Adjustable Fiberglass Transformer Pad Mold

Project #28 – Structural Composite Technologies

Final Design Report

MECH 4860 Engineering Design

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EXECUTIVE SUMMARY

This design report provides an overview of the design process used by the U of M Team to develop a 2-dimensionl adjustable mold for Structural Composite Technologies' **(SCT)** custom transformer pad **(T-Pad)** production process. The purpose of designing the adjustable mold was to reduce the high production costs and long lead times for the current custom T-Pads. Additionally, the adjustable mold was intended to improve the surface quality of the custom T-Pads. Deliverables for the project include a SolidWorks model of the final design, engineering drawings, operation instructions, formal quotes, a Bill of Materials **(BOM)**, and a design report detailing how the mold meets the project metrics.

The adjustable mold needed to meet several target metrics that were composed by SCT and the U of M team at the onset of the project. Key metrics included the mold size which needed to range from 5' x 5' up to a size of 10' x 8' and have a height of 36". Height adjustability was an optional component of the design scope. Additionally, the mold needed to be discretely adjusted in increments of at minimum 6" in both directions. The other key metrics were assembly time and mold maintenance which needed to be limited to two hours for two people and 15 minutes per mold cycle respectively. The mold required a maximum weight of less than 3750 lbm such that it could be transported by forklift intact if required and a maximum individual component weight of 100 lbm to meet the requirement of two workers being able to assemble the mold. Finally, after a detailed economic analysis based on previous custom T-Pad sales volume, it was determined the capital cost of the mold needed to remain under CAD$ 25,000 but would be competitively advantageous if it remained under CAD$ 10,000. A female mold design was preferred over a male mold design to improve the surface finish of the finished T-Pads.

Based on these core metrics the U of M team developed a preliminary list of 62 component-based concepts. These components were then combined into preliminary list of 15 complete concepts. These 15 concepts were then filtered based on research, feedback from SCT, and a Pugh Matrix to a shortened list of eight that was presented to SCT at the first of two external design reviews. Following the external design review, the U of M team used a weighted scoring matrix to identify the two most feasible concepts. Development of detailed designs for each of these concepts was carried out using Failure Modes and Effects Analysis **(FMEA).** After a second external design review at with SCT a final mold concept was selected.

The final concept incorporates four 18" x 18", carbon steel, bent sheet metal corners that are assembled using 8' and 10' Hollow Structural Section **(HSS)** guide rails. The corners are designed to stand independently for assembly and can be secured to the guide rails using bolts, pins, or clamps. The walls sections between the corners are filled with sheet metal insert panels that can also be secured to the guide rails with bolts, pins or clamps. The insert panels come in 6", 12", 24" and 48" varieties such that the mold

can be adjusted in 6” increments up to a maximum size of 8’ x 10’. The smallest mold configuration is 3’ x 3’. The modular nature of the mold allows for longer guide rails and additional insert panels to be fabricated in the future if SCT needs to produce oversized custom T-Pads. The entire assembly can sit on any arbitrary flat base frame. This base frame will be designed and provided by SCT. The corner assemblies are designed such that they can be ergonomically lifted by two workers and clamped or bolted to the base frame to prevent shifting of the mold components. Although the final design presented in this report is for a carbon steel mold, stainless steel and aluminum are both viable options that will reduce the risk of corrosion. SCT will be left to decide their preferred material after submittal of the final project deliverables by the U of M team. Quotes are provided for both carbon steel and stainless steel.

The final step in the design process carried out by the U of M team was to quantify the outstanding metrics by conducting a technical analysis of the mold. The outstanding metrics after selection of a final concept included manufacturing feasibility, mold rigidity, assembly time, and capital cost. First, a meeting was held with one of SCT’s manufacturer’s, Taj Industrial, to discuss the feasibility of fabricating the mold components. The key notes from this meeting were that every component proposed by the U of M team was feasible, that the mold components could be fabricated to fit together with minimal seams, and that 1/8” welds should be used to mitigate weld shrinkage. Next, numerical analysis demonstrated that a deflection of less than 2 mm could be achieved on the mold corners under normal operating conditions after the addition of four new welded gussets. The maximum component weight after conducting the rigidity study was reduced to 100 lb bringing the complete assembly weight to 952 lbm – 1524 lbm depending on the mold size. Next, analysis of the likely mold assembly time based on a set of assembly instructions demonstrated that an assembly time ranging from 55 minutes to 110 minutes was expected for the largest mold size. Mold maintenance expected to be minimal due to the strength, hardness, and corrosion resistance of the potential materials. Finally, quotes obtained from Taj Industrial showed the capital cost for the stainless steel and carbon steel molds to be $12,635.58 and $8,743.58, respectively. These values include fasteners but do not include sales tax or shop drawings. An additional contingency of +/- 20% will be associated with these values based on the fluctuating cost of material and design changes made after the drawings were sent for quotation.

Upon finalization of the design the final model was compared against the complete set of project metrics. Of the 23 design metrics, 14 meet the marginally acceptable values and 9 meet the ideal values indicating that the design was successful in evert aspect defined by SCT.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Name	Symbol/Definition
Inches	in or ”
Millimeters	mm
Feet	ft or ’
Pound-mass	lbm
Two-Dimensional	2D
Three-Dimensional	3D
Force	P
Modular of Elasticity	E
First Moment of Inertia	I’
Bend Allowance	BA
K-Factor	K
Bend Radius	R
Gigapascal	GPa
Canadian Dollars	CAD$
Structural Composite Technologies	SCT
Fiber Reinforced Polymer	FRP
Transformer Pad	T-Pad
Finite Element Analysis	FEA
Computer aided design	CAD
To Be Determined	TBD
Drawing Exchange Format	DXF
Standard for the Exchange of Product model data	STEP
University of Manitoba	U of M
Bill of Materials	BOM
Failure Modes and Effects Analysis	FMEA
Hollow Structural Section	HSS
Female Mold	F
Male Mold	M
External Design Review	EDR
Medium Density Fiberboard	MDF
Von Mises Stress	VMS

1 INTRODUCTION

Structural Composite Technologies (**SCT**) is a fibreglass fabricator providing design, engineering and manufacturing expertise for custom Fiber Reinforced Polymer (**FRP**) process equipment for mining, milling, processing and manufacturing companies in Canada and abroad. Outside of an extensive list of industrial FRP products, SCT mass produces a range of FRP transformer pads (**T-Pads**) as shown in Figure 1. The FRP T-Pads have several advantages over traditional concrete T-Pads such as a reduction in weight, efficient shipping, rapid installation, high customizability, resistance to the conduction of electricity, and long life-cycles [1].

[redacted]

Figure 1. FRP T-Pad [2]

The initial project submitted to the University of Manitoba (**U of M**) Ideas program was to have a capstone engineering team develop a full-scale destructive testing methodology for FRP T-Pads. Lack of access to U of M testing facilities prevented this project from moving forward. Instead, SCT proposed a change in project scope to designing a size-adjustable T-Pad mold. This project will consist of improving upon the affordability and lead time of SCTs custom line of FRP T-Pads that fall outside of their list of commodity T-Pads, or T-Pads made from permanent molds.

SCTs current range of 20 commodity FRP T-Pads does not satisfy the wide array of transformer sizes presently on the market. The reason for this is that the FRP T-Pads are designed to have a 100 mm (4”) gap between the T-Pad side wall and footprint of the actual transformer on all four sides of the pad [2]. If this gap is too large, the T-Pads tend to fail as a result of what SCT calls the ‘trampolining effect’. Similarly, if this gap is too small, transformer installation onto the pad becomes difficult due to lack of edge clearance. Oversized, or long and skinny transformers are also difficult for SCT to accommodate with their current set of molds. This means that SCTs product range of T-Pads does not satisfy the diversity of transformers that are produced.

Currently, SCT modifies the reinforcement and cut-outs for FRP T-Pads that fall in between model sizes. In the case of oversized or odd shape transformers, SCT fabricates FRP T-Pads from scratch by building a wood frame and encasing it in FRP.

The key issue with fabricating FRP T-Pads from scratch is that the plywood frame used to create these custom T-Pads becomes a part of the finished product. Due to limited carpentry resources, this process is costly and inefficient for SCTs shop personnel which results in a high sales price. This is causing potential revenues to be lost to American competitors who are able to supply commodity T-Pads at a lower cost. For the custom T-Pads to be an effective solution to the gaps in SCTs product line, both manufacturing time and manufacturing cost of the current process need to be reduced.

To achieve these goals, SCT has proposed designing a size adjustable mold that can be rapidly adjusted in two directions such that custom T-Pads can be produced at a lower cost and with shorter lead times. This proposal provides the overall definition the design scope of this project which includes a final design complete with engineering drawings and a bill of materials (**BOM**).

This report outlines the actions taken by the U of M Team to define the problem, generate solutions and refine the solutions into feasible designs of an adjustable mold with the highest level of benefit to SCT. The project scope and deliverables defined by SCT are presented in Section 1.2. This is followed by a description of the methodology used by the U of M Team to complete each phase of the project, and a review of the work items relating to both the project definition and concept development phases.

Section 2 provides an overview the project needs, constraints, design metrics, and a description of the overall design process. Section 3 summarizes the concept development and selection processes where preliminary concepts are presented along with a discussion of the filtering process. Also included in this section is a summary of the first External Design Review (**EDR**) containing feedback from SCT to be reflected in the two refined concepts that moved on to the final design phase. A summary of the two selected concepts is provided in Section 3.2.

Section 4 presents a detailed account of the process that the U of M Team arrived at a final design. Section 5 follows Failure Mode and Effects Analysis (**FMEA**) that was used to identify areas for design modification and improvement. Section 6 provides a summary of the decisions made at the second EDR to remove the base plate as a part of the assembly and add constraints that define the technical optimization of the mold. Technical optimization included weld calculations, numerical analysis of the mold rigidity, numerical analysis of the finished T-Pads, and a detailed consideration of mold ergonomics. Lastly, Section 7 provides an overview of the final design and its operation, features, specifications and includes engineering drawings and a Bill of Materials (**BOM**).

1.1 Project Purpose

The purpose of designing an adjustable mold is to expand SCTs current share of the custom FRP T-Pad market by reducing fabrication costs and allowing custom T-Pads to be priced competitively. SCT currently offers 20 different commodity FRP T-Pads that range in size from 30” x 22” x 28” (L x W x H) to 75” x 95” x 28”. When transformers cannot be accommodated by the commodity model T-Pads, SCTs solution is to fabricate completely custom FRP T-Pad or make modifications to the reinforcing in their existing FRP T-Pads. A fully custom FRP T-Pad ranges between $5,000-$20,000 Canadian dollars (**CAD$**) and modifying an existing FRP T-Pad runs between $100-$200 CAD$ over the baseline cost of a commodity FRP T-Pad. However, by utilizing a reusable, adjustable mold these costs can be significantly reduced which would allow SCT to provide a more attractive custom FRP T-Pad price relative to imported commodity models from the United States.

An efficient customizable mold does not only decrease the time to produce a custom FRP T-Pad, but also prevents the time being taken away from other carpentry priorities. Additionally, a mold with customizable height would allow SCT to have access to additional markets outside of Manitoba. SCT estimates by pricing the pads competitively SCT’s production of custom sized T-Pads could increase from 7 to 10 pads per year if the production process was streamlined.

1.2 Scope and Deliverables

The scope of this project is to design a two-dimensional (**2D**) size adjustable mold for SCT. The design should be complete with a three-dimensional (**3D**) model, engineering drawings for fabrication, operation instructions, and a bill of materials for the stock and custom parts.

To deliver a feasible solution the U of M Team outlined the following project objectives:

1. Assess the assembly, transportation, functionality, accessibility, safety, maintenance and thermal properties related to an adjustable mold for SCTs FRP T-Pads.
2. Define needs, metrics, specifications and constraints to set performance requirements for the final version of the adjustable mold.
3. Complete an analysis of the expected payback period. The cost of the mold must be recouped within a reasonable time period.
4. Assess the structural integrity and performance of the proposed design using numerical analysis.

2 PROJECT DEFINITION

Project definition involved developing a detailed list of needs, constraints, and design metrics with the goal of determining a list of specifications that an adjustable mold must meet. The needs, constraints, and metrics were determined through multiple meetings and discussions between stakeholders at SCT and the U of M Team. Also included in this section is a detailed account of the design process that was followed to reach a final design for the adjustable mold.

2.1 Design Needs and Specifications

The project needs are a list of characteristics or attributes that the final design should have. The needs are categorized into safety, economic, user, and function related needs. The two main categories are user and function related needs. Function needs describe functional design aspects that the mold must have. User needs describe ways in which the mold must facilitate operation. The final list of project needs presented in Table I. The needs are sorted by order of importance, as many of the needs have equal importance they were also grouped by priority. High priority needs are absolute requirements for the project. Moderate priority needs are identified as need absolute requirements unless they are found to be infeasible due to economic constraints. Low priority needs are addressed but are not identified as absolute requirements for the project.

TABLE I: RANKED LIST OF NEEDS

Need #	Ranked List of Needs	Category	Priority
1	The mold should be safe to assemble and work around	Safety	High
2	The mold should be reasonably priced relative to the cost of fabricating permanent molds for each custom size	Economic	High
3	The mold should facilitate release of the T-pads after curing	User	High
4	The mold should be capable of producing transformer pads that can support the weight of most transformers	Function	High
5	The mold should leave the option for custom reinforcing on the side walls and top surface of the T-pad	Function	High
6	The mold should be chemically inert when exposed to the release agent, resin, and catalyst	Function	High
7	The mold should be quick to assemble for two people	User	High

8	The mold should be capable of withstanding cure temperatures without degradation	Function	High
9	The mold should be structurally sound to lift and move with or without a T-pad inside	Function	High
10	The mold should be discretely adjustable in both horizontal directions in accordance with the previous custom T-pad sizes	Function	High
11	The mold should allow shop personnel to reach all areas with the chopper spray gun	User	High
12	The mold should be able to produce T-pads without seams that could compromise aesthetic or structural integrity	Function	High
13	The mold should be structurally sound to move in all configurations	User	High
14	The mold should be easy to push around the shop for two people	User	High
15	The mold should require minimal maintenance	Function	High
16	The mold should be easy to transport with a forklift	User	Moderate
17	The mold should incorporate a method of preventing overspray accumulation on the outer surface of the mold	Function	Moderate
18	The adjustable mold should maintain the aesthetic achieved of the commodity T-pad molds	Function	Moderate
19	The mold should have discrete sizes that accommodate most custom orders	Function	Moderate
20	The mold should be designed to remain functional for several years without degradation in product quality	Function	Moderate
21	The mold should facilitate securing the wood reinforcing in place while the final chop-spray layer is being applied	User	Moderate
22	Spray technicians should be able to easily identify which areas of the mold surface have been coated	User	Moderate
23	The mold should be resistant to corrosion when exposed to ambient shop conditions and ambient storage conditions	Function	Moderate
24	The mold should be easily disassembled for storage	Function	Moderate
25	The mold surface should be easily cleanable	User	Moderate
26	The mold should be easily assembled without special equipment	User	Low
27	The mold height should be adjustable	Function	Low
28	The mold should fit through the overhead doors when assembled	Function	Low

The ranked list of needs was used along with qualitative values provided by SCT to compose the product specifications shown in Table II. The list of metrics and specifications displayed in the table reflects the final target and marginally acceptable values. The metrics were used twice during the design process, first, they were used as a baseline for the development of the concept scoring matrix shown in section 3.1.2. Second, they were used to validate the final design. The metric table is revisited in the section 8.1 to confirm that the final design meets the desire specifications.

The metrics are roughly sorted by order of importance and key metric trade-offs are summarized below:

- Increasing the project budget allows nearly every metric to be more easily achieved.
- Focusing on the design’s resistance to corrosion significantly benefits part removal, T-Pad finish, re-usability, and maintenance.
- The lifecycle and maintainability of the mold is largely determined by the mold’s temperature resistance, rigidity, resistance to mechanical wear, and overspray vulnerability.
- Incorporating a method of adjusting the height of the FRP T-pads that the mold can produce limits most of the other metrics indicating that height adjustability is difficult to justify implementing.

TABLE II: FINAL PROJECT METRICS

Metric #	Needs Addressed	Metric	Ideal Value	Marginally Acceptable Value	Units
1	**7, 14, 24**	Average Assembly Time	30 minutes	120 minutes	minutes
2	**1, 11**	Safety	none - pinch points and sharp edges minimized	minimal	# recorded incidents
3	**9, 13**	Strength	Supports an average person	Supports an average person with additional cribbing	pounds'
4	**2**	Capital Cost	$10,000	$25,000	$/custom Tpad
5	**6, 15, 23**	Corrosion Resistance	No corrosion indoors, outdoors, or from chemicals	No corrosion indoors or from chemicals	Qualitative
6	**3**	Part Removal	5-degree draught + integrated removal method	5-degree draught	Qualitative
7	**4, 5, 21**	Customizable Reinforcing	Complete Customizability	Restricted Customizability	Qualitative
8	**12, 18**	Aesthetic/Finish of T-pads	Identical to mass produced units	Better than plywood molds	Surface Roughness
9	**15**	Re-usability (life cycle)	10 units/year for 10 years	10 units/year for 5 years	Years and Production
10	**6, 15, 20, 25**	Maintenance	0.1	0.25	Hours/use
11	**6, 8**	Temperature Resistance	250F	250F	Fahrenheit
12	**4, 10, 28**	Depth-Width	5' to 10'	5' to 8'	feet
13	**11, 22, 25**	Accessibility (height)	40"	50"	inches
14	**4, 12, 18**	Seams	None	Seams do not restrict release	mm/inches
15	**14**	Max Assembly Weight	< 1500	< 3750	pounds
16	**14, 24**	Individual Component Weight	< 50	< 100	pounds
17	**9, 18**	Rigidity (Allowable Deflection)	< 2	< 4	mm
18	**9, 13, 16**	Fork-Lift Access	Built-in fork channels	Flat bottom	Qualitative
19	**15, 17**	Overspray Prevention	Built-in shield/cover	Accommodates poly wrap	Qualitative
20	**10, 19, 24**	Discretization	4"	6"	inches
21	**18, 22**	Color	Black	Not evergreen or white	Qualitative
22	**26**	Assembly Tools	Tools which SCT already has	Tools which SCT would need to acquire	Qualitative
23	**27**	Height Adjustability	36" and 42"	36"	inches

2.2 Design Constraints

The design constraints define a list of design characteristics that the U of M Team avoided incorporating into the mold. The design constraints for the project have been broken down into four general categories: safety and functionality, material, strength and weight, and additional constraints that did not fit into the other categories. A summary of the project constraints grouped by category is provided in Table III. It should be noted that the constraints are not ranked, they are all absolute requirements.

Safety and functionality constraints generally refer to the mold geometry as some geometries may restrict SCTs ability to perform certain tasks safely or at all. For example, if the only way to access a bottom bolt is for someone to crawl underneath the mold, this is unsafe work. Unsafe work is defined as any work which puts SCT personnel at risk of injury, regardless if protective equipment is used.

The materials are limited at SCT's request to carbon steel, stainless steel, aluminum, wood and fiberglass because of their low cost, light weight and compatibility with existing manufacturing capabilities and partnerships. Additional material constraints are presented in Table III to ensure the material does not compromise the curing process, corrode in the SCT shop, or result in an economically infeasible design.

Strength and weight constraints are necessary to limit the mass of the assembly and its components such that individual components can be carried by two individuals. Strength constraints are included to ensure that the mold is sufficiently rigid when in use.

The additional constraints pertain to cost, manufacturing time, surface finish, and maintenance of the mold. To deliver a feasible design, all of the constraints must be met. An outline of the approach taken by the U of M Team is presented in the following section.

TABLE III: PROJECT CONSTRAINTS

Category	Constraint No.	Constraints
Safety and Functionality	1	The mold cannot force SCT personnel into performing unsafe work practices
	2	The mold geometry must not limit the ability of SCT personnel to cover parts of the mold during the chop-spray process that would otherwise prevent future functionality if not covered
	3	The mold must not limit the accessibility of the surfaces to be sprayed - workers cannot be restricted to only standing outside of the mold
	4	The mold geometry must not limit SCTs ability to transport or lift the mold using their forklifts, chain falls, or gantry crane
	5	The mold must not limit the ability of SCT personnel to remove the transformer pads after curing
	6	The mold must not limit complete customizability of wood reinforcing
	7	The mold must not contain corners or edges with a radius smaller than 0.5 inches such that rollers cannot be used to smooth out the spray
Material	8	The mold materials must not react chemically with the release agent, resin, or catalyst currently used by SCT
	9	The mold cannot be fabricated from welded plastic components, multi-ply laminated composites, or unnecessarily expensive metals such as Invar Steel or titanium
	10	The thermal capacity of the mold must be low enough such that the exothermic reaction of the resin-catalyst mixture is not compromised
	11	The mold cannot corrode under ambient shop conditions – it would be beneficial if the mold also did not corrode if stored outside in the winter months
	12	The mold cannot retain moisture or absorb the release agent, resin, or catalyst
Strength and Weight	13	The mold cannot plastically deform during transport or the chop-spray process
	14	The mold cannot warp as the FRP T-Pad cures
	15	The mold cannot be heavier than 3750 lbm so that the shop forklift can move it – ideally the mold would not be heavier than about 2000 lbm so that 2-3 workers could manually roll it around the production floor
Additional Constraints	16	The cost of the mold must not exceed the potential savings related to the transformer pads produced by the mold
	17	The mold cannot require adjustment time which exceeds 2 hours
	18	The mold must not leave a rough surface or sharp seams on the finished FRP T-Pads
	19	The mold must not demand perpetual maintenance from SCT personnel

2.3 Design Process Methodology

The design process methodology covers the complete process used by the U of M Team to develop an optimal mold design. The project was split into three phases, the initial project definition phase, the concept development phase, and the detailed design development phase. Discretization of the design development phases allowed the U of M Team to obtain feedback on design as multiple points during concept development. The key feedback milestones were as follows:

1. At the first EDR, after development of a series of preliminary concepts
2. At the end of the concept development phase, after the preliminary concepts were refined and combined
3. At the second EDR where two highly developed concepts were contrasted against each other

In order to present SCT with a viable design for an adjustable mold the U of M Team outlined work items for each phase. The project definition phase focused on what the design needed to do, limitations on the design and how the design's end performance could be evaluated. The concept development phase required a strategy to generate a wide variety of concepts and reduce the concepts generated to the most viable solutions that were combined, filtered and presented to SCT at the first EDR. SCT directed the U of M Team to move forward with the 4-Wall and 4-Corner designs. Further development and refinement of concepts was done by the U of M Team alone to prioritize modular attributes that would move on to the final design phase.

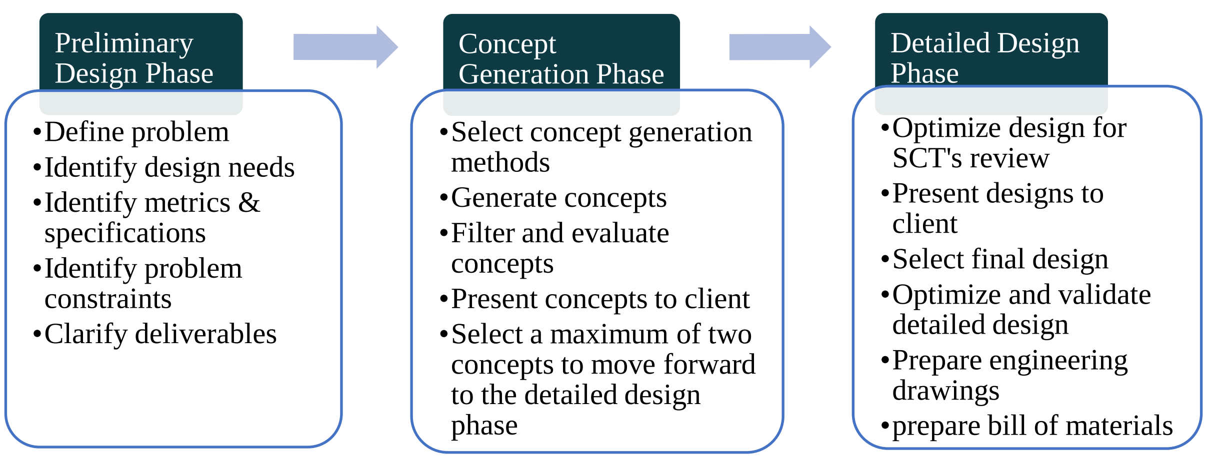


Figure 2. Overview of Project Phases

The flow chart shown in Figure 2 on the following page provides an overview of the design process from project definition to submittal of the deliverables package. The purpose of this flow chart is to provide context for the design steps described in the remainder of this report.

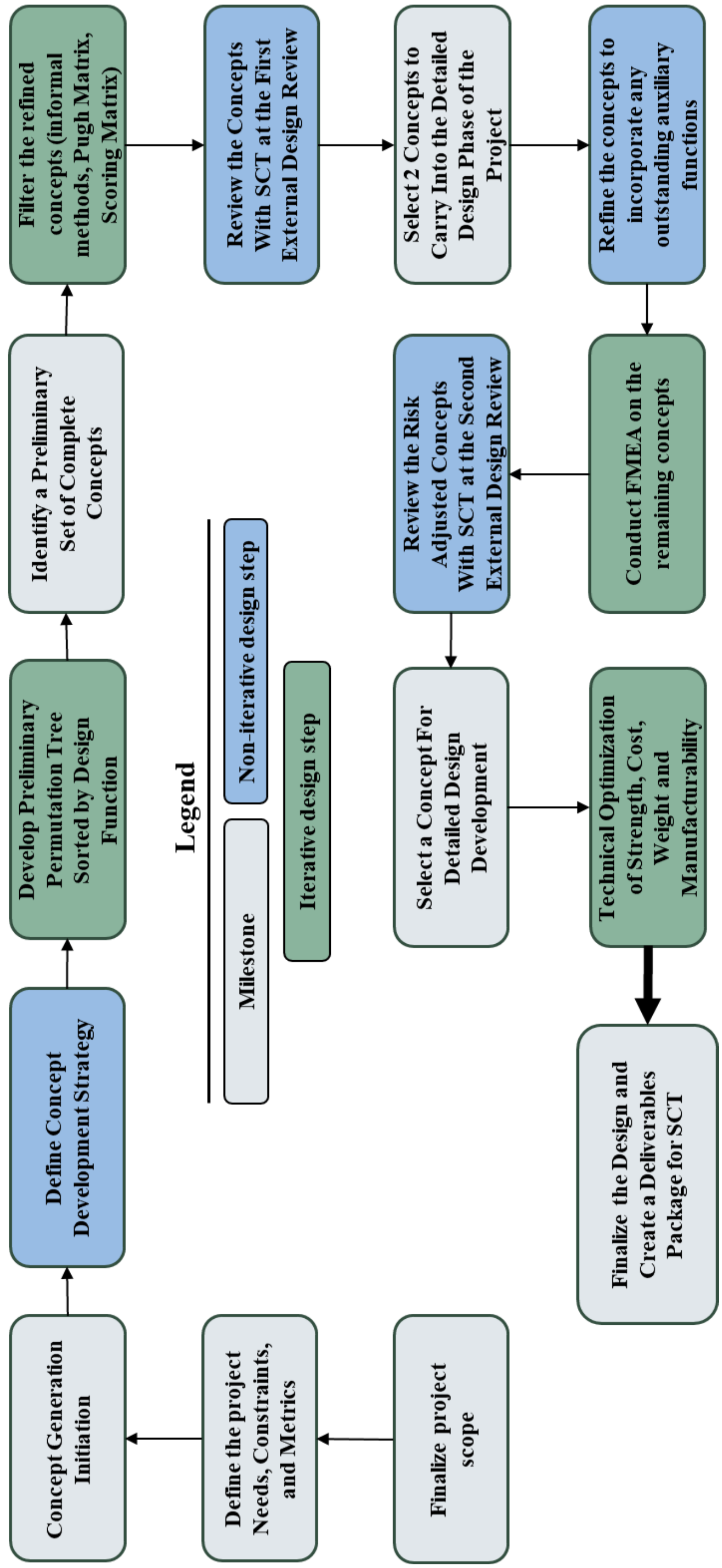


Figure 3. Overall design process flow chart

3 CONCEPT DEVELOPMENT AND SELECTION

This section summarizes the concept generation phase, starting with concept generation initiation shown as step three in Figure 3 and continues through to the selection of two concepts for detailed design development. In this phase, the U of M Team developed fifteen concepts using functional decomposition and synthesis as well as external strategies such as TRIZ 40 and patent research. The purpose of this section is to provide an overview of the concepts that were developed and presented to SCT at the first EDR, as well as the selection process that was used to arrive at the Modular 4-Wall and Modular Corner V2 designs at the end of the concept development phase.

Section 3.1 provides an overview of how informal filtering and a Pugh matrix were used to initially filter the fifteen concepts to four favored designs. Along with the four favored concepts, three additional concepts that were presented to SCT at the first EDR. A summary of the relevant designs presented to SCT are shown in Table V with a schematic and description of the concept along with its key advantages and drawbacks. Designs favoured at the first EDR were subsequently filtered and refined before being evaluated by the U of M Team using a weighted decision matrix.

A detailed overview of the selected concepts is presented in section 3.2. Labelled renders of the two concepts are provided to clearly show what the concepts would look like, and how they would function as an adjustable mold.

3.1 Concept Selection Methodology

The concept selection process consisted of several stages including informal concept filtering, Pugh matrix filtering, client feedback from the first EDR, concept refinement, and lastly concept selection using a weighted decision matrix. Using this methodology, the U of M Team screened the fifteen generated concepts down to two by the end of the concept development phase.

The flowchart displayed on the following page in Figure 4 provides an overview of the rigor implemented in the concept development and selection process. Red lines and text indicate various methods that were used to iterate external concept generation and selection of the concepts.

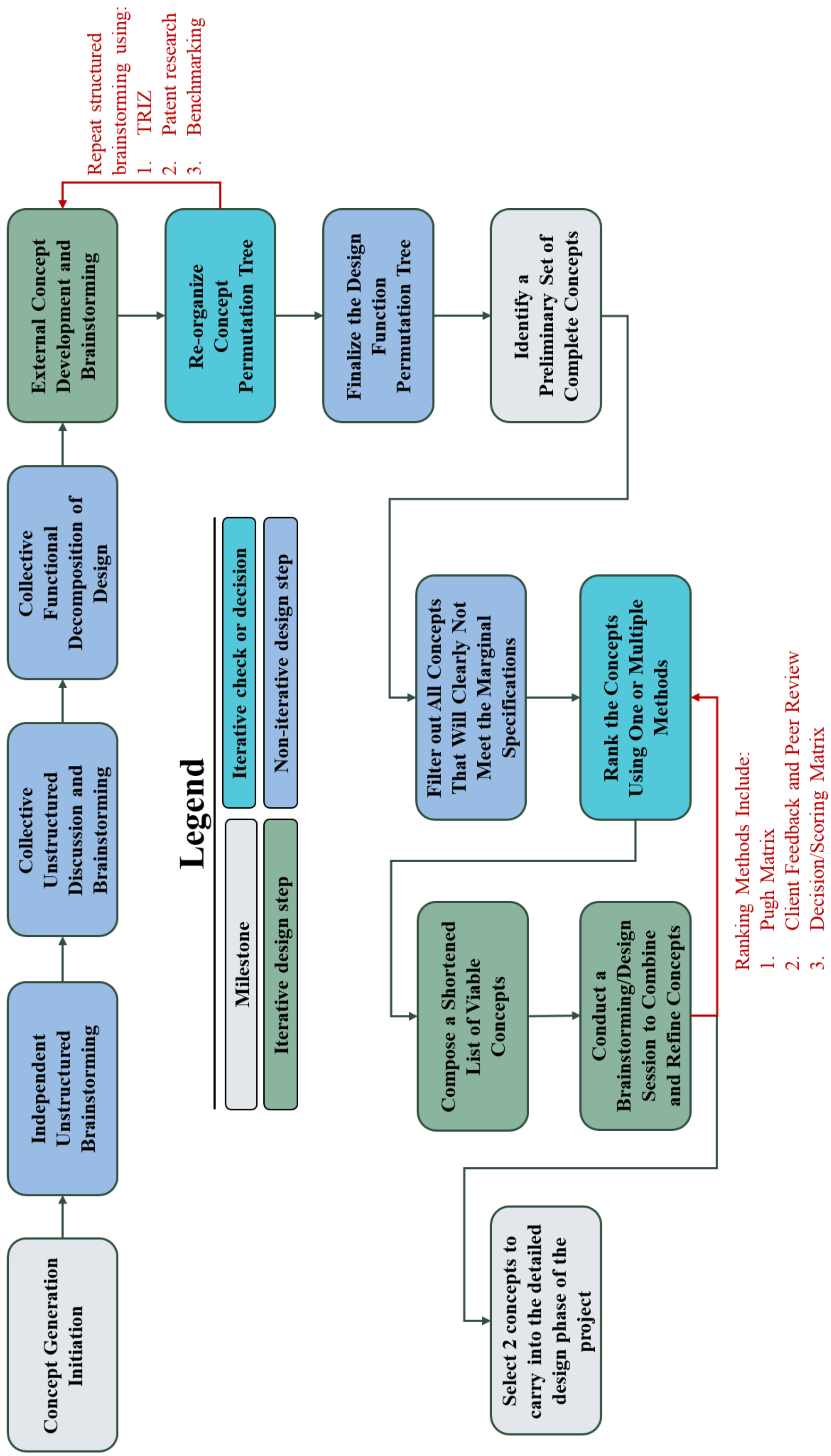


Figure 4. Concept development and selection flow chart

The remainder of this section focuses on providing more detail as to how key steps in the Figure 4 flow chart were executed. The methodology used to select the final two designs for detailed design development is fully defined.

3.1.1 Concept Generation and Preliminary Filtering

The following list provides a chronological overview of the process that was followed to generate and filter concepts prior to the first external design review:

1. Functional decomposition of the design resulted in eight design functions that each had their own unique set of concepts. These functional groups were divided into core and auxiliary functions and are listed below. Core functions defined the overall shape and functionality of the mold. Auxiliary functions were identified as functions that could be independently developed and applied to any of the core functions.

TABLE IV: CORE AND AUXILIARY FUNCTIONS

Core functions	Auxiliary Functions
• Mold walls • Mold top panel • Support frame • Size adjustment mechanism	• Locking mechanism • Locating mechanism • Mold mobility • Release mechanism

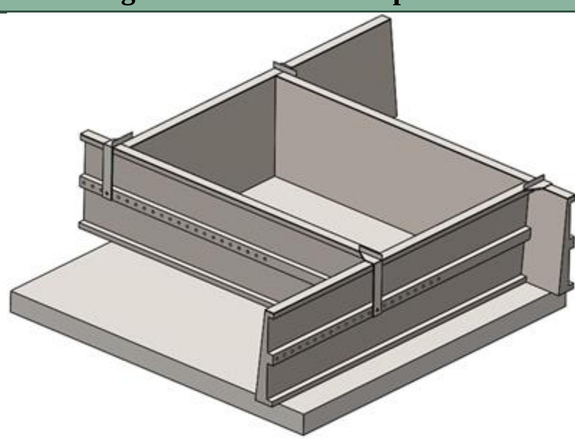
2. TRIZ, patent research, and internal team concept generation were used to develop a list of preliminary concepts that were sorted by design function. In total 62 function-specific concepts were created. For example, the complete list of mold mobility concepts was caster wheels, omni-wheels, tracks, and forklift transport.
3. Following concept generation by functional group, viable function-specific concepts were combined into 15 feasible concepts addressing all the core functions. This step is denoted in the Figure 4 flowchart as the ‘identifying a preliminary set of complete concepts’ milestone.

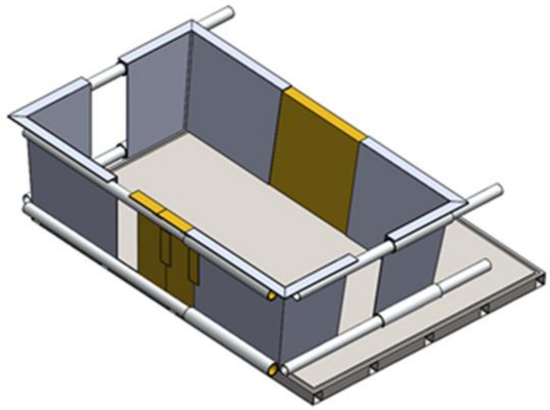
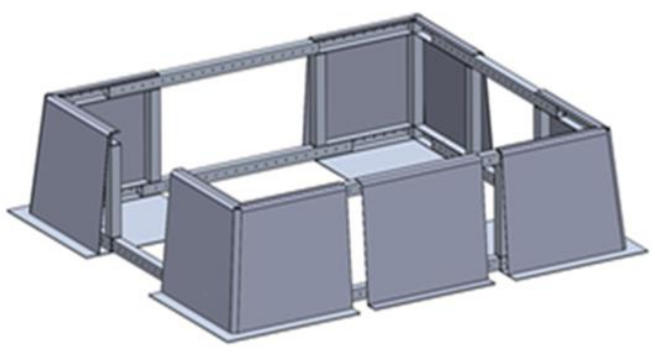
The remaining concept selection steps focused on refining and combining this preliminary list of complete concepts.

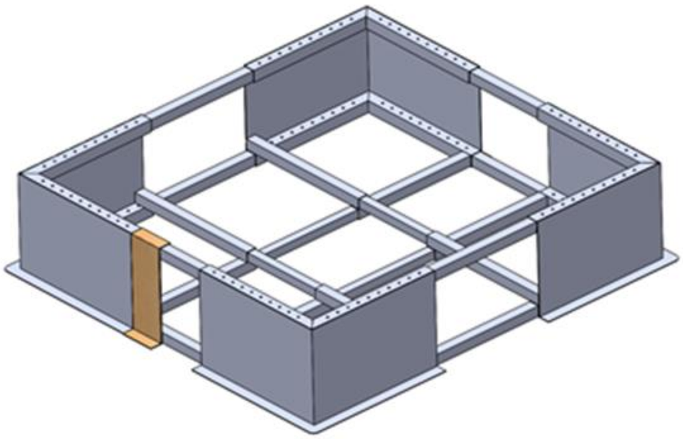
4. First, informal concept filtering was used to eliminate concepts that showed to have no advantages in comparison with any of the other concepts. The decisions in the process reflect the U of M Team's engineering intuition and resulted in a reduction from fifteen to seven unique concepts, or eleven concepts when alternate configurations were considered.
5. Next, A Pugh matrix was used to rank the 11 remaining concepts against a benchmark which reduced the list of feasible concepts to 8. These concepts were presented to SCT at the first EDR. Four of these concepts were identified as 'high potential' concepts and were the primary focus of the meeting, the remaining four concepts were shown as alternatives or 'less feasible designs' to have SCT validate the U of M Team's selection.

Table V shows the high potential concepts that were presented to SCT at the first EDR and lists their alternate configurations. Additional preliminary concepts that were considered not to have high potential can be found in Appendix A.

TABLE V: PRELIMINARY CONCEPTS DEVELOPED

<table>
<tr><th>Core Concept Shown:</th><th>4-Wall - No Alignment</th><th colspan="2">Female Mold</th></tr>
<tr><td>Other Configuration:</td><td>4-Wall - Wheel Alignment</td><td colspan="2">Female Mold</td></tr>
<tr><td>Other Configuration:</td><td>4-Wall - Split Wall</td><td colspan="2">Female Mold</td></tr>
<tr><td colspan="2" rowspan="6"></td><td>Key Advantages</td><td>Key Drawbacks</td></tr>
<tr><td>Simple design</td><td>Potentially heavy walls</td></tr>
<tr><td>Surface finish comparable to commodity pads</td><td>Walls can create an obstacle for smaller pads</td></tr>
<tr><td>Less overspray issues than other female concepts</td><td rowspan="2">Alignment and rigidity of support frame may be in issue</td></tr>
<tr><td>No carpenter time required</td></tr>
<tr></tr>
<tr><td colspan="4">Description</td></tr>
<tr><td colspan="4">Four walls are fastened together with an adjustable bracket that slides along a pin hole rail to set the desired size. One wall is fixed and the three other slide along the bracket and rail. Due to the geometry of the mold, no custom pieces are required, and the entire T-Pad size range is available without any additional pieces added to the mold. The base plate provides a smooth surface for the T-Pad top face. The different configurations include adding wheels to move the walls instead of sliding them and splitting the walls up into pieces to address the accessibility issues of the walls extending out.</td></tr>
</table>

<table>
<tr><td>Core Concept Shown:</td><td>Cantilever Rail – Prefab Walls</td><td colspan="2">Female Mold</td></tr>
<tr><td>Other Configuration:</td><td>Cantilever Rail – TeleWall</td><td colspan="2">Female Mold</td></tr>
<tr><td>Other Configuration:</td><td>Cantilever Rail – Custom Panel</td><td colspan="2">Female Mold</td></tr>
<tr><td colspan="2" rowspan="4"></td><td>Key Advantages</td><td>Key Drawbacks</td></tr>
<tr><td>Lightweight moving parts – ergonomics</td><td>Difficult to manufacture panel inserts</td></tr>
<tr><td>Multiple wall options</td><td>High risk of large seams</td></tr>
<tr><td>Corner units provide consistent surface finish</td><td>Vulnerable to overspray</td></tr>
<tr><td colspan="4">Description</td></tr>
<tr><td colspan="4">Two telescoping cantilever beams on each side of the mold make up a frame with fixed panels in the corners. When the frame telescopes the size of the mold adjusts and insert panels are fastened to the sides of the frame to cover gaps. The base plate provides a smooth surface for the T-Pad top face, no custom top piece is required. Each configuration changes the method of addressing the panel inserts required by using either a fabricated reusable telescoping panels or custom inserts made for every T-Pad produced.</td></tr>
<tr><td>Core Concept Shown:</td><td>Modular Corner (M)</td><td colspan="2">Male Mold</td></tr>
<tr><td>Other Configuration:</td><td>Modular Corner (F)</td><td colspan="2">Female Mold</td></tr>
<tr><td colspan="2" rowspan="4"></td><td>Key Advantages</td><td>Key Drawbacks</td></tr>
<tr><td>Does not require bulky base plate</td><td>Requires custom plywood top for every T-Pad</td></tr>
<tr><td>Individual components weigh less</td><td>Moderate surface prep for seams</td></tr>
<tr><td>Easy access to mold surface (for prep)</td><td>Poor surface finish</td></tr>
<tr><td colspan="4">Description</td></tr>
<tr><td colspan="4">Fixed panel corners are assembled together using a support from with holes for bolts. The four corner pieces can be assembled to different locations on the support frame in order to adjust the mold size as desired. Insert panels are fastened to the sides of the frame to cover the gaps. For every T-Pad a custom plywood top panel is placed on top of the support frame to create the top panel of the mold.</td></tr>
</table>

Core Concept Shown: Flat Plate Custom Top	Male Mold	
	**Key Advantages**	**Key Drawbacks**
	Inherently good alignment	Poor surface finish
	Protection from overspray	Still requires custom wood panels despite complexity
	High structural rigidity	Moderate surface prep for seams
Description		
A telescoping internal frame with fixed panels in the corners. When the frame telescopes the size of the mold adjusts and insert panels are fastened to the sides of the frame to cover the gaps. For every T-Pad a custom plywood top panel is placed on top of the support frame to create the top panel of the mold.		

Feedback from the first EDR directed the U of M Team to proceed with further refinement of the '4-Wall – Split Wall', a female version of the Modular Corner, and the 'Cantilever Rail – Panel Inserts' concepts. The major conclusion was that male mold concepts were no longer desired by SCT due to the feasibility and improved surface finish associated with female molds. Additionally, concerns were raised over the weight of the base plate, its footprint during setup, and the fact that it would become covered in FRP with time.

Despite the 'Cantilever Rail – Panel Inserts' concept not being favoured by the U of M Team prior to the first EDR, SCT asked for further development of the concept. The idea of lightweight panels and simple guide rails were the primary reasons for this decision.

Elements from the '4-Wall – Split Wall', 'Modular Corner', and 'Cantilever Rail – Panel Insert' were substituted and combined to create four improved designs. This process is visually depicted in Figure 5 on the following page. These four refined concepts were carried forward to the weighted selection matrix.

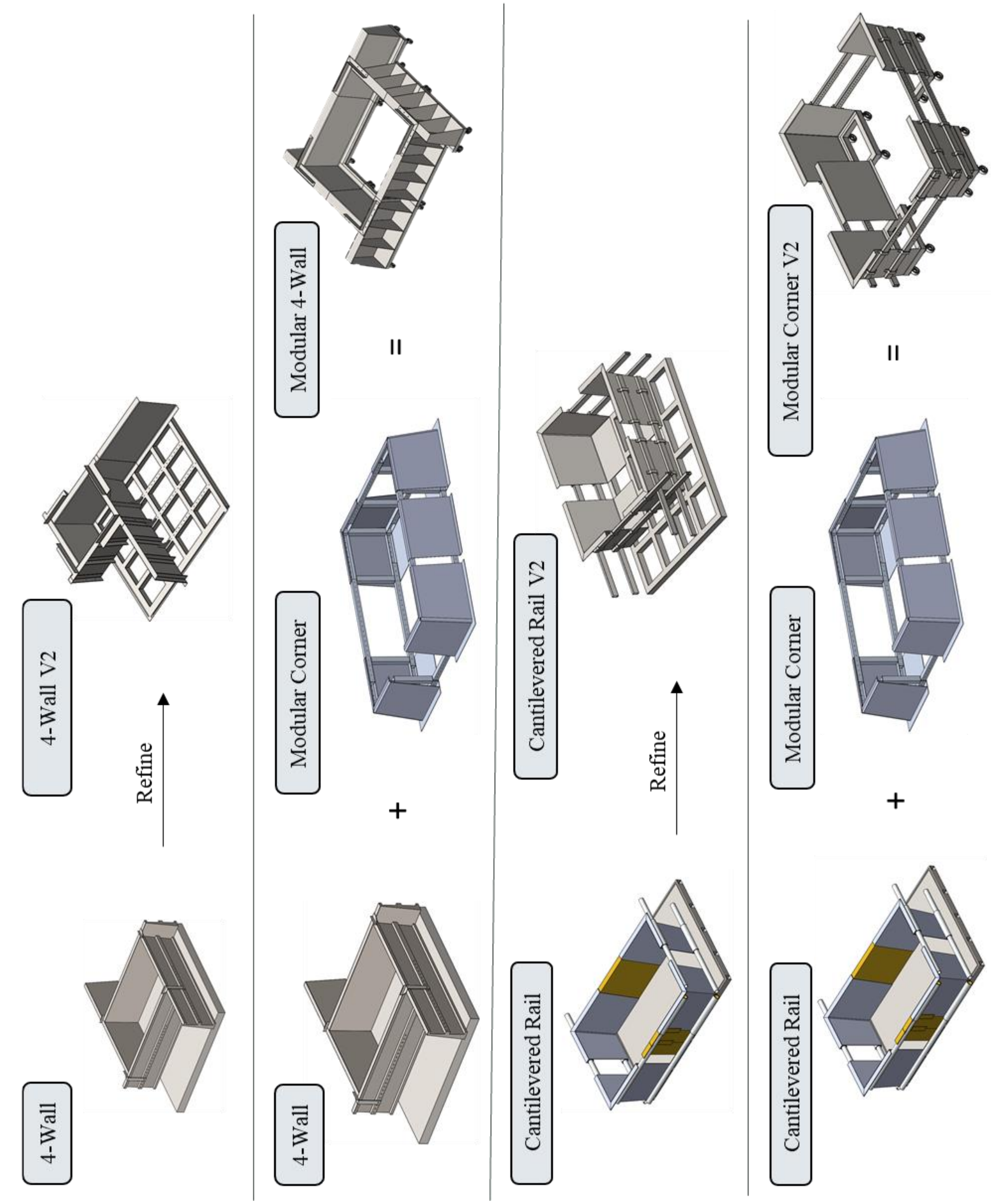


Figure 5. Concept combining and refining after the first EDR

3.1.2 Weighted Selection Matrix

The four concepts shown in Figure 5 were the focus of the weighted selection matrix. The first step in developing the weighted selection matrix was to reduce the list of metrics shown in Table II to only include criteria that would facilitate contrasting the various concepts. Metrics that were identified as nearly identical between concepts or overly subjective at this stage of the design were eliminated. The metrics used in the selection matrix are listed in Table VI.

TABLE VI: LIST OF DECISION METRICS

Decision Metrics	
1	Expected Adjustment Time
2	Ease of Manufacturing
3	Total Number of Parts
4	Expected Rigidity of Structure
5	Corrosion Resistance
6	Mechanical Degradation Resistance
7	Simplicity Part Removal
8	Accessibility
9	Expected Surface Finish
10	Max Weight
11	Ergonomics (Component Weight)
12	Overspray Vulnerability
13	Height Adjustability
14	Equipment Familiarity

After defining the selection metrics, the U of M Team assigned a weight and score definition between 1-4 for each of the metrics to be used in the final selection matrix. Depending on the metric scores between 1-4 were assigned based on a qualitative description, quantitative description or relative comparison between the concepts.

The weighted selection matrix is shown as Table VII and was composed by assigning scores to each of the remaining concepts for each of the decision metrics. These scores were multiplied by the metric weight as a percentage and summed together to give a total score. The results of the weighted decision matrix are shown in Table VII.

TABLE VII: CONCEPT SELECTION MATRIX

Metrics	Weight (%)	Concepts: 4-Wall V2	Modular 4-Wall	Cantilevered Rail V2	Modular Corner V2
Expected Adjustment Time	10.6	2	3	2	2
Total Number of Parts	1.5	4	4	2	2
Expected Rigidity of Structure	12.1	1	2	4	3
Corrosion Resistance	10.6	3	3	2	2
Mechanical Degradation Resistance	15.2	3	4	2	2
Simplicity Part Removal	4.5	1	4	2	3
Accessibility	1.5	1	2	3	4
Expected Surface Finish	9.1	3	3	1	1
Max Weight	9.1	2	1	2	3
Ergonomics (Component Weight)	10.6	2	3	2	2
Overspray Vulnerability	13.6	2	4	2	3
Totals	**100**	**217**	**298**	**214**	**230**

The conclusion of the weighted selection matrix was that the Modular 4-Wall and Modular Corner V2 concepts were superior to the 4-Wall V2 and Cantilever rail V2 concepts and would be further developed during the detailed design development phase of the project. To validate results, alternative metric weights were tested, but also demonstrated that the Modular 4-Wall and Modular Corner V2 concepts were superior designs.

3.2 Summary of Concepts Selected for Detailed Design

The Modular 4-Wall and Modular Corner V2 concepts had several common aspects that ultimately lead to their selection for detailed design development. Both concepts required custom fabrication of a wood base frame for each mold size rather than using a heavy rigid base frame. The rigid base frame was seen as a risk to cost, ergonomics and the overspray vulnerability of the molds. Additionally, both concepts incorporated modular components weighing less than 400 lbm that could be rolled around the shop independently prior to assembly.

A render of the Modular Corner concept model is displayed in Figure 6. Notable features such as the insert panels, wood base and alignment method are labelled in the diagram. Additionally, the key weld and bend locations are shown. Each of the corner pieces weigh approximately 200 lbm and the cantilevered rails, which need to be lifted by hand, weigh approximately 100 lbm. The manageable weight of the individual components of the Modular Corner concept was the most beneficial characteristic of the concept at this stage of the design.

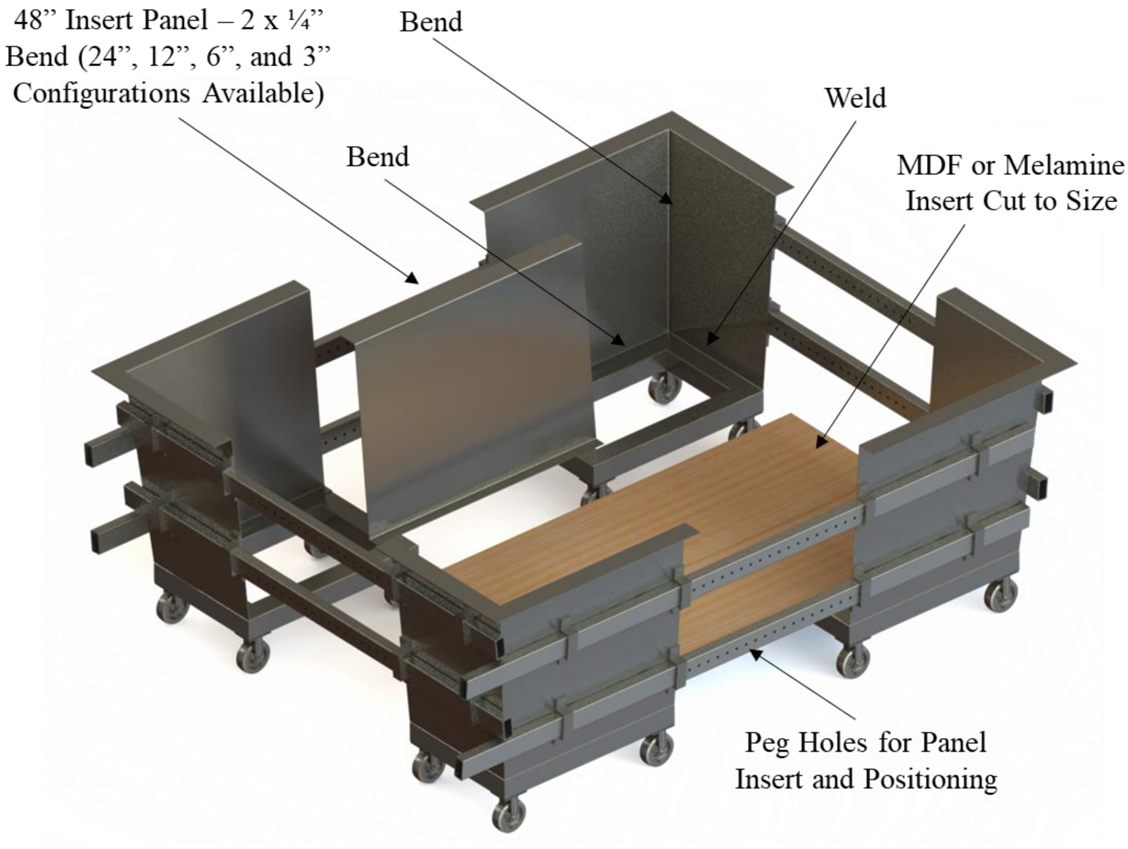


Figure 6. Labelled render of Modular Corner V2

A render of the of the Modular 4-Wall concept model is displayed in Figure 7. Prominent features such as the MDF base, required caulking, modular walls, and opportunity for additional bracing are labelled in the figure. Each of the wall sections weighs approximately 500 lbm. The gusset drawn as red line in Figure 7, is assumed to weigh approximately 50 lbm. The gusset location shown in the diagram could alternatively be placed on the inside of the frame below the plywood sheet to have the added benefit of reducing the sheet deflection during the chop-spray process.

