Bend, break, and learn

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BEND, BREAK, AND LEARN

by

Sarah Margaret Gutowski

A thesis submitted in partial fulfillment of the requirements for the Master of Fine Arts degree in Art in the Graduate College of The University of Iowa

May 2019

Thesis Supervisor: Professor Monica Correia
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PUBLIC ABSTRACT

A continuing study of how failure can lead to success. Through previous attempts to design a chair, I developed a method of bending plywood using Computer Numerically Controlled (CNC) routing. This method resulted in a flexible surface that was easy to bend but difficult to combine with the structural elements necessary for a chair. Unable to resolve the issues at the time, I continued to use my method of bending plywood to create a set of lamps, a side table and stacking stools. The additional fabrication experience gave me the confidence needed to return to the original chair, re-evaluating the shape of the chair back and the overall structure. The final iteration of the chair is complete in a sense; however, I may never feel completely satisfied with the results.
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CHAPTER 1: INTRODUCTION

During my first year as a master’s student in 3D Design, I attempted to create a technically challenging chair with almost no fabrication experience. I wanted to bend wood using the CNC router to create an organic form for a chair back. However, I knew almost nothing about bending wood or using a CNC router.

![Figure 1: My first chair on display with other furniture at ICFF. Back row, second from the right.](image)

My first chair had aesthetic and stability issues that I did not have the experience to solve when I fabricated it three years ago (Figure 1). The vertical relief cuts on the curved back were distracting and do not smoothly transition into the angled cuts. The legs and frame structure were too thin, causing the chair to appear flimsy and fragile. In addition, there were no beams to keep the structure from rocking. I was not proud of the chair at the time and considered it a failure.

However, the research I had done for my chair did not go to waste. Looking back, my initial chair project was not a failure. I was unhappy with the results of the chair itself, but the experience and knowledge I gained from the project ultimately led me to success with
other projects. I completed a set of lamps, which I have already documented (Gutowski 2017). After completing the lamps, I completed a side table, and a set of stools using a similar method of bending wood using a CNC router. The knowledge and experience gained through fabricating projects inspired by my initial chair led me to revisit my chair and attempt to complete it.

**Research Summary**

The development of my chair back started by trying to use the CNC router to kerf-bend plywood. Kerf refers to the amount of material removed by a sawblade when cutting into a piece of material. Kerf bending is the process of making several cuts most of the way through a piece of material to make it flexible. Kerf bending is typically done on a table saw, but I wanted to see if the method would work with a CNC-router due to its precision and ability to make elaborate cut patterns with ease. My CNC-routed kerf bending tests were not flexible enough to apply to my chair back, so I began cutting completely through the material, creating relief cuts and leaving small connections at regular intervals. The relief-cut method allowed me to create flexible plywood with a CNC router. Because I developed the method for myself through trial and error, I did not realize that the flexible surface I was creating had a name. I now know that it is called a lattice hinge.

To communicate my research, it is necessary to establish terminology for the parts of the lattice hinge I could manipulate. I could not find consistent terminology for the parts of a lattice hinge, so I am adopting terminology used by Patrick Fenner, an Automotive Engineer who experiments with lattice hinges. The pattern of relief cuts would create inner junctions, outer junctions, and spring connections which are illustrated in the structure in
Figure 2 (Fenner 2011). In my previous research, I mistakenly called these junctions *flexures*. The lattice hinge itself is a flexure because it creates an area of flexibility. However, the junctions are not areas of flexibility. In fact, the junctions are the most rigid area of the hinge. The flexibility of the joint arises from the spring connections twisting in response to a force (Fenner 2011).

*Figure 2: Lattice hinge created with relief cuts that create with inner junctions (green) outer junctions (yellow), and spring connections (blue)*

*Figure 3: Lattice hinge with no inner junctions*
The simplest and most flexible lattice hinge in my experience has no inner junctions, creating a zig-zag pattern (Figure 3). Without inner junctions, the resulting material can bend and twist because the outer junctions can deflect slightly. My chair back is based on a lattice hinge with no inner junctions, so the wood bends and twists as it curves.
CHAPTER 2: SIDE TABLE

During the Fall of 2017, I began to develop a side table. Although the chair had not been a success, I was excited to try fabricating furniture again. I initially tried to design the side table without using relief cuts, because I did not want my style to be defined by a specific process and material. However, avoiding the relief cuts led me to spend almost half the semester forcing myself to develop furniture that I was not happy with and was not inspiring to me. I was still trying to produce sketches and paper models when I needed to be cutting finalized 1:4 or 1:2 scale models using CNC processes. Time was running out and I started to feel as though I would not be able to produce any furniture that semester.

