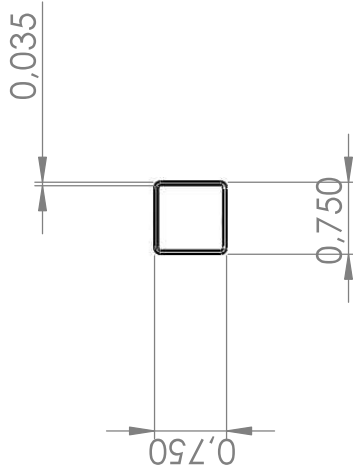
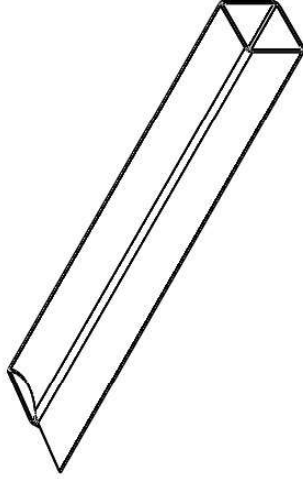


$41,42^\circ$

$6,202$

A

A



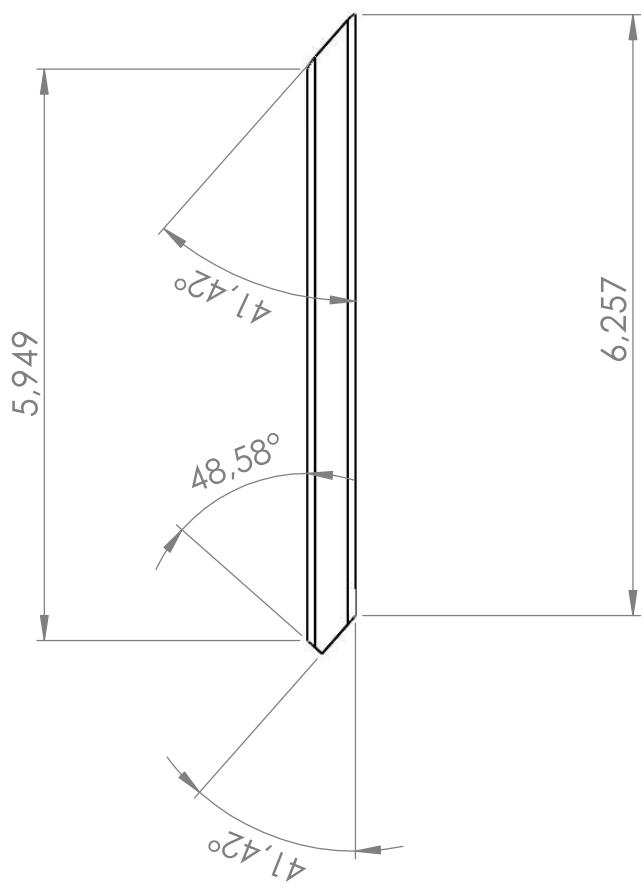
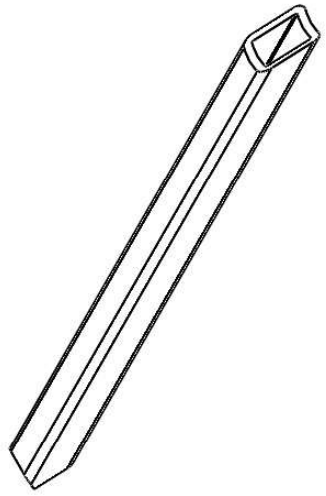
NAME	DATE 05/06/2018
COMMENTS:	DWG. NO.
<b>BLUE BEAM 5 TOP</b>	
SCALE: 1:2	QUANTITY:
SHEET 4 OF 6	

2

1

B

B



A

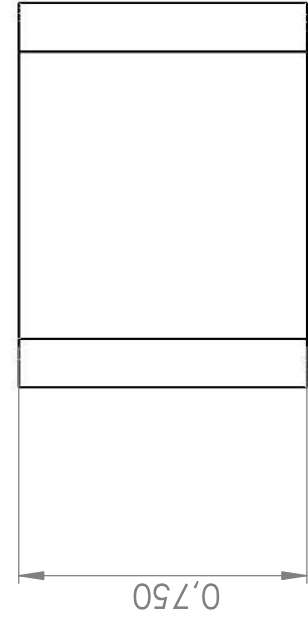
A

THICKNESS: 0.035

NAME	DATE 05/06/2018
COMMENTS:	DWG. NO.
<b>BLUE BEAM 5 TOP</b>	
SCALE: 1:2	QUANTITY: 2
SHEET 5 OF 6	

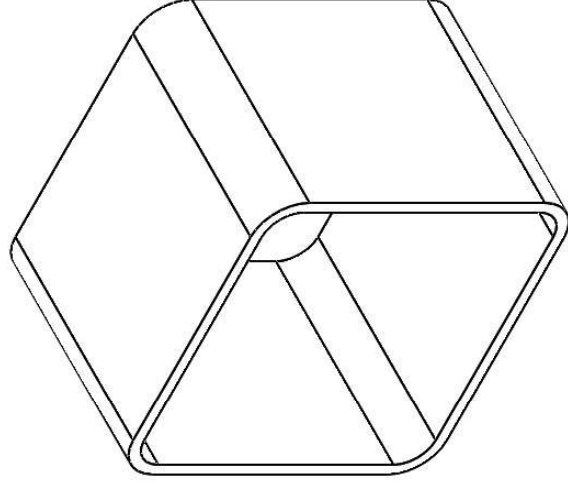
2

1

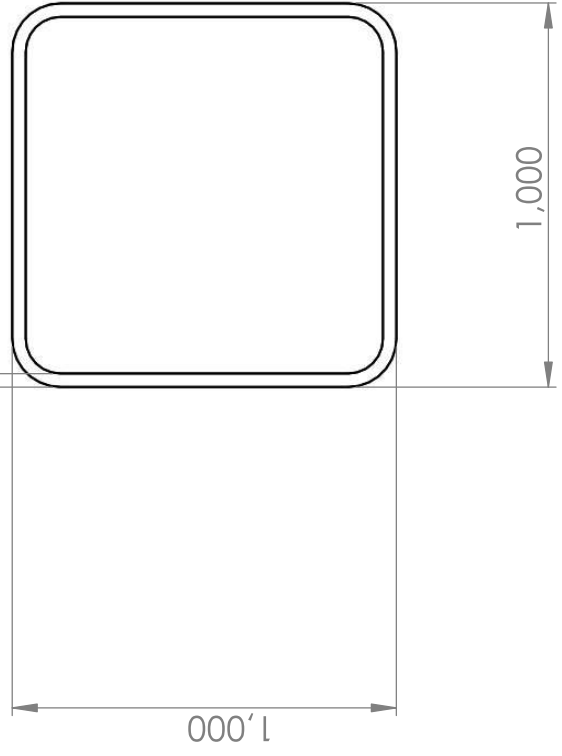


B

B



0,035



A

A

NAME

DATE 05/06/2018

COMMENTS:

DWG. NO.

