The direct and rapid connections between scripting, modeling and prototyping allow for investigations of computation in fabrication. The manipulation of planar materials with two-dimensional CNC cuts can easily create complex and varied forms, volumes, and surfaces. However, the bulk of research on folding using CNC fabrication tools is focused upon surfaces, self-supporting walls and shell structures, which do not integrate well into more conventional building construction models.

This paper attempts to explain the potential for using folding methodologies to develop structural members through a design-build process. Conventional building practice consists of the assembly of off-the-shelf parts. Many times, the plinth, skeleton, and skin are independently designed and fabricated, integrating multiple industries. Using this method of construction as an operative status quo, this investigation focused on a single structural component: the truss. A truss is defined as: "A triangulated arrangement of structural members that reduces nonaxial external forces to a set of axial forces in its members." (Allen and Iano 2004)

Using folding methodologies and sheet steel to create a truss, this design investigation employed a recyclable and prolific building material to redefine the fabrication of a conventional structural member. The potential for using digital design and two-dimensional CNC fabrication tools in the design of a foldable truss from sheet steel is viable in the creation of a flat-packed, minimal waste structural member that can adapt to a variety of aesthetic and structural conditions. Applying new methods to a component of the conventional 'kit of parts' allowed for a novel investigation that recombines zero waste goals, flat-packing potential, structural expression and computational processes.

ABSTRACT

The direct and rapid connections between scripting, modeling and prototyping allow for investigations of computation in fabrication. The manipulation of planar materials with two-dimensional CNC cuts can easily create complex and varied forms, volumes, and surfaces. However, the bulk of research on folding using CNC fabrication tools is focused upon surfaces, self-supporting walls and shell structures, which do not integrate well into more conventional building construction models.

This paper attempts to explain the potential for using folding methodologies to develop structural members through a design-build process. Conventional building practice consists of the assembly of off-the-shelf parts. Many times, the plinth, skeleton, and skin are independently designed and fabricated, integrating multiple industries. Using this method of construction as an operative status quo, this investigation focused on a single structural component: the truss. A truss is defined as: "A triangulated arrangement of structural members that reduces nonaxial external forces to a set of axial forces in its members." (Allen and Iano 2004)

Using folding methodologies and sheet steel to create a truss, this design investigation employed a recyclable and prolific building material to redefine the fabrication of a conventional structural member. The potential for using digital design and two-dimensional CNC fabrication tools in the design of a foldable truss from sheet steel is viable in the creation of a flat-packed, minimal waste structural member that can adapt to a variety of aesthetic and structural conditions. Applying new methods to a component of the conventional 'kit of parts' allowed for a novel investigation that recombines zero waste goals, flat-packing potential, structural expression and computational processes.
1 Introduction

“The design engineer, in his prioritizing of materialization, is the pilot figure of this cultural shift which we have termed “new structuralism.” (Oxman and Oxman 2010)

“It [architecture] must become more primitive in terms of meeting the most fundamental human needs with an economy of expression and mediating man’s relationship with the world…and more sophisticated in the sense of adapting to the cyclic systems of nature in terms of both matter and energy. Ecological architecture also implies a view of building more as a PROCESS than a product” (Pallasmaa 1993).

The designer’s exploration of materials and processes leads to an architecture whose expression is tied to the tools and components used to create it. As exemplified in the work of Mark West and others, material exploration and structural expression can result in novel forms and processes. As new combinations of design and engineering are now the architectural norm, it is necessary to explore the constantly evolving links between materials, fabrication, function and expression.

The direct and rapid connections between scripting, modeling and prototyping allow for investigations of computation in fabrication. The manipulation of planar materials with two-dimensional CNC cuts can easily create complex and varied forms, volumes, and surfaces. However, the bulk of research on folding using CNC fabrication tools is focused upon surfaces, self-supporting walls and shell structures, which do not integrate well into more conventional building construction models.

