PINNED INCREMENTAL METAL FORMING

by

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ABSTRACT

PAUL CONNER STOCKHOFF. Pinned Incremental Metal Forming. (Under the direction of CHRIS BEORKREM)

Advanced design software allows designers to rapidly create huge numbers of design variations. However, these variations do not incorporate material and manufacturing limits, which are typically considered much later during the process of design documentation. By creating a method, which incorporates these limits during the design process, we avoid iterations that would be difficult, costly, or impossible to build. This method allows designers to work in a configured design space, which focuses on feasible designs.

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SECTION 1: INTRODUCTION

Advanced design software allows designers to rapidly create huge numbers of design variations. However, these variations do not incorporate material and manufacturing limits, which are typically considered much later during the process of design documentation. By creating a method, which incorporates these limits during the design process, we avoid iterations that would be difficult, costly, or impossible to build. This method allows designers to work in a configured design space, which focuses on feasible designs.

To test this method, this thesis focuses on a doubly curved with focus on saddle shaped self supporting structural skin systems created by forming sheet metal with an industrial robotic arm using Single Point Incremental Metal Forming (S.P.I.M.F). This system has the following advantages:

-Previous work exists both in our lab and by other researchers using S.P.I.M.F to form doubly-curved sheet metal.

-Saddle shaped surfaces cannot be unrolled onto plane surfaces without testing and verification

-A self-supporting single skin system simplifies and focuses the incorporation of material and structural analysis

This thesis begins by creating a metal positioning system to hold sheets for the use of S.P.I.M.F to form saddle shaped surfaces. A set of tests panels verifies the relationship between the formed piece and the initial forming geometry. The understanding gained these test will be incorporated as a set of parameters as a definition for *Grasshopper*. Finally, a saddle shaped panel is created from multiple panels to explore joining strategies and structural behavior.

The increased generation of complex building form has lead to a series of buildings that require the use of elaborate structural systems to allow for such unique forms to occur. This type of building relies solely on customized structural systems that are hidden by a skin. For example, *Frank Gehry's Fisher Center* uses an intricate structural framing system to allow for it's doubly curved surface to be generated. The building relies on a one-off structural system, which is later skinned. The complexity of the project required the design to be made, and then figured out how to be built. This type of design could be benefitted by the use of a structural skin system that relies solely on the skins own strength to support itself. For this type of system to function, an understanding of how the system works and its limits are a must. By incorporating those limits into a software package before hand would allow designers to design feasible projects, and not require sizeable engineering efforts needed to build complex forms.

To incorporate material and construction constraints in a computational based modeling process, this thesis creates a method which links material limits to the generation of form in advanced design software. This method incorporates and verifies relations between S.P.I.M.F metal forming techniques and Grasshopper/Rhinoceros modeling software.

Specifically, this thesis studies the formation of 20-gauge sheet metal using a modified version of single point incremental metal forming (S.P.I.M.F). This process uses an end effector mounted to a robotic arm that acts very similarly to a ball point pen to trace a set of contour lines into a piece of sheet metal. Traditionally, the piece of sheet metal is held as rigidly as possible, however in this work the piece of metal is pinned in four corners and held in place with the least amount of anchors. This allows for two unique outcomes. Firstly, the piece of metal has the ability to move much more during forming, which allows for greater depth deformation. Secondly, a larger portion of the sheet metal can be formed due to it not being clamped in a frame. The intersection of these two outcomes set up the area of study for this thesis.

The stretching of the metal during this process results in a mismatch in the geometry contained in the design software. By studying and understanding the change of the physical model, we can create a set of parameters in the computational model that will influence the form of both the initial sheet metal blank as well as the toolpath. In addition, the design software must be able to predict deformation of the free edges of the sheet metal blank. In order to prepare joining multiple pieces into a single saddle shaped surface. By taking both of these outcomes into account in the model, from the beginning, designers will have a clearer sense of the realities and possibilities of their designs from the beginning of the process.

Saddle shaped surfaces are inherently difficult to make and require the metal to be stretched instead of shaped. Currently, there is not a method at the architectural scale that is effective in producing custom saddle shaped metal components that can be correlated with design software. The shape of sheet metal blank needed to make saddle shaped pieces is difficult to predict due to stretching. We also require an understanding of how the material reacts to the forming process and the resulting “springback”. An understanding of structural performance is required during the design of a single skin system that can evaluate whether it supports its own weight and how additional layers of deformation can be correlated to high internal stress loads.

SECTION 2: LITERATURE REVIEW

Mass customization is often presented as the technique that will allow for many unique pieces to be built because it leverages digital fabrication’s ability to make a single high quality piece differently many times. While this is true, it is possible because the procedures on how to make the part are understood and all that is changing is a set of input variables. Greg Lynn’s *Embryological House* acts as a case study to show how there is a background logic applied to mass customization “design and manufacture objects that shared regulating principles but that also exhibited variety” (Shubert 2008). This background logic parallels the above proposed model because both frame the design environment by establishing a set of rules. While the rules differ between the works they both establish an understanding of how the designs will be built. That understanding in turn can be turned into the construction method used to produce the piece. To be able to mass customize a design, the limits of both manufacturing and materials must be taken into consideration. The proposed model could be used as a tool for mass customization because it creates an understanding and a set of rules that would allow for a set of input variables to be established.

Generally, the tools used in mass customization are often digitally or CNC driven. A large batch of computer aided machining (CAM) files can be built at once and queued up on a machine. From there the machine can run independently and be able to run whatever routine it is asked at a high level of accuracy. That accuracy and ability to make many unique pieces accurately while important to mass customization is also what helps the proposed work of this thesis to occur. High accuracy is needed because the process used requires such fine movements to form the metal. The proposed work would be almost be impossible to create without the use of the same tools used in mass customization. These tools and processes may never run at the same production speeds as some traditional fabrication processes, but they make up the accuracy and the ability to run a new routine almost instantaneously is what Wes Mecgee's paper *Robotic Fabrication In Architecture and Design* covers the ideas mentioned above. The use of CNC tools or robotic arms allows for a repeat

Besides just looking at how items may be customized, it is also important to look to other fields of industry for ways to build buildings and building components. Looking to the aerospace, automotive, and shipbuilding industries gives insight on how to design and construct buildings better. No longer must architecture stay cocooned in fabrication processes that have not been updated for decades. Other manufacturing groups are performing constant updates and searches for better technology. An example of this is airplanes that have gone from ribbed and skinned construction to being constructed out of composites materials. This type of leap was able to happen because one of two things occurred. The first is a designer had a holistic enough understanding of how an airplane was constructed and leveraged knowledge about composites to make a better designed plane. The second is that a team of designers, fabricators, and material scientists was brought together and they problem solved well as a whole. In *Refabricating Architecture* Stephen Kieran and James Timberlake present the idea of a master builder who can pull on a large, but broad set of knowledge, which can be leveraged towards making better buildings. Architecture could benefit from these other groups because they must constantly innovate in their field, otherwise someone else will.

Custom metal forming itself has been well established for centuries, but only in the last 35 years have there been large advances in being able to produce custom one off pieces. The production of such work goes back to blacksmiths and armor builders who had to form metal by repeatedly striking the piece. While advances in forming have been made since the time of metal fabrication started the principles of metal forming still hold true. *Ed Barr's Professional Sheet Metal Fabrication* book covers all the main types of forming processes created over the years to be able to construct doubly curved metal panels.

Robotic based metal forming has been on the rise since the introduction of robots in architecture firms and schools. There have been many types of forming processes created during that time, but *The Danish Royal Academy's* work on *Stressed Skins and a Bridge Tool Far* along with Ammar Kalo and Michael Jake Newsum's work on *Robotic Incremental Sheet Metal Fabrication* look at one unique type. Both of these groups have focused on the idea of a single tool attached to the end of robotic arm that moves into a piece of sheet metal very gradually. Single Point Incremental Metal Forming is the process these groups have chosen to study and have worked to test the limits of. The work of both groups consists of finding the maximum limits that a piece of sheet metal can be formed to with this process before it tears. The Danish Royal Academy has taken the work a step further and has started optimizing the individual panels in a manner to optimize the strength of the panel. From that point forward the panels are bolted together where two panels touch. However, both of these groups do not focus on making a unified single surface, but more a collection of pieces that make up an object or enclosure.