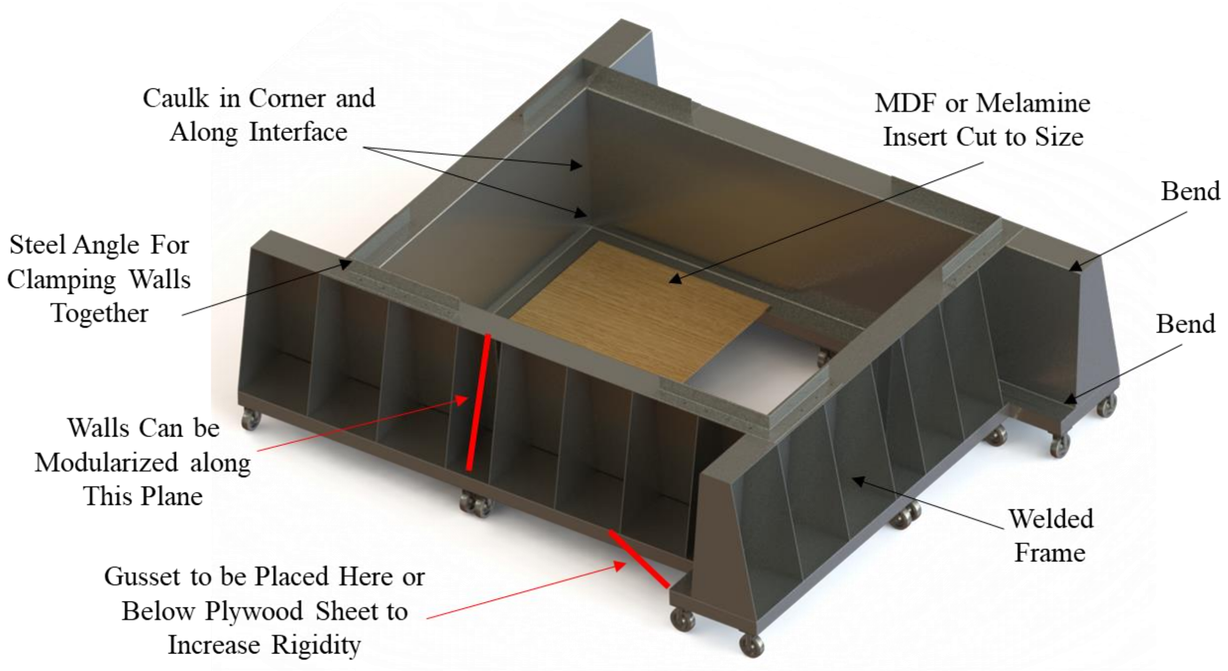


Figure 7. Modular 4-Wall diagram and render

To simplify the name convection for the two remaining concepts, they are referred to as the 4-Wall and the Modular Corner concepts for the remainder of the report. The next section introduces the approach used in the last phase of the project to select a final design.

4 DETAILED DESIGN DEVELOPMENT STRATEGY

The strategy that was used to improve upon and select between the 4-Wall and Modular Corner concepts is outline in this section of the report. As the concept development phase of the project yielded two viable concepts the both required further development prior to deciding on a final concept.

Failure Modes and Effects Analysis was used as the primary tool to improve the 4-Wall and Modular Corner concepts prior to selecting a final design. The decision to use FMEA was made as this method identifies the associated design risks and clarifies what design action is required.

In order to use FMEA, auxiliary design functions were selected based on their ease of integration into existing concept. Although multiple auxiliary functions were conceptualized during the earlier stages of the project it was clear which functions would work best with the 4-Wall and Modular Corner concepts.

After the auxiliary functions were selected, the 4-Wall and Modular Corner concepts were independently evaluated using FMEA to identify risks and redesigned to incorporate or modify features that would reduce the risk of failure. The FMEA adjusted versions of the 4-Wall and Modular Corner concepts were then presented at a second EDR to obtain client feedback.

After the second EDR, a single concept was selected and refined using a more technical approach. The technical methods used by the U of M Team included finite element analysis **(FEA)** to assess the mold rigidity, an analysis of the manufacturing processes that are used to fabricate the mold, and a detailed assessment of assembly time and ergonomics.

The detailed design strategy flow chart shown in Figure 8 provides an overview of the overall detailed design strategy that was followed by the U of M Team in sections 5 and 6 of the report. This flow chart provides a more detailed account of the steps that were followed after the 'Selection of 2 Concepts to Carry for Detailed Design Development' milestone defined in the overall design methodology flow chart shown in Figure 3.

The first iterative loop in the Figure 8 flow chart defines how the FMEA process was implemented for both the 4-Wall and Modular Corner concepts. The second iterative loop indicates that as modifications were made to the design geometry, technical calculations were re-done to ensure that the changes resulted in the design meeting the desired specifications.

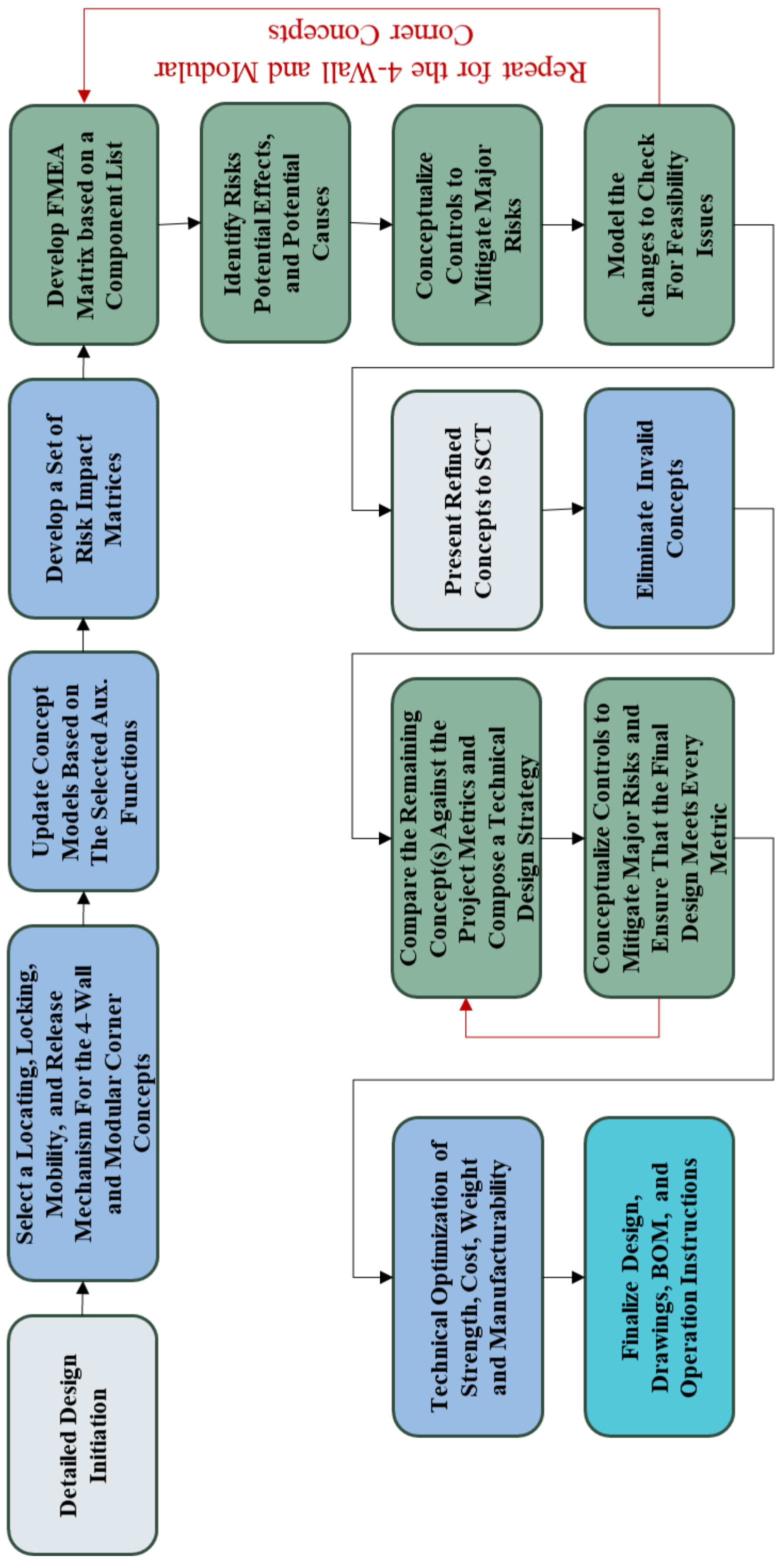


Figure 8. Detailed design strategy flow chart

4.1 Auxiliary Function Selection

Previously undetermined auxiliary functions were selected in order to fully evaluate the designs using FMEA. These functions are locking mechanisms, locating mechanisms, mobility features, and mold release techniques. The auxiliary functions selected for each design were concept dependent and governed by the geometry and functionality of the designs. As a result, the selected auxiliary mechanisms displayed in Table VIII were identified as the most feasible options.

TABLE VIII: AUXILIARY FUNCTIONS SELETED FOR EACH CONCEPT

Auxiliary Function	4-Wall	Modular Corner
Locking Mechanism	Bolts	Bolts, pins and/or clamps
Locating Mechanism	Bolt Holes	Insert Panels
Mobility Feature	Caster Wheels	Caster Wheels
Mold Release Technique	Wall Expansion	Wall Expansion

A brief justification for the selection of each auxiliary function is as follows:

- ***Locking mechanisms*** – Bolts were identified as necessary to hold the heavy 4-Wall components together. An option to use bolts, pins and clamps for the Modular Corner was integrated into the design to allow SCT flexibility during prototyping.
- ***Locating Mechanism*** – As bolts are used to lock the 4-Wall components together bolt holds are the simplest option for locating. The insert panels used in the Modular Corner Concept facilitate assembling the mold to the required size.
- ***Mobility*** – Caster wheels are what SCT uses for all of their existing mold, they are economical, effective, and what the technicians are used to thus are the clear choice for both concepts.
- ***Mold Release*** – Both the 4-Wall and Modular Corner concepts can be disassembled to release the finished T-Pads from the mold.

The mechanisms and overall assemblies of both concepts are now fully defined and can be analyzed using FMEA.

5 FAILURE MODES AND EFFECTS ANALYSIS

Section 5 provides an overview of the refinement of the 4-Wall and Modular Corners using FMEA prior to the second External Design Review. First, an overview FMEA methodology is outlined to provide clarification as to how the analysis was conducted. Second, definitions are assigned to the FMEA scoring. Next, a list of potential failure modes is related to both the 4-Wall and Modular Corner concepts. Each failure mode is then scored with respect to the severity, likelihood, and detectability of the risk. Failure modes for each respective concept were organized by component (e.g. walls, modular corners, wheels) and modifications to the designs is made to address critical failure modes. Failure modes are identified as critical when the product of severity rating and probability rating of occurrence rate is high. This product is referred to as the risk priority number.

5.1 FMEA Methodology

Failure Modes and Effects Analysis was carried out with the goal of managing every potential failure mode independently. Ultimately, the FMEA eliminated all extreme risks associated with the 4-Wall and Modular Corner concepts.

The core principle of FMEA is to assign a risk score to the consequence of failure, detectability of the failure, and frequency of the failure for every identified failure mod. FMEA considers each of these three risks aspects simultaneously to better represent the risks associated with a given design. In other words, failure modes that have a high consequence of failure but are extremely rare events are weighted accordingly based on both aspects of the risk.

The product of severity and frequency are referred to as the risk criticality and serves as the basis for most of the design decisions resulting from the FMEA. The product of severity, frequency, and detectability is referred to as the Risk Priority Number **(RPN)** and is used to identify the most extreme design risks. Only changes to the risk criticality were tracked to simplify the analysis, the RPN served only as a tool to identify aspects of the design that were important to modify.

Within the context of the FMEA, failure is defined as the deviation of a design process or component from its expected behavior as outlined in the project metrics and body of the report. To ensure our FMEA process is as rigorous as possible the U of M Team adopted the following guidelines [3]:

- A minimum of 5-7 individuals including all relevant stakeholders were included in each FMEA phase.
- Each of the U of M Team members were consulted prior to making any design changes based on the failure modes identified with FMEA.
- A multi-level approach was used to validate the results of the FMEA. The U of M Team completed an initial FMEA analysis that was later reviewed by SCT.

The initial iteration of FMEA was completed by the U of M Team alone, with the results of analysis being validated by SCT at the second EDR. This approach ensured that the perspectives of the client project Leaders, General and Production Managers at SCT were included to strengthen the results.

5.2 FMEA Scoring

To conduct the FMEA, a qualitative method of scoring severity, frequency, and detectability was developed to maintain consistency between the criticality numbers assigned to each failure mode. The scoring for failure mode severity was weighted higher than frequency or detectability to avoid not addressing the high severity failure modes. A scoring scale from 1-10 was used for failure mode severity and a scale of 1-6 was used for both frequency and detectability.

Table IX defines the scoring criteria for failure mode severity. Within the context of this project, severity quantifies the impact of a failure mode on T-pad quality, production cost, and technician safety. The qualitative descriptions assigned to each score were referred to during the ranking process.

TABLE IX: SEVERITY DESCRIPTORS FOR SCORING

Severity Descriptors		Score
Very High	Failure mode involves serious personal safety hazards and/or serious defects to the resulting T-pads	**9, 10**
High	High degree of customer dissatisfaction due to the negative impact of the failure such as lost time, high waste, loss of functionality. May require major rework or loss to customer and/or create significant financial hardship.	**7, 8**
Moderate	Failure causes some customer dissatisfaction. Customer experiences notable inconvenience or performance degradation as a result of the failure. Delays may result do to rework or irreversible damage.	**4, 5, 6**
Low	Low severity ranking causes only a slight annoyance to the customer. Customer likely only notices a minor degradation in service performance or successive parts. I.e. Parts may require light rework	**2, 3**
Minor	Minor nature of this failure would not cause any substantial effect on mold performance or on subsequent part. Customer is unlikely to either notice or care about this failure.	**1**

Table X defines the scoring for the expected frequency of a given failure mode. Within the context of this project 'frequency' focuses on the rate at which the mold fails to function or produce T-pads with the desired specifications. The descriptors identify the how often each given failure mode occurs and define frequencies into six levels that are scored between 1-6.

TABLE X: FREQUENCY DESCRIPTORS FOR SCORING

Frequency Descriptors		Score
Very High	Failure is almost inevitable.	**6**
High	Failure is often. Process is not in statistical control.	**5**
Moderate	Occasional failure. Process is in statistical control.	**4**
Low	Isolated failure. Process is in statistical control.	**3**
Very Low	Rare failure. Process is in statistical control.	**2**
Remote	Failure is unlikely.	**1**

Table XI defines the scoring that was used for the detectability of the failure modes. In this project 'detectability' refers to how easily an SCT technician can identify a failure mode in progress. An example of a low detectability failure mode would be misalignment of the corners. As this failure mode would not be easy to detect prior to a faulty T-Pad being produced it would be given a high score. The scoring for detectability is separated into six categories ranging between a high level of detectability (score of 1) and certainty of non-detection (score of 6).

TABLE XI: DETECTABILITY DESCRIPTIONS FOR SCORING

Likelihood of Detection		Score
Very High	Current controls will almost certainly prevent the failure (process automatically prevents most failures)	**1**
High	Current controls have a good chance of detecting the failure	**2**
Moderate	Current controls may detect the failure	**3**
Low	Current controls have a poor chance of detecting the failure	**4**
Very Low	Current controls probably will not detect the failure	**5**
Absolute certainty of non-detection	Current controls will not or cannot detect the failure	**6**

The criticality matrix presented in Table XII indicates the level risk related to each failure mode. Criticality is the product of the impact or severity of the event occurring and its probability of occurrence.

TABLE XII: CRITICALITY MATRIX

		Impact									
		Insignificant	**Minor**		**Moderate**			**Major**		**Extreme**	
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Likelihood of Occurrence	**6. Almost Certain**	6	12	18	24	30	36	42	48	54	60
	5. Likely	5	10	15	20	25	30	35	40	45	50
	4. Unlikely	4	8	12	16	20	24	28	32	36	40
	3. Rare	3	6	9	12	15	18	21	24	27	30
	2. Extremely Rare	2	4	6	8	10	12	14	16	18	20
	1. Remote	1	2	3	4	5	6	7	8	9	10

Color codes indicate the overall level of risk associated with the failure mode. The definition for each risk level was agreed upon by the U of M Team and was used as a visual aid for grouping the different and addressing the different failure modes. The importance for the range of possible criticality scores is shown in Table XIII.

TABLE XIII: RISK RATING BASED ON CRITICALITY NUMBERS

Risk Rating	
1-9	Low Risk
10-19	Moderate Risk
20-39	High Risk
40-60	Extreme Risk

Failure modes with high RPN numbers were not addressed in the same way as failure modes with high criticality numbers. Failure modes with extreme values of criticality were unacceptable and were reduced by a single risk level at minimum. Failure modes with extremely high RPN numbers were looked at as grounds for rejecting concepts as a whole if they could not be addressed. It is shown that there were only a few failure modes with an extreme RPN number (> 160). These failure modes are all related to rigidity and were addressed prior to the second external design review.

These failure mode with high criticality numbers were identified to SCT at the second EDR to ensure all shareholders were aware of the most significant and difficult to control project risks. High, moderate, or low-level risks were addressed in an effort to optimize each remaining concept to a level that they can be equitably compared.

The subsequent sections present the FMEA for the 4-Wall and Modular Corner concepts. An overview of the concepts is presented in detail alongside a comparison of the level of risks before and after the improvement. The actions taken to address the high-risk failure modes are also described in detail.

5.3 4-Wall FMEA

The first of the two concepts selected at the end of concept development was the 4-Wall concept, was updated with the auxiliary functions discussed in section 4.1. This concept consists of eight approximately 500 lbm wall sections which each rest on their own set of four caster wheels. The parallel wall segments are assembled together by bolting through a structural angle welded to each wall module. The orthogonal wall segments are held together with clamps. The walls of this concept are made with sheet metal supported by metal gussets. The base of this concept is made from cut-to-size plywood or melamine and is referred to as the 'custom wood base'.

At the first EDR, SCT had expressed enthusiasm for this simple design that consisted of four walls coming together to result a continuous range of mold sizes. Figure 9 and Figure 10 display an overview of the concept prior to FMEA, with key features shown in more detail. To accelerate the design process, fasteners were not added to the model and therefore are not shown in the figures.

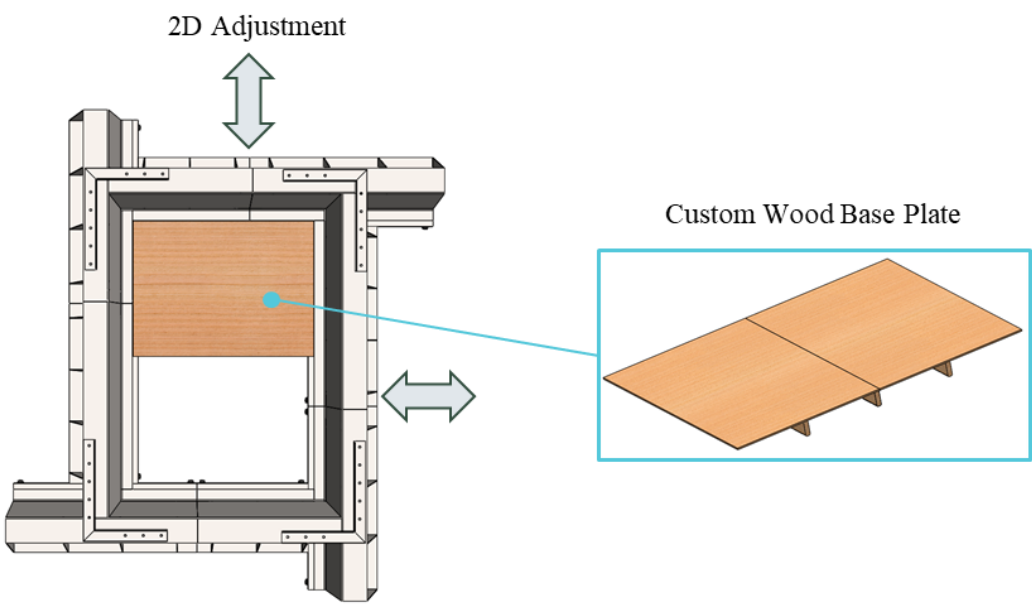


Figure 9. 4-Wall Overview (Top View)

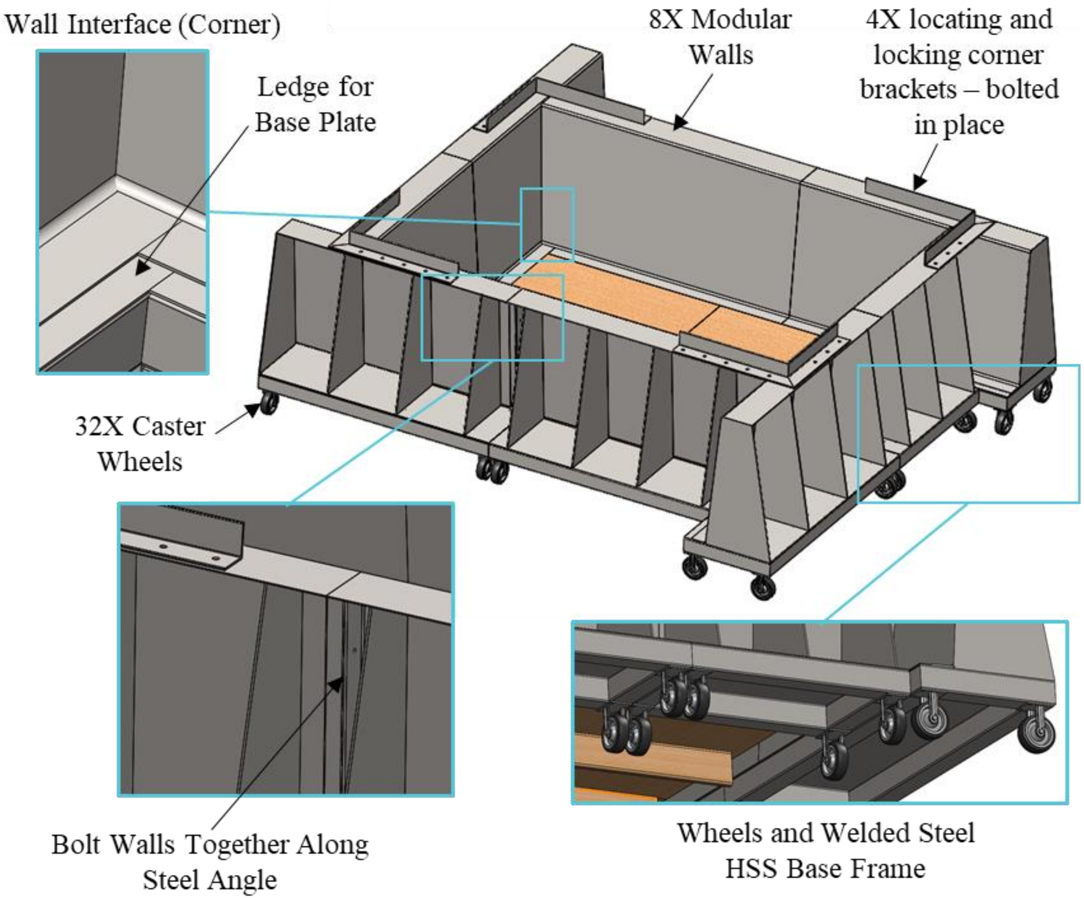


Figure 10. 4-Wall Overview (Isometric View)

Below is list of additional details on the 4-Wall which could not be obtained visually in either Figure 9 or Figure 10. These details are process or function related and highlight potential issues with the 4-Wall concept prior to conducting FMEA.

- Wall sections are moved and arranged by SCT personnel. Larger T-Pads require two wall sections to be used on each side which would be bolted together once positioned.
- Corner brackets are mounted on each corner to lock the dimensions of the mold.
- There is currently no method incorporated into the concept for holding the wood base frame to the steel structure. This custom wood base frame needs to be fabricated or modified for every T-pad.
- Masking tape is applied over all seams prior to the chop-spray process.
- The walls are unbolted to aid release of the T-Pad from the mold.
- The sheet metal in the assembly is gauge 16 and was selected as a lightweight baseline option.
- In total, 16-24 bolts are required to completely assemble the frame.
- The overall assembly has two 96” long wall segments and two 132” long wall segments. Minimum mold size is limited by the smallest transformer.

FMEA was completed on the 4-Wall concept as it is shown in Figure 9 and Figure 10. The list of potential failure modes for the 4-wall as well as scoring used to determine the criticality and RPN numbers is summarized in Table XIV. The most extreme risks have criticality numbers of 40 or above and generally pertain directly or indirectly to the overall alignment and rigidity of the mold.

The causes of low to high level risks are varied. The causes range from alignment concerns originating from improper tolerancing of the design, to inadequate management of overspray and increases of the assembly time. Other factors that present high level risks are related to the weight of components as they increase assembly time, decrease worker safety (ergonomics) and be difficult to assemble resulting in low utilization or dislike of the design.

TABLE XIV: FMEA OF 4-WALL WITH AUXILIARY FUNCTIONS

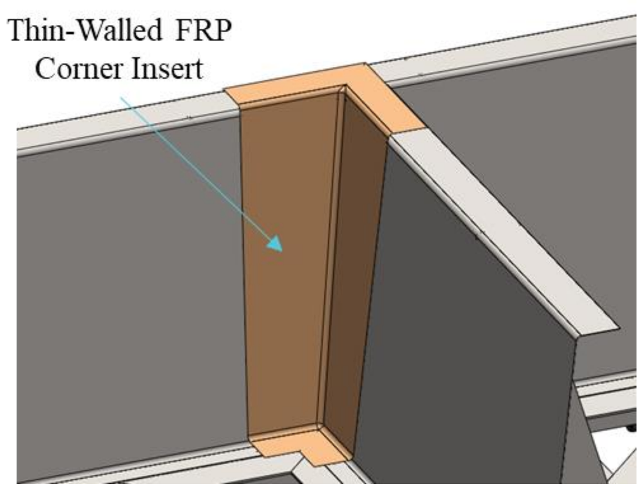
Component or Process Step/Input	Failure Mode, Cause & Effect	Severity (1-10)	Frequency (1-6)	Detectability (1-6)	Criticality	Risk Priority Number
Base Plate Ledge	Negative Effect on Alignment: Tolerancing issues with frame members and uneven ground prevent proper alignment	10	4	4	40	160
	Assembly time Risk: High number of components and fasteners result in a high assembly time	4	5	1	20	20
	Structural integrity risks: Insufficient joists across the floor could result in sagging of the base plate	10	4	3	40	120
Wall Interface (Corners)	Quality Risks: No simple method of securing mitered corner inserts to prevent sharp T-pad corners	6	6	1	36	36
	Quality Risk: Poor design and tolerancing issues result in uneven mold surfaces and cause seams on finished T-pads	4	5	2	20	40
Custom wood base plate	Structural risks: The plate cannot be adequately secured and releases along with the part	6	6	1	36	36
	Quality risks: The thickness or fit of the custom wood base plate is inconsistent resulting in visible seams in high stress locations	7	6	1	42	42
Locating Device	Overspray spray: Accumulation of overspray doesn't allow for walls and pinholes to be used for alignment	7	4	1	28	28
	Structural integrity risks: Environmental conditions and repeated use corrode bolt holes and prevent accurate positioning	4	2	2	8	16
Locking Device	Assembly time risks: Too many components result in a long assembly time and reduced benefit to SCT	4	5	1	20	20
	Structural integrity risks: Aligning members do not pull the structure together compromising the rigidity of the assembly	10	4	4	40	160
Material	Corrosion risks: Material selected corrodes more rapidly than expected resulting in surface defects	4	3	1	12	12
	Maintenance risks: Material selected corrodes more rapidly resulting in high levels of maintenance time and costs	9	2	2	18	36
	Safety & Mobility Risks: Material selected results in heavy components that cannot be moved easily without risking injury	6	6	1	36	36
	Structural integrity risks: Material corrosion occurs more rapidly than expected and compromises structural integrity	8	2	5	16	80
Modular Walls	Alignment risks: Manufacturing tolerances on walls do not allow for proper alignment or seam free surfaces due to improper fit	9	4	3	36	108
	Mobility & Safety risks: Modular components cannot be feasibly moved around by forklift	3	6	1	18	18
	Quality risks: Lack of radius at the corner results in poor mold release and poor product quality	8	6	1	48	48
Mold Exterior	Overspray risks: Geometry prevents use of poly-wrap resulting in overspray accumulation and loss of mold functionality	9	5	2	45	90
	Safety risks: Machining defects and cantilevered components result in sharp corners and tripping hazards compromising workplace safety	7	4	3	28	84
Overall Assembly	Alignment risks: Inadequate locking mechanisms and rigidity of frame members do not maintain alignment when design is moved.	10	6	4	60	240
	Alignment risks: Overspray accumulation prevents components from fitting together as intended	9	4	3	36	108
	Assembly time risk: Complexity of modular components and support structures causes extended assembly time	4	5	1	20	20
	Manufacturing risks: The design cannot be feasibly manufactured to an adequate quality level	2	5	1	10	10
	Mobility & Safety risks: Design is overbuilt with heavy components that cannot be easily or safely manipulated	10	3	1	30	30
	Structural integrity risk: Design did not identify all possible loading cases and is not structurally sound	10	2	4	20	80
Wheels	Overspray risks: Wheels gum up due to overspray accumulation and cannot be moved easily or at all	8	4	1	32	32
	Mobility risks: Wheels cannot properly support the load and lose their ability to swivel	4	4	1	16	16
	Structural integrity: Wheels are overloaded or easily damaged causing abrupt failure	9	2	3	18	54

5.3.1 4-Wall FMEA Physical Failure Mode Mitigation

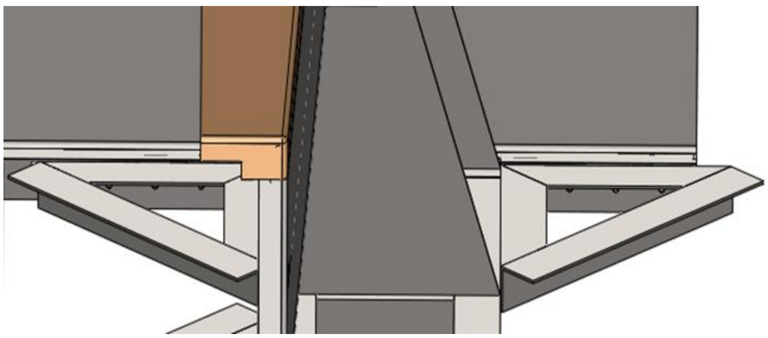
To address the failure modes outlined in Table XIV, several modifications were made to the 4-Wall model. A detailed view of the design modifications made, along with a description of the modification and the relevant failure modes addressed are provided in Table XV.

The key design modifications suggested by the FMEA were to address the issues of alignment, the corner radius, the wall interface tolerancing, as well as the weight and mobility of components. Floor joists and gussets at the interior and exterior corners facilitate alignment of the overall design while supporting a temporary cut to size base plate. Inserts extend over the intersection of the walls to create a corner radius that can be secured in place. A reduction in member thicknesses, as well as utilizing angled steel over square tubing allowed the weight of the assembly to be decreased.

TABLE XV: ACTIONS TAKEN TO ADDRESS 4-WALL FMEA RISKS

<table>
<tr><th colspan="2">Action Taken: Addition of Corner Inserts</th></tr>
<tr><td rowspan="2">Failure Modes Addressed</td><td>Poor tolerancing in the corners causing imperfections in the finished T-pads</td></tr>
<tr><td>Sharp mold corners preventing mold release</td></tr>
<tr><td rowspan="2">
</td><td>Description of Action</td></tr>
<tr><td>• Fabricate a reusable thin fiberglass corner insert to reduce the number of seams at the corner.
• Use masking tape to cover the remaining seams, clamps secure the insert to the walls.</td></tr>
</table>

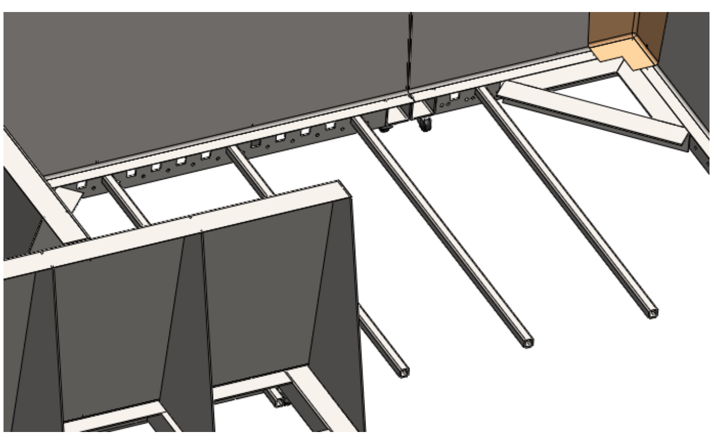
Action Taken: Addition of Corner Gussets	
Failure Modes Addressed	Wall alignment and base frame rigidity
	Overall rigidity of the complete assembly
	Poor custom wood base frame support (sagging of wood panels)



Description of Action

- Add to the inside of the mold – these gussets would sit 5/8” below the bent sheet metal flange to accommodate the custom plywood sheet.
- Add additional gussets to the exterior of the mold to further increase rigidity.
- The gussets are to be installed with fasteners which increase assembly time.

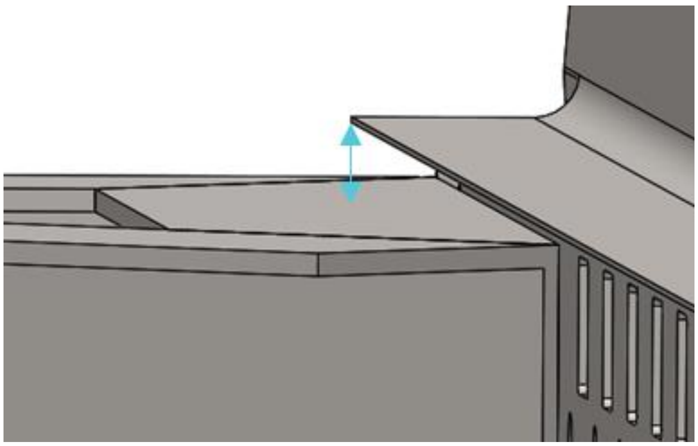
Action Taken: Addition of 2” x 2” HSS Joist	
Failure Modes Addressed	Overall alignment of 4-Wall base frame
	Fabrication time associated with the custom wooden joists
	Sagging of the custom plywood base frame
	Structural integrity of the base frame when workers are inside the mold



Description of Action

- Add holes in the modular wall support frame to accommodate 2” x 2” HSS joists that could be slid into place and support the base frame plywood.
- These joists are held in place under their own weight to decrease assembly time.
- The joists can be positioned every 4” to improve wall locating and mold alignment.

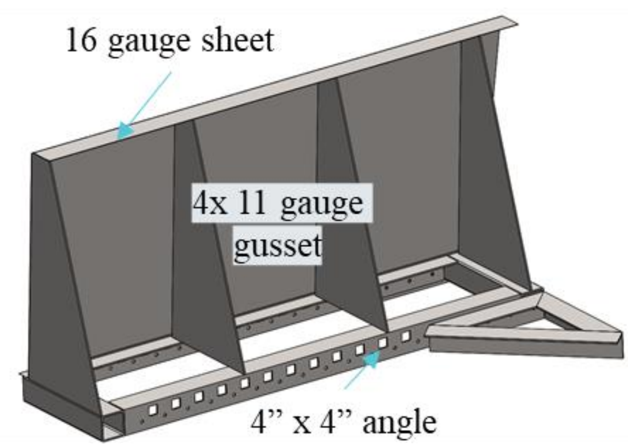
Action Taken: Allowing the sheet metal walls to overhand the gussets	
Failure Modes Addressed	Improves rigidity of full assembled mold
	Prevents custom wood base frame from releasing with the finished T-pad
	Reduces the risk of gaps between the plywood and the corners but adds a step



Description of Action

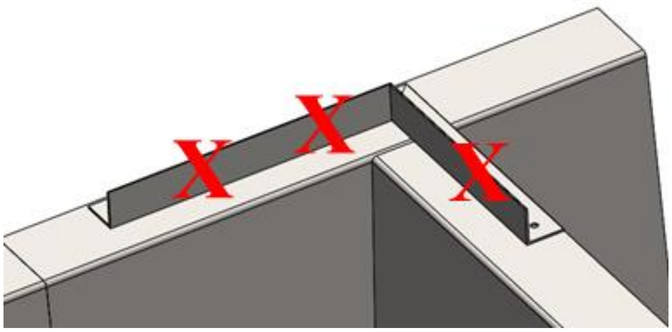
- Extend the bottom of the sheet metal walls to create a lip that extends over the modular wall base frame.
- The custom wood base plate can slide underneath the sheet metal lip to hold it in place during mold release.
- The step created by the overhang is taped over with masking tape.

Action Taken: General weight reduction	
Failure Modes Addressed	Improves mold mobility allowing for fewer personnel to be involved during mold transport
	Ensures that the design is not overbuilt to reduce cost
	Helps ensure that the caster wheels are able to adequately support the mold



Description of Action

- Decrease gusset thickness and sheet metal thickness to 11 gauge and 16 gauge respectively.
- Use angle members for the modular wall base frame rather than HSS members.

<table>
<tr><th colspan="3">Action Taken: Removal of the upper locking brackets</th></tr>
<tr><td rowspan="3">Failure Modes Addressed</td><td colspan="2">Reduces the risk of overspray clogging up bolt holes</td></tr>
<tr><td colspan="2">Improves accessibility to mold and facilitates wedges for mold release</td></tr>
<tr><td colspan="2">Helps ensure that the caster wheels are able to adequately support the mold</td></tr>
<tr><td colspan="2" rowspan="2"></td><td>Description of Action</td></tr>
<tr><td>• The corner brackets used to lock and locate the 4-Wall concept were replaced with the base frame gussets.</td></tr>
</table>

The following section summarizes the outcomes of the modifications described in Table XV and the remaining risks associated with the 4-Wall concept.

5.3.2 4-Wall FMEA Summary

The application of FMEA to assess and mitigate risks associated with the 4-Wall concept was successful in reducing all extreme level risks to a high-risk level or lower. Figure 11 displays the quantity of extreme, high, moderate, and low risk failure modes before and after the FMEA was conducted. Comparison of the risk levels pre-FMEA and post-FMEA show extreme level risks were eliminated, while the number of high-level risks stayed the same resulting in an increase of low to moderate level risks.

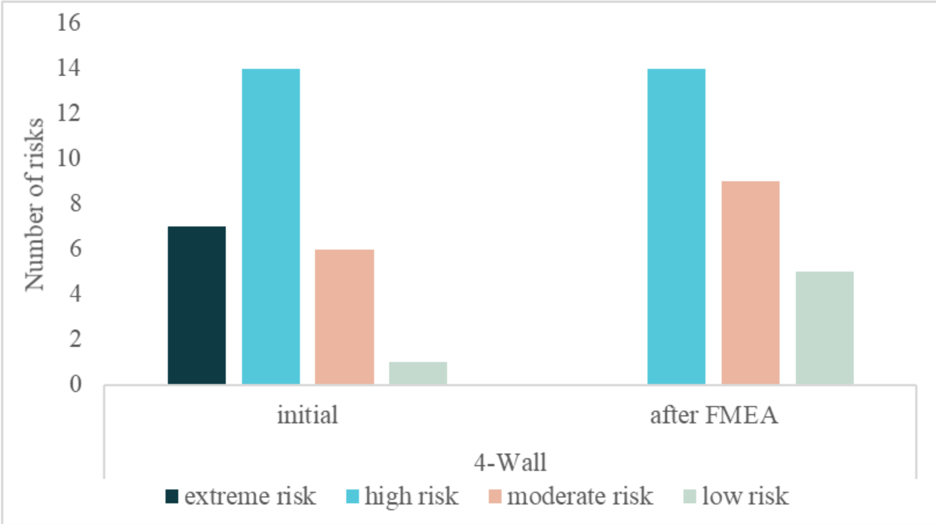


Figure 11. Number of risks at each severity level before and after FMEA of the 4-Wall

After FMEA, there were still a substantial number of high-risk failure modes associated with the design. A summary of the most significant remaining risks is noted below:

- The FRP Corner inserts still pose a significant risk due to the uncertainty associated with fabrication and that fact that it causes seams in the corner region.
- There is a risk that the assembly time exceeds the marginally acceptable value of 2 hours for 2 people. Assembly time increased as a result of the FMEA and added components and fasteners.
- There is still uncertainty associated with alignment of the eight modular wall panels as they are only be secured at the base frame. If the base frame has tolerancing issues resulting from fabrication, there is a chance the modules do not line up.
- Although all the heavy components sit on caster wheels, when two wall segments are assembled, they weigh over 700 pounds making the mold difficult to precisely manipulate during final assembly and risk the alignment of the walls.

Figure 12 displays a render of the 4-wall concept after conducting FMEA. The final mass of the new assembly without the wood base frame is approximately 2750 lbm. Adjustment of the assembly requires up to 40 bolts of which approximately half of these can be left attached after the first assembly. To achieve the desired maximum T-Pad size of 8’ x 10’ a variety of modular wall sizes needed to be incorporated into the design. Figure 12 defines a list of these modular wall configuations where the heaviest individual weld assembly is the 72” interface module which weighs up to 400 lbm.

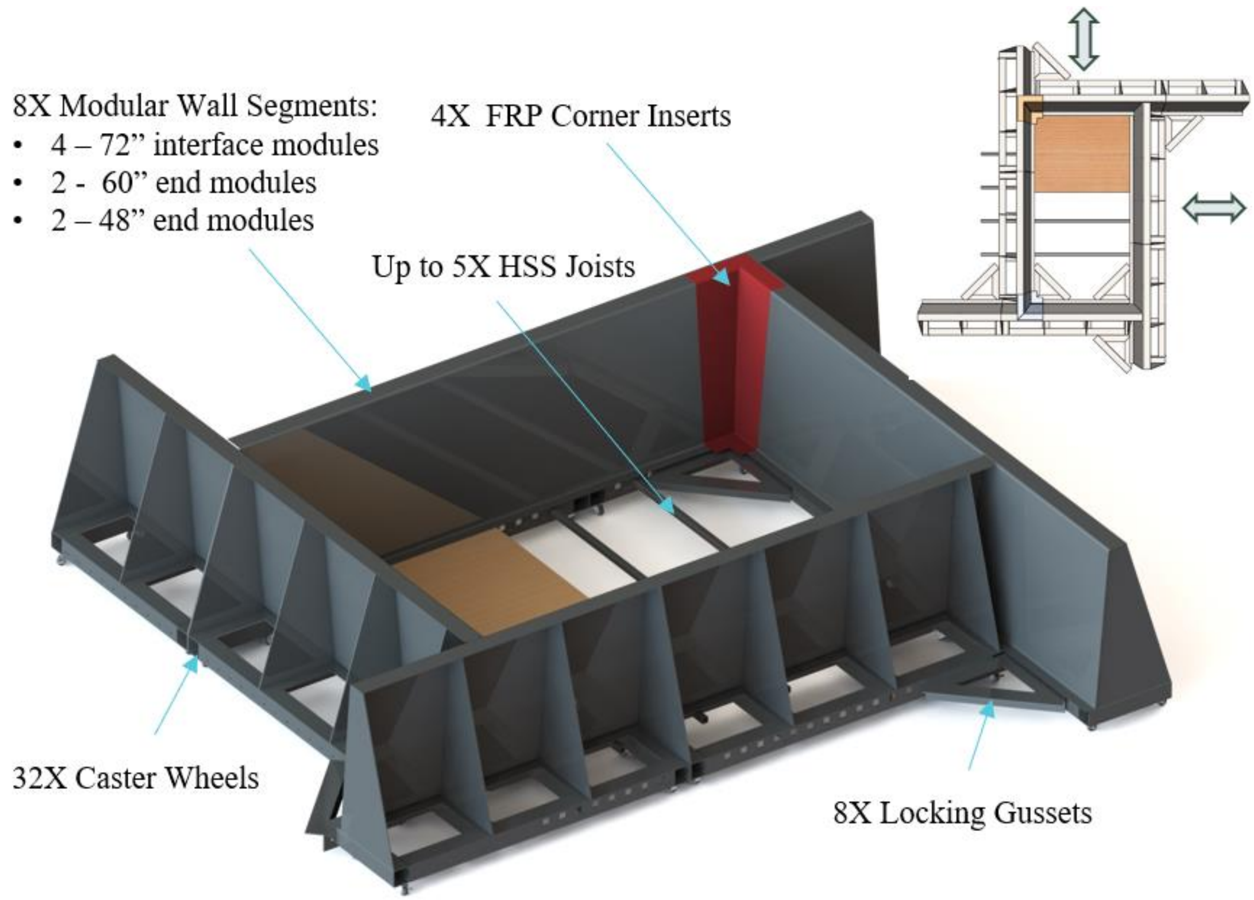


Figure 12. Render of the FMEA adjusted 4-Wall concept

As the material is not yet fully defined, the risks associated with material is discussed in more detail after the meeting with the manufacturer. In general, it was discussed that corrosion inhibitors such as WD-40 should be used on the surface of steel parts to prevent excessive corrosion.

5.4 Modular Corner FMEA

The second of the two concepts assessed using FMEA was the Modular Corner concept, which was updated with the auxiliary functions described in section 4.1. The Modular Corner is composed of four approximately 200 lbm corner sections on caster wheels which are connected by guide rails weighing roughly 100 lbm. Insert panels are used to fill in the walls between the corner modules. The insert panels corners, which come in 6”, 12”, and 24” widths. The corners and insert panels are made out of sheet metal and are fixed to the HSS guide rails. The base of this concept is made from cut-to-size plywood or melamine.

This concept was liked by SCT at the first EDR because of the opportunity to increase the maximum size of the mold or replace components at low cost due to the modularity of the components. An overview of the Modular Corner model prior to the FMEA process is displayed in Figure 13 and Figure 14. The fasteners used to locate and lock the corners in place were not added to the model in order to streamline the design process, and therefore are not shown in the figures.

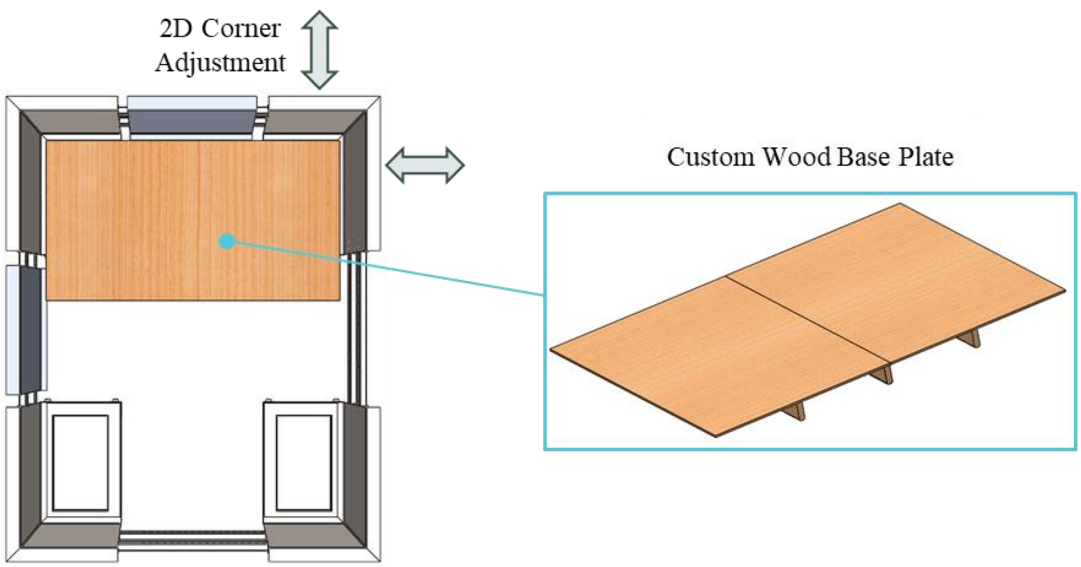


Figure 13. Modular Corner Overview (Top view)

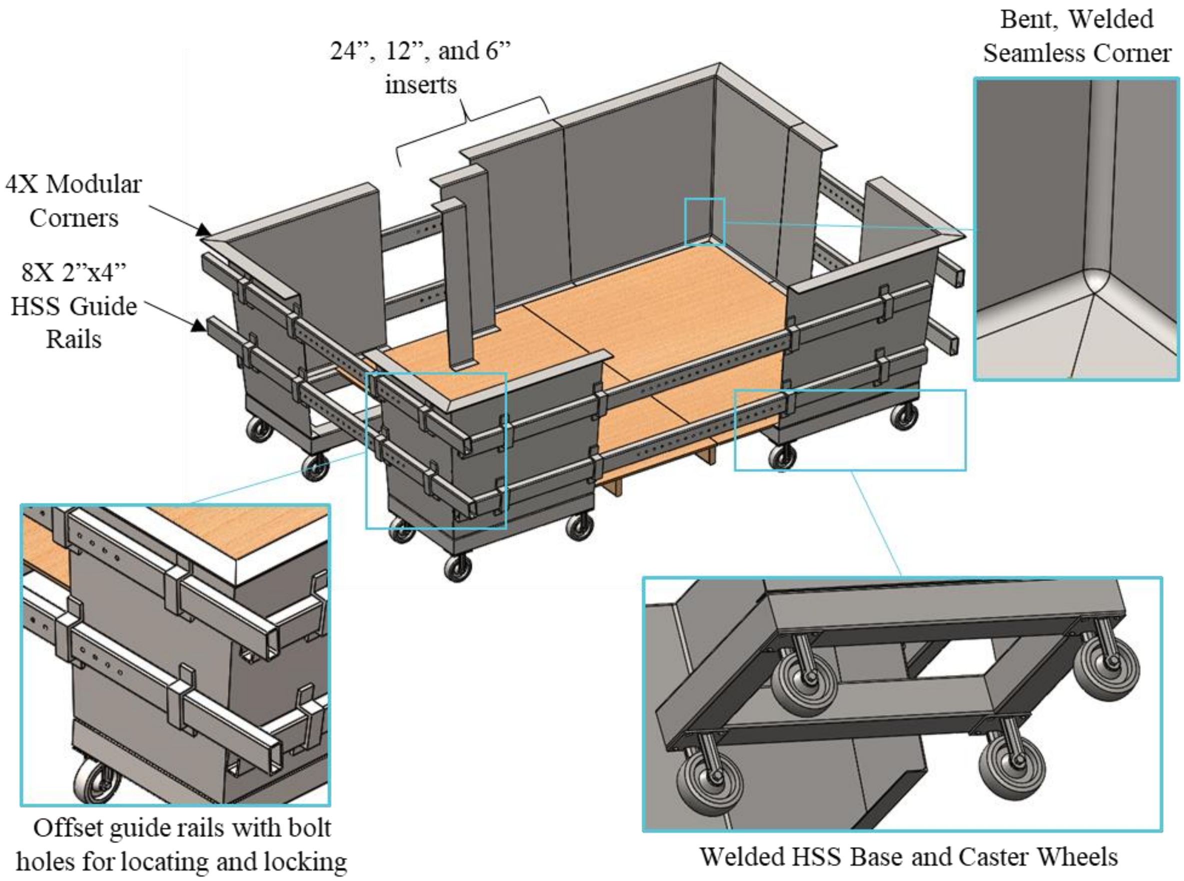


Figure 14. Modular Corner overview (Isometric view)

With the goal of providing further context to the failure modes identified while conducting FMEA on the Modular Corner, a list of additional details regarding the components and function of the concept is provided below.

- Corner sections are moved and arranged manually by SCT personnel.
- Guide rails are installed by sliding them in the rail supports from one end.
- Insert panels are added as required and secured to the guide rails using pins, bolts, or clamps depending on what SCT personnel find works best.
- In total four 24", eight 12", and four 6" insert panels are required to achieve all possible size configurations. This limits the size adjustment increments to the marginally acceptable value of 6" rather than 4". Smaller 3" or 4" panels could be fabricated by SCT in the future if desired.
- There is currently no method incorporated into the concept for holding the wood base frame to the steel structure. A new custom wood base frame needs to be fabricated or modified for every T-pad.

- Masking tape is applied over seams prior to the chop-spray process.
- The insert panels are secured to the guide rails using pins or clamps.
- The finished T-pads do not need to be lifted out of the mold; the walls can be unbolted to facilitate release of the T-pad.
- The sheet metal in the assembly is 11 gauge and there are no additional structural supports to maintain the rigidity of the corner pieces.
- The most significant advantage of the Modular Concept over the 4-Wall concept is that there are no sliding contact faces in the corners. Thus, there are minimal seams and large permanent fillets in the corners which produce a better quality surface finish and avoid compromising mold release.
- In total, 32 bolts and a series of pins and clamps are needed to assemble the Modular Corner concept. The custom wood base also needs to be fabricated or modified for every T-pad.

FMEA was completed for the Modular Corner concept for which the analysis is summarized in Table XIV. The U of M Team evaluated components of the design and identified potential modes of failure as well as their causes and effects. As stated previously, extreme level risks have a criticality score above 40.

For the Modular Corner concept, the primary sources of risks are due to compromised alignment, structural integrity, ergonomics, and susceptibility to overspray. Many of the same factors that compromise the performance of the 4-Wall design pose a risk to the performance of the Modular Corner concept. Most notably, the rigidity and alignment of the concept were identified as issues. Additionally, due to the number of components involved in the alignment of the Modular Corner concept, there is a higher potential risk due to stacked tolerance of the insert panels. The 4-Wall concept has an advantage over the Modular Corner in this aspect of the design as the 4-Wall Concept does not rely on a series of aligned panels that results in fewer seams.

