Design of an Adjustable Press Die

Phase III: Final Design Report

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Engineering Design
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Executive Summary

Sperling Industries performs work in the construction of lattice steel transmission towers. A major component of this operation involves producing bent lengths of steel angles. Their current process involves a cut-and-weld procedure which is both difficult and time consuming. Sperling Industries requested that our design team, HotForm, design a bending solution for steel angle beams which can reduce labour hour requirements. Their low-volume of work in this area necessitates a solution which is flexible in the variety of bends that can be produced. The safety, functionality, and usability of the design are deemed the most critical design needs. Therefore, the objective is to produce a safe, cost effective die press design that allows Sperling Industries to bend a variety of steel angles for the construction of transmission tower. Concept generation was performed to compile various design ideas. Using a decision matrix, a final concept was selected which was rigorously analyzed and rapid prototyped for testing. Testing has shown that the selected concept is feasible.

HotForm has met the project objectives by producing an adjustable press die design which can bend steel angles to the desired shape. The design is composed of a base plate, adjustable supports, bottoming die, and top die. The base plate is centered in a 100 ton press and serves as the backbone of the design; it has a central cut-out to accommodate the bottoming die and bolt holes to hold the adjustable supports in place. A top die is fixed to the hydraulic press cylinder and provides the force to bend beams. Beams are bent as simply supported beams with the adjustable supports providing the reaction forces and the top die providing a centralized point load. The bottoming die serves to define the depth of the top die stroke and also prevents flange buckling, a condition where the flanges deform laterally. A hydraulic jack allows the position of the bottoming die to be adjusted in-process.

Rapid prototyping and testing of the process has shown that acceptable bends can be produced using this method. Testing has shown that using simplified models, the bend angle can be estimated within 1-3°. In-process adjustment will allow the desired bend angles to be obtained. The design is capable of bending steel angle sections of size L2×2×¼ to L 8×8×1 with angles of 0-45°. The total capital cost of the design after applicable taxes is estimated to be $13227.81 with an NPV of $19112.12 over a three-year study period.

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Nomenclature

Angle - A common industry term used to describe beams with an "L" shaped cross-section. In the context of this report, the terms "steel angle" and angle are interchangeable. Not to be confused with a geometric angle.

Cold Working - A metal forming operation which occurs at room temperatures. High residual stresses are typically introduced into the material which increases its yield strength.

Cold Rolling - A process where metal is passed through rollers to achieve a desired shaped, below its recrystallization temperature. The process results in elongated grains in the direction of rolling and the introduction of residual stresses.

Critical Dimensions - Dimensions which influence the function of the design. Significant deviations from the nominal value of these dimensions will alter the functionality of the design.

Hot Working - A metal forming operation which occurs at temperatures above the materials recrystallization temperature. The high temperatures can significantly increase formability.

Double Angle Inside Bend - A steel angle bend configuration which involves bending both legs inward and thus compressing the legs. Also known as a "both legs in" bend.

Double Angle Outside Bend - A steel angle bend configuration which involves bending both legs outward, and thus putting the legs into tension. Also known as a "both legs out" bend.

Leg - Equivalent term for the flange of a beam with an "L" shaped cross-section.

Minimum Bend Radius - Refers to the minimum radius at which a piece of material can be bent before introducing cracks or wrinkles into the bend area.

NPV – An acronym for Net Present Value. The value of a project in today's dollars considering the initial capital investment, yearly returns, and salvage value over a set study period.

Recrystallization Temperature - The temperature at which a metals crystal grain structure will recrystallize. Above this temperature residual stresses are significantly reduced.

Residual Stress - Stresses which persist in a material after all loading is removed. Residual stresses are introduced into metals after plastic deformation. They result in a harder but more brittle material.

Steel Angles - A common industry term used to describe steel beams with an "L" shaped cross-section. An L2×3×¼ steel angle has legs of length 2" and 3" respectively with a material thickness of 0.25".

1 Introduction

Sperling Industries has requested Team HotForm design an adjustable press die for bending steel angle beams. The desired design must be capable of bending steel angles for a variety of beam sizes and geometric angles. The purpose of this design report is to introduce the die design and bending process prepared by Team HotForm and provide details on the features and components, assembly, and operation of the design.

First, a brief introduction into the project’s background and objectives serves to provide context to the project as a whole. The customer’s needs and associated specifications are included to highlight the specific design goals that the design had to meet. Next, the design details are provided with an overview of important features, a description of the designs operation, and a bill of materials. A brief conclusion to the report summarizes the design and highlights some future recommendations that should be considered.

1.1 Project Background

Sperling Industries is a manufacturing company based out of Sperling which employs over 100 personnel. They perform work in the areas of mining and agricultural equipment, process piping, and structural steel construction [1]. Their structural steel operation is focused on the fabrication and assembly of power transmission towers for utility companies. Sperling fabricates each of the structural members from drawings supplied by their clients and then assembles the transmission tower in individual segments.

Transmission towers must gradually narrow towards their top to reduce wind loads, which necessitates that some of the structural members be bent. Figure 1 points out a bent section, which shows the change in slope of the tower. The blue line in the figure continues the profile of the lower structural leg. Clearly an angle exists between the connecting members.

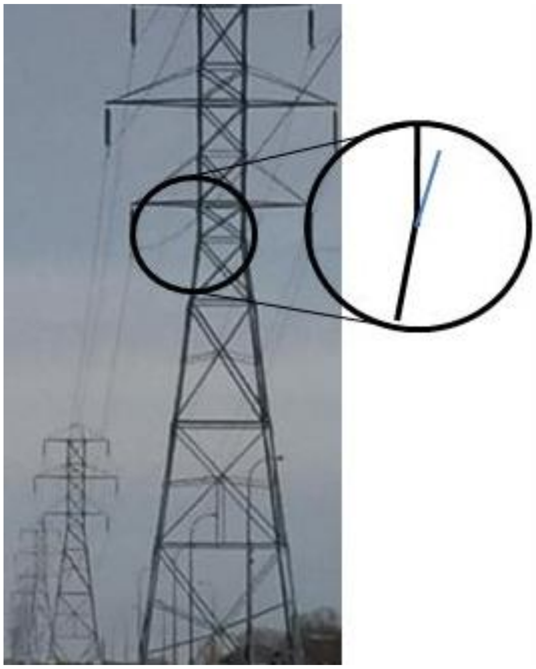

Figure 1: Typical transmission tower showing gradual narrowing [2].

Sperling receives straight steel angle beams from suppliers which they cut to size, drill with boltholes, and bend to a specified angle. Their bending process is composed of cutting wedges out of the steel angle legs and welding the beams to the correct angle. This process is time consuming and can be difficult to achieve the correct bend angle in certain cases. Figure 2 shows a beam which has been cut and welded together by Sperling Industries.

Figure 2: Cut and welded beam with single flange outside bend [2].

The cut and weld process that was used to produce the beam in Figure 2 is illustrated in Figure 3. One flange of the steel angle is cut through and bent outwards. A wedge is cut from steel plate to fit the cut flange. Finally, the wedge is welded into position using a full penetration weld.

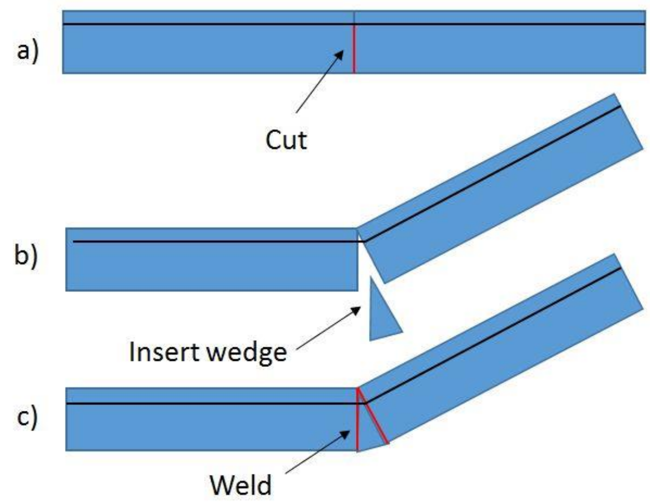

Figure 3: Illustration of the cut and weld process [2].

Sperling Industries processes relatively low volumes of transmission tower beams, around 400 beam orders per year, and very rarely does Sperling produce the same bend angle more than once. The cut and weld process currently in use is a flexible method for producing a wide range of bend angles in the many different beam sizes that Sperling deals with. However, slow processing time and weld inspections make the current process an unattractive option.

A common method of producing bends in steel angles involves using a press die. Press dies tend to bend a limited range of steel angle sizes to an angle determined by the die's geometry. A conventional press die could produce the angles that Sperling Industries requires relatively quickly, but due to the variance in bend angles, Sperling would require a unique die for each bend. An adjustability feature, which would allow for a wider range of bend angles on a single press die, would increase the productivity at Sperling Industries and therefore improve profit margins.

Sperling currently has several presses available for operation of a press die. The maximum tonnage available is 100 tonnes. It is their preference to utilize the current machinery if possible, though they are willing to purchase new equipment should the available machines not be suitable for the final design. It is also preferable to construct the design out of material already stocked by Sperling, which includes CSA 300W and CSA 350W mild steel.

1.2 Problem Statement

Sperling Industries cannot make use of a conventional die press system because of the high variability in angles and beam sizes that they must process. For this reason, Sperling Industries requires a flexible bending solution that can deal with a variety of angles and beam sizes to improve productivity in their structural steel operations. Safety, functionality, and usability are the primary factors that will influence engineering decisions.

1.3 Project Objectives

The objectives of this project have been developed with the input of our client, Sperling Industries, and define what goals must be met achieve project success. The project objectives are summarized below:

1. Produce a safe, cost effective die press design that allows Sperling Industries to bend a variety of steel angles for the construction of transmission towers.
2. Provide a 3-D model of the design that demonstrates the functionality and key features of the final design.
3. Provide assembly drawings and procedures to allow manufacture of the die press.
4. Provide a bill of materials with a cost estimate of the design.
5. Provide an operations manual that allows for safe, repeatable operation of the die press.
6. Base all decisions on relevant calculations, numerical analysis, experience, and engineering intuition. Provide sound justification for all decisions that demonstrates performance of due diligence.

1.4 Customer Needs

The customer needs highlight the important features of the design that should be met to ensure a satisfied customer. The needs were determined by working closely with our Sperling Industry contacts. HotForm refined the needs into 12 focused statements that the client ordered from most to least important. Importance values between 1-5 were assigned to each need by the design team. The importance values were assigned by considering the clients ordering of the needs as well as technical considerations. The list of needs is included in TABLE I.

TABLE I: RANKED CUSTOMER NEEDS

ID	Customer Need	Importance
N.1	Die is safe to operate	5
N.2	Die produces bends within angular tolerance	5
N.3	Die bends a variety of angles and beam sizes	5
N.4	Die is simple to set up and operate	4
N.5	Die maintains structural properties of beams	5
N.6	Die maintains its original dimensions	4
N.7	Die is resistant to high pressures	4
N.8	Die is resistant to high temperatures	3
N.9	Die and fixture are simple to manufacture	3
N.10	Die is simple to take apart	2
N.11	Die is inexpensive to maintain	2
N.12	Die is compatible with existing equipment	1

It is important to note that the customer needs primarily address the safety, functionality, and usability of the design. Sperling Industries is a manufacturing company so they are not concerned with the aesthetics of a tool that will only see internal use.

1.5 Technical Specifications

Technical specifications serve to provide a quantitative method of evaluating a design. Engineering metrics are assigned to each specification which gies a quantifiable value that concepts can be evaluated against. The technical specifications were produced to address the customer needs. Each specification can be linked back to at least one need. The engineering metrics for each specification are assigned a unit, a nominal value, and an ideal value. Units were chosen to ensure that each metric could either be measured or calculated for a given concept. The nominal value is the minimum (or maximum) value that must be met to assure the design is acceptable for the client. The ideal value is the value that would constitute complete satisfaction in the design for a particular specification.

TABLE II: TECHNICAL SPECIFICATIONS AND ENGINEERING METRICS

ID	Component	Specification	Unit	Nominal	Ideal
S.1	Die	Weight per Part	lb	5 (tons)	>100
S.2	Die	Initial Setup Time	hours	8	2
S.3	Die	Adjustment Time	hours	2	0.5
S.4	Die	Dismantle Time	hours	8	2
S.5	Die	Maximum Deformation	thou	Minimize	Minimize
S.6	Die	Complexity	Subjective	---	---
S.7	Die	Maximum Temperature	°F	1004	1328
S.8	Die	Cost	CAD$	30000	10000
S.9	Die	Service Life	years	20	50
S.10	Die	Functional Range of Load	tons	72	124
S.11	Beam	Tolerance	degrees	0.5	0.25
S.12	Beam	Vertical Deflection	feet	12	5
S.13	Beam	Bendable Angles	degrees	0-20	0-45
S.14	Beam	Angle Sizes	Designation	L 2×2×¼ – L 6×6×⅝	L 1¾×1¾×$^{5}/_{16}$ – L 8×8×1
S.15	Beam	Bend Radius Range	inches	Minimize	Minimize

Certain engineering metrics, such as service life and vertical deflection, were determined based on Sperling Industries opinion of what is acceptable. Others, such as the maximum operating temperature and functional range of load, were given values based on external research and industry recommended practices. The bend radius range and maximum deformation of the die are highly dependent on the geometry of the design and cannot be determined until many bending operations have been performed using the design. However, both the maximum deformation and bend radius range should be minimized.

1.6 Project Constraints

The project constraints serve to limit the scope of the design and define what can be accomplished over the life of the project. The project constraints can be broken down into three key areas: technical constraints, resource constraints, and time constraints.

1.6.1 Technical Constraints

Technical constraints limit the scope of technical aspects of the project. The technical constraints that must be considered for this project are the maximum and minimum beam sizes, bend configurations, and geometric bend angles.

Maximum and Minimum Beam Sizes

Sperling Industries deals with a finite number of angle sizes in the construction of transmission towers. The smallest steel angles which Sperling deals with is the L1¾×1¾×$^{5}/_{16}$ and the largest beam is the L8×8×1. Any steel angles within this range, excluding those with unequal legs, are considered to be within the scope of this project. Angles smaller than the L1¾×1¾×$^{5}/_{16}$ size, or larger than the L8×8×1 size do not need to be considered.

Bend Configurations

The next technical constraint which must be considered is the configuration of the bends. There are names for each type of bend depending on which axis they are bent about. Figure 4 gives a visual description of the main types of bends that can be introduced into a steel angle.

Angle Bending Leg Out | **Angle Bending** Leg In | **Angle Bending** Both Leg In | **Angle Bending Both Leg Out**

Figure 4: Bending configurations for steel angles [3, 4].

The four bend configurations shown in Figure 4 are the only configurations that must be considered in the design. Bends that occur about any other axis are out-of-scope for this project. The bend axes are denoted in Figure 5.

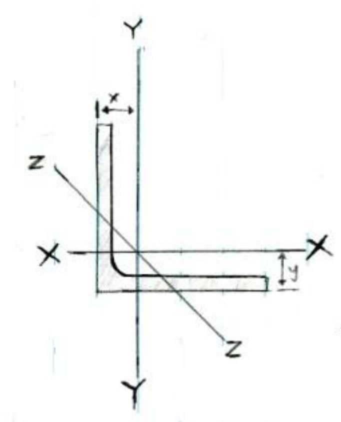

Figure 5: Steel Angle Bend Axis [3, 5]

The “leg in” and “leg out” configurations bend the angle about the X or Y-axis. The “both legs in” and “both legs out” bend the angle about its Z-axis. The “both legs in” configuration is referred to as a double angle inside bend. The “both legs out” configuration is referred to as a “double angle outside bend”.

Geometric Bend Angles

In the construction of transmission towers there is a finite range of geometric angles to which steel angles must be bent. Transmission towers tend to narrow gradually rather than suddenly, so the geometric angles are typically in the range of 0-20°. However, in certain cases, the angles can be much larger. For the scope of this project, the largest angle to be considered will be a 45° bend.

1.6.2 Resource Constraints

Resource constraints limit the scope of the project due to the finite availability of resources to the design team. The resource constraints identified are the design budget and available labour hours.

Design Budget

The project budget reduces the level of freedom that the design team has in regards to materials and functionality. As the rigidity of the material used in the construction of the die increases, the material costs will also increase. The function of the die is also impacted by the budget in regards to the cost of increasing the maximum tonnage through purchase of a new press system or the usage of any electric angle measurement systems. This was an important constraint to take into consideration for the final design since it limited the availability of materials. The purchase of additional structural analysis software was also outside of the design budget.

Labour Hours

There was a finite reserve of labour hours available to the design team to complete this project. Labour hours are required to perform research, write reports, and complete design functions. For this reason, labour was strategically applied to ensure all tasks were completed on time and to specifications. Factors such as conflicting schedules and unforeseen risks further reduced the available pool of labour hours.

1.6.3 Time Constraints

Time constraints limited the scope of the project by compressing the overall timeline. The short duration of the project, which was wholly contained between the dates of 16-Sept-15 to 9-Dec-2015, did not provide time to complete all of the necessary stages to design, manufacture, and test a final design. The project was constrained to the design and prototyping stages.

1.7 Scope Changes

Scope changes are alterations to the planned functionality of the design. Due to the constraints discussed in the previous sections, certain aspects of the design had to be changed in order to allow successful completion of the project. This section discusses the major scope changes which occurred over the duration of the project.

1.7.1 Exclusion of Single Leg Bends

Single leg bends had to be excluded from the project scope. Initial testing showed that single leg bending presented a unique challenge due to the twisting of the beam structure caused by the non-symmetrical geometry. Though the initial goal was to reduce fabrication time on all types of bending processes, Sperling Industries deemed the double angle bending processes to be more critical. Double angle bends are significantly more difficult to produce using the cut and weld method in comparison to the single leg bends since both flanges must be cut. This is considered an acceptable change of scope by Sperling Industries. However, it is recommended that Sperling Industries pursues single leg bending going forward.

1.7.2 Exclusion of Comprehensive Bend Angle Predictions

Metal forming operations are complex and difficult to predict using analytical techniques. Production of a comprehensive bend angle prediction chart has been excluded from the project scope due to time and budget constraints. Production of an accurate chart requires extensive numerical analysis and physical testing. It is recommended that Sperling Industries keeps detailed records of bending operations to assist in producing their own comprehensive prediction chart. However, bend angle estimation tables are included in Appendix G.

2 Design Details

Through research, concept generation, and prototype testing, HotForm has produced a design that will reduce the production time for double angle bends, both inside and outside. The design includes four interchangeable dies which fit into universal fixtures. Different dies must be used for both legs in and both legs out bends, so the fixtures were designed to be simple to load and unload. Though the die geometries differ depending on the bending configuration, the bending process is universal for both types of bends. A labelled figure of the design is included in Figure 6. The configuration shown is for double angle inside bends. Full-sized drawings are included in Appendix F.

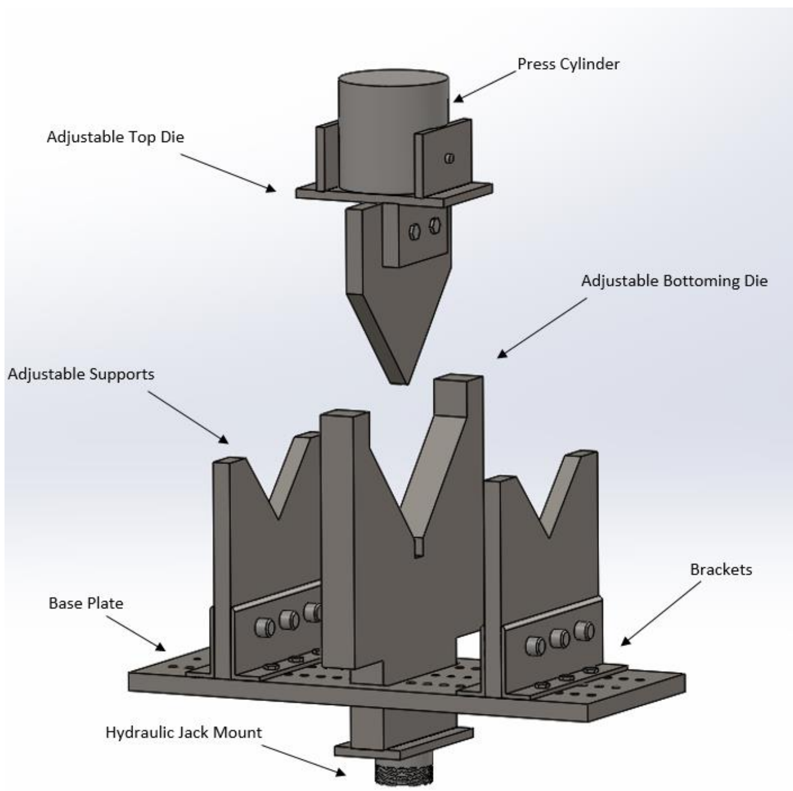

Figure 6: Labelled picture of the design [6]

The top die is mounted onto a top fixture, which is fixed to the press cylinder and moves compresses downwards to deform the beam. Two side dies are mounted within brackets on a base plate surface and can be set to different die openings in order to achieve a wider range of bending angles. Finally, the bottoming die is mounted to a hydraulic jack directly below the top die and centered between the side dies, and can actuate vertically. The bottoming die is in place to guide the beam, as well as reduce warping or flaring of the beam. By adjusting the die gap space and bottoming die height, most beams can be bent to any angle between 0-45°. The following sections describe the design in further detail, including a description of prototyping, details of the key design features, a basic outline of the operation processes, and an overview of the cost of the design.

2.1 Prototyping

Design concept testing was conducted before a detailed analysis of the design occurred. The purpose of this testing was to verify the design concept before investing too heavily in an unproven bending method. Most technical resources related to bending of structural shapes were related to rolling operations or coining operations. Rolling operations were quickly ruled out because they were incapable of producing a tight bend radius. Coining operations, the preferred method, made use of rigid dies which would lack the required adjustability; a coining die is only capable of bending a single steel angle size to a predetermined geometric angle. Air bending was determined to be the best option that would be capable of achieving the required adjustability at a reasonable cost. Appendix A details the various design concepts which were considered. Figure 7 shows the original sketch of the chosen design concept.

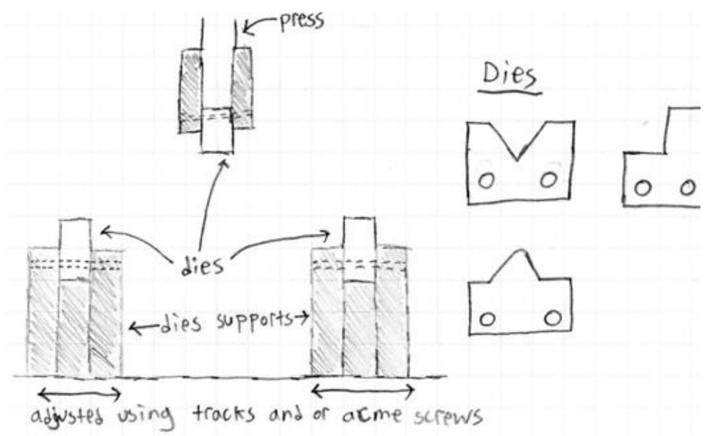

Figure 7: Original sketch of chosen design concept [6].

However, no technical resources could be located that would allow assessment of the design concept. It was determined that performing tests would be the most efficient way to verify that the design could produce the required bends. Two testing sessions were performed to verify the design concept.

2.1.1 Test Session #1

The first testing session was aimed at initial verification of the concept. The test apparatus was composed of two “V” shaped supports that rested on the hydraulic press struts and a “V” shaped top die connected to the hydraulic cylinder. Figure 8 displays a labelled image of the first test session apparatus which performed double angle inside bends.

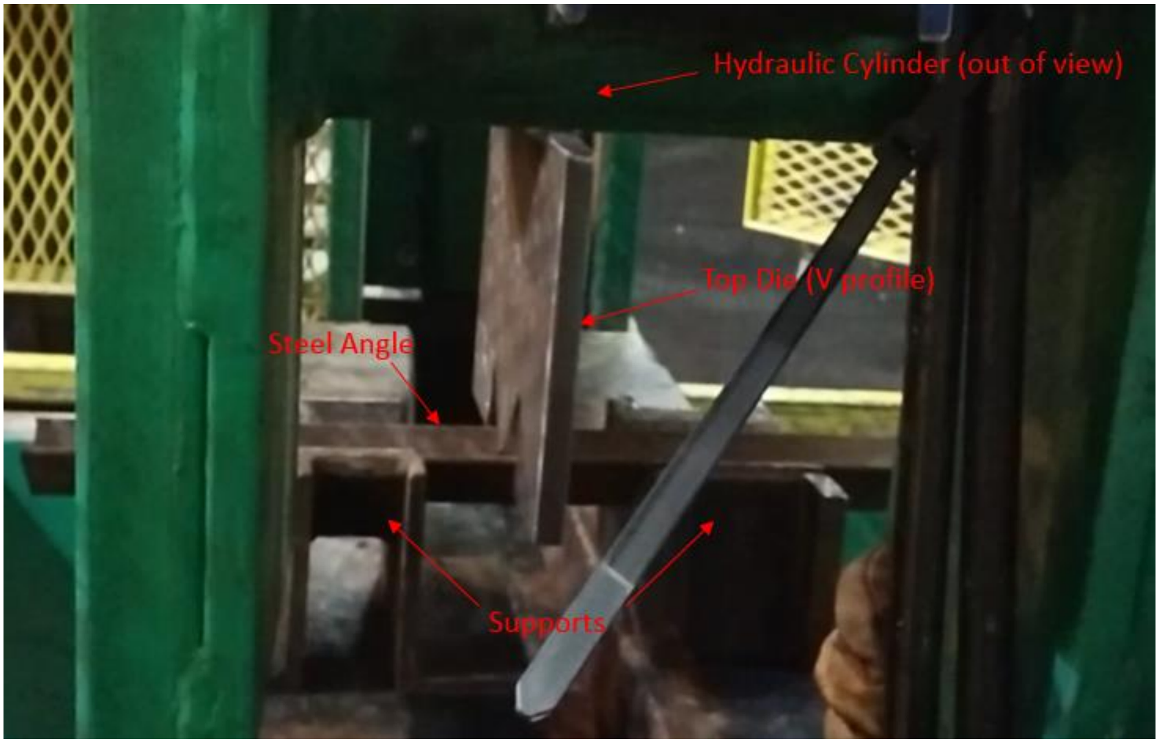

Figure 8: Labelled image of test session #1 apparatus [6].

The steel angle is supported between the two support structures. The hydraulic press, which is out of view, presses the top die into the beam. The profile of the top die matches the profile of the steel angle to ensure the load is evenly distributed. Bending performed on this test apparatus resulted in significant flange buckling which is an unacceptable condition. Flange buckling is a condition where the steel angle flanges push outwards and change the cross-section of the beam in a localized area. Figure 9 shows a test specimen which showed a high level of flange buckling. The buckled flange is circled in red.

Figure 9: Tested steel angle exhibiting flange buckling [2].

The testing results from test session #1 showed that a solution had to be found to prevent flange buckling. A process known as bottoming was found from general research into brake press technology. A “V” shaped “bottoming” die would be located below the top die. The beam would be pushed into the bottoming die which would reform the cross-section of the steel angle.

Single leg inside and outside bends were also attempted during this test session but resulted in severe twisting. Both HotForm and the client agreed that the project should focus on only the double angle bends due to time constraints.

2.1.2 Test Session #2

Test session #2 utilized a bottoming die to verify the concept of bottoming. A labelled image of the session #2 test apparatus is shown in Figure 10. The bottoming die has a 90° “V” opening to match the profile of the steel angles.

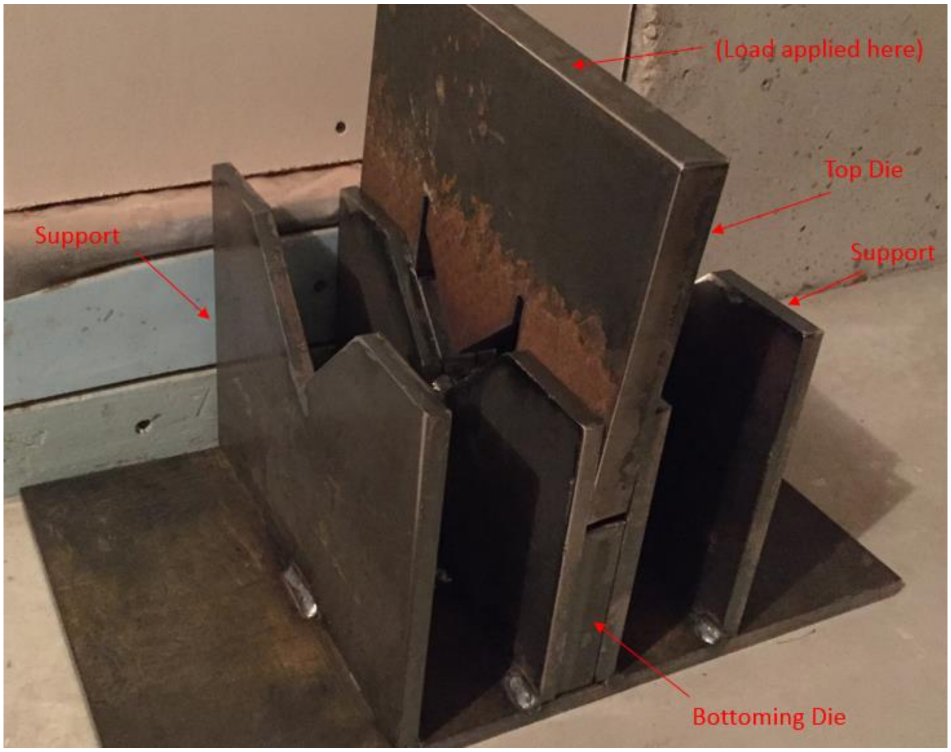

Figure 10: Labelled image of test session #2 apparatus for inside bends [6].

Functionally, the only difference between the test session #1 and the test session #2 apparatus is the inclusion of the bottoming die. The bottoming die was found to effectively reduce flange buckling in steel angles. Figure 11 is an illustration of the bottoming process. The illustration shows a cross-sectional view of the steel angle located at the bend line. Each step is explained in detail following the figure.

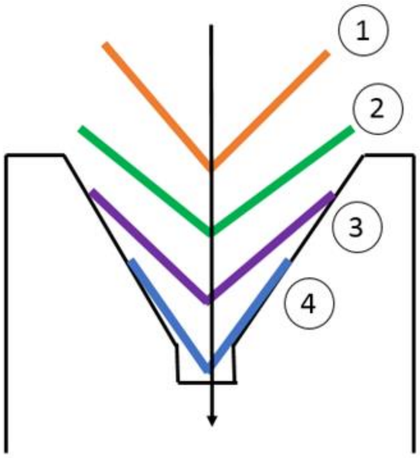

Figure 11: Illustration of the bottoming process [6].

Step #1: Bending has not begun. The beam exhibits its original cross-section.

Step #2: Bending begins. The flanges of the beam begin to buckle outwards.

Step #3: Bottoming begins. The tips of the flanges begin to make contact with the bottoming die.

Step #4: Full bottoming. The beam is forced to make full contact with the walls of the bottoming die which forces it to the desired profile.

Essentially, the steel angle flanges are compressed between the walls of the bottoming die and the top die which forces the material back to the correct profile. Figure 12 shows a test specimen that underwent the bottoming process. Compared to the specimen from the first test session shown in Figure 9, the specimen in Figure 12 has significantly reduced flange buckling. The buckling was not completely removed but the specimen showed that the bottoming concept was feasible. Based on this finding an undercut profile was incorporated into the design which has a “V” opening that is less than 90° to ensure complete removal of flange buckling

Figure 12: Tested steel angle showing reduced flange buckling [2].

During the same test session the double angle outside bend was also tested on a separate test apparatus. The double angle outside bend test apparatus is shown in Figure 13.

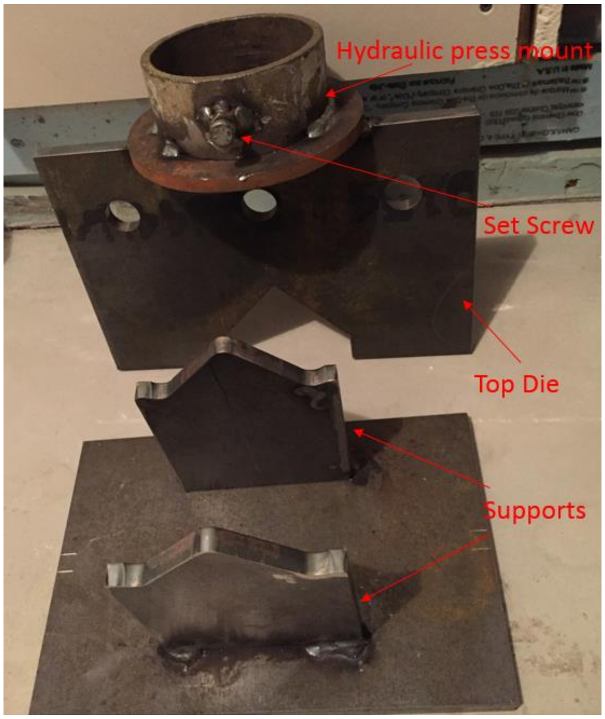

Figure 13: Labelled image of test session #2 apparatus for outside bends [6].

The double angle outside bend tests occurred with relatively little issue. Since the flanges are in tension during the outside bend there was no flange buckling. The only issue that arose occurred because the top die was too thick which restricted the bend radius. Figure 14 shows an outside bend test specimen which exhibited a restricted bend radius. A distinct mark was introduced by the die at the bend line.

Figure 14: Tested steel angle showing restricted bend radius [2].

Through testing it was found that the bend angle could be predicted within 1-3° using simple trigonometry. However, the predictions were based on the erroneous assumption that the beam would not elongate significantly. Testing showed that significant elongation did occur. HotForm altered the prediction method to account for the elongation but further testing is required to definitively determine which method is more accurate. With the knowledge gained from testing, the details of the design began to be formulated.

2.2 Design Features

The major design features are the base plate, adjustable supports, adjustable bottoming die, and adjustable top die. The design is mounted within a 100 ton hydraulic press. The top die fixture is mated to the hydraulic press cylinder. The base plate rests on steel joist-type supports. The bottoming die is mated to a 60 ton hydraulic jack that sits below the assembly. Where possible, components were designed with the clients manufacturing capabilities in mind. Drilling, tapping, and cutter operations are used extensively, while milling is used sparingly. Details of the manufacturing principles considered are included in Appendix D. Furthermore, simple geometries reduce the number of operations required to manufacture components since aesthetics are not a concern in the clients' manufacturing environment. All custom components are machined from CSA 350W mild steel with the exception of the base plate, which is made from AISI 4340 steel. CSA 350W was used where possible because it is readily available in the clients' shop.

2.2.1 Base Plate

The base plate functions as the backbone of the design. It is centered within the hydraulic press during initial assembly. Due to its size and weight it does not need to be rigidly fixed within the hydraulic press. Its weight and the compressive load applied by the hydraulic press will hold it in position. It is manufactured from a single piece of 28”x12”x1” plate. A drawing of the base plate is included in Figure 15.

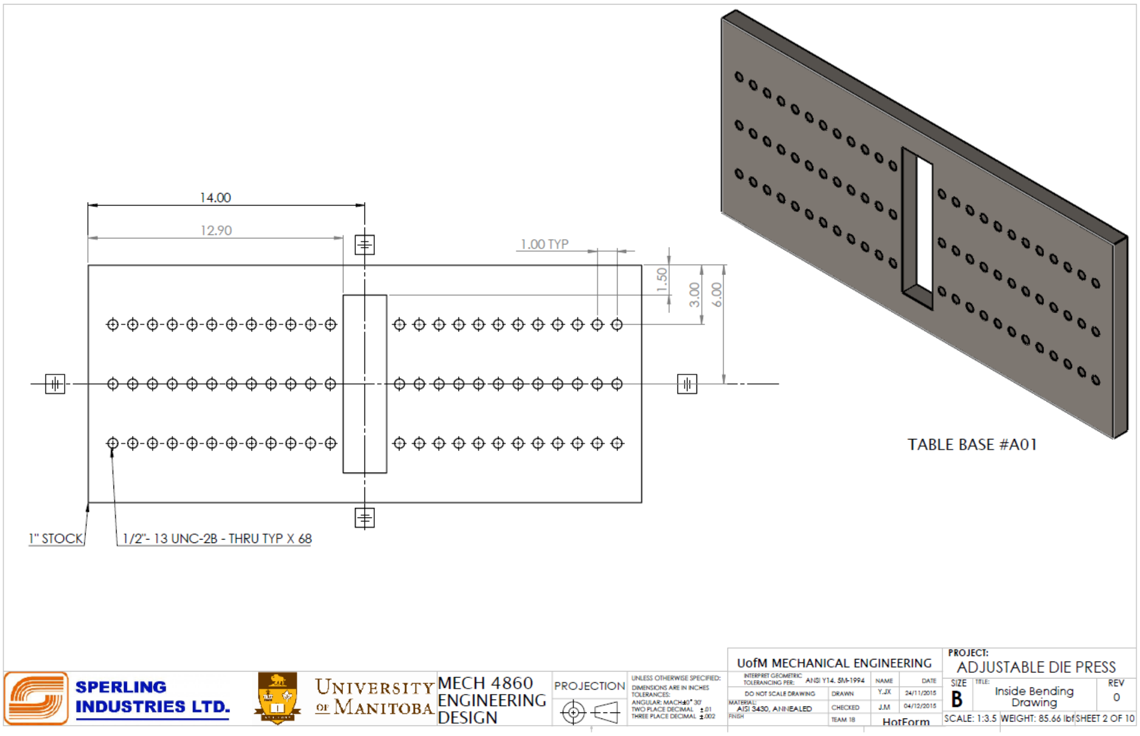

Figure 15: Dimensioned drawing of the base plate [7].

The two main features of the base plate are the central rectangular cut-out and three parallel rows of tapped bolt holes. An 8”x2.2” rectangle is cut out of the center to make room for vertical actuation of the bottoming die. The hydraulic jack is located below the base plate rather than above because of the limited space within the hydraulic press structure. Locating the hydraulic jack below the base plate has the added benefit of transferring load from the bottoming die to the floor rather than to the base plate. The rectangular cut out is slightly oversized to allow easy insertion and removal of the bottoming die.

The bolt hole rows are spaced 3” apart and the individual holes are tapped at 1” increments along the base plate to allow horizontal adjustment of the supports. The 1” increments allow for adjustment of the die opening in 2” increments because the supports must be symmetrically placed on either side of the bottoming die. Bolts are used to mate brackets to the base plate and the brackets determine the position the adjustable supports. The base plate rests directly on the joists of the press, so access to the base plate’s bottom surface is not convenient after initial setup. For this reason nuts cannot be used to fasten the bolts. The threads must be tapped directly into the base plate. In order to reduce the likelihood of stripping the base plates’ internal threads, AISI 4340 was selected as the preferred material because it is significantly harder than CSA 350W mild steel. A more detailed analysis of the material selection is included in Appendix C.

2.2.2 Adjustable Supports

Two adjustable supports are positioned on either side of the base plate center line. Their purpose is to provide reaction forces to counteract the hydraulic press. Together with the top die, the system can be simplified as a simply supported beam in bending with a point load applied at the beams midpoint. The basic loading scenario is illustrated in Figure 16, where the applied load is 2P. Each support accounts for half of the reaction force.

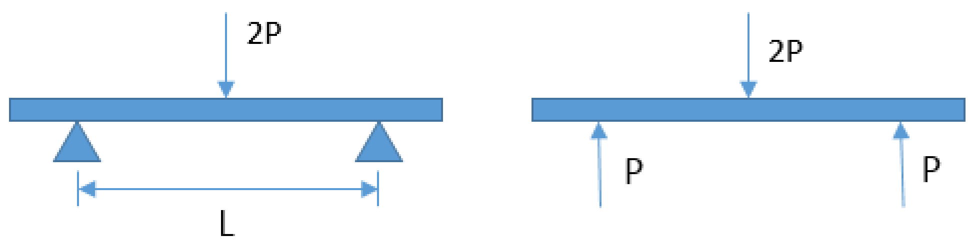

Figure 16: Simply supported beam with centrally applied point load [6].

The distance between the inside faces of the two supports determines the die opening. The die opening must be adjusted depending on the size of the beam being bent. Referring to Figure 17, the ideal opening allows a tight bend radius to form. Small beams require a small die opening to produce a tight bend radius while larger beams require increasingly large die openings to prevent shearing the beam. The ideal die opening is calculated for each beam size using basic beam bending equations. The required force to perform a bend was found from testing to be approximately 2x the calculated force to induce yielding of the beam.

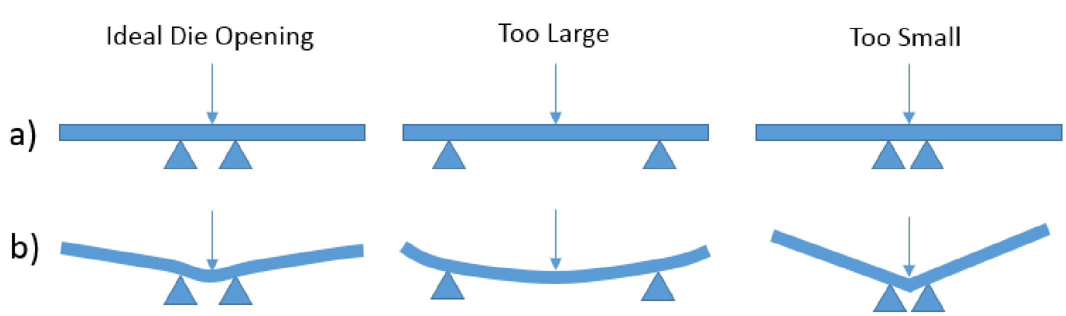

Figure 17: Die opening size comparison [6].

The supports are manufactured from 1” 350W steel plate for the thin configuration and 2” 350W plate for the thick configuration. The thick configuration is required for bending large beams to handle the high stresses. FEA analysis was performed which determined that the 1” support is acceptable for 2” to 4” leg steel angles while the 2” support is required for 5” to 8” legs. The details of the analysis are included in Appendix C. The profile cut into the plate is dependent on the bend configuration. The profile for the double angle inside bend is shown in Figure 18.

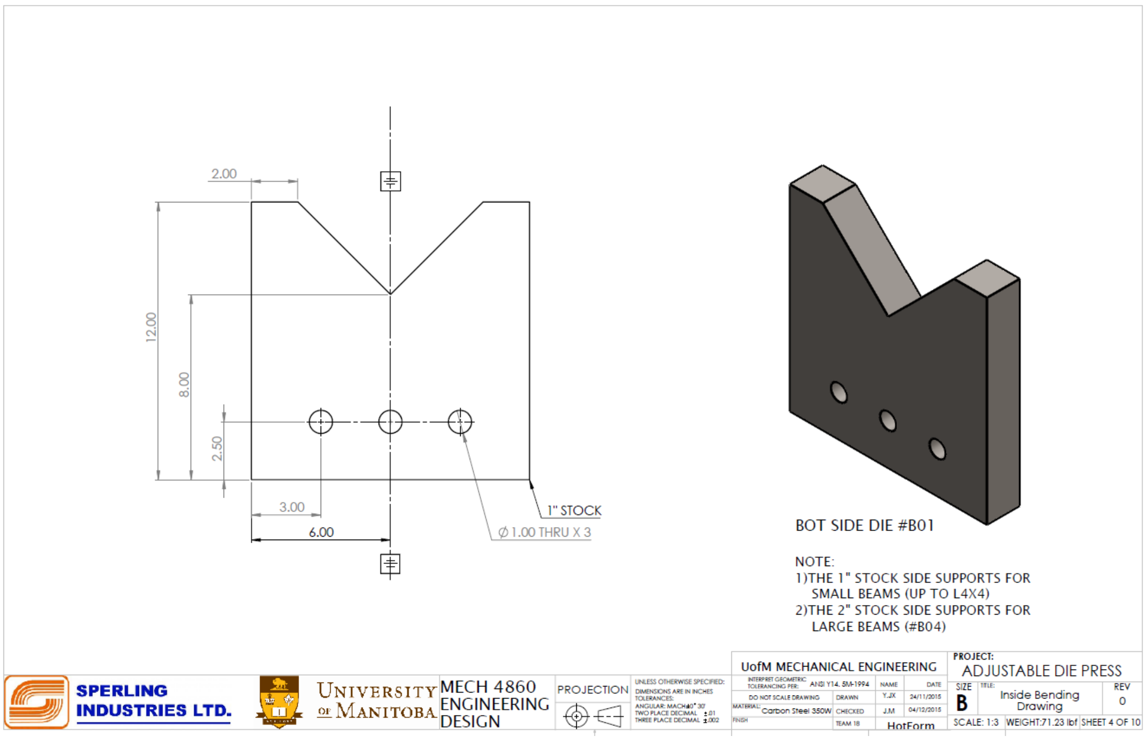

Figure 18: Inside bend adjustable support drawing [7]

A single “V” profile is cut into the plate with a 90° opening to match the outside surface of the beams for the inside bend. The profile is capable of supporting all sizes of beams for the double angle inside bend.

Two configurations are required for the double angle inside bend: a small size with a small radius tip and a large size with a large radius tip. A drawing for the large radius outside bend support is shown in Figure 19.