Complex forms in architecture require a background understanding of how the structures will stand on their own. Before a single piece of material is cut it, often a digital simulation of the project and how its structural loads are going to work is completed. *Form-Finding and Design Potentials of Bending-Active Plate Structures* by Simon Schleicher, Andrew Rastetter, Riccardo La Magna, Andreas Schönbrunner, Nicola Haberbosch and Jan Knippers explores how structure and load can be understood in a 3D modeling environment. No longer must designers guess and check results or constantly refer to outside sources on whether or not a structure will stand on its own. By incorporating more information into models designers can use that information to their advantage. However, it is more than information it is the integration of that information into a visual graphic that designers can use. Programs such as Kangaroo and Karamba allow designers feedback while they are designing.

Moving a set further would be running the analysis of a structure in real time as a designer works and designs a new piece of architecture. Analysis-based CAD allows for this by eliminating the need to have a 3D model passed back and forth for analysis and modification. *Form-Finding of Architectural Membranes in a CAD-Environment Using the AiCAD-Concept* by Benedikt Philipp, Michael Breitenberger, Roland Wuchner and Kai-Uwe Bletzinger explores the idea of integrating structural analysis into a 3D modeling environment. By digging down into how geometry is created in a 3D modeling environment and using that information to create the basis for the structural analysis allows that information to be applied earlier in the design process.

SECTION 3:MATERIALS AND METHODS

This thesis concentrates on creating metal panels that have the intention of being joined later together into structural skins. The final set of individual panels themselves that will have saddle shape to them are 19”x19”. The panels are formed out of 20 gauge mild steel. This thesis is broken into three areas of exploration all which look at surface generation, blank preparation, predictive form generation, workholding, and tool path generation. These explorations are broken down in a ways which allows for knowledge to be gained in each one to guide the next round of exploration.

EXPLORATION 1

The first exploration was exploring a series of panels with a vaulted form generated with the *Grasshopper plugin Kangaroo*. The vaulted geometry was selected because that geometry has been formed successfully numerous times during the early iterations of mastering metal forming with the robot. Also, the geometry went through a relaxing process while in *Kangaroo,* which allows the form to become as stable as possible. The panels are 8” x 24” in size and mounted in the forming frame. Rectangular profiles had not been explored during past study in this area and allowed for quick implementation of existing work holding fixtures. Additionally, rectangular forms are more commonly used in running bond patterns than square profiles. During this first exploration running bond patterns where considered to be a feasible method of aligning the formed pieces together. This format allowed for panels to be created in a way that used previous work in this area of study to give reference and only change the mounting method and panel size. The mounting process went from a panel being held from all four sides to a panel that is now held only at the top and the bottom. Additionally, a switch to CNC plasma cut sheet metal blanks was made. This allowed for a consistent panel to be loaded into the frame every time. This approach allowed for an accurate comparison to be done between the panels formed during in the process. Change in mounting techniques offered enough of a change in how the panels formed that is was chosen to keep with a known surface generation method for these panels.

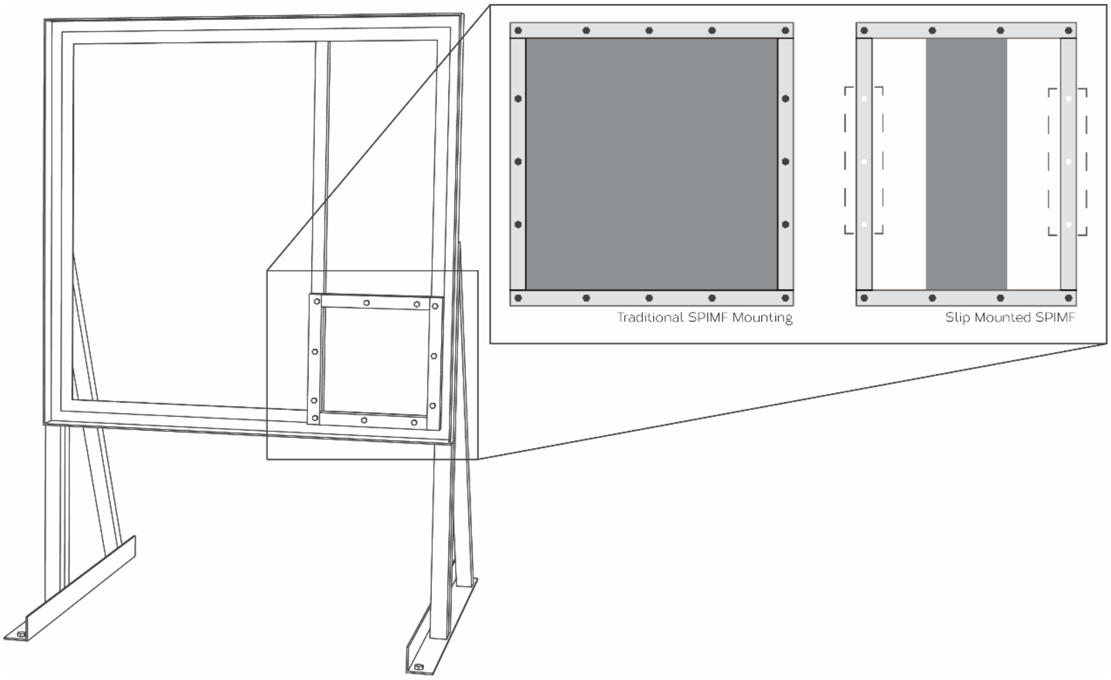

Figure 1: Sheet Metal Blank Work Holding

While this method showed that a high finish panel (None to few tool path marks on the unformed side of the sheet metal) could be created it also showed where improvements to how the surface generation method could be improved. This included being able to modify the edge a single panel form quickly without needing to completely rebuild a new surface 3D model every single time. Additionally, there was not enough adjustability in how the surfaces were generated. More importantly, the edges of the panels would pull in towards the center so much that they would not be able to be joined together into a larger assembly. To allow for more control over the surface a switch to a parametric catenary curve based surface generation method was selected. This switch allowed for changes to the model to immediately take place and be feed into the robot controller unlike the previous method, which would require manually referencing the formed surface into the tool path generation tool.

The catenary curve model uses five adjustable catenary curves to create the form. There is one on each of the four sides of the panel with a fifth that controls the depth of the panel. The catenary curves offer quick manipulation of the surface to allow for it to be changed for either depth of panel, sheet metal blank generation or tool path generation. This method was successful in creating a form that could be changed rapidly without an overwhelming amount of variables. The amount of variables allowed for checks and verifications along the way to see if the form generation and the tool path generation methods were headed towards a working process. The amount of variables was restricted to create change in a controller manner and not produce a surface that could not be traced back to other generated surfaces.