**BLUE BEAM 5 TOP**

SCALE: 2:1 QUANTITY: 1

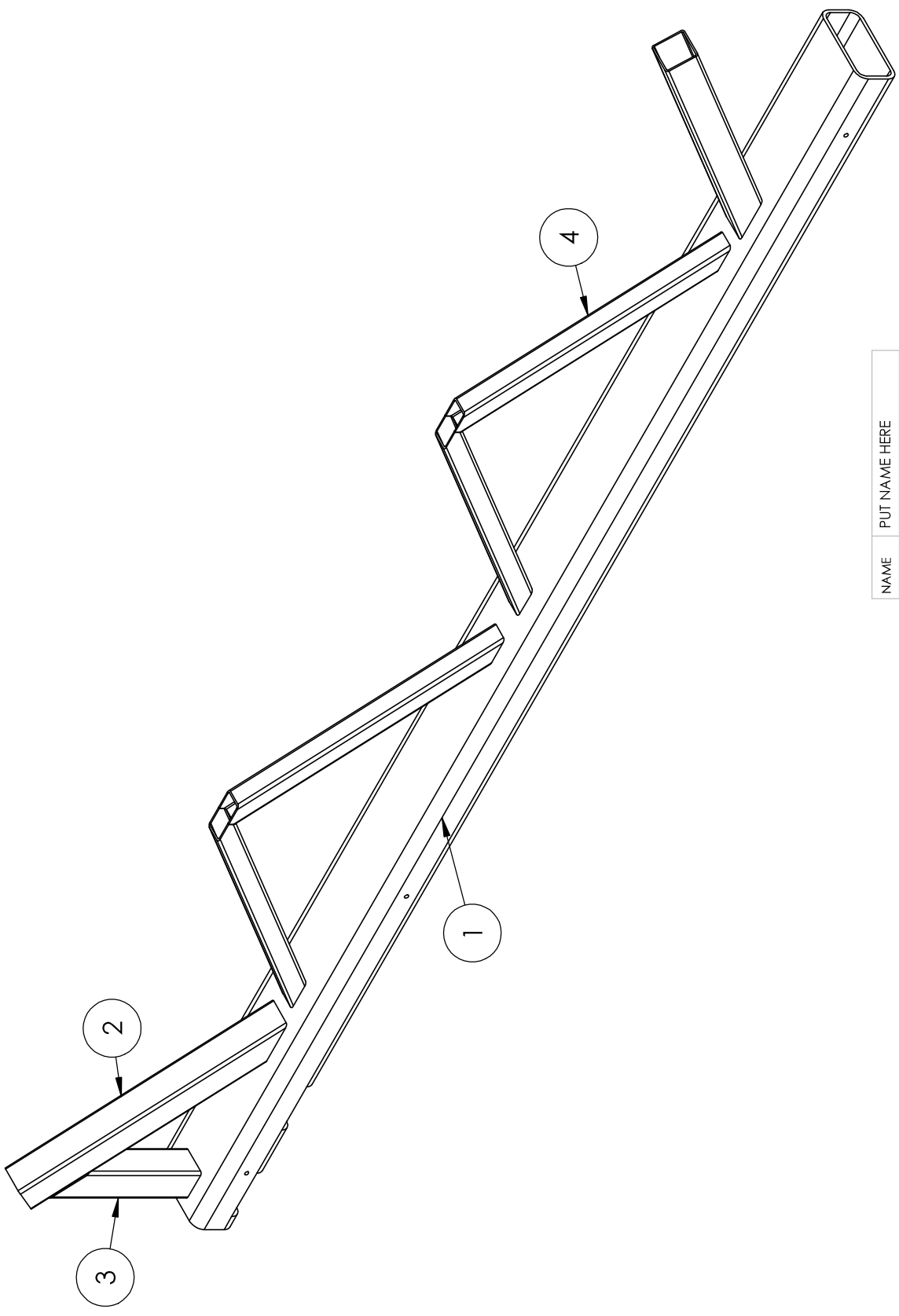
SHEET 6 OF 6

1

2

B

A



NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	SAME AS MAIZE BEAM 4 BOTTOM

DWG. NO.  
BLUE BEAM 4 BOTTOM

SCALE: 1:3    QUANTITY: 1    SHEET 1 OF 6

1

2

1

B

B

ITEM NO.	QTY.	DESCRIPTION	LENGTH
1	1	Rectangular Tube 1x2x0.083	33.25
2	2	Square Tube 0.75x0.75x0.035	6.48
3	1	Square Tube 0.75x0.75x0.035	3.45
4	4	TUBE, SQUARE 0,50 X 0,50 X 0.035	6.81