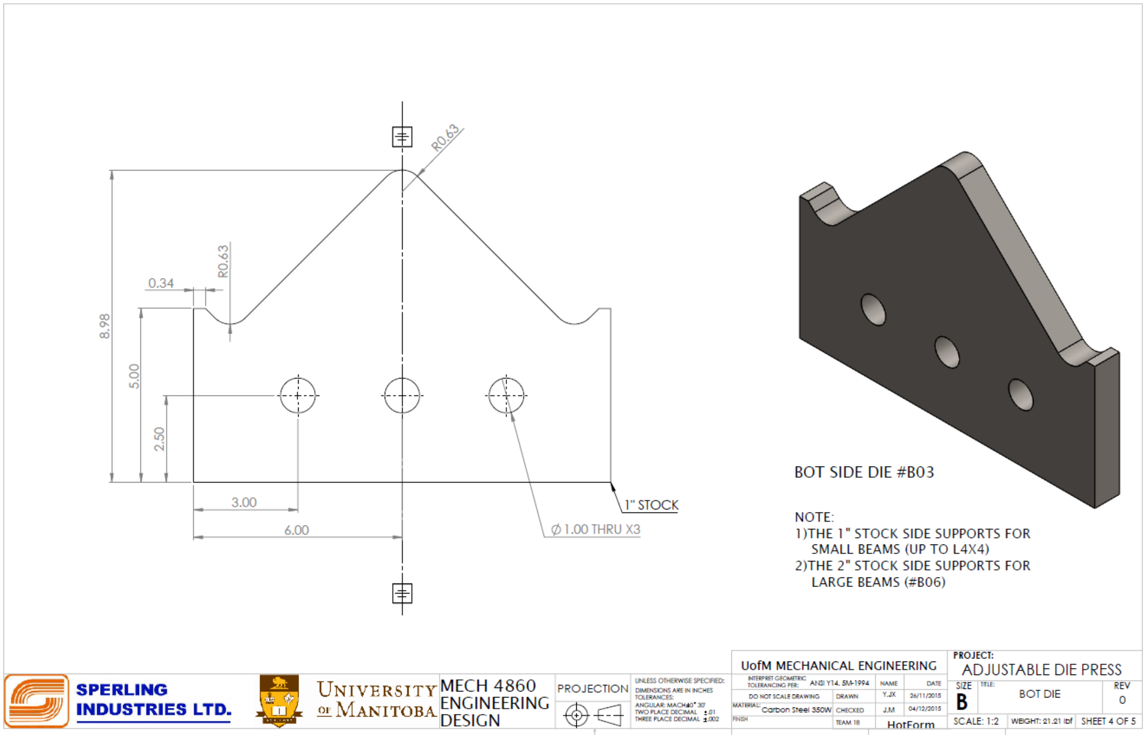

Figure 19: Outside bend adjustable support drawing [7]

The “V” profile is flipped for the outside bend and the tip is rounded to match the radius of the beams. Two different sizes of tip radius are used since the radius of steel angles varies significantly for different steel angles. The small tip radius outside bend support has a smaller radius to hold beams with 2” to 4” legs. The large tip radius outside bend support has a larger radius to accommodate beams with 5” to 8” legs. Ideally, a separate support would be cut to match the radius of every beam size, but this would result in a significant increase in material costs.

Support plates for both configurations have 1” pin holes drilled 3” above their base with a 3” spacing. This commonality allows the same brackets to be used for every unique support plate.

The distance between the tip of the “V” shape and the base plate for both the inside and outside bend configurations are critical dimensions. The difference between the aforementioned dimension and the height of the bottoming die determines how far the beam can be compressed and thus the bend angle which is introduced into the beams. Figure 20 shows how the dimensions of the die impact the work piece.

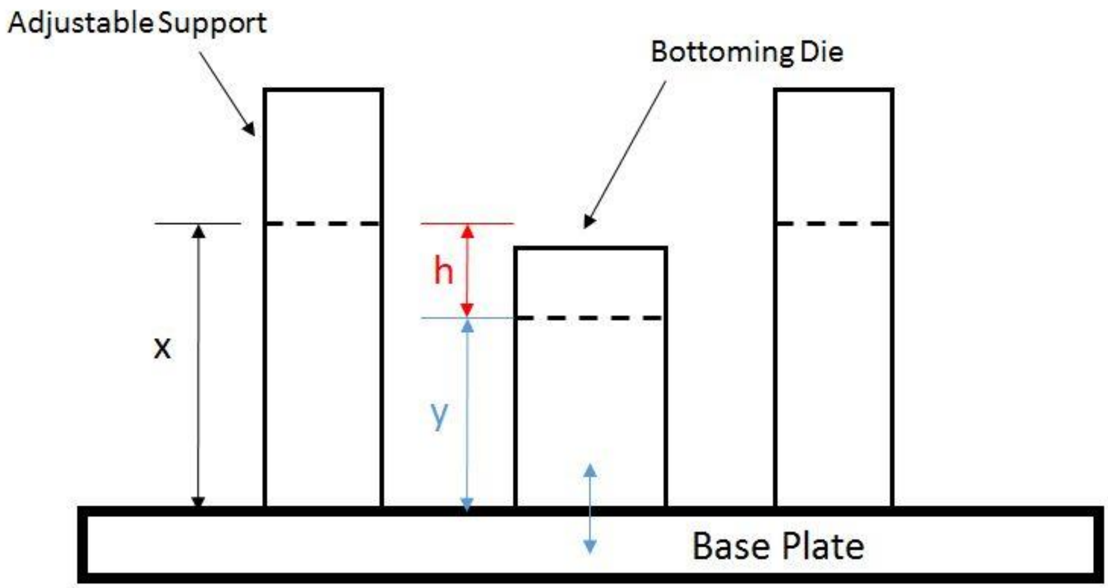

Figure 20: Labelled diagram showing importance of die dimensions [6].

Adjustment of the bottoming die height, denoted by "y", in relation to the support height, "x", alters the height difference denoted by "h". The value of "h" determines how far the beam can be compressed.

The adjustable supports are connected to the base plate using custom brackets manufactured from 4" leg steel angles. Two sizes of brackets are required: a small size made from 0.25" thick angles and a large size made from 0.75" thick angles. A drawing of the small size bracket is shown in Figure 21.

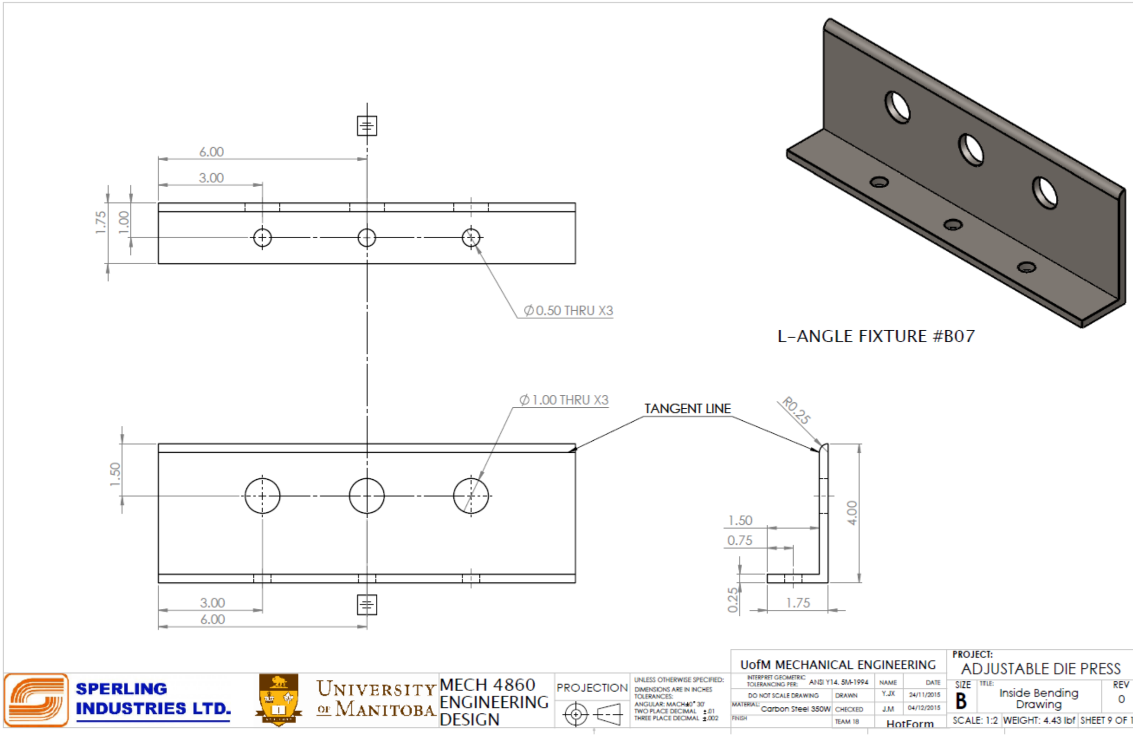

Figure 21: Small size bracket drawing [7]

The brackets are bolted to the base plate along their horizontal flange. The bolt holes in the horizontal flange have the same 3" space as that of the base plate. Two brackets are connected to the base plate on either side of the support and the support is held in place with 1" pins inserted through the brackets vertical flanges. The base of each support is kept flush with the base plate which transfers most of the compressive load into the base plate rather than through the brackets. A horizontal force is also introduced into the supports as the beam bend angle increases. The brackets' structural function is to resist the bending moment introduced by the horizontal force. The brackets were analyzed with the supports using FEA which confirmed that they have sufficient strength to resist the bending stresses. By using the recommended parts for each bend every bend can be completed safely. However, there was insufficient time to analyze the bolts in-depth so test specimens should be used to verify their strength.

The small size bracket is only used for bending small steel angles where the die opening must be minimized. The larger bracket size is oversized and therefore does not permit the die opening to be minimized for the smallest beams. The larger bracket is required for bending large beams and is used whenever possible due to its superior strength.

2.2.3 Adjustable Bottoming Die

The bottoming die is positioned through the center of the base plate. It is manufactured from 2" thick steel bar. It actuates vertically through the use of a 60 ton hydraulic jack. A separate bottoming die is required for double angle inside bends and double angle outside bends.

The difference in height of the adjustable supports compared to the bottoming die determines the stroke of the press as was illustrated in Figure 20. Once the press has bottomed the beam onto the bottoming die the bend is complete. The double angle inside bend bottoming die is detailed in Figure 22.

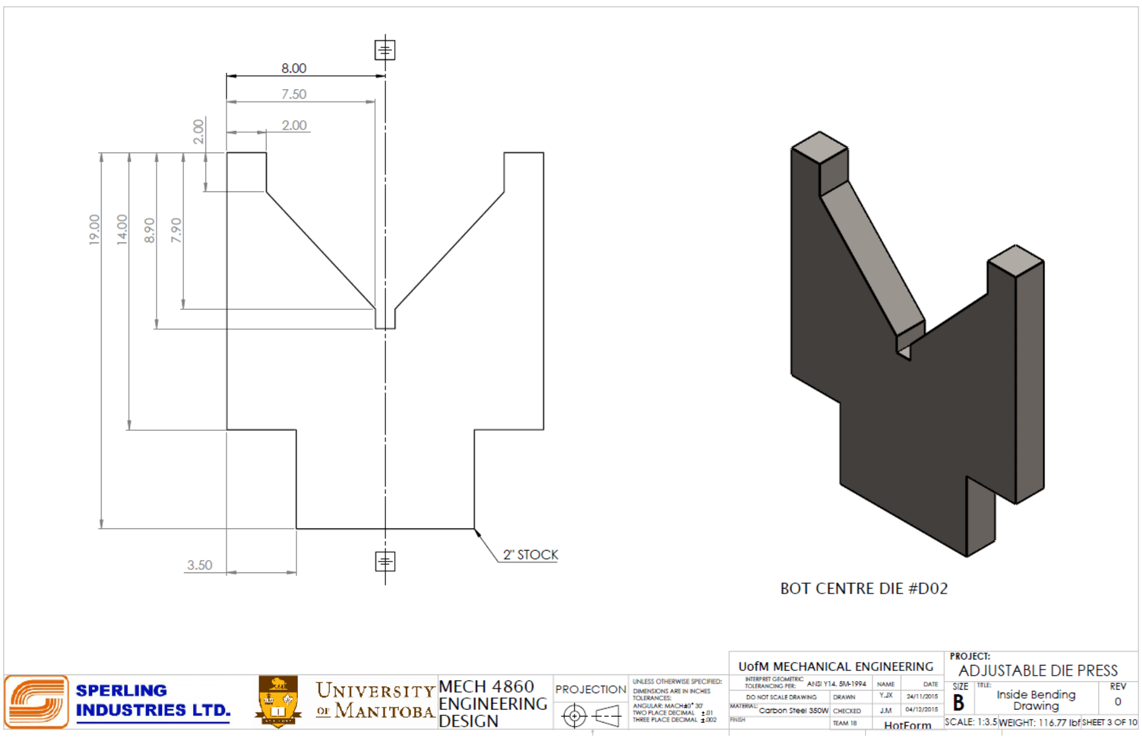

Figure 22: Bottoming die for inside bends drawing [7]

The bottoming die was incorporated into the design based on findings from the first testing session. It was found that the flanges of steel angles tended to buckle outwards during double angle outside bends. The bottoming die has a "V" profile with an undercut angle of 86°. As the beam is forced into the bottoming die, the undercut profile forces the buckled flanges inward. The undercut die ensures that the flanges are fully corrected before the bend is complete which should give the steel angles the desired cross-section [8] at the bend line. A small relief channel is cut into the bottom of the "V" profile to prevent bottoming the corner of the steel angle before the flanges are corrected. The function of the relief channel can be seen in Figure 11 in Step #4. The corner of the steel angle cross-section does not make contact with the bottoming die.

The 2” bar stock for the bottoming die was selected based on observations from the testing sessions. A 1” thick bottoming die was used during testing, which was sufficiently thick to correct the flanges of L3x3x$\frac{3}{8}$ beams. However, larger beams require larger die openings, as described in Section 2.2.2, to avoid shearing the beam. Larger die openings increase the size of the bend area [4], illustrated in Figure 17, which distributes the flange buckling over a larger portion of the beam. In order to accommodate a larger range of beams the thickness of the bottoming die was increased. The optimal thickness and geometry of the bottoming die could not be determined due to time and resource limitations. However, FEA analysis was performed on the bottoming die which shows that the die is structurally capable of withstanding the applied loads. Additional optimization can be done to reduce the weight of the part.

The bottoming die for the double angle outside bend has a reversed “V” profile. Its purpose is to control the stroke of the hydraulic press as shown in Figure 20. This concept was not specifically testing during the testing sessions for the outside bend but it works in a similar fashion as the double angle inside bend for controlling the stroke of the press.

A hydraulic jack is included to allow in-process adjustment of the press stroke. The exact bend angle which will be attained for a given press stroke can be estimated within 1-3°, but is difficult to determine exactly. In-process adjustment of the bottoming die allows an exact bend angle to be achieved. The hydraulic jack has a stroke of 3” which provides sufficient depth for most beams and geometric angles. In the fully retracted position, when the base of the bottoming dies are flush with the base plate, the distance “h” in Figure 20 is equal to 3” for both bend configurations. This allows the hydraulic jack to vary to press stroke anywhere between 0-3”.

2.2.4 Adjustable Top Die

The top die is connected to the hydraulic press cylinder through the use of a fixture. The fixture mates to the press and retains the various top die plates. The fixture is mated to the hydraulic press cylinder by a pin that runs through the press cylinder. The components of the fixture itself are held together by full-penetration welds. The fixture does not require dismantling or adjustment so welding simplifies the assembly. A close-up of the fixture is shown in Figure 23.

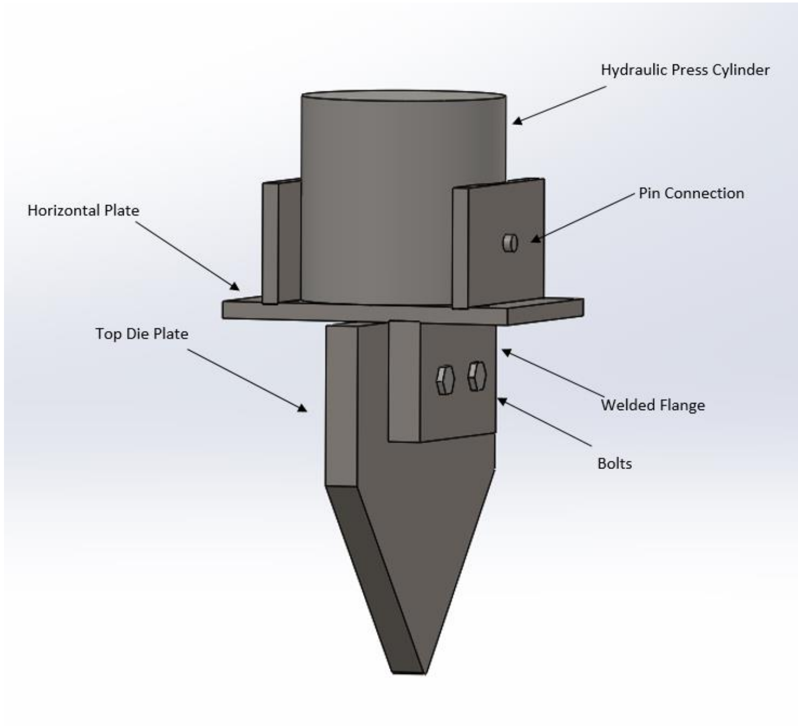

Figure 23: Close-up of the adjustable top die [6]

The top die plates are retained using half inch bolts. Unlike the base plate, fastening is accomplished using nuts. An asymmetric design is used for the fixture. A single flange is welded to the fixture's horizontal plate to mount the die. The flange is positioned so that a 1" thick die will be flush with the flange, and centered relative to the press cylinder. A 0.5" thick die is centered with the press cylinder using 0.25" thick oversized washers which function as spacers. The die plates must be centered relative to the hydraulic press to prevent eccentric loading.

The top die profile varies depending on the specific bend configuration and size of beams. Larger beams with legs sizes from 5" to 8" are bent with a 1" thick plate, as shown in Figure 24.

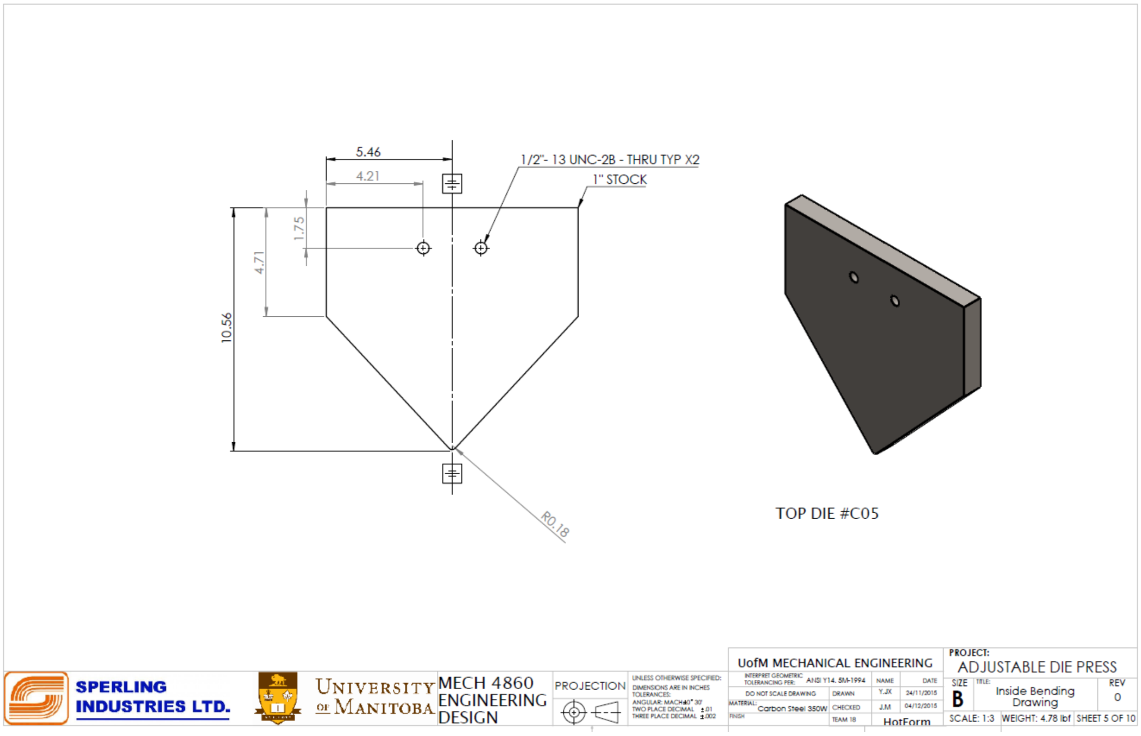

Figure 24: Inside bend top die for large beams [7]

The thick plate ensures that the plate does fail when bending large beams. Smaller beams with legs sizes from 2” to 4” are bent with a 0.5” thick top die. A thinner plate is utilized to prevent the die from restricting the bend radius of smaller beams [8]. This phenomenon was predicted by technical research into sheet metal bending which specifies that the die must be thinner than the work piece thickness to prevent restriction of the bend radius [8]. This was confirmed experimentally during test session #2 as shown in Figure 14.

2.3 Operation

This section describes the basic operation of the design. A description of initial setup, beam preparation, bending operations, adjustment, and beam removal is included it help understand the design. A more detailed operations manual is included in Appendix G for shop personnel use. All reference tables, along with other technical reference material, are not included here because they are primarily for shop personnel use and are more useful to Sperling Industries when compiled in a single location.

2.3.1 Initial Setup

The operator must complete initial setup of the adjustable press die before bending operations can begin. The operator must select the bend configuration, steel angle size, and geometric angle which must be bent from engineering drawings. Based on the bend configuration and steel angle size the operator selects the appropriate top die, supports, and bottoming die. A reference table to assist setup is included in Appendix G. A bend reference table, also located in Appendix G, assists in selecting the appropriate die opening. The support brackets are bolted into position with a torque of $94 ft \cdot lb$ and the supports are fixed in place with pins. Likewise, the top die is bolted into place with a torque of $70 ft \cdot lb$ and the bottoming die is inserted into the center of the base plate. The appropriate press stroke is selected from the bend reference table and dialed in using the hydraulic jack. A high temperature lubricant may be added to the die surfaces if excessive wear is being experienced.

2.3.2 Beam Preparation

The beam is maneuvered into position using the shop's hoist system. The bend line is centered relative to the top die. The hydraulic press can be actuated into position to ensure proper bend line alignment. An oxy-fuel torch is used to heat the bend line and surrounding area to approximately 700°C. Heating will soften the material to 35% of its original strength and increase its malleability without causing significant changes to the steels microstructure [9, 10]. The temperature is approximated based on the luminescence of the steel by using the temperature approximation table included in Appendix G. Once the appropriate temperature has been reached, the oxy-fuel torch is turned off and a digital compass is mounted to the beam several inches from the heated area. The digital compass is zeroed.

2.3.3 Bending

The press is actuated downwards. Once the top die makes initial contact with the beam, the hydraulic pressure spikes. The pressure will stay relatively constant through the bend. For an outside bend configuration, the press will stop when the beam makes contact with the bottoming die.

For the inside bend configuration, the flanges will begin to buckle outwards throughout the bend. The flanges will make contact with the walls of the bottoming die and begin to be pushed back inwards as illustrated in Figure 11. The undercut profile ensures that the flanges are fully corrected before the beam is completely bottomed.

2.3.4 Adjustment

Testing has shown that the method used to calculate the press stroke consistently underestimates the bend angle by 1-3°. Taking a reading from the digital compass will indicate where the bend angle is relative to the desired angle. Actuation of the hydraulic jack and hydraulic press in small increments allow fine tuning of the bend angle. The resolution included in the bend reference table provides the required stroke increment to add 0.5° to the overall bend angle. Once the appropriate bend angle has been achieved, the press can be returned to its original position. Spring back should be negligible because most of the residual stress is relieved at the elevated temperature [10]. The bottoming process will also cause localized compressive stresses which will reduce the size of the elastic core, further reducing spring back [11].

2.3.5 Removal and Inspection

The beam is removed from the die using the shop's hoist system. Once the beam has been safely lowered to the ground, the bend area should be inspected for indications such as cracking, excessive localized compression, and flange deformation.

2.4 Overall Cost and BOM

The overall material cost of the design is summarized in the Bill of Materials contained in TABLE III. Part numbers are assigned to each component to avoid confusion when referring to the components during manufacturing.

TABLE III: BILL OF MATERIALS [12, 13, 14]

Qty	Component	Part #	Item	Material	Unit Price ($USD)	Line Price ($USD)
	Assembly - Base Plate					
1.0	Base Plate	A01	12"x36"x1" Plate	AISI 4340	$343.51	$343.51
	Assembly - Side Supports					
2.0	Side Supports Inside Bend Thin	B01	12"x12"x1" Plate	CSA 350W	$164.00	$328.00
2.0	Side Supports Outside Bend Small Thin	B02	12"x8"x1" Plate	CSA 350W	102.54	$205.08
2.0	Side Supports Outside Bend Large Thin	B03	12"x8"x1" Plate	CSA 350W	102.54	$205.08
2.0	Side Supports Inside Bend Thick	B04	12"x12"x2" Bar	CSA 350W	248.13	$496.26
2.0	Side Supports Outside Bend Small Thick	B05	12"x8"x2" Bar	CSA 350W	199.91	$399.82
2.0	Side Supports Outside Bend Large Thick	B06	12"x8"x2" Bar	CSA 350W	199.91	$399.82
4.0	Support Brackets Small	B07	L4"x4"x0.25" 90 Angle, 1 ft	CSA 350W	$26.08	$104.32
12.0	Bracket Bolts Small	B08	1/2"-13 Full Thread, 1" Long, Steel Cap Screws	Zinc-plated Grade 5	$0.44	$5.28
4.0	Support Brackets Large	B09	L4"x4"x0.75" 90 Angle, 1 ft	CSA 350W	$29.86	$119.44
12.0	Bracket Bolts Large	B10	1/2"-13 Full Thread, 1.5" Long, Steel Cap Screws	Zinc-plated Grade 5	$0.49	$5.88
2.0	Bracket Pins	B11	1"Dia. Rod, 1ft	CSA 350W	$10.82	$21.64
	Assembly - Top Die					
1.0	Top Fixture Base	C01	12"x6"x0.5" Plate	CSA 350W	$37.55	$37.55
2.0	Top Fixture 1	C02	6"x3.5"x0.5" Plate	CSA 350W	$14.29	$28.58
1.0	Top Fixture 2	C03	6"x3.5"x1" Plate	CSA 350W	$23.74	$23.74
1.0	Top Die Inside Bend Small	C04	12"x18"x0.5" Plate	CSA 350W	$145.10	$145.10
1.0	Top Die Inside Bend Large	C05	12"x18"x1" Plate	CSA 350W	$207.06	$207.06
1.0	Top Die Outside Bend Small	C06	12"x18"x0.5" Plate	CSA 350W	$145.10	$145.10
1.0	Top Die Outside Bend Large	C07	12"x18"x1" Plate	CSA 350W	$207.06	$207.06
1.0	Top Pin	C08	0.5"Dia. Rod, 1 ft	CSA 350W	$3.09	$3.09
2.0	Top Fixture Bolts	C09	1/2"-13 Thread 3" Long, Steel Cap Screws	Zinc-plated Grade 5	$1.44	$2.88
2.0	Top Fixture Nuts	C10	1/2"-13 Thread Steel Hex Nuts	Zinc-plated Grade 5	$0.14	$0.28
4.0	Top Fixture Spacers	C11	1/2"Dia. 1/4"Thick Oversized Washers	Zinc-plated steel	$3.02	$12.08
	Assembly - Bottoming Die					
1.0	Bottom Fixture Base	D01	12"x4"x0.5" Plate	CSA 350W	$25.65	$25.65
1.0	Bottoming Die Inside Bend	D02	18"x18"x2" Bar	CSA 350W	$642.32	$642.32
1.0	Bottoming Die Outside Bend	D03	18"x12"x2" Bar	CSA 350W	$431.53	$431.53
1.0	Hydraulic Jack [13]	D04	RCH-606 Hydraulic Cylinder, 60T, 3" stroke		$3,750.00	$3,750.00
	Assembly - Misc.					
1.0	Digital Protractor [14]	E01	Hammerhead 10" Digital Compass		$49.88	$49.88
						$8,346.03

The total material cost of the design is $8346.03 plus applicable taxes. The manufacturing costs to implement the design are estimated to be $3360.00 assuming a labour rate of $70/hour. The details of the manufacturing analysis are included in Appendix E. This brings the total project investment cost to $11706.03 before applicable taxes.

Assuming a 13% tax rate the capital cost comes to $13227.81. The capital cost comes $3227.81 over the ideal budget of $10000.00 noted in TABLE II. However, the capital cost is below the $30000.00 maximum budget which means that the total design cost is acceptable.

Using a 14.30% cost of capital and 200 hours of labour savings per year at $70/hr USD the NPV of the project is estimated to be $19112.12 over a three year study period. The design will pay for itself within the first year. The details of this analysis are included in Appendix E.

3 Conclusions

Sperling Industries is a manufacturer of lattice steel transmission towers for utility companies. Bending of steel angle sections is an important, but difficult, component of Sperlings' operations. The current practice to produce bent beams is to cut and weld the beams to the desired profile. They have contracted HotForm to produce a steel angle bending solution to streamline their operations.

Team HotForm has produced a design for an adjustable press die which meets the clients' defined needs. The design makes use of a base plate which is mounted within a hydraulic press frame. Fixed to the base plate are adjustable supports which determine the size of the die opening. A top die is connected to the hydraulic press cylinder which provides the force to bend the beams. Incorporation of a bottoming die allows for correction of flange buckling and control of the press stroke. A hydraulic jack provides in-process adjustability of the bend angle. A comparison of the customers' needs to the design's main features are included in TABLE IV on the following page.

It is recommended that Sperling Industries only manufacture's the components relevant to the bends being performed. Configurations for all beam sizes are available but they are not necessarily required. Furthermore, Sperling should record the data from their bending operations to improve the bending reference charts. Using the data, Sperling can also determine which of the two prediction methods included in Appendix G produce more accurate bends.

TABLE IV: CUSTOMER NEEDS VS DESIGN FEATURES [8, 9, 10]

ID	Customer Need	Design Feature
N.1	Die is safe to operate	-Sturdy construction validated through testing and FEA analysis ensures that the design does not fail -Use of the existing overhead hoist system allows for safe handling of the largest beams -Safety manual provides guidelines for safe operation
N.2	Die produces bends within angular tolerance	-Initial bend gets within 1-3° of the desired angle and possibly closer using updated prediction method -Hydraulic jack allows in-process fine-tuning of bends until the desired angle is obtained -Bottoming die eliminates flange buckling condition
N.3	Die bends a variety of angles and beam sizes	-Double angle inside bends and double angle outside bends are available -Angles between 0 to 45° can be produced for most beam sizes -Design can accommodate beams from L2×2×¼ to L8×8×1
N.4	Die is simple to set up and operate	-Most interchangeable components are light-weight and can easily be moved by hand -Reference bend table allows easy setup for every beam and angle
N.5	Die maintains structural properties of beams	-Preheat temperature is selected to prevent alteration of the beams crystal microstructure -Bottoming die prevents flange buckling and maintains the beams form -Hot bending process prevents beam fractures and relieves residual stresses
N.6	Die maintains its original dimensions	-Rigid construction reduces die deformation during bends -Working surfaces are easily replaceable once worn
N.7	Die is resistant to high pressures	-All-steel construction provides durability when bending all beam sizes
N.8	Die is resistant to high temperatures	-All-steel construction provides resistance to high temperatures
N.9	Die and fixture are simple to manufacture	-Manufacturing is primarily accomplished with drilling, tapping, and cutting operations -Milling operations are used sparingly -Most materials are readily available at Sperling
N.10	Die is simple to take apart	-Assembly is primarily accomplished using fasteners to allow quick disassembly
N.11	Die is inexpensive to maintain	-Use of inexpensive, on-hand materials and easy-to-manufacture parts keeps maintenance costs down -Rigid construction decreases likelihood of component damage or failure
N.12	Die is compatible with existing equipment	-Die is readily compatible with Sperling Industries hydraulic presses -Preheating of beams significantly reduces required tonnage to increase compatibility with existing, low tonnage hydraulic presses

Rapid prototyping and testing has confirmed that the bottoming operation utilized for the adjustable press die is capable of producing acceptable bends for both double angle inside and outside bends. The adjustable press die presented in this report builds on the lessons learned during these testing sessions as well as thorough technical analysis. The addition of multiple degrees of adjustability have yielded a design which meets the client's needs and remains cost effective. The total capital cost is estimated at $13227.81 after tax with an NPV of $19112.12 over a three year study period. The design will pay for itself after the first year. Use of the design will result in improved productivity and allow Sperling Industries to become more competitive in the transmission tower fabrication market.

4 References

[1] Sperling Industries. (2015). *Sperling Industries.* [Online]. Available: http://sperlingind.com [2015, Sept 29].

[2] Sean Desrosiers. "Photos." Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, 2015, Nov 21.

[3] Fahad Alam. "Hand Drawings." Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, 2015, Nov 28.

[4] Jorgenson Metal Rolling and Forming Inc. (2008). *Steel Forming and Steel Bending Capabilities: Structural Shape, Pipe, Tube, and Plate Rolling*. [Online]. Available: http://www.jorgensonrolling.com/aboutrollingandbending.html [2015, Oct 17].

[5] F. Beer, E. R. Johnston Jr., J. DeWolf, and D. Mazurek, *Mechanics of Materials,* 6th ed. New York: McGraw-Hill, 2009.

[6] Justin Marek. "Labelled Figures." Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, 2015, Dec 2.

[7] Jiaxin Yan. "Engineering Drawings." Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, 2015, Dec 1.

[8] B. L. Rapien, *Fundamentals of Press Brake Tooling,* 2nd ed. Munich: Hanser Publishers, 2010.

[9] J. Chen, B. Young, and B. Uy, "Behaviour of High Strength Structural Steel at Elevated Temperatures," *Journal of Structural Engineering,* vol. 132, no. 12, pp. 1948-1954, 2006.

[10] W. D. J. Callister and D. G. Rethwisch, *Materials Science and Engineering: An Introduction*, 8th ed. Hoboken: Wiley, 2010.

[11] The Library of Manufacturing. (2015). *Sheet Metal Bending.* [Online]. Available: http://thelibraryofmanufacturing.com/sheetmetal_basics.html [2015, Oct 16].

[12] McMaster-Carr. (2015). *McMaster-Carr Website*. [Online]. Available: http://www.mcmaster.com/# [2015, Nov 26].

[13] Acklands-Grainger. (2015). *Cylinder Hyd Hol-Plung SGL Act 60TN*. [Online]. Available: https://www.acklandsgrainger.com/AGIPortalWeb/WebSource/ProductDisplay/globalProductDetailDisplay.do?item_code=ENPRCH603 [2015, Nov 26].

[14] Amazon. (2015). *Hammerhead 10-Inch Digital Level with Laser*. [Online]. Available: http://www.amazon.com/dp/B00OZHIGGE/ref=asc_df_B00OZHIGGE4002369?smid=ATVPDKIKX0DER&tag=shopzilla0d-20&ascsubtag=shopzilla_rev_273-20;14483819967904135438710030301008005&linkCode=df0&creative=395093&creativeASIN=B00OZHIGGE [2015, Nov 26].

Appendix A

Concept Analysis and Selection

Table of Contents

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A.1 Introduction

The concept analysis and selection section contains the results of the conceptual design phase of the project. The developed concepts are compared through a screening system that uses a set of criterion to select the best-suited designs. The criteria used in the screening and scoring sections are derived from the customer needs. Some needs are not suitable as selection criteria, since they are dependent on die geometry and material properties, which are generally the same between designs. The concept designs are reviewed and improved, then scored along with newly developed designs in order to find a few suitable design concepts to pursue. The initial designs with original sketches are included in the following pages. Several design ideas were inspired after performing concept screening. Those designs are included in section A.3. Concept Scoring and Selection.

#	Concept Details

Conceptual Design #1: 3-Point with Support Thread

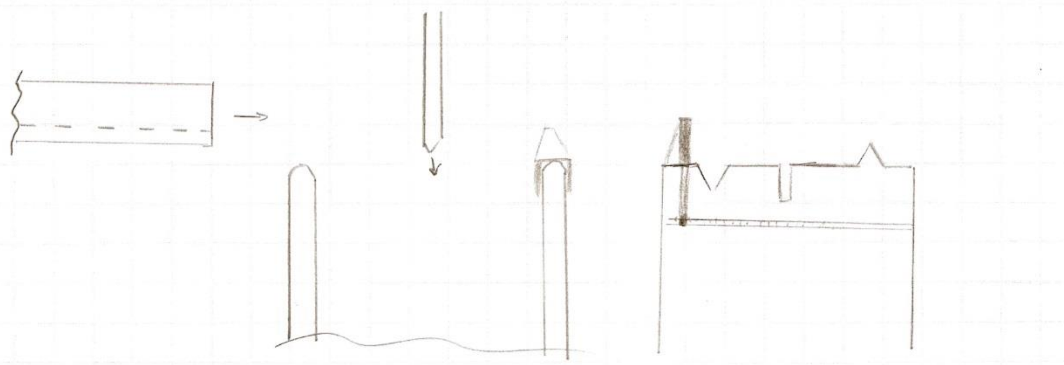

Figure A-1: Concept sketch of 3-Point with support thread [1].

Pros	Cons
• Simple design • Adjustable supports for horizontal support • All bend types can be used • Can bend a large variety of angles	• Bend angle decided by depth of press • Lower accuracy • Free ends displace vertically • Support must be designed for each specific bend • Susceptible to spring back • Susceptible to warping • Multiple operators

Description:

Design is a typical three-point bend using two lower dies and one die attached to a press system. The brake-press lowers and the beam is forced into the gap formed by the two lower dies. The threaded rod attached to the die is for using screw on supports, which are in place to reduce horizontal warping and twisting. Different spaces are in place for each bend type. Initial setup time depends on the placement of the dies relative to each other as well as the placement of supports. Hoists are used to support free ends that will have some vertical displacement during the bending operation. This will require the cooperation of two operators throughout the process. The bend time would be based on the accuracy of the bend with consideration to spring back effects.

Bend Classification/Inspiration for design

Three point brake-press bending/Air bending

Conceptual Design #2: Double Adjustable Bend Table

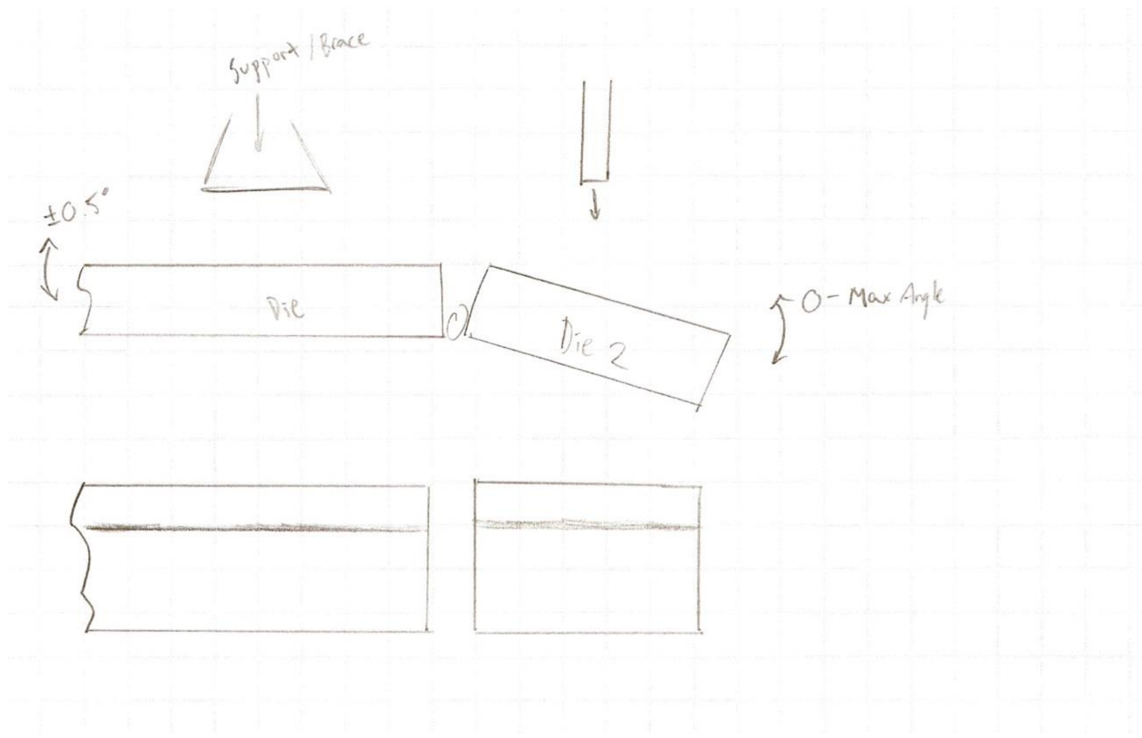

Figure A-2: Concept sketch of double adjustable bend table [1].

Pros	Cons
• Wide range of bend angles • Can accurately set any bend angle in angle range • Supports all bend types by changing die surface • Controlled bend angles. • One operator • Improved safety	• Limit to free end length (Clearance to floor) • Need two presses • Adjustability causes lose in rigidity for bottom dies • Joint between dies could cause issues in bending • Not compatible with existing equipment

Description:

The design uses cantilever bending with two lower dies and one top die. The lower left die holds the beam in a stationary and nearly horizontal position, while the right side of the beam is bent downward. Right side adjusts in 1° increments and left side adjusts for ±0.5°. Design works by setting the lower die surfaces to the required angle and then using the press to bend the beam down to the lower dies. Separate spaces are made on the die for each bend type. The initial setup time is quite long, but since the bend is straight into a bottom die the operation time would be lower. Bracing of the beam would require powerful clamps or a secondary press system. By bracing the long end of the beam the safety for the operator is improved.

Bend Classification/Inspiration for design

Cantilever bending/Bottoming

Conceptual Design #3: Single Die Horizontal Beam

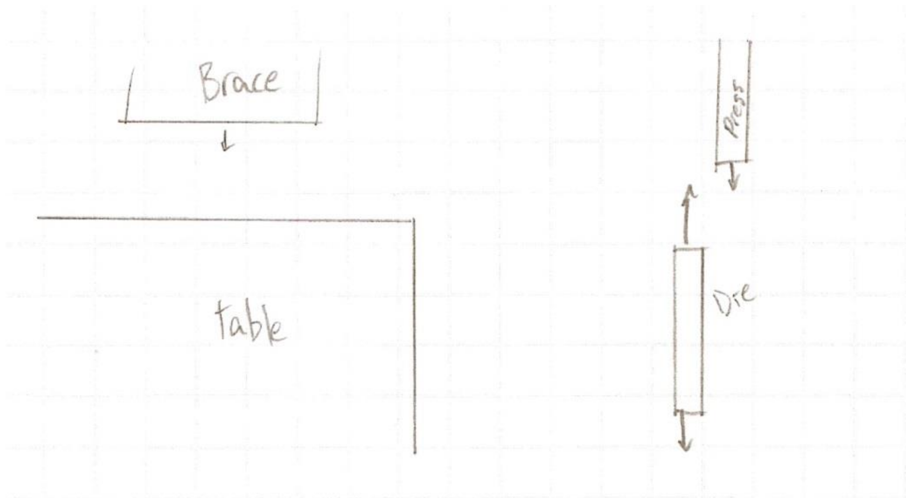

Figure A-3: Concept sketch of single die, horizontal beam [1].

Pros	Cons
• Only need one bottom die • Angle accuracy based on position of bottom die • Brace holds and supports beam horizontal • Changeable dies for different bends • One operator • Improved safety	• Lose rigidity by introducing high adjustability • Free end length is constrained by clearance to floor • Difficult to support warping beam when cantilever bending • Not compatible with existing equipment

Description:
The design works in a cantilever style bending. A horizontally supported beam is bent in cantilever action until it reaches the bottom die. The bend angle is determined by the height of the bottom die. Utilizing different die and table set-ups allows for the use of each bend type. The design would require a longer initial setup, but the bend could be done quickly once the setup is complete. Bracing of the beam would require powerful clamps or a secondary press system. By bracing the long end of the beam the safety for the operator is improved.

Bend Classification/Inspiration for design
Cantilever bending/Bottoming

Conceptual Design #4: Changeable Die with Screw Pins

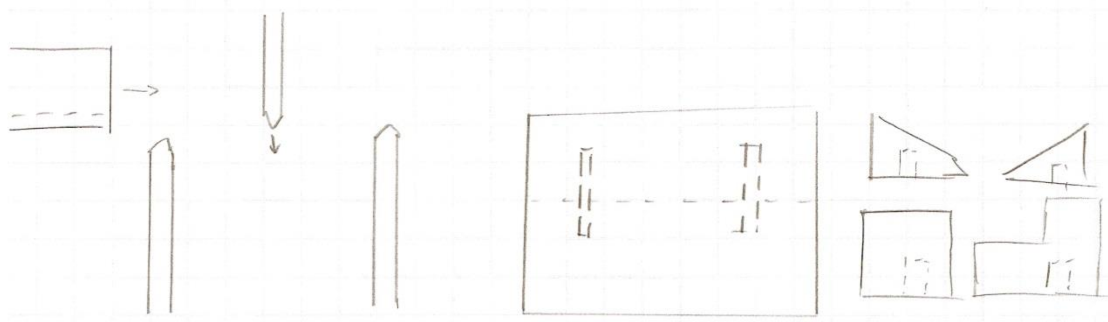

Figure A-4: Concept sketch of changeable die with screw pins [1].