By chance, I found one of my previous lattice hinge tests from my first semester and realized I could apply it to the table top for my side table. The idea for the side table came in a flash of inspiration, almost fully formed in my head. I wanted to apply the 180-degree bend to create an upper and lower surface for the table.

An idea for a design had never come so easily to me, so I was excited to move forward and make it. Because I was excited about my idea, I skipped the sketching phase and moved right into designing a scale model of the table top. I did not know what the support structure needed to look like, but I felt that having a small physical model to play with would be better than modeling or sketching. The lattice hinge pattern was not extensively thought out. I only knew the surface did not have to be as flexible as the chair.
I designed the lattice hinge pattern to alternate between three and four inner junctions, with no outer junctions. These decisions were made quickly, without much thought.
I laser-cut the scale model in 3mm birch plywood and found it was quite flexible. I also enjoyed that the lattice cuts looked more like a texture than a series of parallel lines.

Because the laser-cut model had been so flexible, I went ahead and cut a full-size version of the table top with the exact same cut pattern. The lattice-hinge pattern was not flexible enough to create a 180-degree bend in 3/4-inch material at full-scale (Figure 6). Even bending the surface to 90-degrees felt like it could break the surface.

In retrospect, I realize I did not scale up properly from the small model. However, the scale model was not correct in the first place. The relief cuts were approximately twice as wide as they should have been in relation to the thickness of the material. I was rushing
the design process, which reminded me to be more thoughtful and economical with my materials.

*Figure 7: Refined lattice pattern with an alternating pattern of two outside junctions and two inside junctions*
I re-designed the lattice hinge pattern to cut another full-size version of the table top (Figure 7). I needed the bend to be flexible, but sturdy. I designed the pattern to alternate between two inner junctions and two outer junctions. I added outer junctions because I felt the table top edges looked unfinished without them. I used two inner junctions because I felt that having only one would result in more flexibility than necessary. I still was not completely certain it would be flexible enough to make a 180-degree bend, but I had at least given it more thought than the previous model.

![Figure 8: Updated full-size table surface making a 180-degree bend](image)

The redesigned cut pattern resulted in a table surface that could easily bend 180-degrees, but was not overly flexible (Figure 8).

The development of the support structure for the table surface was a much easier challenge than it had been for the chair. A side table does not need to support a person’s weight, so the structure did not need to be as robust. For each side, there was one piece that made a front and back leg, and a surface to support the upper table surface from
underneath. These pieces nested into pocket-cuts that are underneath the upper and lower surface of the table. The pocket cuts keep the supports in place, however, the table would still rock from side-to-side with little force applied. In hindsight, I would have needed at least one beam connecting the two side-support structures.

Although I was generally quite happy with the results of the side table, I felt the Baltic birch plywood was not doing justice to the form (Figure 9). The plywood was too pale and had areas where the router bit had torn out the top layers of the surface. At the same time, the legs looked too thin and fragile. The table needed additional contrast and depth, and I wanted to emphasize the curve of the table surface. Because of the material thickness and color, the final piece in birch still looked like a model and not a finished prototype. I looked for other types of high-quality plywood with a darker color that could help provide more contrast in my design.
Bamboo plywood was an attractive and relatively convenient option, but I was very skeptical about its ability to bend. Bamboo comes in 4’ x 8’ sheets in a variety of thicknesses and colors. However, it is manufactured differently than the plywood I had tested, and typically only has three layers of material, so I was not sure it would have the right properties to allow it to bend. I ran tests on small scrap pieces that gave promising results. I cut the initial tests on 1/2-inch bamboo with cuts running across the grain on one sample and parallel with the grain on the other (Figures 5 and 6).

*Figure 10: Sample of relief cuts across the grain (1/2”)*
The 1/2-inch bamboo samples were stiffer than originals that I done in regular plywood, but they could make a 180-degree bend easily. The cross-cut samples distorted significantly, however there was almost no chip out or other damage to the wood like there was with the Baltic birch.