This paper attempts to explain the potential for using folding methodologies to develop structural members through a design-build process. Conventional building practice consists of the assembly of off-the-shelf parts. Many times, the plinth, skeleton, and skin are independently designed and fabricated, integrating multiple industries. Using this method of construction as an operative status quo, this investigation focused on a single structural component: the truss. A truss is defined as: “A triangulated arrangement of structural members that reduces nonaxial external forces to a set of axial forces in its members” (Allen and Iano 2004).

Using folding methodologies and sheet steel to create a truss, this design investigation employed a recyclable and prolific building material to redefine the fabrication of a conventional structural member. The potential for using digital design and two-dimensional CNC fabrication tools in the design of a foldable truss from sheet steel is a viable in the creation of a flat-packed, minimal waste structural member that can adapt to a variety of aesthetic and structural conditions. Applying new methods to a component of the conventional ‘kit of parts’ allowed for a novel investigation that recombines zero waste goals, flat-packing potential, structural expression and computational processes.

1.1 This Investigation Involved Three Phases

1) Reconstructing Conventions: Using conventional models of trusses, an exploration of folding methods resulted in the creation of a base model that could be parameterized to express the physics of the member. Intelligent folding, tabbing and joining patterns that minimized waste in the fabrication of a flat pack truss were explored with the goal of creating a truss that involved minimal skilled labor, zero-waste cutting patterns, and a response to the load carried.

2) Parameterization: A parametric truss was developed that can change based on load and length. The parameterization of the truss model explores the limits of the folding geometric pattern. These limits serve as guides for phase three.

3) Testing + Deployment: We selected loading conditions and fabricated a truss from 20 gauge mild sheet steel using a CNC plasma cutter. Feasibility for folding, transportation and application were assessed from these models.

2 Phase 1: Reconstructing Conventions

The first phase of this research consisted of establishing a minimal base line for later parameterization. Using a flat truss model, defined as a truss that has “parallel top and bottom chords” as a starting point (Ching 2008), we used its basic diagram to develop a base truss that...
would fulfill loading, folding, and minimal waste goals. Since a typical flat truss is made up of smaller components, and our goal was to construct a truss from a single sheet of steel, we knew the folding strategies would guide the design of the truss.

The first three attempts at defining a base model informed the final successful model, but each had inherent weaknesses, conflicting between folding methods and the conventions of a component based truss.

2.1 TEST 1

The first exploration of a flat truss model was composed of two sides of a single steel sheet folding into one another (Figures 1, 2). Each side would integrate the excess steel removed from the other to connect each face of the truss. This method resulted in excessive waste and the material overlap was not a clean expression of its fabrication. Although the member was sturdy, it was heavy, clumsy, and there was no clear method for how it might operate in a system.

2.2 TEST 2

The second exploration was based upon improving the first iteration. In an effort to reduce material redundancy, the webbing material was folded from the material waste of the triangular voids, rather than from two pieces sandwiched together, as in the first test. The chords are created from folding the long edges of the sheet to a triangle, which carries through to the final base model. However, the chords were unsupported (Figure 3, side view), making the only connection between the webbing and the chord a single width of material (Figure 4). This model reduced material overlap, but lacked structural integrity.

2.3 TEST 3

The third exploration investigated a prismatic, tri-chord truss. This model used folding patterns and minimal-waste goals, but incorporated componentry through the cutting pattern of independent pieces (Figure 5). In this tri-chord truss pattern, three chords would be cut from the same sheet as the interior webbing. (Figure 5, cutting pattern). The geometry of the truss was compelling, as the web would rotate inside the stringers at 60-degree angles connecting each stringer sequentially (Figure 6). However, the geometry was inherently flawed, as any lateral movement of the chords would cause the truss to collapse. In addition, the construction method involved complicated assembly and folding patterns, contrary to this project’s initial goals.

2.4 TEST 4: FINDING A BASE MODEL

From the three initial explorations, we identified more specific design goals for a base model of the truss. First, the construction method must be simple, avoiding a complex assemblage of components. Second, the model must aspire for zero-waste and minimal material redundancy. Third, the base model must have the potential for parameterization that will reflect the load that it carries. With these goals, we designed a base model that explores expressive construction methods for a structural member.