Pros

- Simple to change between bend types
- All bend types can be used
- Can bend a large variety of angles

Cons

- Bend angle is determined by press height
- Accuracy is determined by operator
- Free ends displace vertically
- No support against twisting or warping
- Susceptible to spring back
- Multiple operators

Description:

This die design uses a three point bending operation, which utilizes a set of specified die sections for each type of bend. Screw pins within the base of each die allow for quick changes between bend types by unscrewing plates from the die base. Since the process is a three-point bend operation, the depth of the press and the gap between the two lower dies determines the final bend angle. Hoists are used to support free ends that will have some vertical displacement during the bending operation. This will require the cooperation of two operators throughout the process. Initial setup for the die would be relatively fast, while the actual time bending could be long depending on the accuracy of initial bends with consideration to bend spring back.

Bend Classification/Inspiration for design

Three point bending/Air bending

Conceptual Design #5: Folding Table

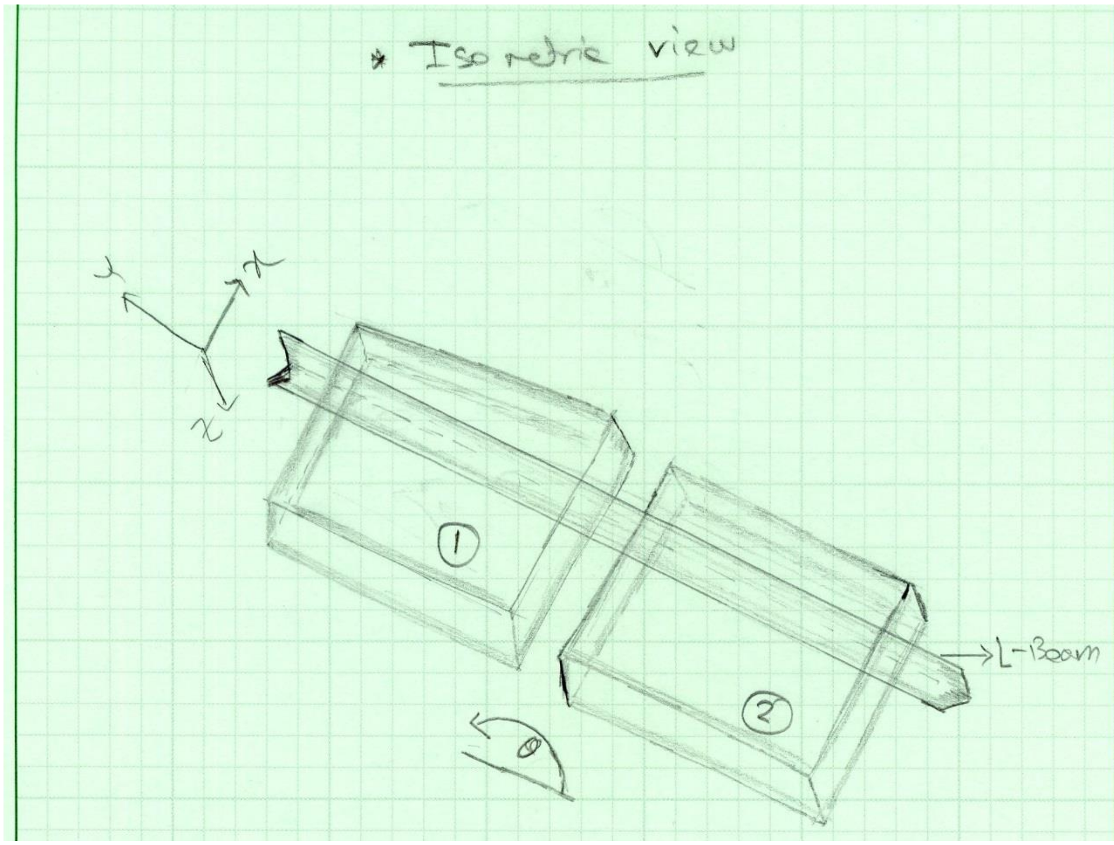

Figure A-5: Concept sketch of folding table [2].

Pros	Cons
• Good angular accuracy • Producing bend is relatively easy • Comparatively safer to use on site	• Unwanted deformation may occur at some point on the beam • Not compatible with existing equipment

Description:
In the picture, there are two tables sitting in front of each other. The tables are at the same height and plane. Table 1 is fixed and Table 2 can rotate about the x-axis. There is a groove on the table where the L-beam will be fixed. Then table 2 will rotate taking the L-beam along with it. In this fashion, the beam will be bent.

Bend Classification/Inspiration for design:
The design is inspired by press break machine used to make L-beam from a metal sheet.

Conceptual Design #6: Rotating Dies and V-Table

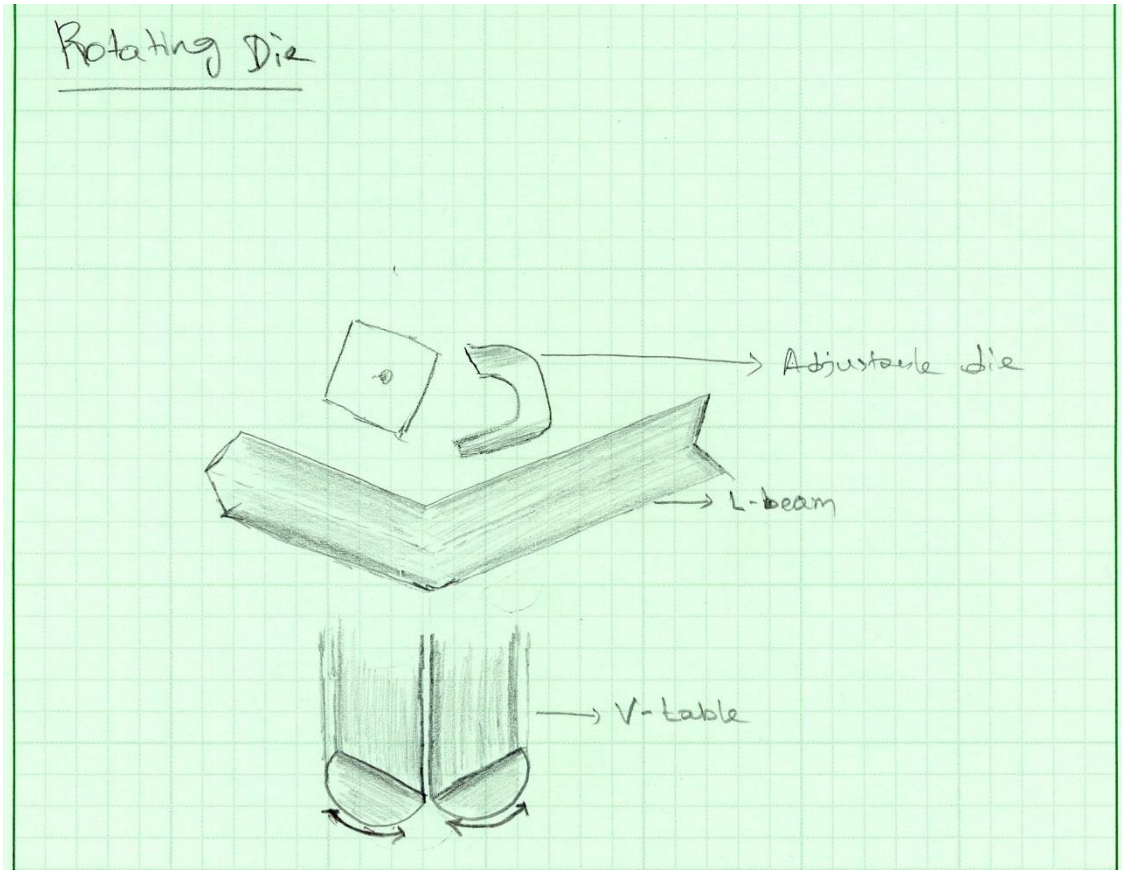

Figure A-6: Concept sketch of rotating dies and V-Table [2].

Pros	Cons
• Highly adjustable • Low setup time • Relatively inexpensive	• Die is easily deformable • Highly complicated • May experience high levels of spring back

Description:
This method includes an automated adjustable die that has two parts. The parts will have a motor and gear system, which will control the phase angle of the die. The L-beam will sit on a V-table that will have a circular bottom, which will help the table to rotate and adjust the angle according to the L-beam by itself.

Bend Classification/Inspiration for design:
The design is based on coining process.

Conceptual Design #7: Adjustable Heavy Dies

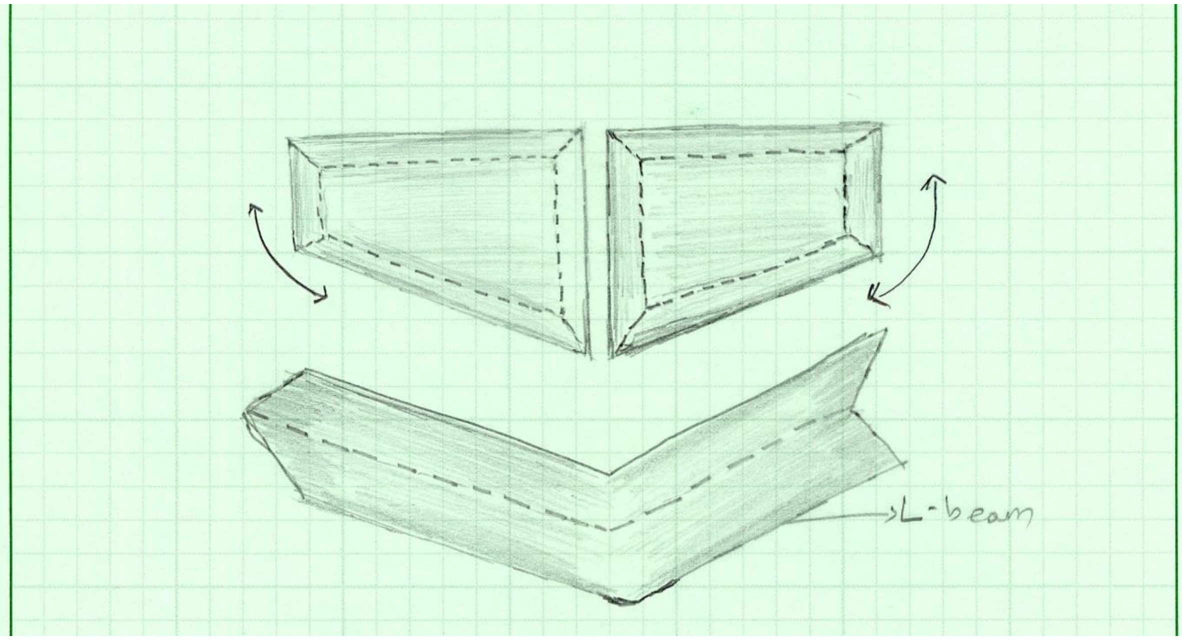

Figure A-7: Concept sketch of adjustable heavy dies [2].

Pros	Cons
• This design is the only proved design which will work • Highly precise angle can be obtained by this design • Easy to handle • Less setup is very straight forward	• Incomplete design since we are not sure if the design can incorporate adjustability into the rigid coining dies • The dies will be heavy • To make the dies are costly • The initial setup is time consuming.

Description:
This design is a coining process. To use the coining process effectively, we are using two adjustable dies, which can change its surface angle by shifting the outside part. The inside of the dies will not be flushed with each other, which may cause deformation in the dies. The process consists of the adjustable dies that will press the L-beam to the desired angle. Note that the L-beam will be bent according to the relative surface angle of the two dies.

Bend Classification/Inspiration for design:
The design is based on coining processes.

Conceptual Design #8: 3 Point with Cylindrical Supports

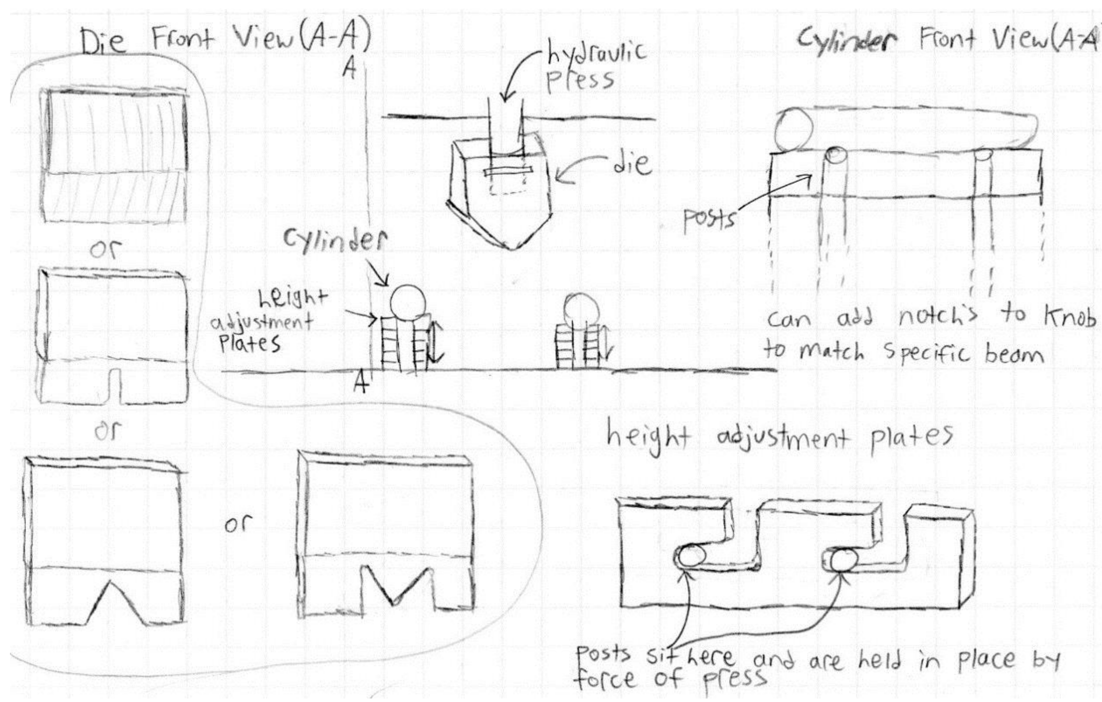

Figure A-8: Concept sketch of 3-point with cylindrical supports [3].

Pros	Cons
• Easy to adjust to many different angles • Limited number of dies and cylindrical supports required • Relatively inexpensive to manufacture and utilizes common metal stock (plate and round bar)	• Cylindrical supports cannot slide side-to-side which prevents control of the bend radius • Supports will be very likely to deflect away from the die • Requires a large assortment of height adjustment plates with varying thickness • Questionable accuracy • Free ends of beam will deflect upwards

Description:

This design utilizes an upper die and two lower cylindrical supports. The cylindrical supports each have two posts, which slide into holes in the base plate. Inserting height adjustment plates between the cylindrical working surfaces and the base plate varies the height of supports. The die slides over the hydraulic press and is fixed with a pin that has been drilled through the press. Four different dies and cylindrical supports must be made to accommodate each bend configuration. The four dies required are shown in the figure. The beam is positioned atop the cylindrical supports with the bend area centered underneath the die. The distance between dies determines the angle of bend that the hydraulic press actuates.

Bend Classification/Inspiration for design:

This design uses a 3-point air bending process. It is based on brake press tooling.

Conceptual Design #9: Cantilever with Heavy Clamp

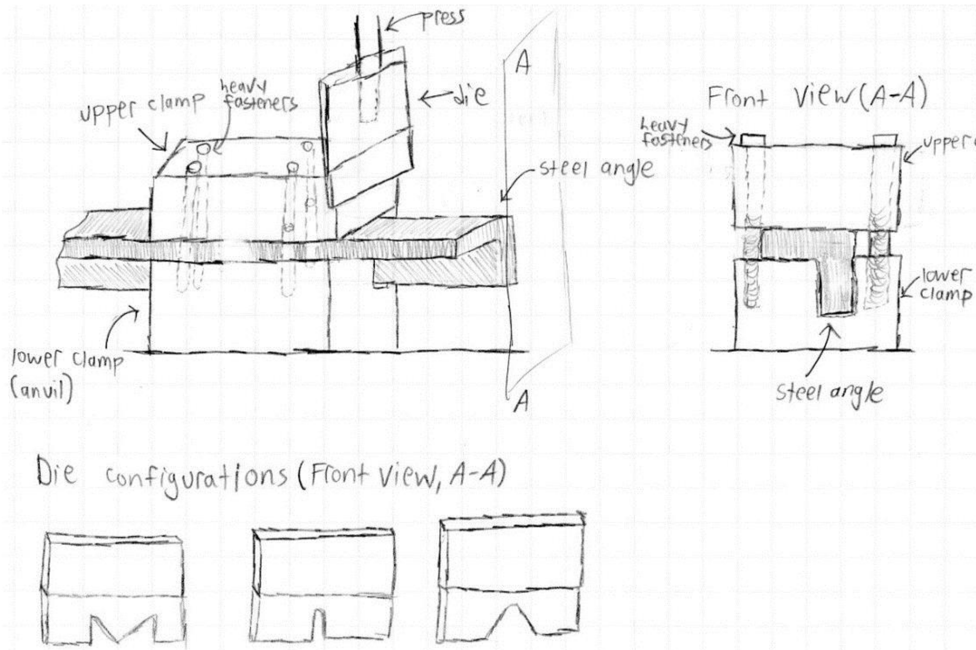

Figure A-9: Concept sketch of cantilever with heavy clamp [3].

Pros	Cons
• Beam does not deflect upwards • Relatively simple design	• For large angles the beam may interfere with the press table before the bend is complete • Difficult to prevent twisting for "leg in" and "leg out" bends • Must generate a huge clamping force to prevent unwanted movement of beams • Upper and lower clamps for four bend configurations will be very heavy and expensive

Description:

This design concept uses a clamping mechanism and press die to bend steel angles in a cantilever-type style. The clamping mechanism consists of an upper and lower clamp which must be designed to match the four possible bending configurations. By matching the profile of the beam for each bend configuration the goal is to prevent twisting motion and keep the applied forces uniformly distributed. Tightening heavy fasteners generates the clamping force. The clamping force must be sufficient to resist the torque generated by the press die. The distance determines the bend angle that the press die actuates. Actuation of the press die will bend the steel angles downward, towards the floor. The die slides along the surface of the upper clamp. The upper clamp is slightly forward of the lower clamp to prevent the die from shearing the steel angles.

Bend Classification/Inspiration for design:

This design utilizes a cantilever-style bend and is based on press brake tooling.

Conceptual Design #10: Coining with Swivel Arms

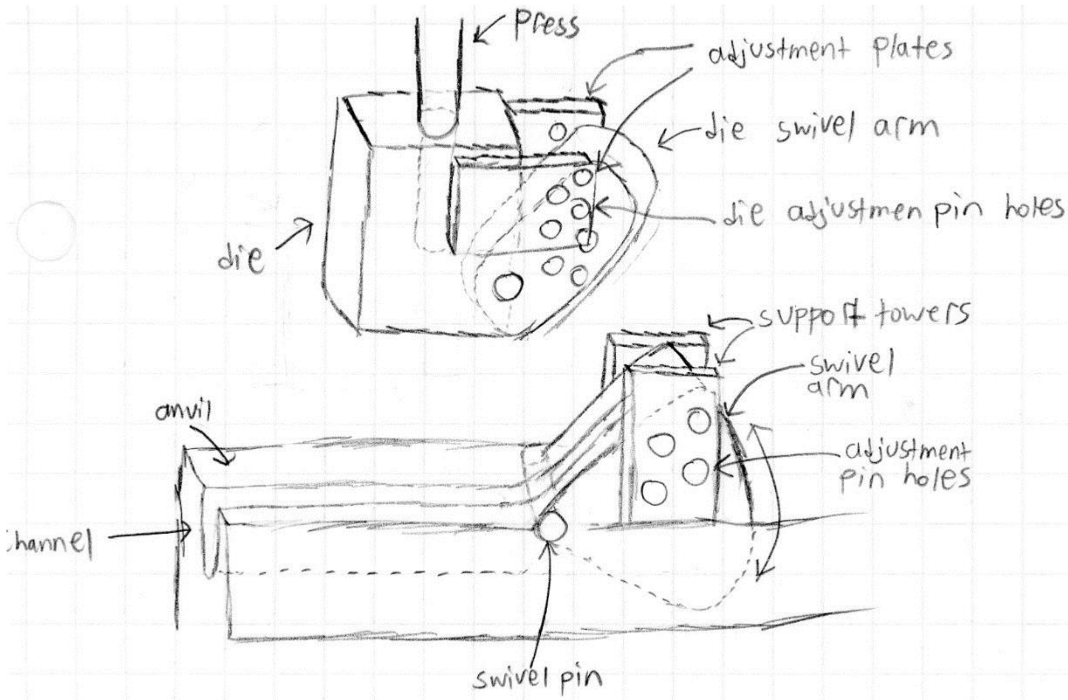

Figure A-10: Concept sketch of coining with swivel arms [3].

Pros	Cons
• Easy to select the desired angle • Bends only one end of the beam upwards which reduces safety risks • Capable of good tolerances due coining operation	• Unbent end of the beam will interfere with the press table • Limited number of angles could be bent, as determined by the number of pin holes on the support tower • Multiple anvils and dies would need to be constructed which makes it expensive

Description:

This design utilizes "swivel arms" on the bottom and top dies to control the angle at which the steel angles are bent. The bottom die, denoted as the anvil, will have several different configurations for each bend configuration. A larger channel is cut into the anvil to accommodate the swivel arm. Support towers sit on either side of the swivel arm and contain large pinholes to select the position of the swivel arm. The swivel arm has corresponding pinholes. The top die works by the same mechanisms, with its own swivel arm and adjustment plates. The beam is positioned on the anvil with the bend location located above the swivel pin. When the press actuates, the beam is bent to the desired profile as determined by the angle selected on the swivel arms.

Bend Classification/Inspiration for design:

This design is based off of coining operations.

Conceptual Design #11: 3 Point with Roller Supports

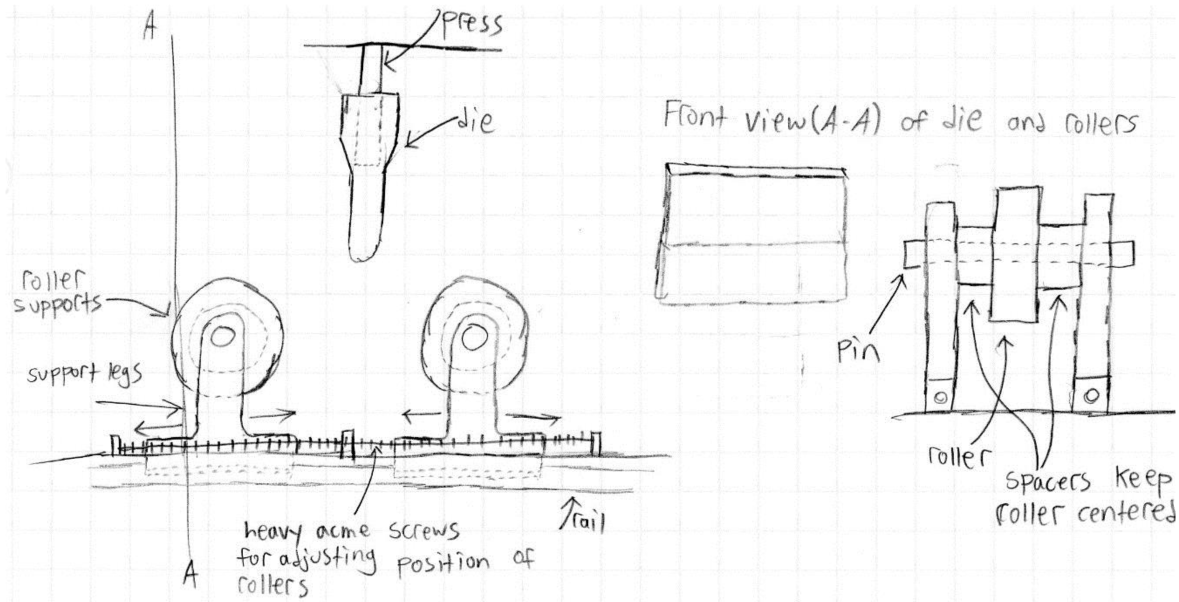

Figure A-11: Concept sketch of 3-point with roller supports [3].

Pros	Cons
• Easy to adjust • Relatively inexpensive compared to other concepts • Dies are easy to manufacture • Capable of bending beams to a wide variety of angles	• Utilizes air bending which may have poor tolerances • Difficult to predict the effect of rollers • Support legs and their pins may deflect under press force • Free ends will deflect upwards

Description:

This design utilizes roller supports and a die constructed from a piece of steel plate. The roller supports are elevated from the base plate by support legs. The support legs are able to move side to side by using a rail system and heavy acme screws. The bend angle is determined by how far apart the rollers are. The rollers are supported between the legs by a heavy pin. The rollers are interchangeable which allows bending of the different configurations. The die must also be changes for different bending configurations. When the press actuates, the steel angles are pushed down and slightly inwards. The rollers move with the angles lateral movement, which reduces frictional, wear on both the steel angles and the rollers.

Bend Classification/Inspiration for design:

This design is based on both air bending and profile rolling tooling.

Conceptual Design #12: Coining with Adjustable Columns

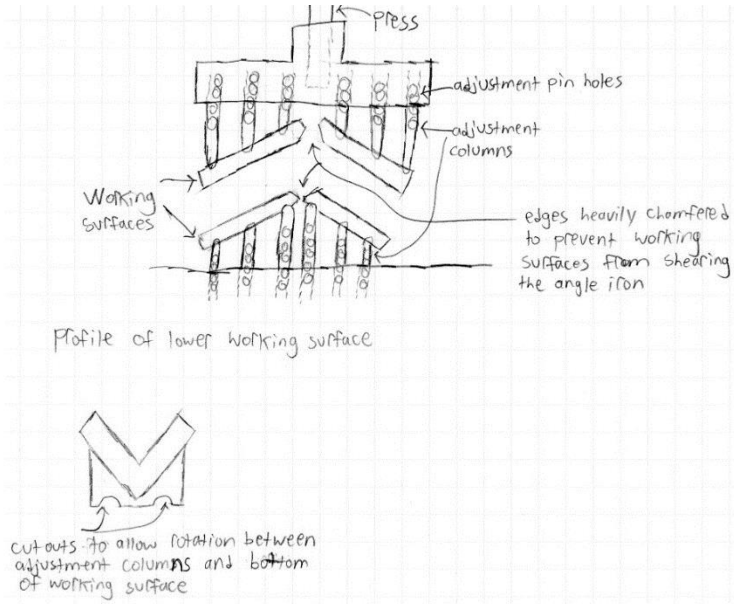

Figure A-12: Concept sketch of coining with adjustable columns [3].

Pros	Cons
• Good tolerances if die rigidity can be maintained • Design will prevent twisting • Small radius bends should be possible	• Difficult and time-consuming to adjust due to weight of dies • Bends beams downwards which will interfere with press table (could be reversed to bend upwards) • Need to manufacture four different dies which will be bulky and expensive • Requires high tonnage compared to air bending

Description:

This design concept is composed of adjustable upper and lower dies, which bend steel angles in a coining operation. The dies shown in the figure are V-shaped for bending “both legs out” but additional dies can be made for the other bending configurations. The die positions are selected by varying the height of the adjustment columns. The adjustment columns positions are selected by inserting pins into the holes in the base plate. The columns connect to the bottom of the dies rest in cut outs. This allows the columns to be raised and lowed for a small range of angles without having to be moved outwards. Additional holes need to be drilled into the base plate to allow movement of the columns for large changes in angles. The edges of the dies are heavily chamfered and do not contact. Ideally, the edges would contact and compress the bend area but making the die adjustable makes that difficult. As the press actuates, the beam is formed to the shape of the dies. Compression of the steel angles reduces spring back but since the bend area is not compressed spring back will still be a factor.

Bend Classification/Inspiration for design:

This design is based off of coining operations.

Conceptual Design #13: Gearbox Design

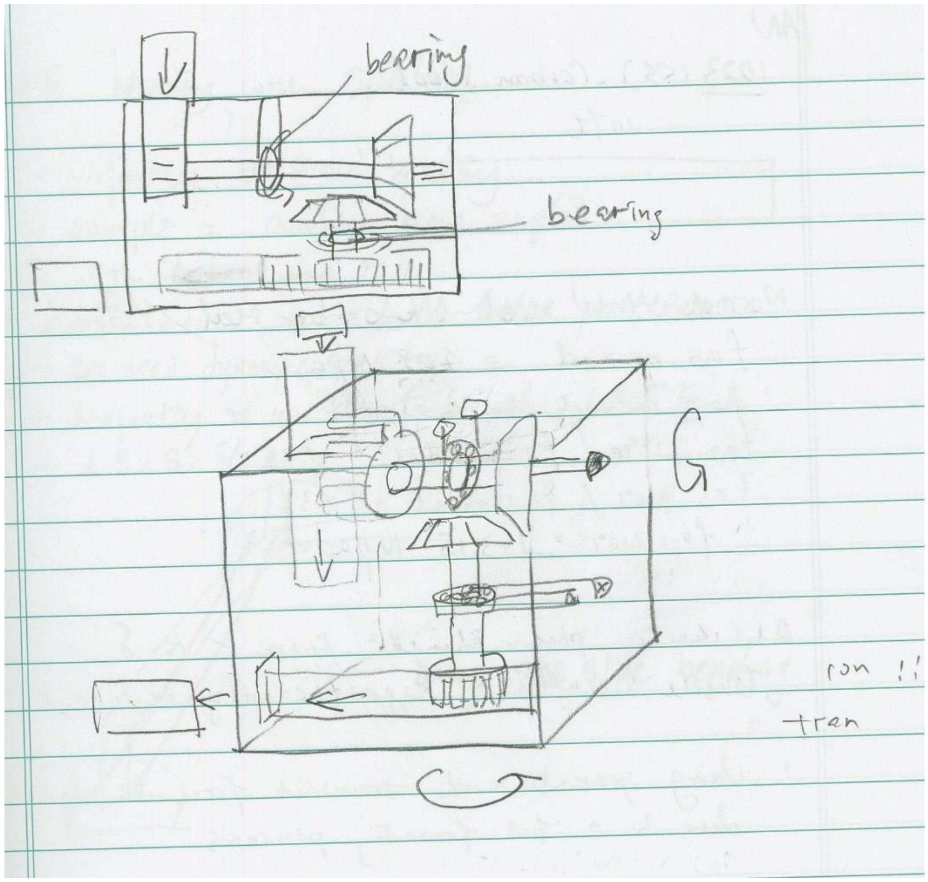

Figure A-13: Concept sketch of gearbox design [4].

Pros	Cons
• Bending beams horizontally removes the hazard of large vertical deflections and space limitations of bending beams downwards • Many of the designs mentioned above could be integrated with the gearbox design	• Horizontal deflections could still pose a safety risk and require a larger work station profile • Gearbox would be very expensive because of the huge forces it would experience • Purchasing a horizontal press would be easier and less expensive in the long run

Description:

The main feature of this design concept is a gearbox that redirects the vertical force of the press to a horizontal press. The press is outfitted with a rack that rotates the input gear of the gear box. A bevel gear transfer's power to a vertical shaft is meshed with another rack. The final rack is connected to a press that bends the beam. The beam is capable of being bent as either a cantilever or in a 3-point bend. Instead of deflecting upwards or downwards, the beam is bent horizontally, which could be significantly safer.

Bend Classification/Inspiration for design:

This design is based off a basic gear design.

Conceptual Design #14: Rolling Die

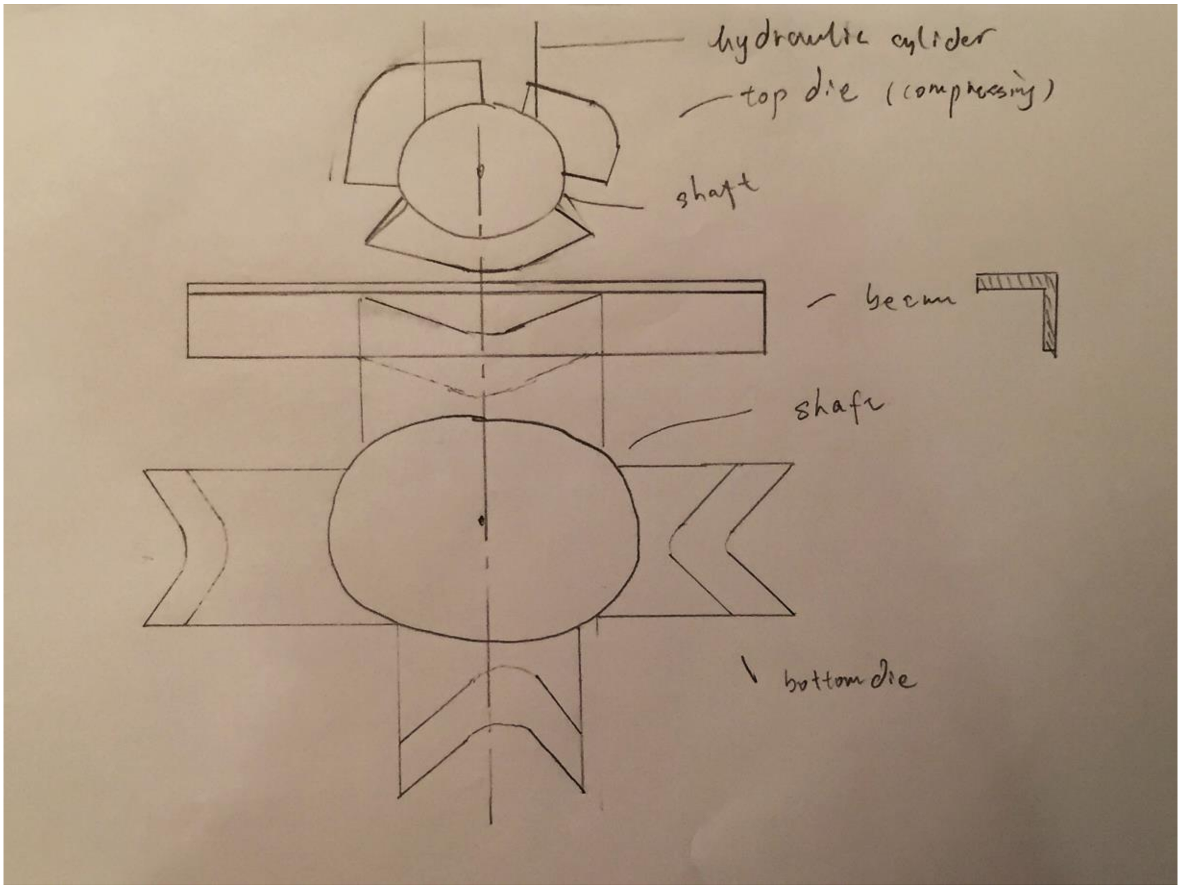

Figure A-14: Concept sketch of rolling die [4].

Pros	Cons
• Bending beams can be compressed once to desire angle • Simple to change different angles (four options are contained per set of dies)	• Heavy force will be transmitted to shaft which might cause hazards • Too many parts to manufacture • Unstable compressing process • Difficult to align top and bottom dies.

Description:
This Rolling Die is adjustable in 4 degrees. As shown in the figure, the top die contains four possibilities of bending angles. The cylinder that is connected with the power supply is attached to the shaft, which can rotate to pick a different bending angle. Ideally, it saves a large amount of time in changing to another set of dies. The bottom die in the figure is cooperating with the top die. Bolts mount all parts that are attached to the top or bottom shaft, which is easy to disassemble in order to change to another set of dies.

Bend Classification/Inspiration for design:
This design is based off a coining design.

Conceptual Design #15: Multi-Press Die

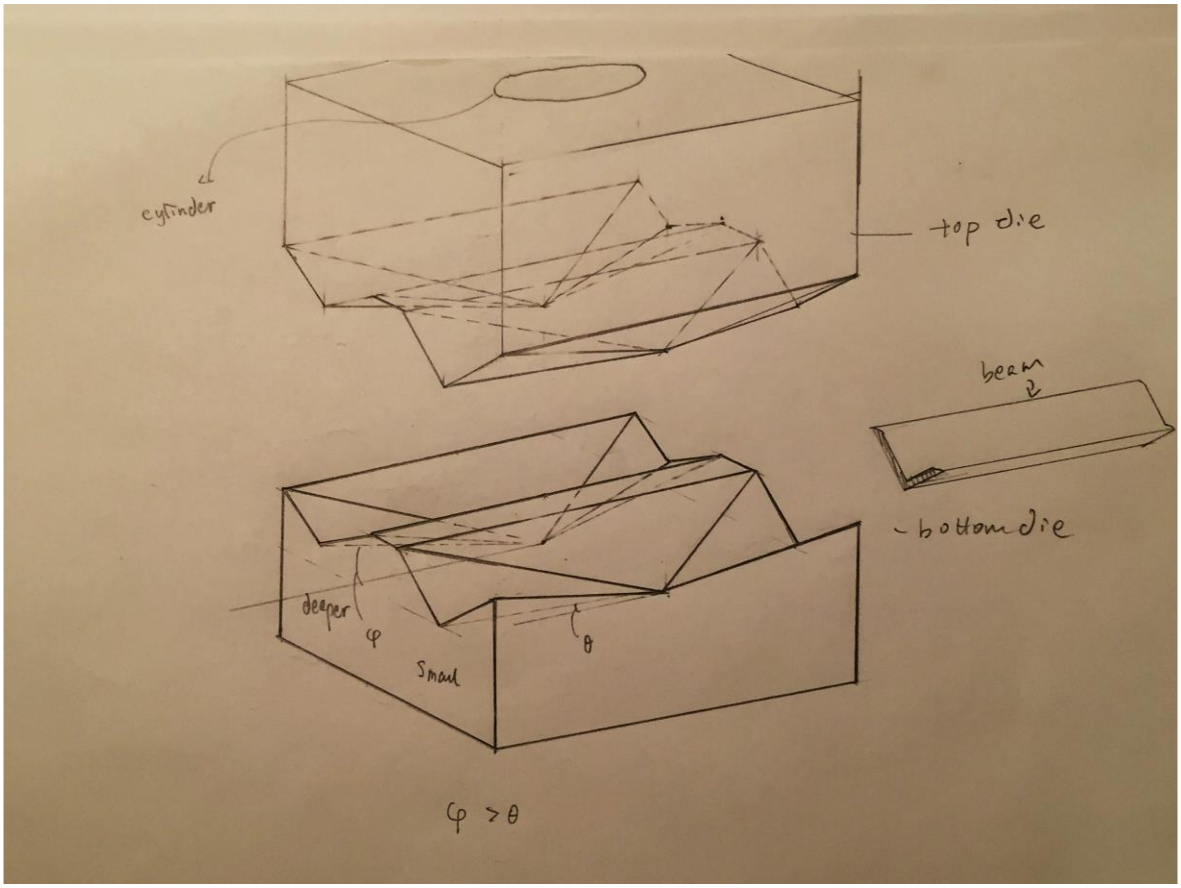

Figure A-15: Concept sketch of multi-press die [4].

Pros	Cons
• Compressing target beam in 2-steps at same angle increment to raise precision of angle tolerance. • Simple operation • Easy manufacturing • Short operating time.	• Not quite sure how it will be adjustable • One set of big dies to operate which can cause safety issue

Description:
The main feature of this design concept is a multi-compressing die design. This design contains 2-steps of operation, which gives us a shorter processing time. Using small angle increment to control deformation of the beam will maintain beam properties. It will also maintain the material properties of the dies. Since this is a coining compressing design, therefore this set of die will perform at a high level of angle precision.

Bend Classification/Inspiration for design:
This design is based on a coining process

Conceptual Design #16: Hand-Pushing Die

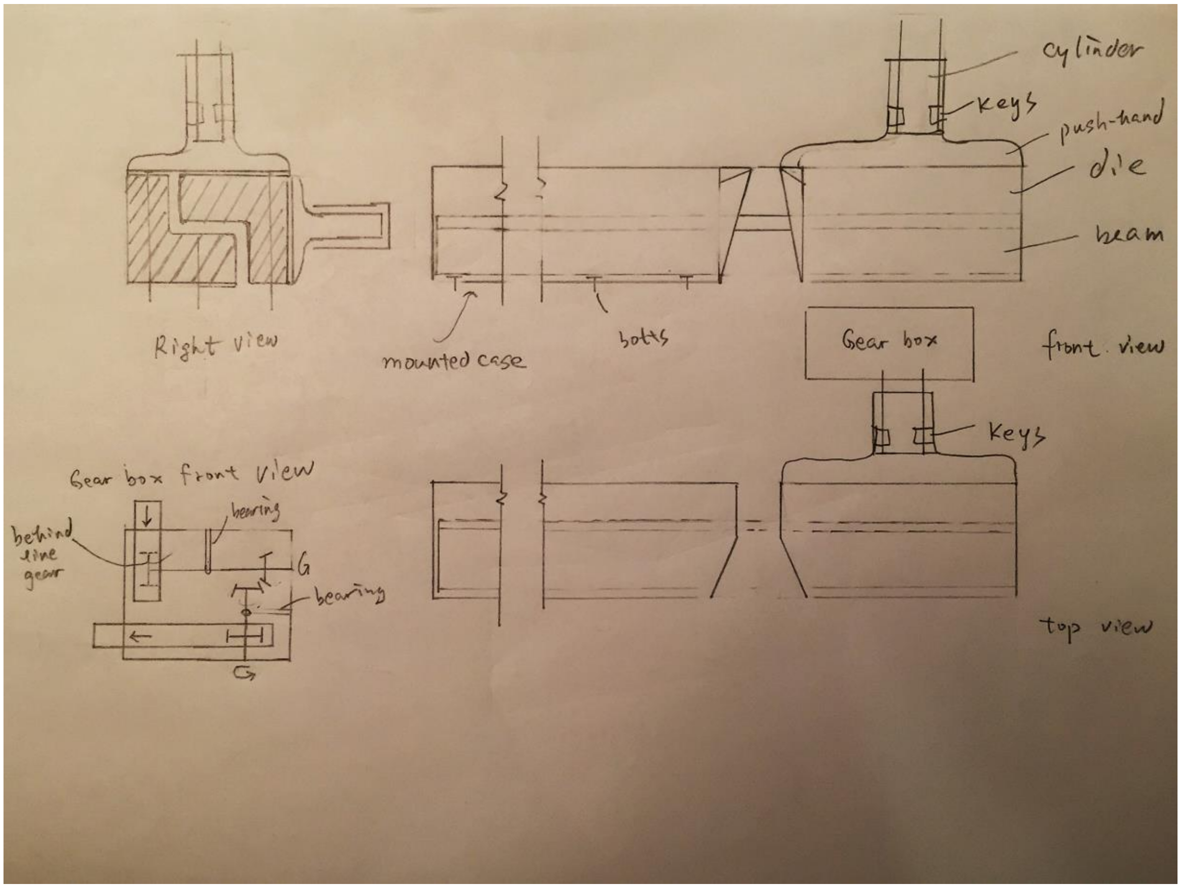

Figure A-16: Concept sketch of hand-pushing die [4].

Pros	Cons
• Maintaining the beam properties • Being adjustable by operating the position of push-hand • Can transmit force from vertical to horizontal in order to maintain double angle setting	• Many parts to manufacture which costs more money • Complexity of operation that needs well trained workers • Life time is shrank by Gear box

Description:

The main feature of this design concept is a combination of cantilever beam bending and air bending, In the figure, the left side of the beam is inserted into a die case, and the right side is attached to a push-hand which is driven by a hydraulic cylinder. At the specific spot, the right die can only go downwards until the incline boundaries are attached each other. The slope of the incline indicates the maximum angle that this set of die can bend. Through a gearbox, vertical forces can be transferred to horizontal force, which can allow us to bend in different angle direction.

Bend Classification/Inspiration for design:

This design is based off an air bending.

A.2. Concept Screening

The focus of this section is on the analysis and screening of design concepts through the use of comparison matrices. Designs are compared based on the expected performance in a variety of selected design criteria that were developed from the customer needs. In order to perform an assessment of the design concepts it was essential to start by comparing them to some base value. The concepts are listed in TABLE A-I where the reference design is number 1. The 3-point bend design was chosen as the reference because it was a relatively simple design and used existing equipment

TABLE A-I: DESIGN CONCEPTS WITH REFERENCE NUMBER, NAMES AND BENDING MODE

Ref #	Concept Name	Inspiration/Bending Type
1	3-Point W/Support Thread	3-Point Air Bend
2	Double Adjustable Bend Table	Cantilever
3	Single Die Horizontal Cantilever	Cantilever
4	Changeable Die W/ Screw Pins	3-Point Air Bend
5	Folding Table	Press Brake Style Bending
6	Rotating Dies And V-Table	Coining Process
7	Adjustable Heavy Dies	Coining Process
8	3 Point W/ Cylindrical Support	3-Point Bending
9	Cantilever With Heavy Clamp	Cantilever
10	Coining With Swivel Arms	Coining
11	3-Point W/ Roller Supports	3-Point Air Bend
12	Coining W/ Adjustment Columns	Coining Process
13	Gearbox Design	3-Point Air Bend
14	Rolling Die	Coining
15	Multi-Compressing Die	Coining
16	Hand-Pushing Die	Air Bending

The selection criteria were developed from the customer needs and refined to better serve in comparing the design concepts. Some criteria are combinations of multiple customer needs in cases where a broader need was simpler to compare. Resistance to effects like wear and temperature were customer needs because they lower the strength of the die and can lead to a reduction on the service life of the die, but the specific values are hard to judge. Therefore, the needs involving the die properties are all grouped together into a more general criterion ‘high die rigidity’, which makes comparison between concepts easier since the new criteria encompasses a broader range of details and can be judged mainly on the bulkiness and simplicity of the design.

Each design was cross-compared to the reference design in multiple criteria categories. The designs were then assigned a rank of worse, equal or better for that designs ability to accomplish the target aspect of the design. The results were tabulated in the concept-screening matrix in TABLE A-II.