TABLE XVI: FMEA OF MODULAR CORNER WITH AUXILIARY BENCHMARKS

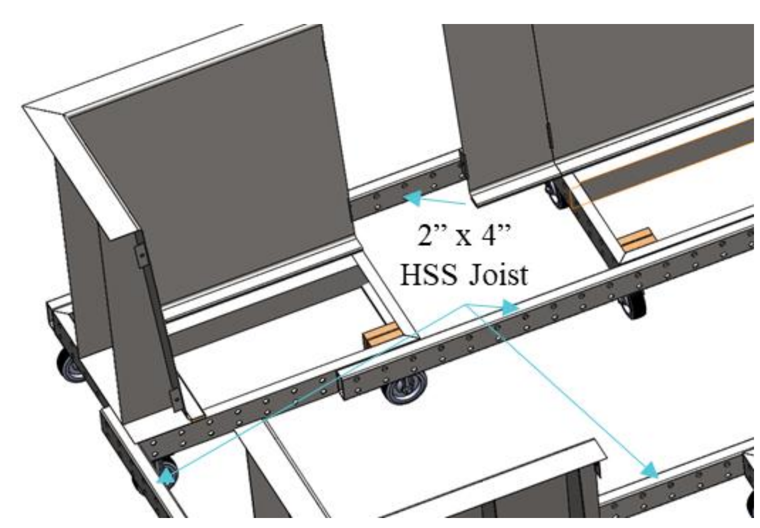
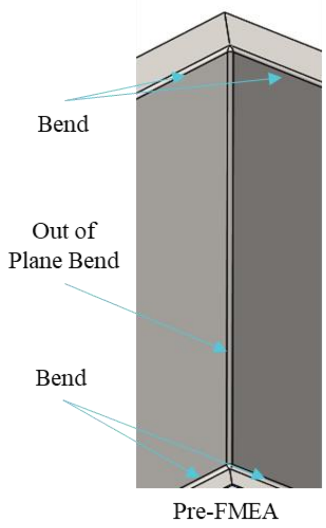
Component or Process Step/Input	Failure Mode, Cause & Effect	Severity (1-10)	Frequency (1-6)	Detectability (1-6)	Criticality	Risk Priority Number
Custom Wood Base Support Structure	Negative Effect on Alignment: Tolerancing issues with frame members and uneven ground cause the wood frame to not be level	10	4	4	40	160
	Assembly time Risk: High degree of custom wood fabrication results in high assembly time per T-pad	4	5	1	20	20
	Structural integrity risks: Insufficient joists across the floor result in sagging of the base plate	10	4	3	40	120
Panel Inserts	Quality Risks: Corner inserts cannot be bolted down	2	6	6	12	72
	Quality Risk: Poor design and tolerancing issues result in uneven mold surfaces and cause seams	8	6	6	48	288
Custom Wood Base	Structural risks: The wood base cannot be adequately secured and releases along with the part	6	6	1	36	36
	Quality risks: The fit of the custom wood base is inconsistent resulting in visible seams at discontinuities between wood sheets	7	6	1	42	42
	Quality risks: Uneven ground or insufficient support structure causes large seams at the wood-sheet metal interface	6	2	1	12	12
Locating Device	Overspray spray: Accumulation of overspray doesn't allow for walls and pinholes to be used for alignment	7	4	1	28	28
	Structural integrity risks: Environmental conditions and repeated use cause the pin holes to wear and prevent accurate alignment	4	2	2	8	16
Locking Device	Assembly time risks: Too many components result in a long assembly time and reduced benefit to SCT	4	5	1	20	20
	Structural integrity risks: Aligning members do not pull the structure together compromising the rigidity of the assembly	10	4	4	40	160
Material	Corrosion risks: Material selected corrodes more rapidly than expected resulting in surface defects.	4	3	1	12	12
	Maintenance risks: Material selected corrodes more rapidly resulting in high levels of maintenance time and costs	9	2	2	18	36
	Safety & Mobility Risks: Material selected results in heavy components that cannot be moved easily without risking injury	6	6	1	36	36
	Structural integrity risks: Material corrosion occurs more rapidly than expected and compromises structural integrity	8	2	5	16	80
Modular Corners	Manufacturing risks: The proposed design is not feasible for fabrication	9	6	5	54	270
	Mobility & Safety risks: Modular components cannot be feasibly moved around by forklift due to their weight and geometry	3	6	1	18	18
Guide Rails	Overspray risk: Rails are difficult to protect from overspray and become non-functional over time	9	6	4	54	216
Mold Exterior	Overspray risks: Geometry prevents use of poly-wrap resulting in damage due to overspray accumulation	9	5	2	45	90
	Safety risks: Machining defects and cantilevered components result in sharp corners and tripping hazards affecting workplace safety	7	4	3	28	84
Overall Assembly	Alignment risks: Overspray accumulation prevents modular components from fitting together as intended	9	4	3	36	108
	Assembly time risk: Complexity of modular components and support structures causes extended assembly time	4	5	1	20	20
	Manufacturing risks: The design cannot be feasibly manufactured to an adequate quality level	2	5	1	10	10
	Structural integrity risk: Design does not identify all possible loading cases and is not structurally sound	10	2	4	20	80
	Mobility & Safety risks: Design is overbuilt with heavy components that cannot be easily or safely manipulated	10	3	1	30	30
	Alignment risks: Inadequate locking mechanisms and rigidity of frame members do not maintain alignment when design is moved	10	6	4	60	240
Wheels	Overspray risks: Wheels gum up due to overspray accumulation and cannot be moved easily or at all	8	4	1	32	32
	Mobility risks: Wheels cannot support the load and lose their ability to swivel	4	4	1	16	16
	Structural integrity: Wheels are overloaded or easily damage with use causing abrupt failure of the component	9	2	3	18	54

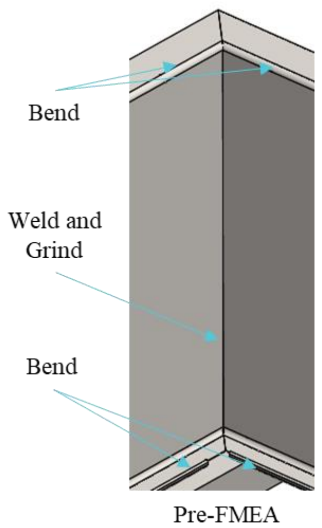
5.4.1 Modular Corner FMEA Physical Failure Mode Mitigation

To address the failure modes outlined in Table XIV, several modifications were made to the Modular Corner concept. A detailed view of the design modifications made, along with a description of the modification and the relevant failure modes addressed are provided in Table XVII. Floor joists and gussets at the interior and exterior corners facilitate alignment of the overall design while supporting a temporary cut to size base plate.

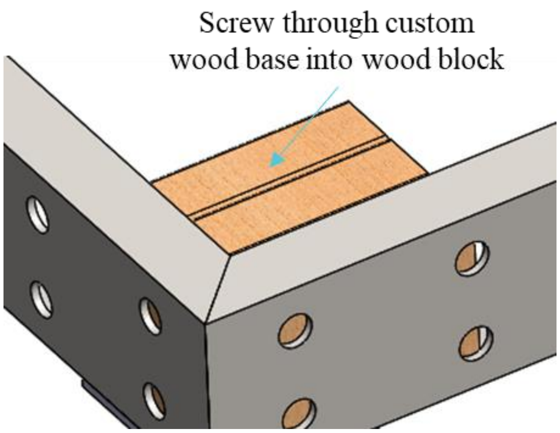
From the FMEA, it was identified that the primary issues to be addressed were the alignment, general manufacturing feasibility, and overspray vulnerability of the design. The exterior wall guide rails were replaced with base frame joists to avoid overspray, and gussets were added to the walls to improve the rigidity. The base frame was modified to be made from C-channel and angled members rather than the previously heavier HSS members. The sheet metal corners were redesigned to be made from two separate sheet metal pieces that would be welded together at the corner. This modification made the corners easier to manufacture with less tolerancing issues. Insert panel tabs and a method for securing the base plate were also incorporated in improving the design of the Modular Corner.

TABLE XVII: ACTIONS TAKEN TO ADDRESS MODULAR CORNER FMEA RISKS

<table>
<tr><th colspan="2">Action Taken: Addition of 2” x 4” HSS base frame joists</th></tr>
<tr><td rowspan="6">Failure Modes Addressed</td><td>Questionable rigidity of the sheet metal corners as the key alignment feature for the mold</td></tr>
<tr><td>Wear on the locating and locking mechanism</td></tr>
<tr><td>Corner alignment on uneven ground</td></tr>
<tr><td>Overall structural integrity of the mold</td></tr>
<tr><td>Unsupported custom wood base frame</td></tr>
<tr><td>Previous guide rails preventing poly-wrap of mold exterior</td></tr>
<tr><td rowspan="2">
</td><td>Description of Action</td></tr>
<tr><td>Six 2” x 4” HSS joists were specified in place of the cantilevered guide rails.
These joists are secured using bolts and rigidly lock and locate the corners together. The joists also serve as additional support for the wood base frame.
Holes are placed at 6” intervals and have two rows for added redundancy to wear and reduced weight.</td></tr>
<tr><th colspan="2">Action Taken: Modification for corner manufacturing method</th></tr>
<tr><td>Failure Modes Addressed</td><td>Potentially infeasible manufacturing methods</td></tr>
<tr><td rowspan="2">


</td><td>Description of Action</td></tr>
<tr><td>An alternatively proposed solution for the fabrication of the modular corner weld assemblies is to weld and grind along the corner seam rather than bending the part out of a single piece of sheet metal.
This design decision was discussed with the manufacturer prior to implementation. The decision is largely based on available tools.</td></tr>
</table>

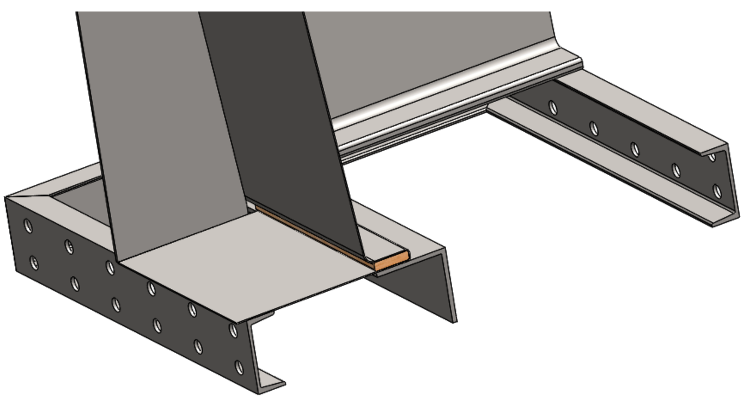
Action Taken: Addition of wood blocks to secure custom wood base frame to the mold	
Failure Mode Addressed	No method of securing the wood base frame to the mold
	Resistance of the mold to wear over time



Description of Action

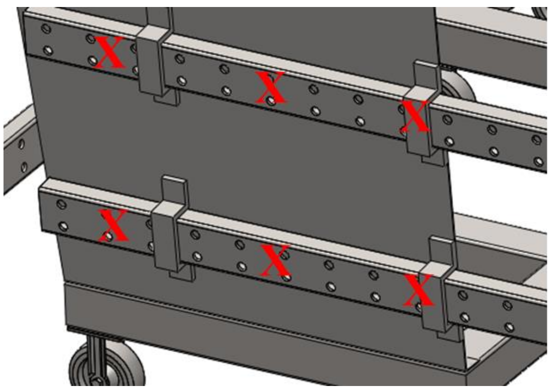
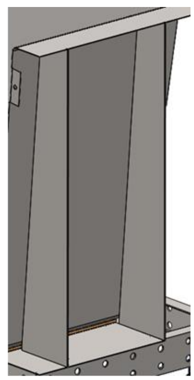
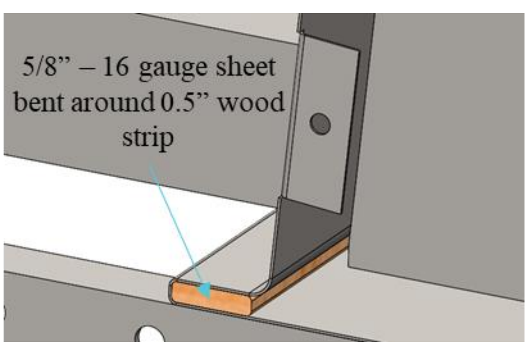
- Wood blocks are to be secured to the base frame C-Channel members such that the custom wood base frame can be screwed down during mold release
- The wood blocks can be permanent or temporary.
- The screws in the wood base plate are taped over prior to application of the gel coat.

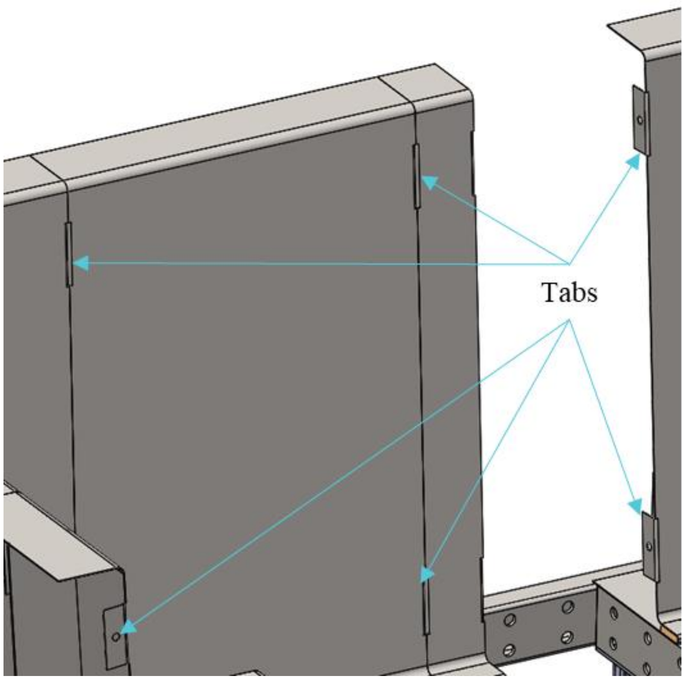
Action Taken: Replacement of the HSS base frame members with angle and C-Channel members	
Failure Mode Addressed	Overall weight of the assembly
	Access to bolt holes
	Difficulties securing the caster wheels to the frame



Description of Action

- The HSS members that previously made up the modular corner base frame were replaced with four C-channel members and an angle member across the center.
- This reduced the weld assembly weight and allowed access to bolt holes for the new HSS joists.
- C-Channel members were selected over angle members to provide a flat surface to attach caster wheels. This same decision would likely apply to the 4-wall as well.

<table>
<tr><th colspan="2">Action Taken: Replacement of the HSS base frame members with angle and C-Channel members</th></tr>
<tr><td rowspan="3">Failure Mode Addressed</td><td>Vulnerability to overspray</td></tr>
<tr><td>Overall weight of assembly and maximum manually lifted weight</td></tr>
<tr><td>Overall rigidity of the corner weld assemblies</td></tr>
<tr><td rowspan="2"> </td><th>Description of Action</th></tr>
<tr><td>As previously discussed, the guide rails were replaced with joists running along the base frame.
To reduce weight the 11-gauge sheet metal was replaced with 16-gauge sheet metal, to maintain rigidity gussets were added.
The new configuration is easier to poly-wrap and is not at risk of overspray accumulation on the guide rails. The new configuration is easier to poly-wrap thus is not at as high of a risk of overspray accumulation on the guide rails.</td></tr>
<tr><th colspan="2">Action Taken: Addition of an embedded wood strip in the sheet metal corner assembly</th></tr>
<tr><td rowspan="2">Failure Mode Addressed</td><td>Large seam or step at the sheet metal-wood base interface</td></tr>
<tr><td>Resistance of the sheet metal corner to mechanical wear</td></tr>
<tr><td rowspan="2"></td><th>Description of Action</th></tr>
<tr><td>A 0.5” thick wood strip was incorporated into the corner weld assembly. The main justification for this decision was to raise the sheet metal by 5/8” so that the custom wood base would sit flush with the sheet metal flange. This design also eliminated the need for additional welds to achieve the desired geometry.
The additional benefit of adding rigidity this region of sheet metal prevents deformation with repeated use of the mold.</td></tr>
</table>

<table>
<tr><th colspan="2">Action Taken: Addition of tabs to the insert panels</th></tr>
<tr><td rowspan="2">Failure Mode Addressed</td><td>Alignment of insert panels</td></tr>
<tr><td>Ease of assembly</td></tr>
<tr><td rowspan="2">
</td><th>Description of Action</th></tr>
<tr><td>The removal of the cantilevered guide rails required a new method for securing the insert panels.
The use of connecting the insert panels in a chain to the corners offered the best solution for alignment and ease of assembly.
The tabs can either be welded onto the insert panels or bent from the original piece of sheet metal.
The tabs are locked together using bolts or clamps as per SCT's preference.</td></tr>
</table>

The following section summarizes the outcomes of the modifications described in Table XVII and the remaining risks associated with the Modular Corner concept.

5.4.2 Modular Corner FMEA Summary

The application of FMEA to assess and mitigate risks associated with the Modular Corner concept was successful in reducing all extreme level risks to a high-risk level or lower. Figure 15 displays the quantity of extreme, high, moderate, and low risk failure mode before and after the FMEA was conducted. Comparison of the risk levels pre-FMEA and post-FMEA show extreme level risks were eliminated, while the number of high-level risks stayed the same resulting in an increase of low to moderate level risks.

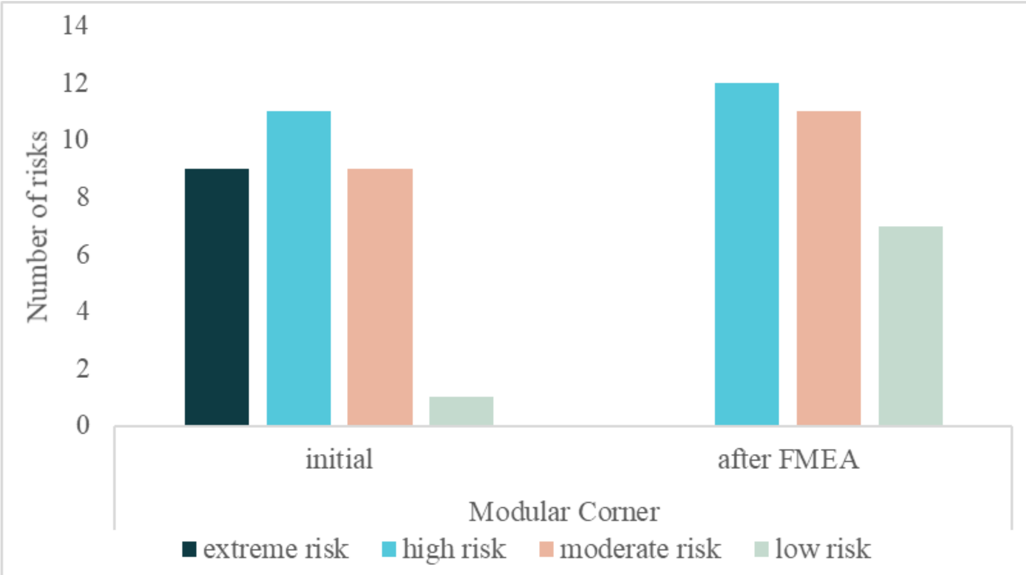


Figure 15. Number of risks before and after FMEA of the Modular Corner

Although FMEA was deemed successful in eliminating extreme risk, there are still a substantial number of high-risk failure modes associated with the design. A practical summary of the most significant remaining risks is noted below.

- There is a risk that the assembly time exceeds the marginally acceptable value of 2 hours for 2 people. Assembly time is expected to increase as a result of the FMEA. The removal of the custom wooden joists has a positive effect but does likely not account for the increase of 24-36 bolts per mold adjustment. The removal of the custom wooden joists has a positive effect but does not make up for the increase of 24-36 bolts per mold adjustment.
- The tabs used to align and bolt the insert panels together are susceptible to failure. The tabs could warp over time due to pressure applied by torqueing down bolts leading to alignment issues. Alternatively, as the internal panels bridge the gap between the corner modules there is a chance that the entire assembly could warp during demolding if the panels are not rigid enough.
- The method of securing the custom wood base to the modular corners using a wooden block is subject to failure and increased assembly time if the blocks are difficult to install. The likely solution is to incorporate a sheet metal overhang similar to the one defined in section 5.3.1 for the 4-Wall FMEA.

- A considerable number of individual weld assemblies need to be fabricated, aligned and stored. There is no guarantee that these individual inserts will wear or warp at the same rate. However, due to the modularity the insert panels, they are inexpensive to replace.
- Overspray accumulation on the insert panels could prevent them from fitting together overtime if maintenance is not performed.

The FMEA adjusted version of the Modular Corner concept is shown in Figure 16. The total mass of the new assembly without the wood base frame is approximately 1600 lbm at maximum size configuration. This is over 1000 pounds lighter than the 4-Wall concept indicating the material costs less and is easier to move. Figure 16 shows the modular components labelled with the the heaviest individual weld assembly being the 3’x 2’ corner which weighs up to 180 lbm. The 120” long 2”x 4” HSS joists are the heaviest component that need to be lifted by hand, and weigh approximately 90 lbm each. Adjustment of the assembly requires between 32 and 72 bolts. The addition of tabs to support these joists while they are being secured is a likely addition to the final design if the Modular Corner concept is selected.

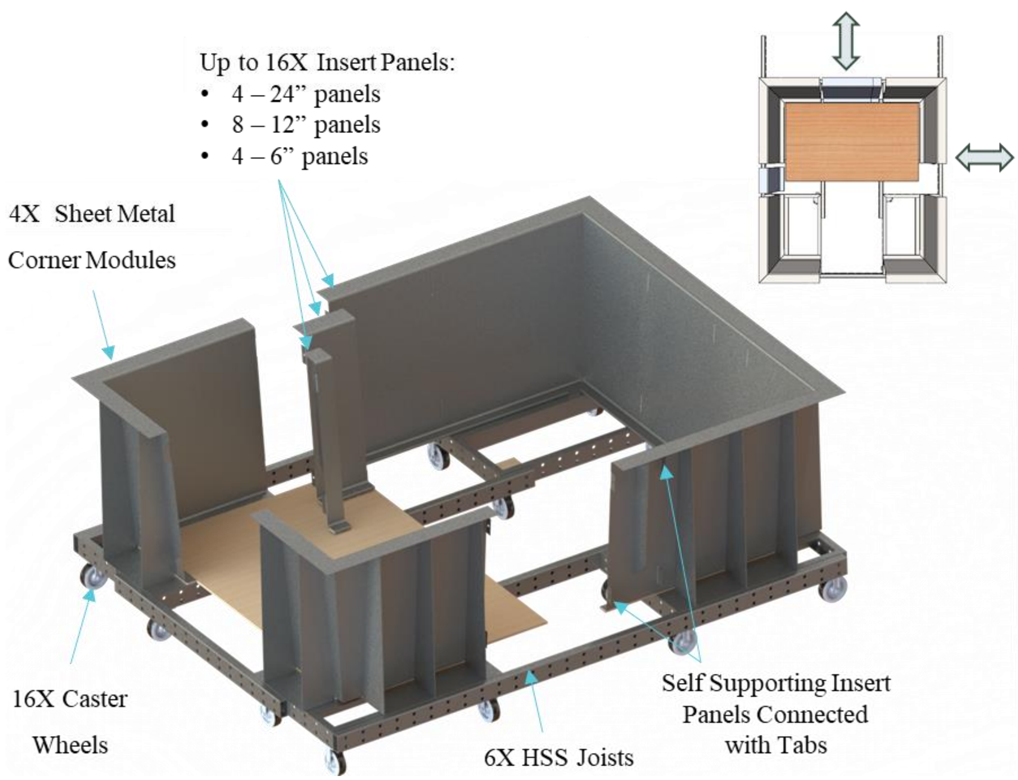


Figure 16. Render of the FMEA adjusted Modular Corner concept

5.5 Unaddressed Risks for the 4-Wall and Modular Corner Concepts

While the modifications made to the 4-Wall and Modular Corner concepts were successful in mitigating most of the risks identified in FMEA, there were still outstanding risks that could not be addressed at this stage of the process. Below is a list of action items that were taken after the FMEA to investigate any remaining risks of the 4-Wall and Modular corner concepts. The second EDR helped to settle some of the manufacturing concerns and is discussed in 6.1. The more technical design actions taken to address assembly time, weld shrinkage, and material are discussed in detail in section 6.

- Set up an in-person meeting with the mold fabricator to address fabrication concerns.
    - Ensure that sharp edges are reduced.
    - Ensure that the geometry is feasible to fabricate.
    - Discuss risks related to weld shrinkage.
    - Discuss potential methods of eliminating gaps at in the corners at the wall interface.
- Since the modified assembly has more assembly steps than the original concept, the prioritization of rigidity over assembly time was discussed in detail with SCT at the second EDR.
- As the material is not yet fully defined, the risks associated with material are discussed after meeting with Taj Industrial. In general, it was discussed that corrosion inhibitors such as WD-40 should be used on the surface of steel parts to prevent excessive corrosion.

The FMEA adjusted versions of the 4-Wall and Modular corner concepts shown in Figure 12 and Figure 16 were be carried forward to the second EDR to ensure the SCT key stakeholders agreed with the design decisions that had been made using FMEA.

6 DETAILED DESIGN DEVELOPMENT

This section of the report outlines the development of the final mold design. First, several major design modifications were made as a result of the second EDR. Prior to technical analysis of the selected concept at the second EDR, the concept was compared against the design metrics to determine the remaining design steps that were required to meet design specifications. sections 6.3-6.7 summarize these design steps. Finally, section 6.8 provides an analysis of the estimated cost of the final design.

The steps that were taken to optimize the design in sections 6.3-6.7 are as follows; first, considerations of how the final design is physically built are explained, as well as how these considerations had an impact on the final design components. Next, the use of FEA to optimize the rigidity of the corner sections is then described. The numerical rigidity study is followed by a discussion of thermal management during the curing process. A second numerical study analyzes the effects of varying the step location and geometry on the top face of the T-Pad. Next, an assessment of mold ergonomics and assembly time was performed with the goal of reducing weight and ensuring the mold components could be easily transported by hand. Lastly, a cost analysis was performed.

6.1 External Client Design Review

The focus of the second EDR was to present improved iterations of the 4-Wall and Modular Corner designs following failure modes and effects analysis. The meeting objective was to obtain feedback from SCT on the two concepts and select a single final design for technical analysis. Outside of the U of M Team, the following project stakeholders from SCT were in attendance:

Brian Zadro	*Sales Manager*
Amarjit Bedi	*Production Supervisor*
Steven Meatherall	*Engineering Manager*
Blair Abrams	*Primary Project Contact*

Improved iterations of the 4-Wall and Modular Corner designs are depicted in Figure 12 and Figure 16 with the key advantages and disadvantages of the updated concepts summarized in Table XVIII.

TABLE XVIII: KEY ADVANTAGES AND DISADVANTAGES OF THE ITERATED CONCEPTS PRESENTED TO SCT

4-Wall Concept	
Key Advantages	**Key Drawbacks**
• Rigid assembly – each of the four wall segments is inherently rigid leading to good quality T-Pad walls. • Low number of seams – alignment issues between corner insert panels are not a problem. • The sheet metal overhang is likely be an effective method of holding the wood base frame in place. • Steel joists provide excellent base plate support deflecting by < 1 mm under the weight of a person.	• Requires carpenter time due to the custom wood base. • Fabrication concerns with the corner insert create high risk associated with the wall segments mating to each other. • The weight of the overall assembly and wall sections is relatively high. • An extended assembly time is associated with the high number of bolted connections in awkward locations.
Modular Corner Concept	
Key Advantages	**Key Drawbacks**
• The overall weight of the assembly and individual components are significantly lower. • Sheet metal corners are welded with a radius eliminating the risk of poor-quality T-Pad corners. • The mold does cause a step along the outside edge of the top face of the finished T-Pads. • Modularity of the insert panels allows them to be fabricated as need with a relatively low cost.	• Requires carpenter time due to the custom wood base. • Large mold sizes require up to 20 panel inserts and 24 additional bolts, creating an extended assembly time. • Insert panels create many seams and overspray accumulation is more of a risk as it could build up on the insert panel tabs over time. • The method for securing the custom wood base to the mold frame is not confirmed as structurally sound.

After reviewing the modified 4-Wall concept at the meeting, it was determined that this concept should not be pursued any further into the design process. The main reason for this decision was that the assembly time and overall weight of the 4-Wall assembly were unacceptable risks to SCT. Additionally, SCT expressed concerns about the seams created by the insert panels. They acknowledged that they were a necessary addition to the concept to prevent sharp corners, but it was recognized that the insert panels would create significant visible seams in the corners that would have the potential to make mold release difficult. Additionally, the seams created by the insert panels would need to be sanded down on the finished T-Pads. This adds an undesirable step in the fabrication process.

Regarding the Modular Corner concept, SCT stated that their only major concern was the assembly time. Similar to the 4-Wall, the number of bolts would likely extend the assembly time over two hours for two shop technicians. SCT also expressed that the assembly time associated with the custom wood base frame could be eliminated completely by focusing on designing modular wall and corner components that could be assembled and secured to any arbitrary flat surface in SCTs shop.

Based on the feedback from SCT at the second EDR, The U of M Team revised the relative importance of design metrics established during concept development to better guide the detailed design. The shift in metric importance before and after the second EDR is summarized in Table XIX.

TABLE XIX: SHIFT IN THE IMPORTANCE OF DESIGN METRICS

Metric	Level of Importance Before the second EDR	Level of Importance After the second EDR
Assembly Time	Moderate	High
Max Assembly Weight	Moderate	High
Individual Component Weight	Moderate	High
Overspray Vulnerability	High	Low

As seen in Table XIX , the biggest shift was in the importance of overspray vulnerability. During the concept development phase of the project, the U of M Team set this metric to have high importance since it was thought that it would be difficult to deal with overspray. More specifically, the U of M Team saw a permanent base plate as an item at extreme risk to overspray accumulation leading to the elimination of the cantilever rail design as shown in Figure 5. However, due to the U of M Team's lack of experience in overspray mitigation, this was found to be an incorrect assumption.

In addition to the shift design metric importance, SCT requested the following design features be implemented into the final version of the Modular Corner design. A visual representation of these design changes is shown in Figure 17.

- Instead of a cut-to-size custom wood base, the mold sits on a separate base provided by SCT.
- The mold is not required to be fixed to the base; self-weight of components can be utilized.
- The bottom of the mold walls should end at the radius which rests on the base – no bottom flange.
- Assembly method should avoid bolts, quick methods of locking components in place are preferred.
- The design must include a minimum of one guide rail along each side to prevent bowing of the sheet metal panels.
- Locking mechanisms should be designed with clearance to mitigate the effects of tolerancing issues.

With the updated metric priorities and requested design features, the U of M Team proceeded to further develop and optimize the Modular Corner concept. The following section provides an overview of the initial state of the Modular Corner concept with the design features requested by SCT integrated.

6.2 Overview of Modular Corner After the Second EDR Revisions

This section details how the decisions made at the second EDR were reflected in the Modular Corner model. Diagrams of the revised concept model are shown in Figure 17 and Figure 18. An assessment of how the Modular Corner design meets the project metrics is also discussed.

Figure 17 displays the Modular Corner design that integrates SCT's requested features and feedback from the second EDR. As discussed in section 6.1, the most notable design changes were the elimination of the steel base plate design from the U of M Team's design scope and re-introduction of the guide rails. These main justification for these changes was to provide a concept that could be installed on any moveable flat surface in SCT's shop. The likely surface of choice is a simple melamine sheet support by a steel frame on caster wheels. The base frame was be modeled as a simple melamine sheet for the remainder of the design and should be considered as an arbitrary representation of the base frame.

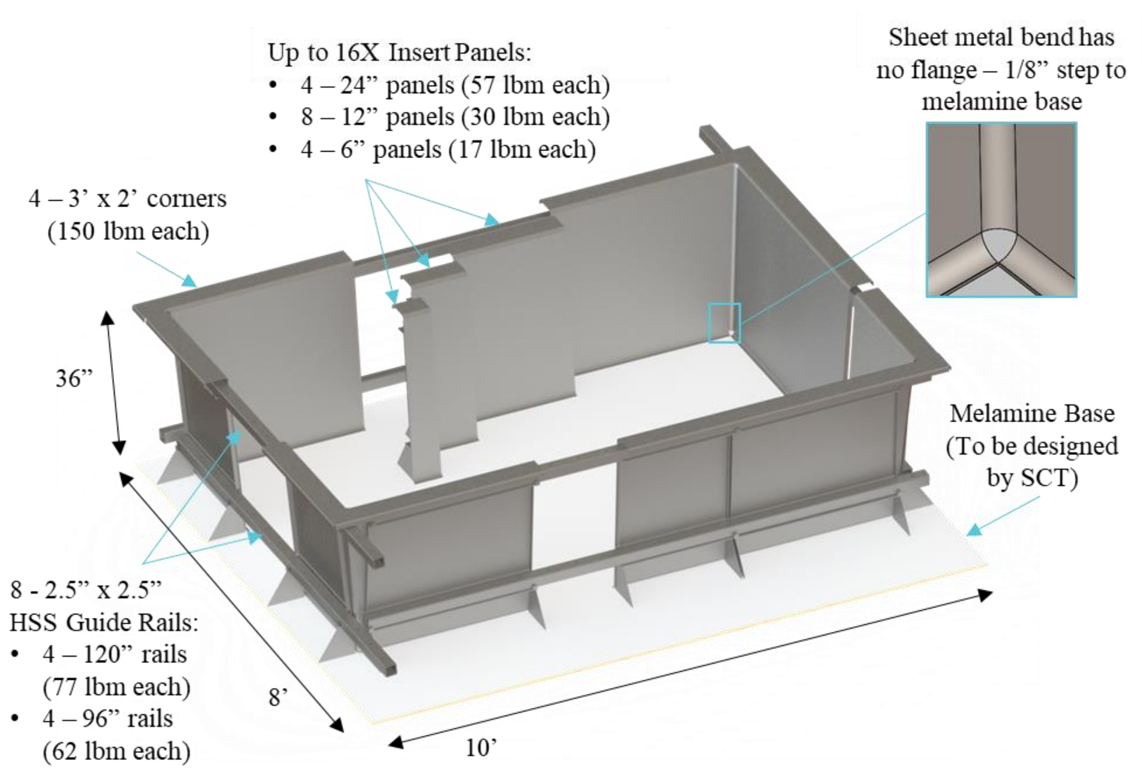


Figure 17. Diagram of the Modular Corner Concept after the second EDR revisions

Figure 18 displays a detailed view of the corner module and 12" insert panel weld assemblies. Four key notes related to these components are as follows.

1. A 1" flange was added to the top edge of the mold components. The purpose of this flange is to add rigidity and facilitate the de-molding process. The 0.25" bend radius allows SCT technicians to drive wedges between the finished T-Pads and the steel mold more easily.
2. The 3" x 3" structural angles that support the guide rails and align the panels are slotted to facilitate bolts, pins, or clamps depending on what SCT finds easiest during the prototyping phase of the project.
3. Trapezoidal gussets were added at the base of the weld assemblies to allow each component to stand on its own without the guide rails. These gussets also serve the purpose of adding rigidity near the base of the sheet metal.
4. 0.125" x 1" x 19" gussets were added along the length of the weld assemblies to add rigidity in the vertical direction and provide a surface for SCT to clamp the panels together for improved alignment of the individual components.

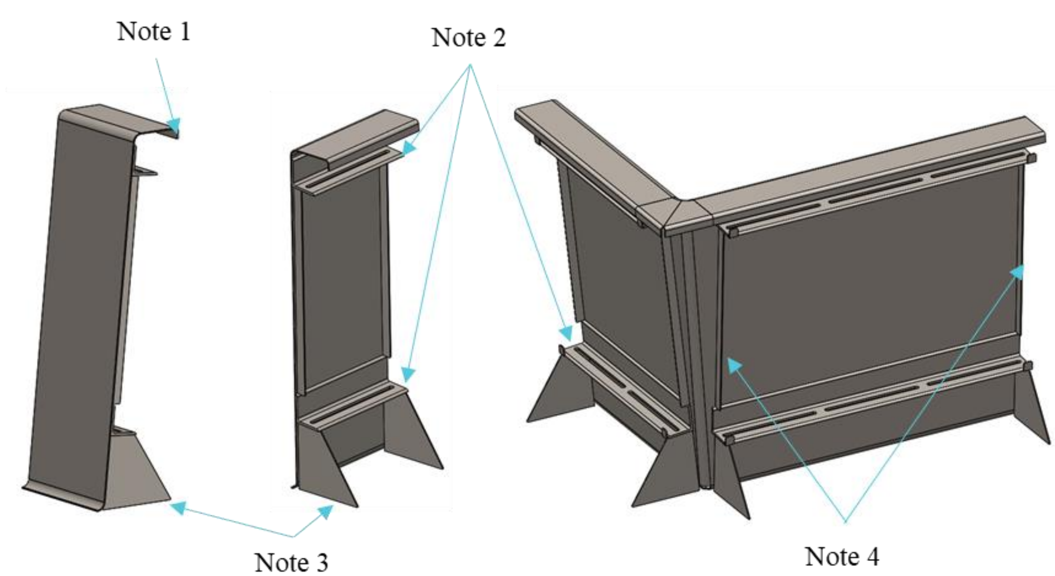


Figure 18. Detail views of the Modular Corner weld assemblies after the second EDR

Table XX identifies the outstanding design metrics related to Modular Corner after the second EDR. These metrics required further investigation or were known to not meet the marginally acceptable values. The remainder of the detailed design development section of the report focuses on carrying out the design processes defined in Table XX to arrive at a final design.

TABLE XX: UNRESOLVED DESIGN METRICS

#	Metric	Current Value and Optimization Strategy
1	Average assembly time	**Current Value:** Undefined **Design Strategy:** Compose a detailed mold transport and assembly procedure and make modifications to the mold geometry to reduce the time it takes to complete various steps if required.
3	Strength	**Current Value:** The strength of the base frame is undefined as the base frame will be designed and provided by SCT. The strength of the wall components is also undefined. **Design Strategy:** Create a list of reasonable operating loading conditions and assess mold deflection under these conditions. Conduct a numerical study of the finished T-pads based on the on the 1/8” step created by the sheet metal transition to the melamine base as shown in Figure 17.
4	Capital Cost	**Current Value:** Undefined **Design Strategy:** Obtain a quotation from Taj Industrial and select the most cost-effective material relative to the benefits it provides, eliminate any economically compromising design elements.
5	Corrosion Resistance	**Current Value:** Material Dependent **Design Strategy:** Stainless steel and aluminum are desirable for their anti-corrosion properties. Carbon steel is likely the most cost-effective option. A contingency plan for preventing corrosion on the carbon steel mold was composed. SCT is given a series of material options complete with costs to select from during the prototyping phase of the project.
6	Part Removal	**Current Value:** 5-degree draft angle; exclude geometries that could compromise part release such as sharp corner. **Design Strategy:** Compose the operation instructions to include a specific list of steps for mold release.
10	Maintenance	**Current Value:** Selection of a metal mold indicates that minimal maintenance is required other than preventing and cleaning oxidation on the surface of the mold. Expected mechanical degradation is undefined. **Design Strategy:** Create a list of reasonable operating loading conditions and numerically assess mold deflection under these conditions. The primary focus is assessing if plastic deformation of the sheet metal components is a risk under normal operating conditions.

#	Metric	Current Value and Optimization Strategy
11	**Seams**	**Current Value:** Multiple seams are situated at the insert panel interface; these are considered as acceptable by SCT if they are taped over. The step created by the sheet metal bend sitting on the base plate as shown in Figure 17 may result in stress concentrations on the top surface of the finished T-Pads **Design Strategy:** Create a numerical mold of the 1/8" step that forms on the top surface of the finished T-pads and confirm that any stress concentrations do not pose a risk to the structural integrity of the finished T-Pads.
16	**Individual Component Weight**	**Current Value:** The heaviest individual component are the corner weld assemblies which weight 150 lbm (liftable by three people). **Design Strategy:** Optimize the mass of the corner assembly through numerical deflection studies and reduce the size and weight of the corner weld assembly to meet the minimum acceptable individual component weight of 100 lbm.
17	**Individual Component Weight**	**Current Value:** Deflection of the mold components under normal operation conditions is undefined. **Design Strategy:** compose a numerical model of the corner weld assembly and study deflection of the component under normal operation loading scenarios. Make modifications to the weld assembly based on the results.

Another remaining concern that is not directly addressed by the project metrics is the manufacturing of the mold components. Section 6.3 provides detail on how the Modular Corner assembly is fabricated based on conversation with the mold fabricator, Taj Industrial.

6.3 Manufacturing Considerations

This section covers the manufacturing process that is used to fabricate the mold components. More specifically bend allowance, weld size, and weld shrinkage related to the corner weld assemblies and insert panel weld assemblies

This section covers the manufacturing process that is used to fabricate the mold components. More specifically bend allowance, weld size, and weld shrinkage related to the corner weld assemblies and insert panel weld assemblies are discussed in detail. There are five manufacturing methods that govern the fabrication for every component in the mold. These methods are as follows:

1. ***Water jet*** – Used to cut any 2D parts and the flat patterns of the bend sheet metal parts. Potentially used to cut slots in the structural angles and guide rails.
2. ***Sheet Metal Bending*** – Used to bend the water jet sheet metal flat patterns into the corner module sheet metal covers and insert panel sheet metal covers.

3. ***Welding and Grinding*** – Used to attach the gussets to the bend corner assembly and insert panel sheet metal covers. Welds on the mold surface are ground flat and then polished.
4. ***Horizontal Band Saw*** – Used to cut the guide rails and structural angle to size.
5. ***Drill Press*** – potentially used to drill the ½" holes in the guide rails.

After discussion sending preliminary drawings of the mold components to Taj Industrial, it was confirmed that every part was feasible to manufacturing using the tools available in their shop. The specific tolerances that can be achieved with each process are omitted from this section of the report. The Engineering drawings provided in Appendix B provides general tolerances for the finished mold parts. After discussion with the Taj Industrial it was determined that general comments should be left on the drawings that specify to what accuracy the parts should align and that they will cut, bend, and weld the parts to meet the final alignment tolerances.

The Machinery's Handbook [4] was utilized to guide the design process so that the drawings and cut files provided to Taj Industrial could be feasibly fabricated. The three items that were addressed were bend allowance, weld size, and weld shrinkage. As the mold components do not experience heavy loads, weld strength was not identified as a risk to the final design. Instead of sizing the welds by strength the welds were sized to be as large as possible for the gauge 11 sheet metal used in the Modular Corner design. The remainder of this section covers the technical details related bend allowance, weld size, and weld shrinkage.

6.3.1 Bend Allowance

Bend allowance for sheet metal fabrication reflects the additional material required in the flat pack design to achieve the desired dimensions of the final part. There are various methods used to calculate the bend allowance for sheet metal, Taj Industrial uses the K-factor method. The K-factor is the ratio of the position of the neutral axis relative to the sheet metal thickness. A K-factor of 0.5 indicates that the neutral axis for a given material is located at the center of the material thickness, though this is often modified by the manufacturer based on the experience. Taj uses a K-Factor of 0.4 in their fabrication process as they have found that the additional material left using a K-Factor of 0.5 is unnecessary. Bend allowance can be calculated from the K-Factor using Eq. 1 where R is the bend radius, T is the material thickness and A is the bend angle [5].

$$BA = \frac{\pi(R + KT)A}{180} \qquad \text{Eq. 1}$$

Figure 19 shows the flat pack version of the sheet metal cover for the corner weld assemblies. The dimension of 1.25" demonstrates how the K-Factor modifies the radius of 0.75" for a bend angle of 89.57° and material thickness of 0.1198". It is worth noting that the bend angle of 89.57° as opposed to a typical 90° bend was a relic of the 5° draft angle incorporated into the corner weld assembly. The bend radius of 0.75" was selected based on SCT's typical T-Pad radii of 1" and the feasible bending radii for gauge 11 sheet metal. 1" bends were not pursued as it was discussed that achieving accurate bend angles on gauge 11 sheet would be easier with a tighter radius. It is recognized by the U of M Team that this price bend angle is difficult to achieve. As such, it was discussed with Taj Industrial that the parts should be fabricated to fit together and sit flat on the base frame rather than focusing on accurately achieving this odd bend angle.

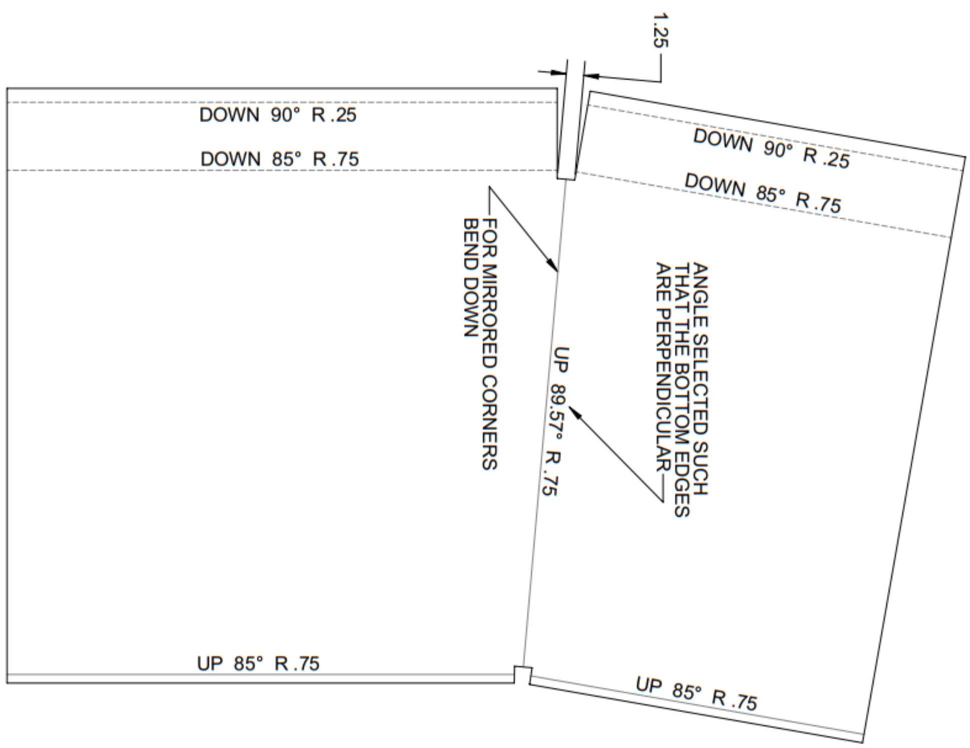


Figure 19. Flat pack of corner assembly sheet metal cover

In summary, the flat pattern drawings incorporate a 1.25" material allowance for every 90°, R0.75" bend on the sheet metal components. The overall dimensions and bend configuration for the corner weld assembly and insert panels were seen as economically feasible by the fabricator Taj Industrial. The following section covers weld size.

6.3.2 Weld Size

Weld size was selected based on a recommendation from Taj Industrial. All welds on the assembly were selected to be 1/8" fillet welds, with the exception of one 1/8" groove weld on the top flange of the corner modules.

The suggestion to use a 1/8" weld was based on the gauge 11 sheet metal which has a thickness of 0.1198" for carbon steel. Welds of significantly greater size than the sheet metal thickness are known to cause warpage of the part which is the main reason for the selection of 1/8" welds. Additionally, smaller welds have a positive impact on the overall weight of the assembly and reduce fabrication time.

In summary, weld size was selected based on typical fabrication practices for the sheet metal thickness being used. All of the welds specified on the drawings were seen as feasible by Taj Industrial.

6.3.3 Weld Shrinkage

Since welding of the assembly elevates the temperature of the metal in the region of the weld, thermal contraction becomes a factor in the manufacturing process. Two examples of the effects of weld shrinkage that are applicable to the manufacture of the adjustable mold are illustrated in Figure 20.

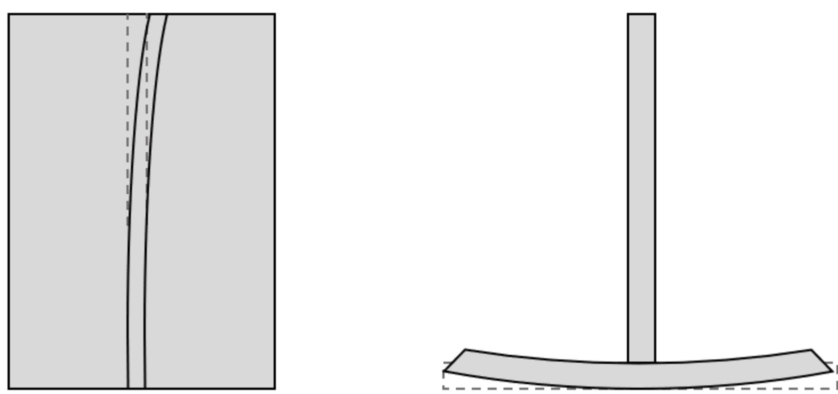


Figure 20. Examples of the effects of weld shrinkage.

After discussion with Taj Industrial regarding weld shrinkage it was determined that a general not should be left on the drawing to allow Taj Industrial flexibility in the way the welding is performed to account for weld shrinkage. Due to lack of experience in welding and the likelihood that manufacturing companies prefer to use their own methods, the U of M Team left it up to the manufacturer of the mold to use proper techniques to account for weld shrinkage.

After addressing potential complications in the fabrication process with an experienced fabricator and SCT personnel, the team was satisfied that the Modular Corner design posed no further manufacturing risks and was acceptable to send out for production. The remainder of the detailed design development focuses on addressing the rigidity, ergonomics, and assembly time for the Modular Corner design.

6.4 Deflection Analysis of the Corner Assembly

This section of the report focuses describing the FEA analysis that was carried out on the corner weld assembly with the goal of improving the overall rigidity of the design. The corner weld assembly was subjected to four 'normal operation' loading scenarios. Within the context of this study, 'normal operation' loading scenarios are defined as lifting, transporting, and positioning the mold components by hand.

To set a quantifiable goal for rigidity, this study focuses on reducing deflection to less than 2 mm. As mechanical failure of the mold components is not a major risk and would be difficult to accurately model, stress concentrations in the mold components were not the focus of this study. The four key loading scenarios examined in this study are classified as the 'opening load', 'guide rail load', 'flange lift load', and 'handle lift load', Figure 21 visually depicts these four key loading scenarios. Any modifications made to the corner weld assembly that are applicable to the insert panels were translated over, thus the insert panels were not modeled. Deflection due to thermal expansion was considered separately in Section 6.5

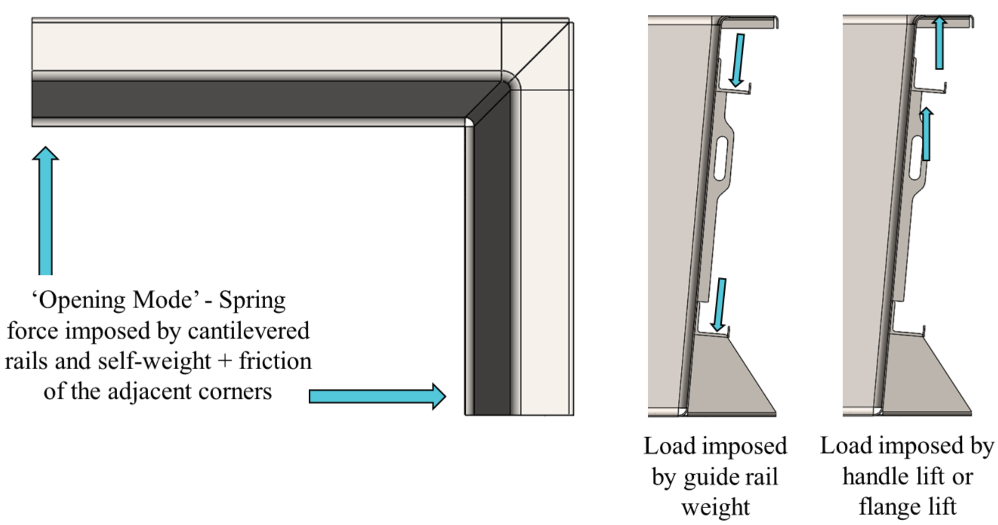


Figure 21. Corner weld assembly loading scenarios

It is important to note that the results presented in this section are a simplification of the loading scenarios that are imposed on the mold once it is fabricated. However, due to the rigor involved in developing the numerical model, deflection is expected to be roughly within +/-50% of the physical mold.

This error is attributed to simplifications made to create a numerical model and uncertainty associated with the welding process. Despite the accompanying error, the study facilitated quantifiable decisions related to the position, quantity and size of the gussets on the back of the corner panels. The results also gave the U of M Team confidence that the mold would be acceptably rigid. It was demonstrated that deflection of the corners can be limited to less than 2 mm after a few modifications when subjected to the loading scenarios defined in Figure 21.

6.4.1 Mesh and Simplified Geometry

This first step in developing a numerical model of the corner weld assembly was to determine the details of the mesh. It was decided that a quadrilateral shell mesh was the best option to conduct the deflection study. The shell mesh was selected over a solid mesh for the following reasons:

- The shell mesh required far fewer nodes to capture the geometry leading to a significantly shorter run time. A solid tetrahedral mesh required at least two elements across the sheet metal thickness to be reasonable. This method was tested resulting in a 16 million node mesh which took over an hour to solve leading to the decision to use a shell mesh.
- As the study was concerned with deflection and not with stress concentrations the shell mesh was a reasonable option. This distinction needed to be made because the shell mesh was recognized as not being capable of capturing stress concentrations at the welds between the assembly components.
- In general, shell mesh is known to model thin bent sheet metal geometry better than solid mesh.

An element size of 0.25" was used to capture the 0.75" sheet metal bends. A 0.125" mesh size was tested to prove that the 0.25" mesh was reasonable by showing that there was not significant difference in the deflection results. The use of a shell mesh required several simplifications to be made to the geometry. Figure 22. contrasts the simplified shell mesh geometry (left) against the actual solid assembly (right). The thickness of each shell element was set to matched that of the actual model. Four notable simplifications required to create the surface model are as follows.

1. The structural angles were modified to be simple 3" long fins to mimic the first moment inertia of the actual geometry. They were assigned a thickness of 0.25". This simplification was conservative as the actual assembly has additional material associated with the structural angles.

2. The software used to create the sheet metal geometry (SolidWorks 2019) limited modeling the same bend geometry with a surface model due to the draft angle on the mold. More specifically the loft used to create the sheet metal surface force the bend radius near the top of the mold to be 4” rather than 0.75”.
3. The 24” long half of the corner assembly was used as a fixture, thus the gussets on the fixed wall were not modelled to save computational power.
4. The corner flange was modelled as a simple surface to mimic the first moment of inertia of the actual geometry. It was assigned a thickness of 0.125”.

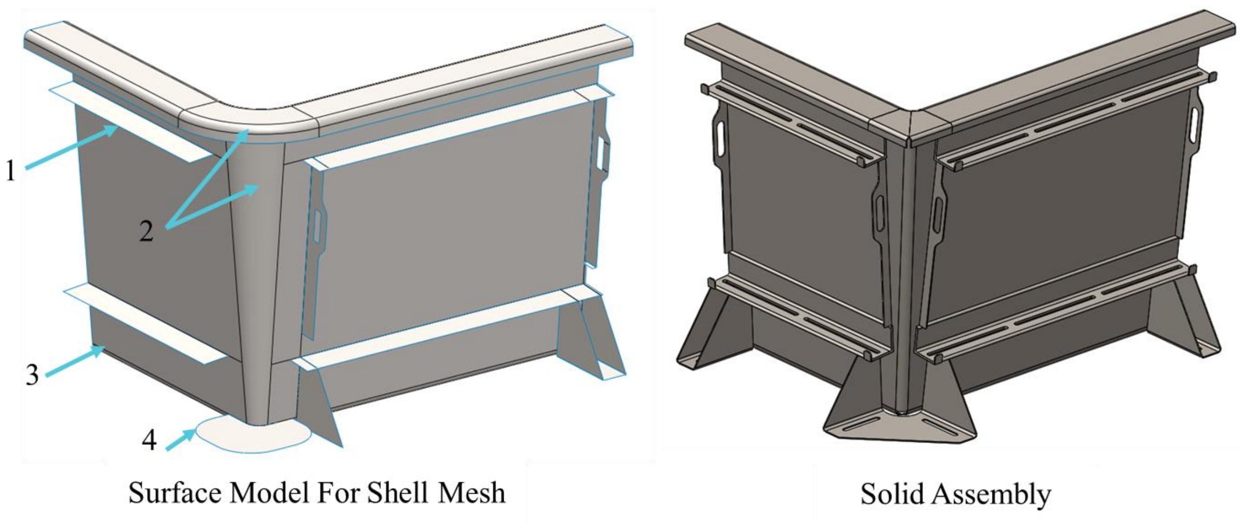


Figure 22. Simplified shell mesh geometry compared to assembly

To help verify that the results obtained using the simplified shell mesh model, an analytically defensible version of the simplified shell mesh geometry was created and tested as is discussed in Section 6.4.2.