After seeing the results of the 1/2-inch samples, I thought the 3/4-inch sample would be flexible as well. I cut one 3/4-inch sample using relief cuts that followed the grain to avoid distortion that had been present in the previous cross-cut sample. This sample could also make a 180-degree bend, although it exhibited a little bit of deformation when
lying flat. I believed the deformation was subtle enough that it would not cause problems at full scale. I hoped to use 3/4-inch material for the side table top, because I felt 1/2” would look thin and fragile. With the small tests complete and relatively successful, I took a risk and purchased enough bamboo plywood for my side table.

![Final side table in natural (light) and carbonized (darker) bamboo](image)

The risk paid off. The surface of the table could bend 180-degrees very easily, and the bamboo added more warmth and depth to the form (Figure 13). I created contrast by using carbonized bamboo for the curved table surface and natural bamboo for the leg structures. The combination of natural and carbonized bamboo creates a contrast between the support structure and the curved table surface, helping to emphasize the curved
surface of the table. I also increased the thickness of the leg structure to give the legs more presence. I am very pleased with the look of the result; however, the rocking issue remains. If I fabricate another side table in the future, I will need to have a beam underneath the lower table surface that connects the side structures to prevent rocking.

The success of the side table led to an accompanying set of stacking stools using the same pattern of bending as in the side table (Figure 14). Because of the prominence of the curved wood in both structures, I named the set Deflect, in reference to the change in direction of the wood surface as a result of the relief cuts.

*Figure 14: Deflect Stools*
CHAPTER 3: REVISITING THE CHAIR

Stepping away from the chair project for three years allowed me to gain more fabrication experience and confidence as a designer. I felt ready to revisit my first chair, but I did not want to attempt the exact same chair. The first chair was meant to be a dining chair. However, the cone shape of the chair back made it impossible to design an appropriately sized dining chair. From the first chair, I had learned that for a person to sit comfortably and lean back, rather than be pushed forward, the seat back must be large. Another complication is that the cone shape tapers towards the back of the seat. For the seat to be wide enough for someone to sit, the back would need to be much wider than I originally thought. Due to the change in the scale, the new chair began as a low lounge chair (Figure 15).

Figure 15: Front and side views of the new chair idea
The foam model served as a three-dimensional sketch to begin designing the form. To create the seat back, I used the original pattern from my first chair, but removed the center section of vertical lines. The model did not address any structural issues, and three problems became apparent immediately. The back legs needed to extend farther back to prevent the chair from tipping backwards under a person's weight. The back of the chair would need a support structure to prevent the curved back from flexing and breaking as someone leaned back. I would also need to address the connection between the seat back and the rest of the frame, just like the first chair.

The most critical issue to solve first was the design of the support frame. Although the connection between the seat and the frame had been the primary challenge with the original chair, I was hopeful that I could use hardware to create a secure connection. The support frame would need to be designed to hug the back to keep from over-flexing when someone leans back while also having surface for hardware.

To ensure the frame hugged the back, I needed to design a structure that exactly matched the shape the curved back was creating. However, it was challenging to understand the exact shape the back was creating when it bent. The chair back is based on
a radial cut pattern. Equally spaced cuts originating from a circle would make a cone when bent (Figure 16).

![Figure 17: radial cut pattern on original chair back resulting from perpendicular lines from two circles](image)

The shape of the chair back is *like* a cone, but it is not exactly conical. The lines from the original chair back originate from two separate circles (Figure 17). I designed the lines to originate from two circles, because using one circle did not allow me to bend the wood into a wide enough shape to accommodate a person’s body. This cut pattern created a shape that appeared to be an oblong cone in my full-size back, but I discovered was more complicated as I continued to try and develop the structure.

The most accurate way I knew to develop the support structure was to draw it in a CAD program like AutoCAD or Rhino. I would have to draw the support structure on the computer in order to use the CNC laser to prototype and the CNC router to cut my full-size piece. To draw the structure to match the back, I also needed a 3D model of the back. However, even though I had drawn the shapes and lines of the back in Rhino, they only represented the shape while it was laying flat. There was no 3D modeling tool in any software that I was familiar with that would allow me to use the relief cut lines to bend the
back on the computer in the same way as the physical structure. This presented a challenge. I tried two ways of overcoming this “physical to digital” challenge.