TABLE A-II: CONCEPT SCREENING MATRIX

		Design Concepts															
Selection Criteria		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	REF(1)
A	Safe to operate	+	+	0	+	0	+	0	+	+	0	+	+	+	+	+	0
B	Bends a variety of angles and beam sizes	0	0	0	0	0	0	0	0	-	0	-	0	-	-	0	0
C	Simple to set up, adjust and operate	-	-	+	0	-	-	+	-	-	0	-	-	-	0	-	0
D	High Die Rigidity	0	0	0	+	0	+	-	+	+	0	+	-	0	+	+	0
E	Simple to manufacture	-	-	0	-	-	-	-	-	-	0	-	-	-	-	-	0
F	Simple to take apart	-	0	0	-	0	-	0	-	-	0	-	-	-	-	-	0
G	Compatible with existing equipment	-	-	0	-	-	0	0	0	0	0	0	0	0	0	+	0
H	Accurate to tolerance	+	-	0	+	0	+	0	+	+	0	+	0	+	+	+	0
	PLUSES	2	1	1	3	0	3	1	3	3	0	3	1	2	3	4	
	ZEROES	2	3	7	2	5	2	5	2	1	8	1	3	2	2	1	
	MINUSES	4	4	0	3	3	3	2	3	4	0	4	4	4	3	3	
	NET	-2	-3	1	0	-3	0	-1	0	-1	0	-1	-3	-2	0	1	
	RANKING	11	13	1	3	13	3	8	3	8	3	8	13	11	3	1	
	REVIEW CONCEPT			√	√		√		√		√				√	√	

At the design team's discretion, all designs that scored equal or better than the reference were pulled into the concept scoring process. Only one of the concepts scored higher than the reference and most designs were within two points of one another. Therefore, there were no clear winners of the screening process. For this reason we pulled all concepts that were equal to or better than the reference into the scoring process. This served to keep the scoring process competitive and prevented ruling out potentially good concepts prematurely.

A.3. Concept Scoring and Selection

Concept scoring was composed of a more detailed analysis of the design concepts. After the first concept screening process, the best design concepts moved into a more detailed ranking phase. The goal was to revise designs, create new designs, or repurpose and combine old designs. Since some of the rejected designs had design components that excelled in the criteria scoring of the concept screening, it was important to take those ideas into consideration when designing new concepts.

The selection criteria were weighted according to their importance and then the concepts were scoring against the weighted criteria. A sensitivity analysis was performed to ensure the best possible design was selected. Finally, a design concept is selected which moved on to the final design phase of the project.

A short list of concepts that were created after the screening phase is included below.

Conceptual Design #5+: Folding Table With a pivot point

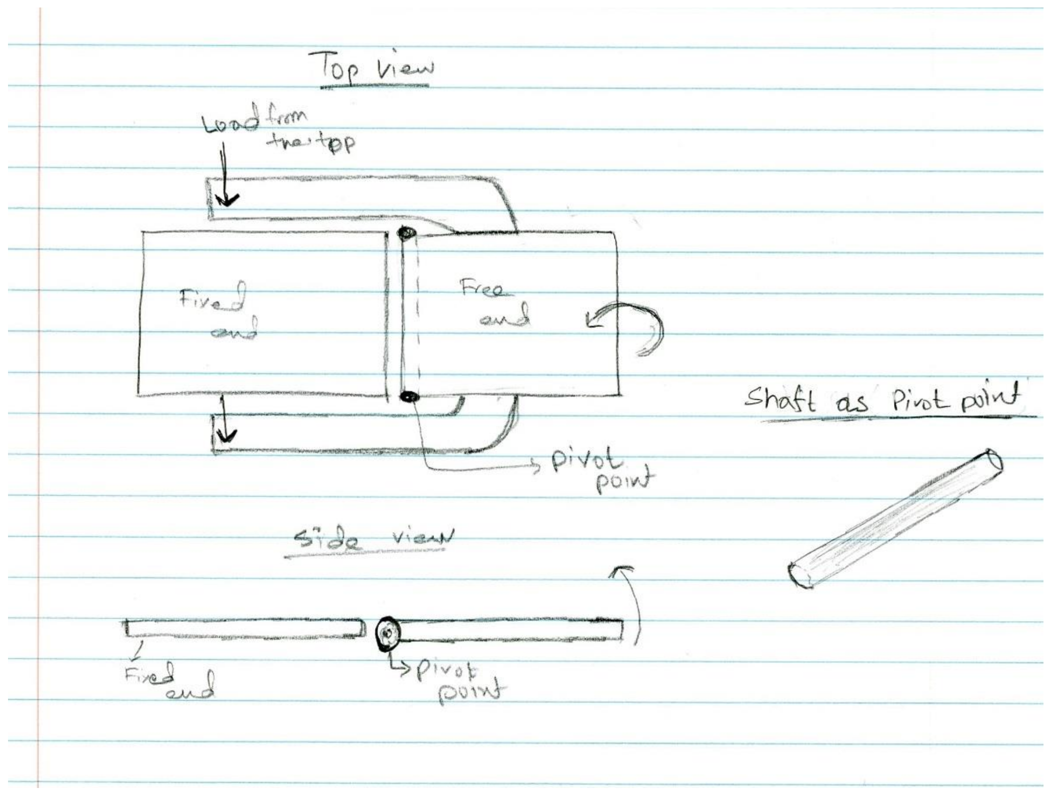

Figure 17: Concept sketch of folding table with a pivot point [2].

Pros	Cons
• Good angular accuracy • Producing bend is relatively easy • Comparatively safer to use on site • The load will be transferred directly and accurately • Compatible with the existing equipment	• Unwanted deformation may occur at some point on the beam • The wing where the load will be placed will bend • The shaft will have to carry over the load to the "Free table". So the shaft might break or deformed • It will be hard to remove the bent L-beam to take out of the table.

Description: According to one of our previous designs, #5 "Folding Table", there was no clear demonstration of how the load will be transferred to the table (given that we are using the machine available on the site). In this conceptual design, we connected the free end of the table to two wings and a shaft as a pivot point. The loads provided by the press will be transferred to the wings. Then the wings will transfer the load to the "Free table" pivoting to the shaft. This method will enable us to transfer translation press load to a rotational torque on the "free table".

Bend Classification/Inspiration for design:
The design is inspired by press break machine used to make L-beam from a metal sheet.

Conceptual Design #17: Changeable Dies W/ Die Supports

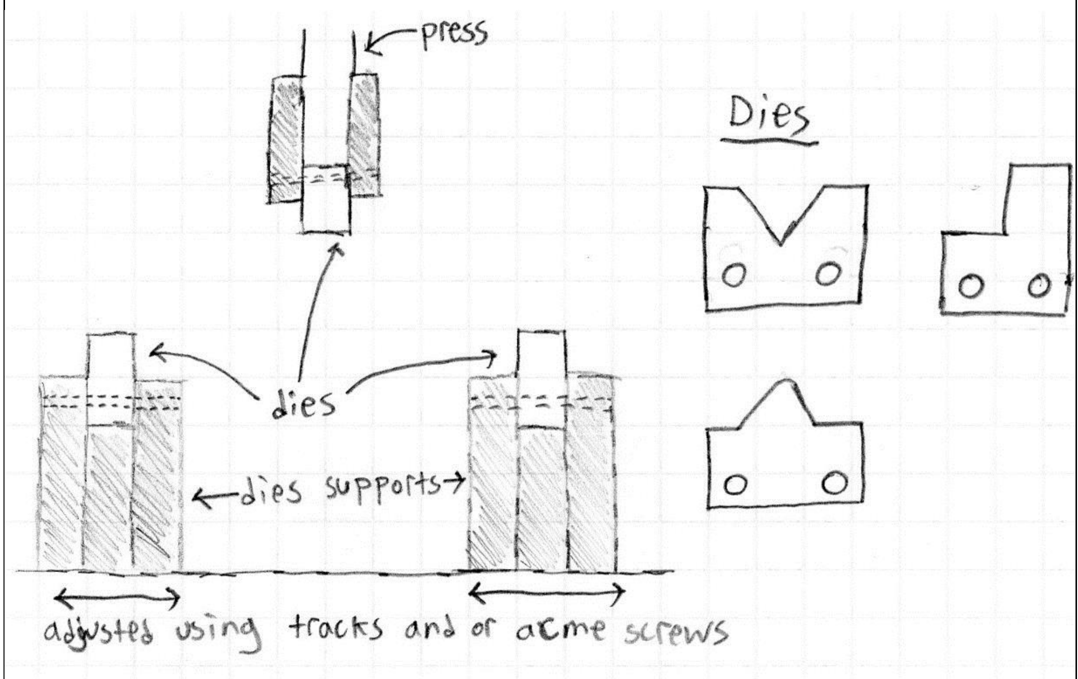

Figure 18: Concept sketch of changeable dies w/ die supports [3].

Pros	**Cons**
• Relatively inexpensive • Large range of die profiles can manufactured for different angle sizes • Easy to adjust location of dies with the track • Die deformation can be kept small by reinforcing the die supports	• Tolerance is difficult to control • Twisting of beams may be difficult to control

Description:
The design is composed of die supports, which hold relatively small dies. The die supports are made very rigid to resist deformation. The dies are housed in slots and are held in place by heavy pins. A die support is connected to the press. A die can be attached to the upper die support using heavy pins. Dies can be manufactured quickly and easily based on the size of the flange size and thickness being bent. The beam is bent depending on how far the press is made to actuate. The distance of the dies from one another will determine the bend radius.

Bend Classification/Inspiration for Design:
This design is based on three point bending.

Conceptual Design #18: Changeable Dies W/ Die and Beam Supports

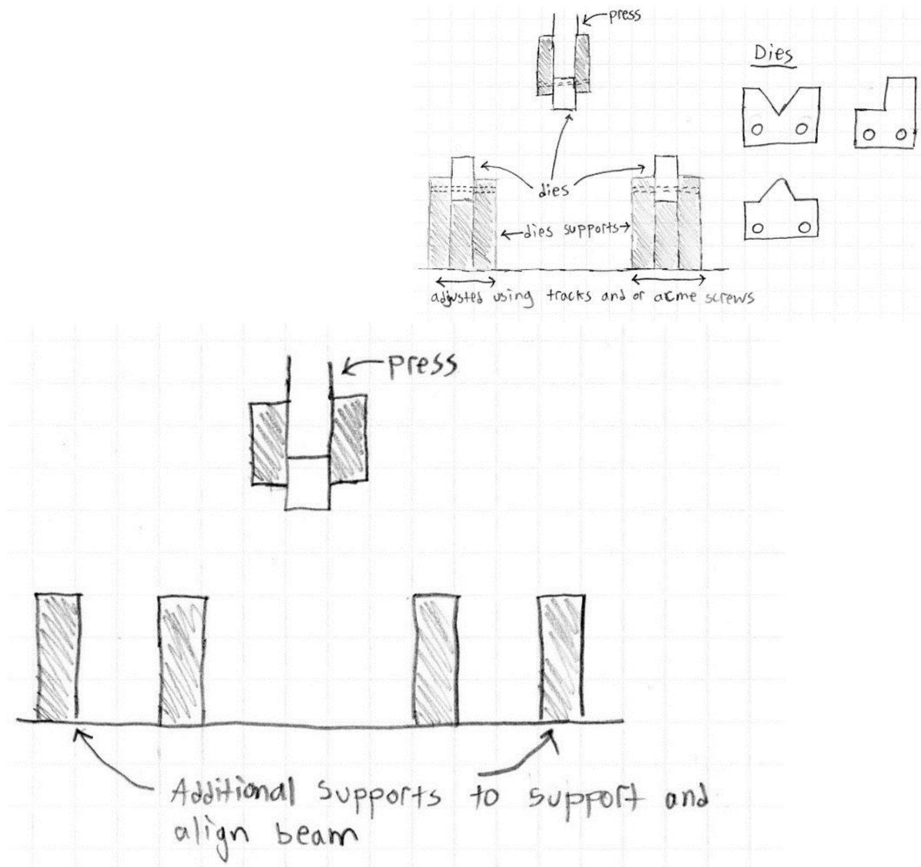

Figure 19: Concept sketch of changeable dies w/ die and beam supports [3].

Pros	Cons
• Relatively inexpensive • Large range of die profiles can manufactured for different angle sizes • Easy to adjust location of dies with the track • Die deformation can be kept small by reinforcing the die supports • Additional safety by adding additional supports for the beam	• Tolerance is difficult to control • Twisting of beams may be difficult to control

Description:
This design is a simplified drawing of design #17 but the principle remain the same. The only difference is that additional supports are added to help support and align the beam before bending. The supports can also be used to provide lateral support for the beam during bending to prevent it from falling out of the die after the load is removed.

Bend Classification/Inspiration for Design:
This design is based on three point bending.

Nine design concepts, including the three additional concepts shown above, were designated to advance into the process scoring stage. A summary of these designs are shown in TABLE A-III.

TABLE A-III: LIST OF CONCEPT'S ADVANCING TO THE SCORING PHASE

Ref #	Concept Name	Inspiration/Bending Type
1	3-Point W/Support Thread	3-Point Air Bend
4	Changeable Die W/ Screw Pins	3-Point Air Bend
5+	Folding Table using downward force	Press Brake Style Bending
9	Cantilever With Heavy Clamp	Cantilever
11	3-Point W/ Roller Supports	3-Point Air Bend
15	Multi-Compressing Die	Coining
16	Hand-Pushing Die	Air Bending
17	Changeable Dies W/ Die Supports	3-Point Air Bend
18	Changeable Dies W/ Die & Beam Supports	3-Point Air Bend

A.3.1 Concept Scoring

Concept scoring was performed on the design concepts listed in TABLE A-III. Using a weighted criteria matrix, the most suitable concepts pursue through Phase 3 were selected. The scoring results are tabulated in TABLE A-IV. Since our project dealt with complex plastic deformation of L-beam sections there are were uncertainties over the effect of each design on the work pieces. It was deemed poor practice to recommend purchasing a new machine when the feasibility of the designs could not be determined beforehand.

Through the concept scoring, the majority of the higher rated designs were air-bending setups using three point bending dies. This bend system offers very little lateral support and the possibility of warping was a major concern, but could make use of existing hydraulic presses. Still, at least one design for each of the types of bending modes were kept for further review in the case that the air bending designs were not feasible.

TABLE A-IV: WEIGHTED SCORING MATRIX

		Concepts																	
		1		4		5+		9		11		15		16		17		18	
Selection Criteria	**Weight**	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Safe to operate	22%	3	0.67	3	0.67	4	0.89	5	1.11	3	0.67	3	0.67	5	1.11	3	0.67	4	0.89
Bends a variety of angles and beam sizes	11%	4	0.44	4	0.44	3	0.33	2	0.22	4	0.44	2	0.22	3	0.33	4	0.44	4	0.44
Simple to set up, adjust and operate	19%	5	0.93	4	0.74	3	0.56	3	0.56	3	0.56	2	0.37	2	0.37	4	0.74	4	0.74
High Die Rigidity	15%	2	0.30	2	0.30	3	0.44	4	0.59	3	0.44	5	0.74	3	0.44	4	0.59	4	0.59
Simple to manufacture	7%	5	0.37	4	0.30	2	0.15	2	0.15	3	0.22	2	0.15	1	0.07	3	0.22	3	0.22
Simple to take apart	4%	5	0.19	4	0.15	3	0.11	2	0.07	5	0.19	3	0.11	2	0.07	3	0.11	2	0.07
Accurate to tolerance	22%	2	0.44	2	0.44	3	0.67	3	0.67	3	0.67	5	1.11	3	0.67	3	0.67	3	0.67

	1	4	5+	9	11	15	16	17	18
Total	3.33	3.04	3.15	3.37	3.19	3.37	3.07	3.44	3.63
Rank	**5**	**9**	**7**	**3**	**6**	**3**	**8**	**2**	**1**
Review	No	No	Yes	Yes	No	Yes	No	No	Yes

A.3.2 Concept Selection

Team Hot Form narrowed down the concepts to three options that were reviewed in even more depth. The main focus of the final design was the top ranked option, concept 18, which had a three point bending system with changeable dies on a rigid base. Concept 17 was very similar to 18 but scored lower because it lacked the additional supports. Concept 15 utilized a coining operation, which was reviewed, but ultimately not used because the rigidity necessary in the bending operation made it hard to incorporate the required die adjustability. Though concepts 9 and 5+ scored lower than some designs they used a form of cantilever beam bending operation and were kept for review in case that three point bending operations do not provide Sperling Industries with the required level of bend accuracy.

Ultimately, concept 17 was selected because the additional support structures used in concept 18 were not required.

A.4 References

[1] Sean Desrosiers. “Concept Drawings.” Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, 2015, Sept 21.

[2] Fahad Alam. “Concept Drawings.” Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, 2015, Sept 21.

[3] Justin Marek. “Concept Drawings.” Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, 2015, Sept 23.

[4] Jiaxin Yan. “Concept Drawings.” Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, 2015, Sept 20.

Appendix B

Concept Design Testing

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B.1 Introduction

Initial design testing was performed to verify the feasibility of the chosen design, concept 17. Die functionality, bend accuracy, and range of angles were the primary requirements that had to be met in order to verify the design concept. Two testing sessions were carried out. The first testing session's purpose was to provide proof of concept. The second testing session's purpose was to perform a more detailed analysis of the die's functionality, making use of the conclusions drawn from the first testing session.

B.2 Test Session #1

The first test session took place on 11-Nov-15 at Sperling Industries. The goal of this testing session was to verify that the selected 3-point bending concept would provide acceptable bends for the double angle inside bend configuration.

B.2.1 Test Equipment and Materials

The test equipment and materials are detailed in TABLE B-I.

TABLE B-I: TESTING EQUIPMENT USED IN INITIAL TEST SESSION

Equipment	Quantity	Comments
100 ton hydraulic press	1	
Bottom supports	2	
Top die	1	
L2x2x1/4, 1 ft length, 300W	6	
L3x3x1/4, 5 ft length, 300W	1	Used for three tests
L3x3x3/8, 2 ft length, 300W	2	
Tape measure	1	
Compass	1	

B.2.2 Test Apparatus

The test apparatus was set up on the 100 ton hydraulic press. Two bottom supports were used to position the beams before bending and provide reaction forces during the bend. The top die was fixed to the press cylinder and transferred the load to the center of the beam.

The bottom supports had “V” profiles which matched the outside profile of the beams. The top die was cut to match the inside profile of the beams. Figure B-1 shows the test apparatus.

Figure B-1: Test Apparatus (Session #1) [1].

The top die was manufactured specifically for this test session. The bottom dies were available at Sperling and were made during a past project. Figure B-2 shows the dimensions of the top die.

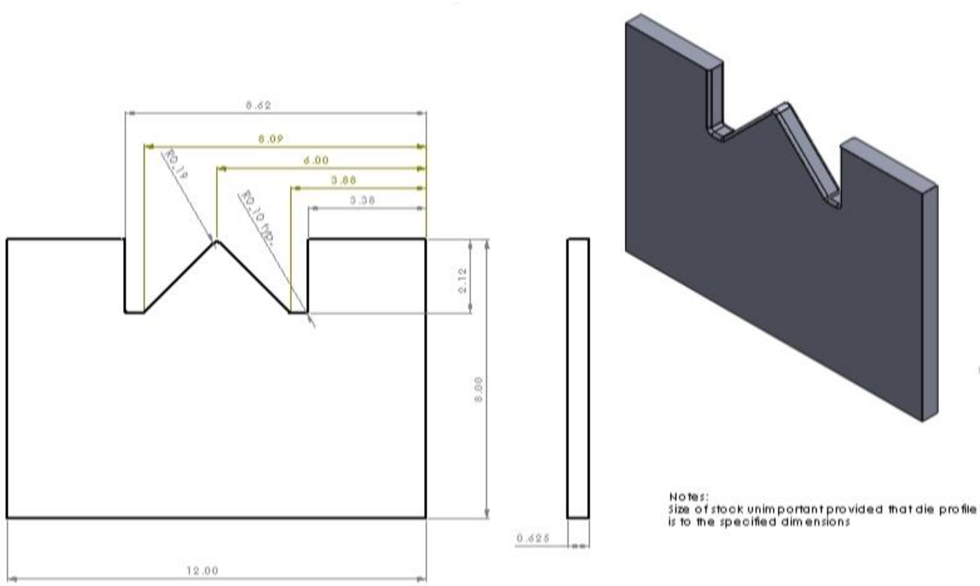

Figure B-2: Drawing of top die (Session #1) [2].

B.2.3 Procedure

The planned procedure is detailed in the original test procedure sheet. The actual procedure was less formal and served to verify the feasibility of the selected design concept. Each of the tests had a unique question to answer. The general test procedure which was used is detailed below.

1. Mount the top die to the hydraulic press cylinder.
2. Position the bottom dies a specified distance apart, centered on the top die.
3. Preheat beam until red hot (if hot bending).
4. Place the steel angle in the bottom die.
5. Actuate hydraulic press to make initial contact with steel angle.
6. Perform check to ensure proper alignment of dies.
7. Actuate press a specified distance to bend the steel angle.
8. Take a maximum pressure reading.
9. Release press and turn off the machine.
10. Remove steel angle from dies.
11. Take bend angle measurement.

B.2.4 Calculations

A rough calculation was formulated to calculate the required “stroke” of the press to obtain a desired bend angle. The calculation is based on simple trigonometry and is based on the assumption that the length of the beam stays constant through a bend.

$$h = L/2 \ \sin(\alpha/2) \qquad \text{(B1)}$$

Where “h” is the required stroke of the press, L is the bottom die separation distance, and “α” is the desired bend angle. The desired bending angle is a known based on customer requirements. However, the separation distance is a more complicated dimension to determine. A simple calculation was derived from sheet metal bending industry practices to guess an acceptable separation distance.

For 90° sheet metal bending, the recommended minimum die separation is $K \approx 6\ to\ 8x$ the thickness of the sheet metal [3]. This will produce the minimum bend radius without damaging the metal. For our design, a minimum bend radius is desirable to keep the bend area as localized as possible. The sheet metal guideline will be used with a small modification. Instead of using the thickness of the steel angles, an "effective thickness" will be used to account for the flanges being at a 45° to the applied load.

$$t_e = 1.41t \tag{B2}$$

The separation distance is therefore estimated with the following calculation [3].

$$L = Kt_e \tag{B3}$$

The metric tonnage of the press was calculated from the measured psi reading based on a 6" diameter hydraulic cylinder.

B.2.5 Results

The results of the tests are summarized in TABLE B-II. Note that not every test has a complete set of data. The reason is that this test session was used to find potential issues with the design. Every test was performed with a difference goal in mind. The predicted tonnage is calculated based on the die opening size calculations formulated in Appendix C.

TABLE B-II: TEST SESSION #1 RESULTS

Thickness (in)	Config.	Die Opening (in)	Compression Distance (in)	Perdicted Angle	Obtained Angle	psi	ton	Pred. ton	Temp.	Comments
0.25	DI	2.75							Cold	Die opening too small. Beam fractured.
0.25	DI	2.88			13				Cold	Large indentation at compression zone. Large bend zone
0.25	DI	2.88			14				Hot	Indentation reduced. Smaller bend zone
0.25	DI	5.00			14				Cold	No indentation. Large bend zone
0.25	DI	5.00				800	2.2	2.11	Cold	Large bend zone
0.25	DI	21.50				500	1.4	0.5	Cold	Very large bend zone
0.25	DI	6.00	0.75	30	29	800	2.2	0.69	Cold	
0.25	SI	8.88				1300	3.5	0.47	Cold	Very large twisting
0.25	SO	9.75				600	1.6	0.42	Cold	Significant twisting
0.375	DI	11.00	1	20	17	1300	3.5	1.28	Cold	
0.375	DI	11.00	1.063			1300	3.5	1.28	Cold	

B.2.6 Discussion

Test #1 was performed with an L3x3x$\frac{1}{4}$ angle. Test #2 was performed with an L2x2x$\frac{1}{4}$ angle. The die opening for both of these tests was approximately 2.75”. According to the calculations used in this testing session both of these beams have the effective thickness and therefore the same recommended die opening. However the #1 specimen, with its larger flanges and moment of inertia, fractured and thus scrapped the beam. The #2 specimen bent without fracture. This shows that the effective thickness calculation is not a valid method of predicting the required die opening.

The #2 specimen was bent at room temperature. The die imparted a significant indentation into the inside surface of the beam. The bend radius was also very large and the flanges buckled outward significantly. The #3 specimen was heated until red hot at the desired bend area. Using the same die opening as the #2 specimen, a smaller bend radius and reduce flange buckling was achieved. While the tonnage was not measured for this test, it was clear from observation that less tonnage was required.

Test #4 was performed with nearly twice the die opening as #2, with all other parameters remaining the same. The observed result was a smaller indentation caused by the top die, reduced flange buckling, but a larger bend radius.

Test #5 was performed with an L3x3x$\frac{1}{4}$ angle with a 5” die opening. Test #6 was performed with the same steel angle except with a 21.5” die opening. Test #6 was observed to create a larger bend radius than #5 which is undesirable. However, test #6 only required 1.4 tonnes of force compared to the 2.2 tonnes of force required in test #5.

Test #7 was used as an opportunity to examine how closely the bend angle could be predicted. An angle of 30° with a 6” die opening was predicted to require a compression distance of about 0.78” by using Eq. B1.

$$h = 6/2\ \sin(30/2) = 0.78" \quad \text{(B4)}$$

Using a tape measure, the compression distance was roughly measured. Measuring the specimen with a compass gave the actual angle to be 29°. Given that the prediction was made using simple trigonometric identities, this was considered a strong result. Specimen #7 also had the largest bend angle of all the test specimens. The flanges were observed to buckle significantly more than specimens #2, #3, or #4.

Test #10 was performed using a similar calculation as test #7. A predicted angle of 20° resulted in an actual angle of 17°. This prediction was significantly less accurate than test #7 predictions. The most likely cause is that since a smaller geometric angle was being formed, the elastic core was significantly larger and thus resulted in more spring back. Other possible/contributing causes are the inaccuracy of the compression distance measurements and the parabolic shape of the bend (rather than triangular).

Test #11 had three bolt holes drilled into one of the flanges. The bend was centered 12” away from one end. Measured from the same end the bolt holes were drilled at 11.25”, 10”, and 8.25” positions. After the bend, the flange buckling warped the first two bolt holes but not the third. Measurement showed that the bolt holes were located at the 11”, 9.875”, and 8.25” locations. Based on these results, bolt holes for this bend configuration, die opening, and angle size must be located approximately 4” from the bend location.

Test #8 and test #9 were performed to determine the feasibility of single flange bends. The results showed significant twisting which produced a completely unacceptable bends.

Angle measurements were found to be somewhat unreliable due to the supplied compass. The compass had short legs which could barely reach the unbent sections of the beams and it was not digital which limited its resolution. The compression distance was measured with a tape measure which was a highly inaccurate method of measuring the compression distance.

B.2.7 Conclusions

1. The die opening should be scaled based on the moment of inertia of a beam rather than just the thickness.

2. Localized heating produces smaller bend radii, reduced flange buckling, reduced indentation, and reduced tonnage. For these reasons, hot bending should be the preferred method of bending.

3. Smaller die opening produce tighter bend radii, but increase tonnage, flange buckling, and indentations.

4. Bend angles can be predicted within several degrees using simple geometry and trigonometry. However, this prediction method does not consider the parabolic shape of the bend or spring back. However, angles were consistently under bent so reapplications of the load can work the beam to the required angle.

5. Bolt holes close to the bend location are prone to warping and shifting locations. A bolt hole test was only performed for cold bending operations. Hot bending may allow bolt holes to be drilled in closer proximity to the bend location.

6. Single flange bends present a significant challenge due to twisting.

7. A digital compass with long legs should be used for angle measurements. A more accurate method of measuring and/or controlling compression distances should be used.

8. The additional supports specified in Concept #18 are not required. Concept #17 will be pursued instead.

B.2.8 Design Concerns

Through initial testing, the design team has confirmed that the three point bending method is a feasible method to successfully bend steel L-beams to a range of angles, but some concerns about the bending process were discovered and need to be addressed in future testing. These concerns are the accuracy of the bending operation, the flaring of beam flanges, and the warping of bolt holes near bending zone.

Accuracy of Bending

The accuracy of the bending depends on the measurement methods being used through the bending process. Trigonometric functions can be used to determine press stroke for any provided configurations for die spacing and bend angle. The problem during the initial testing was the lack of any concrete measurement system to accurately determine or set some important features such as: the press depth, die gap space, symmetry of bottom dies to top die, and final angle for bent beams. Future bend testing, as well as the final design, must have a measurement system implemented to ensure accuracy throughout the bending process.

Flaring

During the bend testing for double inside flange bending a repeating failure in the process was the flaring along the flange edges near the bending zone. The initial bend testing used a three point bending process, with basic bottom dies. Once the beam started to plastically deform the flanges experienced a mode one buckling phenomena along the top edge of each flange, illustrated in Figure B-3.

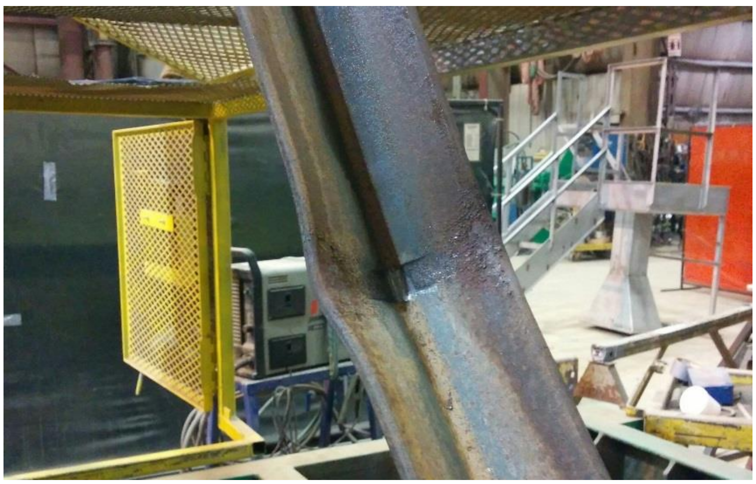

Figure B-3: Specimen #2 illustrating indentation and flange buckling [1].

This flaring of the flange sections remained in a relatively localized area around the location of the load application. The size and area of the flaring is correlated to the bend angle of the steel beam. As the bending angle increased, the size and area covered by the flaring grew as well. In order to reduce flaring for the double inside bend operation, using the three point bending method, lateral support is needed beneath, or on each side of the beam to force the flange edges to remain straight. A client of Sperling Industries provided some specifications for beam flaring, which states that the maximum deviation must be less than 1% of the bend slope.

Warping of Bolt Holes

One test was performed on a beam section, which had a number of bolt holes spaced along one flange, in order to determine the warping effects on the beam. After the beam was bent to an angle of approximately 15°, the bolt holes that were located close to the flaring region experienced major warping, and became oval shaped, rather than circular. At a distance of approximately 3 inches from the centre of bending, the shape and size of the bolt holes were minimally affected. To maintain the geometry of the bolt holes throughout the bending process the edge flaring near the bending zone must be reduced or eliminated.

B.3 Test Session #2

The second test session took place on 21-Nov-15 at Sperling Industries. The goal of this testing session was to expand upon the lessons learned during the first testing session. All bends were performed after localized heating to reduce flange warping. Die openings were minimized to reduce bend radii. A third bottom die with a V-shape was be incorporated to allow bottoming of steel angles. The goal was to force warped flanges back to the required shape. Additionally, double angle outside bending was tested.

B.3.1 Test Equipment and Materials

The test equipment and materials are detailed in TABLE B-III.

TABLE B-III: TESTING EQUIPMENT USED IN SECOND TESTING SESSION

Equipment	Quantity	Comments
100 ton hydraulic press	1	
Bottom supports	2	
Bottoming die	1	
Top die	1	
L3x3x1/4, 1 ft length, 300W	12	
Tape measure	2	
Compass	1	
Bubble Level	1	

B.3.2 Test Apparatus

The test apparatus changed throughout the testing session 2. The first tests used the same dies as the previous testing phase. The following tests used a setup that is similar to the first test session with the addition of a bottoming die, which can be seen in Figure B-4. The final bending tests were the double outside bends which used a reverse die set as seen in Figure B-5.

Figure B-4: Double inside bending apparatus used during test session #2 [4].

Figure B-5: Double outside bending apparatus used during test session #2 [4].

B.3.3 Procedure

The testing procedure was much more rigorous compared to the first test session. Measurements for all relevant parameters were taking for every test. The testing procedure is as follows.

Setup

1. Mount the top die to the hydraulic press cylinder. Ensure that the die will be perpendicular to the steel angle`s axis. Ensure the top surface of the die is parallel to the press cylinder using a bubble level.
2. Position the bottom dies a specified distance apart. Ensure that the bottom dies are centered relative to the top die using a tape measure.
3. Position the bottoming die directly below the top die. Turn on the press and actuate downwards to check alignment.
4. Return press to original position.
5. Position tape measure to record compression distance.

Testing

1. Measure the die opening distance.
2. Measure the initial length of the steel angle.
3. Measure initial bolt hole locations.
4. Preheat the center of the steel angle until red hot.
5. Place the steel angle in the bottom die. Center the heated region relative to the top die.
6. Actuate the hydraulic press to make initial contact with the steel angle. Pause and check for proper alignment of all components.
7. Actuate the hydraulic press until the steel angle bottoms onto the bottoming die. The pressure gauge should show a significant increase in pressure.
8. Take a maximum pressure reading.
9. Measure the compression distance
10. Slowly release pressure.
11. Measure the spring back distance.
12. Return the press to its original position and turn off the machine.
13. Remove the steel angle from apparatus and allow to cool.
14. Measure the obtained bend angle.

15. Measure the inside and outside lengths.
16. Take an approximate measurement of the flange warp angle.
17. Measure bolt hole locations.
18. Write the test number onto the steel angle.
19. Take pictures of the steel angle.

B.3.4 Results

The results for the second round of testing are summarized in the following data sheet in TABLE B-IV and TABLE B-V. The data collected for every test is complete as possible. Some measurements were not possible to acquire during or after testing. The predicted tonnage are calculated using the equations developed for determination of die opening sizes. The bolt hole results table shows the measured distance from a free edge of the beam, measured along its long axis to its location. The goal of this table was to show the movement of bolt holes after a bend.

TABLE B-IV: TEST SESSION #2 RESULTS

#	Beam Size (in)	Config.	Die Opening (in)	Compres sion (in)	Exp. Angle (deg)	Mea. Angle (deg)	Initial Length (in)	Inside Lengt h (in)	Outside Length (in)	psi	psi at bot.	ton	Temp.	Pred. ton	Comments
1	L3X3X3/8	Double Inside	4.00		Break		12			2400		6.53	~500	3.51	Large indent after bend. Fracture did not occur as expected.
2	L3X3X3/8	Double Inside	6.00	52	20		12			1600		4.35	~500	2.34	
3	L3X3X3/8	Double Inside	8.00	1	29	20	18			1400		3.81	<500	1.76	Unexpected fracture. Likely due to lower bend temp.
4	L3X3X3/8	Double Inside	8.00	1	29	27	18	18.50	18.5	1200		3.27	~600	1.76	Indented
5	L3X3X3/8	Double Inside	8.00	1	29	27	18	18.50	18.5	1500	4000	4.08	~600	1.76	
6	L2X2X1/4	Double Inside	8.00	1	29	28	12	12.25	12.5	1600	4000	4.35	~600	0.52	
7	L2X2X1/4	Double Outside	4.00	0.35	20	15	12	12.25	11.75	800		2.18	~600	1.02	Nice bend. No flaring, or warping.
8	L2X2X1/4	Double Outside	4.00	0.35	20	12	12	12.00	12.25	800		2.18	~600	1.03	

TABLE B-V: BOLT HOLE RESULTS FOR TEST SESSION #2

Test #	Bolt #1 Initial (in)	Bolt #1 Final (in)	Bolt #1 Warpage	Bolt #2 Initial (in)	Bolt #2 Final (in)	Bolt #2 Warpage	Bolt #3 Initial (in)	Bolt #3 Final (in)	Bolt #3 Warpage
1									
2									
3	6		No	7		No	8		Yes
4	6	6	No	7	7	No	8	8.000	Yes
5	6	6	No	7	7	No	8	8.000	Yes
6	3	3.125	No	4	4.125	No	5	5.125	Yes
7	3		No	4		No	5		Yes
8	3	3	No	4	4	No	5	5.125	Yes

B.3.5 Discussion

The temperature of the bending was at approximately 600°C and the heating process took roughly 2-3 minutes. In order to optimize time, one person performed the beam heating while another set up the testing space. Tests number 1 thru 5 were all performed using beam size $L3x3x\frac{3}{8}$. The purpose of the 2 initial tests was to determine whether the teams' predictions about fracture were justified, and if the die gap space is related to the fracture point. Neither of the two samples fractured during the testing. We believe this is because the beam received heating prior to the testing. This suggests that the beam will be less likely to fracture at higher temperatures. Since the material becomes more malleable during heating, it should have a higher resistance to catastrophic failure. The lower die opening used in trial 1 produces a much higher bending force for the same press depth, which shows that the beam is indeed receiving more force to perform the same action. It also experienced "bulging" of material on its lower face which would constitute scrapping of the beam.

Tests 3-5 were performed using the new die fixture that incorporates a bottoming feature, which is in place to reduce the effects of flaring. The bottoming die worked on the samples that were forced into the V-shaped bottoming die, and the flaring was significantly reduced at high angles. Test 3 had an unexpected failure, which we are linking to a temperature below requirement, and possible material defects. The failure from test session #2 can be seen in Figure B-6.

Figure B-6: Bending failure in testing session #2 [4].

The failure mode appears to be mode I or mode II. The crack appears at the apex of the bend radius, and quickly spreads outwards along the flanges. The crack travels at 45 degrees, but then changes direction which could be because the direction of force application is different from when the crack appeared since the beam is bending. Upon closer inspection, what appears to be small voids are present within the crack and along the crack edges. This may have been caused during the heating process, by applying heat at one point for too long. If the beam is not heated uniformly, then one area within the bend range could have a lower yield point in comparison to the rest of the beam, and will bend more quickly causing the beam to fail before the rest of the material has a chance to bend.

The rest of the double inside bend tests showed good results, which suggests that the beam that failed had defects present in range of the bend radius. A comparison of the two beam samples can be seen in the following figures.

Figure B-7: Test session #1 bend sample showing extreme flange buckling [4].

Figure B-8: Test session #2 bend sample showing reduced flange buckling [4].

The beam samples shown are approximately the same for size, length and bend angle. The size is L3x3x3/8, length is nearly 2” for each beam and the angle bent is approximately 28°. The purpose of test session #2 was to reduce flaring on the edges of the flange legs using a bottoming die. As seen in the figures, the flaring on a nearly 30° bend reduced by a large amount compared to previous testing. However, the bottoming die used in testing #2 had a middle section that was smaller than the beam flange length which caused indentations at the tip of the beam legs.

The double outside bend tests went better than expected. For up to a 20° bend there were no signs of unforeseen deformations along the length of the beam, or on the flanges. The top die was however too wide for the size of the bent beam, so some large indents were produced on each of the beam specimens. The indents are along the bend radius, so using too large of a top die should be avoided.

Measurements for beam length, in and out, were performed after the beams had cooled using a rope length, and a ruler. The bolt hole measurements were all performed from the outer edge, and the warping was checked using standard hole size pins. At a distance of 1” away from the bend location, the bolt holes suffered significant warping, but at 2” the bolt hole was intact. From observation, it appears that bolt holes at least 1.5” from the bend line should not be significantly warped. It was also noted that the material elongated a significant amount meaning that the beam length does not stay constant during a bend. Note that the equation used to predict the required press stroke assumed that the beam length remained constant. Reformulation of the equation to account for the elongation was required.

The predicted bend tonnage was calculated based on the yield strength of the material. It was relatively consistently half of the observed tonnage. While predicting the exact tonnage required is complex the method used is accurate enough for our purposes.

B.3.6 Conclusions

From the results of the second testing session it is clear that the design can produce bends that meet the client requirements. The client expressed satisfaction with both the double inside and double outside bend results and the design team discussed some updates to the design to improve on the surface finish around the bend. The bottoming die requires improvement, so as to reduce the slight deformation caused during the bending process. The bottoming die also requires vertical movement capability so that all bend angles can be produced. The top die for each of the bending configurations should be made in multiple sizes to improve the bend radius and reduce on surface imprint that is created during bending. Also, in order to reduce flaring to a higher degree the bottoming die will be constructed with a smaller V angle, so the beam makes contact earlier, and is forced further back. The bottoming angle should be approximately 85-89° so that the beam flanges are forced inwards. To improve angular accuracy, an angular measurement during bending is required. The team will look into magnetic compasses, which are capable of high accuracy measurements, so that the press operator has a reference during bending. Finally, heat operations on the beams served to reduce the flaring zone in the beam. The temperature should be applied until a cherry red color is produced in the beam. The bending operation should then be performed quickly so that the temperature does not reduce too significantly before the bending is completed.

Taking into account the elongation of the beams, the calculation to determine the stroke should be changed to the following form.

$$h = L/2 \ \tan(\alpha/2) \tag{B5}$$

This form of the equation provides larger strokes for a given angle which may account for the consistent 1-3° of under bend. Additional testing will be required to determine which form of the equation will provide more accurate bends. Bend tables using both forms of the equation are provided in Appendix G.

B.4 References

[1] Sean Desrosiers. “Photos.” Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, 2015, Nov 11.

[2] Justin Marek. “Engineering Drawings.” Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, 2015, Nov 9.

[3] B. L. Rapien, Fundamentals of Press Brake Tooling, 2nd ed. Munich: Hanser Publishers, 2010.

[4] Jiaxin Yan. “Photos.” Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, 2015, Nov 23.

Appendix C

Technical Analysis

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C.1 Introduction

Technical analysis serves to assist in making informed design decisions. This section contains the details of all technical analysis carried out over the course of the project. The results of each analysis are discussed in detail. Analysis was carried out on the lubrication requirements of the die, the preheat temperature requirements, the material requirements, and the fastener requirements. Furthermore, calculations were performed to determine the optimal die opening for various beam sizes. A short discussion on the selection of a hydraulic jack is included, followed by FEA results.

C.2 Lubrication

During the bending process, the top die is used to force the beam through the gap between the two bottom dies, and through this action achieve a bent beam profile. During the bending process, in order to translate downward, the total volume of the beam within the bottom dies increases relative to the angle being produced. While this occurs, the bottom edge of the beam slides along the contacting die surfaces and produces a contact stress due to friction. Frictional contact stresses between the die and beam surfaces during the bending processes can lead to a large increase in die temperature and a significant reduction in die life due to surface wear and abrasion. The application of lubricants to areas that experience a high level of contact stress is a simple method to improve the life of die surfaces. TABLE C-I shows wear coefficient for several different surface-on-surface contact scenarios.

TABLE C-I: COMPARISON OF FRICTION AND WEAR COEFFICIENTS FOR DIFFERENT CASES [1]

Materials	Temperature	Environment	Friction Coefficient	Wear Coefficient
Metal-metal	Room temp.	Dry	0.2-0.8	0.4 - 70E-4
Metal-metal	400°C	Dry	0.3-1.1	4.0 - 70E-4
Metal-ceramic	Room temp.	Dry	0.3-1.1	0.04E-4
Solid lubricant coatings	Room temp.	Dry	0.1-0.6	0.6E-4
Metal-PTFE	Room temp.	Dry	0.06-0.1	0.25E-4
Steel-steel	Room temp.	Lubricated	0.08-0.2	0.03 - 0.2E-4
Hydrodynamic lubrication	Room temp.	Liquid	<<0.1	0.01 - 0.6E-4

According to the table above, using lubrication can reduce the friction coefficient by up to a factor of 10 depending on the steel used, while the reduction in the wear coefficient can be even more significant. The wear on any surface is determined as a function of the wear coefficient and the loading life of the part. Since the die parts featured in our project are designed for a low cycle life and the contact surfaces will be easily replaceable, the wear on the die surfaces will not be significant. This means that the use of lubricant is not required for the bending operations, though lubrication can still be used to reduce the wear on the die surfaces.

It is important to note that if a lubricant is used in bending operations the type used is dependent on the die being lubricated. The two side dies are experiencing a temperature gradient caused solely by the frictional force occurring between the die and the beam. However, since our bending process will involve beam heating, the top die will be in contact with the beam and receive a large temperature gradient from the heated section of the beam. For lubricating the side dies, the lubricant used is not restricted and a wide range of products may be used. In the case that lubrication is applied to the top die or bottoming die specialty lubricants for high temperature applications or dry, non-combustive lubricants are required. Many high temperature lubricants function for temperature ranges up to 600-1000°C.

C.3 Temperature

Bending structural steel at room temperature is a cold working process. Cold working requires relatively large forces because the steel possesses its full strength. Bending the steel at elevated temperatures, known as warm and hot forming, reduces the strength of the beam, which reduces the required force. Therefore, it is necessary to understand how the variation of temperature affects the material properties of carbon steel such as the yield strength.

CSA 300W or 350W mild steel are the preferred materials for the manufacturing of the die. Based on their composition, carbon steel 300W and 350W belongs to the mild steel family. TABLE C-II shows the material properties of a mild steel at room temperature. Note that these properties are not the same as those for 300W and 350W, but the conclusions drawing from the associated paper can be applied to various grade of mild steel.

TABLE C-II: MATERIAL PROPERTIES OF MILD STEEL AT ROOM TEMPERATURE [2]

Steel	$f_{0.2, normal}$	$f_{0.5,, normal}$	$f_{1.5, normal}$	$f_{2.0, normal}$	$f_{u, normal}$	E_{normal}	ε_f
Units	MPa	MPa	MPa	MPa	MPa	GPa	%
Mild Steel	401	409	445	465	552	220	30

TABLE C-III shows the reduction factors for yield strength and elastic modulus of mild steel. The table shows that the yield strength and elastic modulus of mild steel decrease as temperature increases. Each yield strength reduction factor is associated with an increasing level of strain. The level of strain is signified by the subscript. For example, $f_{0.2, T}$ / $f_{0.2, normal}$ is the reduction factor at 0.2 $^{in}/_{in}$ strain.