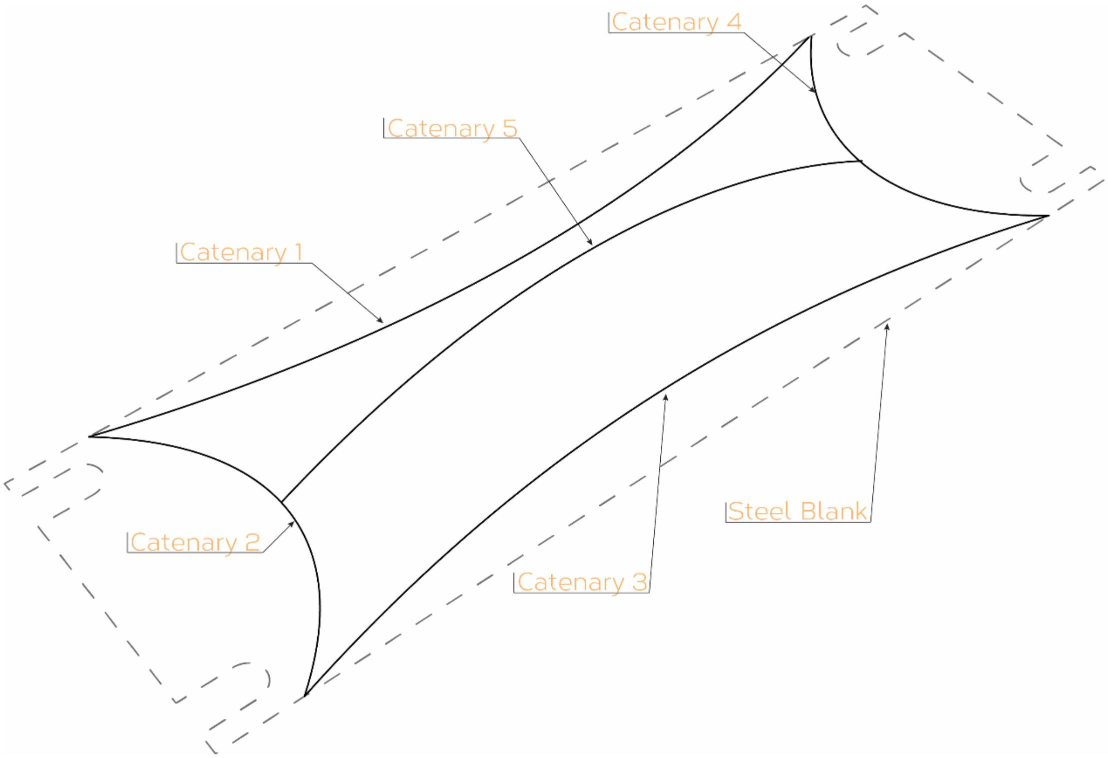

Figure 2: Catenary Curve Model

EXPLORATION 2

During this phase stage of exploration focus was on creating panels that resulted in straight edges that could be later joined together into a larger panel system. To work towards creating panels that have linear edges, tool path generation methods where incrementally changed until a panel with linear edges was created. This portion was successful in being able to create panels with linear edges that could be later joined into large assemblies. This process was done by incrementally changing the surface used to create the tool path. To create linear edges the tool path of sheet metal blank had to be pulled in towards the center of the form. By being able to create edges that are linear also demonstrates that panels with curved edges can be created. This opportunity allows for the panels to be keyed into each other, which could be used as an organization method or as way to later join the pieces together.

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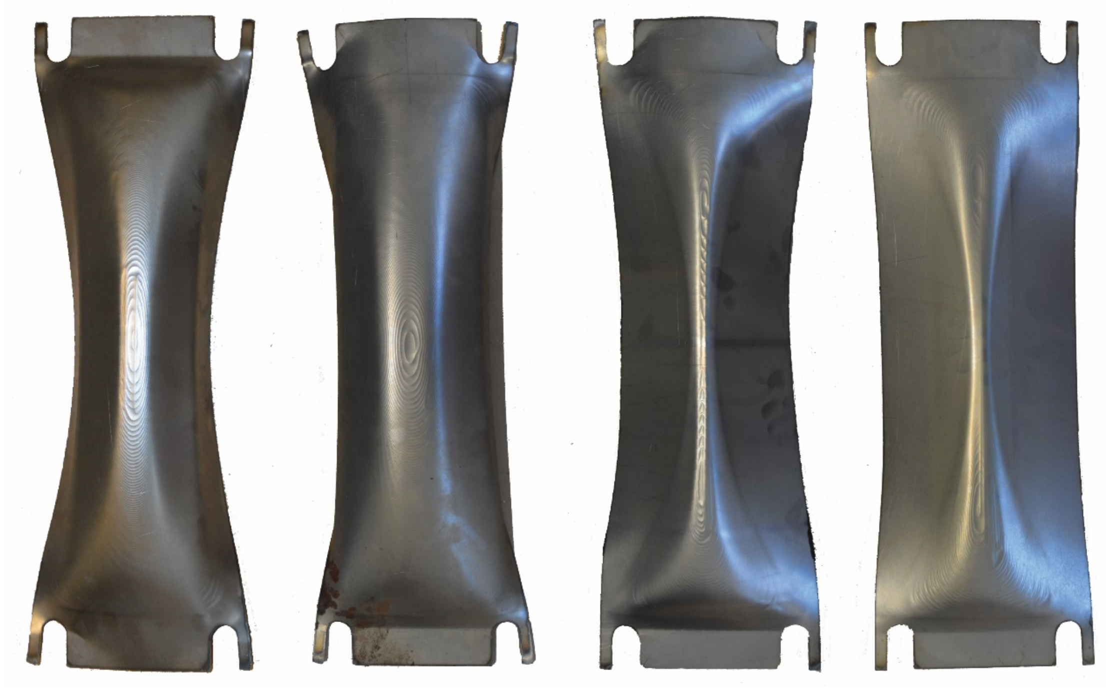

Figure 3: Edge Condition

Running parallel to the tool path generation explorations of exploration two was a parametric sheet metal blank tool. This tool takes in information from the surface form and using it as a base for the sheet metal blank. This particular tool had more adjustments features on it then the surface-forming tool so that the most accurate CNC plasma blank could be made. The blank forming tool uses similar catenary curves, but the anchors of the catenary curves are adjustable. This ability allows for additional material to be added precisely to the piece. During the creation of this tool a shift from round holes to slots was made so that the blanks could be more accurately positioned in the work holding fixture for forming. Before forming of the sheet metal blank occurs the robotic arm moves to the center of the two long edges of the blank so that the blank location could be verified. If adjustments are needed the anchoring bolts can be loosened while the arm is in place and the sheet metal blank brought into alignment. Additionally, this tool is written all in Grasshopper, so that it can interface with all of the other tools and parts of this thesis that are written in Grasshopper.

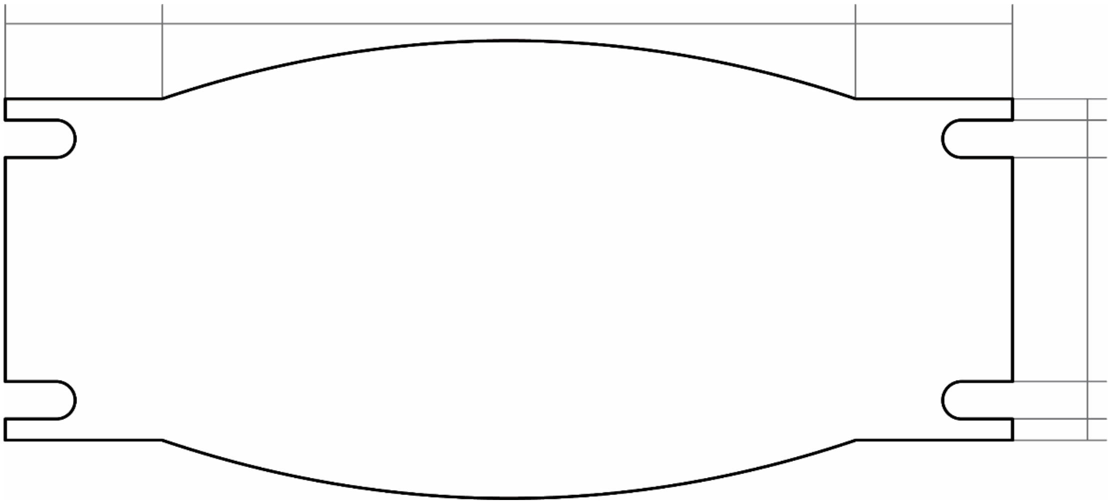

Figure 4: CNC Plasma Sheet Metal Blank

EXPLORATION 3

The third phase of exploration looked at how a saddle shaped surface can be subdivided into smaller panels, which then can be joined in a similar manner as above. The geometry generated for this was constructed in *Grasshopper 3D* and checked to insure that it has Gaussian curvature. Gaussian curvature insures that the geometry is doubly curved. The process used to create the main geometry consists of using catenary curves because both their endpoints and total lengths can be incremental stepped to create stable geometry. The main geometry and the smaller panels that come from the divided panels must all be checked to insure that their draft angle is less than 70 degrees. To verify this either *Rhinoceros's Draft Angle* Analysis program can be used, or a Grasshopper script can highlight these areas, which have too severe of a draft angle.