The first method I tried was an iterative “cut and check” method. I used the laser to cut a one-sixth scale model in 3mm plywood with a rough support structure as a starting point. I created the back supports of the structure roughly at the angle I knew I wanted seat back to be at. I bent the back and taped it into place on the structure. Because the back curved, and the initial back supports were straight, there was a large gap between the back supports and the curved back. I cut strips of paper and taped them at angles tangent to the seat back to fill the void between the back supports and the seat back. Once I had a shape that was close, I took a photo and traced it in Rhino. This method was slow and tedious, but I was able to get an approximation of what the shape of the structure should be. However, in doing this process, I noticed that the curvature was more complex than I had initially thought. The shape of the back was not a smooth curve. Instead of gradually angling outwards, away from the seat, the back would angle inwards and then angle outwards.

Because the curvature was more complex than I had realized, I tried a more precise method of creating a 3D model of the back using photogrammetry. Photogrammetry is a method of taking measurements from photographs, and special software can create three-dimensional models from a series of photographs at different angles.
To create an accurate computer model, I cut a full-size version of the revised chair back, so that I could understand the curvature at full scale in the correct material. I clamped the revised chair back to a seat surface to hold the curve in place (Figure 18). I took fifty photos of the back at different angles and processed them in a photogrammetry software called Zephyr.
The resulting mesh from Zephyr was very close to the physical model, but the mesh was lumpy and needed additional processing (Figure 19).

To smooth the mesh, I first imported it into Autodesk 3D Studio Max and traced out the major contours of the mesh (Figure 20). I exported the contours into Rhino 3D and tried to smooth them without sacrificing accuracy. After smoothing the contours, I used them to create a surface, then extruded the surface by the wood thickness.
The 3D model that resulted from the photogrammetry process appeared to be very close to the shape of the physical model. The 3D model of the full size back revealed even more clearly that the seat back was not behaving like a single uniform cone. The back was behaving like two separate cones, causing the back to stick out on either side of the seat (Figure 21 and Figure 22). I was hopeful that having an accurate 3D model would allow me to develop a support frame even though the shape of the back was not perfectly smooth. To
better understand what shape the back was creating, I tried to develop a support frame for several weeks but was unsuccessful.

Due to the complex curvature of the chair back, I would not be able to use CNC routing or CNC milling with the equipment available in the woodshop to create the structure. It may have been possible with a five-axis mill, which can cut a piece of material from any direction. However, the complex structure required was a direct result of the irregular curvature from the chair back. It seemed at that point that it would make more sense to re-evaluate the shape of the chair back, rather than try to use more advanced CNC technologies that I was less familiar with to continue developing the structure.

I began to re-evaluate the curved seat back. I realized that the way I had to bend the seat back so that it was wide enough for someone to sit in, caused the back to distort into the complicated curve, rather than behaving more like a cone. I tried variations on the overall shape and experimented with making the back larger, but I was resistant to changing the angle of the relief cut lines because of how complicated it had been to develop the radial relief cut pattern in the first chair. In hindsight, it is obvious that I needed to change the angles of the relief cuts. I was still using a pattern that was based on lines coming radially out from two circles, resulting in a shape that bent like two separate cones, rather than one smooth shape. At this phase, I was almost ready to give up, and felt again that I was trying to force a shape into an application it would never be suited for.
However, I had a breakthrough. Although changing the overall shape and scale of the piece was not helping the warping and stretching of the curved back, changing the orientation of the end pieces of the back helped reduce the amount of stretching. In the original chair and the first iterations of the new chair models, the ends bend under (Figure 18). While manipulating the scale model, I realized that they could attach vertically to the rest of the structure, rather than bending under and attaching horizontally (Figure 23).
For some reason, I had not considered changing the direction of the connection between the seat back and the frame. During my design process, it was very easy to fall into a trap of thinking that the design must stay the same as the original concept and then get locked in to constraints that were unnecessary and paralyzing. With the new direction, I thought the remaining structural issues would be straightforward to figure out, and the development process started to go quickly again. I quickly made a revised sketch and cut another third-scale model (Figure 24 and Figure 25).
After the first 1:3 scale model, I realized that the new idea seemed to help with some of the structural issues, however it did not completely solve anything. The middle section of the back still had to stretch a lot to have enough room for a 17 to 18-inch wide seat. When the chair back was bent and stretched so that it was wide enough for someone to sit in, the resulting shape of the back would distort. The distortion of the back was still present even though the end pieces no longer had to fold underneath the seat. At this stage, I finally began revising the angles and spacing of the relief cuts on the chair back.