TABLE C-III: REDUCTION FACTORS OF YIELD STRENGTH AND ELASTIC MODULUS OF MILD STEEL [2]

T (°C)	E_T / E_{normal}	$f_{0.2, T}$ / $f_{0.2, normal}$	$f_{0.5, T}$ / $f_{0.5, normal}$	$f_{1.5, T}$ / $f_{1.5, normal}$	$f_{2.0, T}$ / $f_{2.0, normal}$
460	0.89	0.81	0.85	0.93	0.93
540	0.90	0.78	0.82	0.87	0.86
600	0.82	0.71	0.74	0.76	0.74
660	0.77	0.56	0.58	0.57	0.55
720	0.65	0.35	0.36	0.32	0.31
830	0.48	0.15	0.15	0.14	0.13
940	0.26	0.09	0.09	0.09	0.08

A significant drop in yield strength and elastic modulus occurs at a temperature level above 540°C. For example, in the case of a yield strength corresponding to 2.0% strain level, the reference yield strength of a test specimen is 409MPa at room temperature. When the specimen is heated to 720 °C, the yield strength of mild steel will only be 126.79MPa (0.31x409=126.79). This represents a decrease in yield strength to 31% of its original value.

The study above suggests that the pre-heating procedure needs to achieve a temperature between 540 °C and 720 °C. Any temperature below 540 °C will prevent us from getting a sufficiently low yield strength. Higher temperatures require more energy to heat up but provide little benefit. Additional overheating is not recommended because steels experience a phase change from ferrite to austenite at 727°C which may cause unpredictable variance within the process.

Our specific material requires heating processes for each bend. Heating of the steel angles before bending allows a tighter bend radius to be formed, reduces flange buckling, and decreases the required tonnage. However, heating steel to high temperatures can affect the metallurgical properties of the material.

The material composition of 300W and 350W mild steel is shown below.

TABLE C-IV: ELEMENTAL COMPOSITION OF MILD STEELS (% WEIGHT) [3]

Grade	C	Mn	P	S	Si	Grain Refining Elements
300W	0.22	0.50/1.50	0.04	0.05	0.4	0.1
350W	0.23	0.50/1.50	0.04	0.05	0.4	0.1

Mild steels are characterized by their relatively low carbon content. The microstructure of these steels are typically composed of pearlite and ferrite. Their low carbon content makes mild steel relatively weak but very ductile. Critically, these steels are unresponsive to heat treatments which may form martensite. In practice this means that even under rapid cooling mild steel will not become excessively hard and brittle [4].

Mild steels are responsive to stress relief heat treatments above their recrystallization temperature. The lower recrystallization temperature is defined as 450°C and extends up towards the melting point. Therefore, we can define this as the lower limit of recrystallization [4].

At 727°C, ferrite begins to transform into austenite which has a higher solubility limit of carbon. The carbon in cementite (which forms part of the pearlite microstructure) is absorbed into the austenite. If the steel is slowly cooled it will return to its pearlite-ferrite microstructure. However, if the cooling is too rapid it may form martensite. In order to avoid altering the microstructure of the steel, the heating temperature should be kept below 727°C.

The crystal structure of rolled steel shapes such as steel angles is elongated in the rolling direction. This represents residual stress introduced during the manufacturing process. During the bending process additional residual stress will be introduced. Bending the steel angles above the recrystallization temperature will reduce the residual stresses introduced during bending. However, since the heating time is relatively low (stress relief is a time dependant operation) it should not significantly affect the residual stresses introduced during rolling.

Therefore, the steel angles should be heated to a temperature between 450-727°C to prevent significant alternation to the steels microstructure. A table is included in Appendix G to facilitate temperature estimations.

Based on the temperature estimation table the metal is suitable to be bent as soon as it begins to glow red. However, higher temperatures up to a cherry color are preferred because it will reduce the required press tonnage and improves formability.

The yield strength of 300W and 350W mild steel at ~700°C can be determined using a 35% reduction factor. The yield strength of 300W is 105MPa and the yield strength of 350W is 122.5MPa at ~700°C. The mechanic properties of selected steels at room temperature are included in the next section.

C.4 Material

Selection of suitable materials for the press die are critical it ensure that the structural capabilities of the design are sufficient. This section details the analysis that went into selection of suitable materials.

The steel angles are typically made from CSA 300W and CSA 350W steel which is a form of mild steel. One main characteristic of this material is that has a low carbon content which makes this material malleable. So, theoretically it is better to use a material that is stronger than the L-beam material to ensure that the top die does not deform during the bending process. For smaller L-beam sections the forces required to initiate bending produce a stress on the die that is much lower than the yield strength of the material. For larger beam sections, the forces needed to start plastic deformation are much higher, and so the stress on the dies could cause yielding to occur. When heating is applied to steel beams, the heat transferred to the beam could also be an important factor.

The dies do not necessarily need to be made of a material stronger than the beams because the beams will be softened significantly before bending from preheating. Ideally it would be ideal to keep the overall cost as low as possible. Since Sperling Industries already has 350W steel plate in stock, it is more cost effective to use the available plate to construct the majority of the die assembly. To confirm the use of the material, testing must be performed on a wide range of bend angles, for a variety of beam sections. Stress analysis is carried out on many of the components but fatigue analysis could not be performed due to time constraints.

The selection of materials for the design is critical to its overall function due to the high loads it must withstand. Steels are the primary material because of its high strength and low cost. The weight of the design is not of high importance. TABLE C-V included the mechanical properties of some selected steels.

TABLE C-V: MECHANICAL PROPERTIES OF SELECTED STEELS [3, 5]

Grade	Tensile Strength (MPa/ksi)	Yield Point (MPa/ksi)
CSA 300W	450/65.3	300/43.5
CSA 350W	450/65.3	350/50.8
AISI 4340	745/108.1	470/68.2

The base plate is produced from AISI 4340 steel because of its high strength. The base plate serves as the datum from which the stroke distance is determined so it must be resistant to surface wear. The base plate's bottom surface is difficult to access so nuts cannot be used to fix the bolts in place. For this reason, the internal threads must be tapped directly into the base plate. A strong steel is preferred to reduce the probability that the threads will be stripped.

The remainder of the design is constructed out of 350W mild steel. This material is readily available at Sperling Industries which will allow much of the design to be constructed with on-hand material.

C.5 Fasteners

Bolts are the primary method used to fix the design together. Bolts allow for the construction of a rigid assembly during bends while still retaining the ability to change the die plate and adjust the die opening. The bolts utilized in the design are specifically design to bear as little load as possible. On the top fixture, the bolts are positioned such that they only function to hold the top die plate in position. The load is transferred from the hydraulic press, through the top die plate, and into the work piece. The bolt will experience very little stress. The bolts that secure the brackets to the base plate are also design to carry a small load. Most of the forces that are transferred from the work piece to the side supports are pure compressive and transfer force through the support to the base plate. For large angle bends a portion of the force is applied laterally to the supports which tends to cause a bending moment.

All fasteners used in the design assembly are zinc coated Grade 5 half inch bolts with a course thread. Grade 5 bolts are a common grade of hardened bolt which should be sufficient for this application. The course thread makes assembly quicker and easier.

The recommended torque to achieve sufficient preload is calculated with the following equation.

$$T = KdP \tag{C1}$$

Where K is the friction factor, d is the nominal diameter of the bolt, and P is the preload of the bolt. The preload is generally estimated to be 75% of the yield stress of the bolt. This is based on the assumption that the nut is correctly selected for the bolt. Proper selection ensures that the bolt fails before the nut threads strip which provides easier detection of failure (Greenslade, 2013). The relevant data for the selected fasteners are summarized in TABLE C-VI.

TABLE C-VI: T=KdP PARAMETERS FOR SELECTED BOLTS [6]

Friction Factor Hot Dip Galvanized	Thread Nominal Diameter Half Inch Bolts (in)	Tensile Stress Area Half Inch Bolts (in^2)	Yield Strength Grade 5 (0.25”-1”) (psi)
0.23	0.500	0.142	92000

Inserting these values into Eqn. C1 yields the following torque value.

$$T = KdP = (0.23)(0.500)(0.75)(0.142)(92000) = 1127\ in \cdot lb = 93.9 ft \cdot lb \qquad \text{(C2)}$$

This is the recommended torque for the top die bolts because they are fixed with an appropriately sized nut. However, the bracket bolts mate with the base plate which is made from a softer material, namely AISI 4340 steel. AISI 4340 steel has a yield strength of 68.2 ksi compared to the selected bolts which have a yield strength of 92 ksi. In order to prevent stripping the softer material a lower torque value must be specified. The yield strength of the base plate is 26% less than that of the bolt (100%*[92-68]/92=26%). The recommended torque for the bracket bolts will be reduced by a factor of 26% which yields a recommended torque value of 69.5ft.lb (93.9*[1-0.26]=69.5). This will prevent stripping of the internal threads.

C.6 Die Opening Calculations

Die opening calculations attempt to provide a starting point when performing a bend. For a given material and beam size they provide a recommended die opening. The recommended die opening and desired bend angle can then be used to determine the recommended position for the bottoming die. The data is compiled into tables and charts.

The charts are constructed based on a simply supported beam model. There are two types of stress experienced within a simply supported beam: bending stress and shear stress. The bending stresses are at a maximum at the outermost fibers of a cross-section. One side will be in tension and the other will be in compression. Bending stress, as the same implies, causes the beam to bend. Shear stress is at a maximum towards the center of the cross-section. Shear stress will cause the beam to fracture and thus scrap the beam.

As the die opening is decreased shear stress will tend to dominate and facture the beam before bending occurs. On the other hand, if the die opening is increased the bending stress is be distributed across the length of the beam and create a large radius bend. The die opening charts determine the smallest die opening (creating the tightest bend radius) which will not fracture the beam.

Sample Calculations

The size (h), thickness (t), area (A), radius of gyration (r), and centroid distance (x) are obtained from source (Beer, 2009). The moment of inertia of the cross-section is calculated as follows.

$$I = A \cdot r^2 \qquad \text{(C3)}$$

The largest distance from the neutral axis to the outermost fiber (y) occurs at the “flange edge” of the cross-section. Figure C-1 details how the geometry of the cross-section can be used to determine the distance, y. Note that a simplified geometry is used which considers the L-beam cross-section as two rectangles at right angles to one another. The corner radius is not considered.

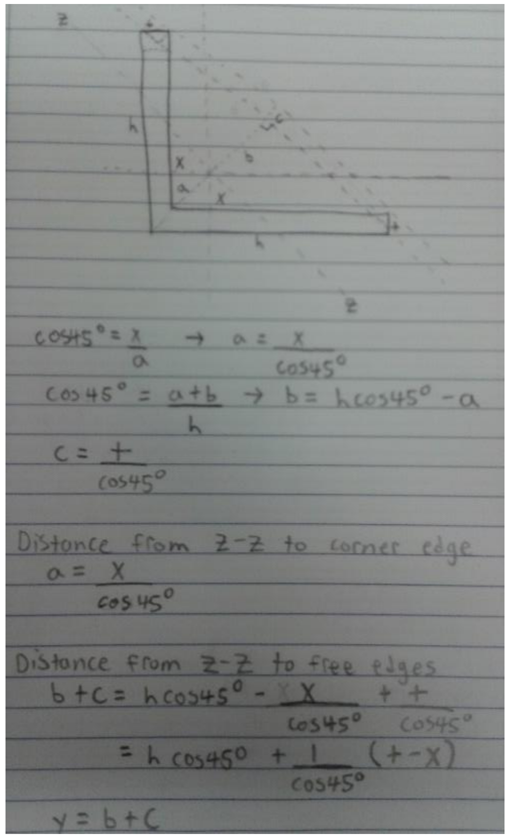


Figure C-1: Geometric Analysis of simplified L-beam cross-section.

Based on the geometric analysis, the distance to the outermost fibers is calculated as follows.

$$y = h \cdot \cos(45°) + (t - x)/\cos(45°) \quad \text{(C4)}$$

The first moment of one leg of the cross-section with respect to the centroid (Q) is calculated using an equation obtained from source [7].

$$Q = t \cdot cos(45°)/2\ \times (h^2 - x^2/(\cos^4\,(45°))) \quad \text{(C5)}$$

The required force (P) from the press to begin yielding is calculated once a die opening (L) is specified.

$$P = (4\sigma_{yield}\, I)/(Ly) \quad \text{(C6)}$$

Using the required force to begin yielding the maximum shear stress in the cross-section is calculated at the centroid.

$$\tau = (P/2 \cdot Q)/(I \cdot t) \quad \text{(C7)}$$

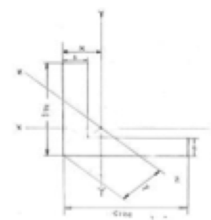
The shear stress is converted to VonMises stress and normalized by the yield stress to produce a "shear factor". Theoretically, the beam should bend without fracturing *due to shear* provided that the shear factor is kept below unity.

$$Shear\ Factor = \tau/(0.59\sigma_{yield}) \tag{C8}$$

The results of the die opening calculations are compiled on the next several pages for 300W and 350W steels. Note that the yield strength used in all calculations was for the heated condition at approximately 700°C.

TABLE C-VII: DIE OPENING CALCULATIONS FOR 300W MILD STEEL

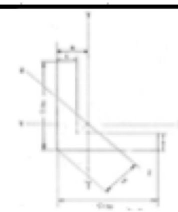
Table of Material Properties for L-angle Beams for 300W steel



Beam	Size (in)	t (in)	A (in)	r (in)	x (in)	I (in4)	y (in)	Q (in3)	Yield (ton)	S.F.	L (in)
L8x8x1	8	1	15	1.56	2.360	36.504	3.73	14.744	13.85	0.69	19.5
L8x8x¾	8	0.75	11.4	1.57	2.260	28.100	3.52	11.548	11.31	0.76	19.5
L8x8x½	8	0.5	7.75	1.59	2.170	19.593	3.29	7.981	8.43	0.84	19.5
L6x6x1	6	1	11	1.17	1.860	15.058	3.03	7.831	8.87	0.57	15.5
L6x6x¾	6	0.75	8.46	1.17	1.770	11.581	2.80	6.220	7.37	0.65	15.5
L6x6x⅝	6	0.625	7.13	1.17	1.720	9.760	2.69	5.338	6.46	0.69	15.5
L6x6x½	6	0.5	5.77	1.18	1.670	8.034	2.59	4.390	5.53	0.74	15.5
L6x6x⅜	6	0.375	4.38	1.19	1.620	6.203	2.48	3.380	4.46	0.79	15.5
L5x5x¾	5	0.75	6.94	0.972	1.520	6.557	2.45	4.176	5.49	0.57	13.5
L5x5x⅝	5	0.625	5.86	0.975	1.470	5.571	2.34	3.613	4.87	0.62	13.5
L5x5x½	5	0.5	4.75	0.98	1.420	4.562	2.23	2.992	4.18	0.67	13.5
L5x5x⅜	5	0.375	3.61	0.986	1.370	3.510	2.13	2.318	3.38	0.73	13.5
L4x4x¾	4	0.75	5.44	0.774	1.270	3.259	2.09	2.530	3.74	0.48	11.5
L4x4x⅝	4	0.625	4.61	0.774	1.220	2.762	1.99	2.219	3.34	0.53	11.5
L4x4x½	4	0.5	3.75	0.776	1.180	2.258	1.87	1.843	2.91	0.58	11.5
L4x4x⅜	4	0.375	2.86	0.779	1.130	1.736	1.76	1.444	2.37	0.64	11.5
L4x4x¼	4	0.25	1.94	0.783	1.080	1.189	1.65	1.001	1.73	0.71	11.5
L3.5x3.5x½	3.5	0.5	3.25	0.679	1.050	1.498	1.70	1.385	2.57	0.58	9.5
L3.5x3.5x⅜	3.5	0.375	2.48	0.683	1.000	1.157	1.59	1.093	2.12	0.65	9.5
L3.5x3.5x¼	3.5	0.25	1.69	0.688	0.954	0.800	1.48	0.761	1.57	0.73	9.5
L3x3x½	3	0.5	2.75	0.58	0.929	0.925	1.51	0.980	2.25	0.59	7.5
L3x3x⅜	3	0.375	2.11	0.581	0.884	0.712	1.40	0.778	1.87	0.67	7.5
L3x3x¼	3	0.25	1.44	0.585	0.836	0.493	1.29	0.548	1.40	0.77	7.5
L2.5x2.5x½	2.5	0.5	2.25	0.481	0.803	0.521	1.34	0.649	1.43	0.44	7.5
L2.5x2.5x⅜	2.5	0.375	1.73	0.481	0.758	0.400	1.23	0.524	1.20	0.51	7.5
L2.5x2.5x¼	2.5	0.25	1.19	0.482	0.711	0.276	1.12	0.374	0.91	0.61	7.5
L2.5x2.5x3/16	2.5	0.188	0.9	0.482	0.687	0.209	1.06	0.289	0.73	0.66	7.5
L2x2x⅜	2	0.375	1.36	0.386	0.632	0.203	1.05	0.318	0.97	0.50	5.5
L2x2x¼	2	0.25	0.938	0.387	0.586	0.140	0.94	0.232	0.75	0.61	5.5
L2x2x⅛	2	0.125	0.484	0.391	0.534	0.074	0.84	0.126	0.44	0.75	5.5

TABLE C-VIII: DIE OPENING CALCULATIONS FOR 350W MILD STEEL

Table of Material Properties for L-angle Beams for 350W steel



Beam	Size (in)	t (in)	A (in)	r (in)	x (in)	I (in4)	y (in)	Q (in3)	Yield (ton)	S.F.	L (in)
L8x8x1	8	1	15	1.56	2.360	36.504	3.73	14.744	16.18	0.69	19.5
L8x8x¾	8	0.75	11.4	1.57	2.260	28.100	3.52	11.548	13.21	0.76	19.5
L8x8x½	8	0.5	7.75	1.59	2.170	19.593	3.29	7.981	9.84	0.84	19.5
L6x6x1	6	1	11	1.17	1.860	15.058	3.03	7.831	10.36	0.57	15.5
L6x6x¾	6	0.75	8.46	1.17	1.770	11.581	2.80	6.220	8.61	0.65	15.5
L6x6x⅝	6	0.625	7.13	1.17	1.720	9.760	2.69	5.338	7.54	0.69	15.5
L6x6x½	6	0.5	5.77	1.18	1.670	8.034	2.59	4.390	6.46	0.74	15.5
L6x6x⅜	6	0.375	4.38	1.19	1.620	6.203	2.48	3.380	5.20	0.79	15.5
L5x5x¾	5	0.75	6.94	0.972	1.520	6.557	2.45	4.176	6.41	0.57	13.5
L5x5x⅝	5	0.625	5.86	0.975	1.470	5.571	2.34	3.613	5.69	0.62	13.5
L5x5x½	5	0.5	4.75	0.98	1.420	4.562	2.23	2.992	4.88	0.67	13.5
L5x5x⅜	5	0.375	3.61	0.986	1.370	3.510	2.13	2.318	3.94	0.73	13.5
L4x4x¾	4	0.75	5.44	0.774	1.270	3.259	2.09	2.530	4.37	0.48	11.5
L4x4x⅝	4	0.625	4.61	0.774	1.220	2.762	1.99	2.219	3.90	0.53	11.5
L4x4x½	4	0.5	3.75	0.776	1.180	2.258	1.87	1.843	3.39	0.58	11.5
L4x4x⅜	4	0.375	2.86	0.779	1.130	1.736	1.76	1.444	2.77	0.64	11.5
L4x4x¼	4	0.25	1.94	0.783	1.080	1.189	1.65	1.001	2.02	0.71	11.5
L3.5x3.5x½	3.5	0.5	3.25	0.679	1.050	1.498	1.70	1.385	3.00	0.58	9.5
L3.5x3.5x⅜	3.5	0.375	2.48	0.683	1.000	1.157	1.59	1.093	2.47	0.65	9.5
L3.5x3.5x¼	3.5	0.25	1.69	0.688	0.954	0.800	1.48	0.761	1.84	0.73	9.5
L3x3x½	3	0.5	2.75	0.58	0.929	0.925	1.51	0.980	2.63	0.59	7.5
L3x3x⅜	3	0.375	2.11	0.581	0.884	0.712	1.40	0.778	2.19	0.67	7.5
L3x3x¼	3	0.25	1.44	0.585	0.836	0.493	1.29	0.548	1.64	0.77	7.5
L2.5x2.5x½	2.5	0.5	2.25	0.481	0.803	0.521	1.34	0.649	1.67	0.44	7.5
L2.5x2.5x⅜	2.5	0.375	1.73	0.481	0.758	0.400	1.23	0.524	1.40	0.51	7.5
L2.5x2.5x¼	2.5	0.25	1.19	0.482	0.711	0.276	1.12	0.374	1.07	0.61	7.5
L2.5x2.5x3/16	2.5	0.188	0.9	0.482	0.687	0.209	1.06	0.289	0.85	0.66	7.5
L2x2x⅜	2	0.375	1.36	0.386	0.632	0.203	1.05	0.318	1.13	0.50	5.5
L2x2x¼	2	0.25	0.938	0.387	0.586	0.140	0.94	0.232	0.88	0.61	5.5
L2x2x⅛	2	0.125	0.484	0.391	0.534	0.074	0.84	0.126	0.52	0.75	5.5

Examination of the data in the above table shows that the calculation methods used have clear limitations. The shear factor increases as the thickness of the beam decreases when the beam size is kept constant. This observation suggests that a larger die opening is required for thinner beams while common sense dictates that the opposite should be the case. Furthermore the high temperatures at which the beams are bent at increase the malleability of the steel which reduces that likelihood of shear. The beams are more likely to elongate at locations of high stress rather than break. With these limitations in mind the calculations served as starting point for concept design testing and were also used for the bend reference chart in Appendix G.

C.7 Hydraulic Jack Selection

Selection of a hydraulic jack is based on the worst-case scenario of the maximum expected load. Testing has shown that the experienced tonnage is roughly double the predicted tonnage to begin yielding of a beam. A 350W L8x8x1 beam has the highest predicted yield tonnage of 16.18 tons. The testing results indicate that the actual tonnage should be 32.36 tons. Applying a factor of safety of 2, the design tonnage is approximately 60 tons. Therefore, the selected hydraulic jack must be 60 tons to prevent failure.

Referring to the required compression distances in the bend reference table (Appendix G), most bends fall within a 3” compression distance band. Only the largest beams with the largest bends require compression distances greater than 3”. It is unlikely, for example, that an 8x8x1 beam would be bent to 45°. For this reason, only a 3” stroke is required for the hydraulic jack. The beams which Hot Form has determined to be unbendable with a 3” stroke have been grayed out in the bend reference table.

The selected jack is the RCH-606 Hydraulic Cylinder with 60tons max load and 3" stroke [8]. This jack has the required maximum load and stroke as discussed in the above discussion. It can be purchased for a reasonable cost of $3,750.00 [8] before taxes from local vendors such as Acklands-Grainger. The availablity of this jack was the primary deciding factor in its selection.

C.8 FEA Analysis

Finite Element Analysis (FEA) was performed on selected components of the design in order to confirm their ability to withstand the applied loads. These components were deemed to be the most likely to fail so they are prioritized for analysis. Time constraints prevented a full analysis of all components. In particular, the threaded fasteners that connect the brackets to the base plate could not be analyzed. This is an area that warrants additional analysis.

A single support was taken and analyzed using the data obtained from testing. Figure C-2 shows how the loading scenario is analyzed.

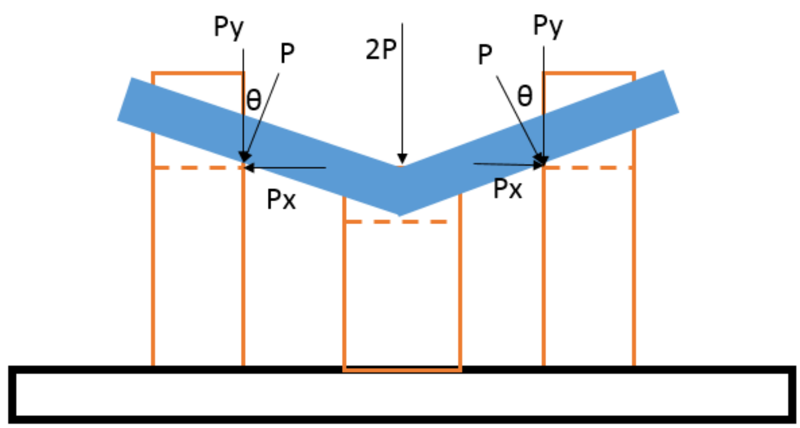


Figure C-2: Simplified loading scenario for a bent beam [9].

For a given bending angle of α, each support will experience an applied load P at an angle θ from the vertical, where $\theta=\alpha/2$. This means that each support will experience both a vertical and a horizontal component of force. Since our analysis focuses on a single support, Figure C-3 will provide the required applied loads.

The mesh elements used in all of the fine mesh analysis had a size of 0.0296" with an element ratio of 3:1. The mesh elements are 3D tetrahedral's with 16 Jacobian points.

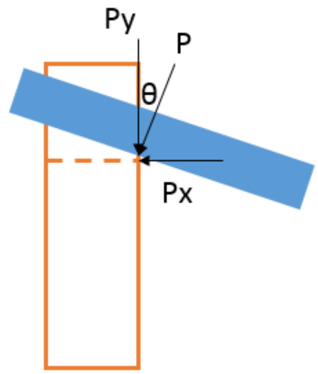


Figure C-3: Simplified loading scenario for a single support [9].

The vertical component of force, P_y, will primarily be compressive, and will generate a small negative moment due to its offset from the central axis of the support. The horizontal component of force, P_x, will generate a positive moment in the support and bend the support like a cantilever beam. The equations for converting the applied load P to each of the components are displayed below.

$$\begin{cases} P_y = P cos\theta \\ P_x = P sin\theta \end{cases} \quad \text{(C9)}$$

Note that CSA 350W is the assumed material for all analysis. The yield strength of CSA 350W mild steel is 350MPA [3] which is greater than the yield strength of the mild steel considered in the FEA results.

C.8.1 Confirmation of Physical Testing Results

The first FEA analysis that was performed was an analysis of the physical testing setup. An assumption made earlier in the analysis was that the system could be modeled as a simply supported beam in bending. For a simply supported beam with a centrally applied load 2P, the reaction for on each support should be P. However, there was uncertainty whether the full reaction forces would be applied due to the plastic deformation of the beam. It was reasoned that a portion of the load may be dissipated during the plastic deformation process. By testing the physical testing setup in FEA we aimed to determine how effect FEA would be in analyzing the adjustable supports. We will analyze Session #2, Test 5. In this test, the measured applied load was found to be 4.08 tons. Therefore, P=2.04 tons (P=4.08/2=2.04). The bend angle was found to be 27° and therefore $\theta = 13.5°$ ($\theta = \frac{27}{2} = 13.5$). The applied load is resolved to be the following.

$$P_y = Pcos\theta = 2.04\cos(13.5°) = 1.98tons = 19417N \tag{C10}$$

$$P_x = 2.04\sin(13.5°) = 0.48tons = 4707N \tag{C11}$$

During testing, the supports were welded to the base plate. Three welds are placed to fix the analyzed support to the plate. Both a course mesh and a fine mesh were run to check the validity of the results. It was found that the stresses were largest at the location of the applied load and at the connection to the base plate on the back side of the support. The stresses are highest on the back side of the support because the compressive bending stress from P_x adds to the compressive stress introduced by P_y. The results of the course mesh are shown in Figure C-4.

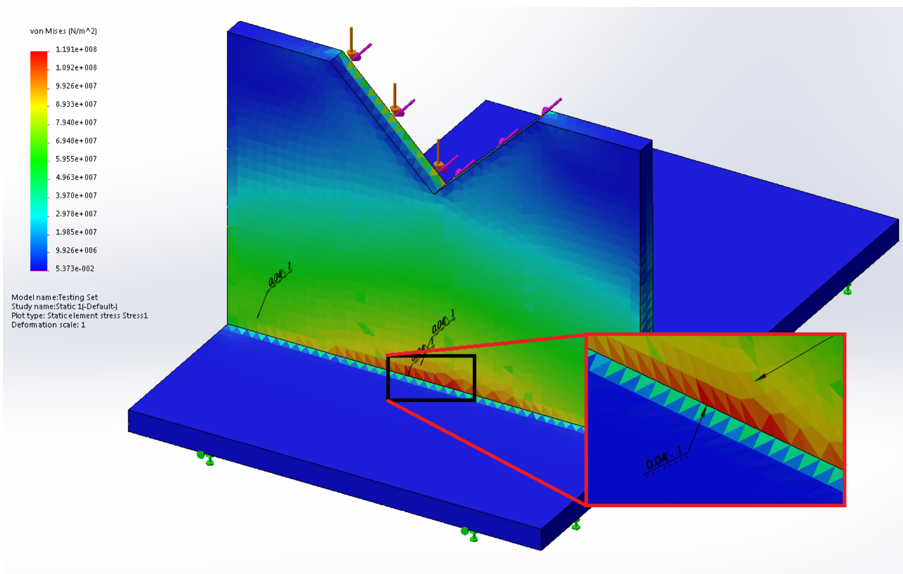


Figure C-4: Course mesh on welded plate [10].

We can see that the maximum stress on the back side of the plate is about 119MPa. This stress is well below 350MPa, the yield strength of CSA 350W steel. FEA predicts that the support should not fail during testing which was indeed the observed result. Running a finer mesh, similar stress were found on the back side of the plate which suggests that the results will converge. Figure C-5 shows the FEA results for a finer mesh.

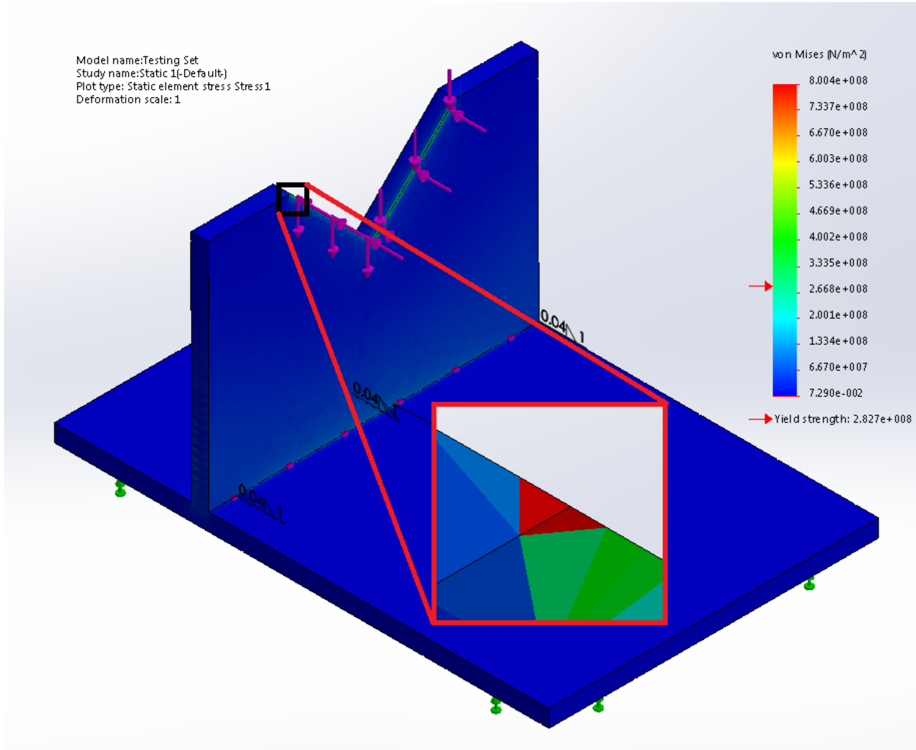


Figure C-5: Fine mesh on welded plate [10].

With the mesh refined, the stresses on the edge of the support where the loads are applied are seen to rise from about 100MPa to 500MPa. At the corner, shown in the expanded view, the stress is measured at 800MPa. These results are ignored because they occurs at the location of the applied force. Further mesh refinement will yield higher and higher stress. However, we can conclude that the stresses at the contact point with the beam will be high. This is not a large concern because it is compressive rather than tensile. At yield, the corner of the support would blunt and better distribute the load, thus reducing the stress.

The results of this analysis provide confidence in the FEA results and show that the reaction forces in the supports can be modelled as the case of a simply supported beam. The energy absorbed by the material during plastic deformation should not significantly impact the reaction forces experienced at the supports.

C.8.2 Relative Effect of Vertical vs Horizontal Load

As discussed previously, the applied load on a support is broken into two components: a horizontal force, which tends to bend the support, and a vertical force, which tends to compress the support. We want to determine which component of force is the most likely to cause failure in the supports.

C.8.2.1 Vertical Load

The only case where the bottom supports receive a pure vertical load is at the beginning of the bending process, when the beam has yet to yield or plastically deform. For the purposes of this study, we assume that the beam is receiving the maximum load without yielding and the force is transferred evenly between the two bottom supports. Since the beam is being forced through the die gap between two die, the vertical load will be on the inner edge of the die, and should be distributed along the V-shape of the beam. So, for the study the load is assumed to be a distributed load along the entire leading edge of the die surface. The applied loading conditions for FEA testing can be determined using the load equations.

$$P_y = Pcos\theta = 5\cos(0) = 5tons = 49033N \tag{C12}$$

$$P_x = 5\sin(0) = 0tons = 0N \tag{C13}$$

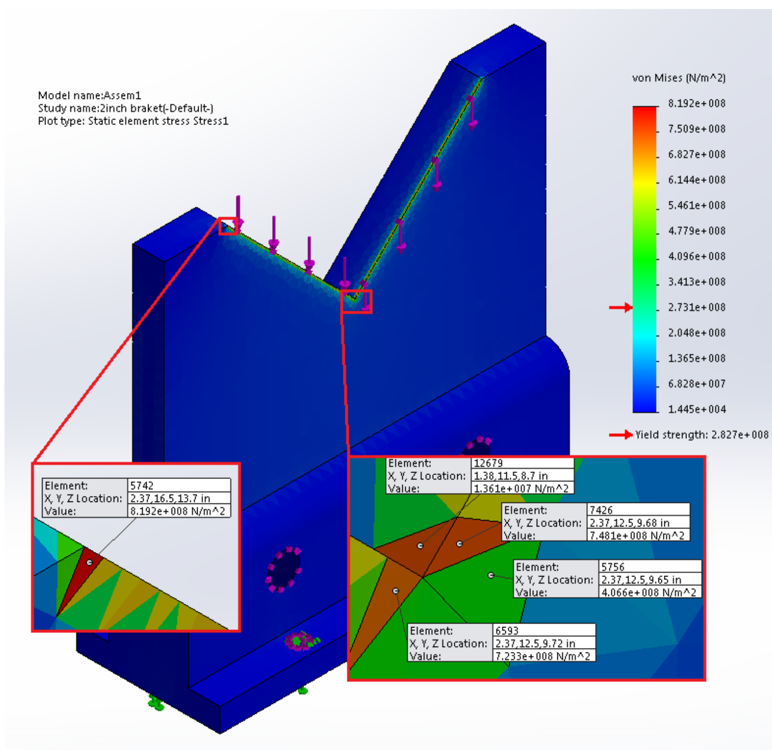


Figure C-6: Stress distribution on the front side of the die for a purely vertical load [10].

As seen in Figure C-6, the stress is higher along the leading edge of the die than any other point within the die. The stress seen in Figure C-6 maximizes at each of the corners, which can be attributed to a diverging result. The high stress along the length of the leading edge is expected, since that is the point of contact between the die and the beam. These FEA results show a stress at approximately 271 MPa (blue-green colour) along the edge, but since the load is applied at this edge, this stress is not a good representation of the stress in the die. Within the die the stress seen is very low (blue colour) and there is no risk of that section failing.

Since the stress is due to a compressive loading, there is less risk of the die failing catastrophically. This test is for a low load level, and it can be expected that the stress seen by the dies will increase as the load increases. Also, the stress on the backside of the die due to the vertical load is negligible.

C.8.2.2Horizontal Load

In no situation will the bottom dies ever be subject to a purely horizontal bending force, but in order to determine the effects of the horizontal loading FEA is performed under the assumption that the loading angle is 90°. The loading conditions are described by the following equations:

$$P_y = Pcos\theta = 5\cos(90) = 0tons = 0N \quad \text{(C14)}$$

$$P_x = 5\sin(90) = 5tons = 49033 \quad \text{(C15)}$$

The effects of the applied horizontal load can be seen in Figure C-7.

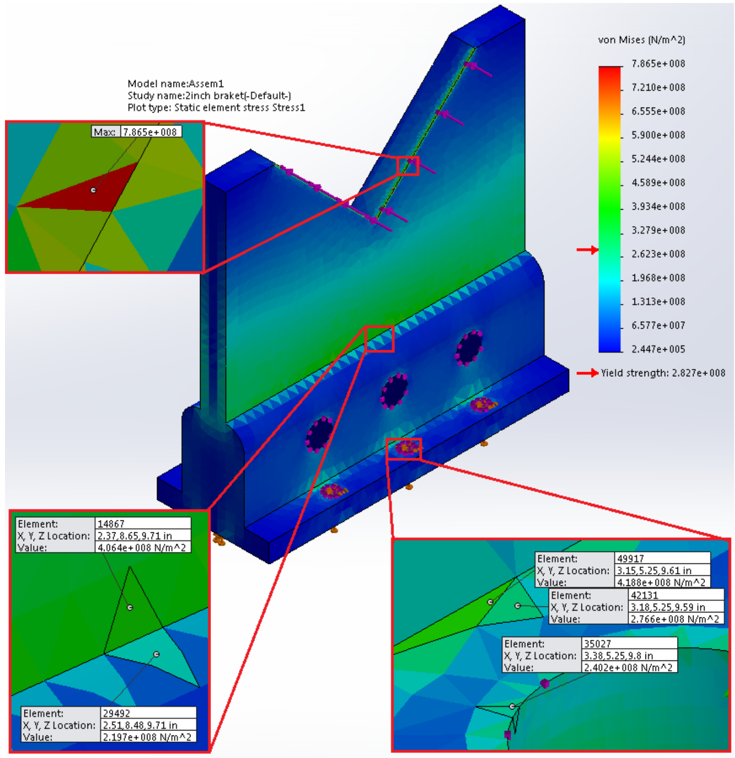


Figure C-7: Stress distribution on the front side of the die for a purely horizontal load [10].

The stress due to the applied horizontal load produces a case of bending within the die, with the front side in tension, and the backside in compression. The stress on the front of the die can be seen in Figure C-7. The stress is distributed evenly along the width of the die, but as the distance from the area of load application increases, the stress does as well. The stress in the die maximizes at the connection between the die and the support fixtures. The stress is also large along the contacting edge between the die and the beam.

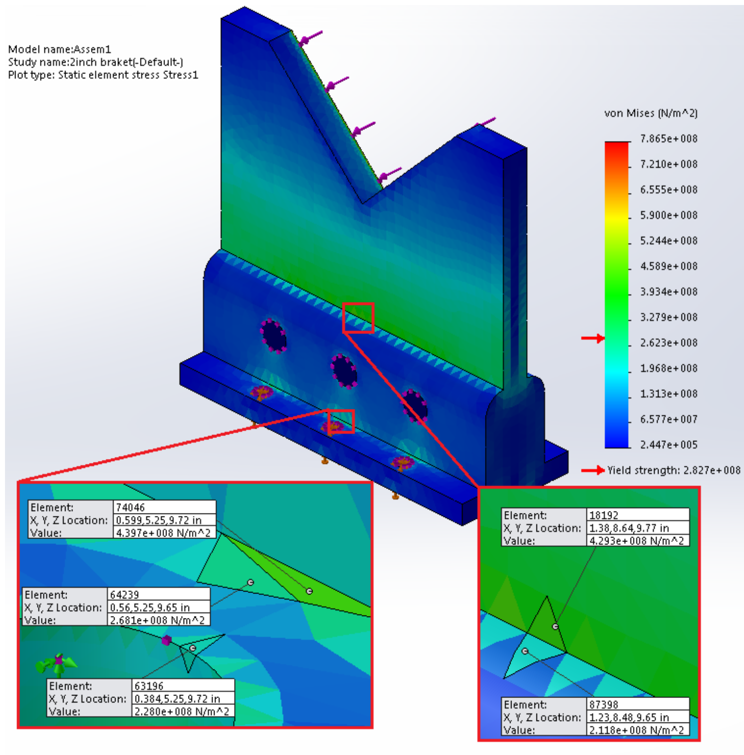


Figure C-8: Stress distribution on the backside of die due for a purely horizontal load [10].

The stress seen in Figure C-8 is on the backside of the die during the horizontal bend loading case. As seen in Figure C-7 and Figure C-8, the stress is even on each side of the die, though the backside doe not have any stress along the top edge. There is also a significant stress around the boltholes, for the bolts that connect to the base plate. The stress at this location does not approach the yield strength of the die, but it is possible that the bolts will not withstand the load transferred to them. Time constraints prevented throughout analysis of the stresses in the bolts.

The average stress seen in the die is approximately 262 MPa (blue-green colour), which is on both the front and backside of the die and also along the contacting edge.

C.8.2.3 Conclusions

From the results seen in sections C.8.2.1 Vertical Load and C.8.2.2Horizontal Load, the stress caused by the vertical load is minimal within the die, where as the stress caused by the horizontal force is distributed within nearly the entire die. The vertical load produces vertically compressive stresses on the die, and will produce a maximum value along the leading edge that is in contact with the beam. The horizontal bending force produces a larger scale stress that bends the die away from its initial position. The bending load also causes the die to push against the support fixtures, which tend to pull away from the base plate. Since, the supports are attached to the base plate via bolt connections, there is a risk of the bolts failing due to the applied tension.

As a result, the FEA study suggests that the horizontal loading is more likely to cause the die structure to fail. It is important to note that the level of horizontal loading applied to the dies will not reach the level seen in this study. Since the maximum loading angle will never exceed 22.5° (corresponding to a 45° bend), the actual horizontal load will be significantly lower than seen in the study and the effects on the stress will be reduced accordingly.

Since the horizontal bending case is the driving force for die failure, a mesh refinement convergence study was performed in order to verify whether the stress results converge to a solution in the die.

Figure C-9 shows the stress distribution on the die using a course mesh setup. The results are as expected, with the highest stress value at the connection between the die and the support fixture. There is also a large stress in the boltholes but this result may not be convergent. Figure C-10 uses a medium level mesh, and the figure shows that the distribution of the stress becomes more distinct within the die. The red area is reduced to a smaller area around the connection to the support. Also, the bolthole stress lowers to a stable result.

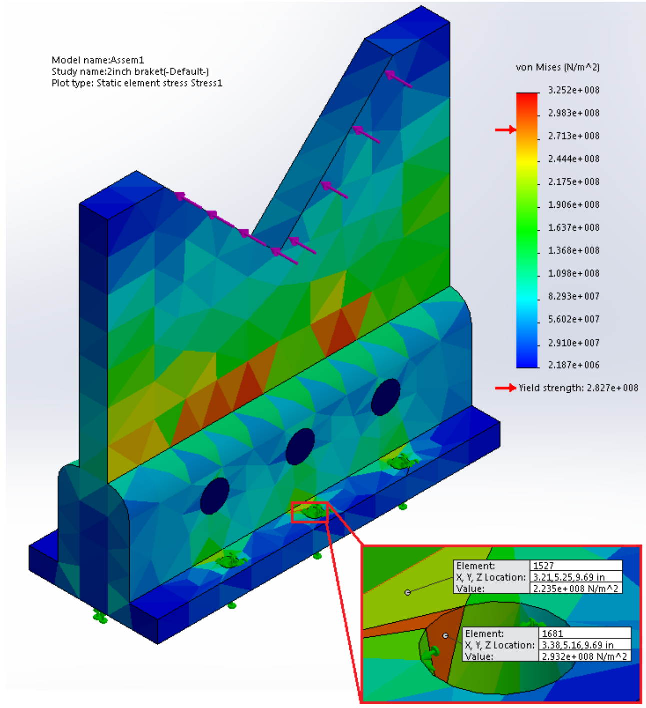


Figure C-9: Horizontal loading study using a course level mesh [10].

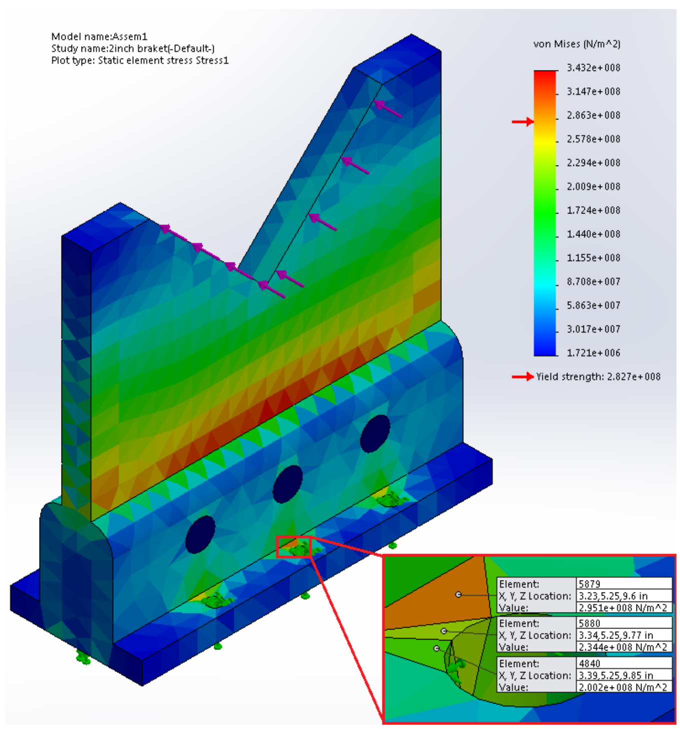


Figure C-10: Horizontal loading study using a medium level mesh [10].