A

A

NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	

DWG. NO.  
**BLUE BEAM 4 BOTTOM**

SCALE: N/A QUANTITY: 1 SHEET 2 OF 6

1

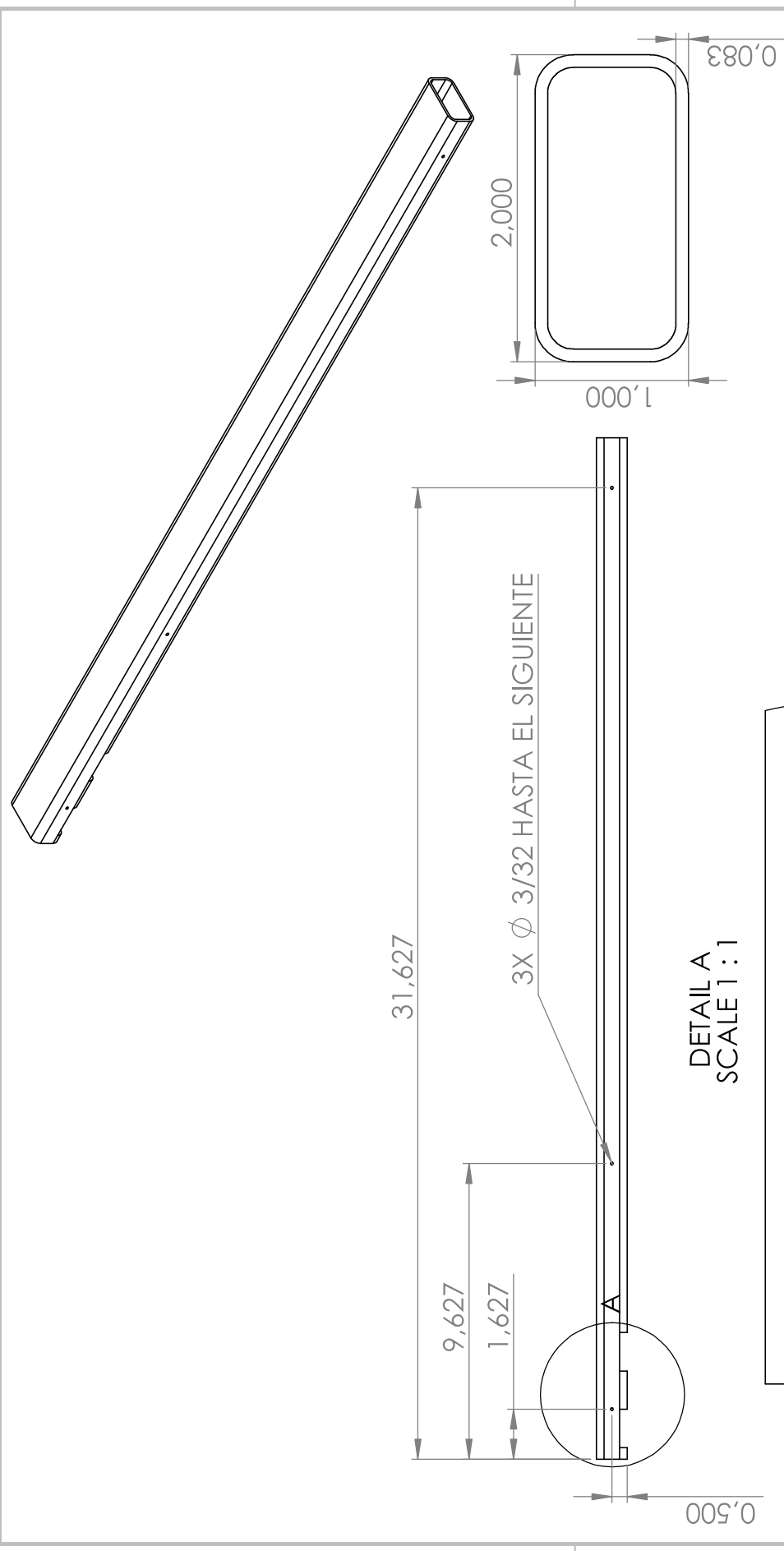
1

2

1

B

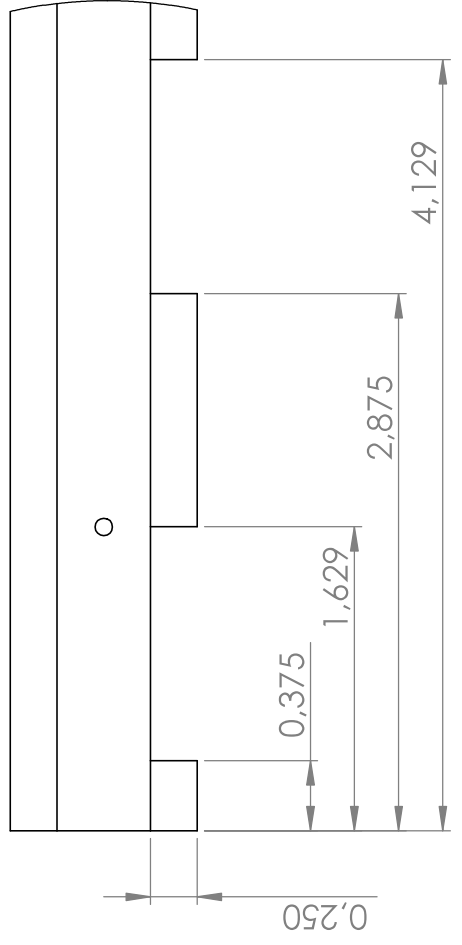
B



DETAIL A  
SCALE 1 : 1

A

A



NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	LASER CUT PIECE B MILLED SLOTS

DWG. NO.  
BLUE BEAM 4 BOTTOM

SCALE: 1:5    QUANTITY: 1    SHEET 3 OF 6

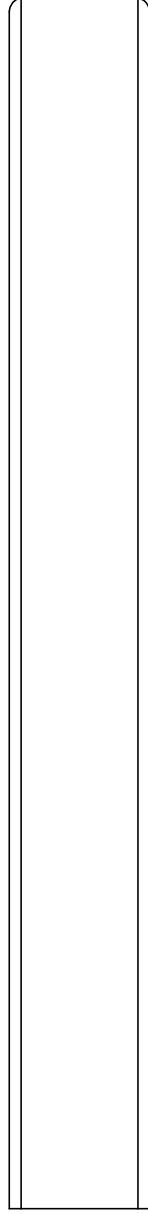
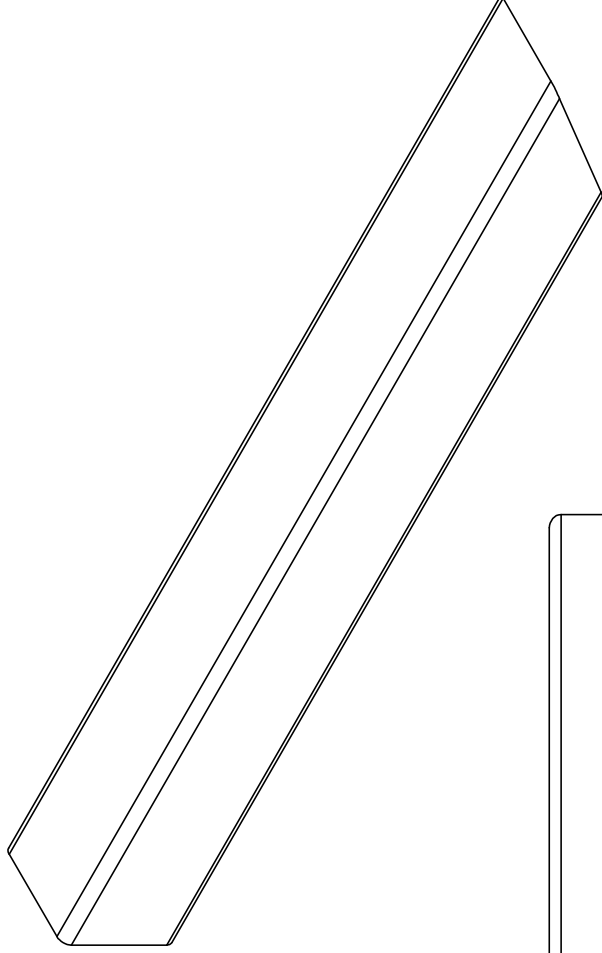
1

2

1

B

B



6,476

5,626

41,423°

0,750

0,750

0,035

A

A

NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	GRINDER

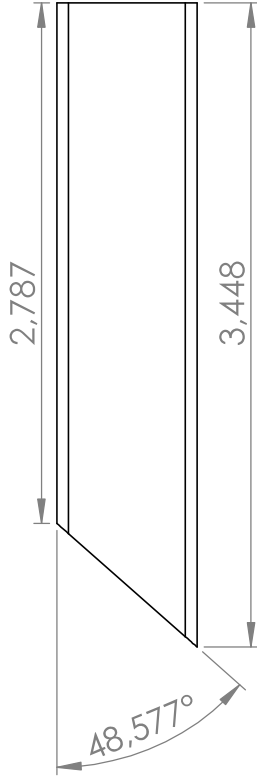
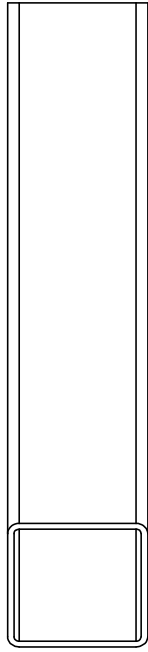
DWG. NO.  
BLUE BEAM 4 BOTTOM

SCALE: 1:1    QUANTITY: 2    SHEET 4 OF 6

1

2

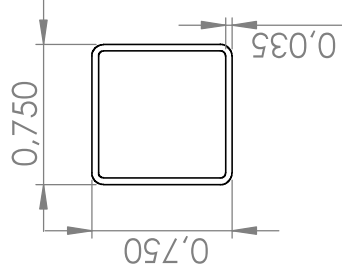
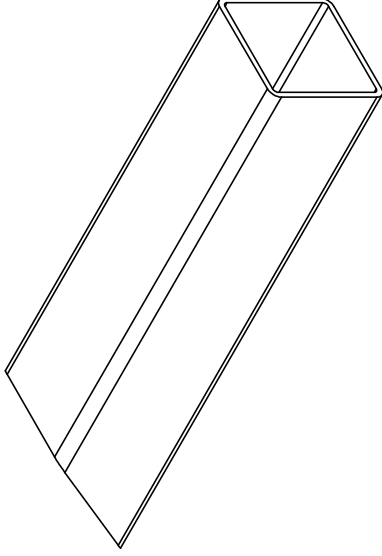
B