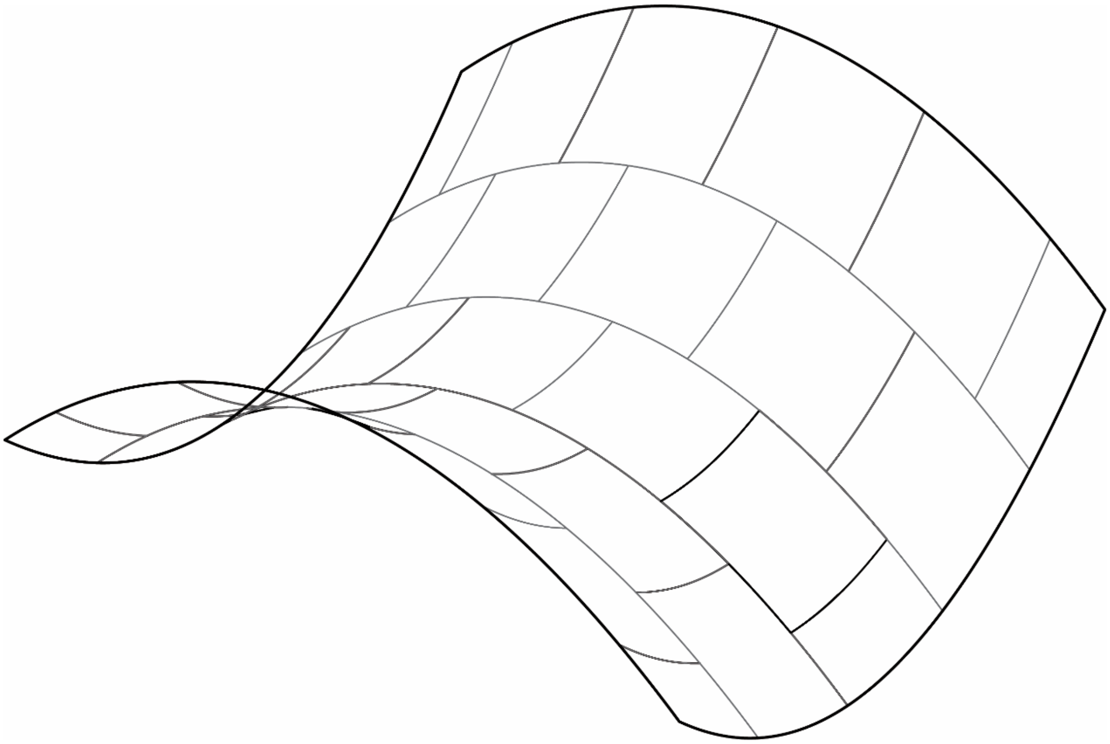

Figure 5:Saddle Shape

Additionally, a second Grasshopper script that uses the Kangaroo physic generator runs a simulation of the forming process ahead of time to show the users an estimation of what the formed geometry will look like ahead of time instead of needing to the run the panel, which is both more costly in time and material use. Additionally looking at the simulation gives an opportunity for adjustments to be made to both the tool path and the sheet metal blank.

The predictive tool was constructed in the same Grasshopper environment as the toolpath generation tool and relies on the Kangaroo physic generator to simulate the loads applied. The predictive tool uses a mesh that is the size and profile of the sheet metal blank. The tool loads the tool path point locations generated for the robotic arm as a series of point loads. The point loads are looped through and with each loop taking in an updated mesh that has been modified from the previous point loads. The positions of the four threaded studs that hold the sheet metal blank are incorporated in the model because they will restrict movement of the sheet metal blank. Once the tool is done looping through the point loads then the user is presented with a mesh that will represent the expected outcome of the forming process. At this point either corrections to the file or sheet metal blank can be made.

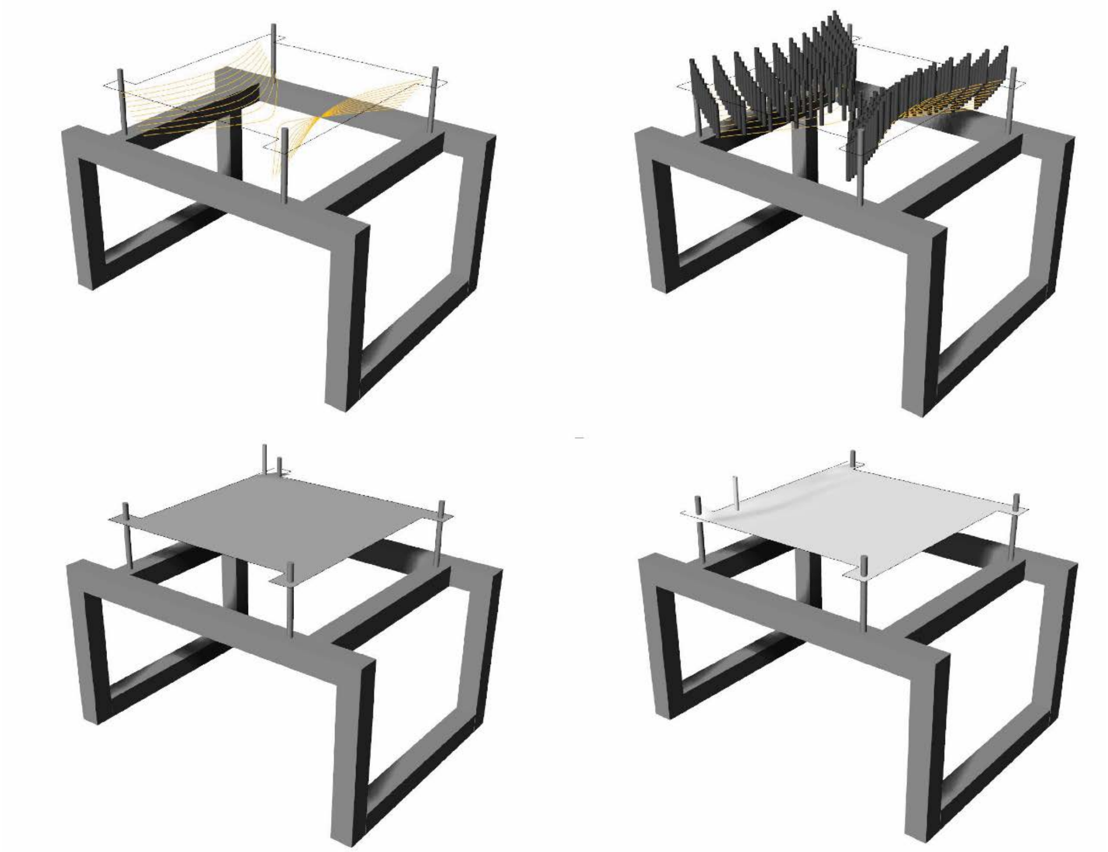

Figure 6: Predictive Tool

Lastly, a third technique was explored which uses four catenary curves to create a saddle shape. Saddle shapes were selected because they have curvature running in two directions at all times. This quality makes them inherently difficult to fabricate and predict their required sheet metal blank. Two catenary curves droop positively in the z-axis and two more droop negatively in the z-axis these two are positioned perpendicular from each other. As with the first catenary surface generation method this allows for an easily controlled surface model to be generated and manipulated. Using the same process as before to be able to gradually control the piece.

The working holding fixture requirements for this exploration required a new fixture to be built. This is because the sheet metal blank is now only being held in the corners instead of along the top and bottom edges of the sheet. This method allows for the greatest amount of deformation and for the entire edge of the sheet to be worked. For this to occur an offset corner pattern is used to hold the panels on the frame. The frame consists of four threaded rods, which the sheet metal blank are bolted to. The threaded rods are threaded into a steel tube frame. The threaded rods have a nut welded to the bottom of the threaded rod so that either a ratchet or an impact gun can be used to level the piece of sheet metal. The need to level the piece can stem from the mount itself and because the sheet metal blank is passed its range of airy points. Airy points is the distance in which a piece of material supported with two points doesn’t deflect.

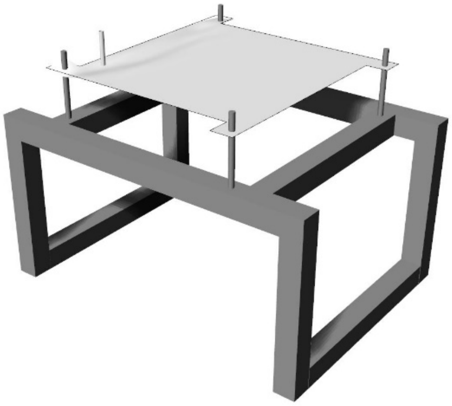

Figure 7: Updated Work Holding Frame

The tool path generation methods for saddle shape forms to be created required significantly more time to develop when compared to the earlier tool path generation methods. A smarter tool path generation method was needed to be able to work with the complex geometry. The points needed for the tool path were generated by dividing the saddle surface into contours lines and having those contour lines divided into segments. The contour lines were broken into two lists based on their position along the saddle. The point of division is based upon the crotch of the saddle. This was necessary to insure that the forming tool didn’t collide with the sheet metal blank when the forming tool transitions to lower contour lines.