This convergence study provides evidence that the stress is converging to a solution at each of the areas of high stress. Along the connection between the die and the fixture, the stress is approaching the yield strength of 350W steel, which is 350 MPa. From the fine mesh seen in Figure C-7, the stress at the connection is approximately 330 MPa.

C.8.3 Effects of Beam Size and Die Geometry

This section explores the effects of the beam size on the stress distribution within the die. In order to determine the die geometry required to support loading from a range of beam sizes, a study is performed for multiple bending cases at a maximum loading angle of 45°. The loading cases considered are separated based on the die thickness used. Initial design parameters are for a 1” plate thickness, which is the initial design pursued by the design team. A secondary design was modelled using a 2” die thickness.

C.8.3.1 Die Designed With a 1” Plate Thickness

Using a 1” die thickness, some FEA studies were performed for multiple loading cases based on the maximum load case resulting from different beam sizes being bent to 45°. The cases studied are tabulated in TABLE C-IX.

TABLE C-IX: LOADING CASES FOR 1" DIE THICKNESS

Bracket Size	Support Width	Beam Size	Load Applied	P_x	P_Y
Thin	1”	2×2×3/8	2.26 Tons	4217 N	10199 N
Thick	1”	6×6×1	20.72 Tons	38834 N	93850 N
Thick	1”	Max Load	8.74 Tons	16377 N	39619 N

The loading produced by a 2×2×3/8 beam sample is the smallest loading case considered. It is expected that the die will not receive excessive load since this case is similar to the testing performed at Sperling Industries. The numerical results produced for each case are explored using similar boundary conditions and loading conditions.

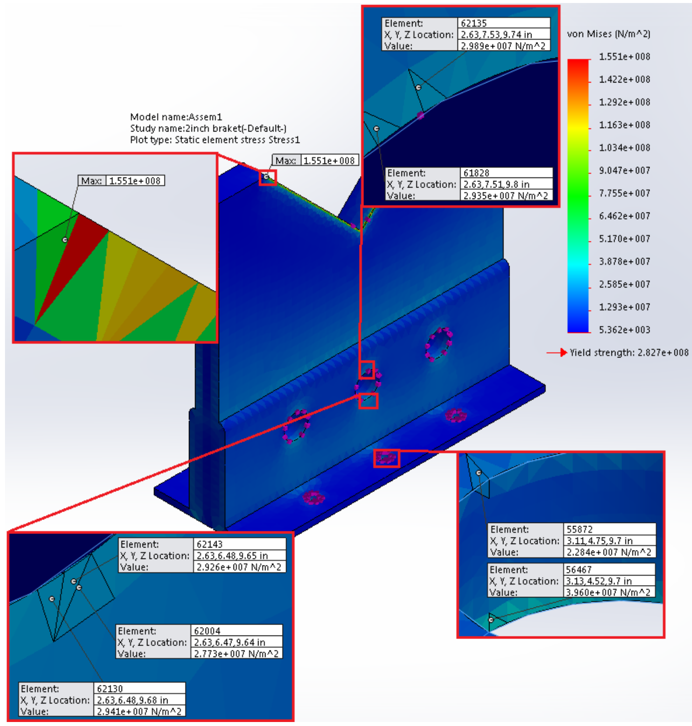


Figure C-11: Stress distribution on the front of die due to a 2x2x3/8 beam [10].

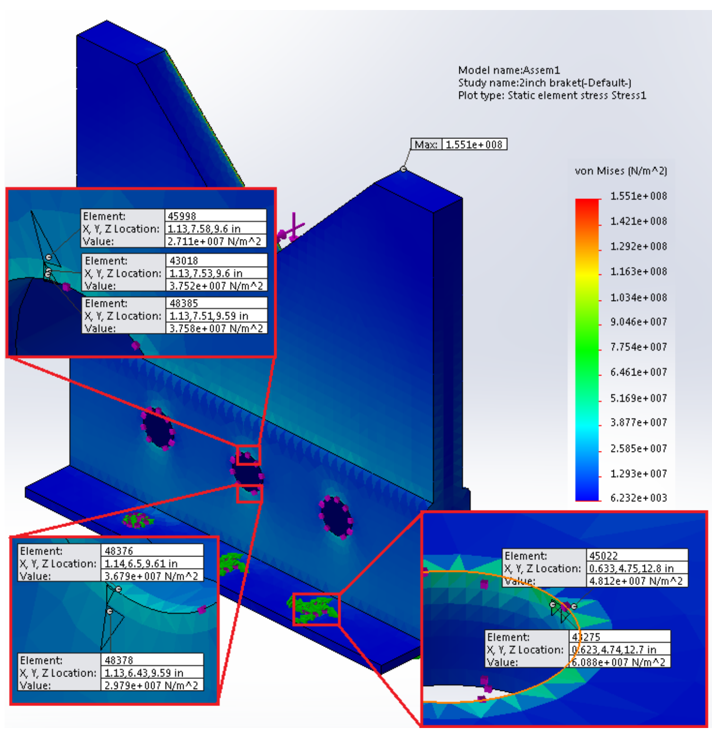


Figure C-12: Stress distribution on the back of die due to a 2x2x3/8 beam [10].

Figure C-11, and Figure C-12 show the stress distribution on the front and back of a 1” thick die, under the load of a 2x2x3/8 beam, respectively. As seen in the figures, there are no areas with high stress concentrations within the beam area. One point in Figure C-11 shows a large spike in stress, but points along the top edge tend to diverge due to the applied loading and boundary conditions. The points of interest for failure in the die structure and fixtures are around the boltholes and the connection between the die and supports. Stresses around the locations of interest are marginally higher than other locations in the die, but the stresses will not cause any major deformation within the die structure. The backside of the die has slightly higher stresses than the front end, which can be explained by analyzing the stresses in terms of their component loads. The front side of the die experiences a tensional stress from the horizontal bending force, and a compressive stress from the downward vertical load. These components produce a smaller total stress in the front end of the beam. The backside of the die experiences a similar compressive stress due to the vertical load but the bending stress is also compressive, which causes a larger total stress on the backside in comparison to the front side.

The numerical results confirm what the design team has tested, which is that the bending case of a 2x2x3/8 beam will not produce a large amount of stress in the dies. The results of the numerical data and physical testing prove that the 1” die structure is sufficient to bend beams up to 2x2x3/8 in size to any range of bend angle.

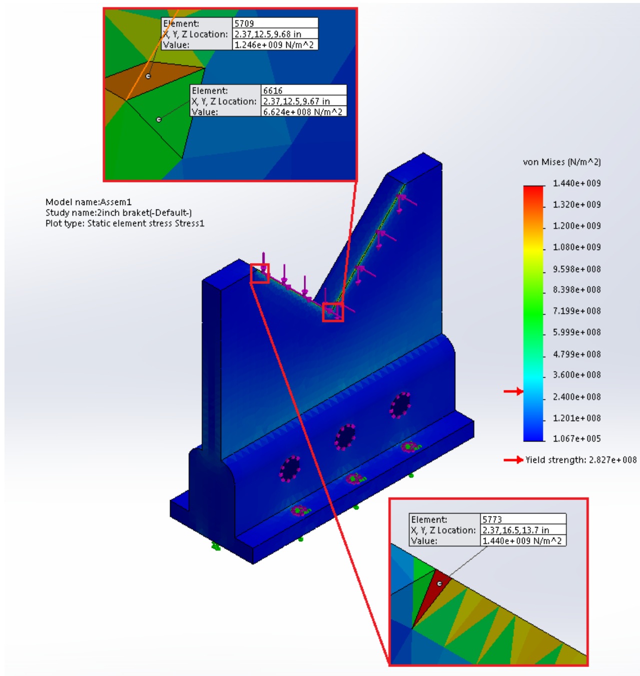


Figure C-13: Stress distribution on the front of die due to a 6x6x1 beam [10].

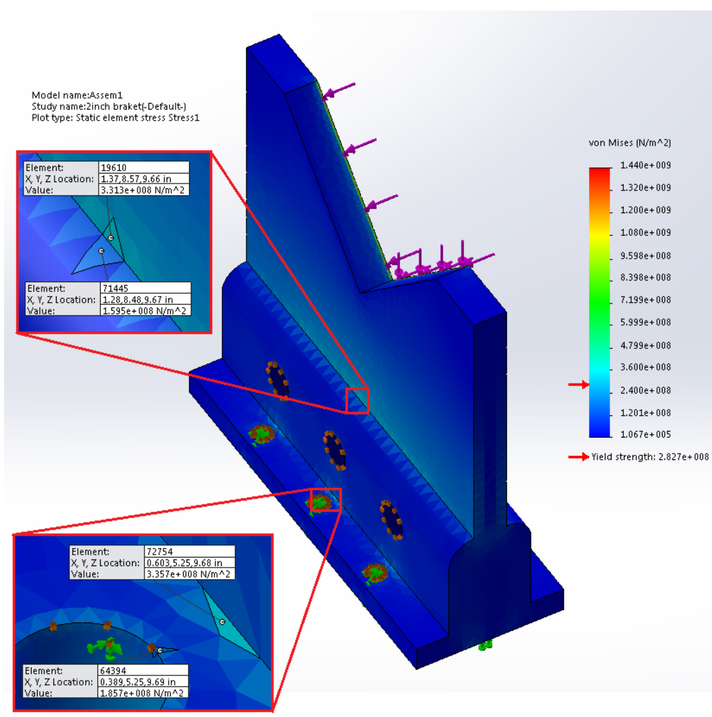


Figure C-14: Stress distribution on the back of die due to a 6x6x1 beam [10].

Figure C-13 and Figure C-14 show the stress concentration produced during the bending of a 6x6x1 beam sample. Similar to the study performed on the smaller beam sample, the stress within the die is concentrated in key areas around the boltholes, and along the connection between the die and support fixtures. Under the loading condition from a 6x6x1 beam the stress in the die at the support connection is starting to exceed the strength of the 350W steel. This loading condition is not at the top of the load range specified by the customer needs, which suggests that the die support thickness of 1” is insufficient to satisfy the design requirements.

With the limitations of the 1” die in mind, the final FEA study using the 1” thickness is performed in order to determine the functional load for the 1” die structure.

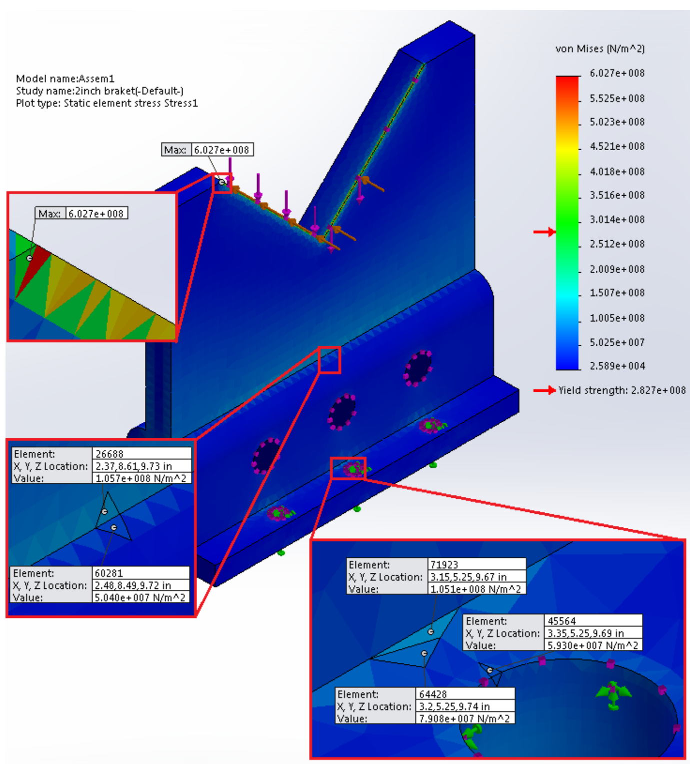


Figure C-15: Stress distribution on the front of die due to 8.74 ton loading [10].

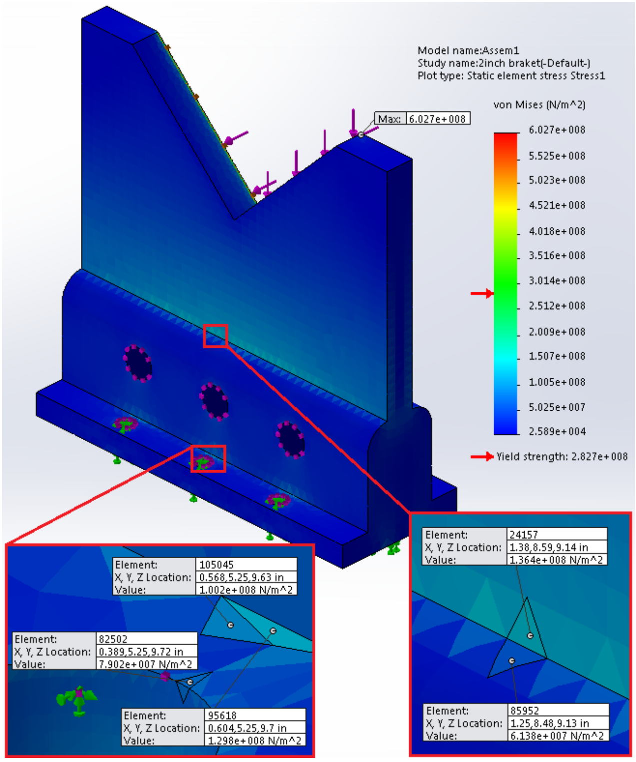


Figure C-16: Stress distribution on the back of die due to 8.74 ton loading [10].

The stress seen in the die supports are well below the yield limit of the material in this case. As seen in Figure C-16, as seen in previous studies, the largest stress in the support is seen at the connection between the die and fixtures.

C.8.3.2 Die Designed With a 2” Plate Thickness

Since the 1” die case was not considered to be sufficient in order to satisfy the design goals, the thickness of the support die was increased. Since the base plate bolthole spacing is constant at 1” centre-to-centre spacing, the simplest solution is to increase the die thickness by a 1” increment. Two additional studies were performed using a die thickness of 2” and a variety of loading conditions. TABLE C-X lists the studies performed using a die thickness of 2”.

TABLE C-X: LOADING CASES FOR 2" DIE THICKNESS

Bracket Size	Support Width	Beam Size	Load Applied	P_x	P_Y
Thick	2”	6×6×1	20.72 Tons	38834 N	93850 N
Thick	2”	8×8×1	32.36 Tons	60703N	146609 N

To start the studies on the 2” die thickness, the first case considered is the case that failed for the 1” thick die. Since the 1” die is sufficient for lower loading the 2” die is assumed to also be sufficient due to the larger die cross-section.

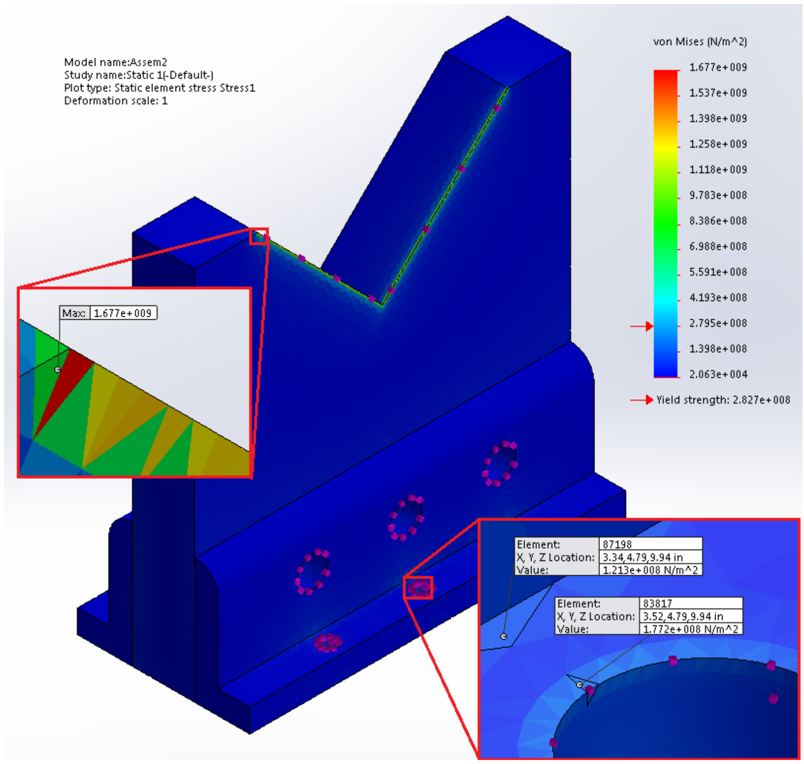


Figure C-17: Stress distribution on the front of die due to 6x6x1 beam [10].

Figure C-17 shows the stress distribution in the 2” die due to the loading created by a 6×6×1 beam in bending. The bend angle considered is 45° about the front face of the die. The stress shown in the die is generally very low. There is an increase in stress along the edge of load application, but Figure C-17 does not accurately show the stress distribution. Along the boltholes in the bracket fixtures there is also a stress concentration, but the stresses do not exceed the strength of the material. The average stress seen in the die is around 100-150 MPa, which is represented by the blue colour.

The second case considered for the 2” plate analysis is for the maximum loading condition using the load produced by an 8×8×1 beam. The load required to bend the 8×8×1 beam is much larger than what was previously required for the 6×6×1 beam. Since the load increases by a large amount, the stress is expected to approach the maximum allowable stress.

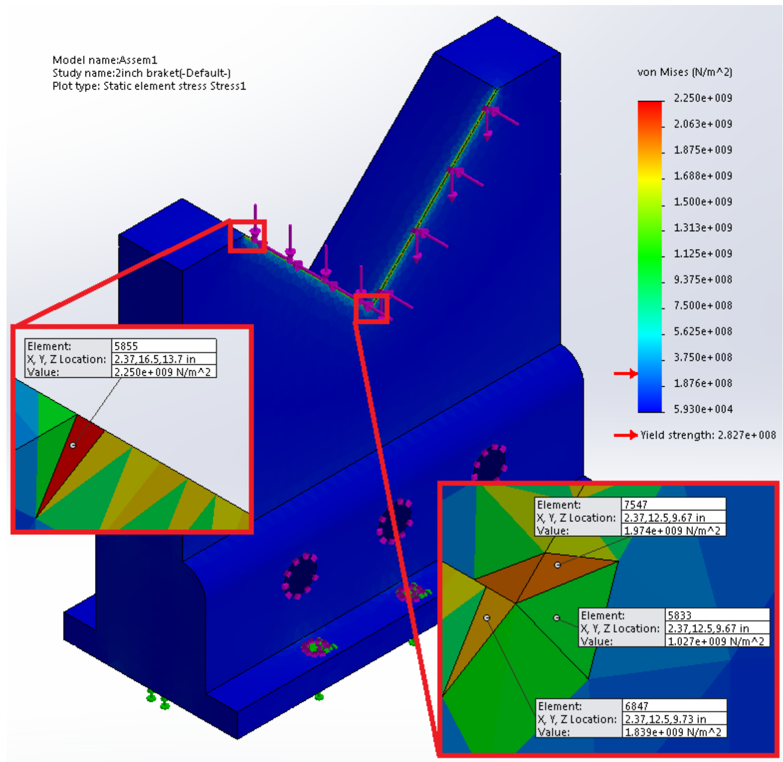


Figure C-18: Stress distribution on the front of die due to 8x8x1 beam [10].

From Figure C-18, it is evident that the stress has increased in comparison to the 6x6x1 beam results since the average stress in the die is approximately 180-200 MPa. The die does appear to be sufficient to support the load created by the 8x8x1 beam. The edge of load application shows a large stress concentration, but as previously mentioned, Figure C-18 does not provide an accurate description of the stress.

C.8.4 Conclusions Regarding Support Dies

It can be concluded from the FEA studies that the main areas for concern regarding failure are the boltholes, connection between die and support and the contact edge. Since the load from the beam is in direct contact with the edge portion of the die, contact stresses will be present as a result of the rubbing between the die and beam. The boltholes connecting the die fixtures to the base plate, as well as the connection between the die and the support brackets are also key failure areas. Though the pinholes on the bracket supports have not shown a large reaction to the load application, it is possible that the pin connection will receive a significant portion of the load.

It is important to note that most of the FEA testing was performed under the assumption that the load is applied in the worst, or maximum possible case, which occurs for 45° bends. This gives a much larger applied horizontal force than vertical force. For the majority of beam bending cases the bend angle will be below 20°, and the vertical load will be larger than the horizontal load. With a reduction in horizontal load, the bending moment produced on the die, and support fixtures will be reduced as well. The FEA studies showed a stress concentration around the boltholes, but at low bending loads it is unlikely that the bracket fixtures will experience large forces in the bolts or bolt holes.

In order to know for certain whether the support dies will be safe to operate under the application of the maximum load range, extensive physical testing must be performed. For safety, it is not recommended to perform bending operations on the worst-case bend scenario, the 8x8x1 at 45°, without prior testing done using lower applied loads, at lower bend angles.

C.8.5 Bottoming and Top Die

During the experimental testing, one study is performed on the bottoming die. The purpose is to determine the forces acting within the bottoming die, and predict the possible failure mechanisms. The assumption is that the bottoming die is taking major compression force but only minor transverse forces. This is because the transverse forces are very small when compared to the compression force and the transverse forces act as a pair. During the compressing process, the pair of transvers2 forces act closely to each other and will cancel out eventually. Hence, for the purposes of FEA testing, the design team only considers the loading due to a pure compression force.

For the FEA study performed on the bottoming die, the condition is set up with a load of 32.36 tons applied to the inside surface of the bottoming die. As mentioned earlier, although a large portion of the total force is compressive, there is a minor portion of the forces acting in the transverse directions. So, for the purpose of this study, 317,343N is applied as a purely compressive force to the bottoming die. In addition, since the beam is heated to about 600 degrees Celsius for bending a temperature boundary condition is set up as 100 degrees Celsius for the bottoming surface[1]. The die brackets are fixed in position to a base plate surface. The overall mesh is built using the fine mesh setting. Edges and surfaces around points of interest use a very fine mesh. Jacobean 4 points were used for element setting, and the size of each element is 0.029" with an element ratio of 3.1. Also, 8 cores parallel computing is used for simulation. The simulation result on the bottoming die is shown in Figure C-19.

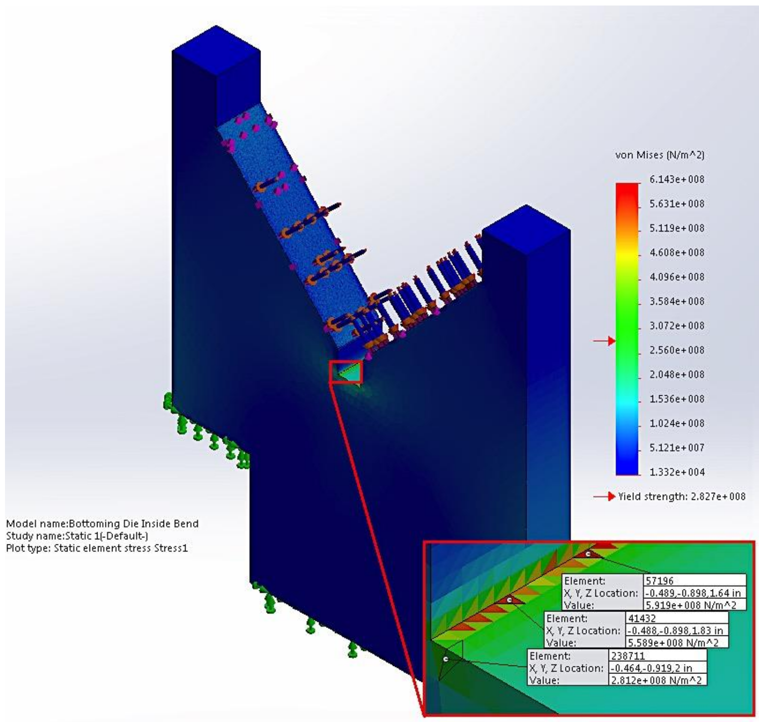


Figure C-19: FEA analysis on bottoming die [10].

As seen in Figure C-19, most of the surface area on the bottoming die is showing a blue color. The blue region indicates that the areas are taking minor stresses. Areas showing a blue-green color experience a stress level around 250 MPa in that region. The maximum stress occurs at the edge of the centre slot. In the enlarged portion of Figure C-19, the red elements are linearly distributed along the edge, which implies that the high stress region could result in a mode I fracture (tearing).

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[1] The temperature setting data is an assumed number. After the testing session, Sean checked the die and observed the bottoming die is warm, but not hot. Therefore, 100 degree Celsius is an approximate value for setting the temperature boundary condition.

Regarding the top die, our team observed that most of the compressive forces are taken by the bottom centre area and the edges of the bottom surface. This loading case is similar to that of the bottoming die, and the transverse forces are minor compared to the compressive forces. Therefore, the points of interest for the top die will also experience a purely compressive loading case.

The top die FEA study is initially loaded with a compressive force of 317,343N as well as a 100 degree Celsius thermal boundary condition applied to the bottom surfaces of the top die. A fixed condition is set upon the top surface of the die to simulate the die fixture in the design. The program is setup with a fine mesh using Jacobean 4 point's elements. The element size is 0.029" and the element ratio is 3.1. Also, 8 cores parallel computing is used for simulation. Figure C-20 shows the overview of the top die experiencing a pure compression loading condition.

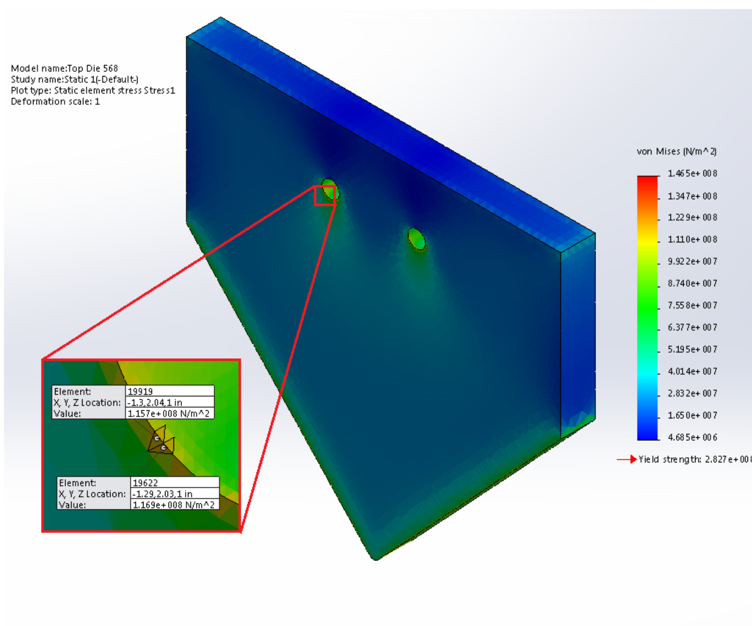

Figure C-20: FEA top die under compression [10].

Through Figure C-20, the entire piece of top die is under yielding strength. The largest stresses occur in and around the pinholes and on the bottom surfaces. In enlarged portion of Figure C-20 we can see the edge of the pinholes is taking larger stresses compared to the other areas, with a maximum of around 120 MPa.

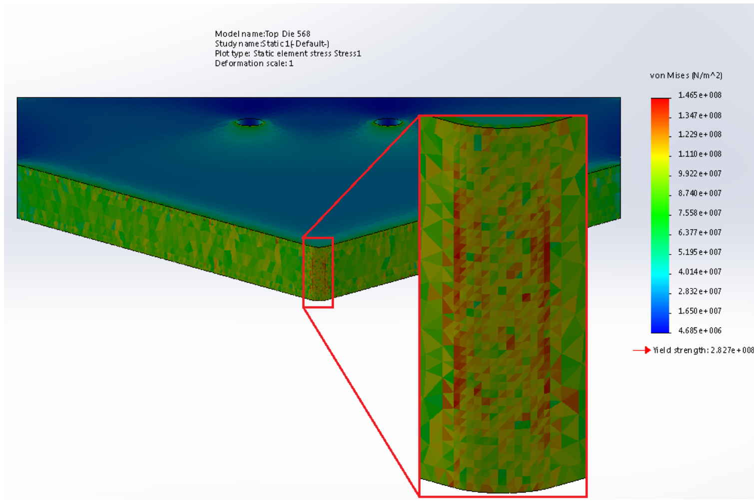

Figure C-21: FEA at bottom surface of testing top die [10].

Figure C-21 shows how the bottom centre area experiences the largest stresses in the die. This implies that the centre of compression in the subject beam will also take the highest stress, which may be where fracture cracks will start to develop. The highest stress is approximately 145 MPa at the very tip of the die, whereas the bottom side areas are showing a green-yellowish colour from the centre to the end. This indicates that the temperature affects the bottom center of top die rather than the sides. Although temperature may affect the yield strength, there is no sign in this FEA study of the material yielding, which suggests that the top die will survive the condition the loading condition that has been set up.

C.9 References

[1] R. Bruce, *Handbook of Lubrication and Tribology*, 2nd ed. Boca Raton: Taylor & Francis Group, 2012.

[2] J. Chen, B. Young, and B. Uy, "Behaviour of High Strength Structural Steel at Elevated Temperatures," *Journal of Structural Engineering,* vol. 132, no. 12, pp. 1948-1954, 2006.

[3] Canadian Standards Association, *CSA Metal Specifications, CSA, 1978.*

[4] W. D. J. Callister and D. G. Rethwisch, *Materials Science and Engineering: An Introduction*, 8th ed. Hoboken: Wiley, 2010.

[5] AZO Materials. (2015). *AISI 4340 Alloy Steel*. [Online]. Available: http://www.azom.com/article.aspx?ArticleID=6772#4 [2015, Nov 28].

[6] J. Greenslade, *Torque Book for Fasteners*, Canada: Industrial Fasteners Institute, 2013.

[7] F. Beer, E. R. Johnston Jr., J. DeWolf, and D. Mazurek, *Mechanics of Materials,* 6th ed. New York: McGraw-Hill, 2009.

[8] Acklands-Grainger. (2015). *Cylinder Hyd Hol-Plung SGL Act 60TN*. [Online]. Available: https://www.acklandsgrainger.com/AGIPortalWeb/WebSource/ProductDisplay/globalProductDetailDisplay.do?item_code=ENPRCH603 [2015, Nov 26].

[9] Justin Marek. "Labelled Figures." Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, 2015, Dec 3.

[10] Jiaxin Yan. "Solidworks FEA Analysis." Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, 2015, Dec 1.

Appendix D

Assembly and Manufacturing Details

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D.1. Introduction

The assembly and manufacturing of the die assembly are to be mostly completed in house at Sperling Industries. Therefore, our design is required to remain moderately simple to produce and construct. The material being considered should be readily available to Sperling Industries and workers should be able to manufacture most parts on site. Some fabricated parts for fixtures may require a forklift to move, but parts that require changing on a regular basis must be moveable by hand.

The main focus of the design team was to maintain a low number of parts within the die structures, and also reduce the weight of the assembly as much as possible. These two ideas have an inverse relation, since the weight of the assembly will increase as the number of components is reduced. Our goal for the assembly was to have the construction be done by a maximum of 2 workers. This means that the total weight of individual components must be moveable by two people. For larger parts, like the base table fixture that holds the bottom dies, a forklift or similar moving device will be required to position during initial die assembly. Essentially, the parts that will be replaceable, or exchangeable must be moveable by two worker, while the fixtures and base structure can be moved using forklift or hoist systems as needed.

Some of the manufactured parts include tolerances that must be met for important design features. These are typically areas that will come into contact with the beam, including die surfaces, die angles, edge chamfers and fillets. The bending surfaces in contact with beams should be machined properly to avoid surface damages that could lead to cracking and premature failure of the dies. Die surfaces should also be well finished to ensure beams are not damaged during bending. For fixtures, the location of bolt holes, and screw holes should be drilled accurately to ensure die gap spacing is accurate to the bending reference chart. The bottom support plate in the design has many bolt holes that act as an integer spacing for the side dies. The top die must be securely fastened to the top fixture, and the top fixture must be securely fastened to the press cylinder. These manufacturing features are necessary to provide a safe and sustainable bending process.

Appendix E

Cost Analysis

Table of Contents

List of Tables

E.1 Introduction

The costs associated with this design can be broken down into two segments: material costs and manufacturing costs. The details of each of these cost segments are included in the following sections. The projected benefits of implementation are discussed as well.

E.2 Material Costs

The costs presented in this section are those related to the purchasing of materials required to assemble the design. These costs are broken down by the specific assembles to which they relate. The bill of materials is included in the main body of the report. All materials costs were acquired from the McMaster-Carr website [1]. Costs for CSA 350W and AISI 4340 steel were based on prices for General Purpose Low-Carbon Steel. The hydraulic jack cost was obtained from the Acklands-Grainger website [2]. The digital protractor cost was obtained from the Amazon [3] and sold by Hammerhead. The bill of materials is included in the main report body. The total material cost comes to $8346.03 USD before applicable taxes.

E.3 Manufacturing Costs

The manufacturing costs required to machine and assemble the design are included in TABLE E-I. These costs are estimates only and are based on a $70.00/hr USD labour rate. The following table summarizes the estimated manufacturing costs. Comments are provided on the required machining operations for each component.

TABLE E-I: ESTIMATED MANUFACTURING COSTS

Hours	Component	Part #	Unit Price ($USD/hr)	Line Price ($USD)	Comments
	Assembly - Base Plate				
13.0	Base Plate	A01	$70.00	$910.00	Initial cutting to size. 72 tapped 0.5" bolt holes. 9"x2.2" milled cutout
	Assembly - Side Supports				
1.0	Side Supports Inside Bend Thin	B01	$70.00	$70.00	Initial cutting to size. Cut profile. Drill pinholes
1.0	Side Supports Outside Bend Small Thin	B02	$70.00	$70.00	Initial cutting to size. Cut profile. Drill pinholes
1.0	Side Supports Outside Bend Large Thin	B03	$70.00	$70.00	Initial cutting to size. Cut profile. Drill pinholes
1.0	Side Supports Inside Bend Thick	B04	$70.00	$70.00	Initial cutting to size. Cut profile. Drill pinholes
1.0	Side Supports Outside Bend Small Thick	B05	$70.00	$70.00	Initial cutting to size. Cut profile. Drill pinholes
1.0	Side Supports Outside Bend Large Thick	B06	$70.00	$70.00	Initial cutting to size. Cut profile. Drill pinholes
2.0	Support Brackets Small	B07	$70.00	$140.00	Cut beam to size. Trim flange. Drill bolt holes and pin holes
2.0	Support Brackets Large	B09	$70.00	$140.00	Cut beam to size. Trim flange. Drill bolt holes and pin holes
2.0	Bracket Pins	B11	$70.00	$140.00	Cut pins to size. Chamfer edges
	Assembly - Top Die				
3.0	Top Fixture Base	C01	$70.00	$210.00	Cut plate to size. Mill channels. Weld fixture together
1.0	Cylinder Fixture	C02	$70.00	$70.00	Cut plate to size. Drill pin hole
1.0	Top Die Fixture	C03	$70.00	$70.00	Cut plate to size. Drill bolt holes
1.0	Top Die Inside Bend Small	C04	$70.00	$70.00	Cut plate to size. Cut profile. Drill bolt holes
1.0	Top Die Inside Bend Large	C05	$70.00	$70.00	Cut plate to size. Cut profile. Drill bolt holes
1.0	Top Die Outside Bend Small	C06	$70.00	$70.00	Cut plate to size. Cut profile. Drill bolt holes
1.0	Top Die Outside Bend Large	C07	$70.00	$70.00	Cut plate to size. Cut profile. Drill bolt holes
1.0	Top Pin	C08	$70.00	$70.00	Cut pin to size. Chamfer edges
	Assembly - Bottoming Die				
3.0	Bottom Fixture Base	D01	$70.00	$210.00	Cut plate to size. Mill channels
5.0	Bottoming Die Inside Bend	D02	$70.00	$350.00	Cut bar to size. Cut profile
5.0	Bottoming Die Outside Bend	D03	$70.00	$350.00	Cut bar to size. Cut profile
				$3,360.00	

The total manufacturing cost to machine and assemble the adjustable press die comes to $3360.00 USD before applicable taxes.

E.4 Projected Benefits

The total cost of the project included material costs and manufacturing costs comes to an estimated $11706.03 before applicable taxes. Assuming a tax rate of 13%, the total capital cost comes to $13227.81

It is estimated that 30 minutes of labour can be saved per beam with an estimated 400 beams per year. Labour is taken at $70/hr USD. Power and material savings will be negligible compared to the cut and weld process currently in use. The per year savings is therefore estimated to be $14000. It is assumed that the salvage value at the end of the study period is negligible. The average cost of capital for the metal fabrication industry is 9.53% [4]. However, since Sperling Industries is a small manufacturer there are additional risks which raise the cost of capital. In order to keep the analysis conservative a 50% increase to the average cost of capital for metal fabrication companies. This sets the cost of capital for Sperling Industries at 14.30%.

The Net Present Value (NPV) is calculated as

$$NPV = -C_0 + \sum_{t=1}^{3} \frac{C_t}{(1+i)^t} + PV_S \qquad \text{(E1)}$$

where C_t is the cash inflow during the time period t, C_0 is the total initial investment costs, i is the cost of capital, and PV_s is the present value of future salvage. The total NPV is calculated as follows for a three year study period.

$$NPV = -13227.81 + \sum_{t=1}^{3} \frac{14000}{(1+0.1430)^t} = \$19112.12 \qquad \text{(E2)}$$

Therefore, this project is estimated to have an NPV of $19112.12.

E.5 References

[1] McMaster-Carr. (2015). *McMaster-Carr Website*. [Online]. Available: http://www.mcmaster.com/# [2015, Nov 26].

[2] Acklands-Grainger. (2015). *Cylinder Hyd Hol-Plung SGL Act 60TN*. [Online]. Available: https://www.acklandsgrainger.com/AGIPortalWeb/WebSource/ProductDisplay/globalProductDetailDisplay.do?item_code=ENPRCH603 [2015, Nov 26].

[3] Amazon. (2015). *Hammerhead 10-Inch Digital Level with Laser*. [Online]. Available: http://www.amazon.com/dp/B00OZHIGGE/ref=asc_df_B00OZHIGGE4002369?smid=ATVPDKIKX0DER&tag=shopzilla0d-20&ascsubtag=shopzilla_rev_273-20;14483819967904135438710030301008005&linkCode=df0&creative=395093&creativeASIN=B00OZHIGGE [2015, Nov 26].

[4] Aswath Damodaran. (2015, Jan.). *Cost of Capital by Sector*. [Online]. Available: http://pages.stern.nyu.edu/~adamodar/New_Home_Page/datafile/wacc.html.htm [2015, Dec 2].

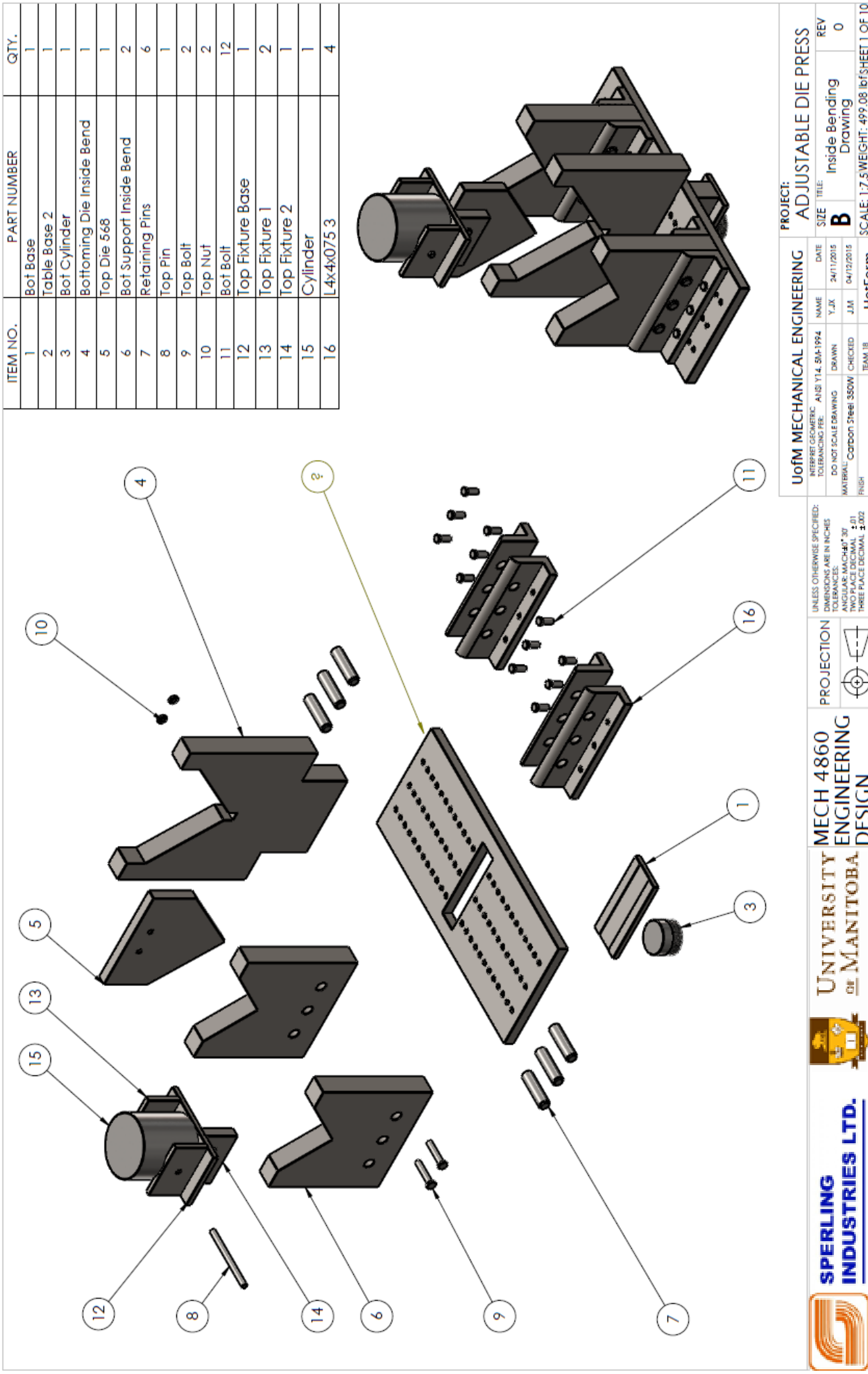
Appendix F

Engineering Drawings

Table of Contents

F.1 Introduction

Detailed engineering drawings are included to facilitate manufacture of the die's many custom components. First, a complete set of drawings are included for the double angle inside bend configurations. Next, the components unique to the double angle outside bend are detailed, along with an assembly drawing of the double angle outside bend configuration.