With the first chair, the cut pattern was designed to make the chair back as flexible as possible throughout the whole shape. I needed the entire back to be as flexible because it curved continuously. However, the new back had a curved back and mostly straight sides, so it did not require maximum flexibility throughout the whole shape.
There were three main factors to manipulate how the back curved (Figure 26). The first was the central shape the cuts radiated perpendicularly out from. The central shape generally dictated the 3D shape the back would curve into. Until this point, I had only been using circles, but I realized I could consider ellipses for the central shape as well. The next factor was the number of radiating lines I had come from the central shape. The number of cuts from the central shape affected how close together the resulting relief cuts would be. Cuts that are closer together result in a surface that is more flexible, but more fragile. The third factor was where the second layer of relief cuts would start. At the beginning of the testing, I did not have a strong prediction of how the second layer of cuts would affect the shape of the back.

*Figure 26: Central shape (blue), secondary shape (red), and radiating cut lines that are perpendicular to the inner shape*
Changing the central shape affects the radial cut spacing. Although the initial spacing is the same for both the circle and the ellipse, the cut spacing for the ellipse does not stay the same. The angles between equally spaced perpendicular lines radiating from a circle will always be the same. However, the angles between equally spaced perpendicular lines on an ellipse will not be the same because the curvature of an ellipse is always changing. Areas with greater curvature will result in perpendicular lines with a larger angle between them. A larger angle will result in the relief lines spaced farther apart, and thus less flexibility.

The spacing of the radiating lines was initially chosen so that there would be a quarter-inch of material left between the start of each relief cut. This created a one-to-one ratio of positive and negative space that my previous research had shown would give the most flexibility without significant risk of breaking. However, as briefly mentioned earlier, the chair back does not require maximum flexibility. Rather it needs to be just flexible enough to create the desired shape for the chair back, while remaining rigid enough to
provide support for a person sitting. The part of the chair back requiring the most flexibility was the back curve, while the sides could remain relatively rigid.

To create the correct cut density for a flexible back and rigid sides, I predicted I would need the relief cuts to radiate from an ellipse. Specifically, I would need a horizontal major axis ellipse, which is an ellipse that is longer than it is tall. Although I generally understood how the central shape would affect the overall three-dimensional form. I did not have an understanding of the minimum and maximum thresholds for the spacing. I also did not know what the proportions of the inside ellipse should be to create the three-dimensional form I needed.

![Figure 28: Inner-cut shapes used for testing the chair backs. From right to left: circle, best-fit ellipse, and a narrow ellipse.](image)

I ran two rounds of tests with six samples each. The first round I tried three different inner cut shapes with two different numbers of divisions each. The inner-cut shapes used were a circle and two types of ellipses. The first ellipse was a best-fit ellipse for the previous chair back that had approximately a 1.17:1 major to minor axis ratio. The second was a narrower ellipse that had a 2:1 major axis to minor axis ratio. Testing from the first round helped determine the most appropriate inner cut shape and an estimate for
how many cuts I would need at full scale. The testing was beneficial to see how each shape would bend, but was not so helpful for understanding the strength of each shape, as most of the samples broke with very little manipulation. The results showed that an ellipse with a 2:1 major to minor axis ratio with approximately 60 cuts would be appropriate, because it provided maximum flexibility for the very back of the seat while making the sides more rigid.

The second round of testing I needed to better understand how the second layer of cuts affected the shape. I ran another six tests using the narrow ellipse as the center shape and varied the placement of the second row of relief cuts. The starting point of the second layer was determined by how much material would be left between each cut at full scale. I tested leaving 0.25” and 0.55”, resulting in cuts that started closer to the center shape or farther away from the center shape. I also tested starting the second layer of cuts based on the center point of the relief cuts, even though it resulted in an unequal spacing.