A

1

B



A

NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	GRINDER

DWG. NO.  
BLUE BEAM 4 BOTTOM

SCALE: 1:1    QUANTITY: 1    SHEET 5 OF 6

1

2

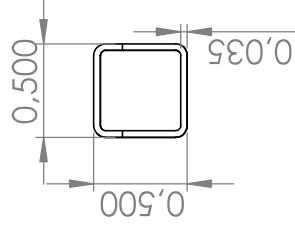
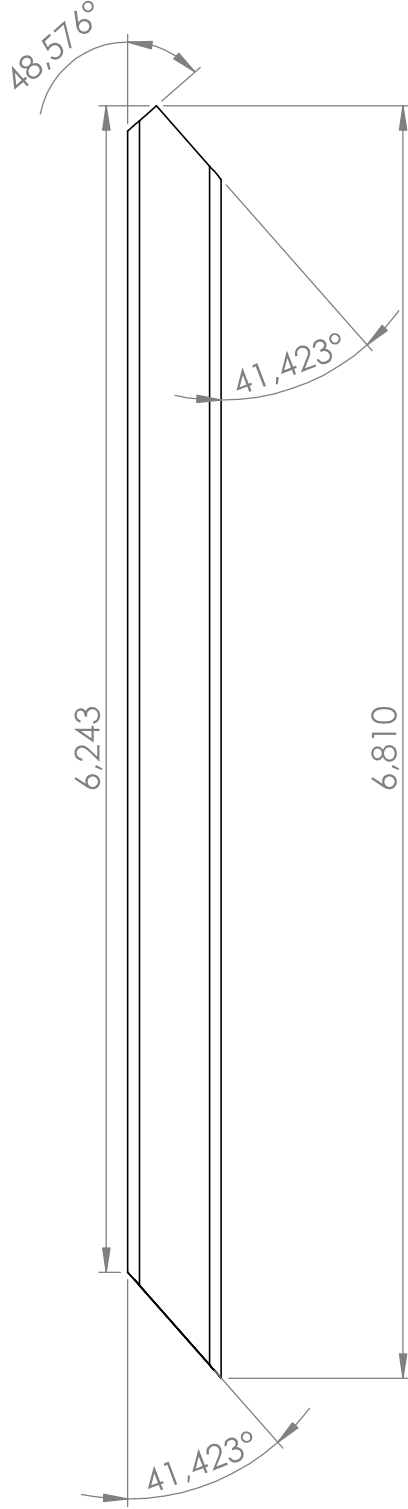
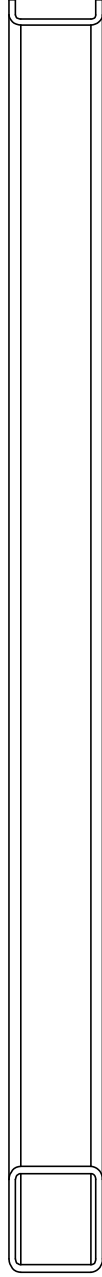
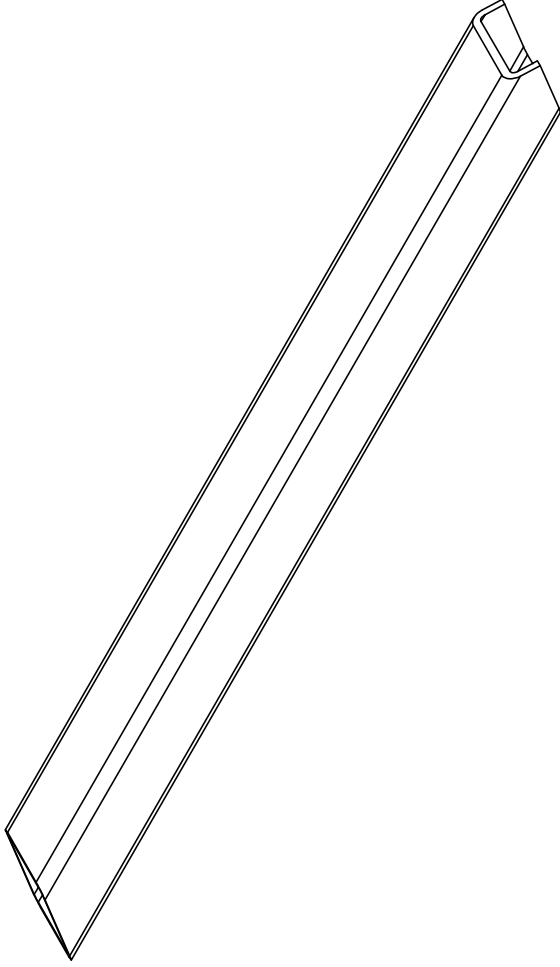
1

B

B

A

A



NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	GRINDER

DWG. NO.  
BLUE BEAM 4 BOTTOM

SCALE: 1:1 QUANTITY: 4 SHEET 6 OF 6

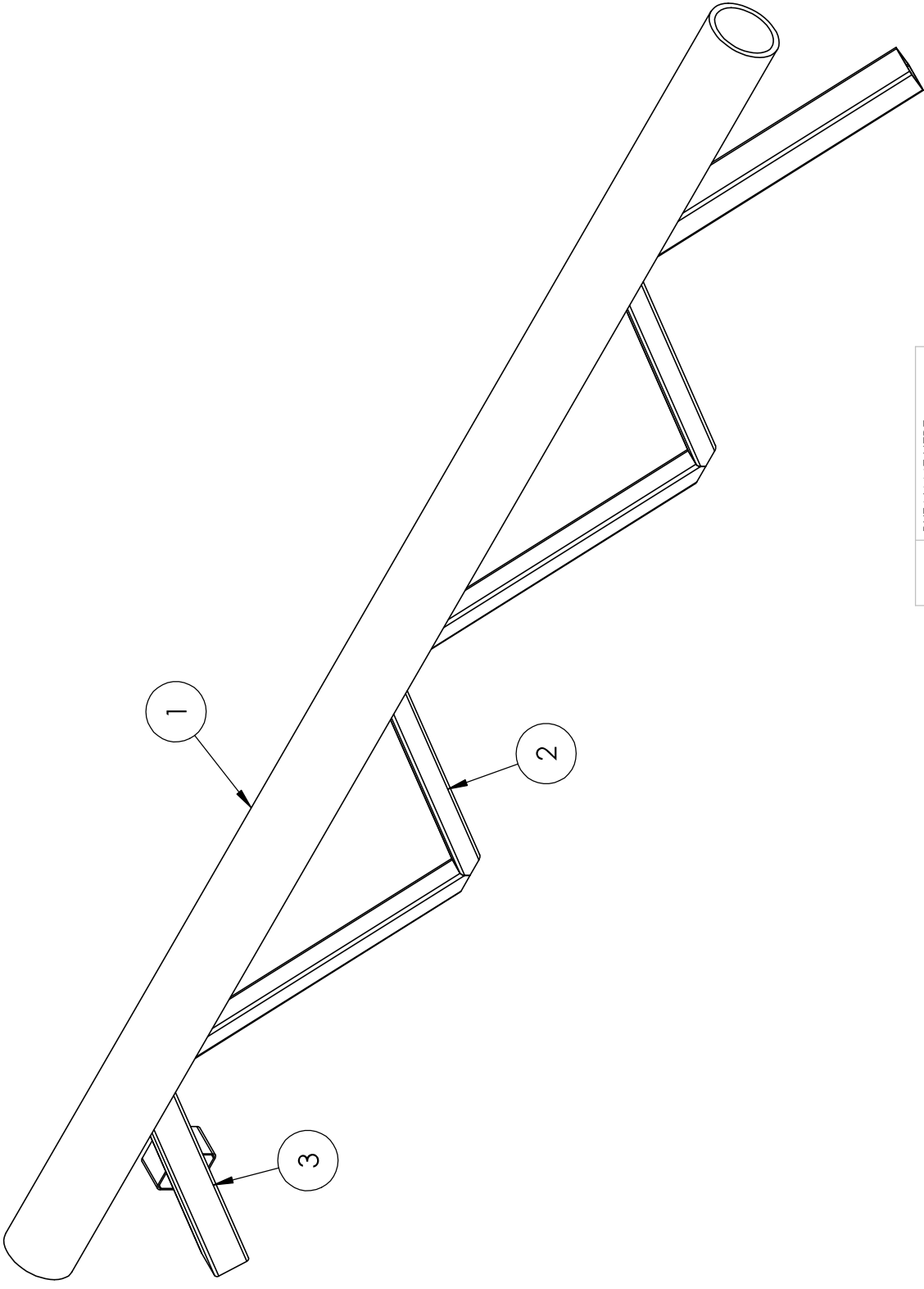
1

1

2

B

A



B

A

NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	SAME AS MAIZE BEAM 4 TOP

DWG. NO.	BLUE BEAM 4 TOP
SCALE: 1:1	QUANTITY: 1
SHEET 1 OF 5	

1

2

1

B

B

ITEM NO.	QTY.	DESCRIPTION	LENGTH
1	1	Pipe 1.5x0.12	33.87
2	4	TUBE, SQUARE ,50 X ,50 X ,035	6.6615
3	2	Square Tube 0.75x0.75x0.035	6.2155
4	1	TUBE, SQUARE 1,00 X 1,00 X ,035	0.75