Figure 8: Formed Saddle Shapes

Three other factors had to be considered unlike previous tool path generation methods. First, the tool must work around the piece and not collide with it. The previous explorations in geometry types avoided this by only having a single concave geometry, which by default allowed for a more streamline generation process to be used. Second, was moving the forming tool off the edge of the sheet metal blank and how to re-engage the tool with material. Earlier studies of Incremental Metal Forming showed that if a piece of sheet metal isn’t worked completely to the edge of the sheet then a lip is generated. The lip causes an upturned edge condition, which isn’t contusive to later joining the pieces together. Additionally, the lip causes the ball bearing to become disengaged from the tool during forming. When this happens the ball bearing becomes pinched and later pops out of its holder. This process was iterated through to find the best procedure when bringing the tool past the edge of the material. These iterations consisted of changing both how the tool entered vertically and horizontally into the material. The first versions of this tool path generation consisted of having both variables fairly equal to allow for an approximate 45 degree point of entry and departure of the tool. However after several runs it was discovered that the approach angle needed to be much steeper otherwise the ball bearing would be come detached during forming because of collision with the edge of the sheet metal. To alleviate the problem a steeper entry and exit angle was tested. By the end of going through several versions it was discovered that a very steep entry was needed into the material along with a 100% vertical exit from the metal blank. The last item that had to be considered was how to avoid the mounting hardware that holds the material in the work holding fixture. This problem was solved by creating a second set of points that were shifted from the original end and start points of each contour and weaving those points into the tool path point list, so that the tool always travels around the mounting hardware. While this process was partially successful in creating saddle shapes the entry and exits persisted in giving problems with the ball bearing becoming dislodged during the forming process.

To remedy the problem a second tool path generation method was constructed to work around some of the short fallings of the first. This process included building the transitions off the total line instead of just the endpoints. This works by splitting the lines in half and taking half the points along the curve and incrementally moving them up to create a lead in that engages the sheet metal blank from the middle of the contour line and works out. This process eliminates the issue of the forming tool snagging the edge of the blank and pulling off the ball bearing. For this method process to work requires the contour line to be run once in each direction to insure that the path has been completely covered. The same issues of having to avoiding the sheet metal blank itself and the hardware are addressed in similar manners as of before. One error though that couldn’t be avoided was how the ball bearing becomes pinched when it exits the sheet metal blank near a tab. While the ball bearing is pushing there it becomes encased by the sheet metal and is held in place. To solve this problem it must be addressed in the holding of the material and not the toolpath. On areas besides near the tab the toolpaths successfully formed the panel.

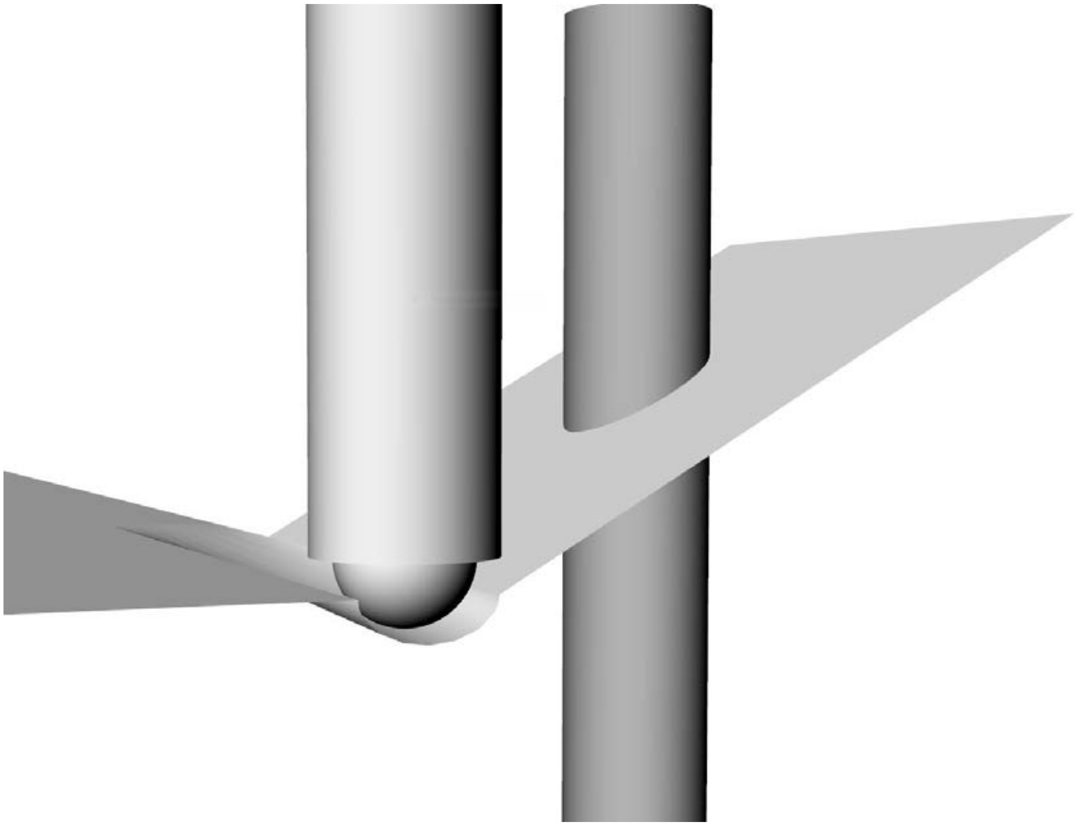

Figure 9:Pinch Point

The difference between the three phases is the first two phases look at how a series of panels would react when the material is only held at the top and the bottom of the sheet. A surface geometry that is known to work was used. The second phase examines how a controlled doubly curved surface influences a set of unique panels that make up that surface. All three phases explore how placing material and manufacturing constraints on the design environment affects the outcome of the final forms. Phase one does this by having the form of the metal panels be defined by iterations of the previously fabricated panels. The earlier iterations have shown what limits exist and those have been used to determine, what kind of form can be generated. Phase two uses limits, which come from both geometry generation and material forming limits created by work holding fixtures. Lastly phase three uses material forming limits, work holding fixtures, and tool path generation limits as a way to define the area of study.