Overall, the results of the second round of testing showed that it was better to have the second layer of relief cuts start farther away from the center shape. The starting point of the second layer primarily affected how the shape of the back deformed as it stretched. Starting the relief cuts closer to the center shape, as in the 0.25” and midpoint samples, resulted in the chair back flexing more at the top, causing the pieces to compress together which deform the shape and limited how far I could stretch the chair back around the size of the seat. Starting the relief cuts farther from the center shape, as in the 0.55” samples, resulted in the chair back flexing more at the bottom, stretching the pieces out, but not causing areas of compression that would have distorted the shape of the back or limiting the size of the seat.
Using the results of the 1:6 scale testing, I cut a 1:3 scale model (Figure 29). I was happy with the overall shape of the back. However, the design of the joints and structure were not yet solved.

![Figure 29: Last 1/3 scale model](image)

To simply the structure, I changed the seat back so that it did not fully become the front legs. It did not make sense to have the flexible seat back become a main structural component. Instead the back would wrap around like a jacket and be supported by the frame.

I initially tried to create this chair so that it would not need hardware. However, this created complicated joints that were not sturdy since too many components needed to be connected and locked together. It was not practical to continuing designing without hardware when there were types of hardware designed for the exact connections that I needed to make.
I found appropriate hardware for the connection of the seat back to the frame of the chair. I utilized tee nuts, which are threaded metal inserts that are embedded into a wood surface. The inserts would allow me to use a screw to secure my chair back flush with the legs, providing a stable connection between my chair back with the rest of the structure.
Finally, three years after my initial sketches of the chair, I completed a full-size model of my chair (Figure 31). Although I had completed a full-size prototype of my first chair, it was not stable enough to sit in. The full-size version of the new design was quite solid, and I felt confident having others sit and test it.

It was exciting to have a full-size version that was structurally sound enough for someone to sit it, but the full-size model still had design issues. I had aligned too many surfaces, creating areas that were very thick. The thick areas caused the legs and back support structure to appear heavy and unbalanced with the lightness of the curved chair back. To lighten the structure, I reduced the thickness of the material for the structure of the chair from 3/4-inch plywood to 1/2-inch plywood, reduced the size of several structural elements, and dis-aligned the chair back from the rest of the structure. I hoped these changes would help to de-emphasize the structure and highlight the curved back.

In addition to the aesthetic issues, the chair back had remaining design and structural issues. Depending on the height of the user, the chair back would curve around to be the same height and position as an armrest. He or she may be tempted to use the sides of the chair back to support themselves as they stand up or sit down in the chair. Putting weight on the chair in that manner would cause the sides of the curved back to flex, not only disrupting the user, but threatening to break the back. To minimize the issue, I reduced the length of several relief cuts on the sides of the back, which would make the back more rigid in the problem areas.
Figure 32: Final version (front)

Figure 33: Final version (side)
The final prototype is a significant improvement from the first full-size model. By making structural elements thinner and dis-aligning the chair back from the surface of the legs, the whole chair feels lighter (Figure 32). The curved back stands out more clearly as the focus of the chair and is especially dramatic from the side (Figure 33). The swooping curve of the chair back in combination with the series of relief cuts creates a sense of motion. To me, the back resembles a still frame of a bird’s wing while in flight. Because of this reference to wings and motion, I decided to name the chair Flutter.

Although this is the most recent and most finished version of the Flutter chair, it is far from being functional. There continue to be structural and aesthetic issues that I do not think can be solved in wood. The legs of the chair are still too heavy in relation to the lightness of the back, and the back-support structure is too thick. The challenge I face is that the structural elements supporting the back need to shrink dramatically but remain strong enough to hold the seat back in place. Continuing to shrink the current wooden structure will cause it to become weak. I believe the only material that can be strong and thin enough to achieve the visual lightness needed is metal tubing. I do not have the fabrication abilities to bend metal tubing into the precise shape that is needed to support the back structure. In addition, I am not sure if I fully understand what the shape of the metal tube would need to be at this stage. I believe I would need at least another four years of graduate school to develop the rest of the chair structure to be as light as I want it to be.
REFERENCES


   https://doi.org/10.17077/etd.6ubabqtu.