A

A

NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	

DWG. NO.  
**BLUE BEAM 4 TOP**

SCALE: N/A QUANTITY: 1 SHEET 2 OF 5

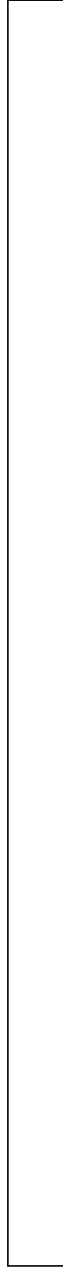
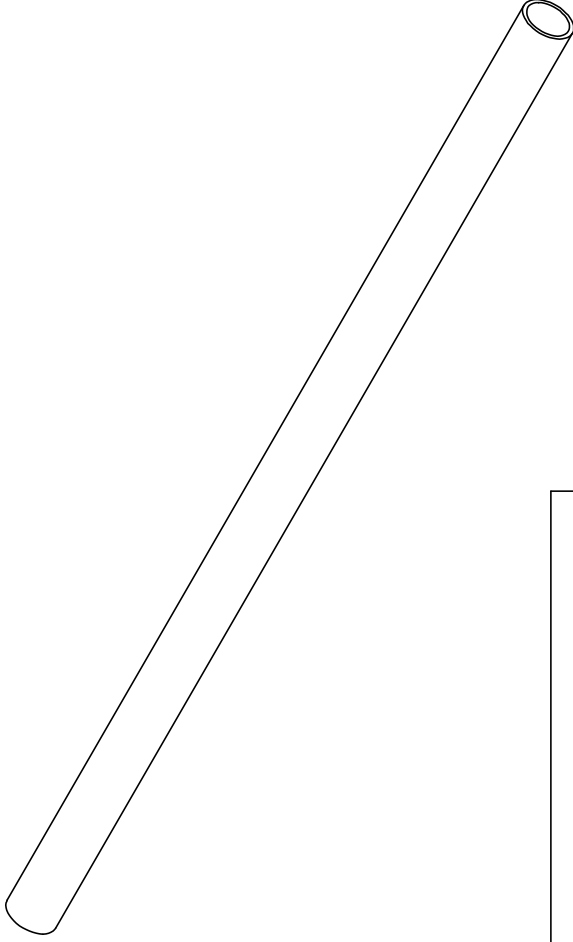
1