The final design of the base member began by defining the profile of the chords. Since the method of construction was based on folding, the ideal chord strength is based on folding the material to create a triangulated member (Figure 7). This profile of the truss worked well for the creation of a top and bottom chord, but created a diagonal webbing orientation, which presented a design challenge for the web.

The diagonal orientation of the webbing required an understanding of how the truss would work as a system and successfully carry a load. The cutting pattern is (Figure 8) a series of triangles that were alternately folded, one side of the truss to another (Figures 9, 10). The folding of the chords is supported by the webbing waste, while leaving enough material to create the webbing (Figure 11). The triangulation also allows for three points that can later be parameterized within a system to respond to different loads.
Phase 2: Parameterization

Inspired by the work of Mark West's work in concrete (Figure 12), this project aimed to use a structural member's loading to inspire its response. Using parameterization with Grasshopper (McNeel, Dave Rutten) in Rhino (McNeel), we were able to explore the integration of a moment diagram to the expression of a truss' webbing. This response manifested itself in the two-dimensional cutting pattern of the truss, and a three-dimensional expression of the loads on the truss.

3.1 CONTROL POINTS

The control points of the web respond to the associated moment diagram. In Figure 13, points 'a' and 'b' are fixed and point 'c' was variable. The location of point c was contingent upon the intersection of the moment curve and the crease of the folded web (Figure 13, line cb).

The moment diagram was a variable input, describing the loading of a specific scenario. The moment diagram of the load was input to the script as a curve. The script that was made could interpret any moment diagram into the cut pattern of the truss. To construct example models, we chose three conditions of loading: a uniform load, a uniform load with a point load, and a cantilever with a uniform load (Figure 14).

3.2 SCRIPTING IN GRASSHOPPER

As shown in Figure 15, a Grasshopper script was used to correlate variable loading conditions to the cutting file. First, the moment curve is derived mathematically, drawn in Rhino, and referenced in Grasshopper. Then, a regular set of lines that represent the spacing of the base model's webbing is drawn in Rhino and referenced in Grasshopper. The intersections of the set of lines and the moment diagram are converted to list data. This list is then correlated to the 'c' point (Figure 13) on the cutting pattern. Once the points are located on the cutting pattern, cut lines are drawn between the variable points and their corresponding stationary points (Figure 13 lines 'ac' and 'bc'). The rest of the script is used for three-dimensional modeling and speculation in Rhino. The information from this section is used for visualization and expression of the folding method.

Phase 3: Testing + Deployment

The following phase involved turning speculative on-screen work into steel trusses that successfully carried various types of loads. This phase involved lessons in fabrication, labor and material constraints. Beginning with a set of iterative paper models to better understand the folding principles and proportion of the design, the work quickly moved to steel.

4.1 FULL-SCALE TESTING

The first cut sequence began on a scrap piece of steel (16 gauge sheet, approximately an 8' x 19" piece). As this was scrap, there were a few abnormalities in the cut pattern. However, this test piece led to important discoveries about the production process. First, the blast radius of the machine's plasma head was 1/16". The cut files that had been drawn accounted for this radius on either side of the cut line, but did not consider that at each line the cut would extend an 1/8" as well. In certain areas where an 1/8" of material was specified for bending, it left little to no material for the bend. This led to structural degradation as well as a complete loss of some fins. It was also discovered that to successfully bend the triangulated chord, a uniform fold was difficult to achieve with the first stitching pattern (Figure 16). The tabs on the beam was MIG welded at a feed rate of 210, and voltage of 17.0 amps.

4.2 FULL-SCALE DEPLOYMENT

After the first test truss, the subsequent trusses were cut from new, more regular pieces of sheet steel allowing for more consistent results. In addition, a thinner sheet (20 gauge) was used to allow for easier folding, cutting and manipulation. The three different iterations in folding techniques would respond to a uniform load, a point load, and a cantilevered load. However, we only fabricated the truss specified for the uniform load.