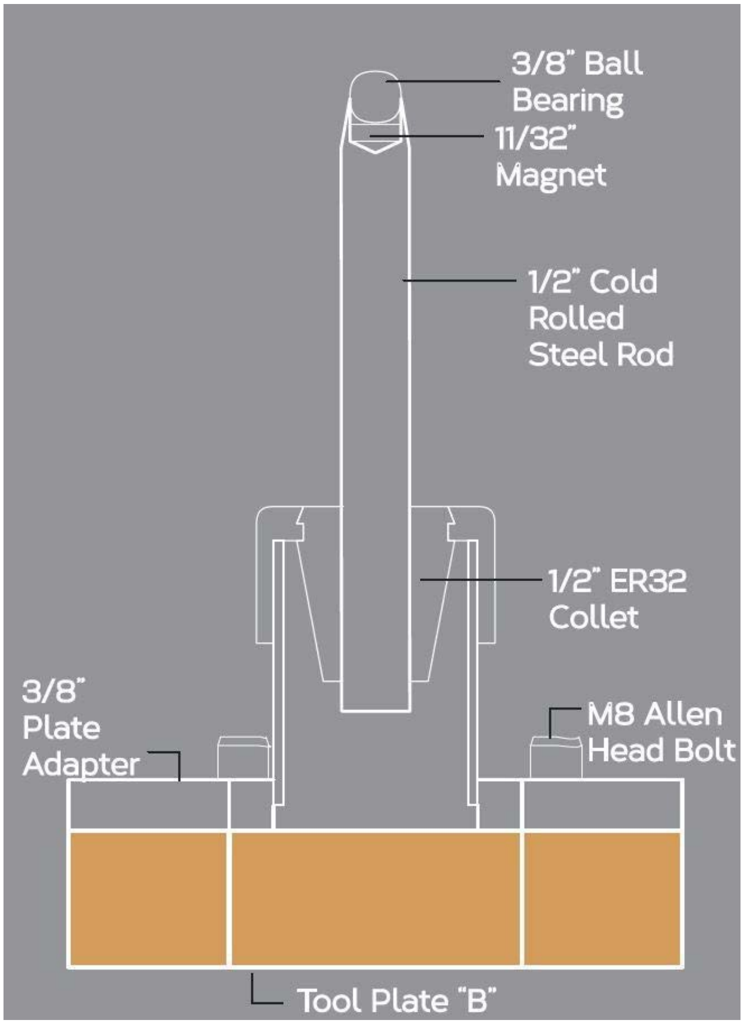

Figure 10: Cross Section of Forming Tool

The process used to create the panels includes the use of a S.P.I.M.F. end effector attached to a 6-axis KUKA KR60HA industrial robot. S.P.I.M.F. employs a ball bearing held in place with a magnetic retainer attached to the end of a 6-axis industrial grade robotic arm. The ball bearing succeeds at being the forming tool because it is hardened and highly polished to help reduce the amount of friction generated during the forming process. The robotic arm traces a series of contours and gradually pushes into the steel. A steel frame constructed out of angle and tube profiles, which is bolted to the floor, holds the sheet metal vertically along with resisting the force applied by the arm. The frame has a series of 9/16" holes drilled around the perimeter of the frame, which another frame with matching holes bolts to. A CNC plasma cut blank is sandwiched between the two frames.

SECTION 4: RESULTS

The three explorations have resulted in tool path generation methods, a predictive tool, and workholding fixtures that have not been utilized before for incremental metal forming. Those combined have resulted in greater depth of draw on sheet metal blanks, a workflow for designers to test, correct and then fabricate panels, and increased tool life for the forming tool. These advances are tools that designers can start to use to make informed design decisions without needing to rely on other parties.

SECTION 4.1: TOOL PATH GENERATION

Early explorations were based off of simple contouring strategies that were effective in dealing with single concave forms. In these cases a surface was simply contoured and the outlines traced into the panel by the robotic arm. This process worked well and surface quality could be controlled by step over, but the process would cause a small but consistent flaw where the robotic arm would push in for the next contour. To achieve a better surface quality it was determined that a helixing tool path method was needed. A helix tool path would mean there would be a single start point, which would remove the issue of the consistent flawing. Helixing was an effective tool path generation method, which could return near flawless panels with no visible tool marks.

However, once presented with the challenge of creating saddle shapes the effectiveness of helixing became nullified because the generation method couldn’t handle the more complex form. If this process were used on a saddle shape it would eventually collide with the piece. This spawned the creation of a saddle specific tool path generation method, which handles the complexity of the saddle shape without colliding into it. The tool path works well on its own and during initial simulations looked promising, but during actual use it struggled with dealing with the ever-moving piece of sheet metal, which would cause the ball bearing to pop off when the tool neared an edge. The more complex nature of the saddle also more than doubled the run time for a formed panel because the tool works back and forth and returns to a center point instead of a constant engagement with the material.

The mid section toolpath generation method was successful in forming material up until the ball bearing became pinched when the tool would pass near an area that had a tab. The tab and main sheet metal body would deflect significantly and hold the ball bearing enough that when the tool lifted the ball bearing would stay engaged with the sheet metal. The pinching would only occur on the edges that had a tab running in line with the front the material. Once pinching started to occur it became difficult to recover the piece from unwanted deformation and continued pinching of the ball bearing.

SECTION 4.2: PREDICTIVE TOOL

The predictive tool offers insight on how a panel will look to designers when a particular sheet metal blank and tool path are used together. The tool gives indications if a particular setup will work. However at this time it isn’t able handle such factors as non-consent force applied to the panel by the robot. Besides force applied by the arm the tool presumes that all factors related to the forming process are consistent during every panel forming session. Items that offer possible areas of inconsistency are how tight the bolts are to hold the piece, the amount of wax applied to the sheet metal blank, and the position of the blank in regards to the robotic arm.

When the time is compared between running the predictive tool and running the actual robotic arm the predictive tool is a huge advantage because it is offering feedback almost immediately, so that a design can be tweaked without needing to spend additional time setting up a new sheet metal blank and prepping the robot to run the file. While those tasks only take about 8 minutes per run that amount of time starts to add up when a designer is trying to test out a design. Additionally, it is saving on material use.

SECTION 4.3: WORK HOLDING FIXTURE

The work holding fixture has evolved over time from a fixture that clamps the material as tightly as possible on all sides to clamping just two sides to finally a fixture that is more for alignment than clamping the work. Both work holding fixtures were successful in allowing forming explorations to occur. The large vertical fixture allowed for varied sizes of sheet metal blanks to be held and formed. The hole pattern around the perimeter of the frame allowed for quick modification and experiments in vertically holding to be tried. However, the vertical fixture lacked fine adjustments to get the sheet metal blanks held perfectly to the robot. Do to the orientation of the sheet metal blank being held vertically causes the piece to bow backwards when held in this fashion. This caused the forming tool to not always engage with the material right away. It was discovered that the top of fixture leans away from the robot. The required shimming to get a sheet metal blank loaded presented an issue because it was being shimmed with washers instead of flat bar stock initially. The washers were causing small areas of clamping force to occur at the top of the sheet metal blank instead of the consistent clamping pressure like the bottom of the blank was receiving. This allowed for a small area of unwanted deformation to occur at the top of the blank.

This unwanted deformation did however show that if the sheet metal blank was held with as little interference from a fixture as possible then a sheet metal blank could be allowed to flex and deform in a similar way that the unclamped sides of sheet metal blank. This insight spurred the idea of holding the sheet metal blank in a way that would limit interference from the work holding fixture. The second work holding fixture holds the sheet metal blank in the horizontal position, which causes the sheet metal blank to droop slightly towards the center of the blank. This caused the edges of the sheet to become formed first and would leave the first several layers of the contours not completely formed.

SECTION 4.4: FORMED SHEET METAL

The three different areas of exploration allow for the sheet metal blanks to be joined together into panels, which can later be arrogated into a large structural skin. The explorations using a vaulted and catenary form allow for the greatest amount of change to the panel size as long as that panel size fits the six-inch on center grid bolt pattern. Also during these explorations time was spent ensuring that joinable edges existed for latter joining of the piece. This might include making pieces that notch into each other or using a running bound pattern to join the pieces. The later saddle panels where only thought of as a running bound that could be fitted together and then welded together and pulled on the understandings of how much additional material is needed in a per cases bases. All three explorations required that additional material can be added to the sheet metal blank to insure that enough material exist on the edges so that the formed sheet metal blanks can be joined together. The saddle shaped panels are the only one out of the three that is capable of producing curvature in opposite directions from itself unlike the first two explorations which are consist of a single concave form. Lastly, the saddle shaped forms are currently limited in their size because of the work holding fixture because that fixture can only be adjusted in the Z-direction.

SECTION 5: CONCLUSION

As the field of architecture continues to push forward for more complex form whether for performance or aesthetics reasons designers are going to need to know how it all goes together. This thesis showcases how complex forms created with industrial robotic arms in sheet metal can be designed, tested, and fabricated. This is done by creating a design environment that packages material and manufacturing limits into a set of tools that designers can use to insure that their designs can be fabricated. By exploring three different ways of using Single Point Incremental Metal Forming this thesis encapsulates the critical elements of the process into the tools created for this thesis.

By going through three separate iterations of tool path generation, work holding, and surface generation allowed for critical elements of the process to refined into usable tools. The decision to create saddle shapes was purposeful because if saddle shapes can be manufactured implies that other less complex geometries can be created as well. Additionally, by going through three smaller iterations allowed for changes to be implemented and tested. This allowed for comparisons to be made with earlier work and be able to see overall trends evolve over the course of the thesis. A trend that did appear was making the three areas studied as robust and linked together as possible. The linking of all the areas allowed for quicker exploration to occur and modifications to be implemented. If the linked tools are unable to handle changing variables then the tool is not supporting the designer. By tying all three tools together streamlines the workflow process and eliminates errors by being insuring that correct information is being passed.