2

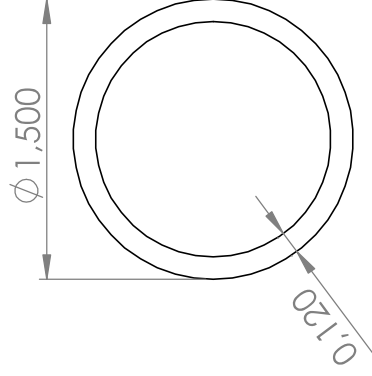
1

B

B



33,870



A

A

NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	LASER CUT PIECE H

DWG. NO.	BLUE BEAM 4 TOP
SCALE: 1:5	QUANTITY: 1
SHEET 3 OF 5	

1

2

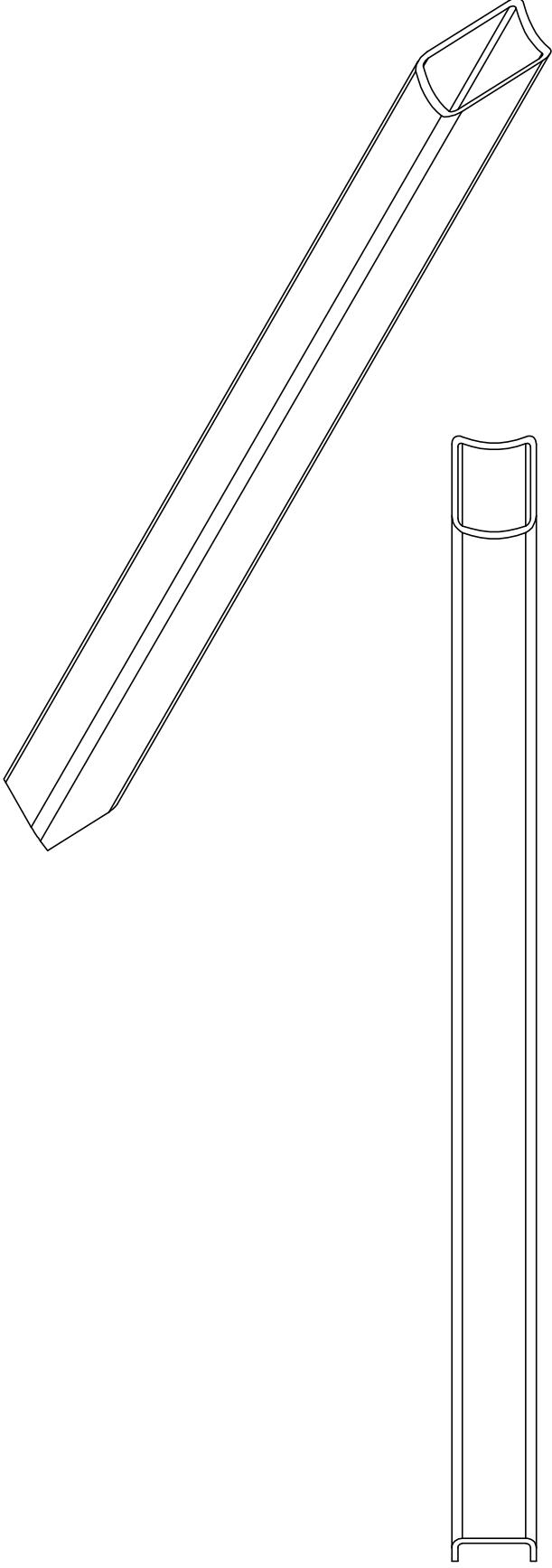
1

B

B

A

A



NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	

**GRINDER  
1.5 TUBE NOTCH**

DWG. NO.  
**BLUE BEAM 4 TOP**

SCALE: 1:1    QUANTITY: 4    SHEET 4 OF 5

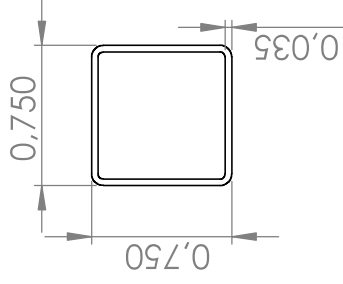
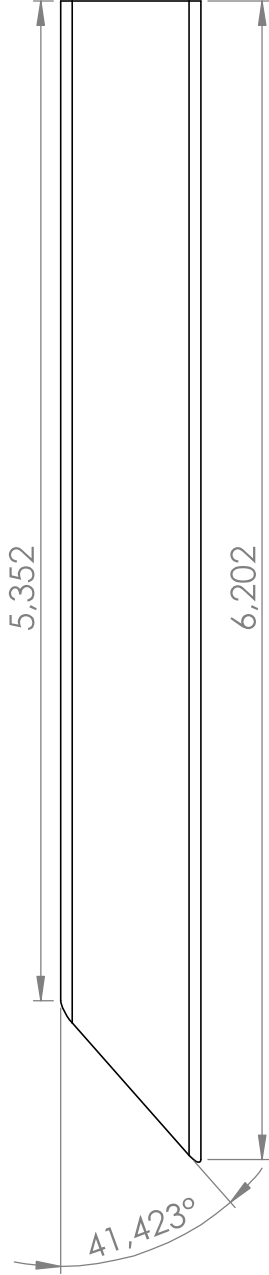
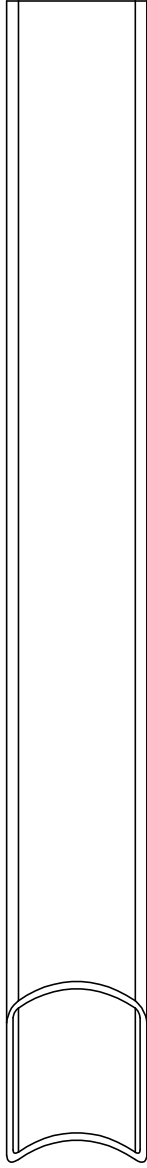
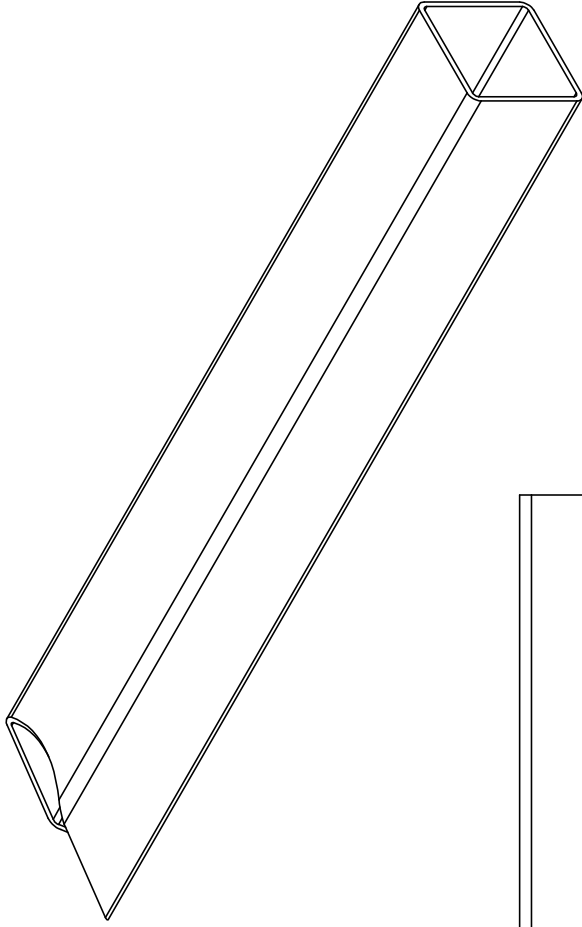
1

2

1

B

B



A

A

NAME	PUT NAME HERE
DATE	23/04/2018
COMMENTS:	GRINDER 1.5 TUBE NOTCH

DWG. NO.	BLUE BEAM 4 TOP
SCALE: 1:1	QUANTITY: 2
SHEET 5 OF 5	

1

1

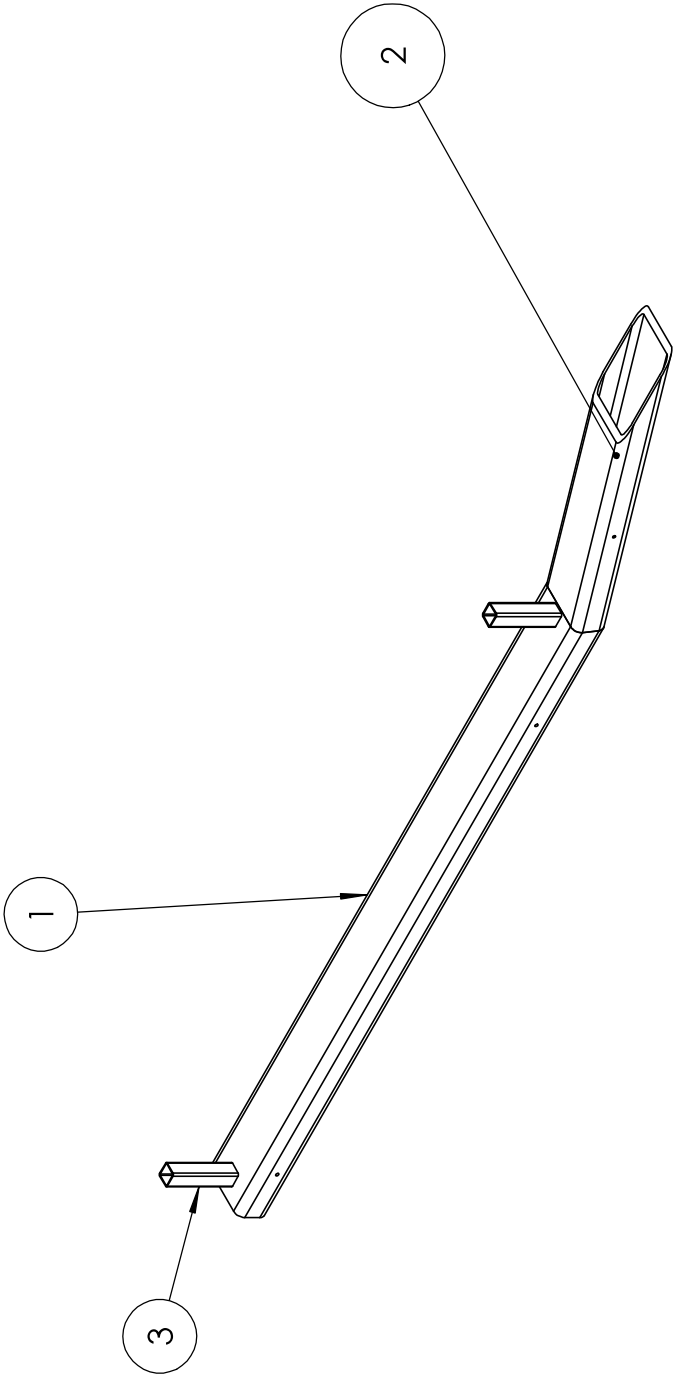
2

B

B

A

A



NAME	PUT NAME HERE
DATE	22/05/2018
COMMENTS:	

DWG. NO.  
**BLUE BEAM DEPTH 1**

SCALE: 1:5    QUANTITY:    SHEET 1 OF 5

1

2

1

B

B

ITEM NO.	QTY.	DESCRIPTION	LENGTH
1	1	RECTANGULAR TUBE 2 X 1 X 0.083	22.253
2	1	RECTANGULAR TUBE 2 X 1 X 0.083	10.895
3	2	TUBE SQUARE .50X.50X0.035	2.132

A

A

NAME	PUT NAME HERE
DATE	22/05/2018
COMMENTS:	

DWG. NO.

# BLUE BEAM DEPTH 1

SCALE: 1:10 QUANTITY: SHEET 2 OF 5

1

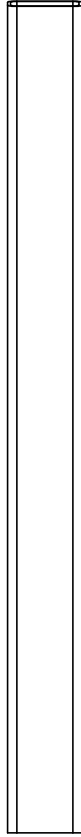
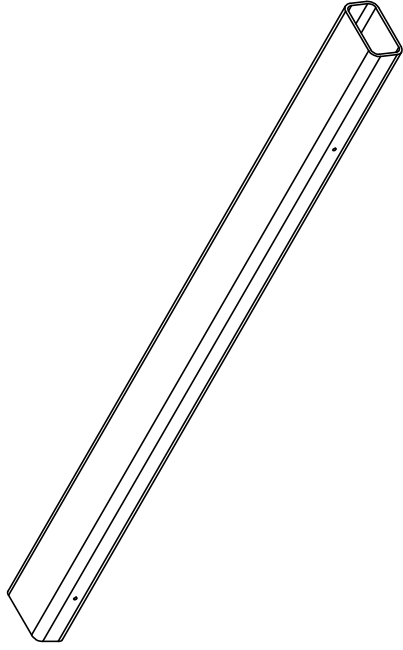
1