6.4.2 Analytical Validation

The analytically defensible shell mesh model aimed to mimic the 36” long wall of the corner weld assembly. This further simplified model is shown in Figure 23 The defensible model is a 36’ x 36” square surface with a 2” tab for fixturing and two symmetric 3” flanges running along the length of the surface. This geometry mimics the 36” wall of the corner assembly. The analytical calculations demonstrated the deflection at the end of the simplified surface with a rigidly fixed end, and imposed bending load of 50 N was 0.02853 mm. These calculations are shown in Eq. 2 and Eq. 3.

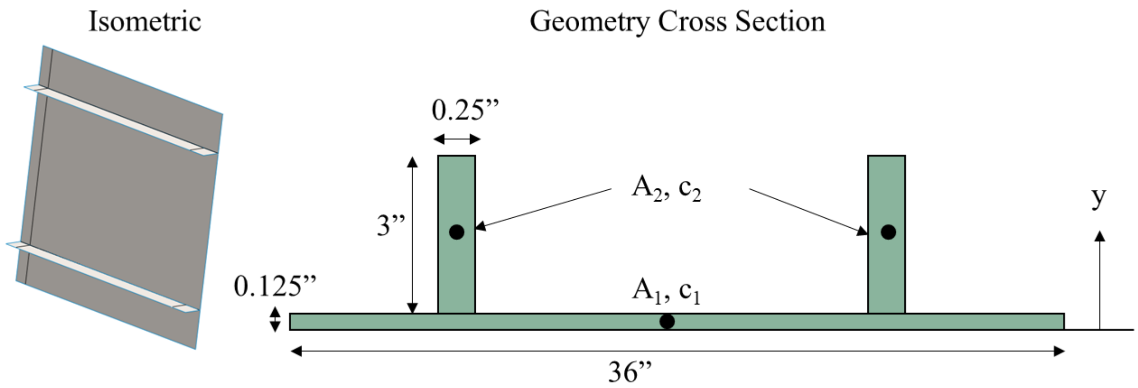


Figure 23. Simplified geometry and cross section

The first step in analytically determining the deflection at the end of the simplified panel was to determine the first moment of inertia (I') of the cross section shown in Figure 23. I' was calculated using Eq. 2 where A is the region area, d is the distance between y = 0 and the centroid of each region, and I represented the moment of each region about its middle axis.

$$I' = I_1 + A_1 {d_1}^2 + 2(I_2 + A_2 {d_2}^2) \qquad \text{Eq. 2}$$

$$I' = \frac{36(0.125)^3}{12} + 36(0.125)\left(\frac{0.125}{2}\right)^2 + 2\left(\frac{0.25(3)^3}{12} + 0.25(3)\left(0.125 + \frac{3}{2}\right)^2\right) = 5.1093\ in^4$$

$$I' = 2.1267 \times 10^{-6}\ m^4$$

Knowing I' and that the cross-sectional geometry is symmetric about its center plane the deflection at the end of the wall was calculated using Eq. 3. ∂ is the deflection in [m], P is the load in [N], l is the wall length in [m] and E is the modulus in [Pa]. The modulus had a value of 210 GPa and was taken from the SolidWorks material properties [5].

$$\partial = \frac{Pl^3}{3EI} \qquad \text{Eq. 3}$$

$$\partial = \frac{50(0.9144)^3}{3(210 \times 10^9)(2.1267 \times 10^{-6})} = 2.853 \times 10^{-5}\ m = 0.02853\ mm$$

Figure 24 shows the loads, fixtures, and numerical results for the simplified geometry. The numerical study shows a deflection of 0.03682 mm and differs from the analytically solved value by 22%. The mesh was refined without a change in the results, this indicates that it is a reasonable, but not perfect approximation of the load condition being studied. The difference in the results can be attributed to the imperfect load transfer between perpendicular surfaces and limitations on the loading and fixturing options provided by SolidWorks.

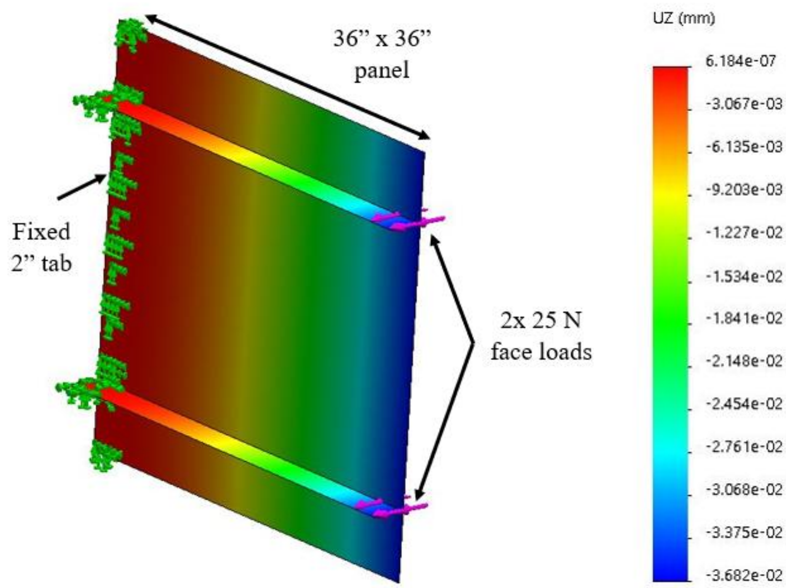


Figure 24. Simplified geometry study results

6.4.3 Opening Mode Analysis

After verifying that the shell mesh captured load transfer between adjacent shell mesh surfaces to a reasonable accuracy, the first load case was modelled. This load case is referred to as the ‘opening mode’ and is visually depicted in Figure 25 and Figure 26. This load case describes the condition where the adjacent walls of the weld assembly are spread apart by opposing forces. The first step in assessing the corner weld assemblies’ resistance to deformation under the opening mode was to determine reasonable values for the loads that the corner would be subjected to under normal operation. To solve these loads the U of M Team assessed how the mold corners might skew when sitting on the base frame as shown in Figure 25. This condition would occur due to the self-weight of the corners bending the guide rails if the corners are not properly aligned when first assembled.

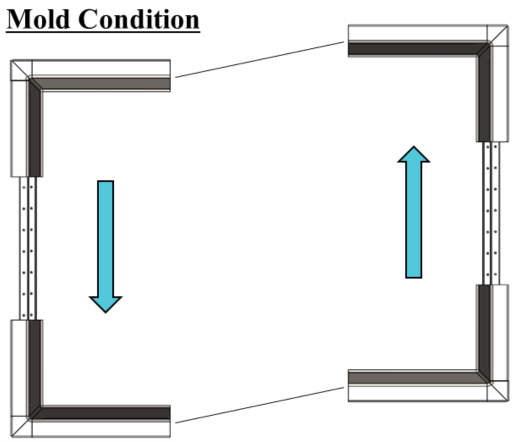


Figure 25. Skewed mold condition

Using the skewed mold condition defined in Figure 25 as a basis, a model relating this condition to the loads imposed on one of the corner weld assemblies was created. It was determined that the opening load imposed on one of the corner walls could be approximated as the maximum spring load in the guide rails prior to overcoming the friction force between the adjacent corner and the base frame. Figure 26 visually depicts this scenario.

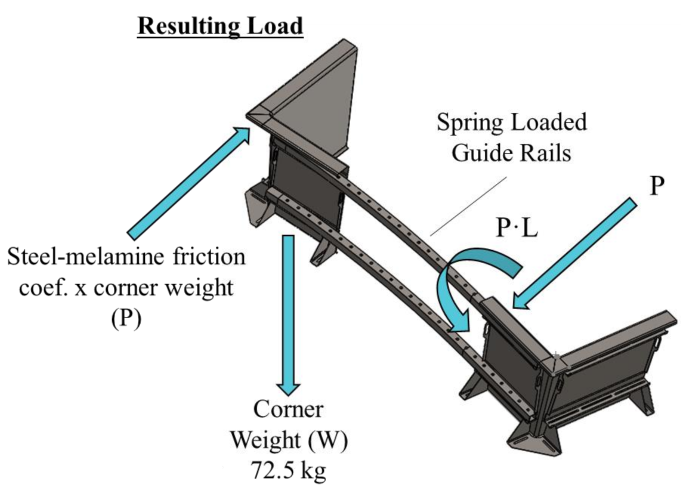


Figure 26. Spring loaded rail loading condition

To quantify this loading scenario a series of assumptions was made to define the equation variables. The friction coefficient between steel and melamine was conservatively taken to be 0.5 based on a series of researched steel-polymer coefficients that ranged from 0.2-0.5 [6]. The effective length (L) of the spring-loaded guide rail was taken to be 1.68 m. The length of the wall is known to be 0.914 m. For clarity, Figure 27 defines the variables used in Eq. 4 and Eq. 5 to determine the effective loading on the corner assembly.

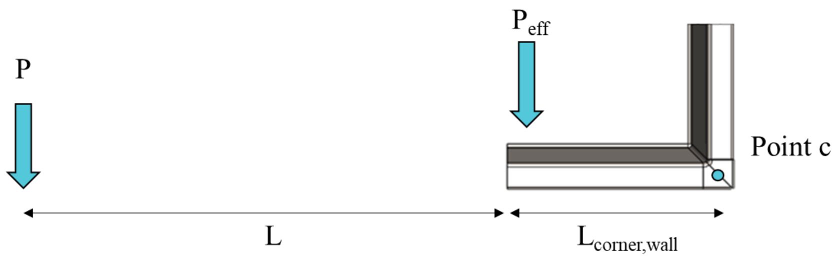


Figure 27. Effective wall load variables

Eq. 4 display how the Eq. 5 display how the spring load was converted to an effective load that could be applied directly to the sheet metal surface. This step was taken to avoid using the SolidWorks remote loading tool that would add further uncertainty to the results.

$$P = W(g)(f) \qquad \text{Eq. 4}$$

$$P = 72.5 \cdot 9.81 \cdot 0.5 = 355\ N$$

$$0 = \sum M_c = P(L + L_{corner,wall}) - P_{eff} L_{corner,wall} \qquad \text{Eq. 5}$$

$$P_{eff} = \frac{355 \cdot 2.5944}{0.914} = 1008\ N$$

Using the load of 1008 N, a numerical study was run on the corner assembly. The results of this study including the loads and fixtures applied to the model are displayed in Figure 28. It can be observed that a maximum deflection of 2.453 mm occurs where the upper guide rail pulls on the corner assembly.

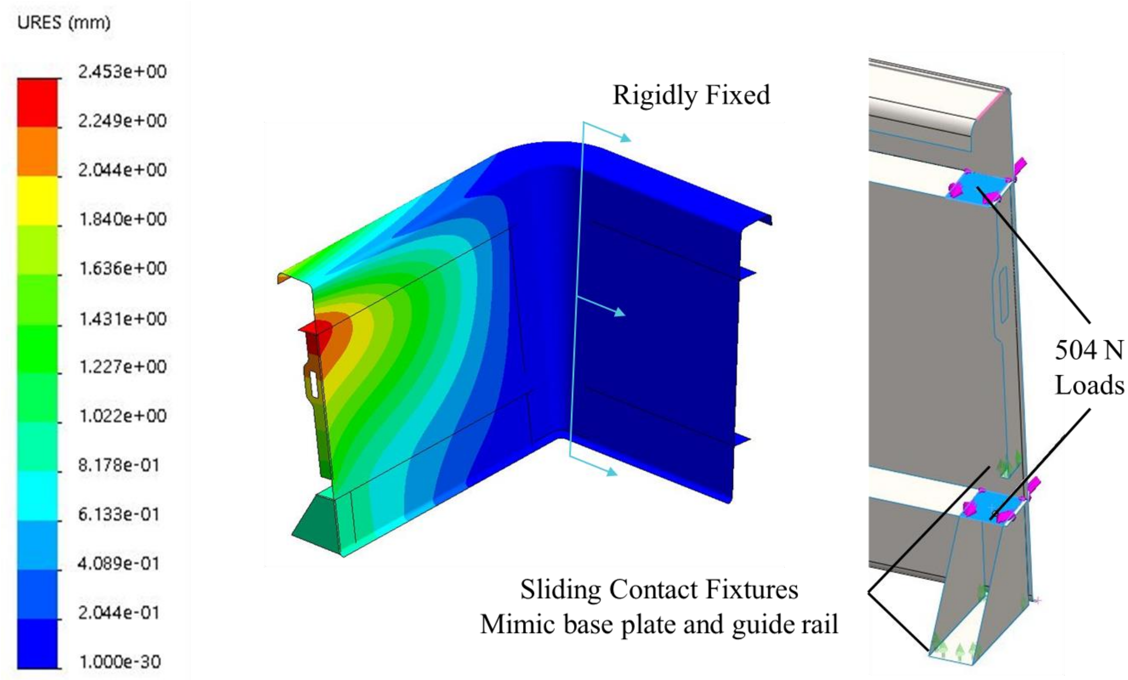


Figure 28. Opening mode study results

The results of this study showed that the frame did not meet the deflection metric of maintaining a value less than 2 mm. To improve the rigidity of the corner weld assembly without drastically increasing the weight, additional gussets were added to the outside of the assembly as shown in Figure 29. The addition of these gussets reduced the maximum deflection to 1.405 mm meeting the design goal. Section 6.4.7 discusses how this addition is physically realised in the actual weld assembly.

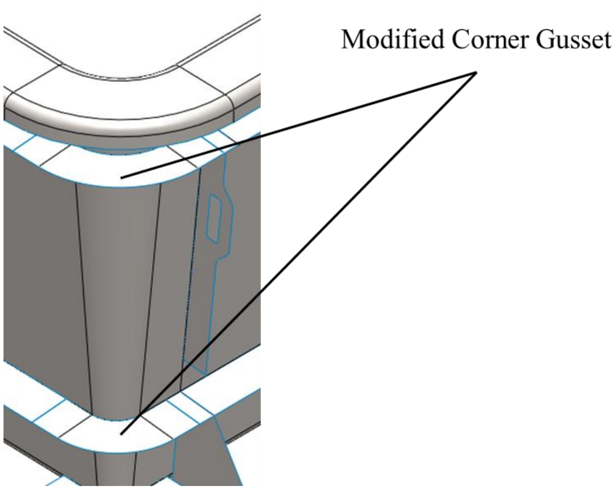


Figure 29. Modified corner gusset geometry

6.4.4 Guide Rail Weight Analysis

Prior to conducting the remaining studies, a mesh size of 0.125” was tested to ensure the results of the opening mode study did not differ from the 0.25” mesh results. The results of this convergence study confirmed that the mesh was reasonable as the maximum deflection only increased by 3.7 % to 1.459 mm. A 0.25” mesh was used for the remainder of the studies to save computing power.

The second load case tested involved modelled the weight of the guide rails on the weld assembly flanges. Figure 30 shows the results of this study and highlights how the corner assembly deflects under the weight of the 90 lbm guide rails. The maximum deflection of 0.1259 mm is acceptable within the specified metrics thus the mold geometry is acceptable when subjected to loading scenario.

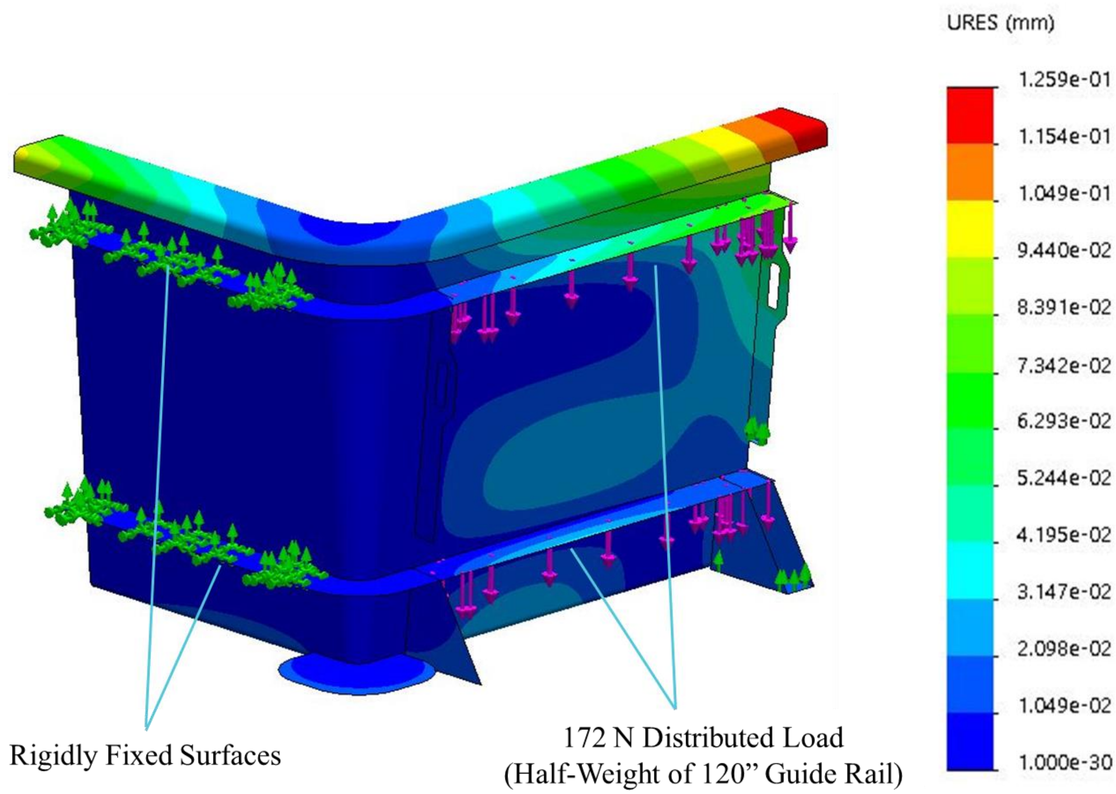


Figure 30. Guide rail load study results

6.4.5 Handle Load Analysis

The third load case study involved modelling an SCT technition lifting the mold from one of the gusset handles. Figure 31 shows the results of this study including the load placement and fixture. The study results deomonstrate how the corner assembly deflects under these condtions.

Justifying the loads and fixtures, the 400 N load represents the weight of the 36" half of the mold. The adjacent wall is fixed as it is assumed that the remainder of the weight is supported by another lifting point. A refined mesh of 0.0625 mm was used on the loaded gusset for this study to ensure that any deflection was accurately captured. The maximum deflection shown on the countour plot of 0.2708 mm is acceptable within the specified metrics thus the mold geometry is acceptable under this loading conditions.

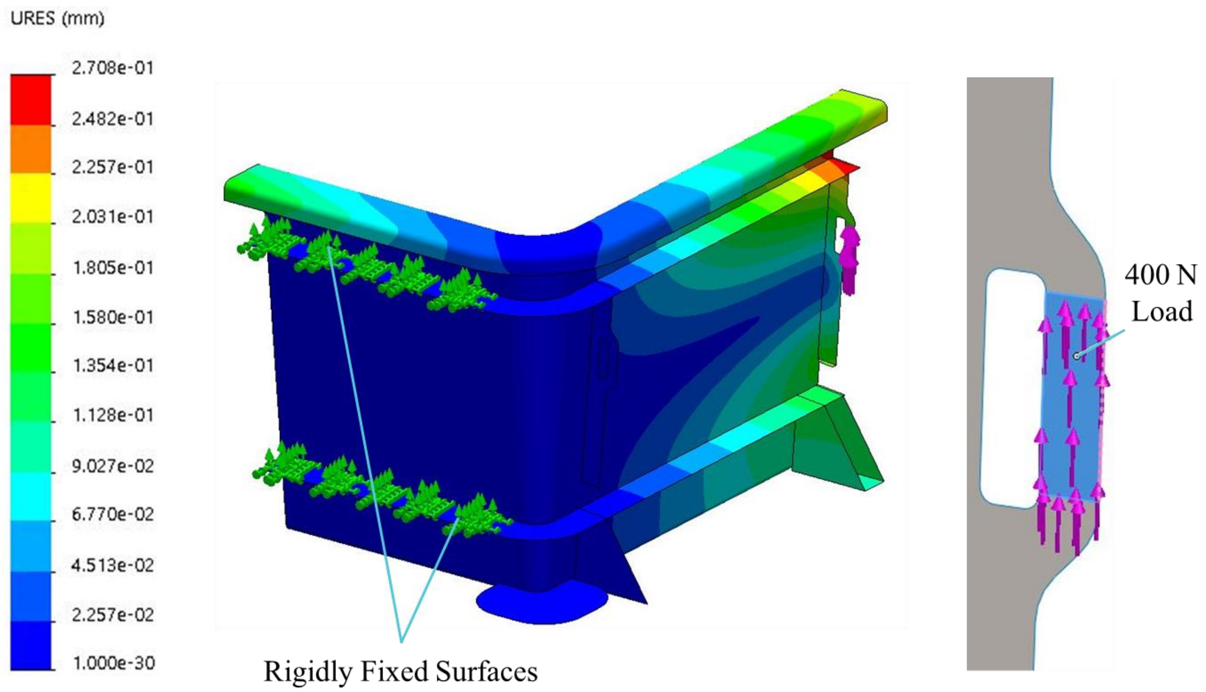


Figure 31. Handle lifting load study results

For this loading case the maximum Von Mises Stress on the loaded gusset was also analyzed using the shell model. As there are no surface connections or welds between the load and the region of interest, the stress contour defined by the shell mesh was representative of the actual stresses that will be imposed on the fabricated parts. Figure 32 displays the results of this study. The maximum Von Mises stress lies on the inside corner of the handle and has a value of 12.25 MPa. This indicates a safety factor of close to 20 when considering the yield strength of carbon steel. As the safety factor is larger than typically safe values of 3 or 4, fatigue and fracture on the handle is a significant risk.

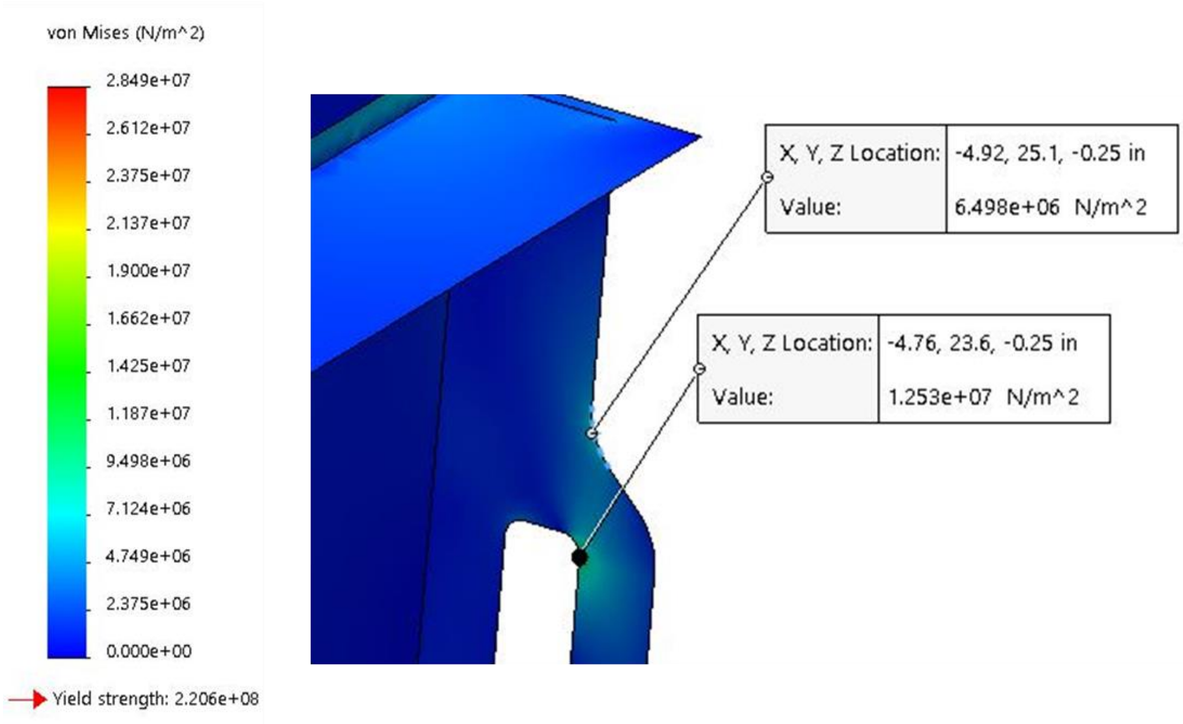


Figure 32. Von mises stress results on the loaded handle

To summarize the handle lifting study, the results showed that no modifications were required to the gusset or the handle to ensure the structural integrity and rigidity of the mold within the project metrics.

6.4.6 Flange Load Analysis

The final loading case that was addressed was a lifting load placed on the flange. This case was identified as being important as the flange may be used to lift and manipulate the mold corners by SCT technicians. The study was setup by placing a 400 N lifting load on a 4” x 4” segment of the flange as shown in Figure 33. The 400 N load is representative of the weight of the 36” long half of the corner assembly. The results of the study showed that the flange deflected by 2 mm under these conditions.

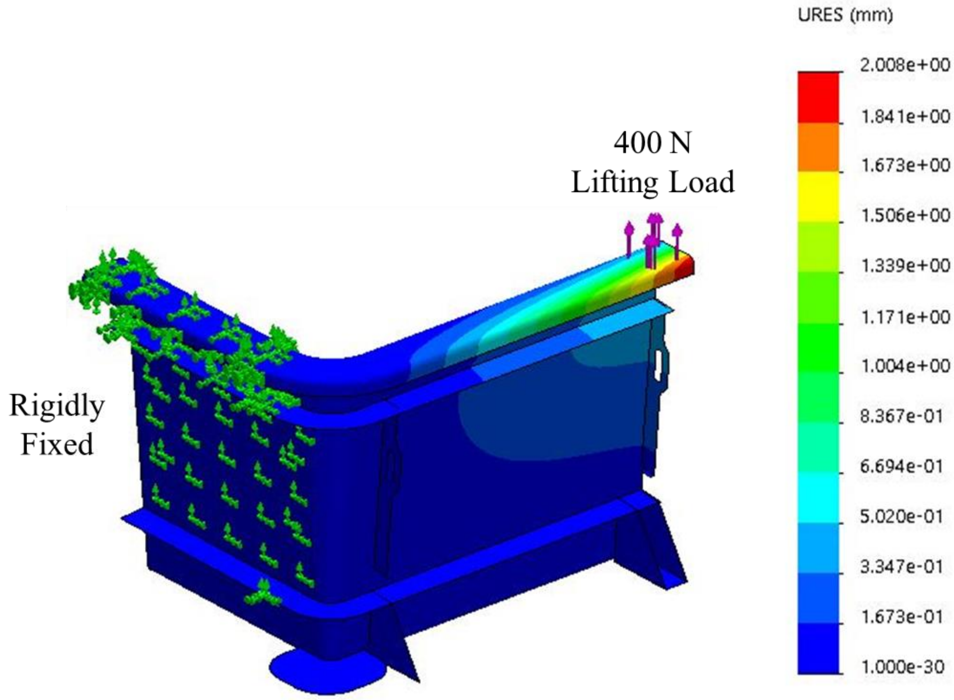


Figure 33. Flange load results

Based on the fact that the study showed deflection was approaching the maximum acceptable value for deflection under this loading condition, an additional gusset was added at the ends of the corner to brace the flange. A visual depiction of this flange as it was modelled in the shell model is shown in Figure 34. The study was re-run with this additional gusset resulting in a deflection of 1.01 mm under identical loading conditions.

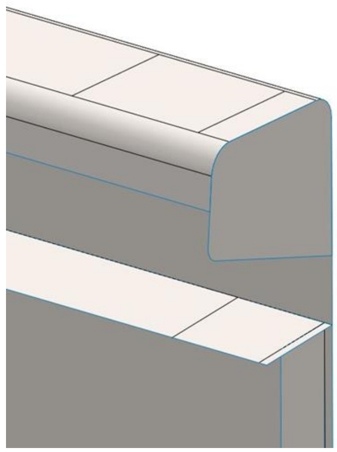


Figure 34. Additional upper gusset

In summary, a gauge 11 sheet metal gusset with a slot that can act as a handle was added to the corner weld assembly in the location shown in Figure 34. This gusset allows SCT technicians to safely manipulate the mold corner from anywhere on the flange without risking deformation.

6.4.7 Adjusted Geometry

The following list summarizes the modifications made to the actual corner weld assembly model as a result of the deflection study. Elements of the solid corner weld assembly that meet the rigidity metric of 2 mm are also shown on the list. Figure 35 visually depicts the changes.

- The sheet metal thickness of 0.1198" (gauge 11 carbon steel) meet the rigidity requirements.
- The mid gussets and handle geometry meet the rigidity requirements.
- The lower support gussets used to secure the weld assembly to the base frame meet the rigidity requirements.
- If an aluminum mold is selected the sheet metal and gusset thickness needs to increase to maintain an acceptable level of rigidity. Suggested modifications are discussed in Section 8.2.
- An overhang was added to the mid-gussets such that upon deflection of the mold, the gussets will be braced by the HSS guide rails. The overhang has a 0.05" clearance to the HSS rail top surface.
- Additional corner gussets are required to meet the desired rigidity. This design change is reflected in Figure 35.
- A method is required for bracing the bottom face of the gussets against the guide rails to simulate the sliding contact fixture shown in Figure 28. This design change is reflected in Figure 35.

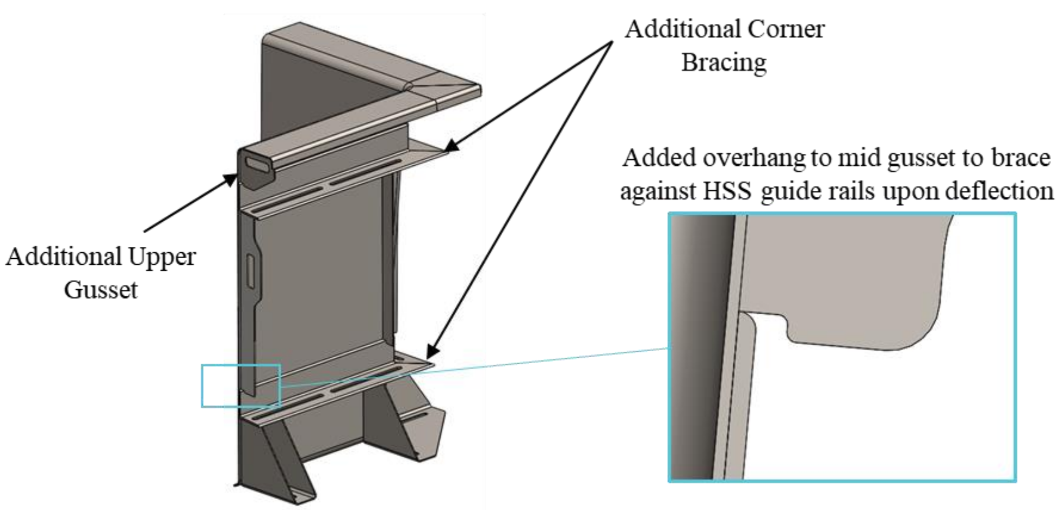


Figure 35. Deflection study adjusted corner weld assembly geometry

6.5 Thermal Expansion Considerations

Outside of deflection due to mechanical loading, thermal expansion of the sheet metal while the resin is curing could cause the sheet metal to warp. This section provides an analysis of this effect with the goal of confirming that thermal expansion is not a risk to the finished T-Pad quality.

The chop-spray process used by SCT requires a low viscosity resin that cures at room temperature. SCT uses a polyester resin system that is heated and dispensed from the chopper gun at about 90°F. The low viscosity spray is able adequately wet the chopped fibers and gel quickly by the time it contacts the mold surface. During the curing process of the resin mixture, and exothermic chemical reaction takes place which results in temperatures up to 250°F.

Given the mold walls are made of aluminum or steel sheet metal, a temperature gradient across the mold walls could result in warping due to linear thermal expansion. To quantify the effects of the exothermic reaction the relative elongation of an insert panel across the panel thickness is evaluated for the maximum gradient associated with peak exotherm. Eq. 6 is used to determine the relative elongation, ΔL for the panel height, L

$$\frac{\Delta L}{L} = \alpha \Delta T \quad \text{Eq. 6}$$

Aluminum has a thermal expansion coefficient, α of 23.6 x 10^{-6}/°C [7] while carbon steel has an α of 14.6 x 10^{-6}/°C [8]. For linear thermal expansion this means that aluminum would expand roughly 1.6 times more than carbon steel for the same temperature difference. The maximum warp occurs during peak exotherm when the temperature is greatest between the mold surface and the shop. Using standard room temperature of 23°C and the maximum temperature of 121°C (250°F) we have a temperature difference of 98°C. The results of this analysis are strains of 0.00141 and 0.00231 that translate to 5 and 8 hundredths of an inch difference in height elongation across the sheet metal panel for steel and aluminum respectively. For a panel of 36” height this minimal difference is not a concern. At the second EDR it was discussed that bowing of the mold walls due to thermal expansion should not exceed ¼”, therefore the mold needed to be designed to account for these effects.

6.6 Numerical Optimization of Top Face Step

This section focuses on the analysis of the 0.1198” step that the Modular Corner weld assemblies will create on the top surface of the finished transformer pads. This step is visually depicted in Figure 36. It was raised as a concern that this step would potentially create stress concentrations on the finished T-Pads. The goal of this study is to show that the stress concentrations created by the step will not compromised the structural integrity of the finished T-Pads.

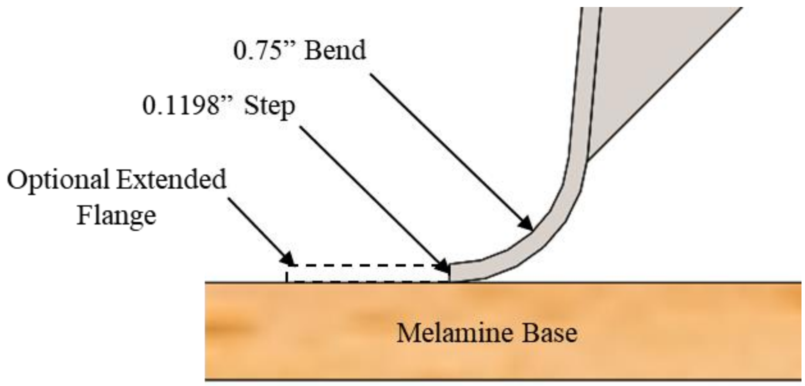


Figure 36. 0.1198" step between the sheet metal and melamine base

It is important to note that this study only aims to prove that the stress at concentrations on the step are comparable to the stress concentrations on the inside corner of the mold. The assumption was made that as the current T-Pads are structurally sound, introduction of the step should not impose higher stress concentrations than what exist on the commodity T-Pads that do not have a step. In other words, this study does not attempt to assess the load at which a finished T-Pad will. Instead, an arbitrary load will be selected and the relative difference of the stress concentrations for various step geometries will be compared against the stress concentrations that would otherwise appear without the step.

The reason a relative difference study is being conducted rather than a study of T-Pads failure due to the large uncertainty associated with numerical loading, fixturing. Additionally, delamination between the chop-spray and plywood layer is not accurately captured by the numerical model.

Both step position and step shape are considered in the study. Initially, the step is defined to have 90° corners and is located right along the outside edge of the top face of the finished T-Pads. The following section covers a list of general assumptions that were made to carry out the study. The maximum Von Mises Stress is referred to as the **(VMS)** throughout this section of the report.

6.6.1 General Assumptions

The following list of assumptions will cover the simplifications made to the geometry and mesh to capture the physical reality of the transformer pads.

- Both the chop-spray and spruce plywood layers are assumed to be isotropic materials. Specifics on the material properties are omitted from this report to maintain client confidentiality.
- It is assumed that a 6’ x 6’ T-Pad is the largest pad that will not have additional 2x8 timber joists. This decision was made to simplify the analysis of the 1/8” step by considering only T-Pad models without the joists.
- The results of this study are assumed to be cross compatible with larger custom T-Pad configurations that do include joists.
- The maximum load on a 6’ x 6’ transformer pad is assumed to be 10,000 kg, this was the arbitrary load defined in Section 6.5 used to conduct the relative comparison study.
- Openings on the top face of the transformer pad were ignored.
- The load applied to the T-Pad top face was assumed to be uniform.
- Contact stresses between the interior and exterior fill surrounding the transformer pad were ignored.
- The buried portion of the mold was assumed to be rigidly fixed and not at risk of failure.

The following section adds further definition to the numerical study by discussing the Software and limitations of the Software used to conduct the study.

6.6.2 Software and Limitations

ANSYS Workbench 19.2 was used to carry out the study. SolidWorks 2019 was used to create the initial geometry. The SolidWorks models were imported into ANSYS as .STEP files. There are two critical limitations that governed the way the study was carried out. They are listed as follows along with an explanation of how they were addressed.

- ANSYS 19.2 Student edition limits the solver to 200,000 nodes – To reduce the impact of this limitation a 2D shell mesh was used to drastically reduce number of nodes required to simulate the geometry. Split lines were added so that mesh refinements could be made in the regions of interest. A convergence study was run to ensure that the placement of these 200,000 nodes was done optimally within the domain and that a reasonable solution was possible.

- The ANSYS mechanical meshing algorithm does not allow control over the mesh growth rate at transitions between mesh size control regions for 2D multi-body models. To reduce the impact of this limitation split lines were manually added to the model so that mesh size control regions could gradually step down the mesh size towards the region of interest.

6.6.3 Geometry, Loads, and Fixtures

After defining the assumptions and limitations for the study, the first step in creating the model was to determine how the T-Pad geometry, loading, and fixtures were translated from real world conditions into a numerical model. The numerical loads and fixtures, along with justification is shown in Figure 37. The geometry used to simulate a 2D cross section of a 6' x 6' T-Pad is shown in Figure 38 on the following page. All dimensions are in inches unless otherwise noted.

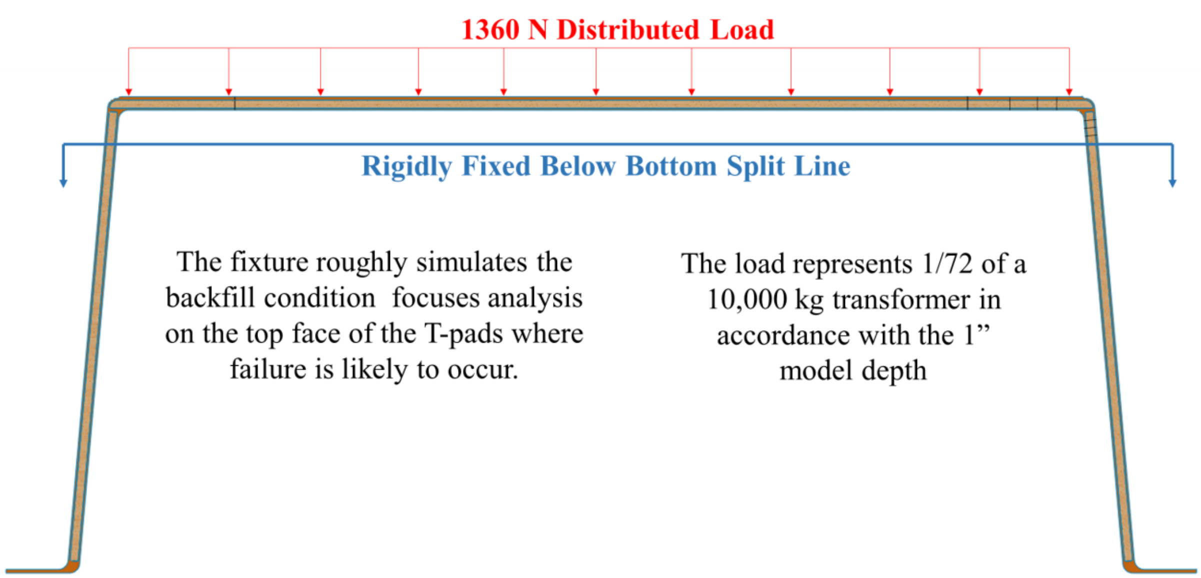


Figure 37. Loads and fixtures

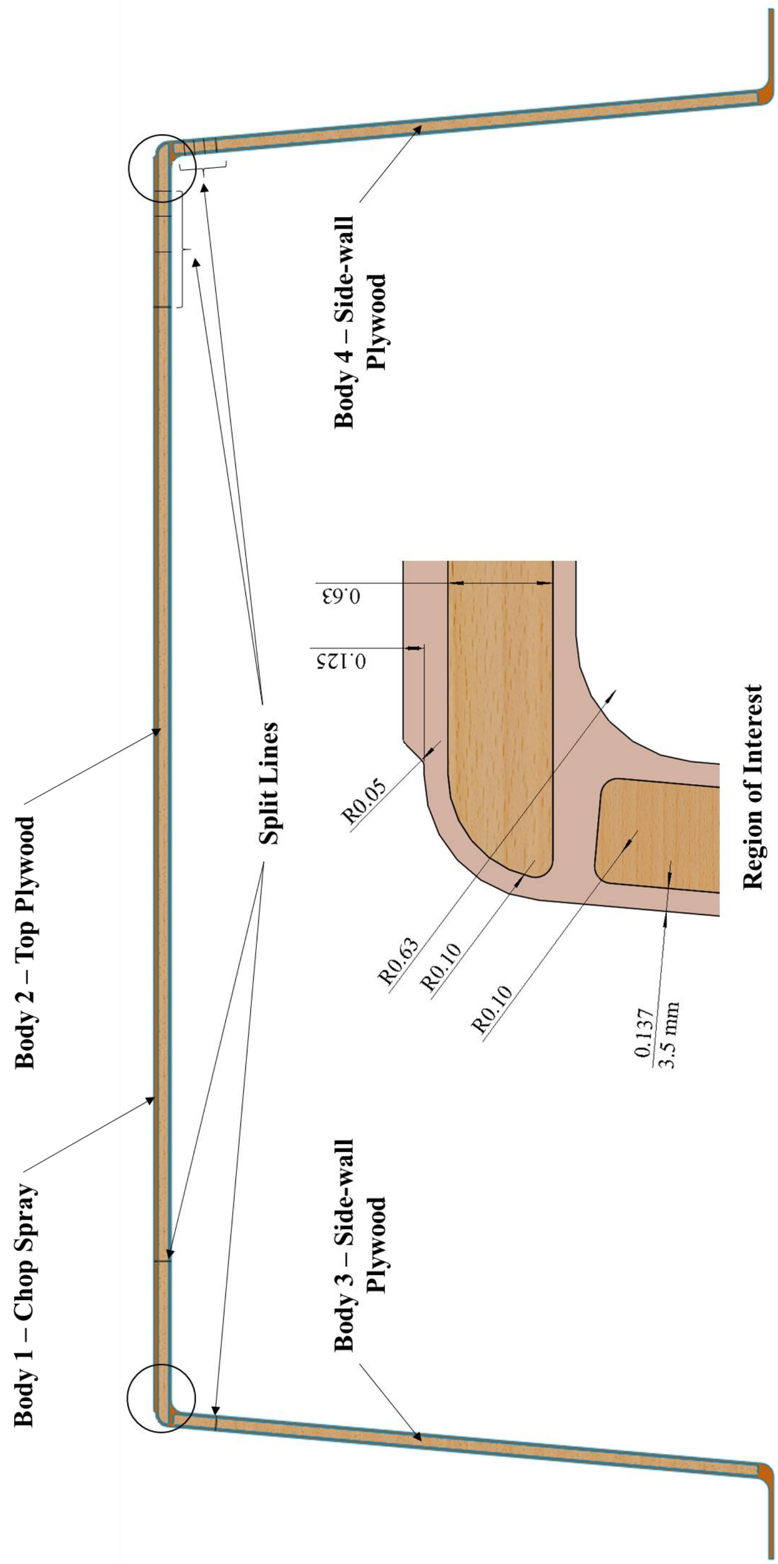


Figure 38. Step and plywood embed geometric assumptions

6.6.4 Mesh

After defining the geometry, loads, and fixtures, development of the shell mesh was the next step towards developing a numerical model.

After defining the geometry, loads, and fixtures, development of the shell mesh was the next step towards developing a numerical model. The following list provides an overview of the final mesh that was used to capture the T-Pad cross section geometry.

- The 2D cross section of the T-Pad was split into 4 independent bodies – one for the top face plywood layer, one for each side-wall plywood layer, and one for the chop-spray that encapsulates the plywood reinforcing.
- Split lines were added across all bodies near the corners to allow for a smaller mesh size to be used. These lines are shown in Figure 38.
- 2D 6-node triangular shell mesh with an element depth of 1" – this depth was used to calculate the model loading. Figure 39. displays a single triangular quadratic shell element.

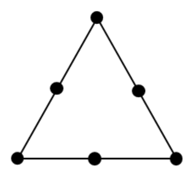


Figure 39. 6-node shell element

- All models used a default 1.75 mm maximum element face length – soft characteristic allowed for smaller geometries to be captured.
- Sizing control was applied to the region of interest – in general the mesh near the corner ranged from 1 mm - 0.125 mm. The smaller elements were used to capture the minimum fillet radius of 1.27 mm.
- Contact sizing was implemented between the 4 bodies such that loads would transfer between the chop-spray and plywood. The potential for delamination between these layers was ignored as it was not the focus of the study and has never been the source of a commodity T-pad failure.
- For mesh size transition regions – the maximum jump between control regions was limited to 400% over two elements. This was discussed in section 6.6.2 as a simulation limitation.
- Defeaturing and 'capture curvature' set such that no geometry was ignored by the meshing algorithm.
- In general, 150,000 – 160,000 nodes were used to capture the complete geometry.

Using the geometry, loads, fixtures and mesh defined in section 6.6.3 and section 6.6.4 the numerical model was build and a convergence study was performed to verify the mesh size. Figure 41 provides a diagram of the final mesh including the mesh size control regions. Further detail related to this figure is provided in section 6.6.5.

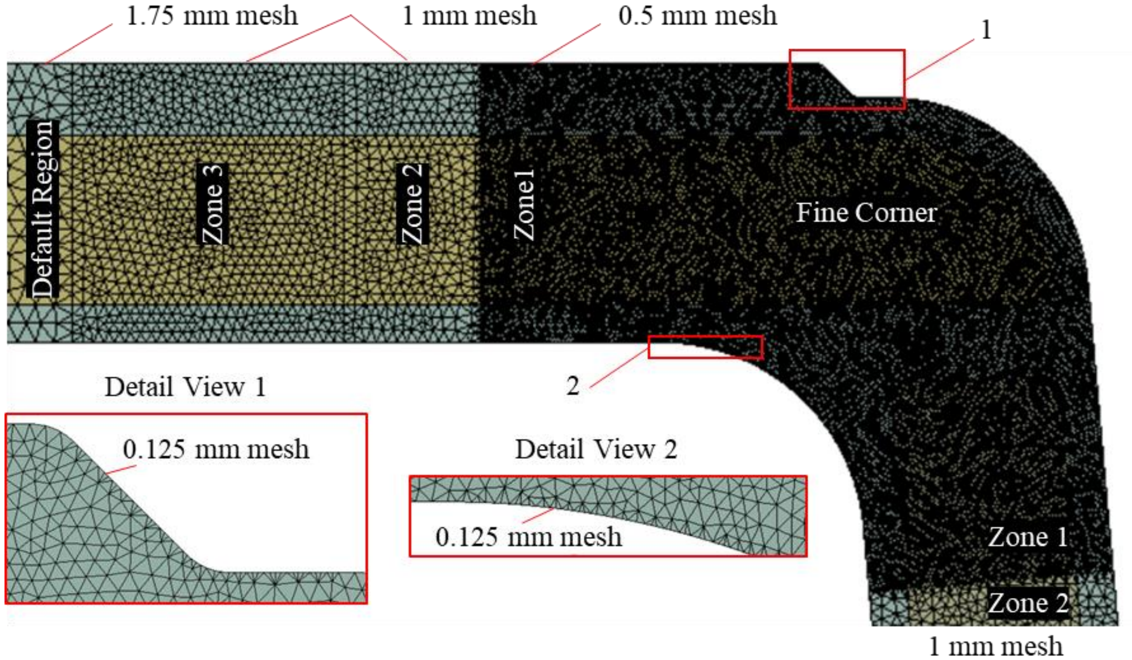


Figure 40. Final mesh diagram

6.6.5 Convergence Study

The convergence study focused on confirming that the stress concentration at the step and on the inside corner of the 2D T-Pad geometry did not change as mesh size was decreased. The goal of this study was to determine the largest mesh size that could repeatably show the location and magnitude of the maximum stress.

Table XXI displays the results of the convergence study run on the mesh prior to making any design decisions. As the total number of nodes remained relatively constant the important trend that was followed to prove convergence was edge mesh size versus the stress at the step and on the inside corner of the T-pads. The maximum stress altered between these two positions. For context, an arbitrary stress contour plot is shown in Figure 41, red elements indicate regions of high stress. A 45° step was used for every run in the convergence study as shown in Figure 42

TABLE XXI: CONVERGENCE STUDY RESULTS

Run	Nodes	Zone 3	Zone 2	Zone 1	Fine Corner Region	Edge
1	129646	1.75	1.75	1	1	1
2	129680	1.75	1.75	1	1	0.5
3	161354	1.75	1.75	1	0.5	0.25
4	155673	1.75	1	0.5	0.5	0.125

Run	Max VMS [Pa]	Max VMS Location	Inside Corner VMS [Pa]	Max Shear Stress [Pa]
1	9.47E+07	Inside Corner	9.47E+07	4.98E+07
2	1.05E+08	Step	9.42E+07	5.32E+07
3	1.09E+08	Inside Corner	1.09E+08	5.52E+07
4	1.11E+08	Step	1.07E+08	5.65E+07

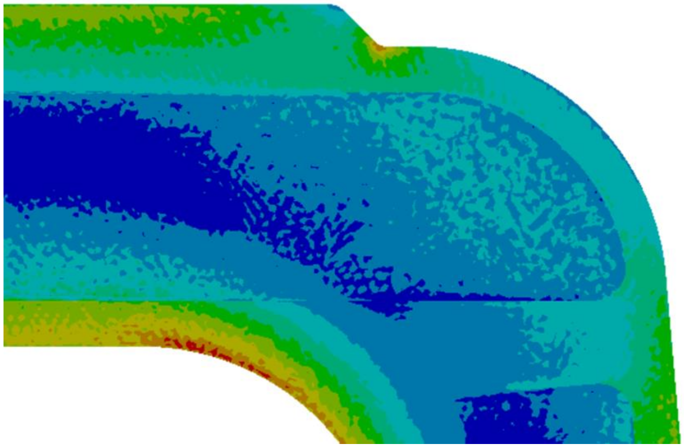


Figure 41. Arbitrary VMS stress distribution in the region of interest

The important takeaway from the convergence study results is that convergence was achieved at the inside corner at Run 3. The location of the maximum stress continued to vary between the step and the inside corner indicating that the mesh was not ideal. The run 4 mesh was determined to give the best possible solution within the software limitations defined in section 6.6.2. This is because using a mesh size smaller than 0.5 mm in the fine corner region pushed the number of nodes over the software limit. Additionally, decreasing the mesh size along the high stress edges pushed the aspect ratio of the elements in this region to an unacceptable extreme due to the growth rate limitation. Thus, the run four mesh size distribution was applied to the remainder of the numerical models described in this section of the report.

6.6.6 Step Geometry Study

To address the different ways that the edge of the sheet metal could be finished and the different angles at which masking tape could be used to smooth out the step transition, six unique step geometries were modelled and compared against each other. Figure 42 shows the six step geometries that were considered. The ‘No Step’ geometry represents a commodity T-Pad. The 30°, 45°, 60°, and 90° geometries represent different masking angles. The last geometry contrasts how filleting the edge of the sheet metal changes the stress concentration when compared to a sharper fillet. It is worth noting that the ‘no step’ condition was treated as a baseline for the results, and that the thickness of the chop-spray layer is reduced from 6.7 mm to 3.5 for this case as no additional material is required to fill the space left by the step.

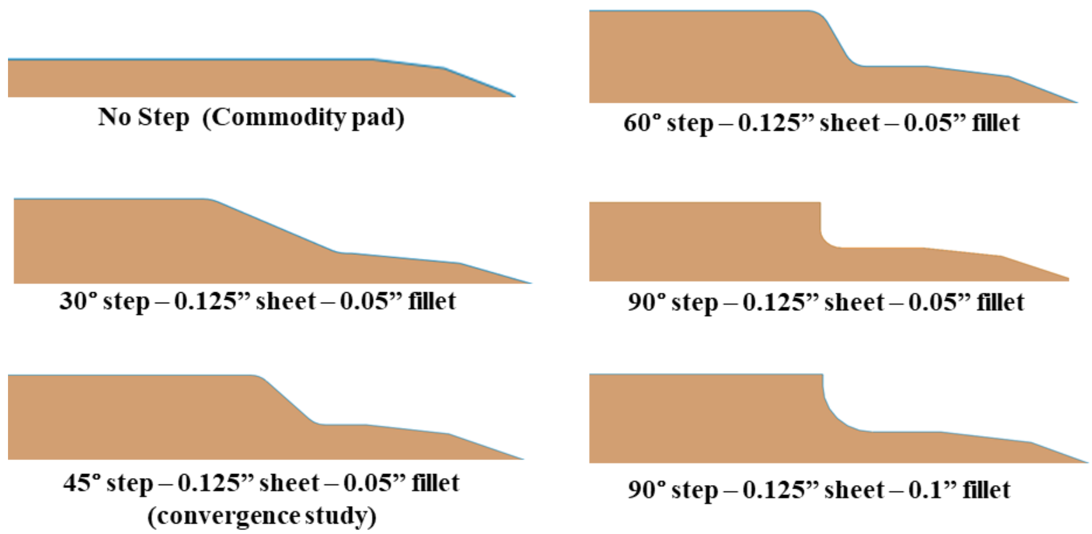


Figure 42. Step study geometries

The results of the step geometry study are displayed in Figure 43 on the following page. The results conclude that the step geometry has no effect on the stress at the inside corner of the T-pads. The only exception to this is the no-step configuration where the overall amount of chop-spray material is reduced, leading to a higher maximum stress.

The 30° - 0.05” fillet case definitively shows that shallower step angles lead to reduced stress concentrations at the step. The 90° - 0.1” fillet case confirms that the same trend can be observed for increased fillet radii. In general, the results of this study show that a rounded edge and shallow slope should be used. It should also be noted that these recommendations are not critical as the maximum stress at the step will be comparable to the stress at the inside corner of the mold.

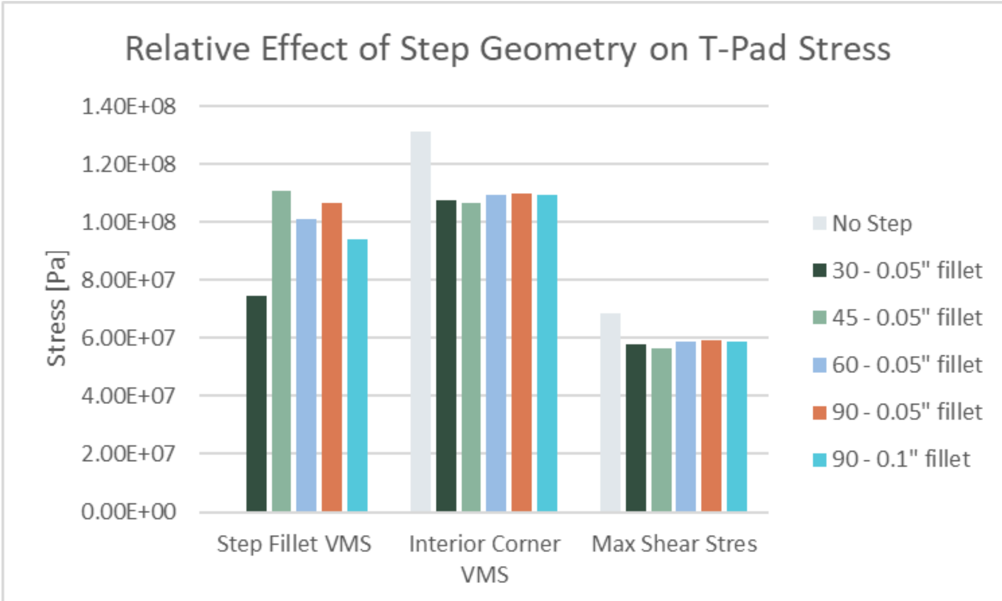


Figure 43. Max. Von Mises Stress and Max. Shear Stress at points of interest

The final recommended step geometry based on this study is a 90° step where the edge of the sheet metal parts is rounded. The 90° is preferred as it is the most repeatable geometry to achieve with masking tape. Specifying a shallow angle would increase assembly time which is an undesired result of this study. If the tape is placed at a shallower angle it will only reduce the stress concentration at the step indicating that selection of a 90° step is a conservative conclusion to this study.