The tools created during this thesis highlight the fact that digital fabrication tools can be integrated into the design process both for as a production tool, but also a way to test ideas before moving forward with a design. By using the predictive tool that was created allows for a designer to very quickly see if an design should move forward based on whether or not it can be constructed. No longer must a designer finish a design and pass the idea off to fabricator and then have to have a discussion on how to build the design. The integration of these tools into the design environment allows for designs to know that it will work in the field.

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APPENDIX A: SLIP MOUNTED SINGLE POINT DEFORMED STRUCTURAL SKINS

INTRODUCTION

Slip Mounted Single Point Deformation expands upon the ideas of single point incremental metal forming, using a 6-axis robotic arm, by exploring the possibilities of how sheet metal can be deformed with minimal support bracing. The goal of this technique and research is to develop controlled methods for fabricating precise, double-curved, structural panels. The slip mounted technique requires mounting a piece of material in the vertical plane while only bracing two edges of the sheet. The material in this method is allowed to stretch, flex and twist during forming unlike in traditional incremental metal forming.

Single point incremental forming is the process in which a hardened metal stylus is attached to either a robotic arm or CNC machine and then programmed to trace the contours of a shape gradually into a deformed piece of metal, allowing for far more complex shapes than traditional forming methods. While each pass is made the piece of equipment pushes between .3mm – 1mm causing the sheet to deform into the desired geometry. During the development period of the single point incremental forming process, we identified three control variables; tool design, tool path generation, and the deformation limits of 20-gauge cold rolled steel sheets for doubly-curved surfaces. This initial research, along with explorations by others, became the underpinning for the work examined in this paper, where single point incremental metal forming is used to create doubly-curved panels which can create a self-supporting structural surface.

The initial catalyst for this project began with Ammar Kalo and Michael Jake Newsum's work in robotic-based incremental metal forming. Their work created a proof of concept for the idea of incremental metal forming made with an industrial grade robotic arm. Their work consisted of showcasing the basics needed to get incremental metal forming to work. They demonstrated how to fixture the material and offered a starting point on tool design3. 1 Their tool design uses a spherical end attached to a piece of steel, which then attaches to a robotic arm. Centre of Information Technology and Architecture's (CITA) Stressed Skins and a Bridge Too Far introduced the idea that these panels could be used together to form installation scale pieces. CITA focuses on three different levels in regards to incremental metal forming, macro, meso, and micro.2 By focusing their efforts at these three scales CITA defined a clear understanding of how the sheet metal will deform and also methods for creating stable geometry at the scale of the cross section of the sheet of metal to an assembly of parts. Phillip Azariadis and Nikos Aspragathos' work touches on the elasticity or stretch required to create doubly-curved panels.3

TOOL DESIGN

The tool created for the forming process went through several iterations, each of which progressively minimized artifact creation and created a better surface finish. The tool itself is attached to the end effector of the arm by an ER type collet. Early tool iterations used a piece of high-speed steel that had been ground to a tapered rounded point. These early iterations created too much friction because the finish of the tools was not fine enough compared to the surface finish of the steel. The next iteration was finished with 220 grit, 400 grit, 600 grit sandpapers, and finally emery cloth. The improved surface quality reduced artifacts and the amount of friction generated during the forming process. Nevertheless, the finish of the part did not create an acceptable level of finish quality on the tool. The next iteration of the tool used a piece of ½” steel rod that was center drilled to accept a small magnet, which in turn would hold a 3/8” ball bearing. The ball bearing is held tightly enough so that it remains attached to the end of the tool, but maintains enough freedom to spin in place, much like a ballpoint pen. This method greatly increased the quality of the surface panel because the ball bearing is free to spin were the tool assembly to start to bind up during the forming process. Additionally, the surface finish of the ball bearing is of high enough finish to help the tool avoid artifacts and chatter marks.

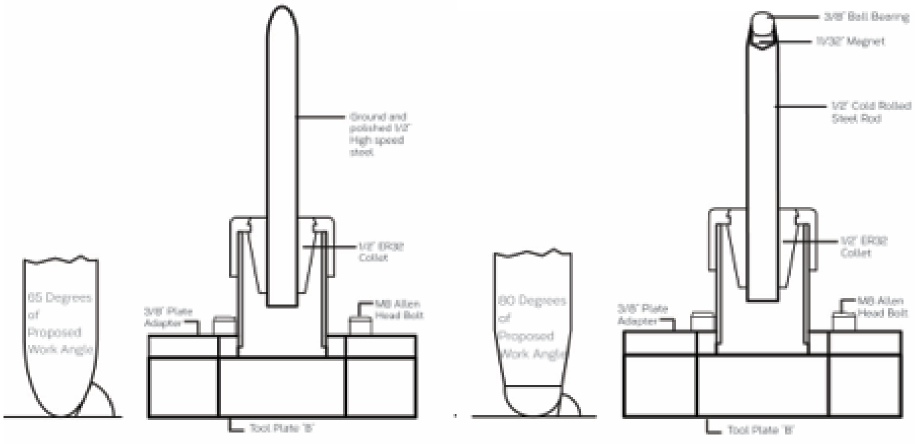

Figure 1 Progression of forming tools used during the exploration of single point incremental metal forming. First iteration (Bottom) Last iteration (Top)

TOOL PATHS

The tool paths generated to operate the robot arm used for the forming of the panels are based on four different ideas, but all focused on the overarching objective of creating the smoothest possible surface finish. Each type of tool path generation has advantages and disadvantages as expected from any type of CAM or robotic tool path generation.

STANDARD CONTOURING

Contoured tool path generation works by slicing up a surface or polysurface into sections that determine the quality of the final piece, much like a topographic drawing. Slicing increments between 0.3mm and 1mm were tested to decrease the time needed for each panel, while balancing the amount of precision in the final surface formation . Once the contours are created then they are divided up to create points. The amount of points also increases or decreases the accuracy of the final surface produced. The final step is to create tangential planes at each respective point, rotated to be parallel to the face of the unformed steel sheet.

Advantages and Disadvantages (Standard Contouring)

- Run time of 5-15 minutes depending on depth and quality for a 16” square piece
- Creates an accurate form with minimal spring back.
- Works with all types of surface geometry
- One side will show almost no tool marks if step over is kept below .3mm. However, a small indention is made where the robotic arm “steps down” to the next contour line during forming.

- Tearing is avoided if draft angle is kept below 55 degrees
- Transfers between multiple low spots must be programmed

STEPPED PARALLEL FINISHING

Stepped parallel finishing was tested in response to contouring's inability to handle multiple low points, without individual repairs to the tool paths. With this process a surface is scaled in one direction multiple times, so that it is nearly flat in the beginning. Each time the surface is scaled it is also contoured. Contours are then divided into points and converted into planes. This process allows a doubly-curved surface to be made without having to build multiple files.

Advantages and Disadvantages (Stepped Parallel Finishing)

- Run time of 15-30 minutes depending on depth and quality for a 16" square piece
- Causes sheet to have a distinct bow in one direction.
- Works with all types of geometries
- Tool marks are visible and distinct. Not the best method for finish pieces.
- Tearing does occur where the tool makes multiple passes in similar locations.
- Useful for initial experimentation, not practical enough to move forward.

STEPPED CONTOURING

Stepped contouring is an advanced version of standard contouring. The distinction with this process is done by taking the same set of contours, flattening them into the same plane, then incrementally moving them back from the plane while reducing the number of contours on each pass. This process created much higher quality final pieces but required programming repairs in instances where the surface design has multiple unconnected maximum or extreme deformations.

Advantages and Disadvantages (Stepped Contouring)

- Run time of 25-45 minutes depending on depth and quality for a 16” square piece
- Gradually pushes the metal and offers little spring back and makes for accurately formed pieces.
- Works with all types of geometries
- Tool marks are barely visible, and this process offers very high quality surface finish.
- Tearing is avoided if draft angle is kept below 55 degrees.
- While useful for experimentation, not practical enough to carry forth do the time needed to construct a single panel.

HELICAL FORMATION

Helix based tool paths offer up some of the best quality pieces in the least amount of time. This process works by placing a curve that gradually spirals down the inside of a surface. The spacing between rings can be controlled which allows for maximum control over the quality of the finished piece. Currently, the only geometry that has tested successfully with this technique is circle based. In some cases circles can be distorted and formed into other profiles. Similar to other tool paths, once a curve is created it can then be turned into points and then planes. Further exploration with this method could be used to create more formal options.