2

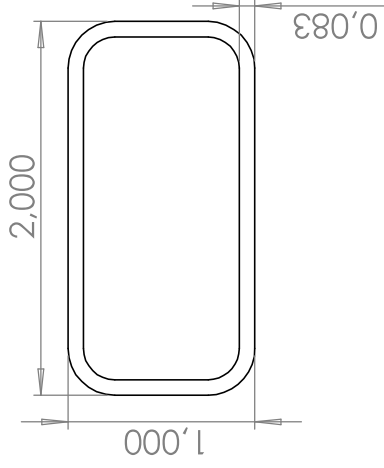
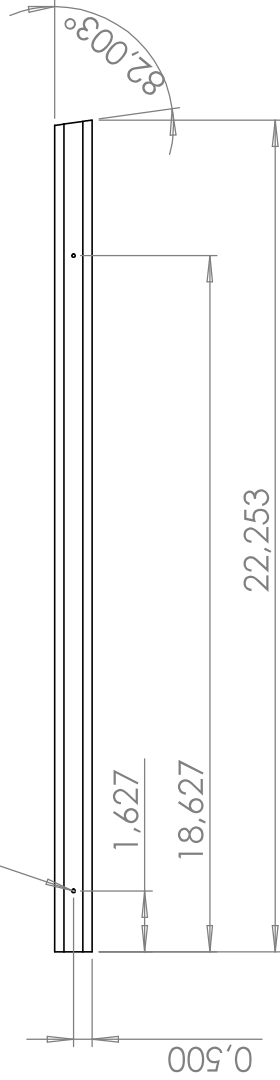
1

B

B



2X  $\phi$  3/32 HASTA EL SIGUIENTE



A

A

NAME	PUT NAME HERE
DATE	22/05/2018
COMMENTS:	SAME PART FOR MAIZE BEAM DEPTH 2

DWG. NO.  
BLUE BEAM DEPTH 1

SCALE: 1:5    QUANTITY: 2    SHEET 3 OF 5

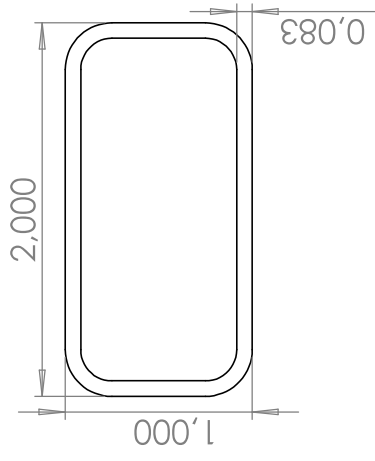
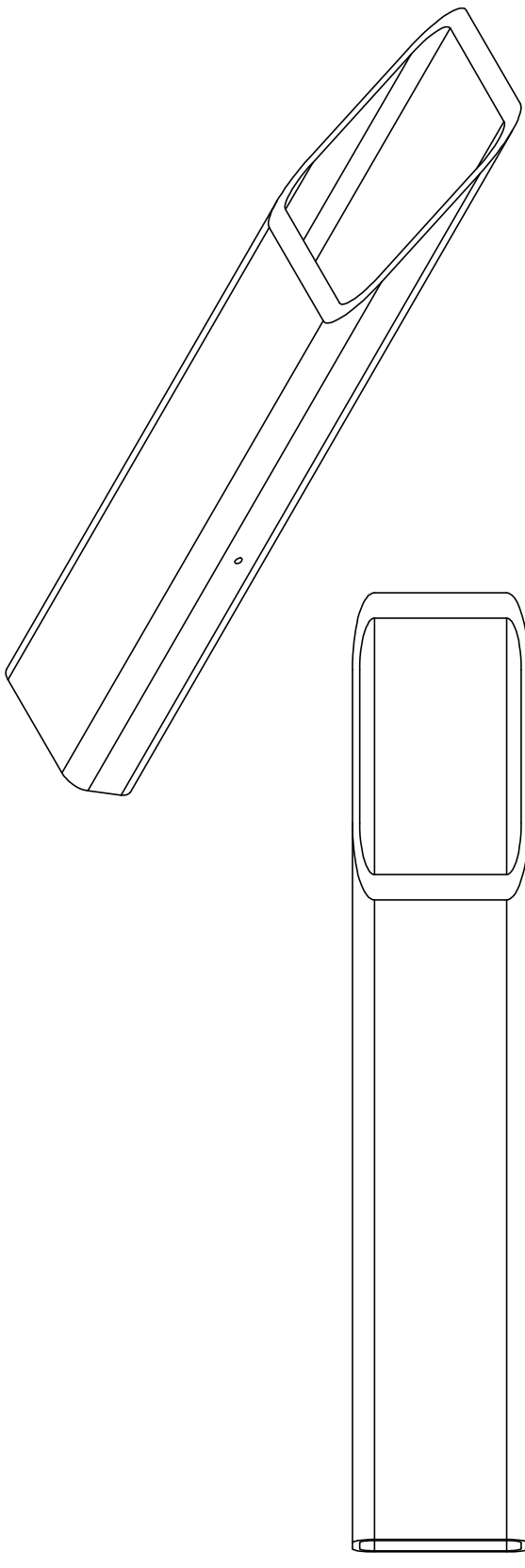
1

2

1

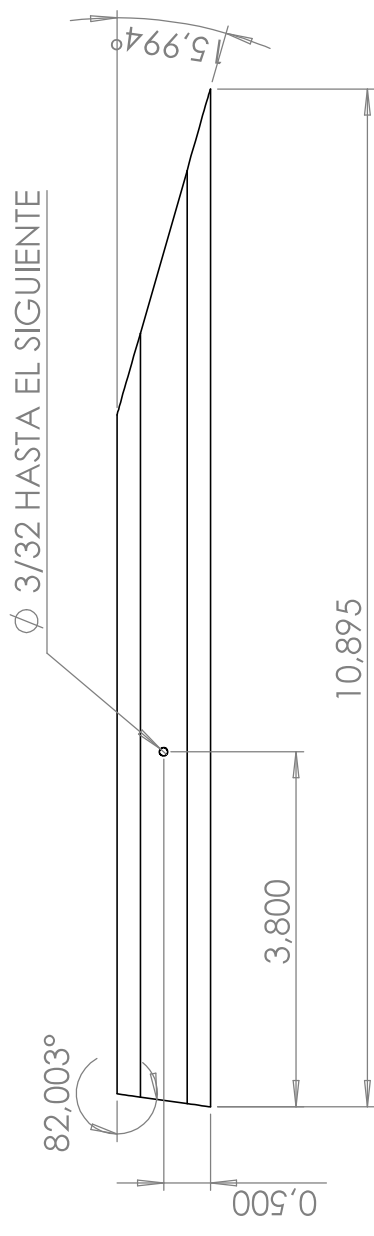
B

B



A

A



NAME	PUT NAME HERE
DATE	22/05/2018
COMMENTS:	SAME PART FOR MAIZE DEPTH 2

DWG. NO.	
SCALE: 1:2	QUANTITY: 2
SHEET 4 OF 5	

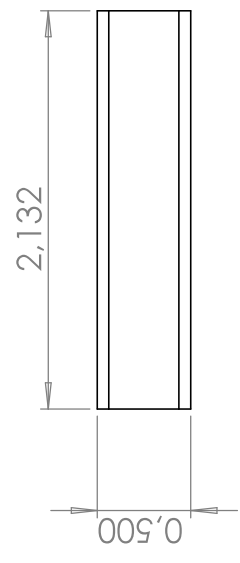
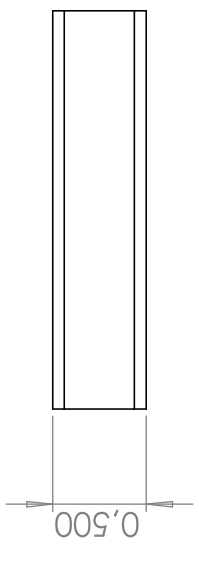
1