6.6.7 Step Position Study

To address the different flange lengths that are possible with the Modular Corner design a study was conducted that compared different step positions relative to the vertical face of the T-Pads. Figure 44 shows the three insert panel flange geometries that were analyzed. It is worth noting that the 'no flange' case is SCT's preference and the default geometry. The 1360N load was applied over a reduced area for the 2" and 4" flange configurations due to the notion that large transformers may overhang the step if it is pushed inwards.

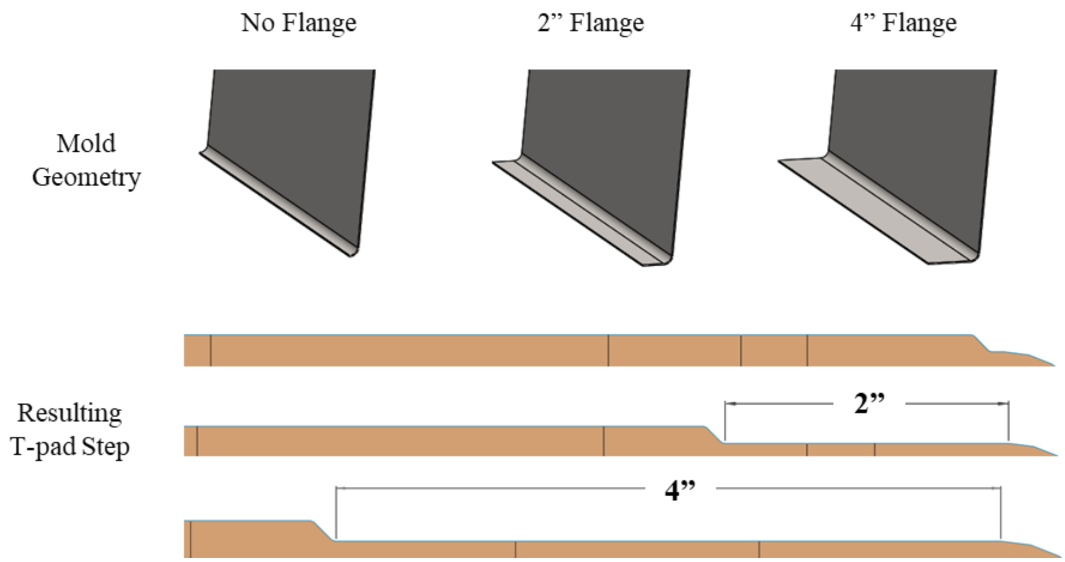


Figure 44. Step position study geometries

The results of the study are displayed on the bar chart shown in Figure 45. The trends demonstrated that as flange length increases, the stress at the step decreases while the stress on the inside corner increases. The increasing stress at the inside corner can be explained by the increasing moment load imposed by the 1360 N being offset from the corner. The conclusion of this study is that the maximum VMS is minimized for the no-flange configuration even though this configuration yields the highest stress at the step. Thus, the no-flange configuration will be carried forward for the rest of the design.

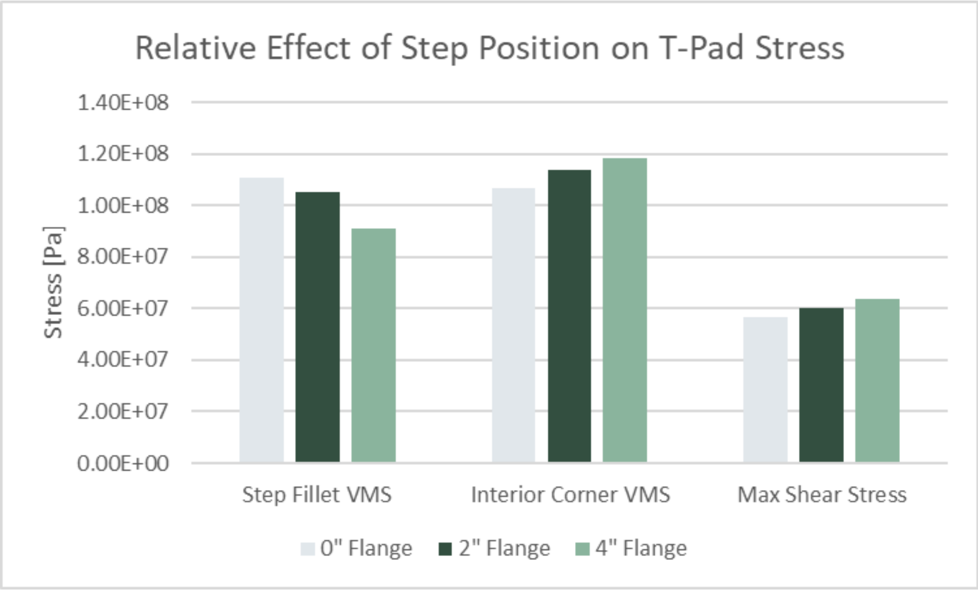


Figure 45. Relative effect of step position on T-Pad VMS

6.6.8 Conclusion

It is understood that modification to the mold edge will be done by hand with a grinder tool, or will be taped over to create a tapered edge. Due to the imprecise nature of these methods a general recommendation was made for the mold step geometry rather than specific dimensions. This geometry is shown in Figure 46. In general the edge should be rounded as much as possible with a grinder, masking tape should be applied to create as shallow of an angle as possible, however, a 90° angle is acceptable. Sharp geometries should be sanded out of the step after the T-Pad is released from the mold to ensure optimum performance of the custom pads.

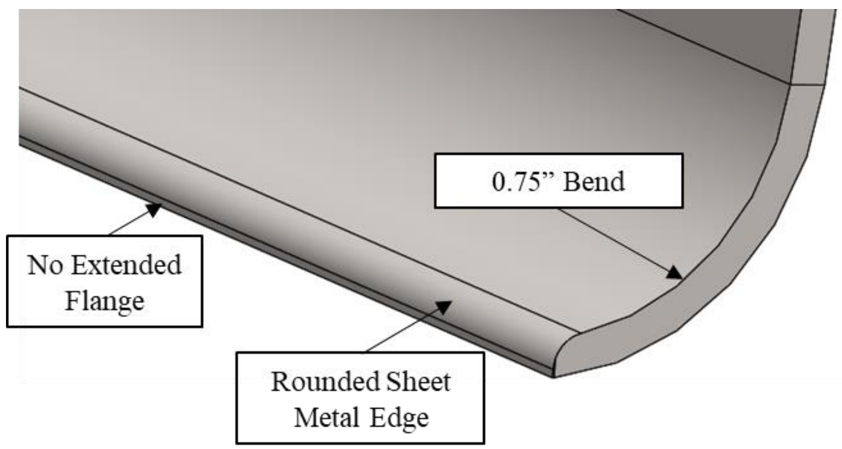


Figure 46. Final mold edge geometry

6.7 Assembly Time and Ergonomics Optimization

The goal of this section is to assess the time that it takes to assemble the adjustable mold to the point where the remainder of the process is identical to that of the existing commodity pads. The ways in which the mold corners can be carried are also addressed. Based on this assessment, cost effective modifications to the mold geometry were made to either reduce assembly time or improve the overall ergonomics of the mold. The following list identifies the steps that are required to assemble the mold into the largest size configuration once the required mold size is known, and base plate is set up on production floor. Appendix C includes detailed assembly instructions and illustrations for all configurable sizes and is intended to be a document for shop technicians to follow when assembling the mold.

1. ***Mobilization of Mold Corners and Insert Panels (Estimated 10-20 minutes)*** – Two people carry and place each of the four corner sections on the melamine base plate. The required insert panels are brought to the mold assembly area.
2. ***Set up of the Guide Rails (Estimated 10-20 minutes)*** – The HSS guide rails are carried and placed by 1-2 people on the angled supports of the corner sections. This is repeated all four corners of the mold are assembled together providing the overall mold outline. The HSS guide rails are clamped, pinned or bolted securely in place. If the guide rails used are longer than the sides of the mold, they need to be placed such that only one end of the guide rail protrudes out so that the guide rails do not interfere with each other.
3. ***Insert Panel Installation (Estimated 15-30 minutes)*** – Insert panels are added one by one in both the length and width directions, starting from the corner section placed. One wall is left open as long as possible for access. Once an insert panel is in place with minimal gaps in between sections, the insert panel are clamped, pinned or bolted securely in place using the guide rails and adjacent gussets. Each insert panel should be placed tightly against each other while maintaining as straight of a line as possible. After this step is complete three of the four walls are constructed.
4. ***Final Wall Insert Panel Installation (Estimated 5-10 minutes)*** – The remaining insert panels for the last wall are put inside the mold. The same procedure is followed as is defined in step 3.
5. ***Adjustment of Mold Alignment (Estimated 10-20 minutes)*** **–** The mold size is measured, and the adjacent walls are checked such that they are square with each other. Minor adjustments are made, and the corners are bolted or clamped down to hold the shape of the mold during the gel coat and chop-spray process.
6. ***Seam Taping (Estimated 10-15 minutes)*** **-** A bench or step ladder is used to gain access to the inside of the mold where all seams are covered with masking tape or waxed to improve the exterior surface finish of the final product. After this is complete, the fabrication process, including the addition of reinforcing lumber, is the same as for the commodity pad molds.

The total assembly time before any optimization features were implemented was estimated to range from 60-115 minutes, depending ease of alignment, ease of access to stored components, and speed of the technicians. To improve the efficiency of the assembly procedure, three cost effective modifications to the geometry of the corner sections and insert panels were made. The assembly time optimization features are listed and described in Table XXII with an estimation of the impact on assembly time.

TABLE XXII: ASSEMBLY TIME OPTIMIZATION FEATURES

Assembly Time Optimization Feature	Description of Benefit	Expected Effect
Addition of dual handle flange on corner sections	Improved ergonomics allowing workers to carry the corner sections more effectively.	5-minute reduction in mold mobilization
Addition of holes in the gussets for corner sections and insert panels	Reduction in overall weight of corner sections and insert panels by 3 lbm. The holes can also act as a handle for manipulating the insert panels.	Allows 2 people to carry panels rather than 3
The thickness of the angles was reduced from ¼" to 3/16"	Reduction in overall weight of the corner sections by 7 lbm.	Allows 2 people to carry panels rather than 3
Reducing corner dimensions from 2'x3' to 1.5'x1.5'	Significant reduction in the overall weight of corner sections. If corners are made from carbon steel, weight is decreased from 140 lbm (after angle thickness modification and bottom gusset modification) to 101 lbm.	Allows 2 people to carry panels rather than 3

From Table XXII, it is seen that the optimization features are estimated to reduce to the assembly time by approximately 5 minutes and reduced the weight of the heaviest component to 100 lbm rather than 150 lbm. The adjusted version of the corner weld assembly is visually depicted in Figure 47.

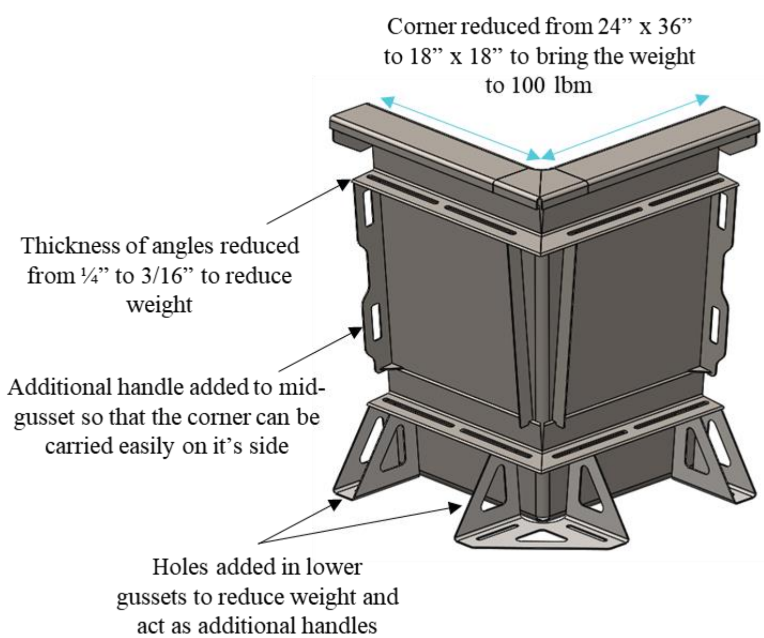


Figure 47. Assembly and ergonomics optimized corner weld assembly

The total assembly time after the optimization features were implemented is now estimated to be 55-110 minutes. Although this isn't a substantial change, the main benefit in looking at assembly time and ergonomics was improving the number of options technicians have for grabbing, transporting, and making small adjustments to the mold positioning. Additionally, the individual component weight metric of 100 lbm is now met. The one drawback to decreasing the size of the corner weld assemblies is that an additional 48" insert panel is now required for the larger mold configurations. This change will be reflected in the final BOM and engineering drawings.

In conclusion the U of M Team is confident that the final version of the Modular Corner design meets the assembly time and ergonomics metrics that were set out at the start of the project. The following section provides an estimated cost for the optimized Modular Corner design.

6.8 Cost Analysis

To compose a cost estimate for the final design the U of M Team obtained budget quotations from Taj Industrial. The drawings sent to Taj Industrial for quotation were based on the design at its state immediately after the second EDR as shown in Figure 17. As a series of modifications were made to the assembly during detailed design development, the costs presented in this section have an associated error of +/- 20%.

Taj supplied quotes for stainless steel and carbon steel alloys that were the most economical, suitable for welding, and suitable for bending. Alloy selection was left to the fabricator as there were no restrictions on the specific alloys that needed to be incorporated into the design. The following values do not include costs relating to the composition of the shop fabrication drawing, taxes, or material freight. The formal quotations can be found in Appendix D. A summary of the stainless steel and carbon steel quotes provided by Taj Industrial, including the specified alloys is shown Table XXIII.

TABLE XXIII: BUDGET QUOTATION AND SELECTED MATERIALS

Quotation	Stainless Steel	Carbon Steel
Plate Material	Gauge 11, stainless 304	Gauge 11, A1011
HSS Tubing	SS304	A500C
Angles	SS304	44W
Quote (CAD$)	**$12,435.00**	**$8,543.00**
(Quote+20%) with 12% Sales Tax	**$16,712.64**	**$11,481.80**

The quotation for carbon steel met the target budget of CAD$ 10,000, while a stainless steel mold is within the marginally acceptable budget of CAD$ 25,000. In addition to the cost of custom metal fabrication, the cost of standard fasteners must be included. SCT indicated that it was unnecessary for the

U of M Team to include clamps or products related to mold use or maintenance. Included in this quotation is the price for 100-½" UNC zinc-plated hex-head bolts and accompanying hex nuts priced at CAD$ 184 [9] and $16.58 [10] from McMaster Carr. This brings the total cost for the stainless and carbon steel molds to $12,635.58 and $8,743.58, respectively.

The remainder of this section models two economic scenarios to generate potential payback periods for the carbon and stainless-steel molds at the quoted price plus 20% and taxes. Historical sales data was used to obtain the average sales price, material, labor costs and hours for a custom mold to calculate the net annual profit. Further details on this economic model are presented in Appendix D. Current net annual profit was compared against net annual profits for conservative and optimistic economic scenarios. The cost of the mold was divided by this difference in annual profit to determine the payback period of the quoted values (+20%) from Taj Industrial. Descriptions of the economic scenario are as follows:

Conservative – the adjustable mold reduces the material costs by 15% and average labor hours are reduced from 11.3 to 2 hours. The sales price of the mold and the sales volume remain the same

Optimistic – the adjustable mold reduces the material costs by 15% and average labor hours are reduced from 11.3 hours to 2 hours. The sales price of the mold is priced 20% lower than previously, and competitive pricing increases the sales volume from 7 to 10 units per year.

A comparison of the results is shown in Table XXIV. For both scenarios, it is assumed the mold reduces the raw materials and their cost by 15%

TABLE XXIV: PAYBACK PERIODS OF CONSERVATIVE AND OPTIMISTIC SCENARIOS

Payback Period (years)		
Economic Scenario	**Conservative**	**Optimistic**
Stainless Steel	5.4	2.7
Carbon Steel	3.7	1.6

If SCT does not see an increase in custom orders of T-Pads the cost of the mold is recovered in 5.4 years for the stainless-steel design and 3.7 years for the carbon steel mold. Alternatively, if SCT sees an increase in custom orders from 7 to 10 units per year due to the increased quality, shortened lead time and reduced cost of the custom T-pads significantly shorter payback periods of 2.7 years and 1.6 years are possible. Regardless of material or if a conservative or optimistic approach is taken to the economic analysis of the mold, the design meets the marginally acceptable budget of CAD$ 25,000.

7 DETAILED DESIGN SUMMARY

This section of the report presents an overview of the final version of the size adjustable mold proposed by the U of M Team. First, an overview of final design including a render of the final concept is provided. Next, specific design features is provided with more detail about the final concept. Description of the features is followed by a detailed Bill of Materials **(BOM)** describing all of the sub-assemblies and parts related to the final design.

7.1 Overview of the Final Design

The final mold is a carbon steel assembly consisting of modular corners, various sizes of insert panels and perforated HSS guide rails. Figure 48 on the following page shows a render of the final assembly. The U of M Team's final recommendation is to fabricate the mold out of carbon steel as it is the least expensive option. However, stainless steel and aluminum are also viable options and would improve the molds resistance to corrosion. An aluminum mold would require further analysis to prove that it would be rigid enough. The stainless-steel mold has the highest associated cost at a value of CAD$ 12,435, the carbon steel mold is less expensive at a cost of CAD$ 8,543. Although a quote was not provided by Taj Industrial the cost for an aluminum mold is expected to fall somewhere between these values.

The entire assembly rests on a mobile melamine base that will be provided by SCT. The base frame will likely comprise of a melamine surface with a rigid support structure. The design is assembled by placing four of the corner weld assemblies on the base frame. Guide rails are then used to align and secure the four corners together before insert panels are aligned on the guide rails to construct the mold walls. To allow flexibility in the way that the mold is assembled, the mold components are compatible with bolts, pins, and clamps to secure the guide rails and insert panels in place.

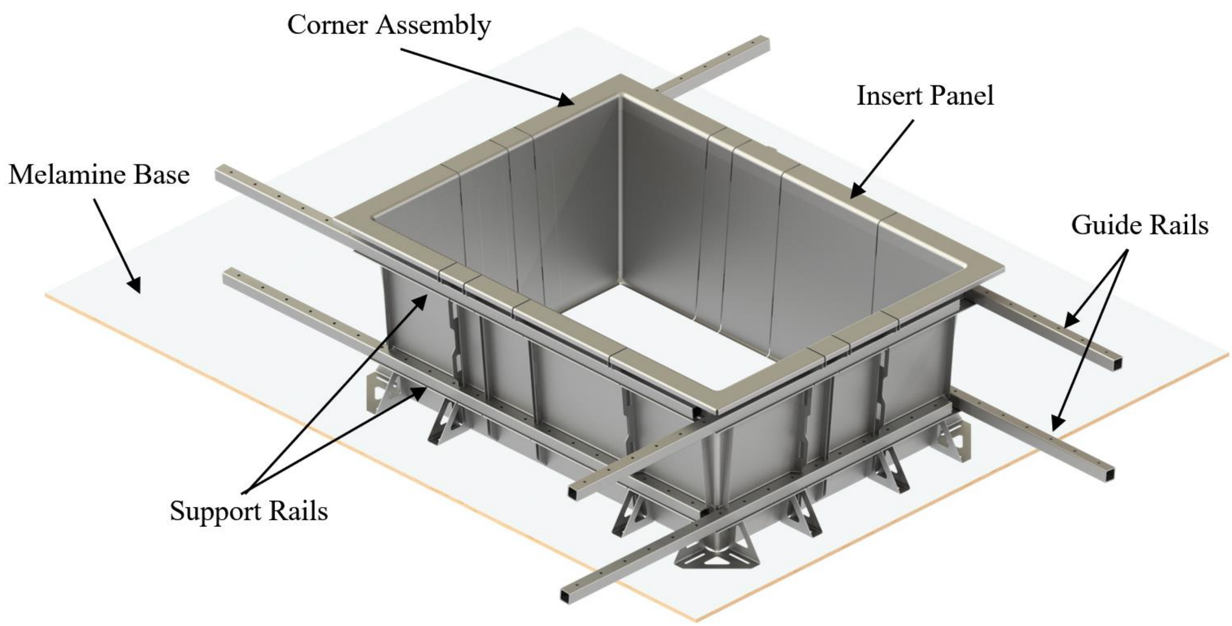


Figure 48. Fully assembled adjustable mold in an intermediate size configuration

The mold depicted in Figure 48 can be used to produce 110 unique sizes of FRP T-Pads ranging from 3 ft x 3 ft up to 10 ft x 8 ft (L x W). The length and width dimensions are adjustable in 6” increments between the minimum and maximum sizes. It is worth noting that the modularity of the design allows additional insert panels to be fabricated and longer guide rails to be purchased if SCT wants to use the mold for larger T-Pads in the future. Additionally, smaller 3” or 4” insert panels could be fabricated to achieve discrete sizes in increments less than 6”.

As illustrated in Figure 49, the size of the mold depends on the quantity and size of insert panels installed onto the guide rails. To accommodate the range of mold sizes available, four of each insert panel size are required. The available sizes of insert panels specified with the final design are 6”, 12”, 24” and 48”. The panels can be fabricated as SCT requires them to cut down the initial cost of the mold. However, it would be beneficial to have all the insert panels fabricated at once to allow the fabricator to align each of the panels such that they are all compatible.

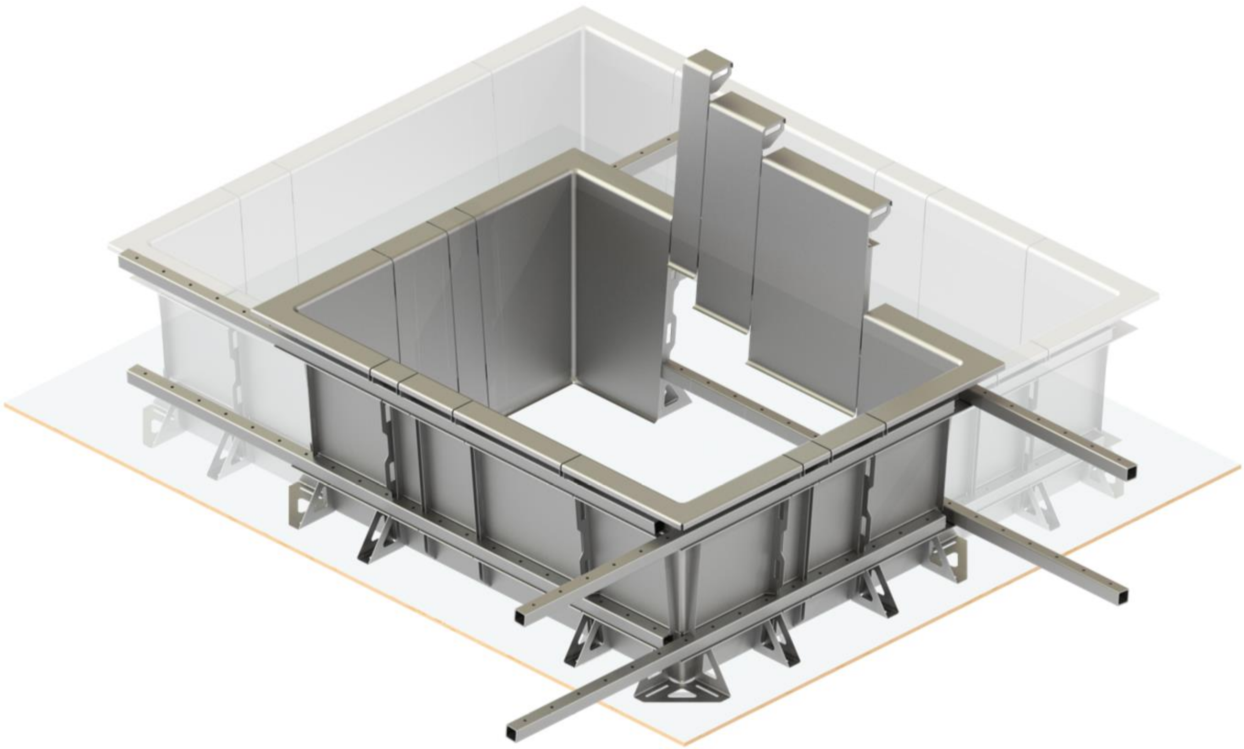


Figure 49. Illustration showing the size adjustability of the mold

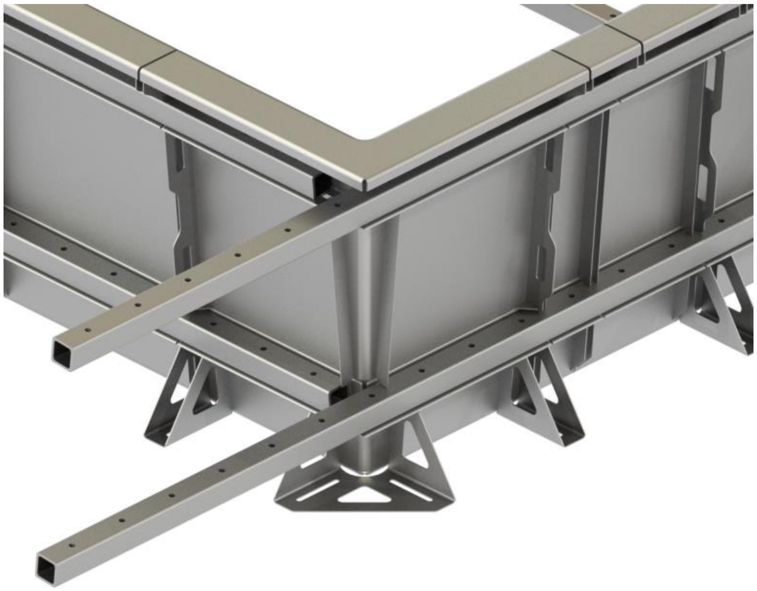
Once the adjustable mold is setup in the desired configuration, masking tape is applied to the seams between individual panels and corners as well as at the step between the walls and base plate. The process that follows is similar to that followed by SCT for commodity molds, a release wax is applied to the mold surface followed by a gel coat. Immediately after, the mold is moved to the area where the FRP is applied. The previous step is crucial to avoid cracking of the gel coat due to minor shifts in the assembly during transport and is unique to the adjustable mold. The final design incorporates locations where the corners can be clamped to the base frame to help avoid this issue. The next steps include application of the outer layer of FRP, placement of the wood reinforcements, and application of the encapsulation layer of FRP.

The mold utilizes the same demolding process that SCT uses for their commodity molds, where lugs are placed around the edge flange and lifted with a crane. In the event that SCT has issues with the traditional demolding process, the adjustable mold allows for the mechanical release of the finished T-pad by removing the insert panels and sliding out the corners. Appendix C includes detailed assembly instructions and illustrations for all configurable sizes and is intended to be a document for shop technicians to follow when assembling the mold.

Using the adjustable mold, SCTs custom FRP T-Pads achieves a comparable surface finish and equivalent production quality to commodity FRP T-Pads. This process also reduces the excess material used to encapsulate a plywood core required by SCTs previous custom T-Pad fabrication process and avoids the longer production times by eliminating the need for carpentry resources to create the plywood core. Table XXV provides further details into the features present on the corners, insert panels and guide rails that contribute to the functionality of the overall design.

TABLE XXV: SUMMARY OF FINAL DESIGN FEATURES

Insert Panels (12" Shown)	
	**Description of Features** • Low profile gussets provide support and rigidity to the corners while allowing the panels to be stacked for storage. • The gussets also facilitate clamping or bolting the panels together if additional thru holes are added after the mold is fabricated. • Handles on the upper gusset allow for ergonomic transport and manipulation of the panels.
Modular Corners	
	**Description of Features** • The upper gussets and dual handle mid-gussets provide rigidity and allow ergonomic manipulation of the corner assemblies. • U-shaped gussets at the bottom of the weld assembly allow the corners to stand on their own, provide rigidity to the lower section of the sheet metal, and facilitate securing the corners to the base frame by using clamps or bolts. • Sheet metal fabrication allows for a smooth corner radius and flange after fabrication

<table>
<tr><th colspan="2">Guide Rails</th></tr>
<tr><td rowspan="2"></td><td>Description of Features</td></tr>
<tr><td>Two rows of guide rails add rigidity to the overall assembly and provide alignment at the top and bottom of the insert panels.
Holes spaced at 6” intervals allow the mold to be sized using the bolt holes if it is found to be a more convenient option.</td></tr>
<tr><th colspan="2">Slotted Support Rails</th></tr>
<tr><td rowspan="2"></td><td>Description of Features</td></tr>
<tr><td>The structural angles on the back of the insert panels and corner weld assemblies are slotted to facilitate the use of bolts, pins, or clamps to secure the guide rails.</td></tr>
</table>

The corner and insert panel weld assemblies are made up of bent sheet metal for the mold wall faces and structural waterjet plates that are welded to the sheet metal. Standard structural angle members make up the support rails with slots water jet into the pieces for securing the corner and insert panel assemblies to the guide rails. Guide rails are made from standard 2.5” x 2.5” x ¼” wall HSS members. Engineering drawings sent to Taj industrial show details on exact dimensions and fabrication notes for the adjustable mold and can be found in Appendix B. The following section provides a detailed account of all the sub-assemblies and parts that make up the complete assembly and is presented in the form of a BOM.

7.2 Bill of Materials

This section presents the final BOM for a carbon steel version of the final design. The complete BOM is displayed in Table XXVI. The cells in light green are the sub-assemblies and parts that make up the complete assembly. The cells in white and grey are the parts that make up the subassemblies.

The total required quantity for each subassemblies and part is listed beside each item. The part quantity is obtained by multiplying by the number of parts required to fabricate each sub assembly by the total number of required sub-assemblies. Part numbers that incorporate an A, B, C, or D indicate different lengths of parts with an identical cross-section.

TABLE XXVI: BILL OF MATERIALS FOR FINAL DESIGN

Part No.	Description	Material	Qty.
0009	**Corner Weld Assembly**	**-**	**4**
0001	Corner Assembly Sheet Metal Cover	A1011	1
0002	Corner Handle Brace	A1011	2
0003	Top Gusset	A1011	2
0004	2-Handle Corner Gusset	A1011	2
0005	Plain Mid Gusset	A1011	2
0006	Bottom U-Gusset	A1011	2
0007	Bottom Corner Gusset	A1011	1
0008A	URH Corner - 3x3 Structural Angle	44W	1
0008B	ULH Corner - 3x3 Structural Angle	44W	1
0008C	LRH Corner - 3x3 Structural Angle	44W	1
0008D	LLH Corner - 3x3 Structural Angle	44W	1
0016A	Top Flange Insert	A1011	1
0016B	Top Flange Insert - Mirrored	A1011	1
0013A	**6" Insert Panel Assembly**	**-**	**4**
0003	Top Gusset	A1011	2
0005	Plain Mid Gusset	A1011	2
0011	Insert Panel Lower Gusset	A1011	2
0010A	6" Insert Panel Sheet	A1011	1
0014A	6" 3x3 Structural Angle	44W	2
0013B	**12" Insert Panel Assembly**	**-**	**4**
0003	Top Gusset	A1011	2
0005	Plain Mid Gusset	A1011	2
0011	Insert Panel Lower Gusset	A1011	2
0010B	12" Insert Panel Sheet	A1011	1
0014B	12" 3x3 Structural Angle	44W	2

Part No.	Description	Material	Qty.
0013C	**24" Insert Panel Assembly**	**-**	**4**
0003	Top Gusset	A1011	2
0005	Plain Mid Gusset	A1011	2
0011	Insert Panel Lower Gusset	A1011	2
0010C	24" Insert Panel Sheet	A1011	1
0014C	24" 3x3 Structural Angle	44W	2
0013D	**48" Insert Panel Assembly**	**-**	**4**
0003	Top Gusset	A1011	2
0005	Plain Mid Gusset	A1011	2
0011	Insert Panel Lower Gusset	A1011	2
0010D	48" Insert Panel Sheet	A1011	1
0014D	48" 3x3 Structural Angle	44W	2
0014A	**96" Guide Rail**	**A500C**	**4**
0014B	**120" Guide Rail**	**A500C**	**4**

From Table XXVI, it is seen the mold is made from three different types of carbon steel which are A1011, A500C and 44W. These steels were chosen by Taj Industrial who provided the quote for the carbon steel mold. A1101 was selected as the material for making the bent sheet metal and gusset parts while A500C was chosen for HSS parts, and 44W was chosen for structural angle parts. The next section concludes the report, describing how the final design meets the project metrics, and recommendations for future work.

8 CONCLUSION

SCT commissioned the design of a size adjustable mold to improve their existing custom size T-Pad fabrication process. For the design to accommodate SCTs custom orders, the mold needed to be adjustable in 4-6" increments and allow for various configurations of wood reinforcements to be incorporated into the finished T-Pads. The mold size range requested by SCT was 5' x 5' up to 8' x 10', with a height of 36". An optional design scope was suggested to accommodate 42" tall T-Pads with the same mold concept but was identified as non-critical.

Regarding assembly time, SCT required the mold to be assembled by two technicians in two hours. This assembly time was selected to reduce the custom T-Pad frame fabrication time of approximately 8 hours to a more cost-efficient value. For two technicians to be capable of setting up the mold, the components either needed to be set on caster wheels or weigh less than 100 lbm to be lifted by hand.

An economic analysis was conducted based on sales data for custom T-Pads provided by SCT. The analysis resulted in a target budget of $10,000, with values up to $25,000 being acceptable. A successful design would be fabricated using metal, wood or fiberglass and have a lifespan of 10 years with less than 15 minutes of maintenance between uses. A series of more specific metrics were produced through discussion with SCT and are described in Table XXVII. Project deliverables included submission of a SolidWorks Model, engineering drawings, operation, instructions, a BOM, and a final design report to SCT.

The remainder of this section will discuss how the final design met the client needs. The proposed design is a size adjustable female mold that consists of custom carbon steel modular corners and panels that form configurations ranging from 3'x 3' ft to 8 x 10 ft (L x W) where dimensions can be adjusted in 6" increments. The mold has a fixed height of 36". A 42" variant of the mold could be produced by SCT if it was it as economically advantageous. The modular design has a maximum individual component weight of 100 lbm indicating that every component could be carried by two technicians and quickly assembled on any flat surface. The U of M Team estimated the mold setup can be completed within 55-110 minutes depending on the size of the mold. Assembly steps consist of platform setup followed by placement of the corner pieces, securing the guiderails, securing the inert panels, and application of tape to cover the seams.

The design is compatible with a variety of fasteners including bolts, pins and clamps to secure the assembly and accommodate manufacturing tolerances. A fastener size of ½" was selected based on SCT's common tool set. Selection of carbon steel as the mold material results in a durable, low maintenance design with an expected lifespan over 10 years, but with periodic maintenance to address corrosion. The proposed design is within budget with the costs for a carbon steel mold being CAD$ 8,744 +/- 20% without sales tax. This results in a conservative payback period of approximately 3.7 years if SCTs volume of business remains constant. Components of the assembly were designed with storage in mind, thus are roughly stackable and should be easily stored indoors.

In conclusion, the U of M Team successfully designed a size adjustable mold that reduces the excess material and production time associated with SCTs current fabrication process for custom sized T-Pads. The fact that the final design is a female mold allows for complete customization of the wood reinforcing and ensures that the custom T-Pads can be produced with a similar quality surface finish to the commodity T-Pads. As a result of the improved process, we expect SCT will be able to price custom orders competitively and increase their volume of business.

8.1 Final Specifications

This section summarizes how the final mold design meets the 23 specified design metrics. Table XXVII provides detailed values and descriptions for the ideal, marginal, and actual value of each metric. To summarize the table, it is shown that the final design meets every metric. Several metrics are dependent on decisions made by SCT after submittal of the final design. Most notably maintenance, expected life, and corrosion resistance are dependent on material selection.

TABLE XXVII: FINAL DESIGN METRICS

Metric #	Metric	Metric value
1	Average Assembly Time	**Ideal:** 30 minutes
		Marginal: 120 minutes
		Actual: 55-110 minutes
2	Safety	**Ideal:** None - pinch points and sharp edges minimized
		Marginal: Sharp edges minimized
		Actual: SCT is satisfied with the apparent safety of the final design.
3	Strength	**Ideal:** Does not fail under any normal loading conditions, supports a person standing in the center of the mold.
		Marginal: Does not fail under any normal loading conditions, supports a person standing in the center of the mold with additional bracing.
		Actual: Structurally sound under every identified normal loading condition, SCT to provide base frame design.
4	Capital Cost	**Ideal:** CAD$ 10,000
		Marginal: CAD$ 25,000
		Actual: CAD$ 11,482 - CAD$ 16,713
5	Corrosion Resistance	**Ideal:** No corrosion indoors, outdoors, or from chemicals
		Marginal: No corrosion indoors or from chemicals
		Actual: Material dependent - carbon steel will require corrosion inhibitors and maintenance to remain rust free. Stainless steel and aluminum are preferred options for corrosion.

6	Part Removal	**Ideal:** 5-degree draft angle + integrated removal method
		Marginal: 5-degree draft angle
		Actual: 5-degree draft angle and movable corners for part release
7	Customizable Reinforcing	**Ideal:** Complete customizability of wood reinforcing.
		Marginal: Restricted customizability of wood reinforcing.
		Actual: Complete customizability of wood reinforcing as a female mold concept was selected as the final design.
8	Aesthetic/Finish of T-pads	**Ideal:** Identical to commodity T-Pads.
		Marginal: Better than the current custom transformer pads fabricated using a wood frame coated in FRP.
		Actual: Like commodity T-Pads with additional seams.
9	Re-usability (life cycle)	**Ideal:** 10 units/year for 10 years
		Marginal: 10 units/year for 5 years
		Actual: Dependent on storage conditions, and how the mold is maintained. If properly maintained, the metal mold components could last indefinitely. As such, the mold meets the ideal value.
10	Maintenance	**Ideal:** 5 minutes per use
		Marginal: 15 minutes per use
		Actual: Dependent on material selection as preventing and cleaning oxidation from a carbon steel mold is more time consuming.
11	Temperature Resistance	**Ideal:** 250F
		Marginal: 250F
		Actual: Carbon steel is the least resistant to degradation due to temperature and performs at a similar level up to 900F [11].
12	Depth-Width	**Ideal:** 5' to 10' in both directions
		Marginal: 5' to 8' in both directions
		Actual: 3' to 10' in one direction and 3' to 8' in the adjacent direction. If longer guide rails and more insert panels are fabricated the mold could theoretically produce 20' x 20' T-Pads. Further analysis would need to be conducted to confirm the rigidity of a configuration this large.

13	Accessibility (height)	**Ideal:** 40" top flange height from floor
		Marginal: 50" top flange height from floor
		Actual: 36" + the height of the base frame that SCT provides
14	Seams	**Ideal:** No seams
		Marginal: Seams do not restrict release
		Actual: Many seams running vertically along the side walls of the finished T-Pad that will not impact mold release.
15	Max Assembly Weight	**Ideal:** < 1500 lbm
		Marginal: < 3750 lbm
		Actual: 1524 lbm for the 8' x10' configuration + the weight of the base frame and 952 lbm for the 3' x 3' configuration + the weight of the base frame.
16	Individual Component Weight	**Ideal:** < 50 lbm
		Marginal: < 100 lbm
		Actual: 100 lbm corner weld assemblies and 100 lbm 48" insert panels.
17	Rigidity (Allowable Deflection)	**Ideal:** < 2 mm
		Marginal: < 4 mm
		Actual: < 2 mm under a select set of loading conditions with an accuracy of +/- 50%.
18	Fork-Lift Access	**Ideal:** Built-in fork-lift channels
		Marginal: Flat bottom
		Actual: The method used to transport mold components by forklift will be left to SCT to determine. All the components are light enough to be transported by hand which was not the case for the original concepts and why this metric was implemented. The original intent was that the larger 400-600 lbm assemblies would keep forklift transport in mind.
19	Overspray Prevention	**Ideal:** Built-in shield/cover
		Marginal: Accommodates poly-wrap
		Actual: Accommodates poly-wrap

20	Discretization	**Ideal:** Adjustable in 4" increments
		Marginal: Adjustable in 6" increments
		Actual: Adjustable in 6" increments. However, the modular nature of the design allows smaller 3" or 4" panels to be manufactured if required.
21	Color	**Ideal:** Black
		Marginal: Not evergreen or white
		Actual: Metallic (darker colors are preferred as they contrast the gel coat when it is applied).
22	Assembly Tools	**Ideal:** Assembly of the mold only requires tools which SCT already has.
		Marginal: Assembly of the mold only requires the purchase of new tools.
		Actual: Assembly of the mold only requires tools which SCT already has.
23	Height Adjustability	**Ideal:** 36" and 42" height adjustability
		Marginal: 36" Height
		Actual: 36" Height

In conclusion the final mold configuration meets each of the 23 design metrics. Of the 23 attained metrics 14 meet the marginally acceptable values and 9 meet the ideal values indicating that the design was successful based on the criteria laid out at the onset of the project.

8.2 Future Work and Recommendations

This section covers the work that will need to be done by SCT to fabricate the mold after the U of M Team submits the final model, drawings, and report. Additionally, a short list of optional components and design suggestion are included to close out the report.

The following list describes the action that should be taken by SCT after submittal of the final deliverables by the U of M Team:

- First, selection of a material must be made from the available options of carbon steel, stainless Steel and aluminum. The decision should be made based on the desired weight of the individual components, the mold's resistance to corrosion, and the capital investment that SCT is willing to make.

- If aluminum is selected as the desired mold material further assessment of the corner weld assembly rigidity and guide rail rigidity should be pursued. To facilitate this analysis the U of M Team will provide the shell model used to assess the carbon steel mold to SCT. Additionally, if aluminum is selected as the desired mold material a formal quote will need to be requested from Taj Industrial or SCT's preferred fabricator for this material.
- The second major decision that will need to be made is how many insert panels to fabricate. Due to the time value of money, and uncertainty related to prototyping the mold it is a potentially desirable to only fabricate one set of smaller 12" or 24" insert panels to test the desire. However, fabricating the insert panels at various times may lead to alignment issues between the components as the fabricator will not be able to easily benchmark against the existing components.
- Finally, SCT will need to select what they would like to use for a base frame. A custom metal option detailed by the U of M Team in Appendix B
- After the mold is fabricated, SCT personnel will need to determine the best way to secure the components together. Due to the lack of a prototyping phase where the U of M Team could be involved, the decision was made to provide a final design that facilitated clamping, bolting, or pining the various modular components together. It is still undetermined which method will provide acceptable rigidity with the shortest possible assembly time.

Regarding the optional components that SCT could have fabricated, the U of M Team recognized the following items:

- Fabrication of Shorter 48" and 72" guide rails for the smaller mold configurations would be beneficial. These guide rails would facilitate the poly-wrapping process and make working around smaller mold configurations easier.
- Fabrication of longer guide rails up to 20' and production of additional insert panels would allow SCT to fabricate a wider range oversized T-Pads. Analysis of the rigidity of the larger mold would need to be conducted prior to fabrication.
- Fabrication of smaller insert panels such as 3" or 4" versions of the final design would allow SCT to offer a more precise range of mold sizes.
- Finally, it was recognized by the U of M Team that fabrication of a custom metal base plate might be desirable in the future if it is found that the rigidly supported melamine sheet is difficult to move around the shop. A rough conceptual sketch of the proposed base frame is shown in Appendix B. The frame could be supported on caster wheels or moved around by forklift.

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[8] F. Cverna, *ASM Ready Reference - Thermal Properties of Metals*. ASM International, 2002.

[9] “McMaster-Carr,” *Grade 5 Steel Square-Neck Carriage Bolt*. [Online]. Available: https://www.mcmaster.com/. [Accessed: 01-Dec-2019].

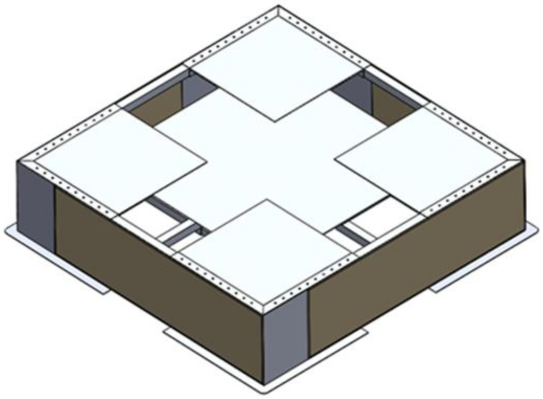
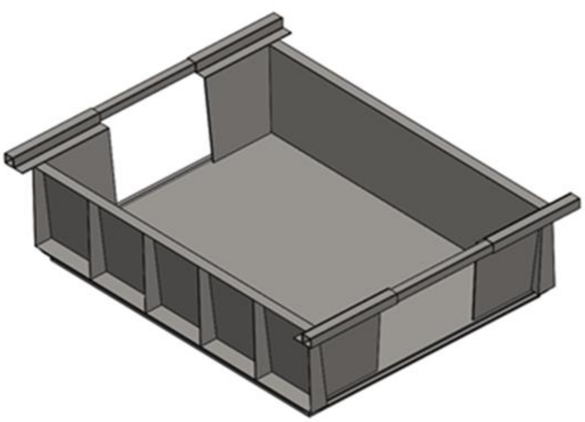
[10] “McMaster-Carr,” *Medium-Strength Steel Hex Nut*. [Online]. Available: https://www.mcmaster.com/. [Accessed: 01-Dec-2019].

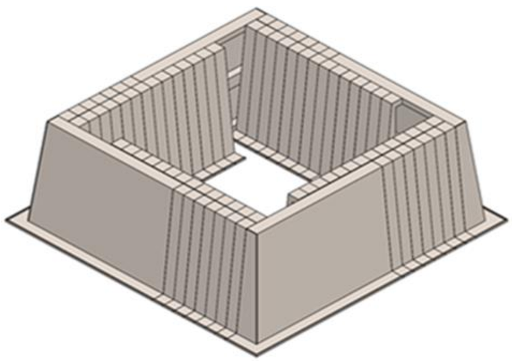
[11] TEADIT, “Metallic Materials,” 2008. [Online]. Available: https://www.allsealsinc.com/teadit/TypicalMetalProperties.pdf. [Accessed: 28-Nov-2019].

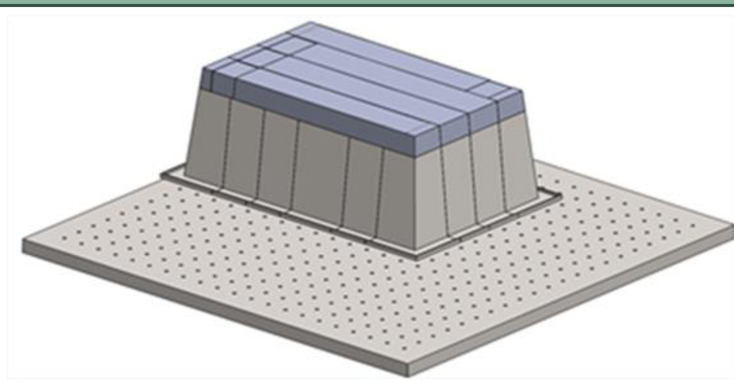
APPENDIX A: Additional Preliminary Concepts

Appendix A includes a list of additional concepts that were developed prior to the first EDR. These concepts are shown in Table I.

TABLE I. ADDITIONAL PRELIMINARY CONCEPTS

Core Concept Shown: 2D TeleTop	**REF #1**	**Male Mold**
	**Key Advantages**	**Key Drawbacks**
	Not vulnerable to overspray	Requires custom plywood top for every T-Pad
	Easy access to mold surface	Requires panel inserts to be made and stored
	Supports the plywood top from sagging	Poor surface finish
Description		
A telescoping internal frame with fixed panels in the corners. When the frame telescopes the size of the mold adjusts and insert panels are fastened to the sides of the frame to cover the gaps. In its smallest setting the top panel is rigid. As the top panel telescopes out gaps are introduced which are minimized by having a second internal top panel revealed. For every T-Pad a custom plywood top panel will be placed to cover the top panel gaps.		
Core Concept Shown: Pre-Cast Block Mold	**REF #8**	**Female Mold**
	**Key Advantages**	**Key Drawbacks**
	Inherently good alignment	Difficult to manufacture
	Quick adjustment	Still requires custom wood panels despite complexity
	Potentially high structural rigidity	Difficult to mitigate seams
Description		
Two walls are fixed in length and two adjustable walls vary in length. The adjustable walls also slide along the fixed length walls in order to adjust the dimensions. Due to the geometry of the mold insert panels are only required to fastened to the sides of the frame to cover the gaps in the two adjustable walls. The base plate provides a smooth surface for the T-Pad top face.		

Core Concept Shown:	Folding Wall - Inward	REF #13	Female Mold
Other Configuration:	**Folding Wall - Outward**	**REF #12**	**Male Mold**
		**Key Advantages**	**Key Drawbacks**
		No separate pieces	Difficult to manufacture
		Protection from overspray	Requires custom plywood top for every T-Pad
			High risk of seams
Description			
Four walls placed together with an internal frame to form the mold walls. The walls are adjusted to a desired size by extending one wall out and swinging around a hinged insert piece. All insert pieces are hinged together and fold into the inside of the mold for the male configuration and fold around the outside of the walls for the female configuration. For every T-Pad a custom plywood top panel will be placed on top of the support frame to create the top panel of the mold			

Core Concept Shown:	LEGO (M)	REF #14	Male Mold
Other Configuration:	**LEGO (F)**	**REF #15**	**Female Mold**
		**Key Advantages**	**Key Drawbacks**
		High potential to customize height	Poor surface finish, lots of seems
		Smaller lightweight parts (ergonomics)	Parts will be difficult to fabricate as shown
		Not vulnerable to overspray	Would require tight tolerancing
Description			
Each wall is a separate distinct piece used to build each of the four mold walls. To adjust the mold to a desired size, pieces are added and removed accordingly as needed. The walls are built by inserting pegs located on the bottom of the pieces into a perforated base grind. For the male configuration the top pieces telescope length wise and are built in the same way by inserting pegs located on the bottom of the pieces into holes located on the top of the wall pieces. In the female configuration only has wall pieces as the base plate also acts are the top panel of the mold. Additional pieces can be added to the top of the female configuration in order to adjust the height of the mold as well.			

APPENDIX B: Engineering Drawings

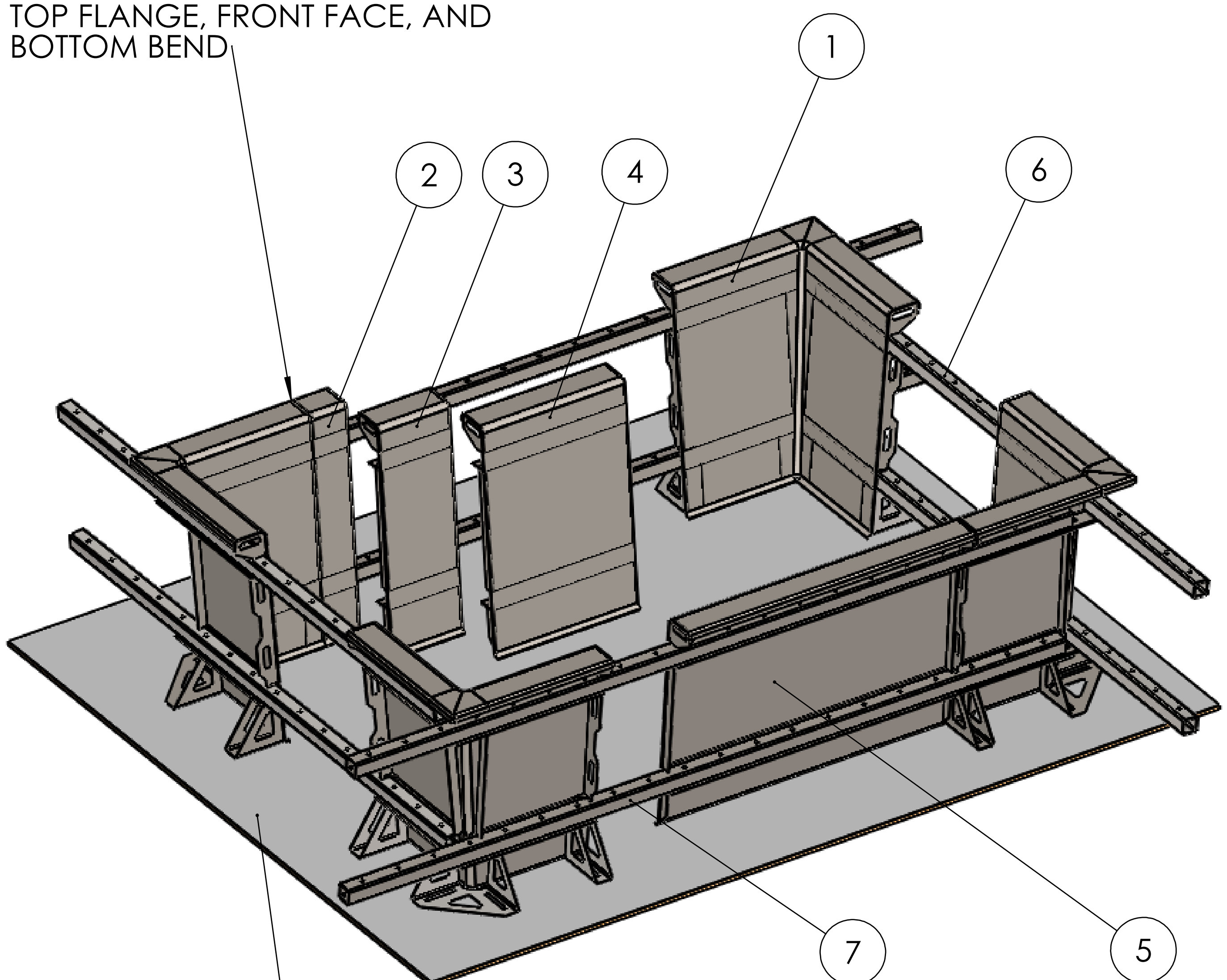
Appendix B provides the engineering drawings for adjustable mold created for SCT. Also included is a conceptual drawing for an optional base frame. The list of drawings is presented in the following table of contents.