From the test truss, we changed the stitching pattern from a "smile" (Figure 17) cut 3" in length with a ¾" material gap in between, to a "smile" 3' in length with a ½" of material gap. This decrease of the material gap was to limit because of the difficulty in folding the running chords and the
resulting undesirable deformation in the folding edges. The “smile” is used so that the fold has a radius, therefore allowing for more material to have a consistent fold line and resistance to failure.

In addition, the method of the chord folding was improved by the use of a vice, rather than attempting to fold the chord with the use of a hammer and pliers. However, once the chord was folded, an additional tack weld was added between webbing voids to hold the chord in place (Figure 18).

Once folded and welded, the truss was tested for loading capacity. Two pieces of 1/8" steel plate were welded to each end of the truss and 1/8" steel angle was welded to the plate to create a connection with the vertical supports (Figure 19). For the first loading test, the angles were attached to the top chord, and the truss was hanging, with the bottom chord in tension and the top in compression. However, this resulted in failure of the truss after 410 lbs (Figure 20). The truss was then flipped so that the supporting angles bore the weight, allowing the vertical supports to prevent the tension in the bottom chord from deforming the top chord. We then tested the same truss (after failure) and it held the 410 pounds again, without failure.

The final truss in this investigation was 7'11.5" long, weighed 7.071 pounds and carried a load of 410 pounds. The conventional ‘weight versus load carried’ are slightly better than our truss, but further critical analysis can improve this ratio. In addition, further testing should include a more precise loading scenario that allows the truss’ bottom chord to act in compression, rather than tension on the first test, with a loading platform that better distributes the weight.

5 Conclusion

This investigation of folding patterns, structural response and minimal waste goals is the beginning of rethinking a conventional structural member through the use of digital design and fabrication. The combination of computer-aided design, CNC fabrication, and structural responsiveness in this project shows how conventional materials can be applied to a parametric model and result in a novel method of fabrication and expression. Although this model is far from the production line, the methodology behind our process allows for a new combination of flat-pack, minimal waste and structural responsiveness. The appearance of the truss follows its form, which in turn maps the function (carrying loads). The aesthetic of functional expression is beyond revealing the structure in a finished building, but shows the forces at work in a way that melds mathematic interpretation and design thinking.
This research was successful in identifying a set of goals for the design of a flat-packed foldable truss. Minimal skilled labor, the reuse of webbing waste, structural responsiveness and minimal material redundancy are principles that future research on this topic may build upon.

Further investigations could include a deeper analysis of useful stitching patterns, loading responses, and variations of the base pattern. After the testing and deployment of this project, another phase of research could return to the computer and critically analyze the cutting geometry and pattern in structural simulations or generating variations of size ratios through genetic algorithms (such as Galapagos). In addition, parameterization could be extended from only controlling the webbing geometry to managing the combinations of depth and width of the truss. In this investigation, the user controls the moment diagram, but the application of structural simulations may allow for further automation.

This project demonstrates speculative opportunities for the responsive design of a flat-packed truss. The fabrication benefits and real-world applications are broad and yet undefined. Since the unit is from a single sheet of steel, there is no assembly of parts, allowing for a simple delivery process. The flat sheets minimize shipping volume, and therefore may reduce packing waste. The folding patterns are relatively simple, and welding is minimized to simple tack welds, allowing for a minimal skill level to construct this truss. The cutting process requires few laborers and a CNC plasma cutter, rather than a full factory for fabrication. Possibly, the economy of shipping and labor would allow this model to be used in locations that have little skilled labor or construction equipment, like relief situations. Furthermore, we could simplify the construction process by the integration of tabs and folds as connections between panels to minimize or eliminate the need for welding. The parameterized model allows for the truss to be quickly custom sized to an application without material repercussions, which could translate into the rapid fabrication of custom structural members.

References