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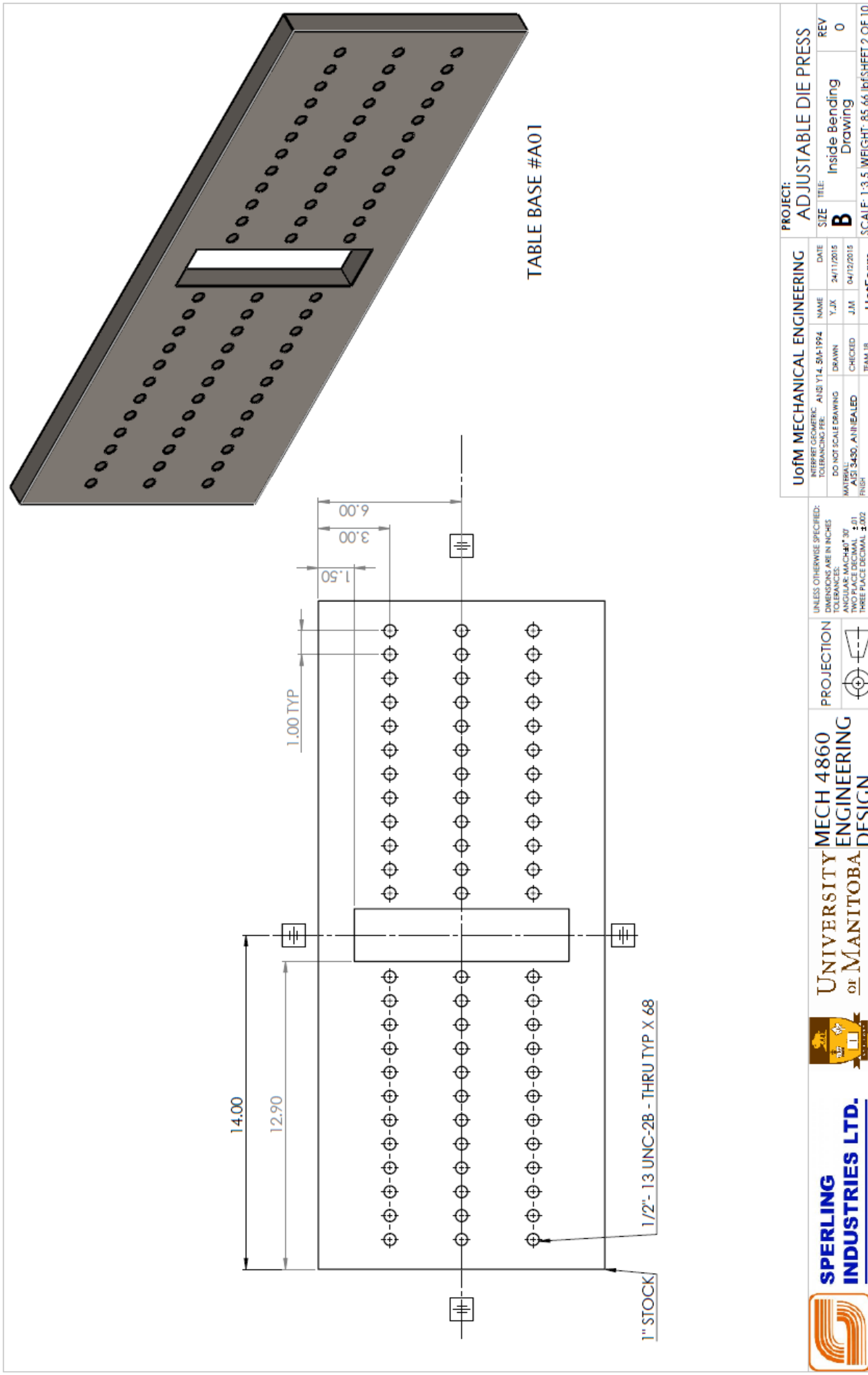
2	Table Base 2	1
3	Bot Cylinder	1
4	Bottoming Die Inside Bend	1
5	Top Die 568	1
6	Bot Support Inside Bend	2
7	Retaining Pins	6
8	Top Pin	1
9	Top Bolt	2
10	Top Nut	2
11	Bot Bolt	12
12	Top Fixture Base	1
13	Top Fixture 1	2
14	Top Fixture 2	1
15	Cylinder	1
16	L4x4x075 3	4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CHECKED J.M 04/12/2015
TEAM 18
HotForm
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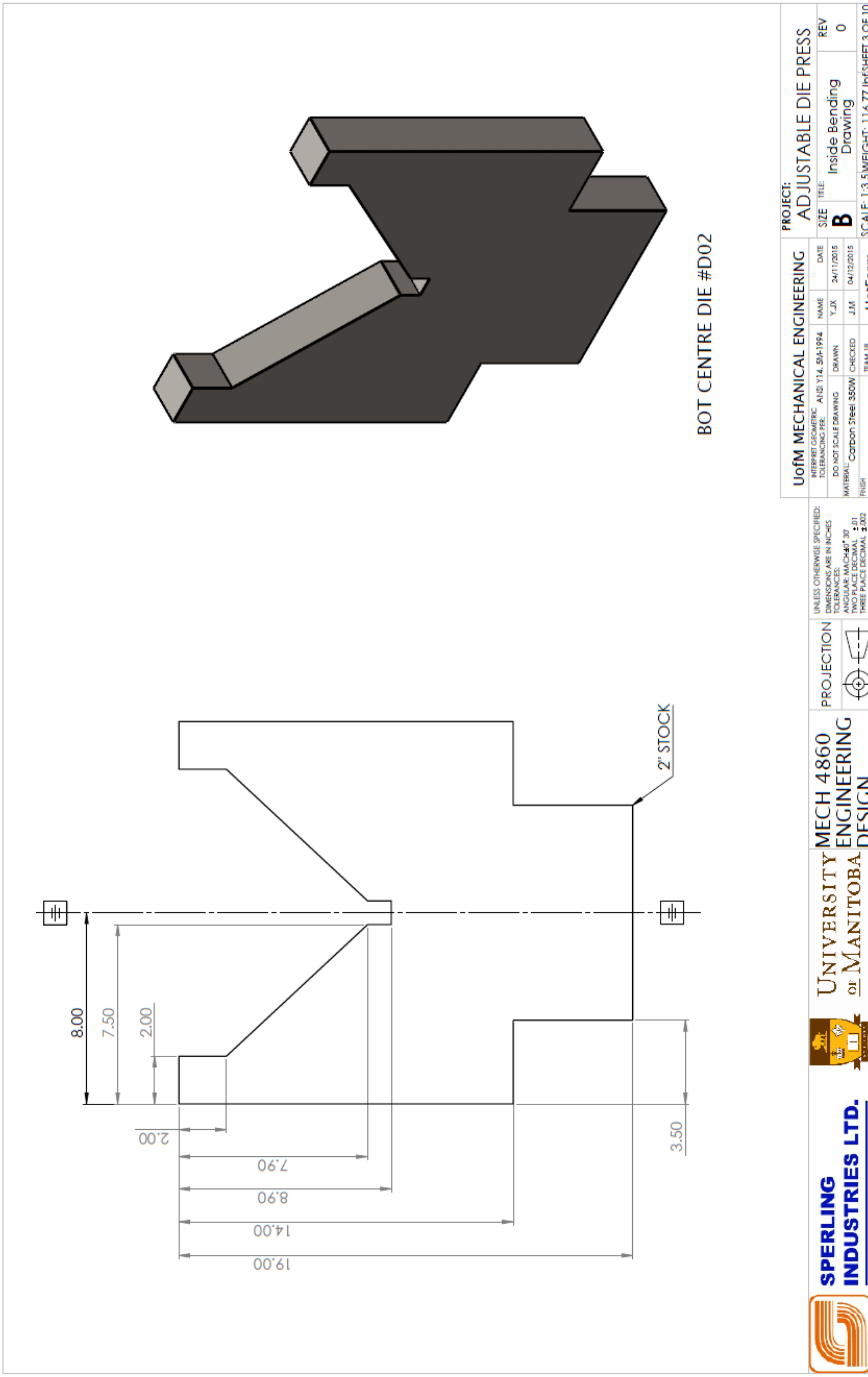
UNIVERSITY OF MANITOBA
SPERLING INDUSTRIES LTD.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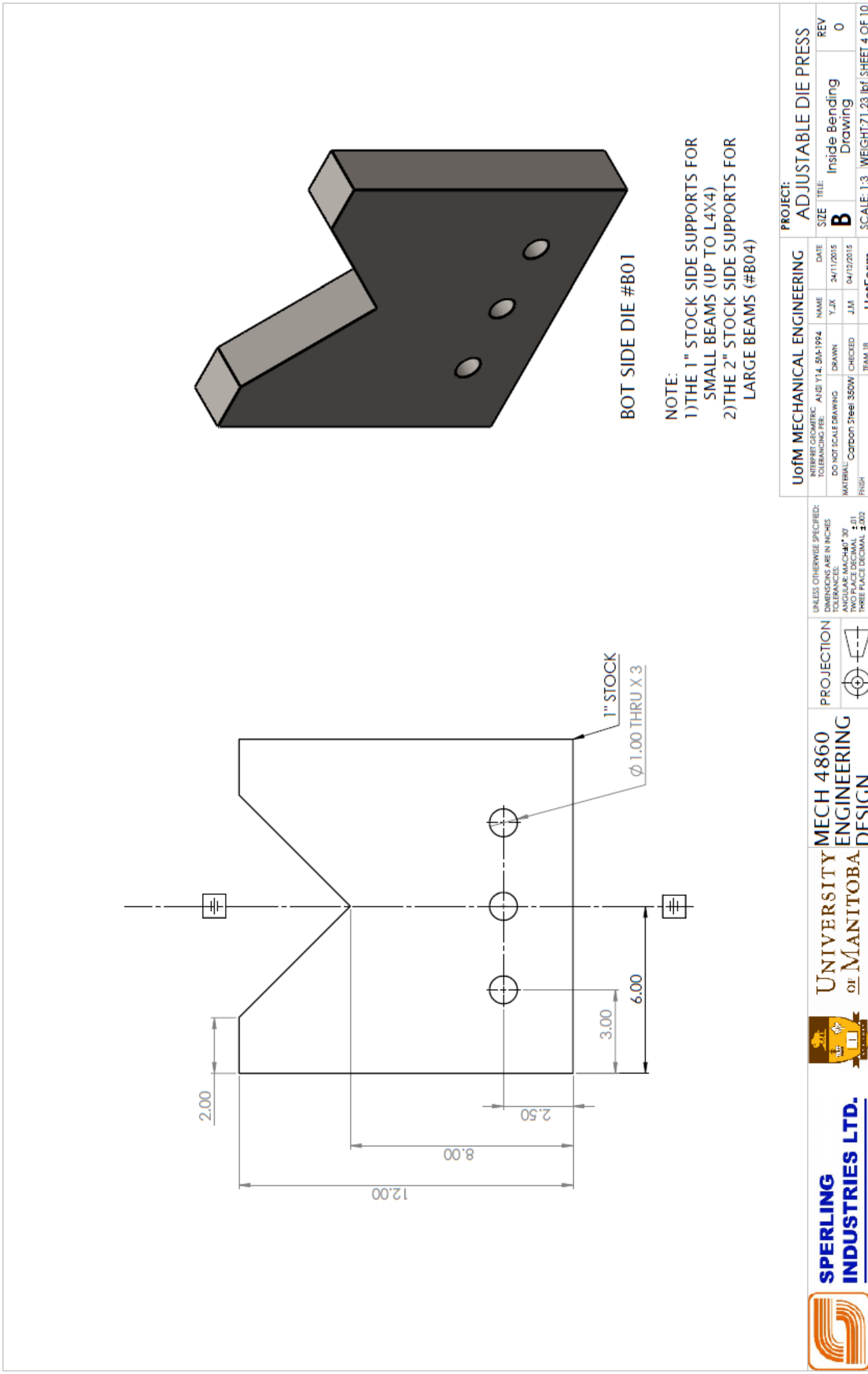
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2)THE 2" STOCK SIDE SUPPORTS FOR LARGE BEAMS (#B04)
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2.00
3.00
6.00
2.50
8.00
12.00
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SIZE
B
TITLE:
Inside Bending Drawing
REV
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SCALE: 1:3
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DRAWN
Y.JX
24/11/2015
CHECKED
J.M
04/12/2015
TEAM 18
HotForm
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Carbon Steel 350W
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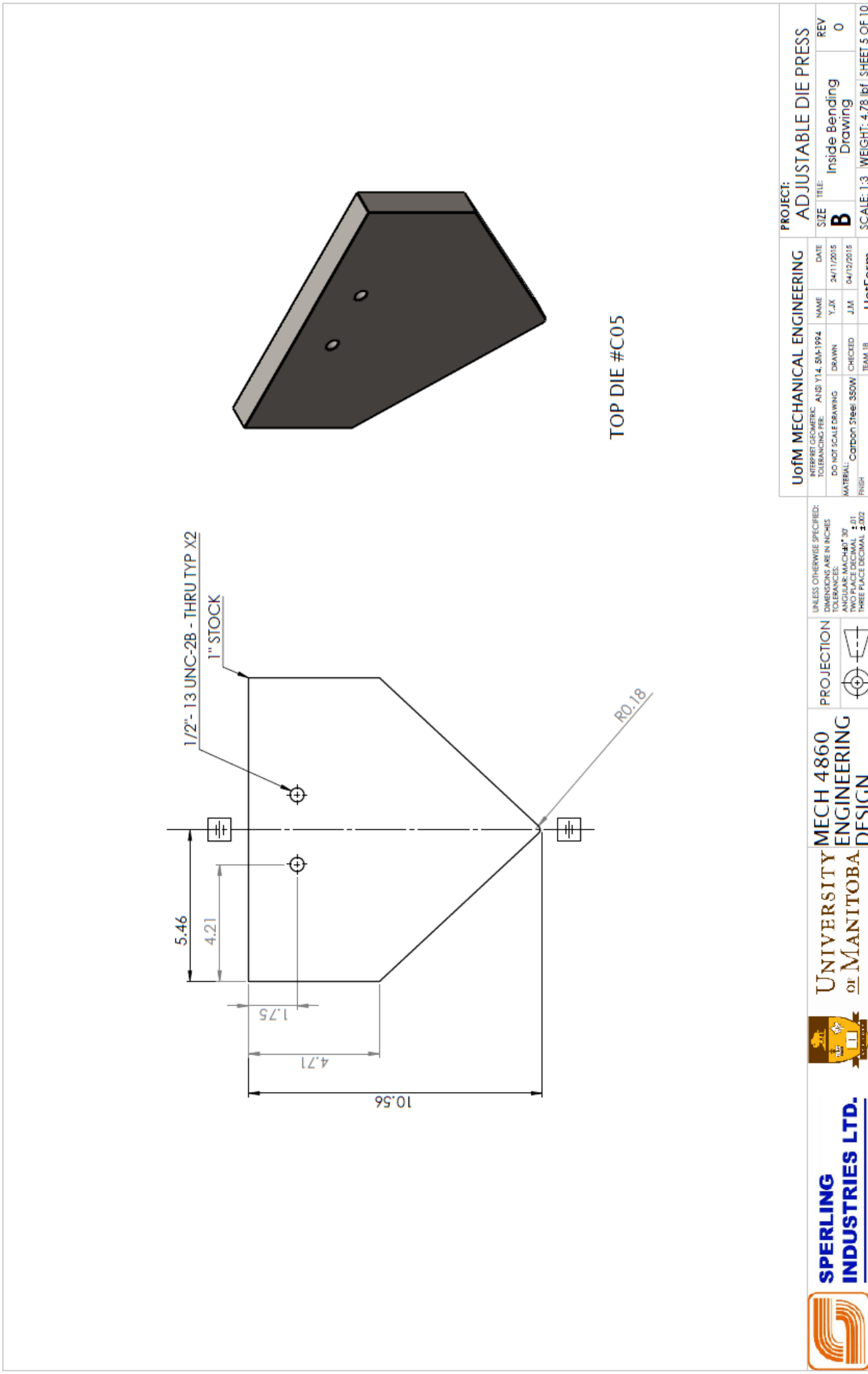
MECH 4860
ENGINEERING
DESIGN
UNIVERSITY OF MANITOBA
SPERLING
INDUSTRIES LTD.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NAME
DATE
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CHECKED J.M 04/12/2015
TEAM 18
HotForm
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UNIVERSITY OF MANITOBA
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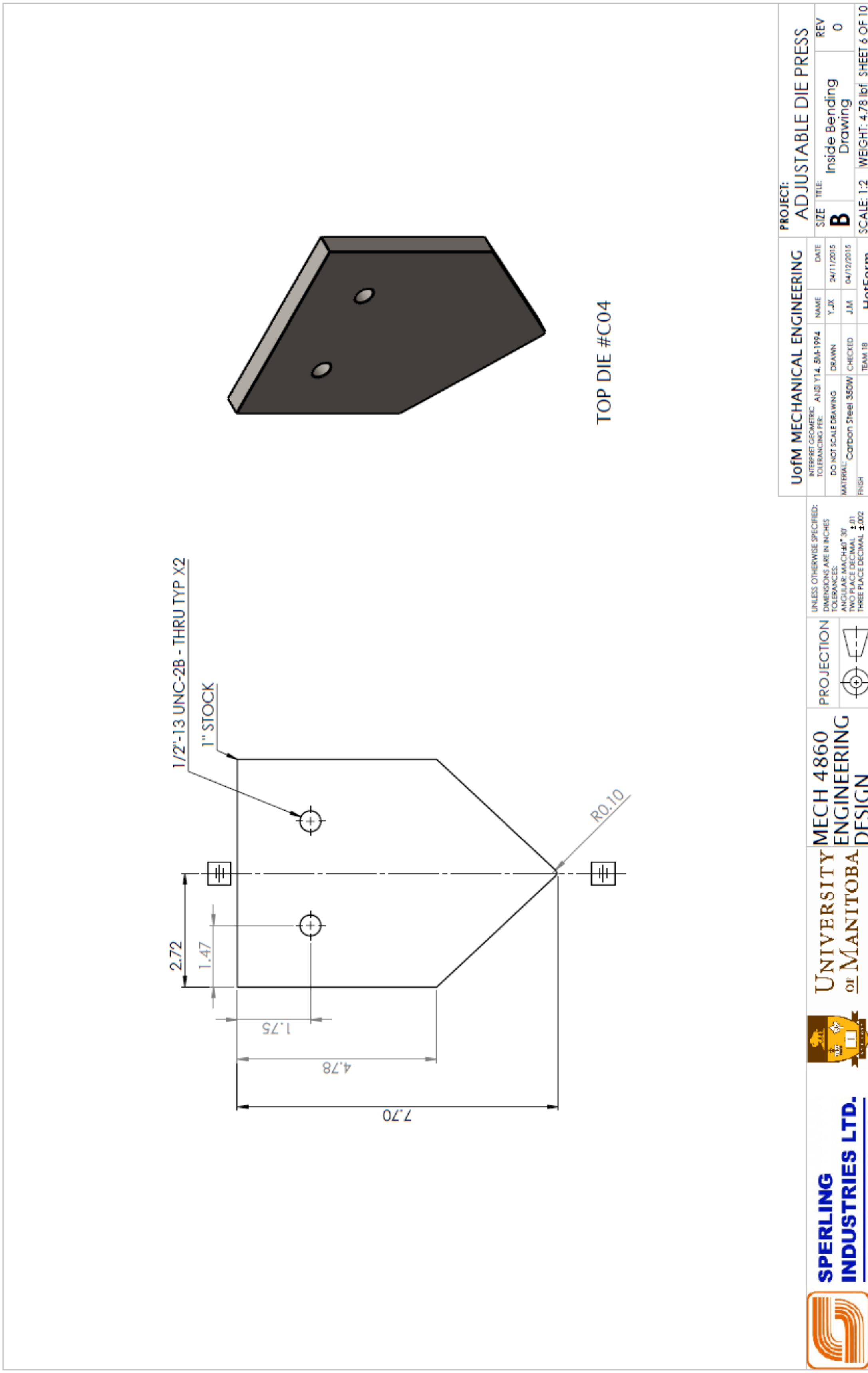
INDUSTRIES LTD.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JJM
04/12/2015
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UNIVERSITY of MANITOBA
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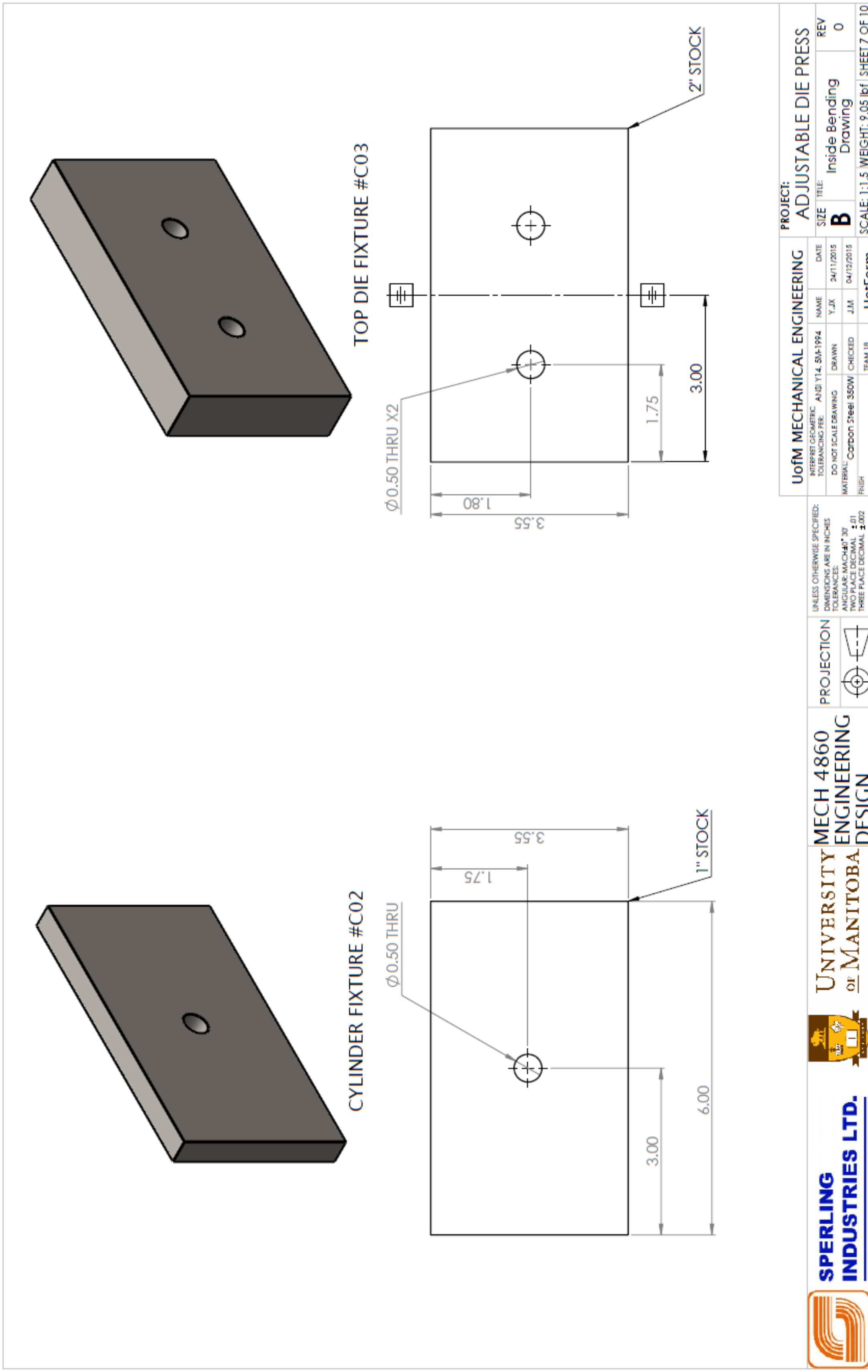
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UNIVERSITY OF MANITOBA
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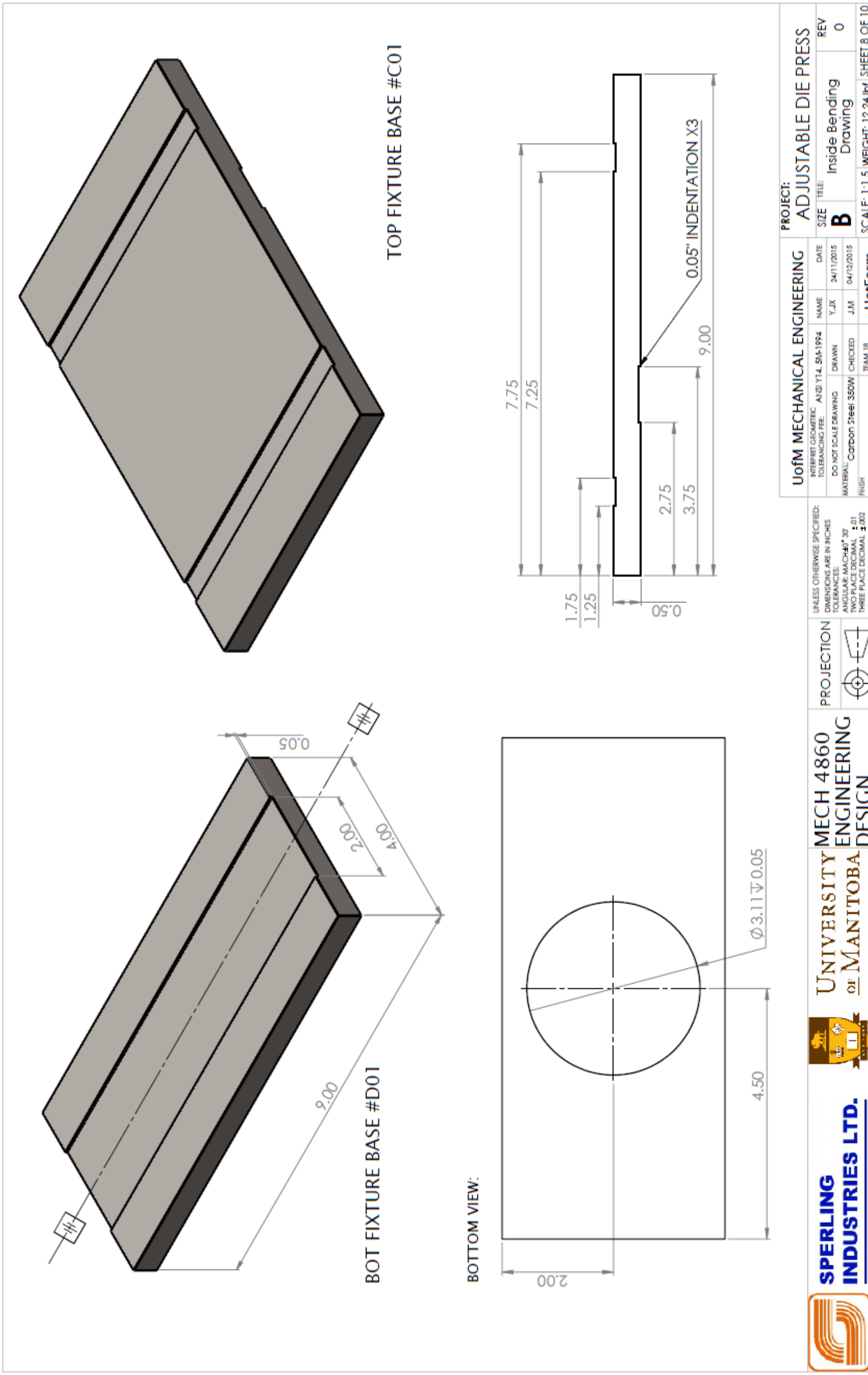
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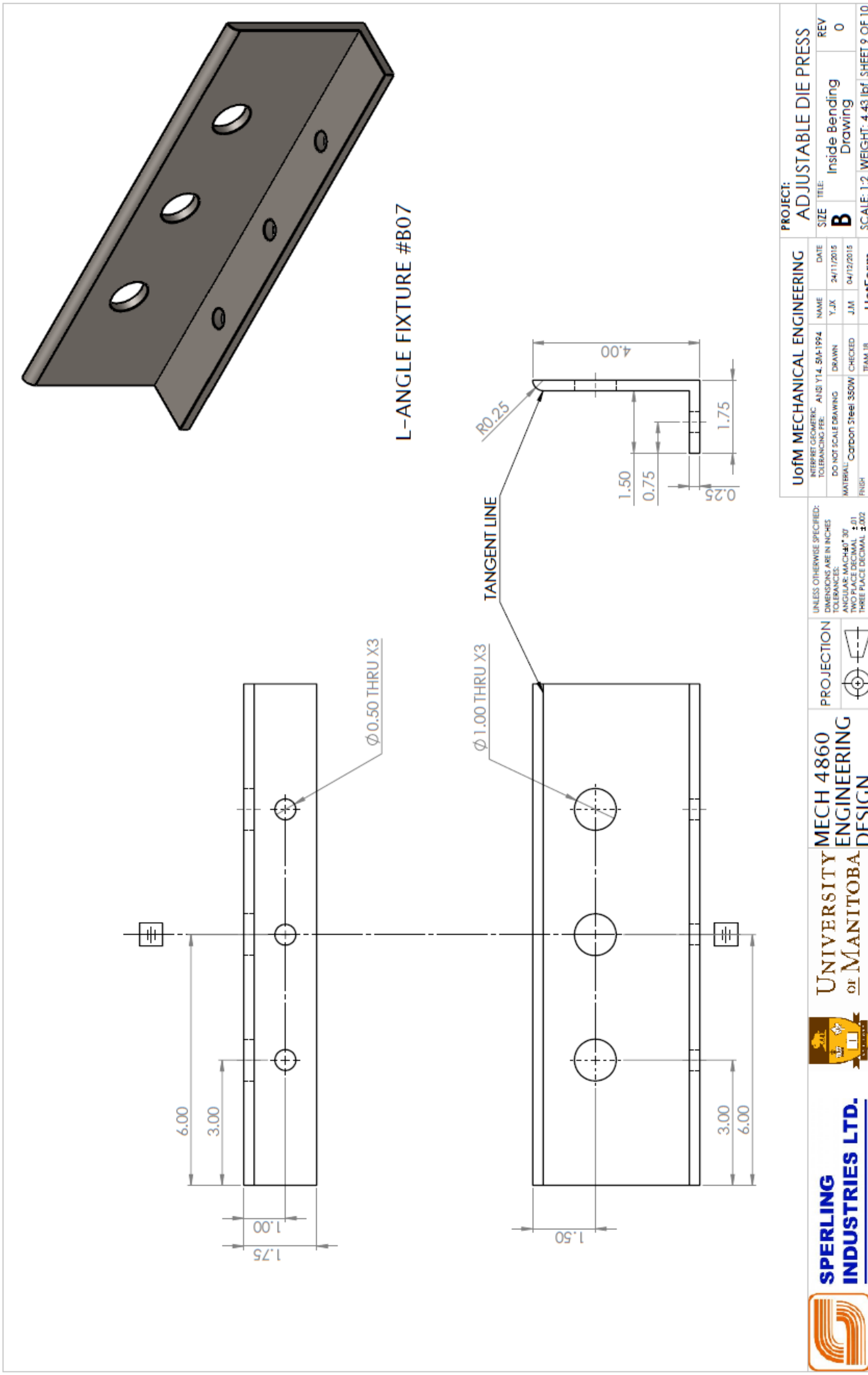
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04/12/2015
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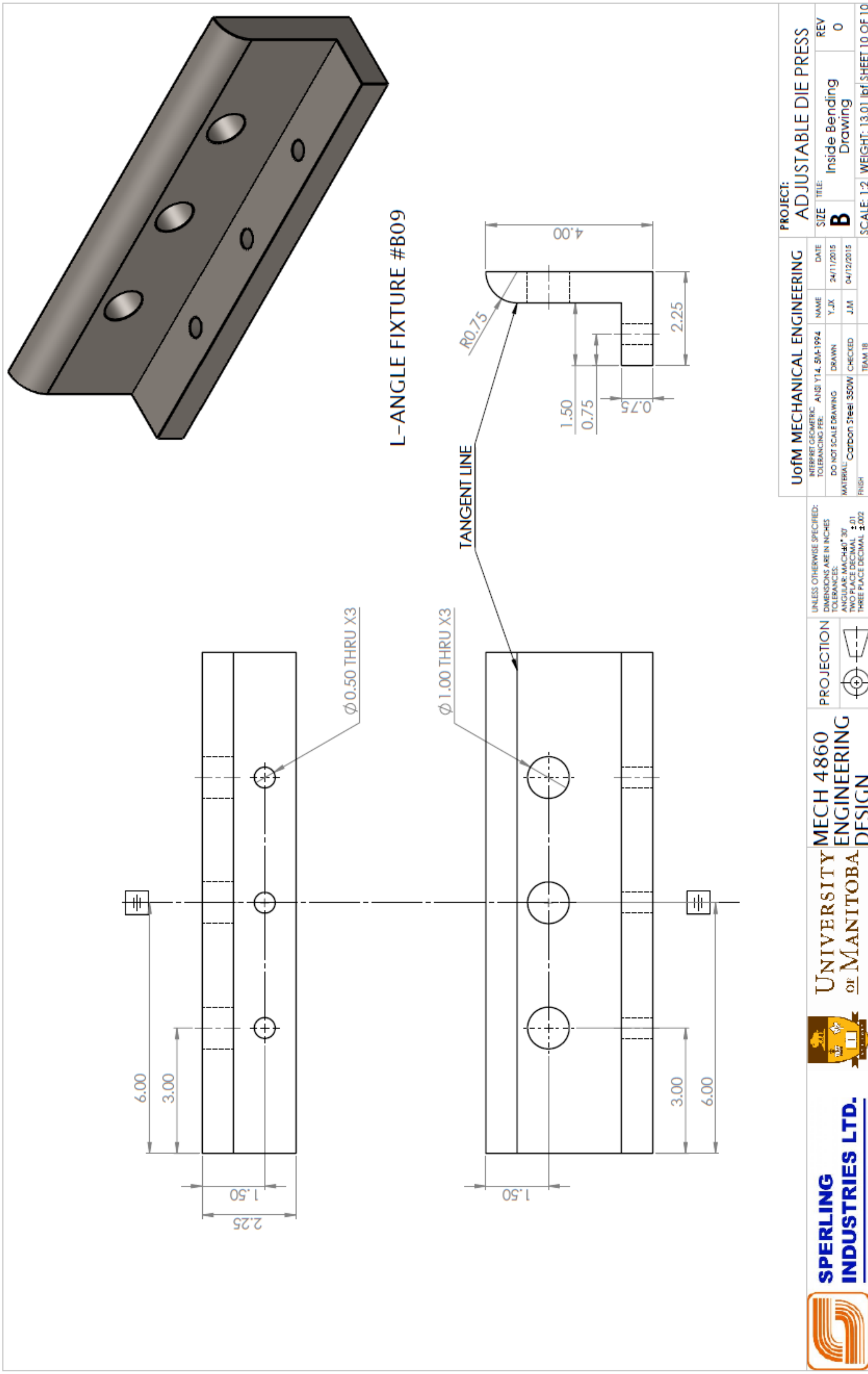
UNIVERSITY OF MANITOBA
SPERLING INDUSTRIES LTD.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1.50
2.25
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SIZE
B
TITLE:
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MATERIAL: Carbon Steel 350W
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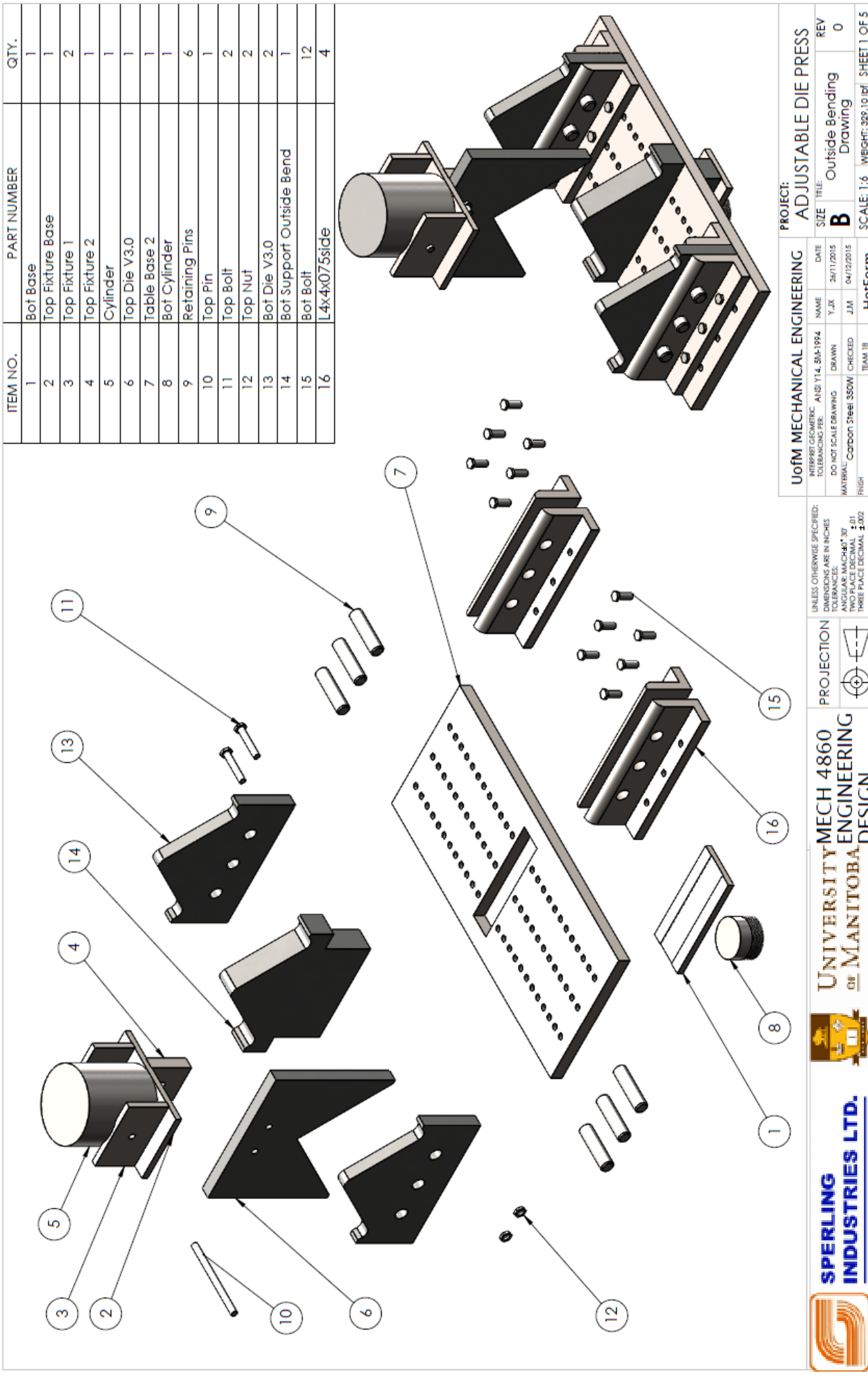
TEAM 18
PROJECTION
MECH 4860 ENGINEERING DESIGN
UNIVERSITY OF MANITOBA
SPERLING INDUSTRIES LTD.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5 | Cylinder | 1
6 | Top Die V3.0 | 1
7 | Table Base 2 | 1
8 | Bot Cylinder | 1
9 | Retaining Pins | 6
10 | Top Pin | 1
11 | Top Bolt | 2
12 | Top Nut | 2
13 | Bot Die V3.0 | 2
14 | Bot Support Outside Bend | 1
15 | Bot Bolt | 12
16 | L4x4X075side | 4
SPERLING INDUSTRIES LTD.
UNIVERSITY OF MANITOBA
MECH 4860 ENGINEERING DESIGN
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THREE PLACE DECIMAL ±.002
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DATE
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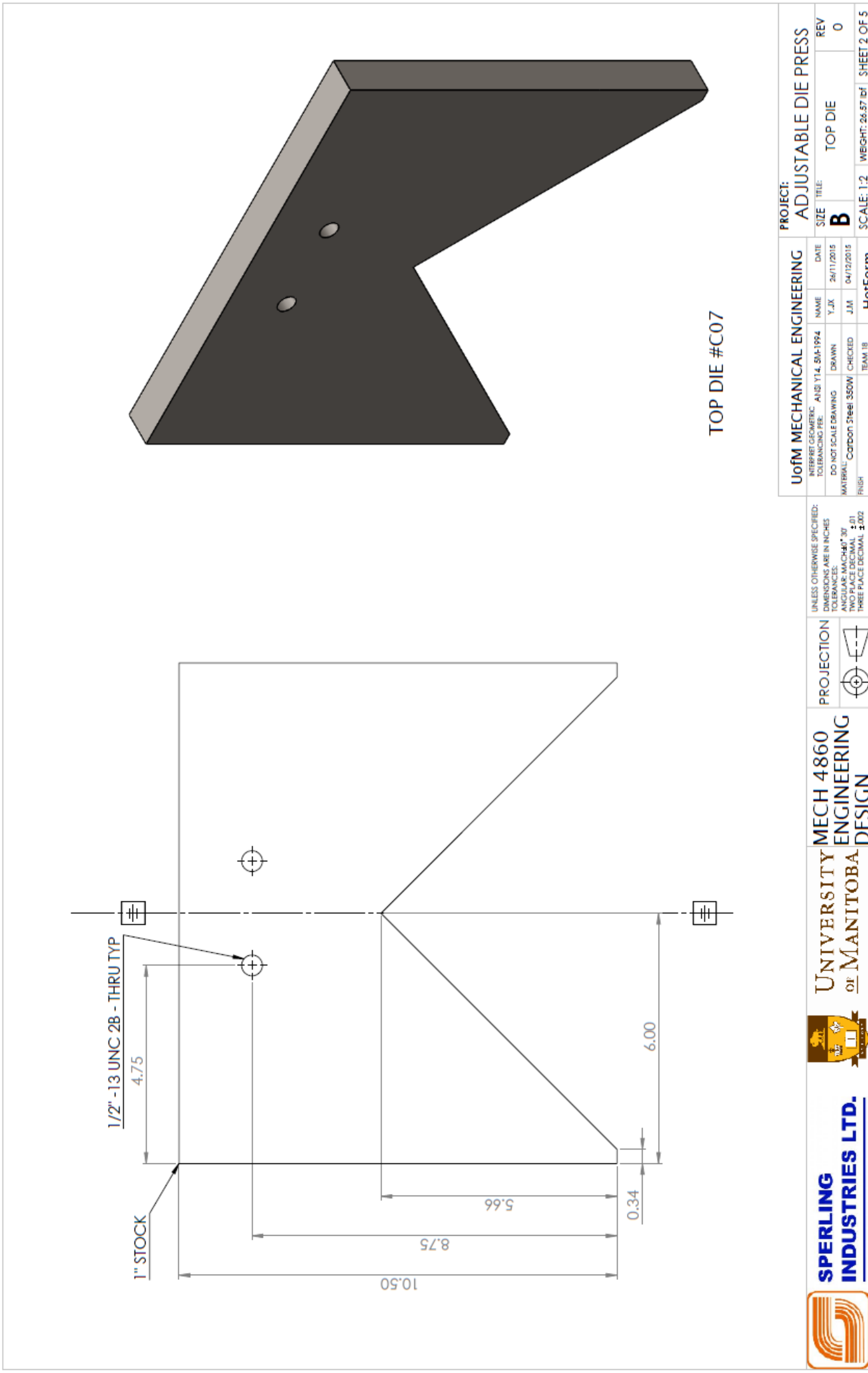
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TITLE:
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REV
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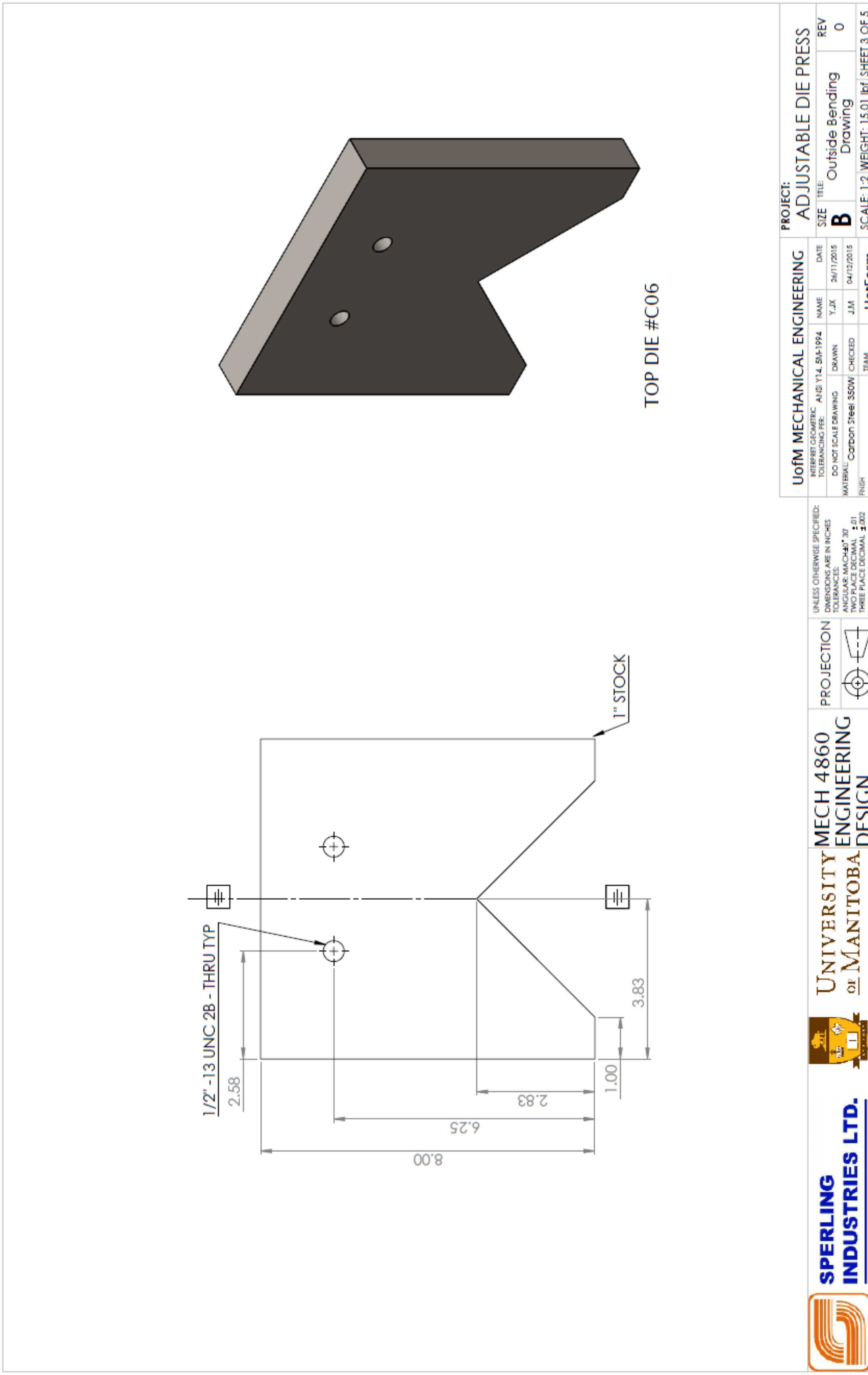
PROJECTION
UNIVERSITY OF MANITOBA
MECH 4860 ENGINEERING DESIGN
SPERLING INDUSTRIES LTD.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SPERLING INDUSTRIES LTD.
UNIVERSITY OF MANITOBA
MECH 4860 ENGINEERING DESIGN
PROJECTION
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TEAM HotForm
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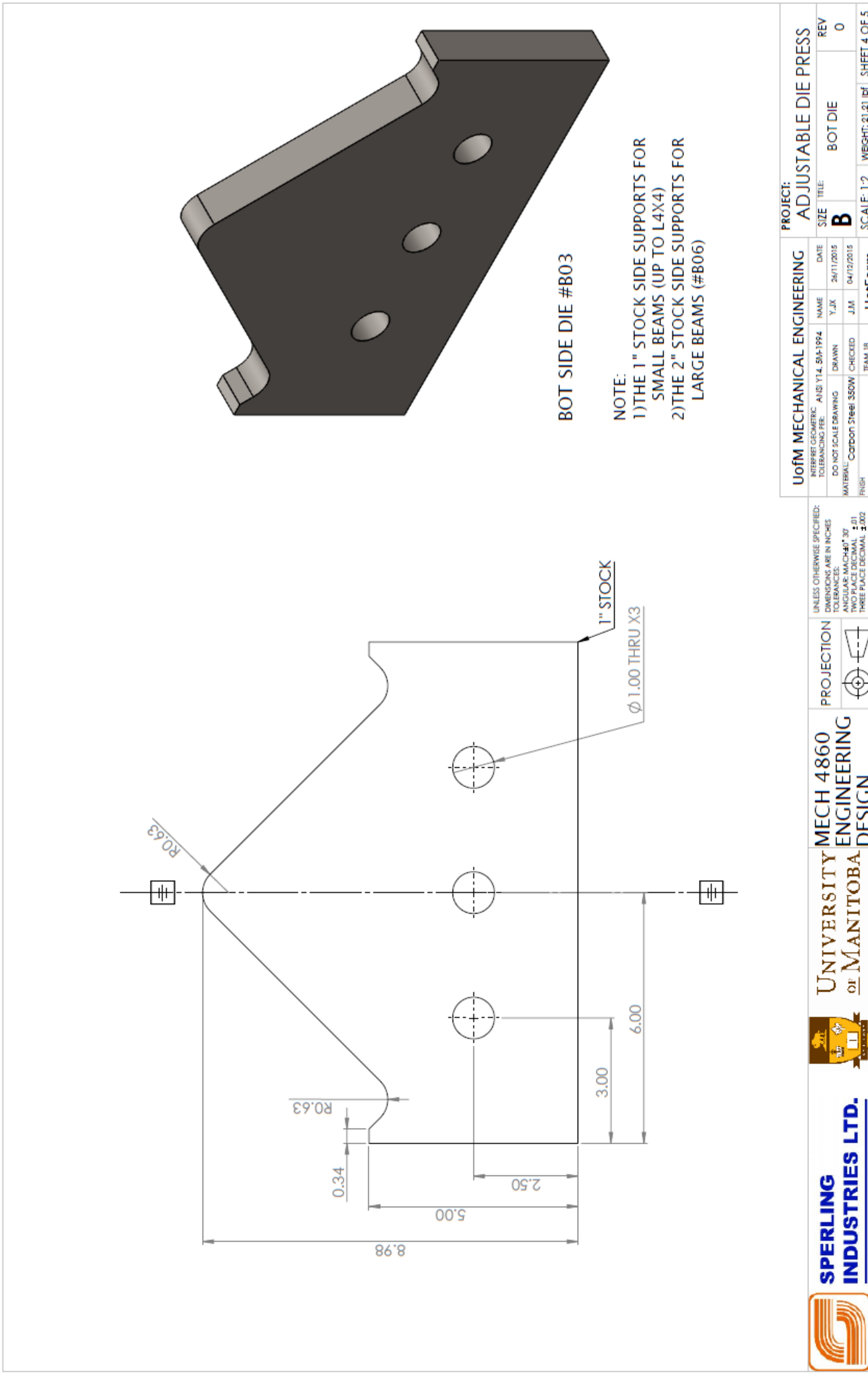
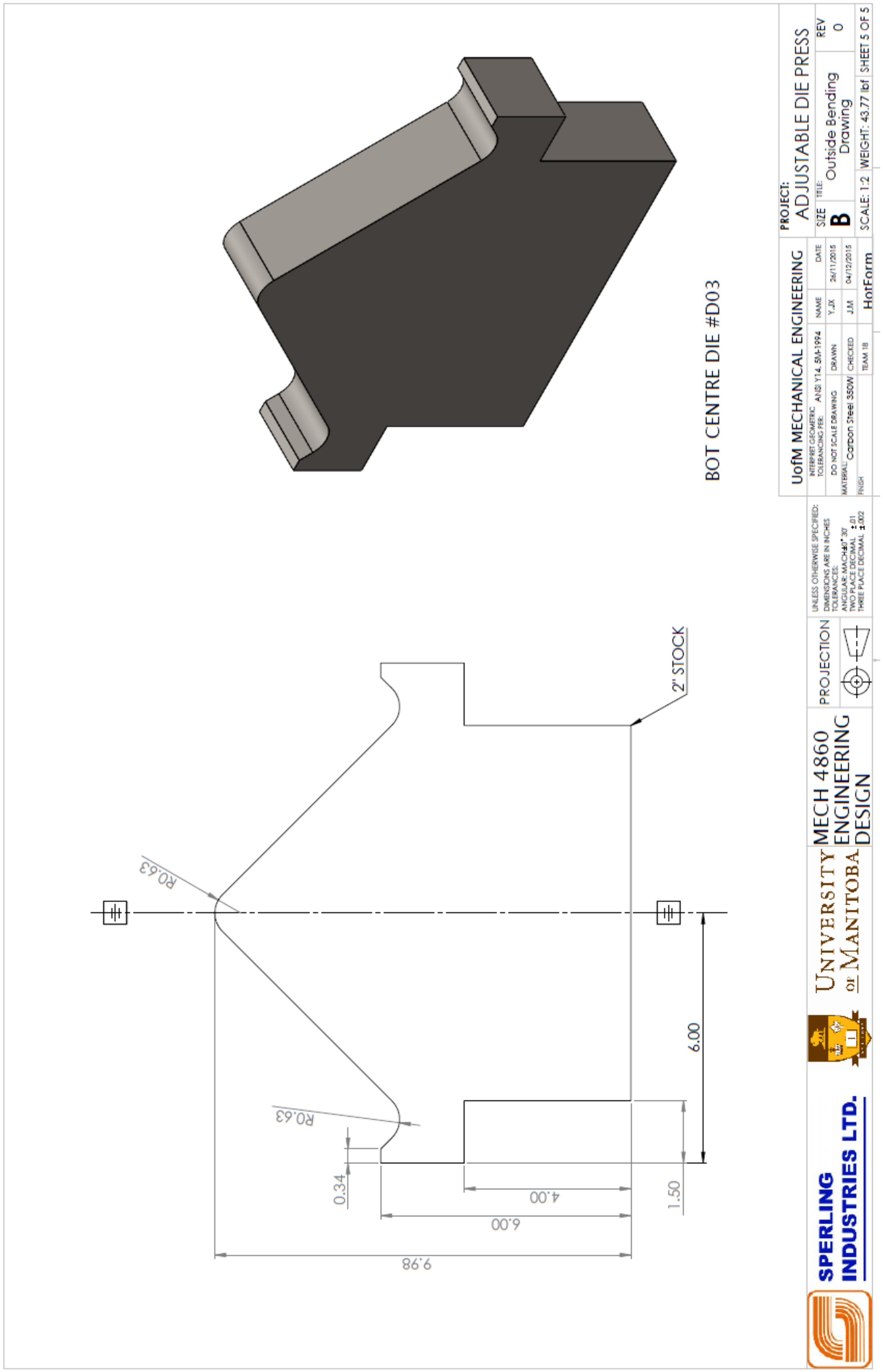
TITLE: Outside Bending Drawing
REV 0
SCALE: 1:2 WEIGHT: 15.01 lbf SHEET 3 OF 5