2

1

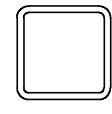
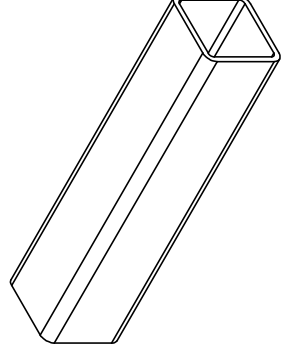
B

B



A

A



NAME	PUT NAME HERE
DATE	22/05/2018
COMMENTS:	

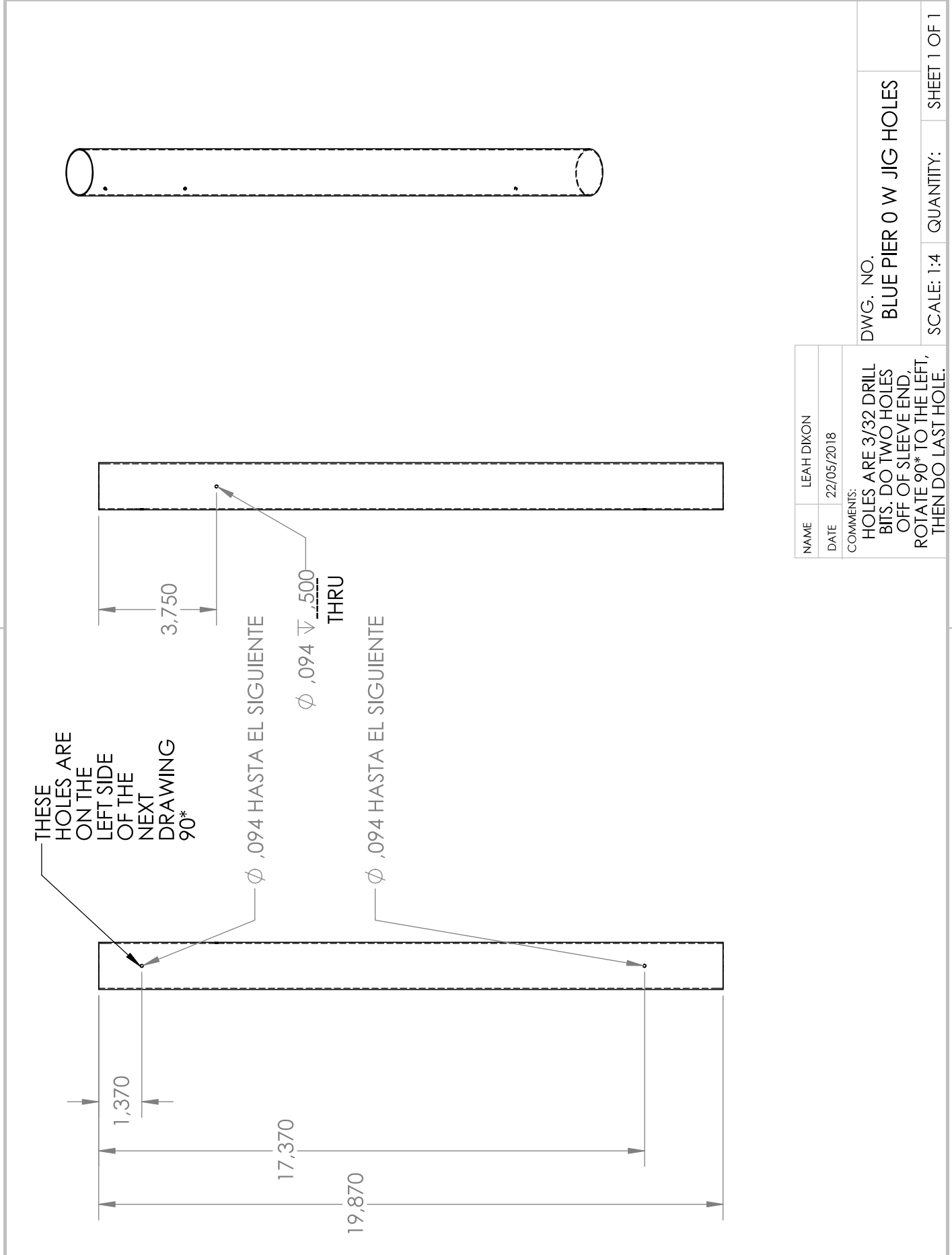
DWG. NO.  
**BLUE BEAM DEPTH 1**

SCALE: 1:10 QUANTITY: SHEET 5 OF 5

1

1

2



THESE HOLES ARE ON THE LEFT SIDE OF THE NEXT DRAWING 90\*

Ø ,094 HASTA EL SIGUIENTE

Ø ,094  $\nabla$  ,500 THRU

Ø ,094 HASTA EL SIGUIENTE

3,750

1,370

17,370

19,870

NAME	LEAH DIXON
DATE	22/05/2018
COMMENTS:	Holes are 3/32 drill bits. Do two holes off of sleeve end, rotate 90* to the left, then do last hole.

DWG. NO.  
BLUE PIER 0 W JIG HOLES

SCALE: 1:4 QUANTITY: SHEET 1 OF 1

1

2

2

1

$\phi .094 \nabla ,250$

3,495

3,495

28,990

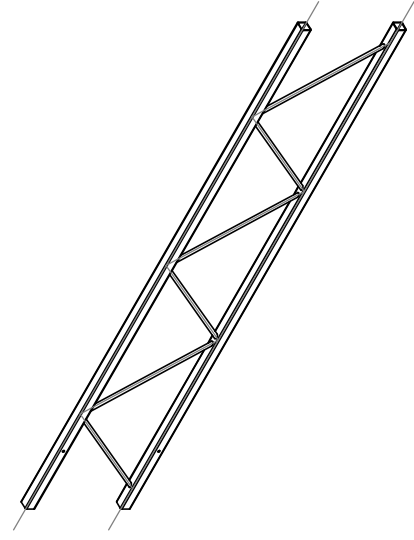
$\phi .094 \nabla ,250$

B

B

A

A



NAME	LEAH DIXON
DATE	22/05/2018
COMMENTS:	THE WEBBING WON'T BE THERE SO JUST DRILL 3/32" HOLES IN THE .5/.5 TUBES

DWG. NO.  
**CROSS BRACING 2**  
**JIG HOLES INCLUDED**

SCALE: 1:4    QUANTITY:    SHEET 1 OF 1

1

# Document III

## Budget





<b>2017-18 Budget</b>	
<b>Expenses</b>	<b>Expected</b>
Tooling/Fabrication Supplies	\$1.500,00
Meeting Expenses	\$250,00
Steel	\$2.500,00
Northfest	\$25,00
Mass meeting	\$100,00
<i>Sub-total:</i>	<i>\$4.375,00</i>

<b>Regionals</b>	<b>Expected</b>
Van Rental, Gas	\$600,00
Team Apparel	\$750,00
Banner	\$100,00
Poster	\$30,00
Registration	\$1.200,00
<i>Sub-total:</i>	<i>\$2.680,00</i>

<b>Nationals</b>	<b>Expected</b>
Hotels	\$1.400,00
Travel Costs (Stipend & Shuttle)	\$5.270,00
Equipment/Supplies	\$125,00
Shipping Bridge	\$1.250,00
Registration	\$1.235,00
<i>Sub-total:</i>	<i>\$9.280,00</i>

<b>Sponsor Income</b>	<b>Expected</b>
Industry/Personal Sponsorship	\$7.000,00
AISC Regional Stipend	\$250,00
ASCE Contribution	\$1.000,00
Department of Civil Engineering	\$3.700,00
College of Engineering	\$3.100,00
<i>Sub-total:</i>	<i>\$11.950,00</i>