Advantages and Disadvantages (Helical formation)

- Run time of 5-15 minutes depending on depth and quality for a 16” square piece
- Makes accurate formation with minimal spring back.
- Works with geometry based on circles. Hexagons and pentagons work if the line work created to make the surface is a rebuilt circle that gets overlaid onto the above mentioned shape.
- One side will show almost no tool marks if step over is kept below .3mm creating a near perfect finish.
- Tearing is avoided if draft angle is kept below 55 degrees
- Transfers between multiple low spots must be programmed, but quality of finish makes it worth it.

ROBOT CELL SETUP

Traditionally, single point metal forming relies on a ridged frame to hold the work in a way that limits twisting and unwanted deformation of the sheet metal. A vertical outer steel frame bolted to the floor, accepts another smaller inner frame, which in turn is used to orientate and keep the panels straight. These frames sandwich the piece of sheet metal by through-bolting the frames together. Instead of restricting movement of the sheet and forcing the metal into a desired shape, Slip Mounted Single Point Deformed Structural Skins(SMSPDS) allow the sheet metal to shift and twist during forming. While this allows for a greater amount of deformation to occur it also allows for a greater amount of forming depth to occur when compared to rigid

forming practices.

Figure 3 Metal forming stand used for both rigid and slip mounted forming.

In slip forming the sheet is pinched only at the top and bottom of the sheet. By reducing the amount of clamping area used to hold the sheet, it allows the material to stretch and twist thereby reacting more in response to the force of the forming tool. This freedom also allows the entire unsupported part of the sheet to be formed and bent instead of only the worked area accessible in a fully framed sheet. Additionally, the amount of wasted material is minimized as only two edges need to be trimmed post forming as opposed to the four edges in a fully framed sheet.

The relationship of distance and orientation between the robotic arm and the frame is critical to successful forming. The arm needs enough room to move into position to form the panel, without being obstructed by the frame while not pushing the arm to the limits of its reach. Due to the force needed for the arm to push against the metal it is optimal to use the major axis of the robot nearest the floor mount (axis one through axis three) because they are the larger and more powerful motors. The amount of force the robot is able to apply to the system varies greatly based on orientation and the number of motors working in a given instance. While it is nearly impossible to coordinate maximum effort throughout a program, the orientation of the panel relative to the arm can ensure that these larger motors are in use more frequently. Even while the larger motors are doing the majority of forming and have proper orientation the robotic arm can trip load limit switches during the program as the metal has stiffened during the forming process, due to the geometry of the piece becoming too step to form. When a piece of sheet metal has been formed to such an extreme the sheet starts acting in a similar way to how a piece of angle iron operates.

GEOMETRIC LIMITATIONS

Doubly-curved geometry in steel, as in most materials, is one of the more complex and time intensive geometries to fabricate. It typically requires a large time investment in the actual forming or in the production of stamping dies. For example, doubly-curved panels produced by hand by a skilled fabricator can take hours. The fabricator must slowly(and imprecisely) finesse the sheet metal into the desired form typically using a English wheel or other metal forming equipment. This is at best a slow process, and at worst highly inaccurate even when done by a professional with years of experience. The use of stamping dies allows for quick production, but those dies can only produce a single form, requiring a unique die for each panel shape.

Unlike developable or ruled surfaces, which can be laid out onto a flat sheets and then formed, the amount of material needed for doubly-curved forms can only be estimated. Because only estimates of the amount of material needed for a doubly-curved surface can be made, extra material must be used in forming and then later trimmed.

Slip mounted incremental forming starts to address many of the problems caused by the inaccuracies of attempting to make doubly-curved surfaces. By clamping only the top and bottom edge of the piece of metal to a rigid frame, the amount of material needed for forming can be minimized because a constraint is being removed and a new variable is being added. Additionally, the non-clamped sides do not require any trimming to bring them into alignment, this edge condition can be predicted computationally before forming commences.

PRE-TRIMMING

Using a two-dimensional CNC plasma cutter, we began testing methods for pre-trimming panels before they are formed. This process avoids the costly and inaccurate process of attempting to trim doubly-curved panels after forming. Additionally, this process greatly decreases the amount of wasted material by being able to nest many panels near each other in a sheet. Because of the inability to predict the final edge conditions in other methods, significant amounts of materials were left to accommodate mounting and trimming. Through a series of tests and verifications we were able to accurately predict the deformations of the edge conditions of given sheet computationally, and reverse engineer new panel shapes to predict their needed two-dimensional shape before forming.

VERIFICATION

The process of verification required a feedback loop which balanced the amount of deformation in the sheet which pulled from the existing panel and the amount of thinning or stretching in the steel. The feedback loop was constructed by using both a 3D scanner and a 3D digitizer to create models of formed pieces, which were then tested against the original model employed to generate the routine for the robotic arm. After forming is complete, a 3D digitizer is used to translate the now formed part back into a 3D modeling environment. This process includes tracing over a set of grid lines drawn onto the back of each panel before forming began. This provides a set of line work, which can be used to create a model. By testing along two-dimensional lines we are able to monitor the specific amount of stretching which occurred along that axis, compared with the amount of forming. The contrast between the contour of the robotic arm movement, the final form along that axis, and the original amount of material along that axis, created a series of diagrams that we could use to estimate the reactions of the metal to particular geometries.

In addition to the scanner, an infra-red 3D scan is taken of each panel. The 3D scan produces a field of points, which were converted into a surface to be tested against the computational surface geometry used to form the panel. The test makes use of both modeling types to help average out any inaccuracy in both the measuring and modeling technique. It also allows for the measurement of three-dimensional deformations that maybe occurring within a given surface. The actual test will have each of the two reconstructed models centered on the forming geometry. At that point a field of points will be projected onto the three separate surfaces from the same XY coordinates. Once projected onto the surfaces the Z-axis values from the two reconstructed surfaces can be averaged and then divided by the actual Z-axis value. This deformation created values that can be used to calculate the amount of stressed induce thinning in the sheet and compare it to the amount of forming which was created along the same contour.

The forming model is parametrically defined, so that small adjustments can be made to the surface with little effort. This offers the ability to check for changes over an extended set of panel tests. Through an extensive series of panel test we developed an approximate calculable understanding of how the metal reacts during forming. The understanding gained by this feedback loop also allows for a panel to be formed to an exact finished dimension instead of requiring additional material to be removed. From this point, we created a parametric model which can be used to generate both two-dimensional shapes and three-dimensional programs for tooling and forming.

FUTURE DEVELOPMENT

With doubly-curved panels able to be formed, we are proposing the fabrication of a self-supporting segmented shell structure. The proposed structure would sweep a catenary arc along a vault shape. Segments of the shell would be used to create structural sections. The segments themselves would be trapezoidal in shape to adjust for the increasing width needed to fill the space. The panels used to construct each segment are of similar shape, and they are placed in a running bond pattern to help transfer the structural load from one panel to the next. To help add greater stiffness to the form every other panel is flipped to work in compression or tension as with the 2010 ICD/ITKE Pavilion.4 The panels are joined by braking over the unformed segments of the sheet, which were held in the fixture. The bolt holes used for fixturing can be used to secure panels to one another. Utilizing the pre-fabricated(plasma cut) holes, which are all the same, allows for a variable to be removed, and now fabricators only must be concerned with accurately braking the panels to the right angle.

Slip mounted single point deformed structural skins offer up a method to take single point incremental metal forming to the next level, by increasing the amount of depth available in the form and by linking the forming geometry to the geometry produced. This process allows for production of geometry which can express their structural conditions.

CONCLUSION

The process of single point incremental metal-forming to create doubly-curved geometry based on allowing the metal to react to deformations instead of forcing metal into desired conditions, creates a form more closely linked to its expressive properties . By understanding the edge geometry needed before forming, preprocessed sheets can be used, saving time and expense when compared to cutting the preformed.

With slip mounted single point deformation, a focus on constructing an installation scale piece out of a self-supporting skin constructed is possible. Joint details and the analysis of possible stable geometries can be undertaken. As panels are arranged and assembled they will inevitably undergo more deformation and stressing, which can be analyzed using similar techniques to the individual panels analyzed here.

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