Table of Contents

4 3 2 1

B

FABRICATOR TO BUILD ALL INSERT PANELS AND CORNER WELD ASSEMBLIES TO BE FLUSH WITH EACHOTHER WITHIN 1/8" ON THE TOP FLANGE, FRONT FACE, AND BOTTOM BEND



MELAMINE BASE SHOWN FOR REFERENCE ONLY

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	0009	CORNER WELD ASSEMBLY	SEE WELD ASSEMBLY DRAWING	4
2	0013A	6" INSERT PANEL ASSEMBLY	SEE WELD ASSEMBLY DRAWING	4
3	0013B	12" INSERT PANEL ASSEMBLY	SEE WELD ASSEMBLY DRAWING	4
4	0013C	24" INSERT PANEL ASSEMBLY	SEE WELD ASSEMBLY DRAWING	4
5	0013D	48" INSERT PANEL ASSEMBLY	SEE WELD ASSEMBLY DRAWING	4
6	0014A	96" GUIDE RAIL	TBD	4
7	0014B	120" GUIDE RAIL	TBD	4

B

NOTES:

1. UNLESS OTHERWISE NOTED, DIMENSIONS SHOWN IN FT-IN TO INSIDE OF THE STRUCTURE
2. DO NOT SCALE DRAWINGS
3. BOM QUANTITIES ARE INDICATIVE OF THE NUMBER OF PARTS REQUIRED, NOT THE NUMBER OF PARTS SHOWN ON THE DRAWING
4. CORNER ASSEMBLY AND INSERT PANEL ASSEMBLY BENDS SHOULD BE FABRICATED SUCH THAT THE PANELS CAN ALIGN WITHIN 1/8"
5. GUIDE RAILS SECURED USING CLAMPS, BOLTS, AND/OR PINS

A

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FIBERGLASS FABRICATION — WINNIPEG, CANADA

CUSTOMER: STRUCTURAL COMPOSITE TECHNOLOGIES	DESCRIPTION: COMPLETE ASSEMBLY
DRAWN: NC	CLIENT PO NO.: N/A
DATE: 2019-11-30	SCALE: 1:24
PROJECT NO.: N/A	DRAWING NO.: 0015
REV.: 01	

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4 3 2 1

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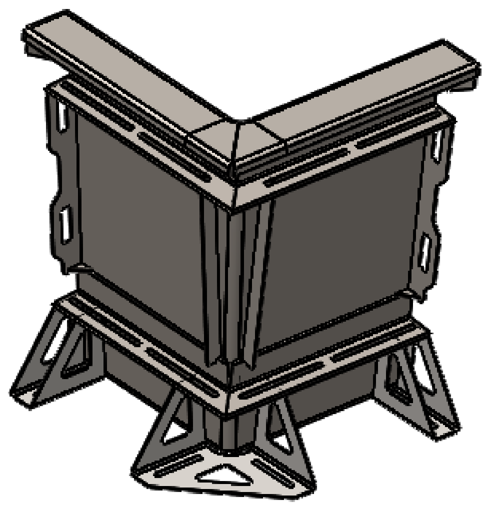

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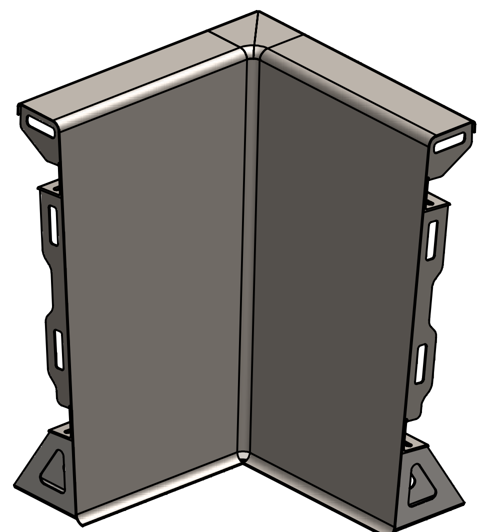

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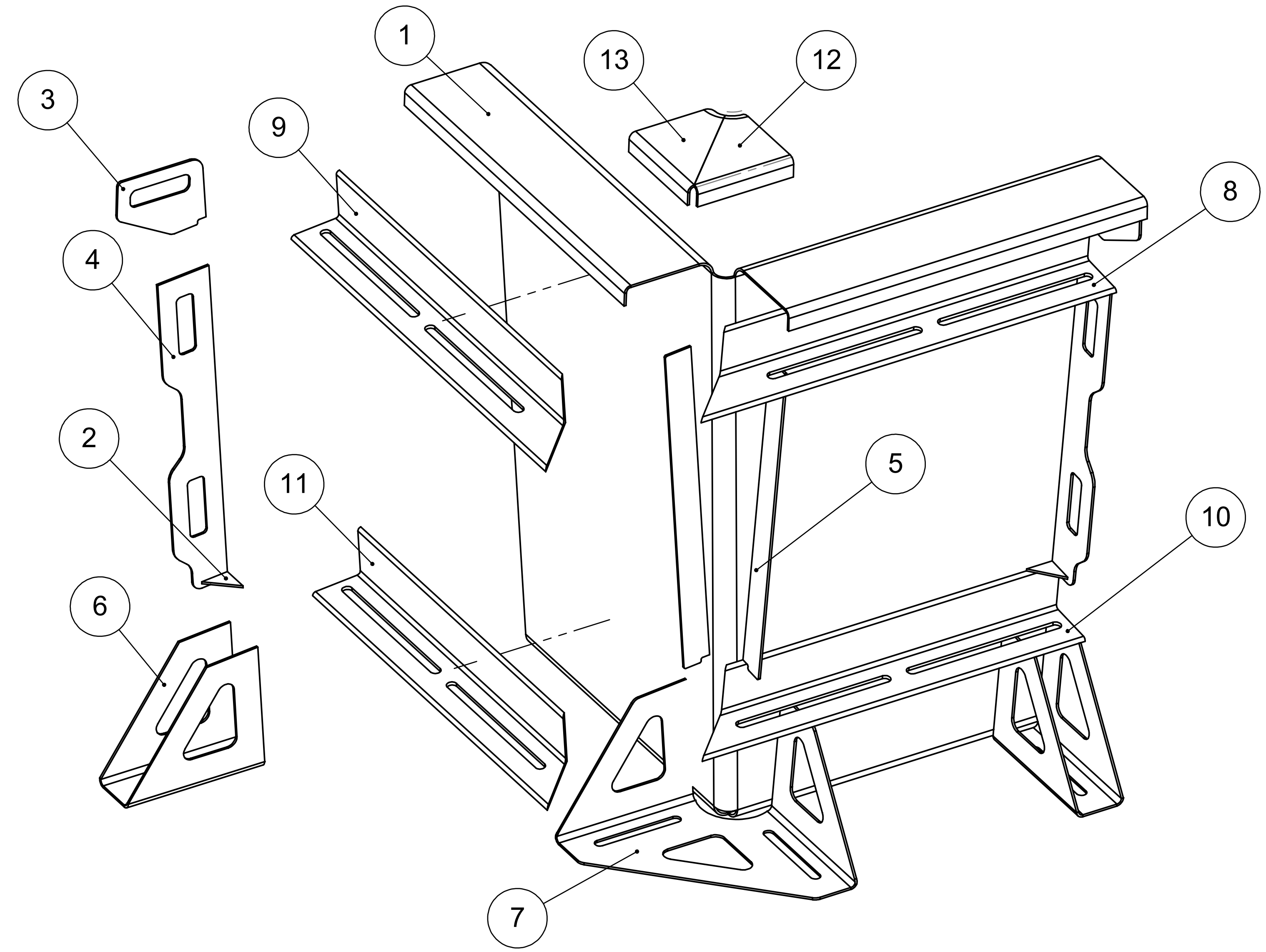

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	0001	CORNER ASSEMBLY SHEET METAL COVER	TBD	1
2	0002	CORNER HANDLE BRACE	TBD	2
3	0003	TOP GUSSET	TBD	2
4	0004	2-HANDLE CORNER GUSSET	TBD	2
5	0005	PLAIN MID GUSSET	TBD	2
6	0006	BOTTOM U-GUSSET	TBD	2
7	0007	BOTTOM CORNER GUSSET	TBD	1
8	0008A	URH CORNER - 3X3 STRUCTURAL ANGLE	TBD	1
9	0008B	ULH CORNER - 3X3 STRUCTURAL ANGLE	TBD	1
10	0008C	LRH CORNER - 3X3 STRUCTURAL ANGLE	TBD	1
11	0008D	LLH CORNER - 3X3 STRUCTURAL ANGLE	TBD	1
12	0016A	TOP FLANGE INSERT	TBD	1
13	0016B	TOP FLANGE INSERT - MIRRORED	TBD	1

NOTES:

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DESCRIPTION: CORNER WELD ASSEMBLY

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NC	N/A			
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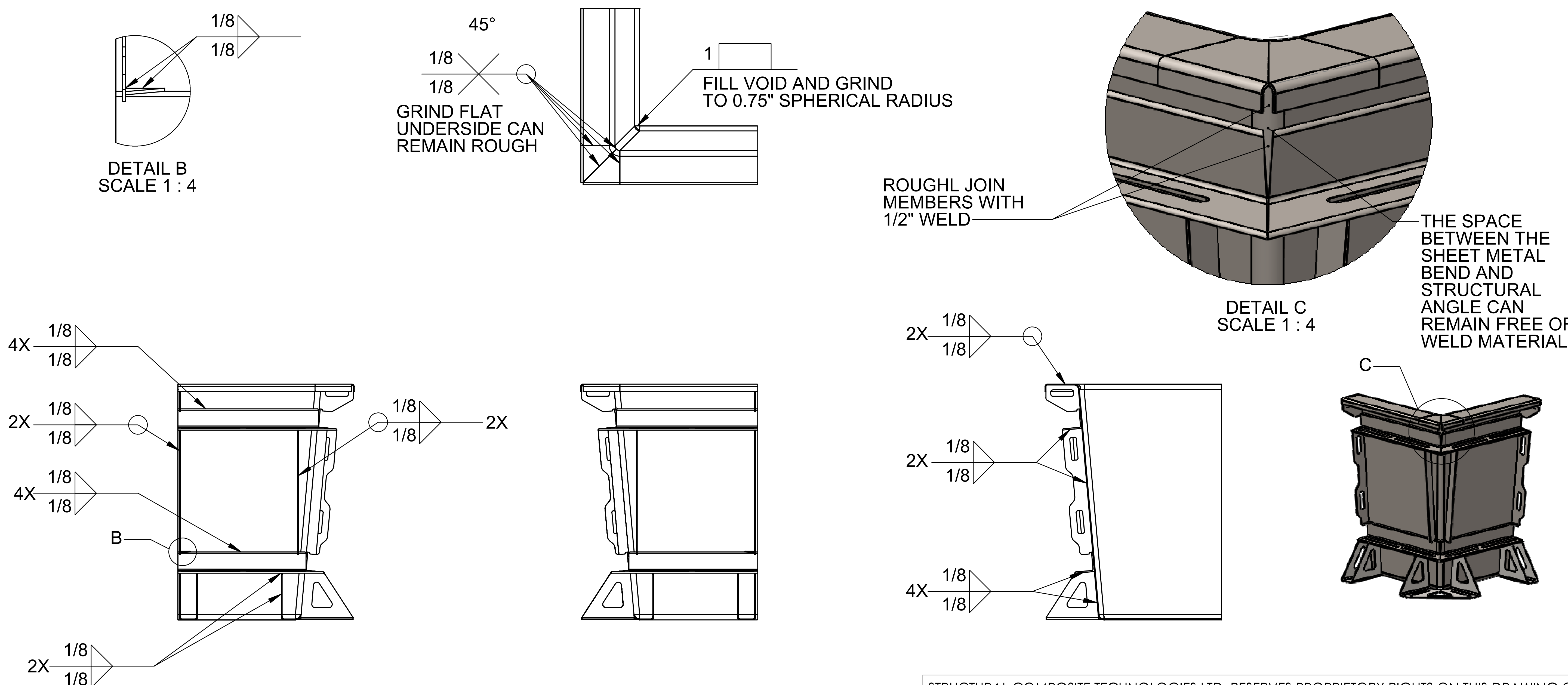

NOTES:

1. UNLESS OTHERWISE NOTED, DIMENSIONS SHOWN IN FT-IN TO INSIDE OF THE STRUCTURE
2. DO NOT SCALE DRAWINGS
3. IN THE EVENT THAT THE WELD INSTRUCTIONS ARE NOT CLEAR, A GENERAL RULE CAN BE FOLLOWED TO APPLY A 1/8" FILLET WELD TO ALL PERPENDICULAR SURFACES SURFACES
4. GRIND WELDS TO SMOOTH SURFACE ON MOLD SURFACE

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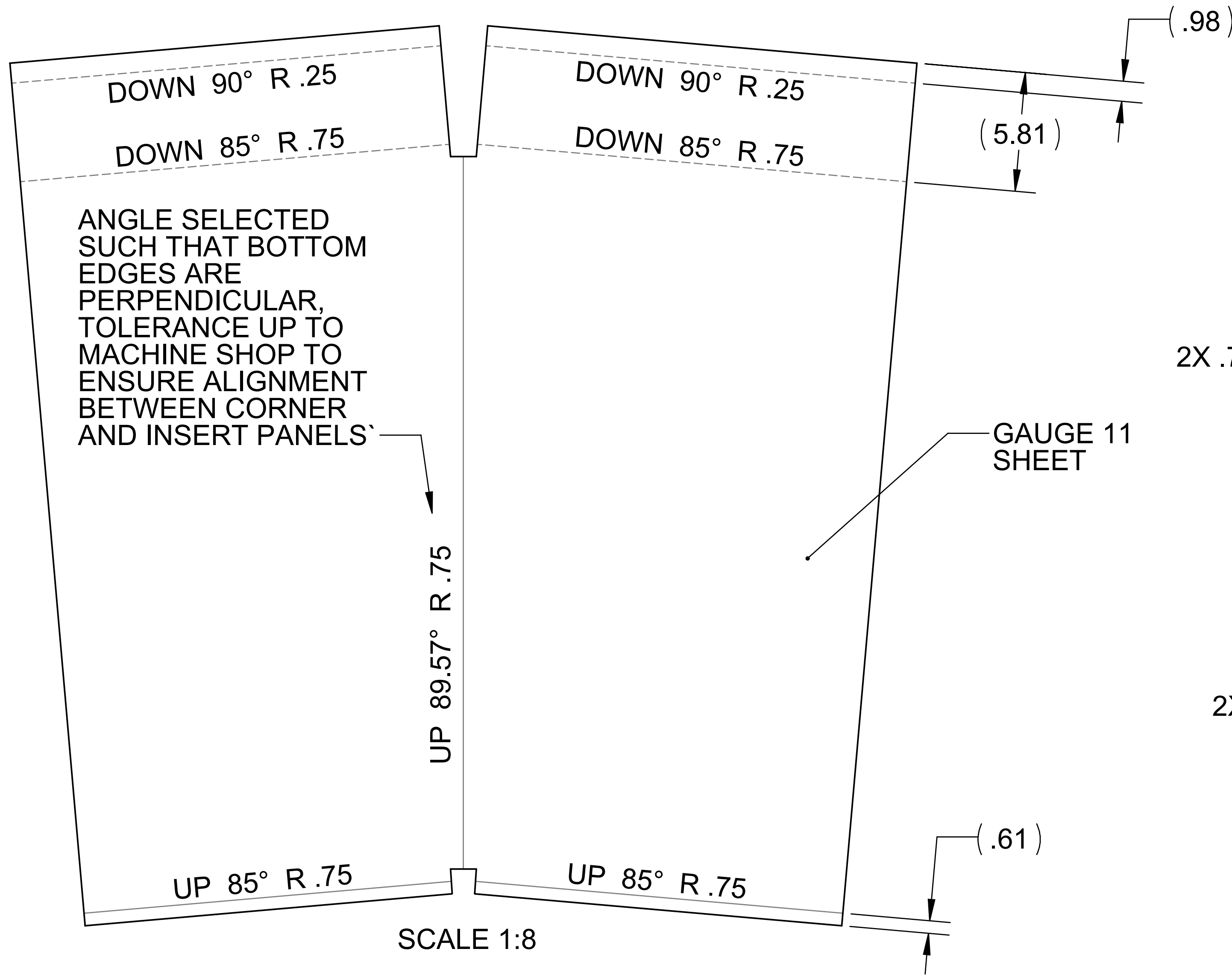

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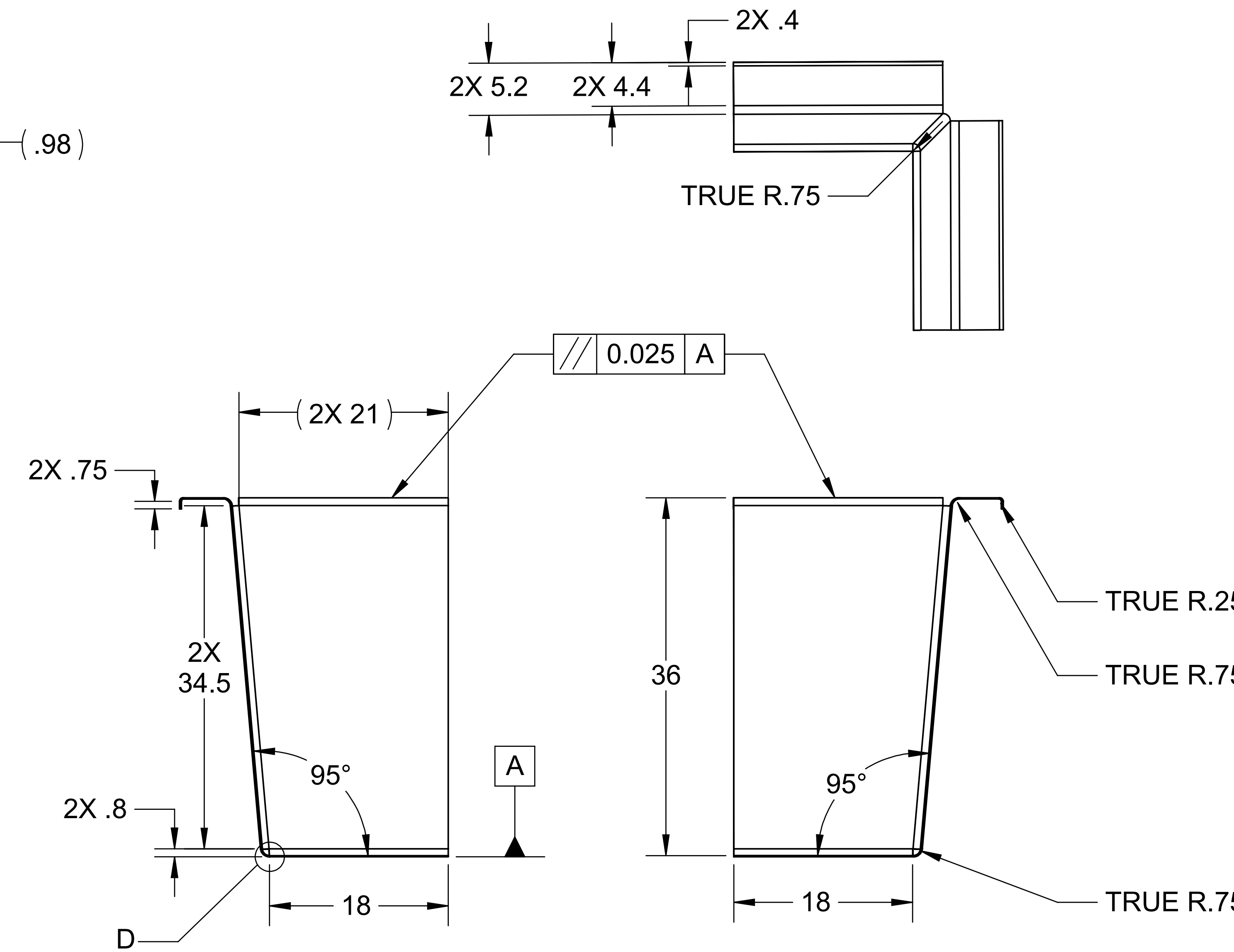

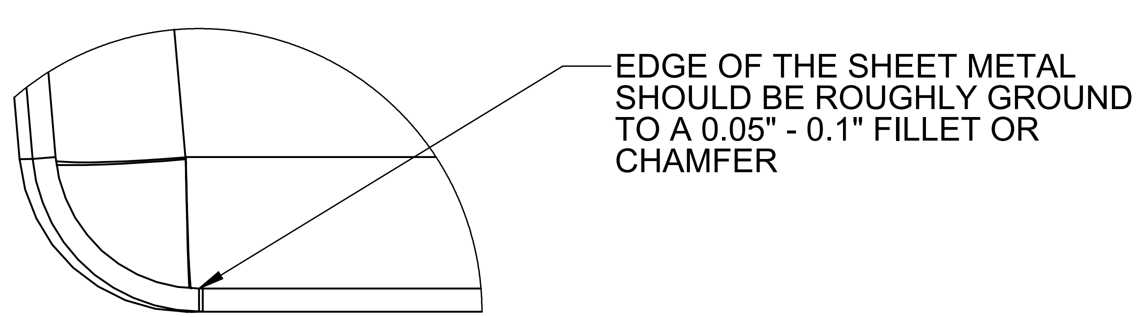

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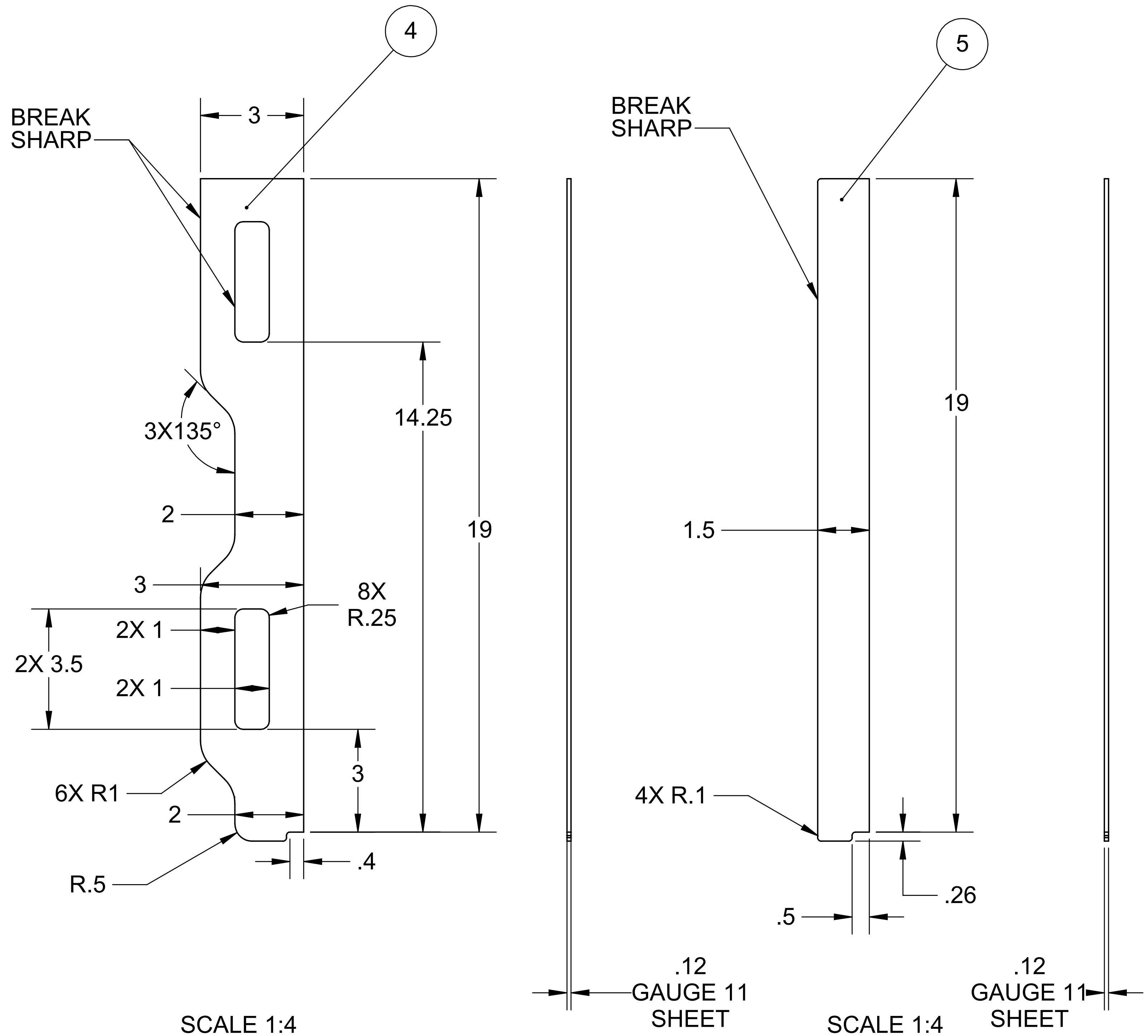

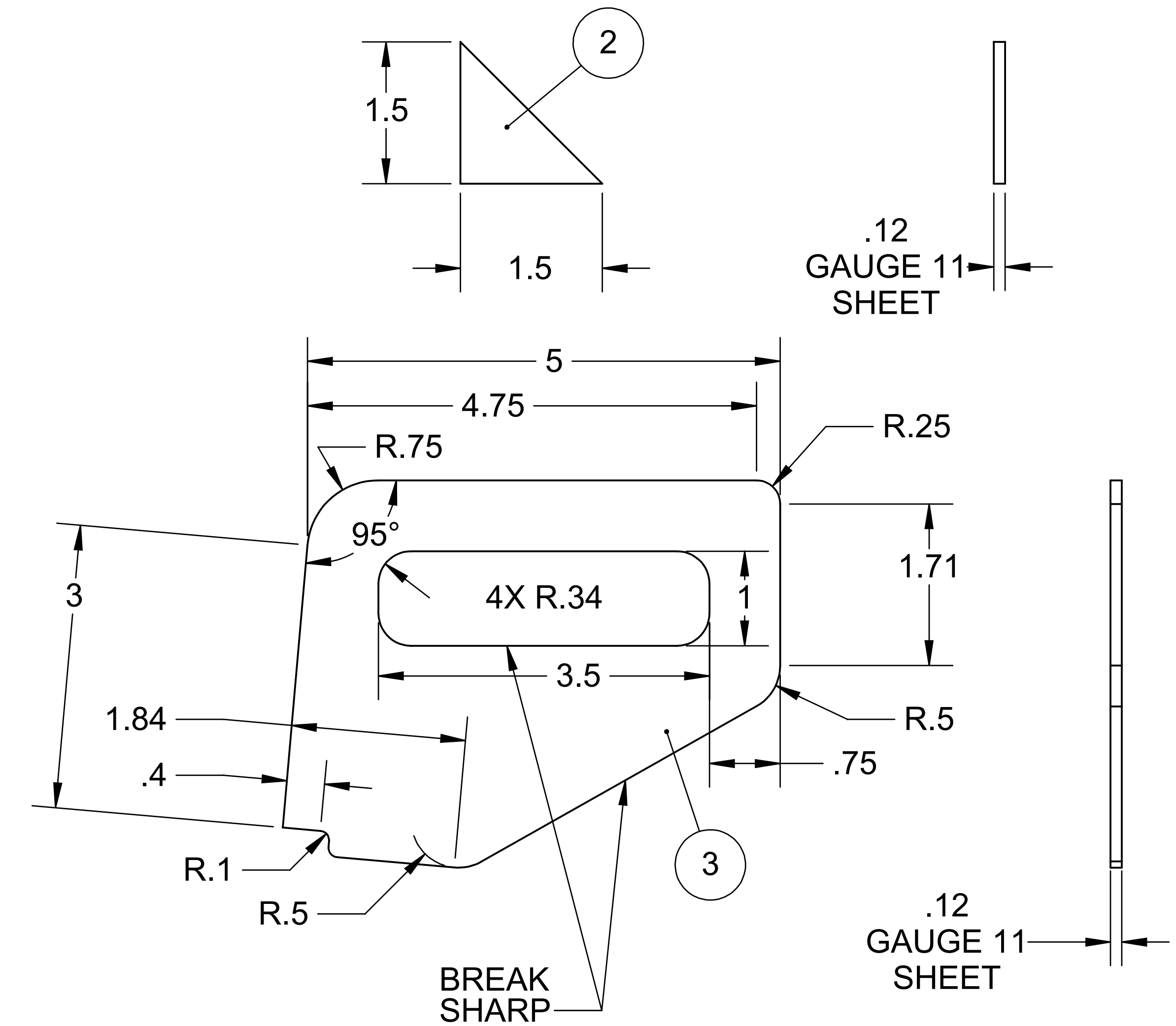

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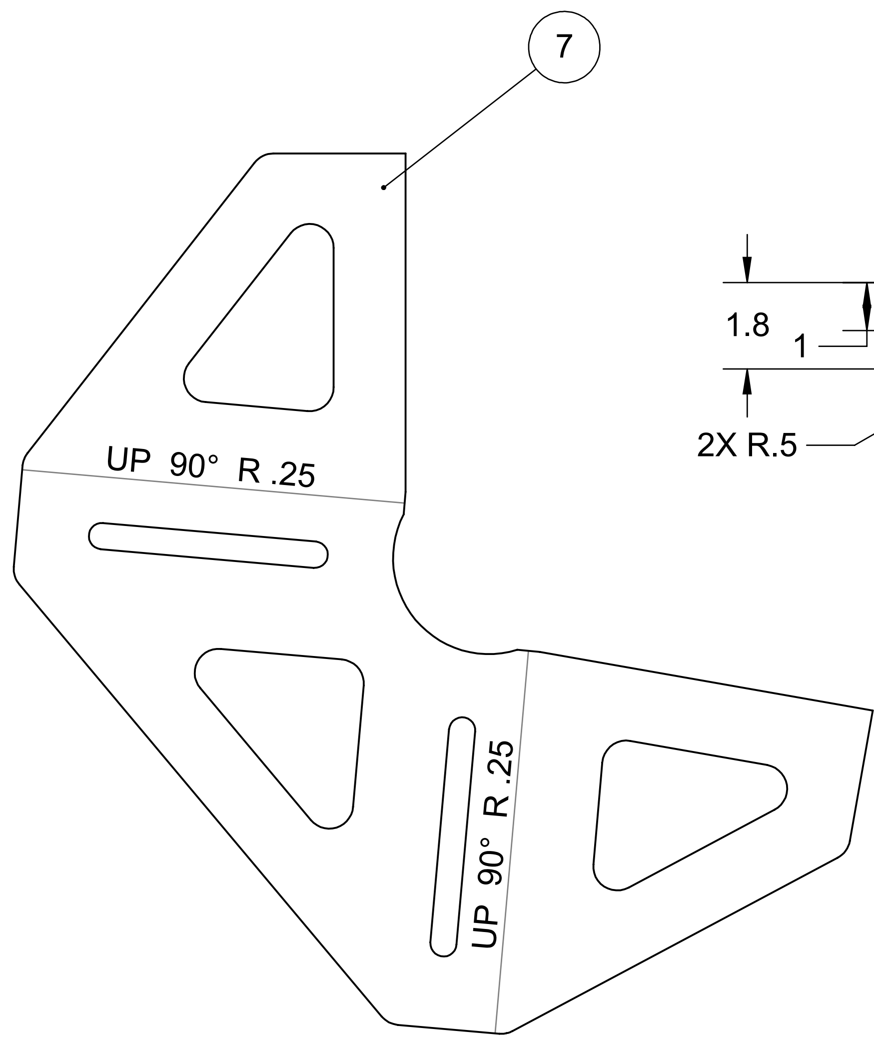

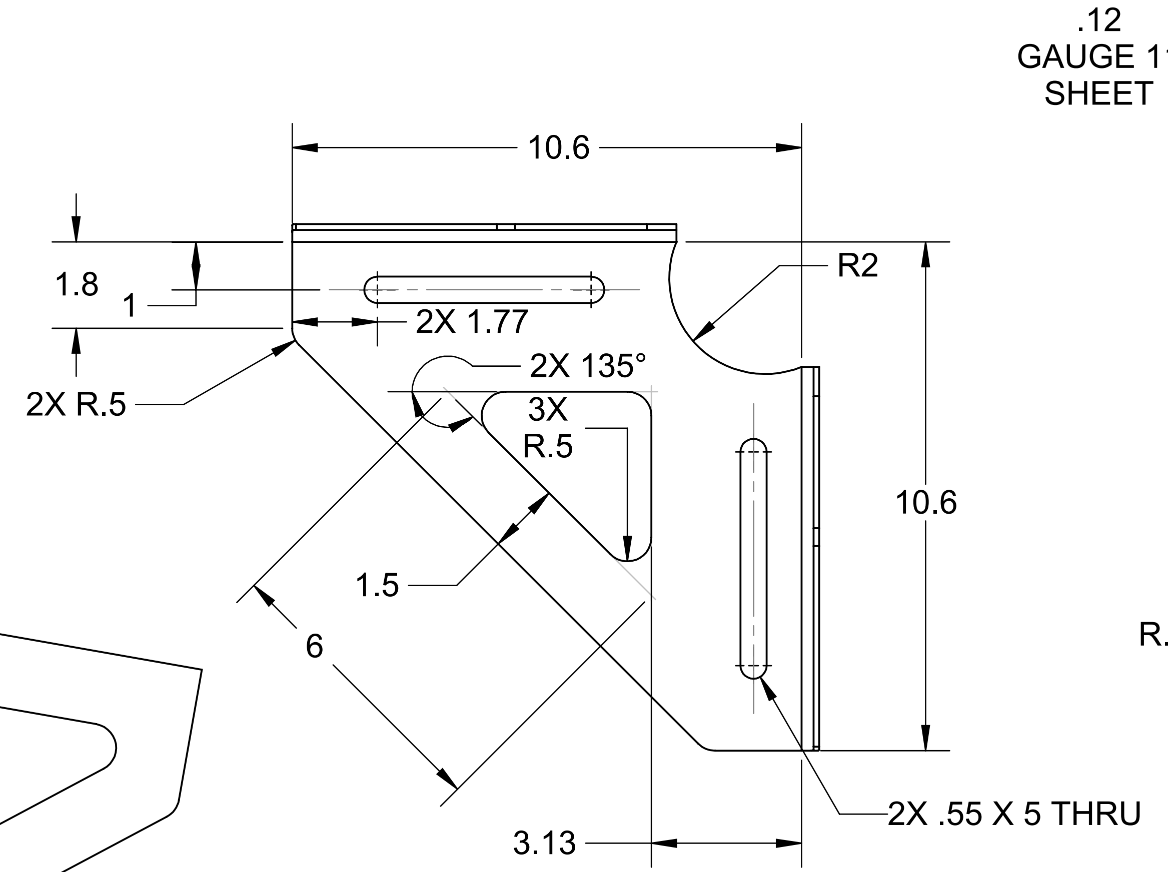

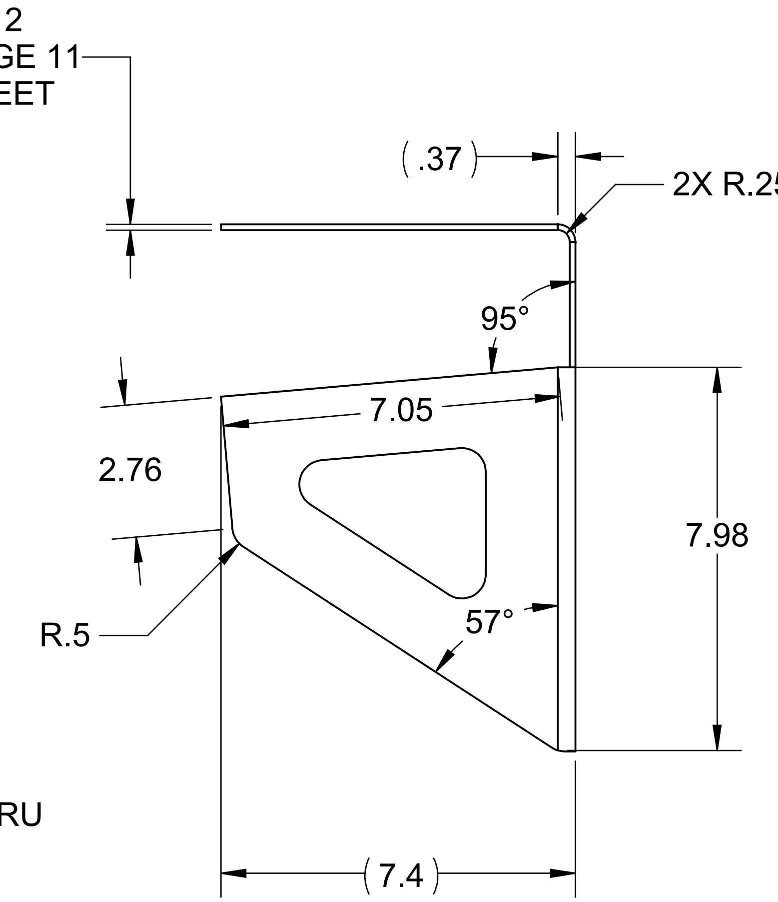

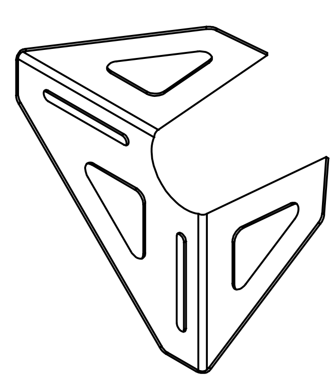

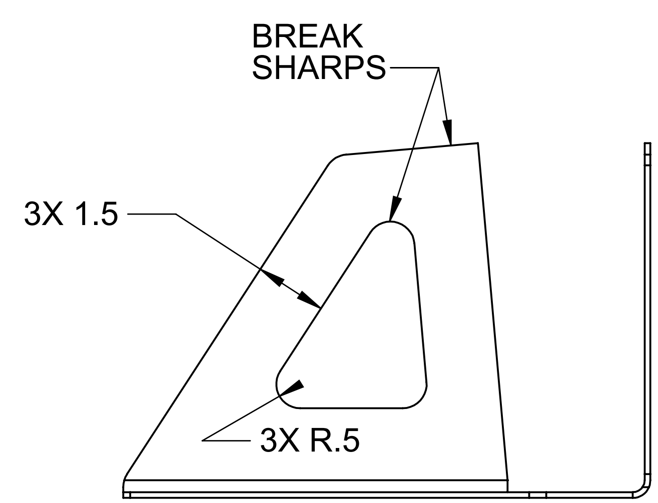

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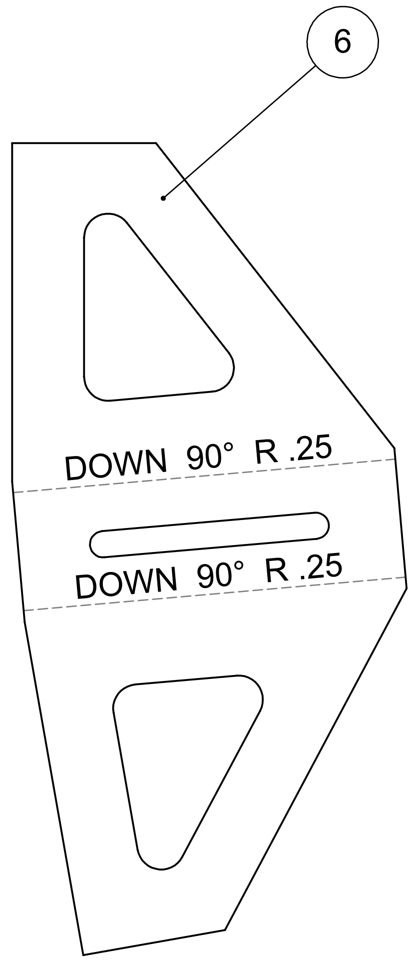

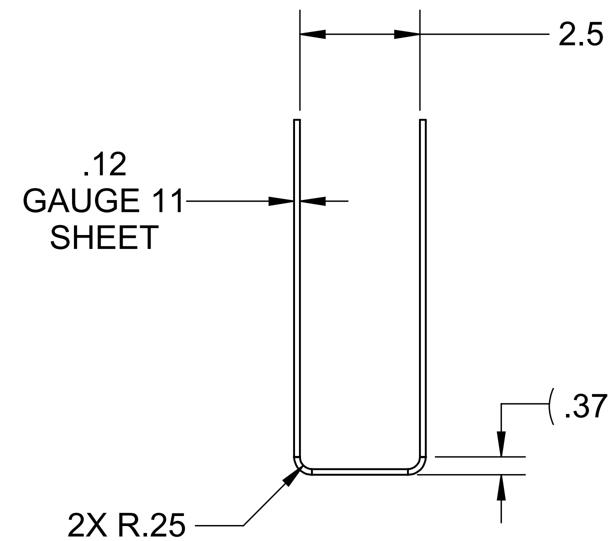

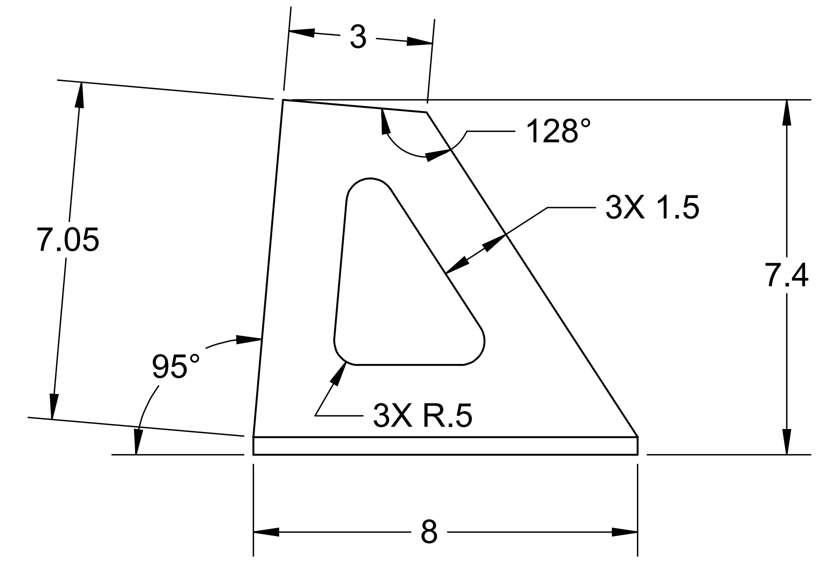

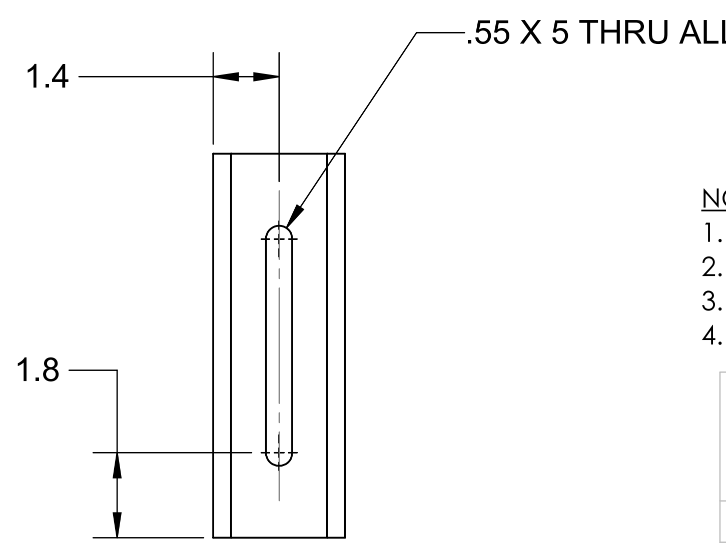

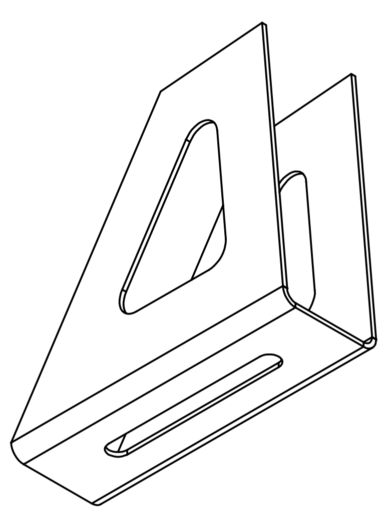

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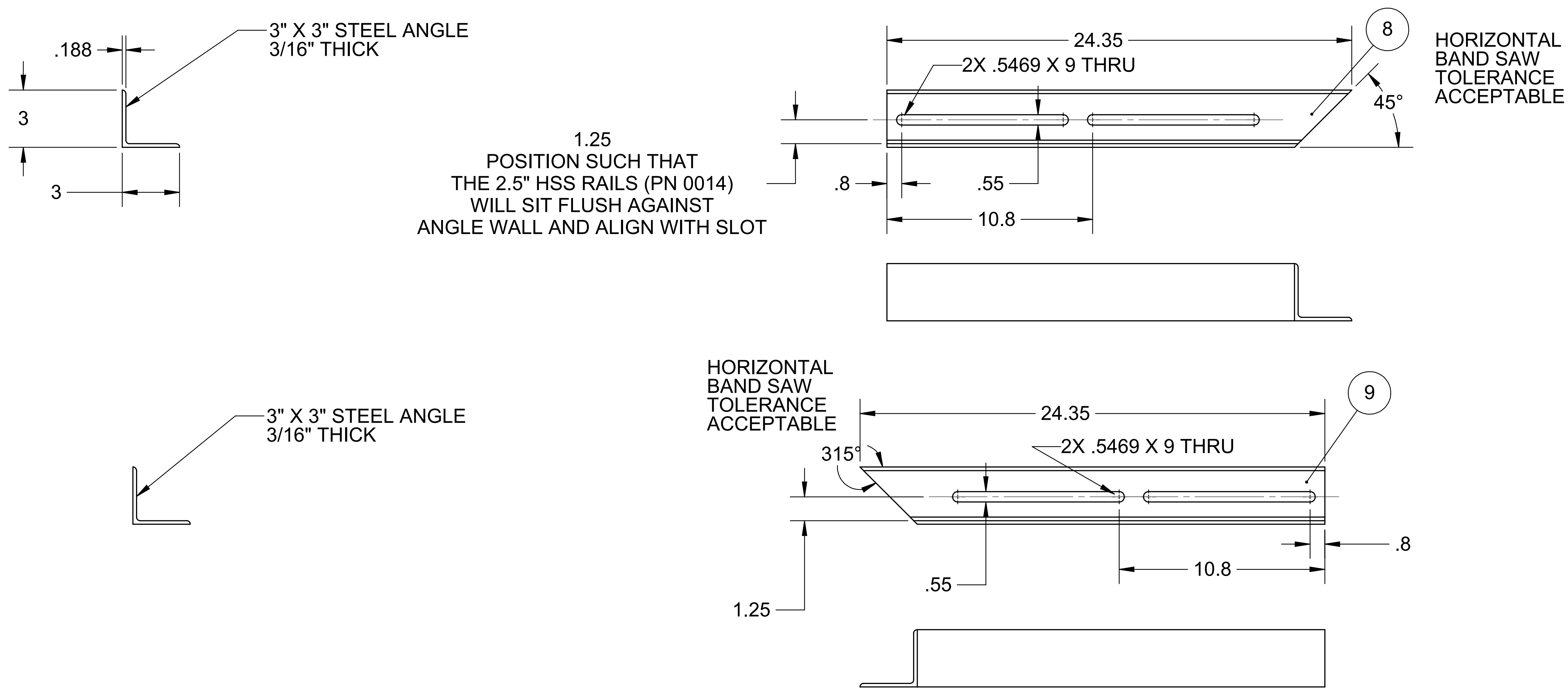

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CUSTOMER: STRUCTURAL COMPOSITE TECHNOLOGIES		DESCRIPTION: CORNER WELD ASSEMBLY		
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DATE: 2019-11-30	SCALE: 1:6	PROJECT NO.: N/A	DRAWING NO.: 0009	REV.: 01

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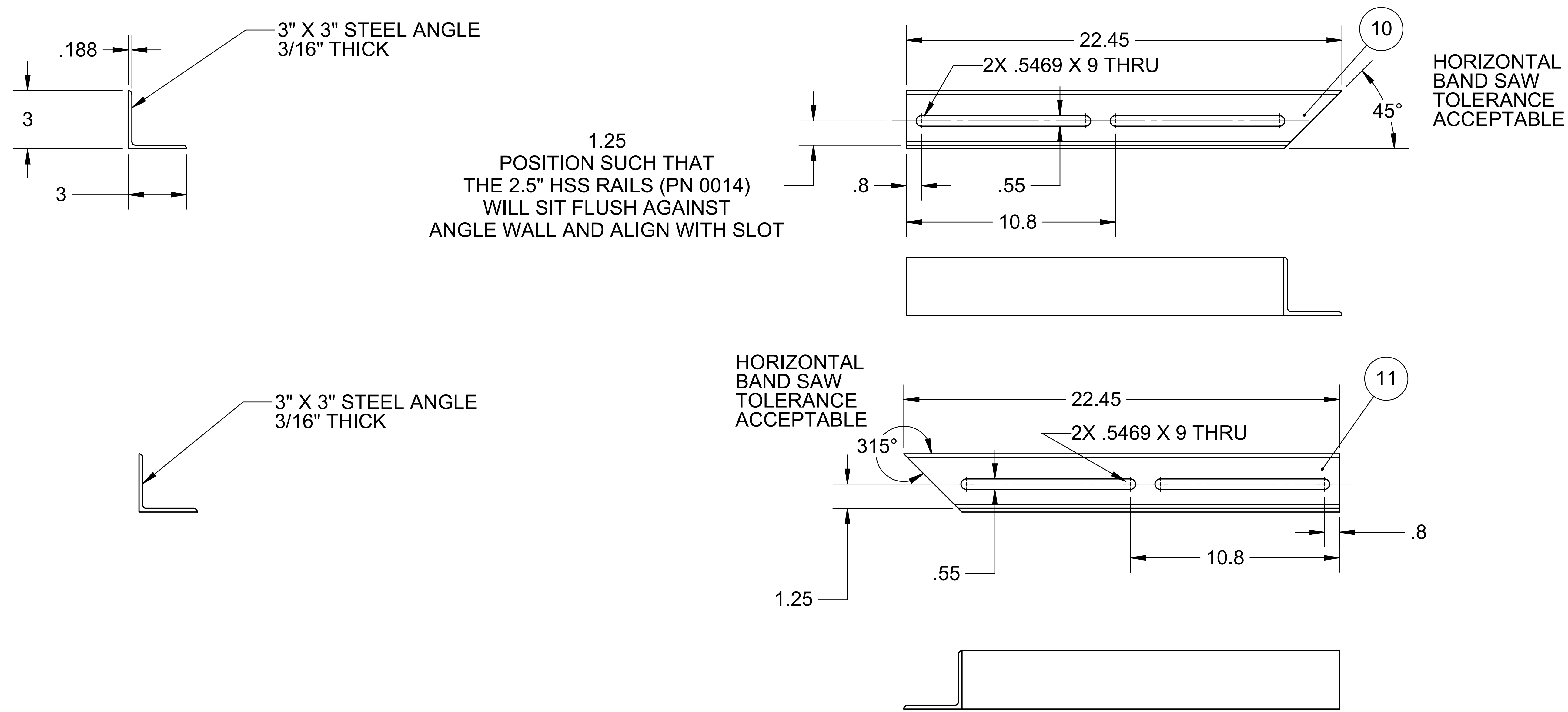

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1. UNLESS OTHERWISE NOTED, DIMENSIONS SHOWN IN FT-IN TO INSIDE OF THE STRUCTURE
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CUSTOMER:		DESCRIPTION		
STRUCTURAL COMPOSITE TECHNOLOGIES		CORNER WELD ASSEMBLY		
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DATE: 2019-11-30	SCALE: 1:6	PROJECT NO.: N/A	DRAWING NO.: 0009	REV.: 01

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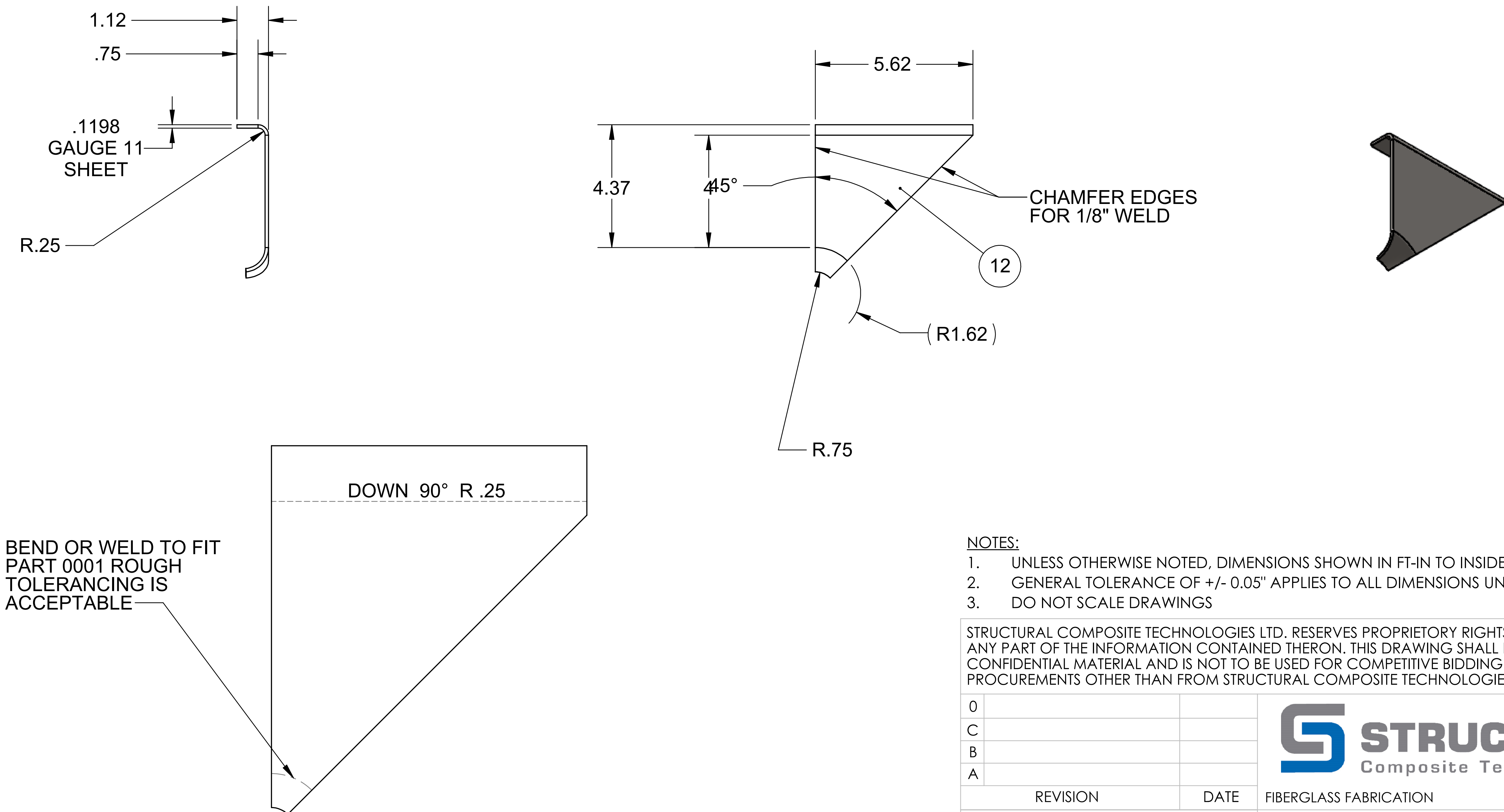