BOT SIDE DIE #B03
NOTE:
1)THE 1" STOCK SIDE SUPPORTS FOR SMALL BEAMS (UP TO L4X4)
2)THE 2" STOCK SIDE SUPPORTS FOR LARGE BEAMS (#B06)
1" STOCK
⌀ 1.00 THRU X3
R0.63
R0.63
0.34
2.50
5.00
8.98
3.00
6.00
UofM MECHANICAL ENGINEERING
PROJECT:
ADJUSTABLE DIE PRESS
SIZE
B
TITLE:
BOT DIE
REV
0
DRAWN
Y.JX
26/11/2015
CHECKED
J.M
04/12/2015
MATERIAL: Carbon Steel 350W
TEAM 18
HotForm
SCALE: 1:2
WEIGHT: 21.21 lbf
SHEET 4 OF 5
PROJECTION
MECH 4860
ENGINEERING
DESIGN
UNIVERSITY OF MANITOBA
SPERLING
INDUSTRIES LTD.


BOT CENTRE DIE #D03
2" STOCK
R0.63
R0.63
6.00
0.34
1.50
4.00
6.00
9.98
PROJECT:
ADJUSTABLE DIE PRESS
SIZE
B
TITLE:
Outside Bending Drawing
REV
0
SCALE: 1:2
WEIGHT: 43.77 lbf
SHEET 5 OF 5
UofM MECHANICAL ENGINEERING
INTERPRET GEOMETRIC TOLERANCING PER: ANSI Y14.5M-1994
DO NOT SCALE DRAWING
MATERIAL: Carbon Steel 350W
FINISH
NAME
DATE
DRAWN
Y.JX
26/11/2015
CHECKED
J.M
04/12/2015
TEAM 18
HotForm
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
PROJECTION
MECH 4860
ENGINEERING
DESIGN
UNIVERSITY of MANITOBA
SPERLING
INDUSTRIES LTD.

Appendix G

Technical Reference

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G.1 Introduction

Technical references are included to facilitate use of the design. The material contained within this section is relevant for those who will be directly interacting with the bending process. The major features of this section are an operations manual, a safety precautions guide, a temperature estimation table, and a bend angle reference chart.

G.2 Operations Manual

The operation of the adjustable die press requires an initial placement and setup of the fixtures. There are a total of three fixtures within the main design. There are 2 bottom fixtures and 1 top fixture. The top fixture attaches to the press cylinder, while the bottom dies are fixed to a solid table surface and symmetrically spaced about the top die.

G.2.1 Initial Setup

The initial setup should be done according to these instructions and should be handled by at least two workers:

1. Locate a position in the press where there is an unobstructed view from the hydraulic cylinder to the ground. This position should have at least a 1ft by 1ft profile free of any obstructions and be as close to the center of the press as possible
2. Place two joists across the hydraulic press frame on either side of the 1’ by 1’ profile. Ensure that the joists are parallel.
3. Place two more joists across the hydraulic press frame on either side of the first two joists. Set them approximately 6” from the first joists
4. Place the base plate table in position within the press machine with the centre gap directly above the 1’ by 1’ profile. The base plate should be properly levelled within the press.
5. Position the hydraulic jack below base plate table, centered in the 1’ by 1’ profile. Connect the bottom fixture to the jack. The top surface of the bottom fixture should be located 3” below the lower surface of the base plate.
6. Slide the bottoming die into the base plate cut-out. It should rest snugly in the bottom fixture. When the hydraulic jack is fully retracted the bottom fixture should be flush with the base plate.
7. Mount the top fixture to the cylinder using the pin. Orient the fixture in the direction that allows for the simplest die mounting.
8. Position the hydraulic press cylinder so that it is centered relative to the bottoming die.

G.2.2 Die Selection

The required die geometry will be determined depending on the desired bending process. Refer to TABLE G-I to determine the correct equipment for a given bend. Utilize the part numbers to ensure the correct die geometry is selected.

TABLE G-I: DIE SELECTION TABLE

Bend Configuration	Leg Size	Top Die	Bottoming Die	Supports	Brackets
Double Angle Inside	2	0.5" Inside Top Die (C04)	Inside Bend Bottoming Die (D02)	1” Inside Bend Support (B01)	Thin Brackets (B07)
Double Angle Inside	3	0.5" Inside Top Die (C04)	Inside Bend Bottoming Die (D02)	1” Inside Bend Support (B01)	Thick Brackets (B09)
Double Angle Inside	4	0.5" Inside Top Die (C04)	Inside Bend Bottoming Die (D02)	1” Inside Bend Support (B01)	Thick Brackets (B09)
Double Angle Inside	5	1" Inside Top Die (C05)	Inside Bend Bottoming Die (D02)	2” Inside Bend Support (B04)	Thick Brackets (B09)
Double Angle Inside	6	1" Inside Top Die (C05)	Inside Bend Bottoming Die (D02)	2” Inside Bend Support (B04)	Thick Brackets (B09)
Double Angle Inside	8	1" Inside Top Die (C05)	Inside Bend Bottoming Die (D02)	2” Inside Bend Support (B04)	Thick Brackets (B09)
Double Angle Outside	2	0.5" Outside Top Die (C06)	Outside Bend Bottoming Die (D03)	1” Outside Bend Supports (B02)	Thin Brackets (B07)
Double Angle Outside	3	0.5" Outside Top Die (C06)	Outside Bend Bottoming Die (D03)	1” Outside Bend Supports (B02)	Thick Brackets (B09)
Double Angle Outside	4	0.5" Outside Top Die (C06)	Outside Bend Bottoming Die (D03)	1” Outside Bend Supports (B02)	Thick Brackets (B09)
Double Angle Outside	5	1" Outside Top Die (C07)	Outside Bend Bottoming Die (D03)	2” Outside Bend Supports (B06)	Thick Brackets (B09)
Double Angle Outside	6	1" Outside Top Die (C07)	Outside Bend Bottoming Die (D03)	2” Outside Bend Supports (B06)	2” Outside Bend Supports (B06)
Double Angle Outside	8	1" Outside Top Die (C07)	Outside Bend Bottoming Die (D03)	2” Outside Bend Supports (B06)	Thick Brackets (B09)

G.2.3 Die Setup and Operation

The following are instructions to setup the device for a bending process and perform the bending operation.

1. Determine the type of bend that is to be performed. This includes:
    a. Bend Configuration (Inside or Outside double angle bend)
    b. Beam size (Cross-Section geometry)
    c. Required bend angle
2. Select dies. Bottoming dies are universal for bend type, where as the top die and supports depends on beam size.
    - Thinner top die and supports for smaller beam sizes (2” leg size – 4” leg size)
    - Thick top die and supports for larger beam sizes (5” leg size and up)
3. Determine required gap spacing and stroke depth for specified bend angle using bend reference tables.
4. Set bottom die gap spacing to suggested increment. Die gap must be centered on top die, so each of the bottom dies must be placed to the same position. Tighten fixtures to base table and attach dies to fixtures. Tighten the bolts to $70 ft \cdot lb$.
5. Attach top die and tighten to top fixture using bolts. Tighten the bolts to $94 ft \cdot lb$ using a torque wrench.
6. Adjust bottoming die to recommended height for the specified bend angle.
7. Apply lubrication to die contact surfaces as required. Flammable lubrication is not to be used on centre dies, since the beam will be heated.
8. Load beam into dies with bend location directly below the top die. Check and adjust supports on long end of the beam.
9. Check that dies are straight so that the load is applied properly on beam.
10. Preheat beam to the recommended temperature. Determine the temperature based on the color.
11. Check the bend angle during the bending process. If the required angle is not met, then adjust the stroke depth/height to allot for a deeper bend.
12. Take note of any deviation from recommended stroke to update reference tables.
13. Allow beam to cool.
14. Check beam for defects after bending, measure the final angle, and inspect bolt holes

G.3 Safety Precautions

This section details safety precautions which should be followed when operating the adjustable press die.

Use of welding goggles

During the preheating process the oxy-fuel torch will generate extreme levels of light. This light can be harmful to the eyes if looked at with the naked eye. Welding goggles should be worn to protect against eye damage.

Use of heat resistant gloves

After preheating the steel angles before a bend a large portion of the beam will be hot enough to cause burns. Even after cooling to the point where the metal no longer glows the beam is still capable of causing burns. Heat resistant gloves should be used at all times until the beam is confirmed to have cooled to room temperature.

Maintaining a safe distance

The hydraulic press machine generates extreme levels of force which may result in failure of components. Workers who are not operating the adjustable press die or hoist system should not stand in the vicinity during bending operations.

Switch off the machine

The hydraulic press should only be turned on immediately before a bend, and shut off immediately after a bend.

Caution in handling heavy parts

Heavy components should be handled with extreme caution. Gloves should always be worn when handling parts. Any part heavier than 50lb should be moved by at least two workers. Fork lifts should be used when possible. Watch that hands or other body parts are not pinched between two heavy components.

Beam should be transported and supported using a hoist

The length of the steel angles may vary from 10’ to 40’ and the beams will be too heavy to handle by hand. Hoists must be used to move beams into the press. Hoists must also be used to support the deflected end of beam during the bending process.

Wearing Personal Protection Equipment (PPE)

Eye protection, head protection, and foot protection should be worn at all times when operating the adjustable press die.

G.4 Temperature Estimation Table

Temperature estimation is an important part of the hot bending process. Referencing TABLE G-II will help to sufficiently estimate the heating temperature for bending purposes.

TABLE G-II: TEMPERATURE ESTIMATION BASED ON TEMPERATURE [1]

Color	Temp. (°C)
Faint Red	500
Blood Red	580
Dark Cherry	635
Medium Cherry	690
Cherry	745
Bright Cherry	790
Salmon	845
Dark Orange	890
Orange	940
Lemon	1000
Light Yellow	1080
White	1205

G.5 Bend Angle Reference Charts

The die opening and bend angle reference charts provides a starting point for various bends. Two charts are provided: a chart used during testing (TABLE G-III) and a chart used after reformulation of the equations. It is theorized that the reformulated version of the chart will provide more accurate bends. The resolution is the required alteration to the bottoming die height to cause a 0.5° change in the beams angle. The greyed region denote bend configurations which may not be possible with the current design. This is not deemed to be an issue because large beams are rarely, if ever, bent at such a severe angle. The die openings are calculated from the die opening tables in Appendix C. The press strokes are calculated based on the press stroke equations used in Appendix B.

Tests performed using the same methodology contained within the first reference chart have shown that bends can be brought to within 1-3° of the final bend angle. The equation B1 is included here for reference. This equation was formulated based on the assumption that the beam length remains constant throughout a bend. The results of this calculation are shown in TABLE G-III. However, based on testing is was determined the beam length could not be considered constant. Figure G-1 shows how the beam is modelled with simple trigonometry for the reformulated equation.

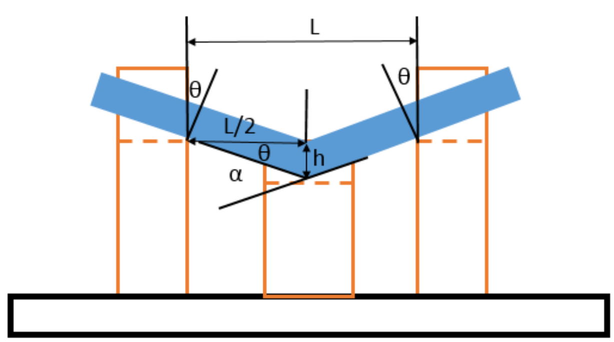

Figure G-1: Illustration of bend angle parameters [2].

Therefore, the equation B5 should be applied.

TABLE G-IV presents the result of the reformulated equation. Testing will have to be performed to determine which table provides the most reliable results. However, Hot Form believes that

TABLE G-IV should provide more accurate predictions of bends because it accounts for the elongation of the beams during bending.

TABLE G-III: BEND ANGLE REFERENCE CHART FROM TESTING [2]

			Angle																																												
Beam	L	Res	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
L8x8x1	19.5	0.04	0.09	0.17	0.26	0.34	0.43	0.51	0.60	0.68	0.76	0.85	0.93	1.02	1.10	1.19	1.27	1.36	1.44	1.53	1.61	1.69	1.78	1.86	1.94	2.03	2.11	2.19	2.28	2.36	2.44	2.52	2.61	2.69	2.77	2.85	2.93	3.01	3.09	3.17	3.25	3.33	3.41	3.49	3.57	3.65	3.73
L8x8x.75	19.5	0.04	0.09	0.17	0.26	0.34	0.43	0.51	0.60	0.68	0.76	0.85	0.93	1.02	1.10	1.19	1.27	1.36	1.44	1.53	1.61	1.69	1.78	1.86	1.94	2.03	2.11	2.19	2.28	2.36	2.44	2.52	2.61	2.69	2.77	2.85	2.93	3.01	3.09	3.17	3.25	3.33	3.41	3.49	3.57	3.65	3.73
L8x8x.5	19.5	0.04	0.09	0.17	0.26	0.34	0.43	0.51	0.60	0.68	0.76	0.85	0.93	1.02	1.10	1.19	1.27	1.36	1.44	1.53	1.61	1.69	1.78	1.86	1.94	2.03	2.11	2.19	2.28	2.36	2.44	2.52	2.61	2.69	2.77	2.85	2.93	3.01	3.09	3.17	3.25	3.33	3.41	3.49	3.57	3.65	3.73
L6x6x1	15.5	0.03	0.07	0.14	0.20	0.27	0.34	0.41	0.47	0.54	0.61	0.68	0.74	0.81	0.88	0.94	1.01	1.08	1.15	1.21	1.28	1.35	1.41	1.48	1.55	1.61	1.68	1.74	1.81	1.87	1.94	2.01	2.07	2.14	2.20	2.27	2.33	2.39	2.46	2.52	2.59	2.65	2.71	2.78	2.84	2.90	2.97
L6x6x.75	15.5	0.03	0.07	0.14	0.20	0.27	0.34	0.41	0.47	0.54	0.61	0.68	0.74	0.81	0.88	0.94	1.01	1.08	1.15	1.21	1.28	1.35	1.41	1.48	1.55	1.61	1.68	1.74	1.81	1.87	1.94	2.01	2.07	2.14	2.20	2.27	2.33	2.39	2.46	2.52	2.59	2.65	2.71	2.78	2.84	2.90	2.97
L6x6x.625	15.5	0.03	0.07	0.14	0.20	0.27	0.34	0.41	0.47	0.54	0.61	0.68	0.74	0.81	0.88	0.94	1.01	1.08	1.15	1.21	1.28	1.35	1.41	1.48	1.55	1.61	1.68	1.74	1.81	1.87	1.94	2.01	2.07	2.14	2.20	2.27	2.33	2.39	2.46	2.52	2.59	2.65	2.71	2.78	2.84	2.90	2.97
L6x6x.5	15.5	0.03	0.07	0.14	0.20	0.27	0.34	0.41	0.47	0.54	0.61	0.68	0.74	0.81	0.88	0.94	1.01	1.08	1.15	1.21	1.28	1.35	1.41	1.48	1.55	1.61	1.68	1.74	1.81	1.87	1.94	2.01	2.07	2.14	2.20	2.27	2.33	2.39	2.46	2.52	2.59	2.65	2.71	2.78	2.84	2.90	2.97
L6x6x.375	15.5	0.03	0.07	0.14	0.20	0.27	0.34	0.41	0.47	0.54	0.61	0.68	0.74	0.81	0.88	0.94	1.01	1.08	1.15	1.21	1.28	1.35	1.41	1.48	1.55	1.61	1.68	1.74	1.81	1.87	1.94	2.01	2.07	2.14	2.20	2.27	2.33	2.39	2.46	2.52	2.59	2.65	2.71	2.78	2.84	2.90	2.97
L5x5x.75	13.5	0.03	0.06	0.12	0.18	0.24	0.29	0.35	0.41	0.47	0.53	0.59	0.65	0.71	0.76	0.82	0.88	0.94	1.00	1.06	1.11	1.17	1.23	1.29	1.35	1.40	1.46	1.52	1.58	1.63	1.69	1.75	1.80	1.86	1.92	1.97	2.03	2.09	2.14	2.20	2.25	2.31	2.36	2.42	2.47	2.53	2.58
L5x5x.625	13.5	0.03	0.06	0.12	0.18	0.24	0.29	0.35	0.41	0.47	0.53	0.59	0.65	0.71	0.76	0.82	0.88	0.94	1.00	1.06	1.11	1.17	1.23	1.29	1.35	1.40	1.46	1.52	1.58	1.63	1.69	1.75	1.80	1.86	1.92	1.97	2.03	2.09	2.14	2.20	2.25	2.31	2.36	2.42	2.47	2.53	2.58
L5x5x.5	13.5	0.03	0.06	0.12	0.18	0.24	0.29	0.35	0.41	0.47	0.53	0.59	0.65	0.71	0.76	0.82	0.88	0.94	1.00	1.06	1.11	1.17	1.23	1.29	1.35	1.40	1.46	1.52	1.58	1.63	1.69	1.75	1.80	1.86	1.92	1.97	2.03	2.09	2.14	2.20	2.25	2.31	2.36	2.42	2.47	2.53	2.58
L5x5x.375	13.5	0.03	0.06	0.12	0.18	0.24	0.29	0.35	0.41	0.47	0.53	0.59	0.65	0.71	0.76	0.82	0.88	0.94	1.00	1.06	1.11	1.17	1.23	1.29	1.35	1.40	1.46	1.52	1.58	1.63	1.69	1.75	1.80	1.86	1.92	1.97	2.03	2.09	2.14	2.20	2.25	2.31	2.36	2.42	2.47	2.53	2.58
L4x4x.75	11.5	0.03	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.20	1.24	1.29	1.34	1.39	1.44	1.49	1.54	1.58	1.63	1.68	1.73	1.78	1.82	1.87	1.92	1.97	2.01	2.06	2.11	2.15	2.20
L4x4x.625	11.5	0.03	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.20	1.24	1.29	1.34	1.39	1.44	1.49	1.54	1.58	1.63	1.68	1.73	1.78	1.82	1.87	1.92	1.97	2.01	2.06	2.11	2.15	2.20
L4x4x.5	11.5	0.03	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.20	1.24	1.29	1.34	1.39	1.44	1.49	1.54	1.58	1.63	1.68	1.73	1.78	1.82	1.87	1.92	1.97	2.01	2.06	2.11	2.15	2.20
L4x4x.375	11.5	0.03	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.20	1.24	1.29	1.34	1.39	1.44	1.49	1.54	1.58	1.63	1.68	1.73	1.78	1.82	1.87	1.92	1.97	2.01	2.06	2.11	2.15	2.20
L4x4x.25	11.5	0.03	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.20	1.24	1.29	1.34	1.39	1.44	1.49	1.54	1.58	1.63	1.68	1.73	1.78	1.82	1.87	1.92	1.97	2.01	2.06	2.11	2.15	2.20
L3.5x3.5x.5	9.5	0.02	0.04	0.08	0.12	0.17	0.21	0.25	0.29	0.33	0.37	0.41	0.46	0.50	0.54	0.58	0.62	0.66	0.70	0.74	0.78	0.82	0.87	0.91	0.95	0.99	1.03	1.07	1.11	1.15	1.19	1.23	1.27	1.31	1.35	1.39	1.43	1.47	1.51	1.55	1.59	1.62	1.66	1.70	1.74	1.78	1.82
L3.5x3.5x.375	9.5	0.02	0.04	0.08	0.12	0.17	0.21	0.25	0.29	0.33	0.37	0.41	0.46	0.50	0.54	0.58	0.62	0.66	0.70	0.74	0.78	0.82	0.87	0.91	0.95	0.99	1.03	1.07	1.11	1.15	1.19	1.23	1.27	1.31	1.35	1.39	1.43	1.47	1.51	1.55	1.59	1.62	1.66	1.70	1.74	1.78	1.82
L3.5x3.5x.25	9.5	0.02	0.04	0.08	0.12	0.17	0.21	0.25	0.29	0.33	0.37	0.41	0.46	0.50	0.54	0.58	0.62	0.66	0.70	0.74	0.78	0.82	0.87	0.91	0.95	0.99	1.03	1.07	1.11	1.15	1.19	1.23	1.27	1.31	1.35	1.39	1.43	1.47	1.51	1.55	1.59	1.62	1.66	1.70	1.74	1.78	1.82
L3x3x.5	7.5	0.02	0.03	0.07	0.10	0.13	0.16	0.20	0.23	0.26	0.29	0.33	0.36	0.39	0.42	0.46	0.49	0.52	0.55	0.59	0.62	0.65	0.68	0.72	0.75	0.78	0.81	0.84	0.88	0.91	0.94	0.97	1.00	1.03	1.07	1.10	1.13	1.16	1.19	1.22	1.25	1.28	1.31	1.34	1.37	1.40	1.44
L3x3x.375	7.5	0.02	0.03	0.07	0.10	0.13	0.16	0.20	0.23	0.26	0.29	0.33	0.36	0.39	0.42	0.46	0.49	0.52	0.55	0.59	0.62	0.65	0.68	0.72	0.75	0.78	0.81	0.84	0.88	0.91	0.94	0.97	1.00	1.03	1.07	1.10	1.13	1.16	1.19	1.22	1.25	1.28	1.31	1.34	1.37	1.40	1.44
L3x3x.25	7.5	0.02	0.03	0.07	0.10	0.13	0.16	0.20	0.23	0.26	0.29	0.33	0.36	0.39	0.42	0.46	0.49	0.52	0.55	0.59	0.62	0.65	0.68	0.72	0.75	0.78	0.81	0.84	0.88	0.91	0.94	0.97	1.00	1.03	1.07	1.10	1.13	1.16	1.19	1.22	1.25	1.28	1.31	1.34	1.37	1.40	1.44
L2.5x2.5x.5	7.5	0.02	0.03	0.07	0.10	0.13	0.16	0.20	0.23	0.26	0.29	0.33	0.36	0.39	0.42	0.46	0.49	0.52	0.55	0.59	0.62	0.65	0.68	0.72	0.75	0.78	0.81	0.84	0.88	0.91	0.94	0.97	1.00	1.03	1.07	1.10	1.13	1.16	1.19	1.22	1.25	1.28	1.31	1.34	1.37	1.40	1.44
L2.5x2.5x.375	7.5	0.02	0.03	0.07	0.10	0.13	0.16	0.20	0.23	0.26	0.29	0.33	0.36	0.39	0.42	0.46	0.49	0.52	0.55	0.59	0.62	0.65	0.68	0.72	0.75	0.78	0.81	0.84	0.88	0.91	0.94	0.97	1.00	1.03	1.07	1.10	1.13	1.16	1.19	1.22	1.25	1.28	1.31	1.34	1.37	1.40	1.44
L2.5x2.5x.25	7.5	0.02	0.03	0.07	0.10	0.13	0.16	0.20	0.23	0.26	0.29	0.33	0.36	0.39	0.42	0.46	0.49	0.52	0.55	0.59	0.62	0.65	0.68	0.72	0.75	0.78	0.81	0.84	0.88	0.91	0.94	0.97	1.00	1.03	1.07	1.10	1.13	1.16	1.19	1.22	1.25	1.28	1.31	1.34	1.37	1.40	1.44
L2.5x2.5x.1875	7.5	0.02	0.03	0.07	0.10	0.13	0.16	0.20	0.23	0.26	0.29	0.33	0.36	0.39	0.42	0.46	0.49	0.52	0.55	0.59	0.62	0.65	0.68	0.72	0.75	0.78	0.81	0.84	0.88	0.91	0.94	0.97	1.00	1.03	1.07	1.10	1.13	1.16	1.19	1.22	1.25	1.28	1.31	1.34	1.37	1.40	1.44
L2x2x.375	5.5	0.01	0.02	0.05	0.07	0.10	0.12	0.14	0.17	0.19	0.22	0.24	0.26	0.29	0.31	0.34	0.36	0.38	0.41	0.43	0.45	0.48	0.50	0.52	0.55	0.57	0.60	0.62	0.64	0.67	0.69	0.71	0.73	0.76	0.78	0.80	0.83	0.85	0.87	0.90	0.92	0.94	0.96	0.99	1.01	1.03	1.05
L2x2x.25	5.5	0.01	0.02	0.05	0.07	0.10	0.12	0.14	0.17	0.19	0.22	0.24	0.26	0.29	0.31	0.34	0.36	0.38	0.41	0.43	0.45	0.48	0.50	0.52	0.55	0.57	0.60	0.62	0.64	0.67	0.69	0.71	0.73	0.76	0.78	0.80	0.83	0.85	0.87	0.90	0.92	0.94	0.96	0.99	1.01	1.03	1.05
L2x2x.125	5.5	0.01	0.02	0.05	0.07	0.10	0.12	0.14	0.17	0.19	0.22	0.24	0.26	0.29	0.31	0.34	0.36	0.38	0.41	0.43	0.45	0.48	0.50	0.52	0.55	0.57	0.60	0.62	0.64	0.67	0.69	0.71	0.73	0.76	0.78	0.80	0.83	0.85	0.87	0.90	0.92	0.94	0.96	0.99	1.01	1.03	1.05

TABLE G-IV: REFORMULATED BEND ANGLE REFERENCE CHART [2]

			Angle																																												
Beam	L	Res	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
L8x8x1	19.5	0.04	0.09	0.17	0.26	0.34	0.43	0.51	0.60	0.68	0.77	0.85	0.94	1.02	1.11	1.20	1.28	1.37	1.46	1.54	1.63	1.72	1.81	1.90	1.98	2.07	2.16	2.25	2.34	2.43	2.52	2.61	2.70	2.80	2.89	2.98	3.07	3.17	3.26	3.36	3.45	3.55	3.65	3.74	3.84	3.94	4.04
L8x8x.75	19.5	0.04	0.09	0.17	0.26	0.34	0.43	0.51	0.60	0.68	0.77	0.85	0.94	1.02	1.11	1.20	1.28	1.37	1.46	1.54	1.63	1.72	1.81	1.90	1.98	2.07	2.16	2.25	2.34	2.43	2.52	2.61	2.70	2.80	2.89	2.98	3.07	3.17	3.26	3.36	3.45	3.55	3.65	3.74	3.84	3.94	4.04
L8x8x.5	19.5	0.04	0.09	0.17	0.26	0.34	0.43	0.51	0.60	0.68	0.77	0.85	0.94	1.02	1.11	1.20	1.28	1.37	1.46	1.54	1.63	1.72	1.81	1.90	1.98	2.07	2.16	2.25	2.34	2.43	2.52	2.61	2.70	2.80	2.89	2.98	3.07	3.17	3.26	3.36	3.45	3.55	3.65	3.74	3.84	3.94	4.04
L6x6x1	15.5	0.03	0.07	0.14	0.20	0.27	0.34	0.41	0.47	0.54	0.61	0.68	0.75	0.81	0.88	0.95	1.02	1.09	1.16	1.23	1.30	1.37	1.44	1.51	1.58	1.65	1.72	1.79	1.86	1.93	2.00	2.08	2.15	2.22	2.30	2.37	2.44	2.52	2.59	2.67	2.74	2.82	2.90	2.97	3.05	3.13	3.21
L6x6x.75	15.5	0.03	0.07	0.14	0.20	0.27	0.34	0.41	0.47	0.54	0.61	0.68	0.75	0.81	0.88	0.95	1.02	1.09	1.16	1.23	1.30	1.37	1.44	1.51	1.58	1.65	1.72	1.79	1.86	1.93	2.00	2.08	2.15	2.22	2.30	2.37	2.44	2.52	2.59	2.67	2.74	2.82	2.90	2.97	3.05	3.13	3.21
L6x6x.625	15.5	0.03	0.07	0.14	0.20	0.27	0.34	0.41	0.47	0.54	0.61	0.68	0.75	0.81	0.88	0.95	1.02	1.09	1.16	1.23	1.30	1.37	1.44	1.51	1.58	1.65	1.72	1.79	1.86	1.93	2.00	2.08	2.15	2.22	2.30	2.37	2.44	2.52	2.59	2.67	2.74	2.82	2.90	2.97	3.05	3.13	3.21
L6x6x.5	15.5	0.03	0.07	0.14	0.20	0.27	0.34	0.41	0.47	0.54	0.61	0.68	0.75	0.81	0.88	0.95	1.02	1.09	1.16	1.23	1.30	1.37	1.44	1.51	1.58	1.65	1.72	1.79	1.86	1.93	2.00	2.08	2.15	2.22	2.30	2.37	2.44	2.52	2.59	2.67	2.74	2.82	2.90	2.97	3.05	3.13	3.21
L6x6x.375	15.5	0.03	0.07	0.14	0.20	0.27	0.34	0.41	0.47	0.54	0.61	0.68	0.75	0.81	0.88	0.95	1.02	1.09	1.16	1.23	1.30	1.37	1.44	1.51	1.58	1.65	1.72	1.79	1.86	1.93	2.00	2.08	2.15	2.22	2.30	2.37	2.44	2.52	2.59	2.67	2.74	2.82	2.90	2.97	3.05	3.13	3.21
L5x5x.75	13.5	0.03	0.06	0.12	0.18	0.24	0.29	0.35	0.41	0.47	0.53	0.59	0.65	0.71	0.77	0.83	0.89	0.95	1.01	1.07	1.13	1.19	1.25	1.31	1.37	1.43	1.50	1.56	1.62	1.68	1.75	1.81	1.87	1.94	2.00	2.06	2.13	2.19	2.26	2.32	2.39	2.46	2.52	2.59	2.66	2.73	2.80
L5x5x.625	13.5	0.03	0.06	0.12	0.18	0.24	0.29	0.35	0.41	0.47	0.53	0.59	0.65	0.71	0.77	0.83	0.89	0.95	1.01	1.07	1.13	1.19	1.25	1.31	1.37	1.43	1.50	1.56	1.62	1.68	1.75	1.81	1.87	1.94	2.00	2.06	2.13	2.19	2.26	2.32	2.39	2.46	2.52	2.59	2.66	2.73	2.80
L5x5x.5	13.5	0.03	0.06	0.12	0.18	0.24	0.29	0.35	0.41	0.47	0.53	0.59	0.65	0.71	0.77	0.83	0.89	0.95	1.01	1.07	1.13	1.19	1.25	1.31	1.37	1.43	1.50	1.56	1.62	1.68	1.75	1.81	1.87	1.94	2.00	2.06	2.13	2.19	2.26	2.32	2.39	2.46	2.52	2.59	2.66	2.73	2.80
L5x5x.375	13.5	0.03	0.06	0.12	0.18	0.24	0.29	0.35	0.41	0.47	0.53	0.59	0.65	0.71	0.77	0.83	0.89	0.95	1.01	1.07	1.13	1.19	1.25	1.31	1.37	1.43	1.50	1.56	1.62	1.68	1.75	1.81	1.87	1.94	2.00	2.06	2.13	2.19	2.26	2.32	2.39	2.46	2.52	2.59	2.66	2.73	2.80
L4x4x.75	11.5	0.03	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.66	0.71	0.76	0.81	0.86	0.91	0.96	1.01	1.07	1.12	1.17	1.22	1.27	1.33	1.38	1.43	1.49	1.54	1.59	1.65	1.70	1.76	1.81	1.87	1.92	1.98	2.04	2.09	2.15	2.21	2.26	2.32	2.38
L4x4x.625	11.5	0.03	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.66	0.71	0.76	0.81	0.86	0.91	0.96	1.01	1.07	1.12	1.17	1.22	1.27	1.33	1.38	1.43	1.49	1.54	1.59	1.65	1.70	1.76	1.81	1.87	1.92	1.98	2.04	2.09	2.15	2.21	2.26	2.32	2.38
L4x4x.5	11.5	0.03	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.66	0.71	0.76	0.81	0.86	0.91	0.96	1.01	1.07	1.12	1.17	1.22	1.27	1.33	1.38	1.43	1.49	1.54	1.59	1.65	1.70	1.76	1.81	1.87	1.92	1.98	2.04	2.09	2.15	2.21	2.26	2.32	2.38
L4x4x.375	11.5	0.03	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.66	0.71	0.76	0.81	0.86	0.91	0.96	1.01	1.07	1.12	1.17	1.22	1.27	1.33	1.38	1.43	1.49	1.54	1.59	1.65	1.70	1.76	1.81	1.87	1.92	1.98	2.04	2.09	2.15	2.21	2.26	2.32	2.38
L4x4x.25	11.5	0.03	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.66	0.71	0.76	0.81	0.86	0.91	0.96	1.01	1.07	1.12	1.17	1.22	1.27	1.33	1.38	1.43	1.49	1.54	1.59	1.65	1.70	1.76	1.81	1.87	1.92	1.98	2.04	2.09	2.15	2.21	2.26	2.32	2.38
L3.5x3.5x.5	9.5	0.02	0.04	0.08	0.12	0.17	0.21	0.25	0.29	0.33	0.37	0.42	0.46	0.50	0.54	0.58	0.63	0.67	0.71	0.75	0.79	0.84	0.88	0.92	0.97	1.01	1.05	1.10	1.14	1.18	1.23	1.27	1.32	1.36	1.41	1.45	1.50	1.54	1.59	1.64	1.68	1.73	1.78	1.82	1.87	1.92	1.97
L3.5x3.5x.375	9.5	0.02	0.04	0.08	0.12	0.17	0.21	0.25	0.29	0.33	0.37	0.42	0.46	0.50	0.54	0.58	0.63	0.67	0.71	0.75	0.79	0.84	0.88	0.92	0.97	1.01	1.05	1.10	1.14	1.18	1.23	1.27	1.32	1.36	1.41	1.45	1.50	1.54	1.59	1.64	1.68	1.73	1.78	1.82	1.87	1.92	1.97
L3.5x3.5x.25	9.5	0.02	0.04	0.08	0.12	0.17	0.21	0.25	0.29	0.33	0.37	0.42	0.46	0.50	0.54	0.58	0.63	0.67	0.71	0.75	0.79	0.84	0.88	0.92	0.97	1.01	1.05	1.10	1.14	1.18	1.23	1.27	1.32	1.36	1.41	1.45	1.50	1.54	1.59	1.64	1.68	1.73	1.78	1.82	1.87	1.92	1.97
L3x3x.5	7.5	0.02	0.03	0.07	0.10	0.13	0.16	0.20	0.23	0.26	0.30	0.33	0.36	0.39	0.43	0.46	0.49	0.53	0.56	0.59	0.63	0.66	0.70	0.73	0.76	0.80	0.83	0.87	0.90	0.93	0.97	1.00	1.04	1.08	1.11	1.15	1.18	1.22	1.25	1.29	1.33	1.36	1.40	1.44	1.48	1.52	1.55
L3x3x.375	7.5	0.02	0.03	0.07	0.10	0.13	0.16	0.20	0.23	0.26	0.30	0.33	0.36	0.39	0.43	0.46	0.49	0.53	0.56	0.59	0.63	0.66	0.70	0.73	0.76	0.80	0.83	0.87	0.90	0.93	0.97	1.00	1.04	1.08	1.11	1.15	1.18	1.22	1.25	1.29	1.33	1.36	1.40	1.44	1.48	1.52	1.55
L3x3x.25	7.5	0.02	0.03	0.07	0.10	0.13	0.16	0.20	0.23	0.26	0.30	0.33	0.36	0.39	0.43	0.46	0.49	0.53	0.56	0.59	0.63	0.66	0.70	0.73	0.76	0.80	0.83	0.87	0.90	0.93	0.97	1.00	1.04	1.08	1.11	1.15	1.18	1.22	1.25	1.29	1.33	1.36	1.40	1.44	1.48	1.52	1.55
L2.5x2.5x.5	7.5	0.02	0.03	0.07	0.10	0.13	0.16	0.20	0.23	0.26	0.30	0.33	0.36	0.39	0.43	0.46	0.49	0.53	0.56	0.59	0.63	0.66	0.70	0.73	0.76	0.80	0.83	0.87	0.90	0.93	0.97	1.00	1.04	1.08	1.11	1.15	1.18	1.22	1.25	1.29	1.33	1.36	1.40	1.44	1.48	1.52	1.55
L2.5x2.5x.375	7.5	0.02	0.03	0.07	0.10	0.13	0.16	0.20	0.23	0.26	0.30	0.33	0.36	0.39	0.43	0.46	0.49	0.53	0.56	0.59	0.63	0.66	0.70	0.73	0.76	0.80	0.83	0.87	0.90	0.93	0.97	1.00	1.04	1.08	1.11	1.15	1.18	1.22	1.25	1.29	1.33	1.36	1.40	1.44	1.48	1.52	1.55
L2.5x2.5x.25	7.5	0.02	0.03	0.07	0.10	0.13	0.16	0.20	0.23	0.26	0.30	0.33	0.36	0.39	0.43	0.46	0.49	0.53	0.56	0.59	0.63	0.66	0.70	0.73	0.76	0.80	0.83	0.87	0.90	0.93	0.97	1.00	1.04	1.08	1.11	1.15	1.18	1.22	1.25	1.29	1.33	1.36	1.40	1.44	1.48	1.52	1.55
L2.5x2.5x.1875	7.5	0.02	0.03	0.07	0.10	0.13	0.16	0.20	0.23	0.26	0.30	0.33	0.36	0.39	0.43	0.46	0.49	0.53	0.56	0.59	0.63	0.66	0.70	0.73	0.76	0.80	0.83	0.87	0.90	0.93	0.97	1.00	1.04	1.08	1.11	1.15	1.18	1.22	1.25	1.29	1.33	1.36	1.40	1.44	1.48	1.52	1.55
L2x2x.375	5.5	0.01	0.02	0.05	0.07	0.10	0.12	0.14	0.17	0.19	0.22	0.24	0.26	0.29	0.31	0.34	0.36	0.39	0.41	0.44	0.46	0.48	0.51	0.53	0.56	0.58	0.61	0.63	0.66	0.69	0.71	0.74	0.76	0.79	0.81	0.84	0.87	0.89	0.92	0.95	0.97	1.00	1.03	1.06	1.08	1.11	1.14
L2x2x.25	5.5	0.01	0.02	0.05	0.07	0.10	0.12	0.14	0.17	0.19	0.22	0.24	0.26	0.29	0.31	0.34	0.36	0.39	0.41	0.44	0.46	0.48	0.51	0.53	0.56	0.58	0.61	0.63	0.66	0.69	0.71	0.74	0.76	0.79	0.81	0.84	0.87	0.89	0.92	0.95	0.97	1.00	1.03	1.06	1.08	1.11	1.14
L2x2x.125	5.5	0.01	0.02	0.05	0.07	0.10	0.12	0.14	0.17	0.19	0.22	0.24	0.26	0.29	0.31	0.34	0.36	0.39	0.41	0.44	0.46	0.48	0.51	0.53	0.56	0.58	0.61	0.63	0.66	0.69	0.71	0.74	0.76	0.79	0.81	0.84	0.87	0.89	0.92	0.95	0.97	1.00	1.03	1.06	1.08	1.11	1.14

G.6 References

[1] Hearth. (2013, April 22). *How to tell what temperature a glowing object (metals) might be*. [Online]. Available: http://www.hearth.com/talk/wiki/know-temperature-when-metal-glows-red [2015, Nov 20].

[2] Justin Marek. “Labelled figures and Tables.” Winnipeg: Design Eng., Univ Manitoba, Winnipeg, MB, 2015, Dec 4.