NOTES:

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CUSTOMER:		DESCRIPTION		
STRUCTURAL COMPOSITE TECHNOLOGIES		CORNER WELD ASSEMBLY		
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DATE: 2019-11-30	SCALE: 1:4	PROJECT NO.: N/A	DRAWING NO.: 0009	REV.: 01

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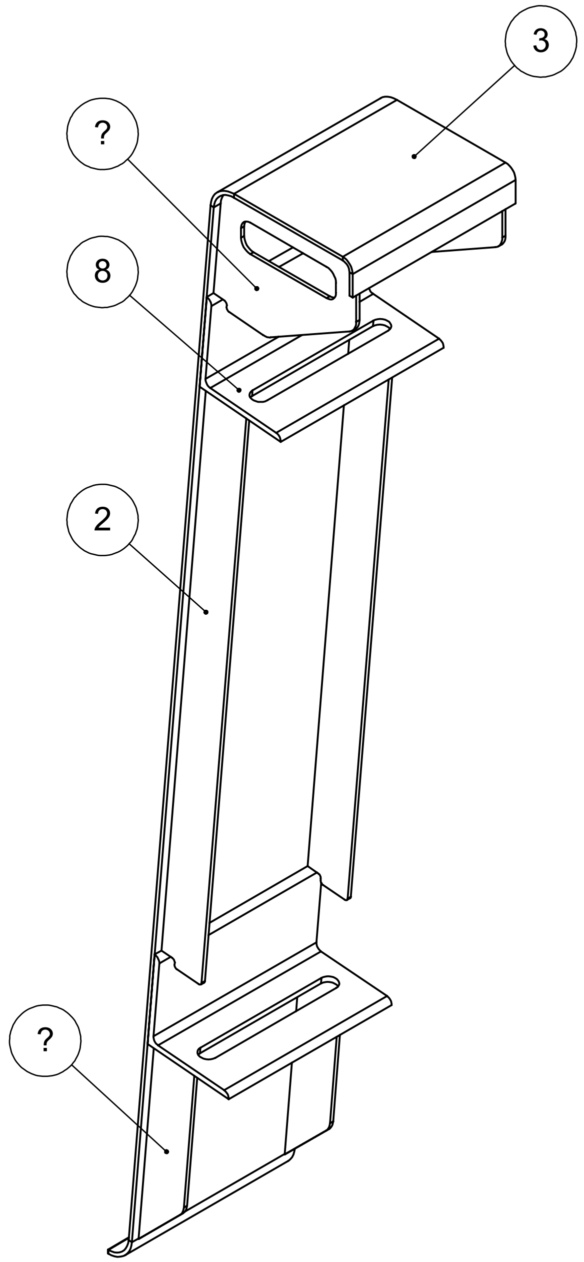
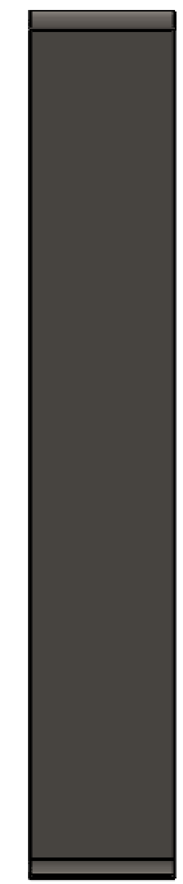
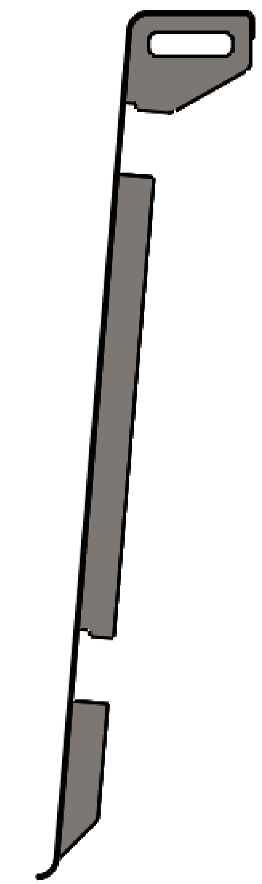
6" INSERT PANEL





SCALE 1:8



SCALE 1:8

NOTES:

1. UNLESS OTHERWISE NOTED, DIMENSIONS SHOWN IN FT-IN TO INSIDE OF THE STRUCTURE
2. DO NOT SCALE DRAWINGS

BOM QUANTITIES ARE INDICATIVE OF FABRICATING 1-6" PANEL, 1-12" PANEL, 1-24" PANEL AND 1-48" PANEL

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	QTY.
1	0003	TOP GUSSET	TBD	8
2	0005	PLAIN MID GUSSET	TBD	8
3	0010A	6" INSERT PANEL SHEET	TBD	1
4	0010B	12" INSERT PANEL SHEET	TBD	1
5	0010C	24" INSERT PANEL SHEET	TBD	1
6	0010D	48" INSERT PANEL SHEET	TBD	1
7	0011	INSERT PANEL LOWER GUSSET	TBD	8
8	0014A	6" 3X3 STRUCTURAL ANGLE	TBD	2
9	0014B	12" 3X3 STRUCTURAL ANGLE	TBD	2
10	0014C	24" 3X3 STRUCTURAL ANGLE	TBD	2
11	0014D	48" 3X3 STRUCTURAL ANGLE	TBD	2

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REVISION		DATE
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STRUCTURAL Composite Technologies Ltd

FIBERGLASS FABRICATION WINNIPEG, CANADA

CUSTOMER: STRUCTURAL COMPOSITE TECHNOLOGIES		DESCRIPTION: INSERT PANEL WELD ASSEMBLY		
DRAWN: NC	CLIENT PO NO.: N/A			
DATE: 2019-11-30	SCALE: 1:5	PROJECT NO.: N/A	DRAWING NO.: 0013	REV.: 01

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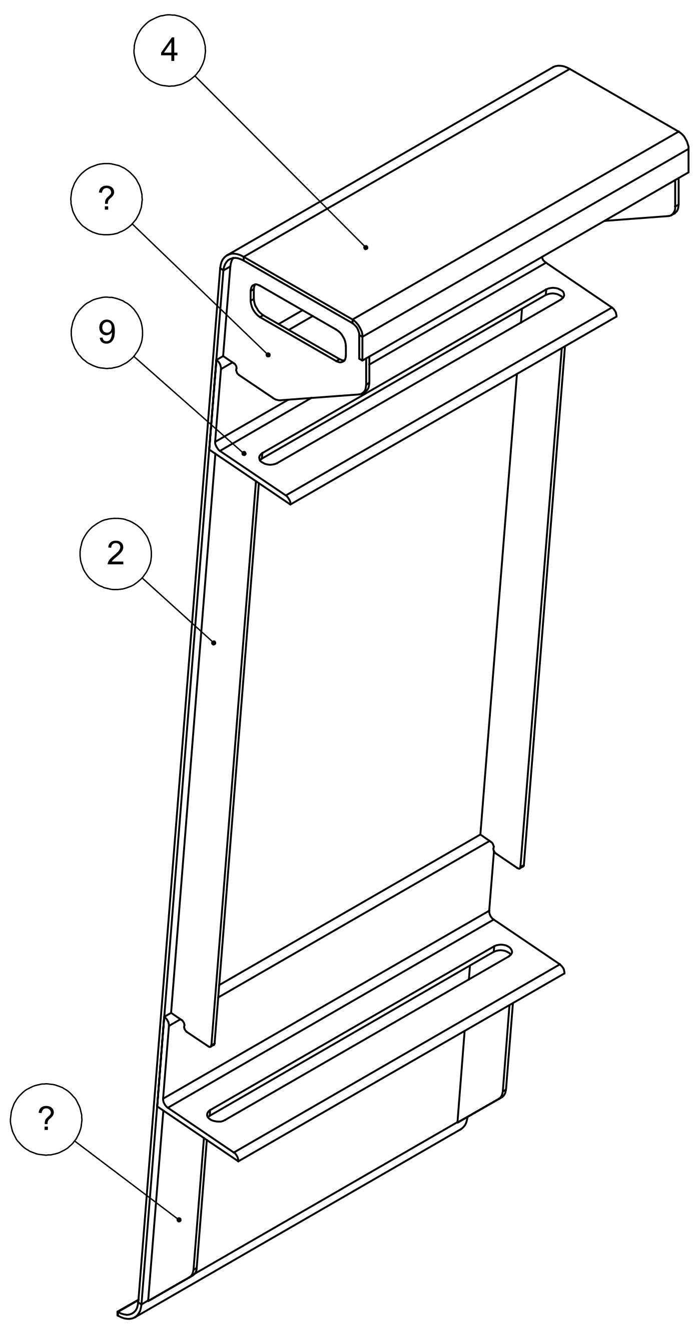
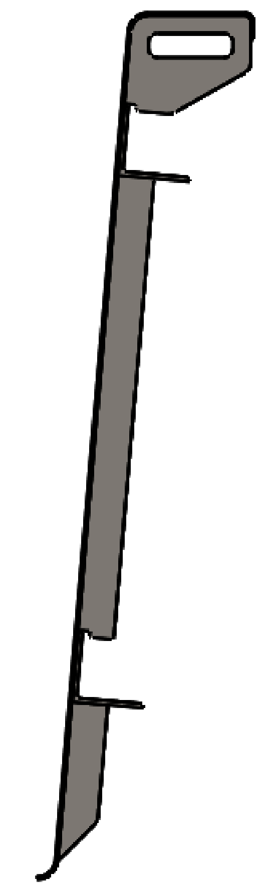
12" INSERT PANEL



SCALE 1:8



SCALE 1:8

NOTES:

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STRUCTURAL Composite Technologies Ltd

FIBERGLASS FABRICATION WINNIPEG, CANADA

CUSTOMER:		DESCRIPTION		
STRUCTURAL COMPOSITE TECHNOLOGIES		INSERT PANEL WELD ASSEMBLY		
DRAWN: NC	CLIENT PO NO.: N/A			
DATE: 2019-11-30	SCALE: 1:5	PROJECT NO.: N/A	DRAWING NO.: 0013	REV.: 01

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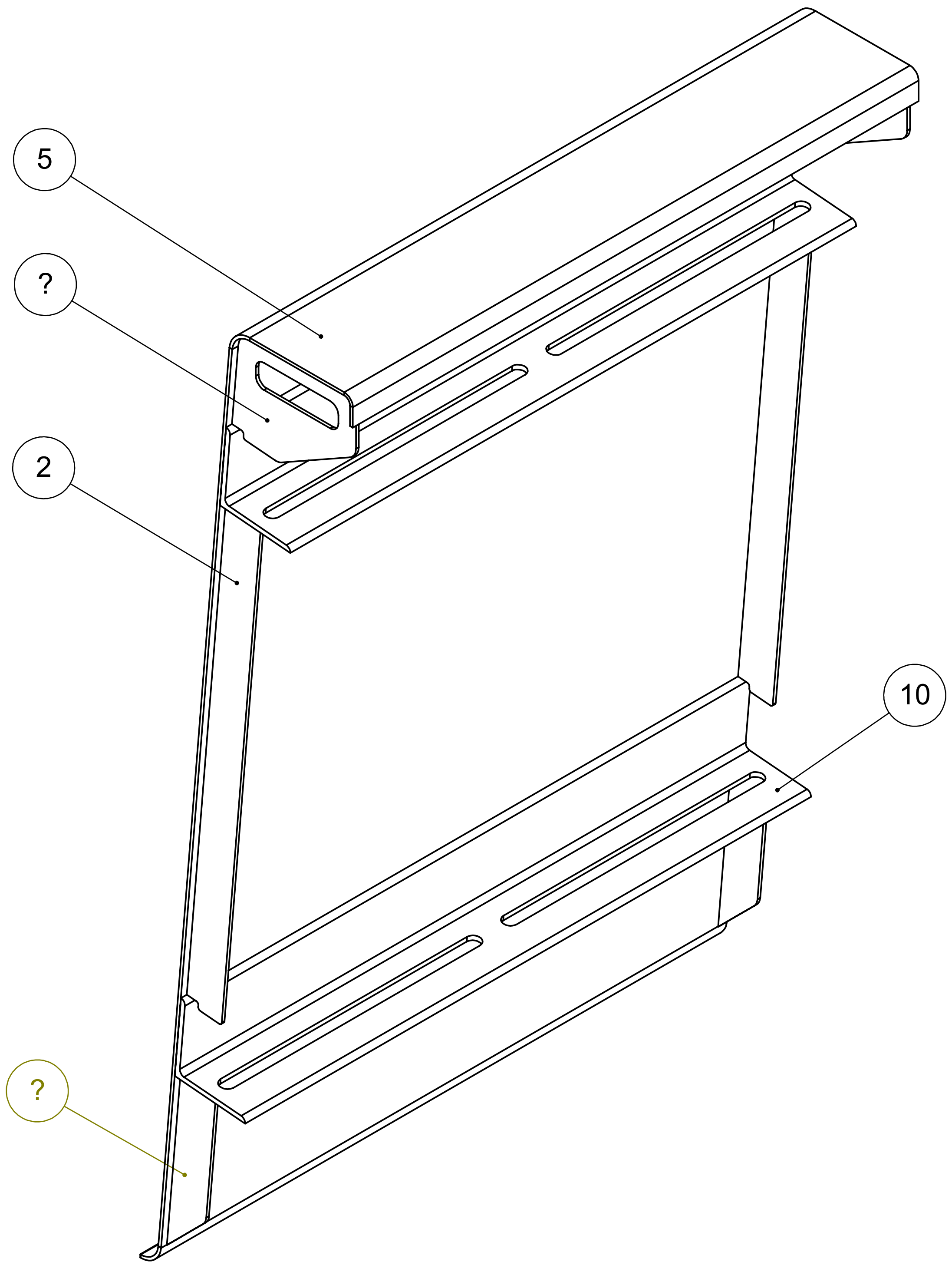
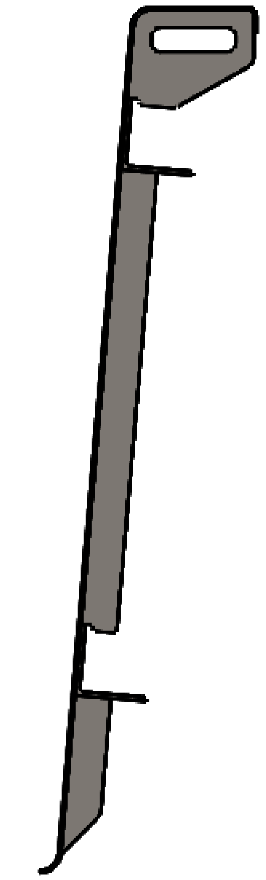
24" INSERT PANEL





NOTES:

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STRUCTURAL Composite Technologies Ltd

FIBERGLASS FABRICATION WINNIPEG, CANADA

CUSTOMER:		DESCRIPTION		
STRUCTURAL COMPOSITE TECHNOLOGIES		INSERT PANEL WELD ASSEMBLY		
DRAWN: NC	CLIENT PO NO.: N/A			
DATE: 2019-11-30	SCALE: 1:5	PROJECT NO.: N/A	DRAWING NO.: 0013	REV.: 01

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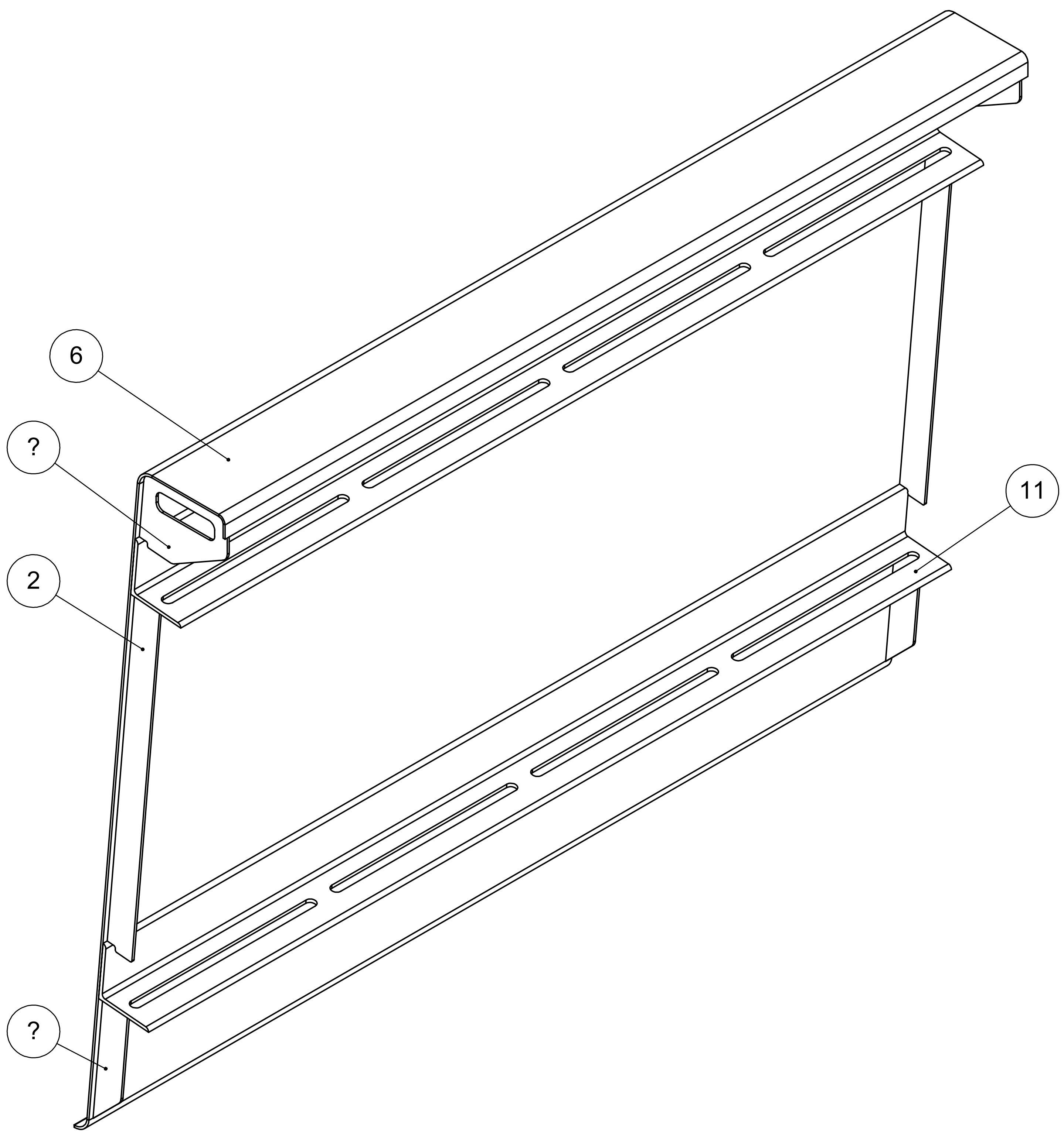
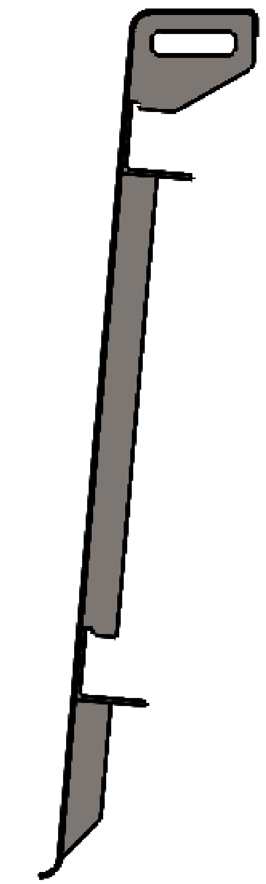
48" INSERT PANEL





NOTES:

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STRUCTURAL Composite Technologies Ltd

FIBERGLASS FABRICATION — WINNIPEG, CANADA

CUSTOMER: STRUCTURAL COMPOSITE TECHNOLOGIES		DESCRIPTION: INSERT PANEL WELD ASSEMBLY		
DRAWN: NC	CLIENT PO NO.: N/A			
DATE: 2019-11-30	SCALE: 1:5	PROJECT NO.: N/A	DRAWING NO.: 0013	REV.: 01

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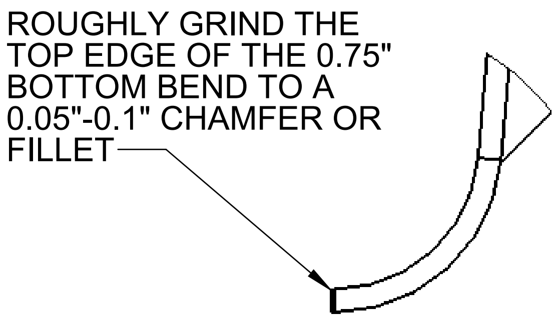
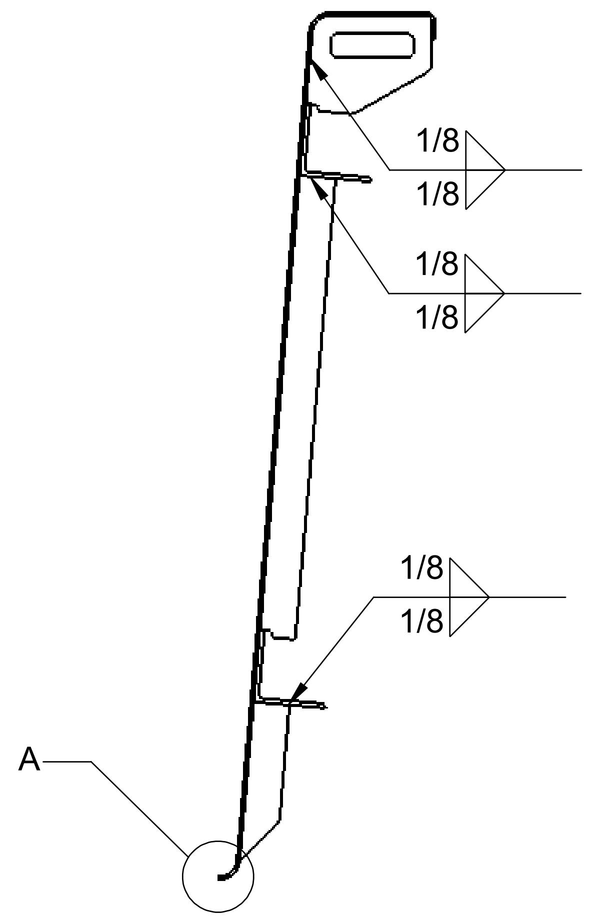
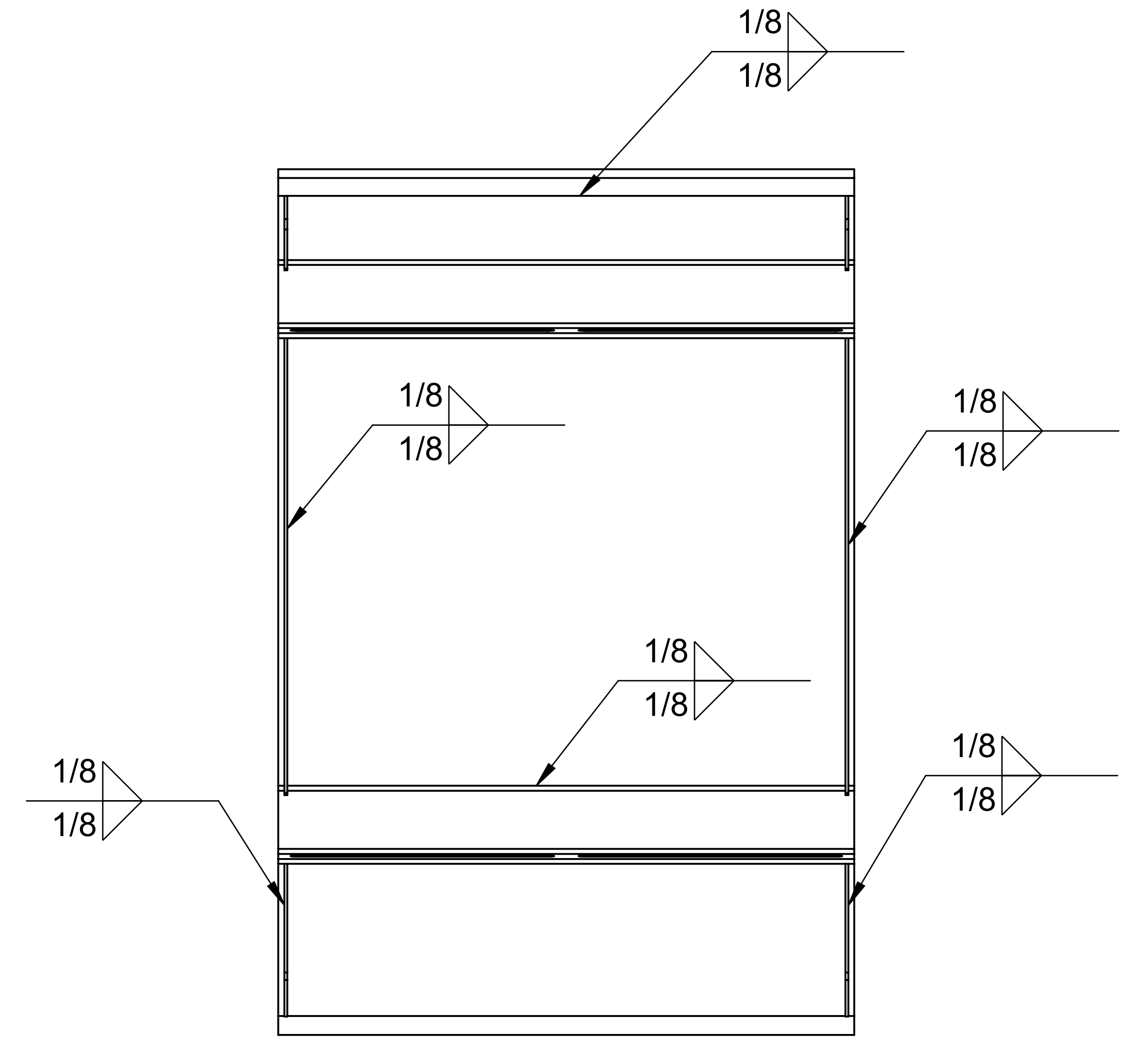


DETAIL A
SCALE 1 : 1





NOTES:

1. UNLESS OTHERWISE NOTED, DIMENSIONS SHOWN IN FT-IN TO INSIDE OF THE STRUCTURE
2. DO NOT SCALE DRAWINGS
3. IN THE EVENT THAT THE WELD INSTRUCTIONS ARE NOT CLEAR, A GENERAL RULE CAN BE FOLLOWED TO APPLY A 1/8" FILLET WELD TO ALL PERPENDICULAR SURFACES SURFACES
4. GRIND WELDS TO SMOOTH SURFACE ON MOLD SURFACE
5. WELD INSTRUCTIONS ARE IDENTICAL FOR 6", 12", 24", AND 48" INSERT PANELS

STRUCTURAL COMPOSITE TECHNOLOGIES LTD. RESERVES PROPRIETARY RIGHTS ON THIS DRAWING OR ANY PART OF THE INFORMATION CONTAINED THERON. THIS DRAWING SHALL BE CONSIDERED CONFIDENTIAL MATERIAL AND IS NOT TO BE USED FOR COMPETITIVE BIDDING NOR FOR USE WITH ANY PROCUREMENTS OTHER THAN FROM STRUCTURAL COMPOSITE TECHNOLOGIES LTD.

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	REVISION	DATE

STRUCTURAL Composite Technologies Ltd

FIBERGLASS FABRICATION WINNIPEG, CANADA

CUSTOMER: STRUCTURAL COMPOSITE TECHNOLOGIES

DESCRIPTION: INSERT PANEL WELD ASSEMBLY

DRAWN	CLIENT PO NO.
NC	N/A

DATE	SCALE	PROJECT NO.	DRAWING NO.	REV.
2019-11-30	1:8	N/A	0013	01

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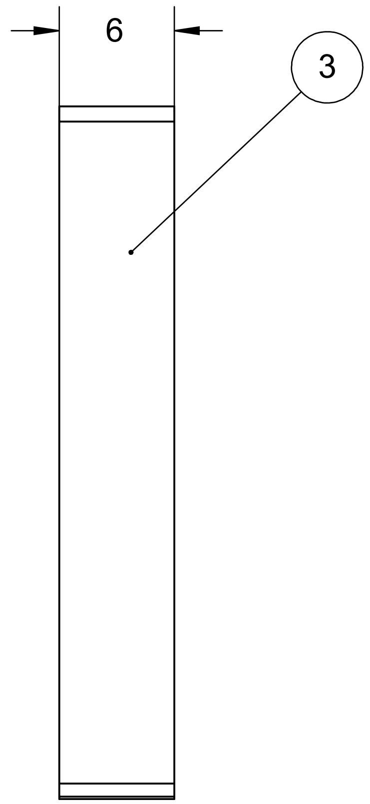

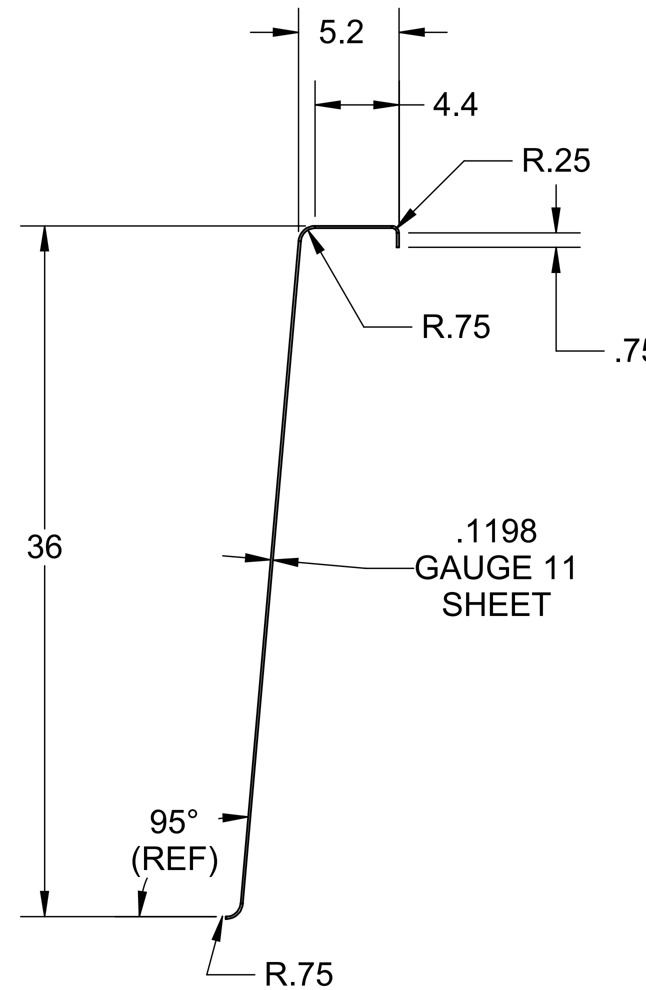

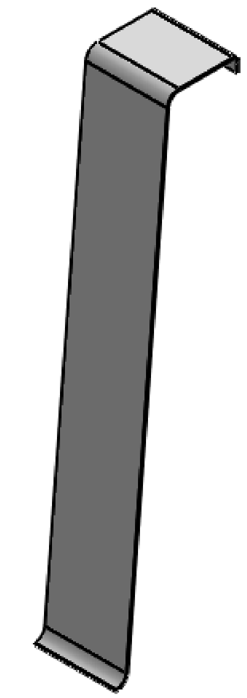

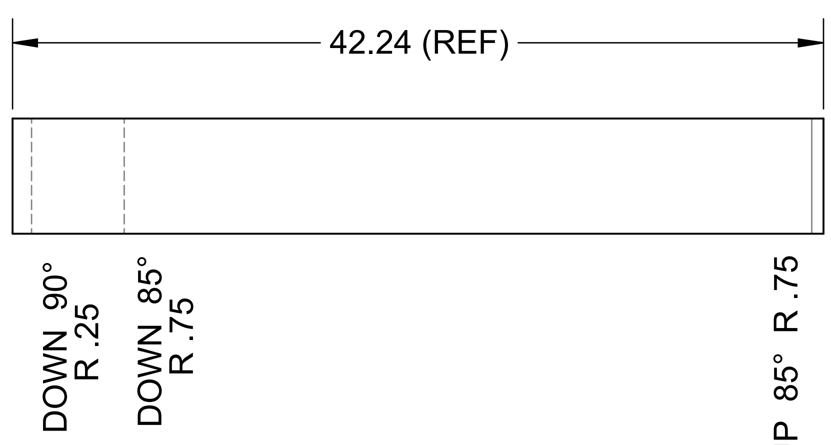

FLAT PATTERN

NOTES:

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STRUCTURAL Composite Technologies Ltd

FIBERGLASS FABRICATION WINNIPEG, CANADA

CUSTOMER: STRUCTURAL COMPOSITE TECHNOLOGIES		DESCRIPTION: INSERT PANEL WELD ASSEMBLY		
DRAWN: NC	CLIENT PO NO.: N/A			
DATE: 2019-11-30	SCALE: 1:10	PROJECT NO.: N/A	DRAWING NO.: 0013	REV.: 01

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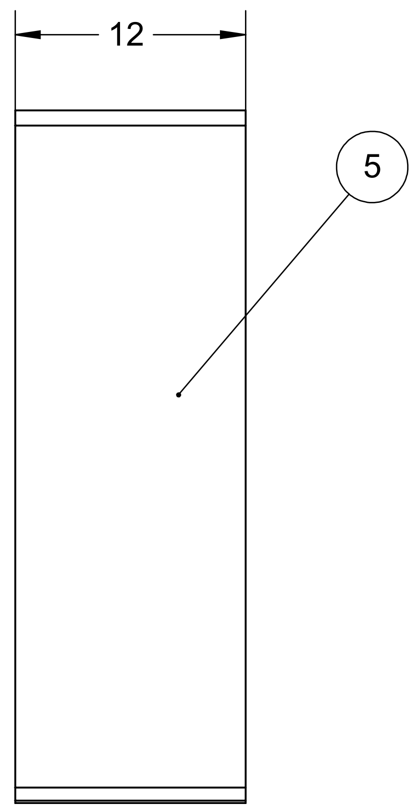
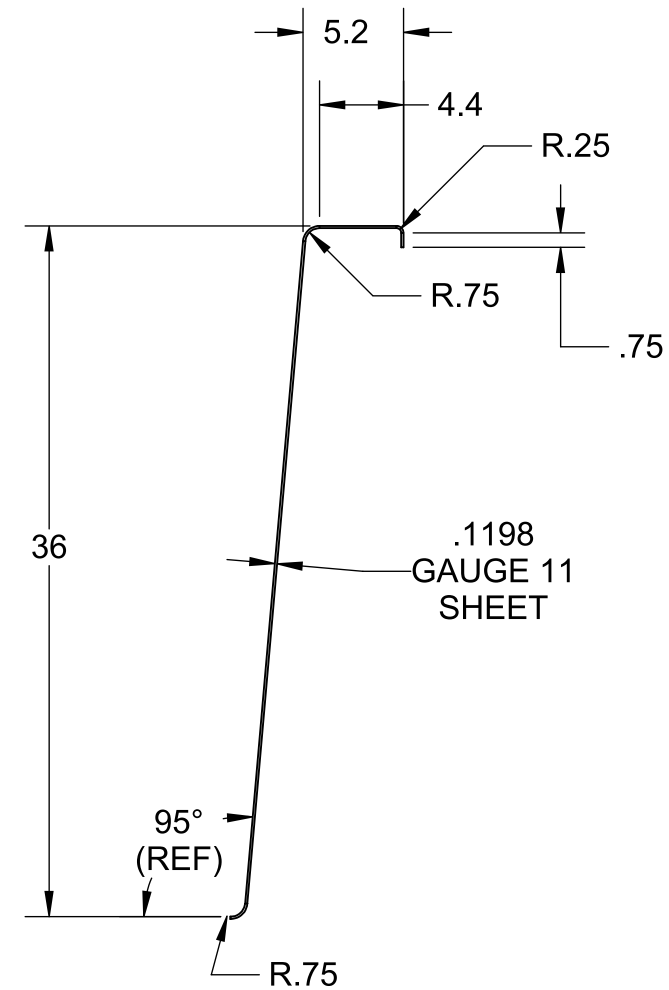
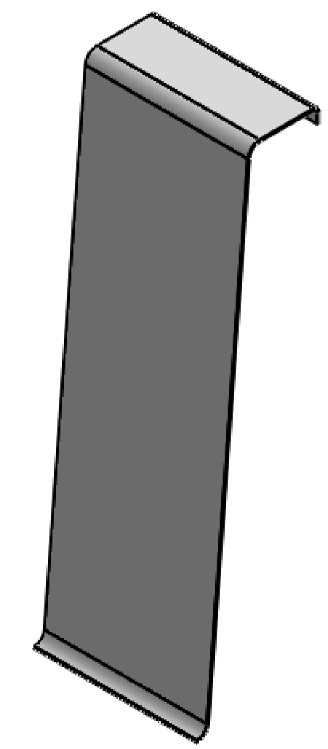
B







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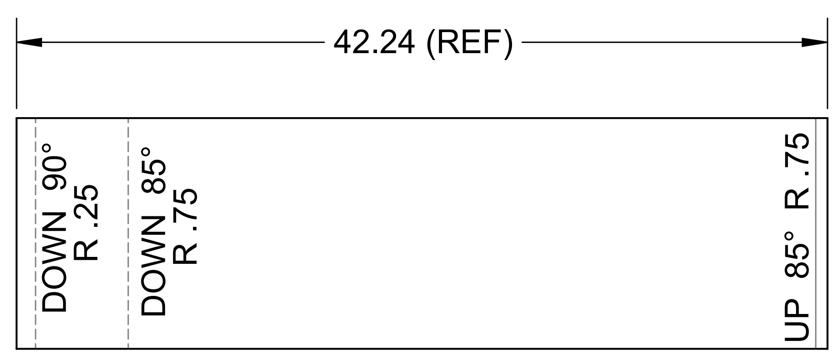

FLAT PATTERN

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STRUCTURAL Composite Technologies Ltd

FIBERGLASS FABRICATION WINNIPEG, CANADA

CUSTOMER:		DESCRIPTION		
STRUCTURAL COMPOSITE TECHNOLOGIES		INSERT PANEL WELD ASSEMBLY		
DRAWN: NC	CLIENT PO NO.: N/A			
DATE: 2019-11-30	SCALE: 1:5	PROJECT NO.: N/A	DRAWING NO.: 0013	REV.: 01

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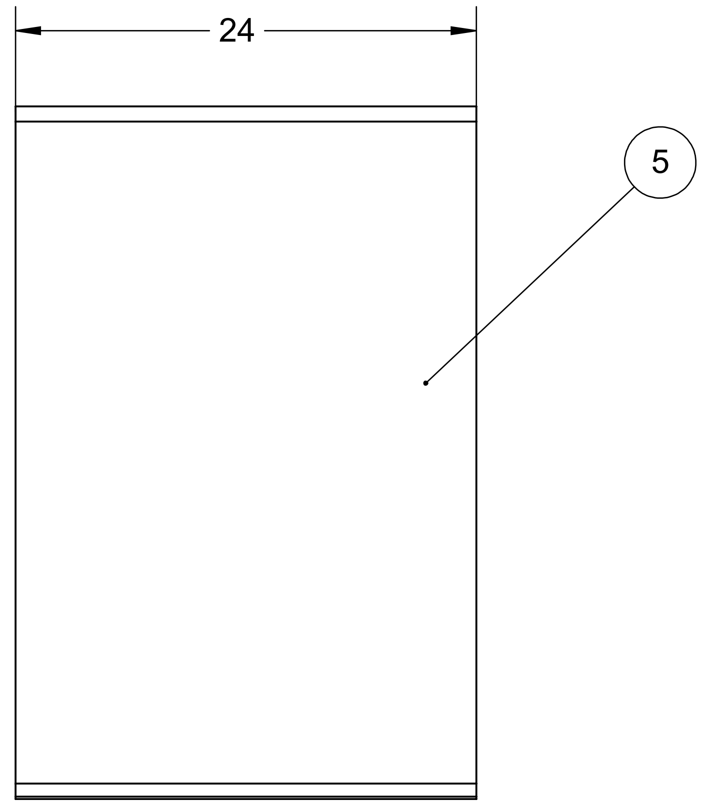

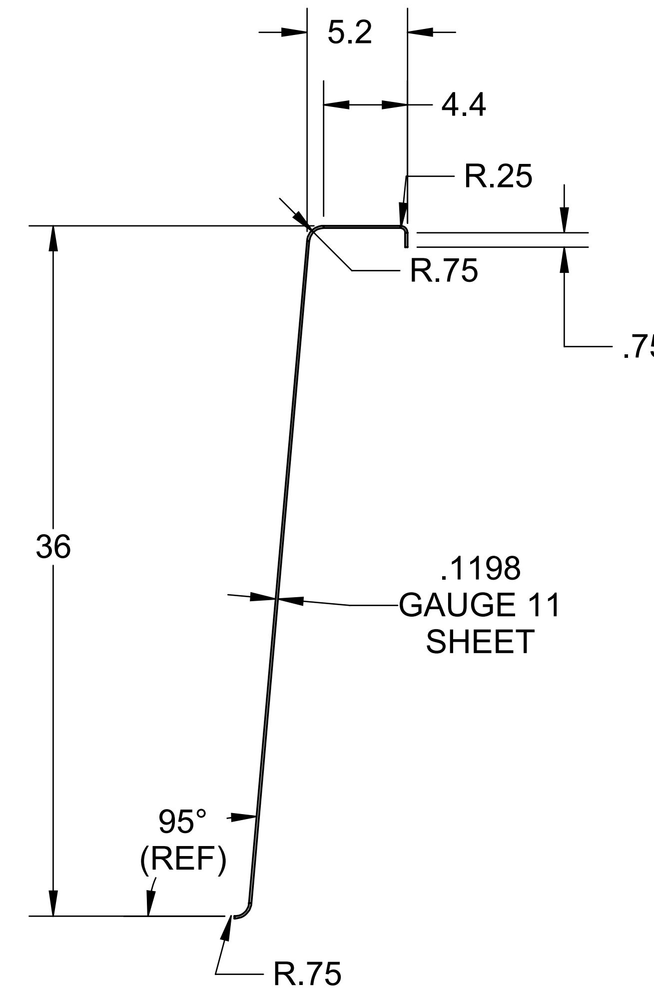

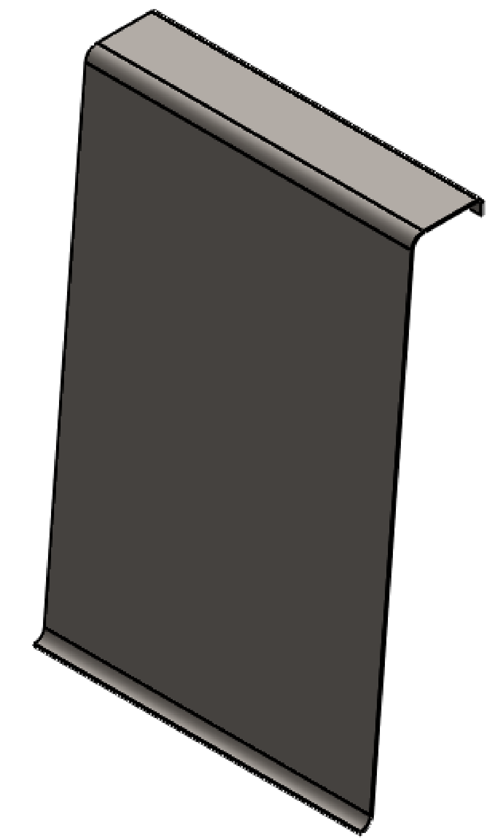

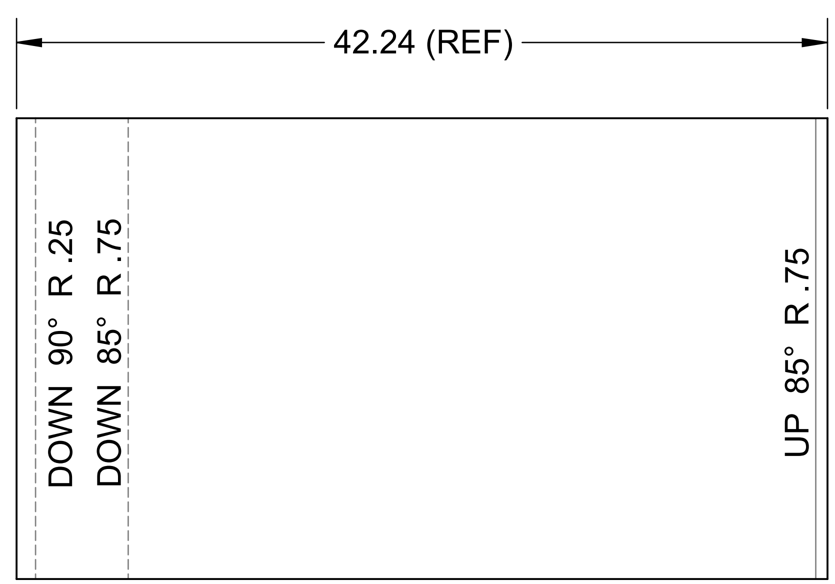

FLAT PATTERN

NOTES:

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STRUCTURAL Composite Technologies Ltd

FIBERGLASS FABRICATION — WINNIPEG, CANADA

CUSTOMER:		DESCRIPTION		
STRUCTURAL COMPOSITE TECHNOLOGIES		INSERT PANEL WELD ASSEMBLY		
DRAWN: NC	CLIENT PO NO.: N/A			
DATE: 2019-11-30	SCALE: 1:10	PROJECT NO.: N/A	DRAWING NO.: 0013	REV.: 01

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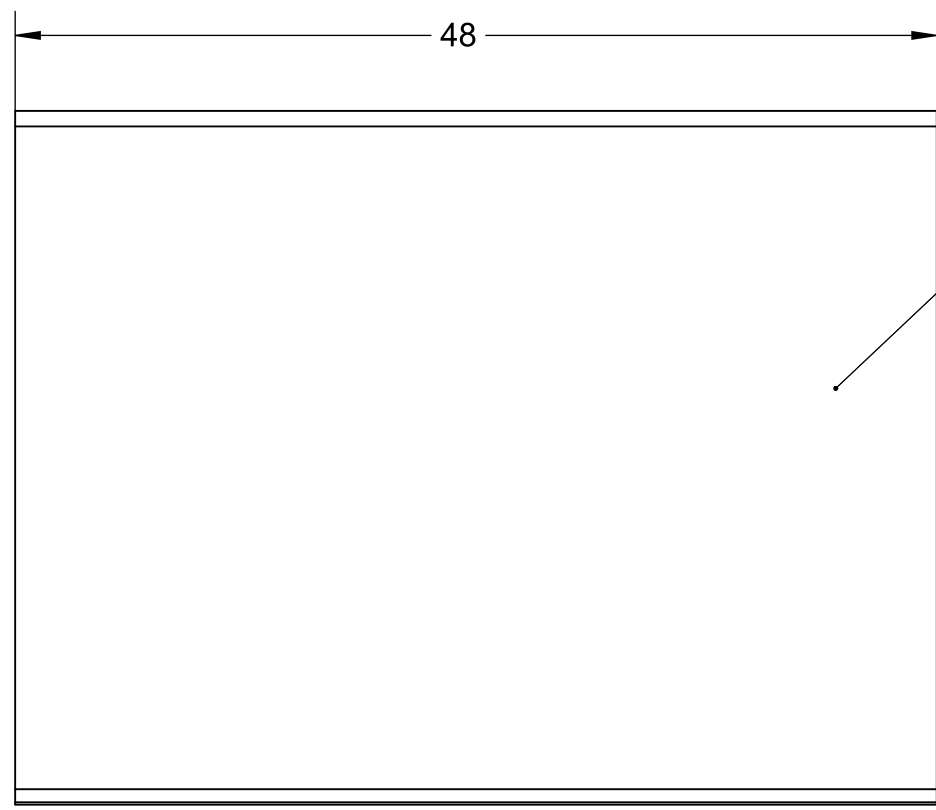

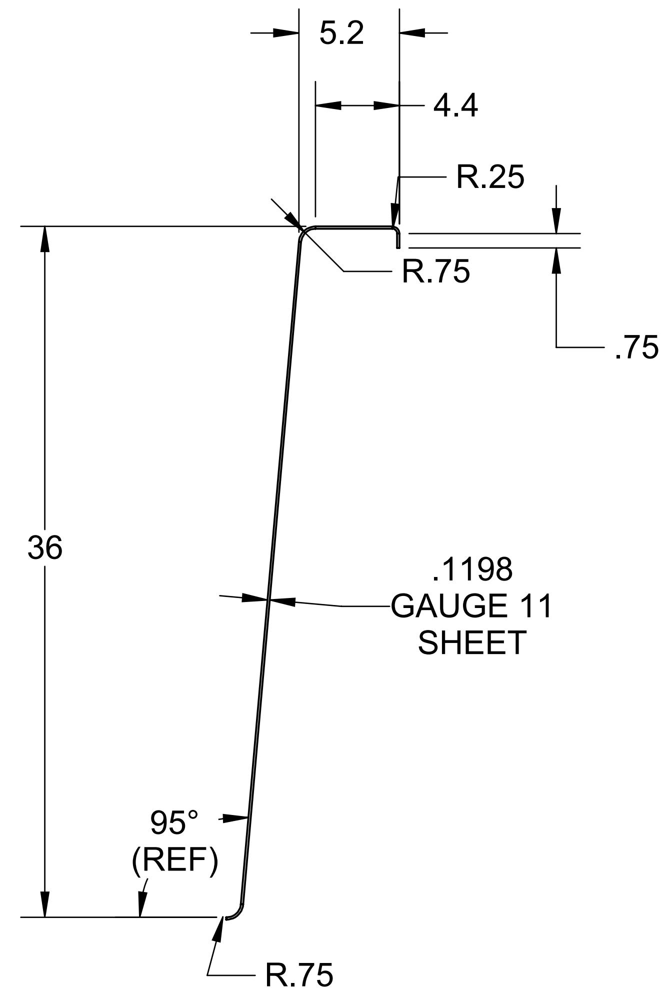

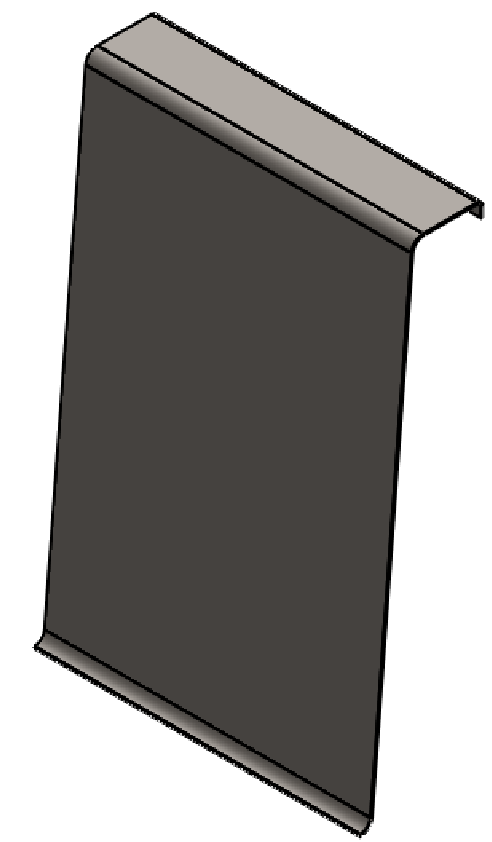

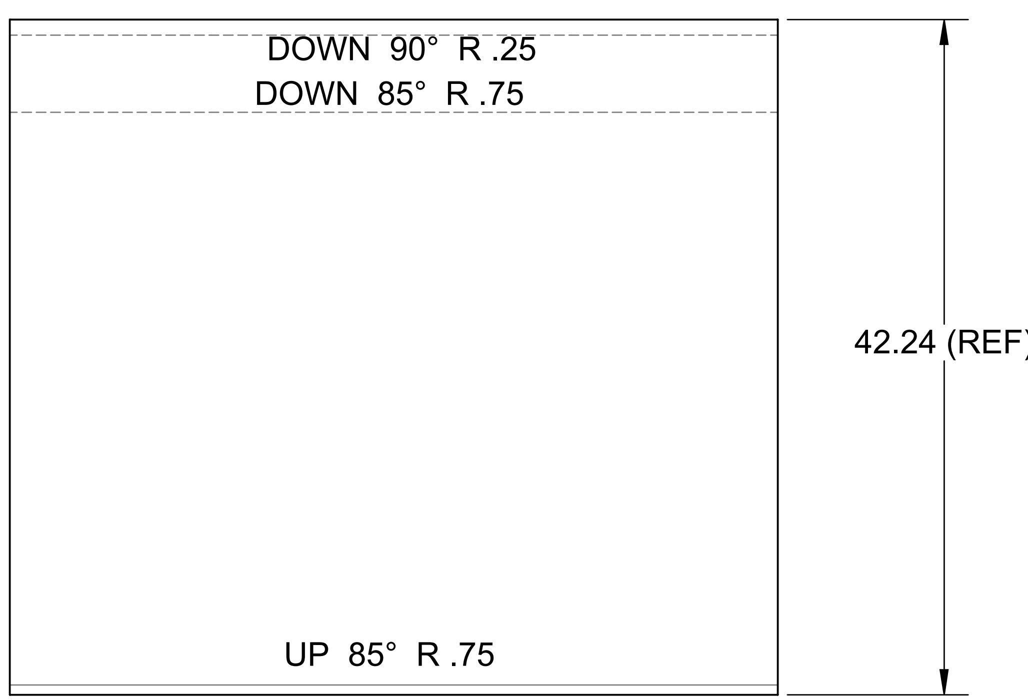

FLAT PATTERN

NOTES:

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STRUCTURAL Composite Technologies Ltd

FIBERGLASS FABRICATION WINNIPEG, CANADA

CUSTOMER: STRUCTURAL COMPOSITE TECHNOLOGIES

DESCRIPTION: INSERT PANEL WELD ASSEMBLY

DRAWN	CLIENT PO NO.			
NC	N/A			
DATE	**SCALE**	**PROJECT NO.**	**DRAWING NO.**	**REV.**
2019-11-30	1:10	N/A	0013	01

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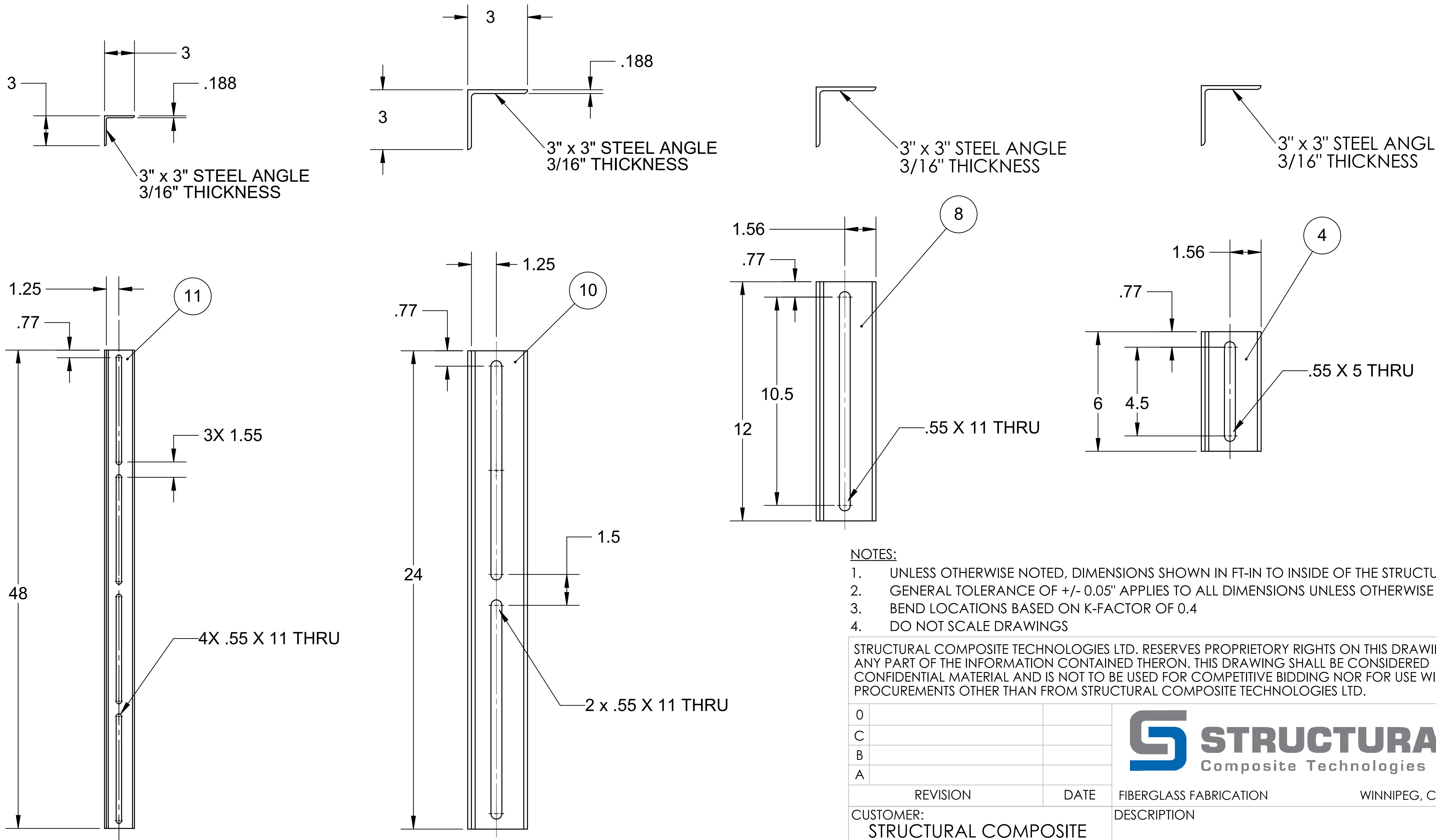

SCALE 1:10

NOTES:

1. UNLESS OTHERWISE NOTED, DIMENSIONS SHOWN IN FT-IN TO INSIDE OF THE STRUCTURE
2. GENERAL TOLERANCE OF +/- 0.05" APPLIES TO ALL DIMENSIONS UNLESS OTHERWISE NOTED
3. BEND LOCATIONS BASED ON K-FACTOR OF 0.4
4. DO NOT SCALE DRAWINGS

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STRUCTURAL Composite Technologies Ltd

FIBERGLASS FABRICATION WINNIPEG, CANADA

CUSTOMER:		DESCRIPTION		
STRUCTURAL COMPOSITE TECHNOLOGIES		INSERT PANEL WELD ASSEMBLY		
DRAWN: NC	CLIENT PO NO.: N/A			
DATE: 2019-11-30	SCALE: 1:5	PROJECT NO.: N/A	DRAWING NO.: 0013	REV.: 01

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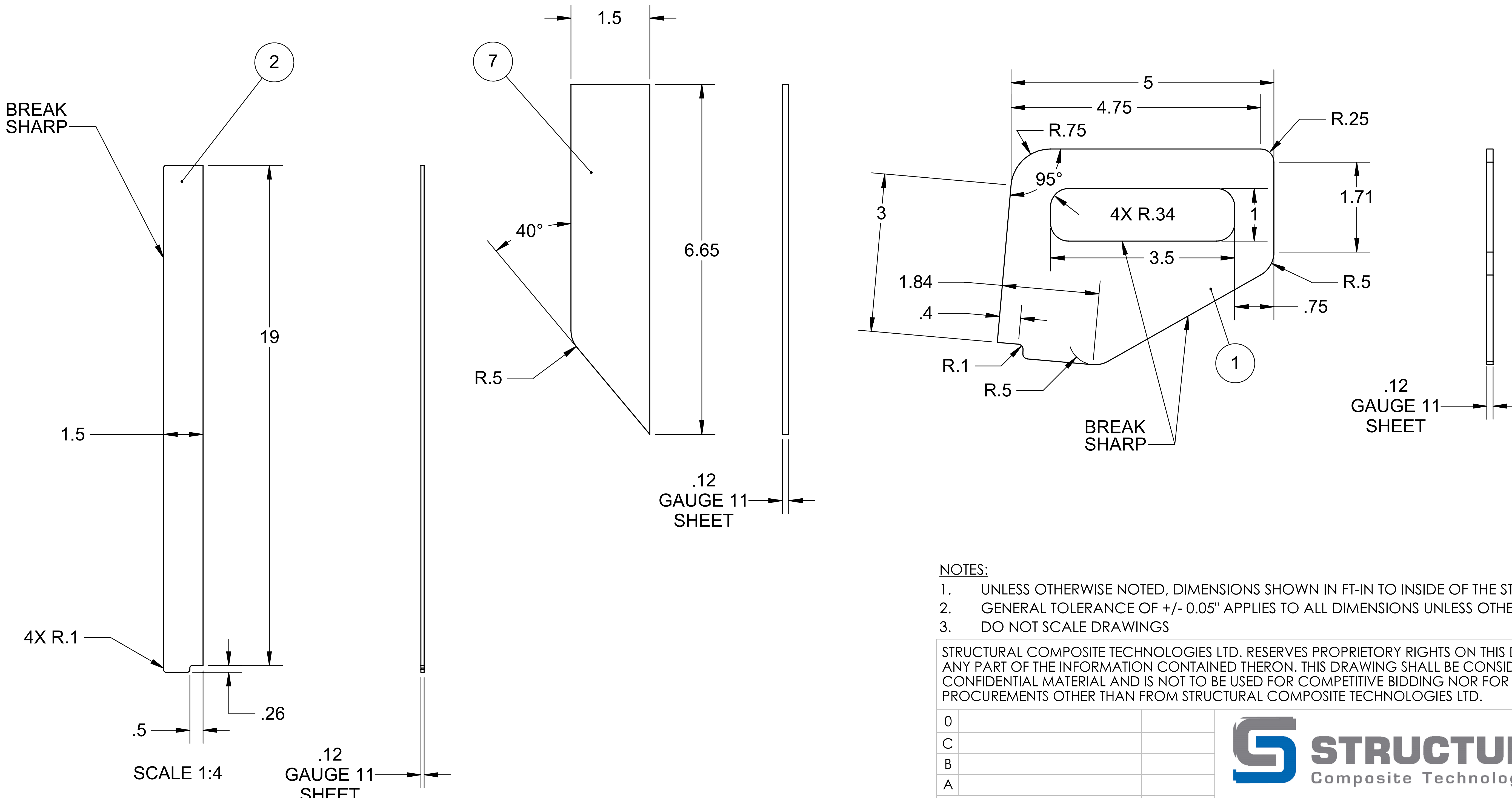

NOTES:

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STRUCTURAL Composite Technologies Ltd

FIBERGLASS FABRICATION WINNIPEG, CANADA

CUSTOMER: STRUCTURAL COMPOSITE TECHNOLOGIES		DESCRIPTION INSERT PANEL WELD ASSEMBLY		
DRAWN NC	CLIENT PO NO. N/A			
DATE 2019-11-30	SCALE 1:2	PROJECT NO. N/A	DRAWING NO. 0013	REV. 01

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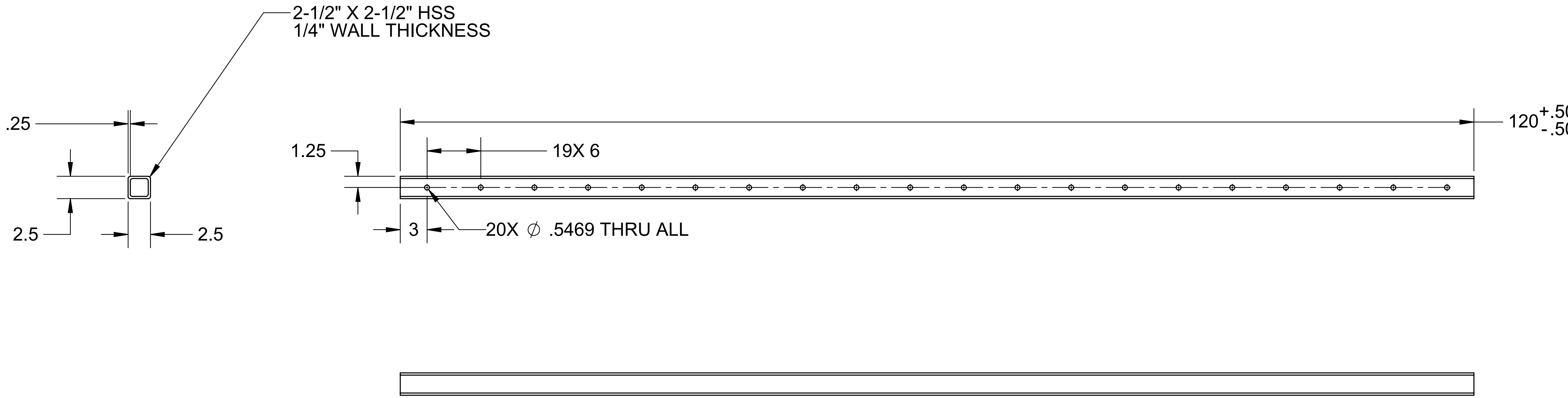

NOTES:

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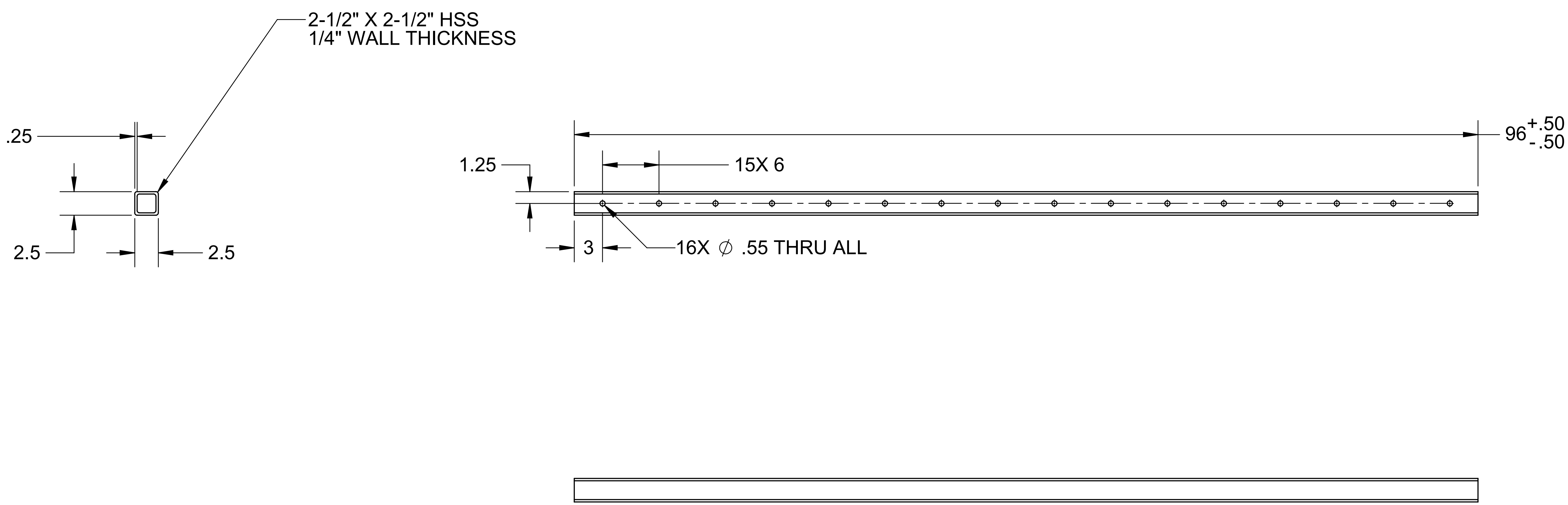
STRUCTURAL Composite Technologies Ltd

FIBERGLASS FABRICATION WINNIPEG, CANADA

CUSTOMER:		DESCRIPTION		
STRUCTURAL COMPOSITE TECHNOLOGIES		120" GUIDE RAIL		
DRAWN: NC	CLIENT PO NO.: N/A			
DATE: 2019-11-30	SCALE: 1:12	PROJECT NO.: N/A	DRAWING NO.: 0014B	REV.: 01

SOLIDWORKS Educational Product. For Instructional Use Only.



NOTES:

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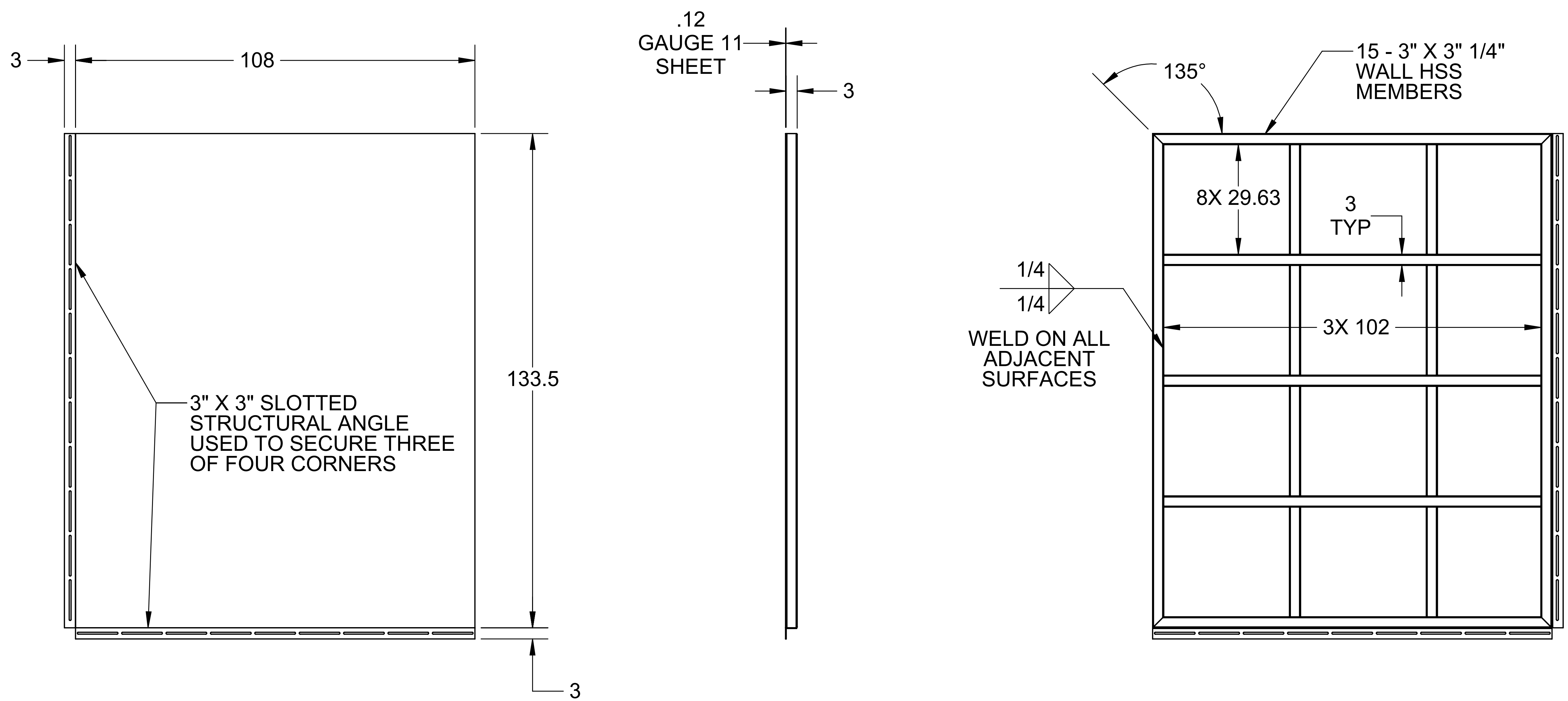
STRUCTURAL Composite Technologies Ltd

FIBERGLASS FABRICATION — WINNIPEG, CANADA

CUSTOMER: STRUCTURAL COMPOSITE TECHNOLOGIES		DESCRIPTION: 96" GUIDE RAIL		
DRAWN: NC	CLIENT PO NO.: N/A			
DATE: 2019-11-30	SCALE: 1:12	PROJECT NO.: N/A	DRAWING NO.: 0014A	REV.: 01

SOLIDWORKS Educational Product. For Instructional Use Only.



STRUCTURAL COMPOSITE TECHNOLOGIES LTD. RESERVES PROPRIETORY RIGHTS ON THIS DRAWING OR ANY PART OF THE INFORMATION CONTAINED THERON. THIS DRAWING SHALL BE CONSIDERED CONFIDENTIAL MATERIAL AND IS NOT TO BE USED FOR COMPETITIVE BIDDING NOR FOR USE WITH ANY PROCUREMENTS OTHER THAN FROM STRUCTURAL COMPOSITE TECHNOLOGIES LTD.

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STRUCTURAL Composite Technologies Ltd

FIBERGLASS FABRICATION — WINNIPEG, CANADA

CUSTOMER:	DESCRIPTION
STRUCTURAL COMPOSITE TECHNOLOGIES	Custom Base Frame

DRAWN	CLIENT PO NO.	DATE	SCALE	PROJECT NO.	DRAWING NO.	REV.
NC	N/A	2019-11-30	1:33.3	N/A	0016	01

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APPENDIX C: Assembly and Maintenance Instructions

Appendix C includes the assembly instructions for the Adjustable Mold. A step by step guide is included, starting from initial setup and ending at preparation prior to FRP T-Pad production. Maintenance instructions are briefly stated. Refer to SCTs designated personnel for specifics on mold maintenance instructions. Also included are examples of intermediate, maximum and minimum size configurations of assembled molds to aid with assembly. The information in this document is only a recommendation, SCT personnel may modify the procedures as needed.

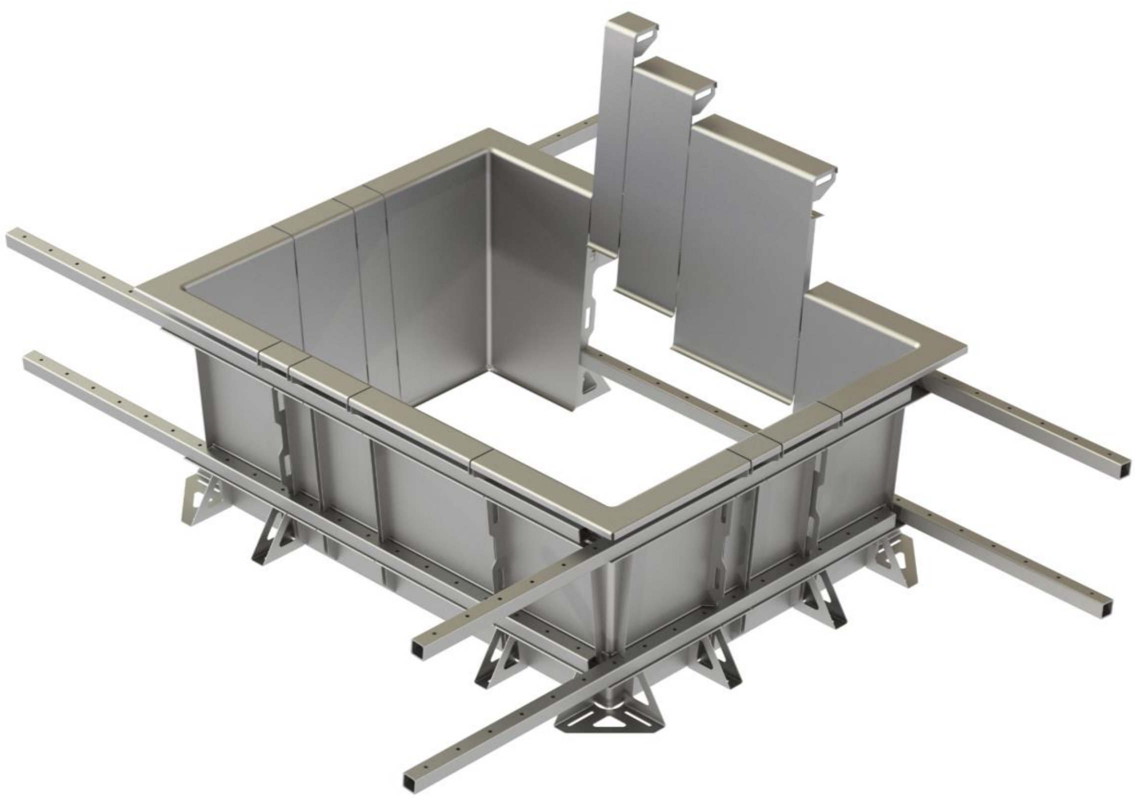

Figure 1. The Adjustable Mold with Insert Panel Assembly's being placed.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Name	**Symbol/Definition**
Inches	in or ”
Feet	ft or ’
Pound-mass	lbm
Part Number	PN
Structural Composite Technologies	SCT
Fiber Reinforced Polymer	FRP
Transformer Pad	T-Pad
Bill of Materials	BOM
Hollow Structural Section	HSS

C-1. ASSEMBLY INSTRUCTIONS

(Estimated Assembly Time: 55-110 minutes)

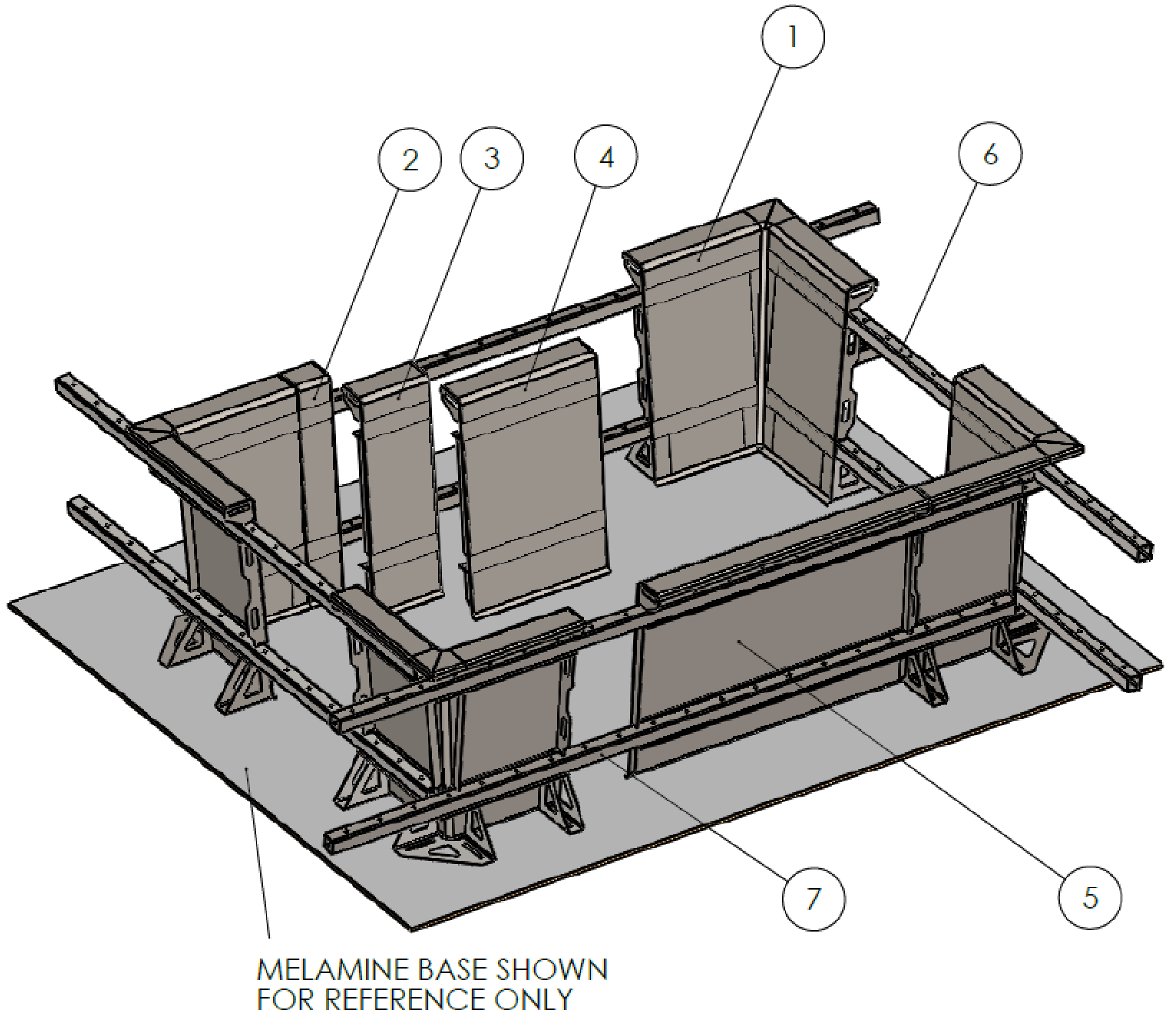

Figure 2. Assembly parts in bill of materials

TABLE I: BILL OF MATERIALS

Item Number	Part Number (PN)	Description	Quantity
1	0009	Corner Assembly	4
2	0013A	6” Insert Panel Assembly	4
3	0013B	12” Insert Panel Assembly	4
4	0013C	24” Insert Panel Assembly	4
5	0013D	48” Insert Panel Assembly	4
6	0014A	96” Guide Rail	4
7	0014B	120” Guide Rail	4

C-1.1 STEP 1 – Select Mold Size

The Insert Panels Assembly's (PN 0013) are used to adjust the size of the mold walls to a desired size. Figure 3 shows the different sizes of Insert Panels Assembly's available.

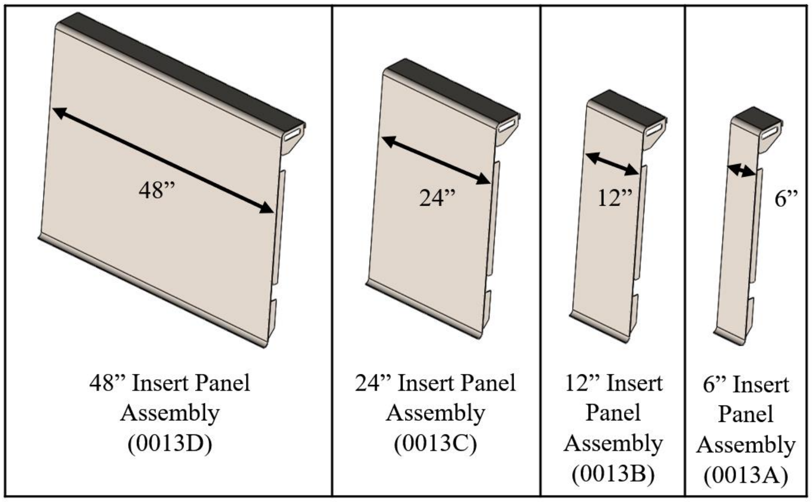

Figure 3. Insert Panel Sizes Available

Table II includes a selection table to determine the number of Insert Panels Assembly's required for a desired mold wall size. Selection is based on producing an FRP T-Pad with the least amount of seems.

TABLE II: RECOMMENDED INSERT PANEL SELECTION TABLE

Mold Size (L or W) Per Wall	6" Insert Panel Quantity	12" Insert Panel Quantity	24" Insert Panel Quantity	48" Insert Panel Quantity
3ft	-	-	-	-
3.5ft	1	-	-	-
4ft	-	1	-	-
4.5ft	1	1	-	-
5ft	-	-	1	-
5.5ft	1	-	1	-
6ft	-	1	1	-
6.5ft	1	1	1	-
7ft	-	-	-	1
7.5ft	1	-	-	1
8ft *	-	1	-	1
8.5ft	1	1	-	1
9ft	-	-	1	1
9.5ft	1	-	1	1
10ft **	-	1	1	1

*Mold maximum designed width
**Mold maximum designed length

C-1.2 STEP 2 – Mobilization and Corner Placement

(Estimated time: 10-20 minutes)

The Corner weld assembly pieces (PN 0009) create the corners of the mold and are the first items assembled on the base frame as seen in Figure 4. Mobilization and corner placement should be carried out as follows:

- Transport the corner assemblies and required insert panels to the location which the mold will be fabricated. Transport can be done be hand or using a forklift.
- Place the four Corner Assembly pieces (PN 0009) on the melamine base, use designated lifting handles. The corners should be aligned accurate enough that the guide rails are able to sit on the structural angles attached to each corner assembly without skewing.
- Position the four Corner Assembly pieces (PN 0009) with the inside face facing each other.
- NOTE: Corner assembly pieces are 100lbs each, two people required to lift.

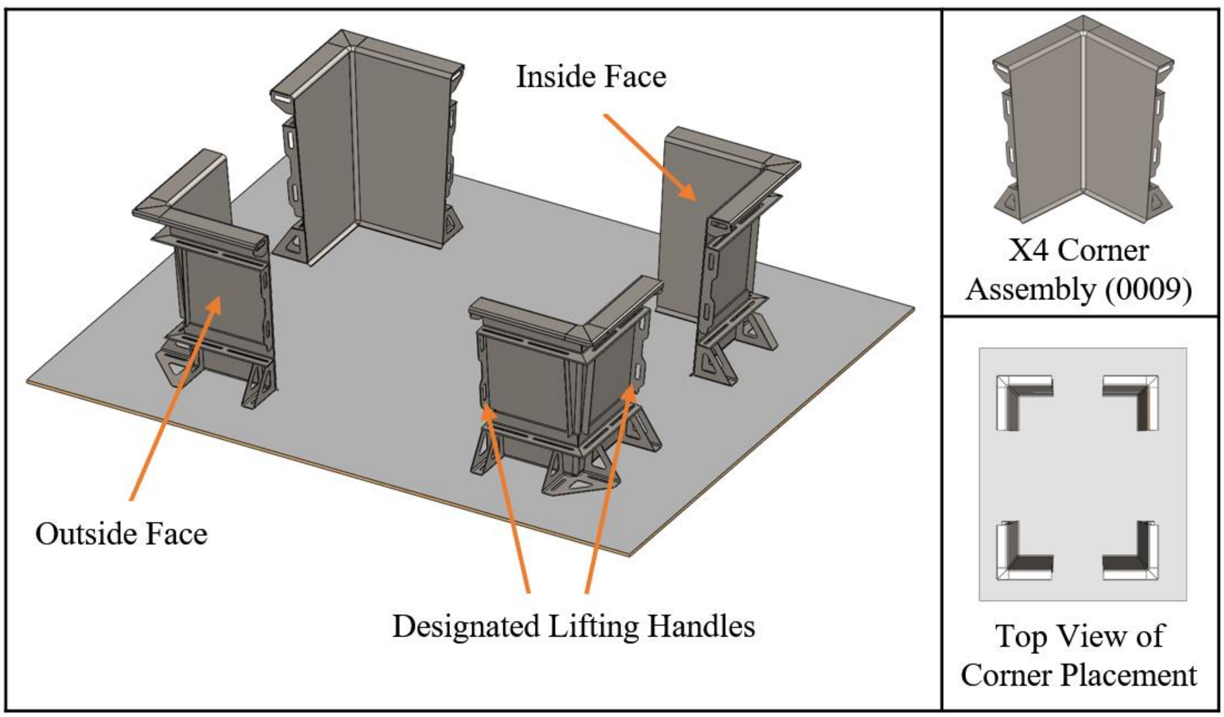

Figure 4. Corner Assembly Placement

C-1.3 STEP 3 – Attach Guide Rails

(Estimated 10-20 minutes)

The Guide Rail's (PN 0014A and 0014B) align the Corner Assembly pieces (PN 0009) and are used to mount the Insert Panel Assembly's together to create the mold. As seen in Figure 5 and Figure 6,

- Place two 120" Guide Rails (PN 0014A) and four 96" Guide Rails (PN 0014B) in the alignment supports located on the Corner Assembly pieces (PN 0009).
- Position the guide rails so the ends protruding out do not interfere with each other.
- Install only three sides of the Guide Rails as access to the inside of the mold is needed when aligning and securing the Insert Panel Assembly's.
- NOTE: It is recommended that two people align and secure the guide rails for best alignment of mold.
- Secure the Guide Rail's to the Corner Assembly piece's with either bolts, pins or clamps.
- Bolts and pins are put through holes in the Guide Rails and slots in the angled Guide Rail supports on the back of the Corner Assembly pieces.

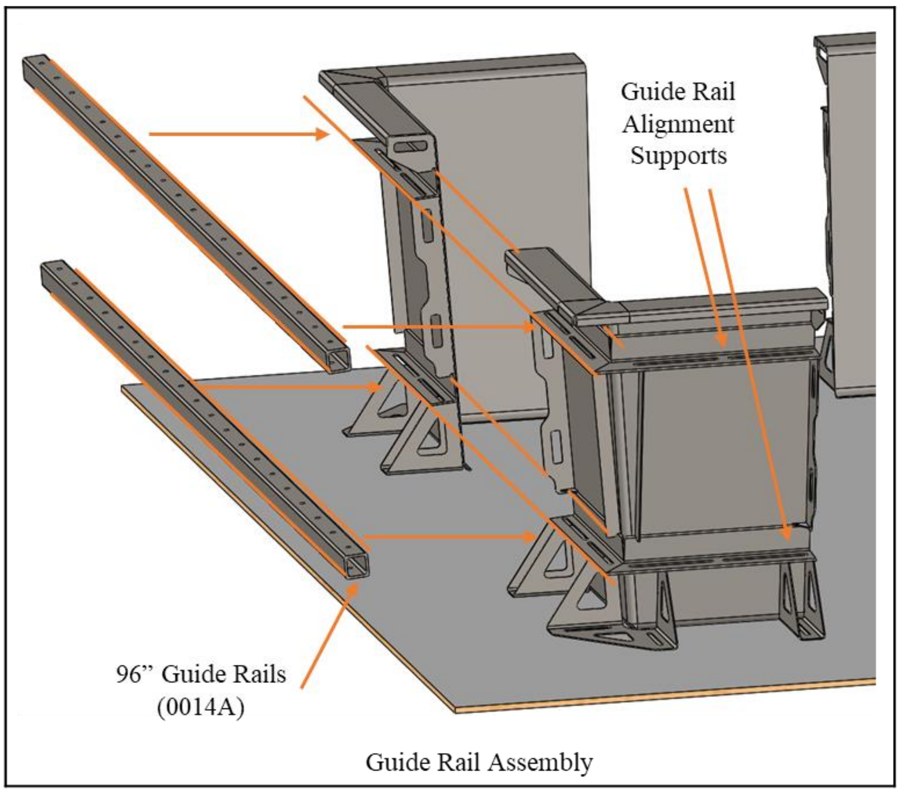

Figure 5. Guide Rail placement on angled supports

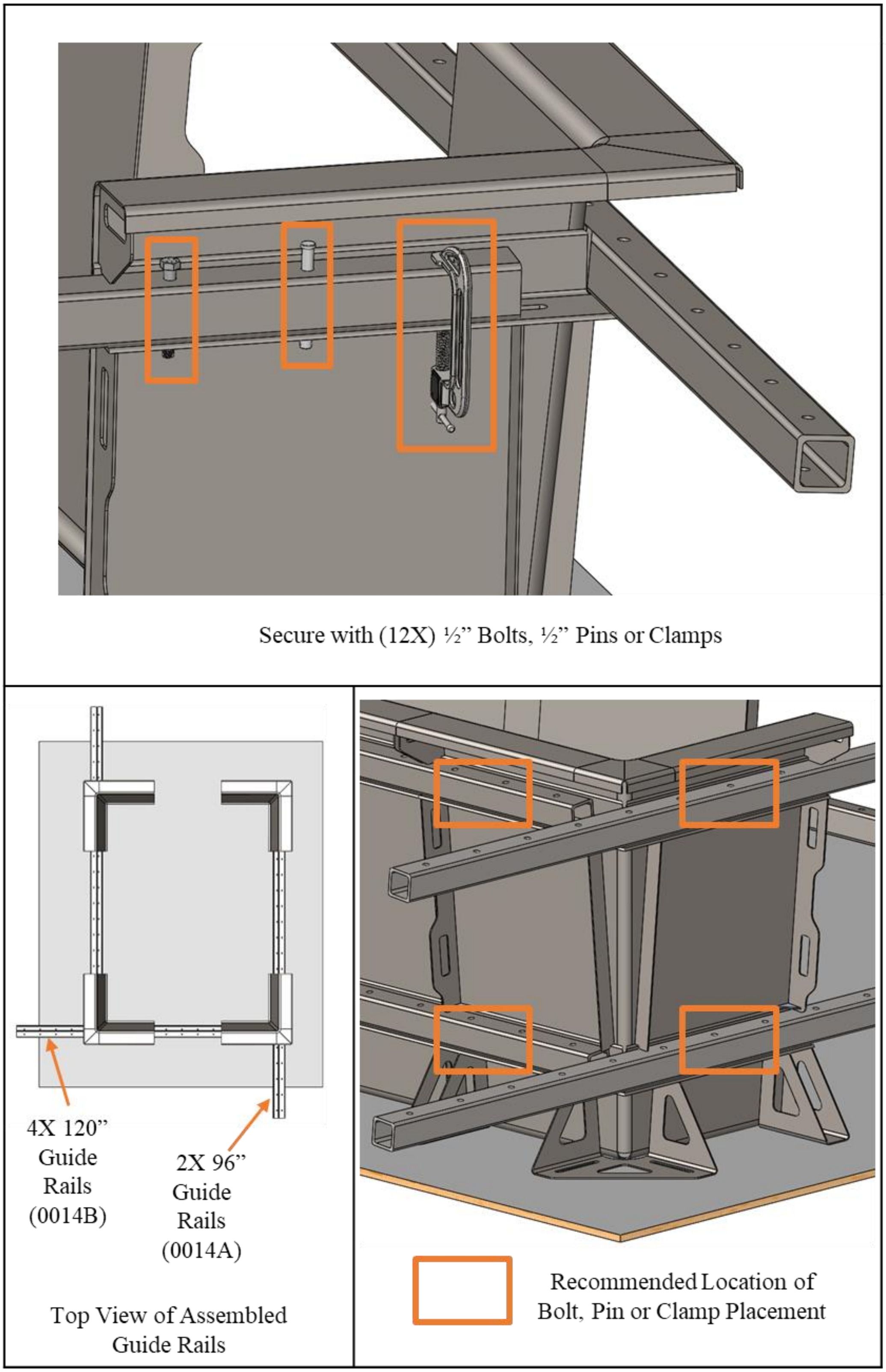

Figure 6. Guide rail assembly

C-1.4 STEP 4 – Insert Panel Placement

(Estimated 15-30 minutes)

The selected Insert Panel Assembly pieces in STEP 1 are used to adjust the mold to a desired size. As seen in Figure 7 and Figure 8,

- Place the selected Insert Panel Assembly pieces inside the mold using the designated lifting handles.
- Align the slots in the back of the selected Insert Panel Assembly pieces against the Guide Rails.
- Align and secure the Insert Panel and Corner Assembly's as close to square as possible and minimize the gaps in order to produce a high-quality mold.
- Secure the Insert Panel Assembly pieces to the Guide Rails with either bolts, pins or clamps.
- Bolts and pins are put through the holes in the Guide Rails and slots in the angled Guide Rail supports on the back of the Insert Assembly pieces, similar to securing Corner Assembly pieces to Guide Rails in STEP 3.
- NOTE: It is recommended that two people align and secure the Insert Panel Assembly's, be careful not to dent the bottom radius on the Insert Panel Assembly's when moving.

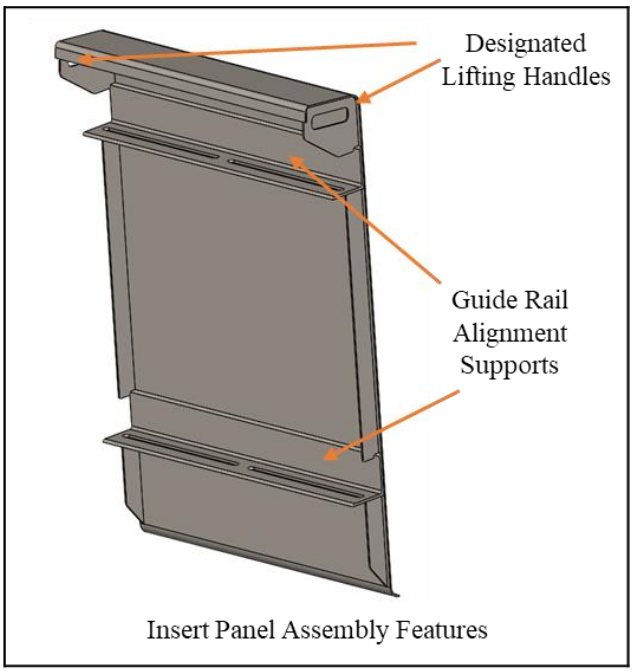

Figure 7. Insert Panel Assembly lifting and alignment features

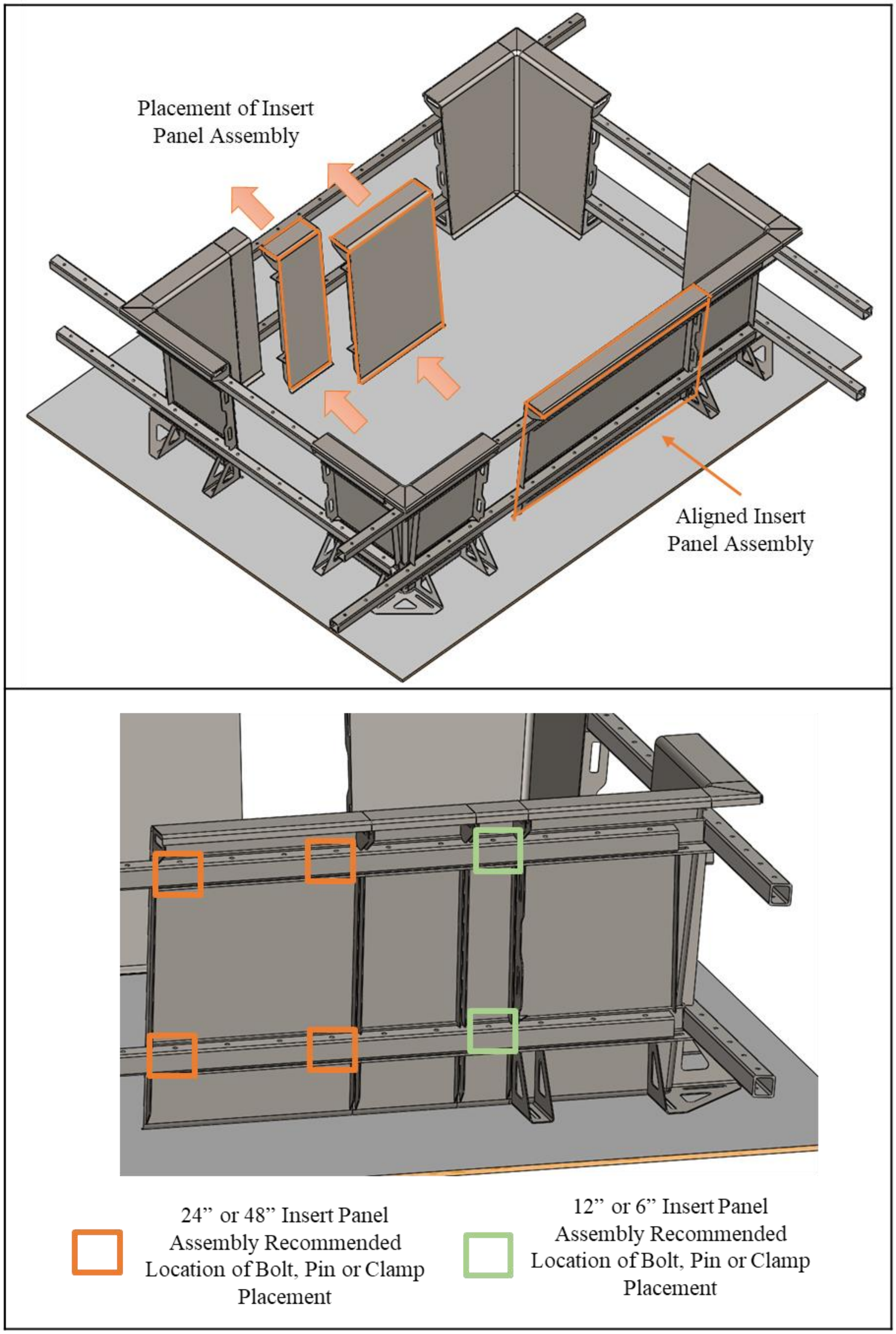

Figure 8. Aligning and Securing Insert Panel Assembly’s

C-1.5 STEP 5 – Final Guide Rail & Insert Panel

(Estimated 5-10 minutes)

Complete STEP 3 for the final Guide Rail and either have one person go inside the mold or place the Insert Panel Assembly's over top of the Guide Rails. Align and secure the final wall of Insert Panels to the Guide Rails as in STEP 4.

C-1.6 STEP 6 – Adjustment of Mold alignment

(Estimated 10-20 minutes)

Measure the mold size for accuracy and to check that the installed number of panels is correct. Check that adjacent walls are square with each other. Minor adjustments to the corner alignment should be made if the corners are not square to ensure optimal geometry for the finished transport pads. Once alignment is confirmed bolt or clamp the corners to the base frame to maintain alignment.

C-1.7 STEP 7 – Mold Preparation

(Estimated 10-15 minutes)

In order to produce a high-quality mold, it is recommended that all seems between Insert Panel and Corner Assembly's are taped over. Also tape over the bottom radius of the Insert Panel, Corner Assembly's and the melamine base. An example of the taping locations is shown in Figure 9. Standard masking tape is recommended. Melamine base not shown. Additionally, it is recommended that the outside of the mold is protected during FRP T-Pad production. The use of poly-wrap is recommended. Before the application of a gel coat refer to SCTs designated personnel as carbon steel molds require different types of coatings than the standard fibreglass molds SCT currently uses. Follow SCTs standard fabrication procedure from this point on.

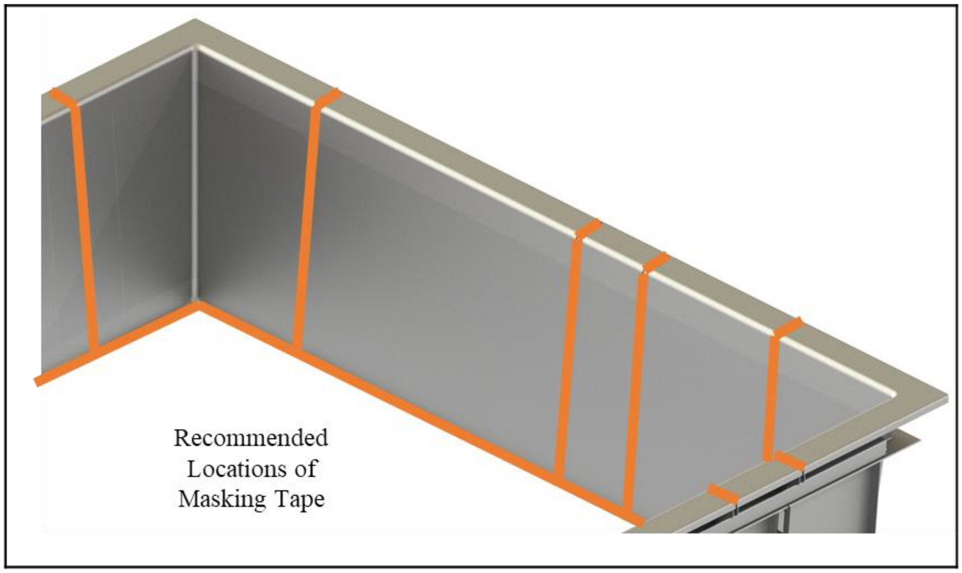

Figure 9. Example of recommended locations for masking tape

C-2. MAINTINENCE INSTRUCTIONS

- As the mold is made of Carbon Steel (AISI 1020) general maintenance procedures will need to be followed as per SCTs current carbon steel molds.
- It is not recommended to store the mold in an outdoor environment.
- Refer to SCTs designated personnel for specifics on mold maintenance instructions.

C-3. EXAMPLES OF ASSEMBLED MOLDS

Figure 10, Figure 11 and Figure 12 show examples of intermediate, maximum and minimum size configurations of assembled molds. It is recommended to use optional additional sized Guide Rails to limit the Guide Rails protruding out as seen in the minimum sized mold shown. Note the melamine base is not shown.

Figure 10. Intermediate size mold configuration (fully assembled)

Figure 11. Maximum size mold configuration (fully assembled)

Figure 12. Minimum size mold configuration (fully assembled) *

* It is recommended to use optional additional sized Guide Rails to limit the Guide Rails protruding out.

APPENDIX D: Detailed Cost Breakdown and Quotations

Appendix D contains all the information related to the cost analysis of the size adjustable mold. Section D-1 contains an overview of the approach used to determine the payback period of the carbon and stainless steel designs given two different economic scenarios. Section D-2 contains the budget quotes from Taj Industrial used to obtain an estimate of the final design cost.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

D-1. ECONOMIC MODEL

The following economic assessment was conducted using sales data and prices for previous custom T-Pads produced by SCT from January 2018 to September 2019. The dataset included T-Pad dimensions, as well as estimated carpentry hours, lumber and fiberglass costs to arrive at the production cost.

The Excel model requires averaged values from the dataset to apply to multiple economic scenarios that vary the sales price, units sold annually, adjustment time and material costs. To eliminate non-relevant data the spreadsheet was set up to eliminate data points that would not be addressed through the maximum dimensions of a 10 x 8 ft mold. Table I displays the period averages and totals for the labor hours, costs, and revenue associated with custom T-Pad production as a function of a 120-inch or 10 ft maximum mold length.

TABLE I: HISTORIC CUSTOM T-PADS SALES DATA AND ANALYSIS ASSUMPTIONS

Assumptions and Constants				
Mold Length [in]	**Labor Cost ($/h)**	**Sales Period [years]**	**Desired ROI (years)**	
120	45	1.75	2	
SCT Data Averages				
Adjustable mold production over Sales Period	**Average Estimated Labor Hours**	**Average Material Cost ($)**	**Average Mold Cost ($)**	**Average Sale Price ($/Unit)**
10	11.3	170	$ 678.50	$ 4,989.20
Average T-pad Max. Dimension	**Total Estimated Labor Hours**	**Total Material Cost ($)**	**Total Costs ($)**	**Total Revenue ($)**
98	116	1700	$ 6,920.00	$ 49,892.00

Notably, this assessment does not account for the material and labor associated with spray-up fabrication or overhead. To simplify the problem, it was assumed that these would be constant between the current custom process and the custom fabrication process using the adjustable mold.

Using averaged sales data, the U of M Team prepared several economic scenarios to identify potentially feasible budgets using tabulated costs for a maximum payback period of three years. Table II shows the payback period for the current volume of business where the mold allows for the raw material costs to be reduced by 15% and the setup time is reduced from 11.3 to 1 hours.

TABLE II: CONSERVATIVE ECONOMIC SCENARIO

SCT assumed sales price and sales volume					
	Economic Scenario Assumptions				
	Assume Sales Price remains the same				
	Assume Sales volume remains at 7 units per year				
	Conservatively assume mold adjustment time is 2 hours				
	Material costs are reduced by 15% (marginally accepted metrics)				
	Quantified Assumptions and Data				
	Assumed Sales Price ($/unit)	**Assumed Set-up (hours/unit)**	**Assumed Material Cost ($/unit)**	**Average Cost ($/unit)**	**Assumed Sales Volume (Units/year)**
	$4,989.2	2	$144.50	$234.50	7
	Budget				
	Current Annual Profit ($/year)	**New Annual Profit ($/year)**	**Payback period for $11,481.80 carbon steel mold (years)**	**Payback period for $16,712.64 stainless steel mold (years)**	
	$30,174.90	$33,282.90	**3.7**	**5.4**	

The results of this analysis show that annual profit will increase by $3,108 per year that covers the cost of the carbon steel ($11,481.80) and stainless steel ($16,712.64) molds over a period of 3.7 and 5.4 years.

A second feasible economic scenario proposed by SCT is an increase in the volume of sales from 7 to 10 units per year if the sales price is decreased by 20%. This decrease is possible as a result of the reduced materials and labor used. Table III shows the payback period for the projected sales volume of 10 units per year where the mold allows for the raw material costs to be reduced by 15% and the setup time is reduced from 11.3 to 2 hours.

TABLE III: OPTIMISTIC ECONOMIC SCENARIO

<table>
<tr><td rowspan="10">Least Conservative Estimate</td><td colspan="5">Economic Scenario Assumptions</td></tr>
<tr><td colspan="5">Assume Sales Price Decreases by 20%</td></tr>
<tr><td colspan="5">Assume Sales volume increases to 10 units per year as a result of a reduced lead time and improved quality</td></tr>
<tr><td colspan="5">Assume Mold Adjustment takes 2 hours</td></tr>
<tr><td colspan="5">Assume Material cost is reduced by 15%</td></tr>
<tr><td colspan="5">Quantified Assumptions and Data</td></tr>
<tr><td>Assumed Sales Price ($/unit)</td><td>Assumed Set-up (hours/unit)</td><td>Assumed Material Cost ($/unit)</td><td>Average Cost ($/unit)</td><td>Assumed Sales Volume (Units/year)</td></tr>
<tr><td>$3,991.36</td><td>2</td><td>$144.50</td><td>$234.50</td><td>10</td></tr>
<tr><td colspan="4">Budget</td><td></td></tr>
<tr><td>Current Annual Profit ($/year)</td><td><b>New Annual Profit ($/year)</td><td>Payback period for $11,481.80 carbon steel mold (years)</td><td>Payback period for $16,712.64 stainless steel mold (years)</td><td></td></tr>
<tr><td></td><td>$30,174.90</td><td>$37,568.60</td><td>1.6</td><td>2.7</td><td></td></tr>
</table>

With the projected increase in sales volume, SCT can expect a $7,393.70 increase in profit which will result in 1.6 year and 2.7-year payback periods for the carbon steel and stainless-steel molds respectively.

D-2. MOLD FABRICATION QUOTES

Budgetary quotes were provided by Taj Industrial, the original invoice is provided in this section for the carbon and stainless steel quotes shown in Figure 1 and Figure 2 respectively.

[redacted]

Figure 1. Fabrication quote from Taj Industrial for Carbon Steel

[redacted]

Figure 2. Fabrication quote from Taj Industrial for Stainless Steel