

Zero-Waste, Flat Pack Truss Work: An Investigation of Responsive Structuralism

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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, 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 exploration of materials and processes leads to an architecture whose expression is tied to the function of the tools and components used to create it. As exemplified in the work of Mark West and others, the 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. (mark west photo/diagram here?)

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. 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 focuses 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, Iano,

2004)

Using folding methodologies and sheet steel to create a truss, this design investigation employs 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’ allows 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 the potential for 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 a set of variable loading conditions and fabricated each version 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.”(Ching, 2008), as a starting point, 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 goals were to construct a truss from a single sheet of steel, we knew the folding strategies would guide the design of the truss.

The first two 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 and 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 the cut.. Although the member was sturdy, it was heavy, clumsy, and there was no clear method for how it might operate in a system.

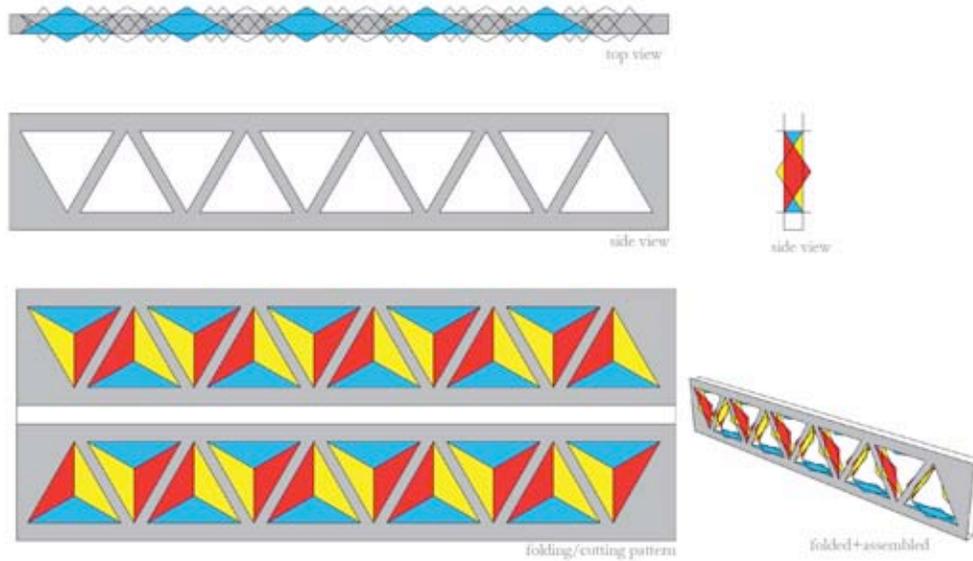


Figure 1. The first test study of folding methods with a flat truss.

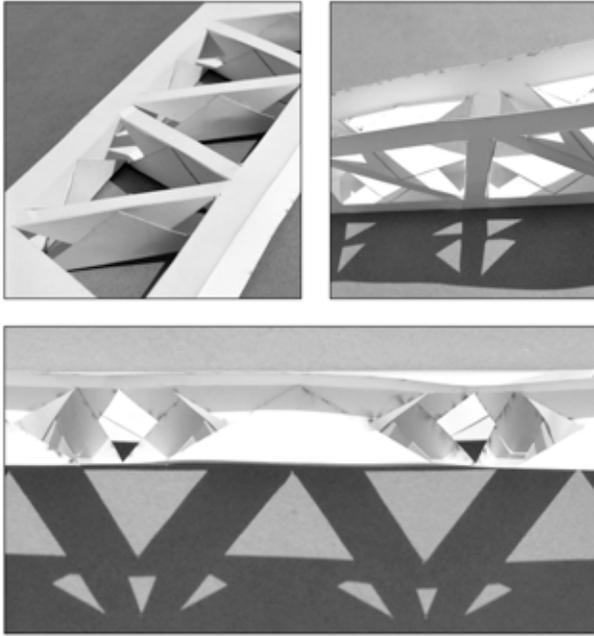


Figure 2. Paper model of the first test study.

2.2 Test 2

The second exploration was based upon improving the first iteration. In an effort to reduce material redundancy, the webbing is folded from where the voids are in the front view, rather than from two pieces sandwiched together. 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.

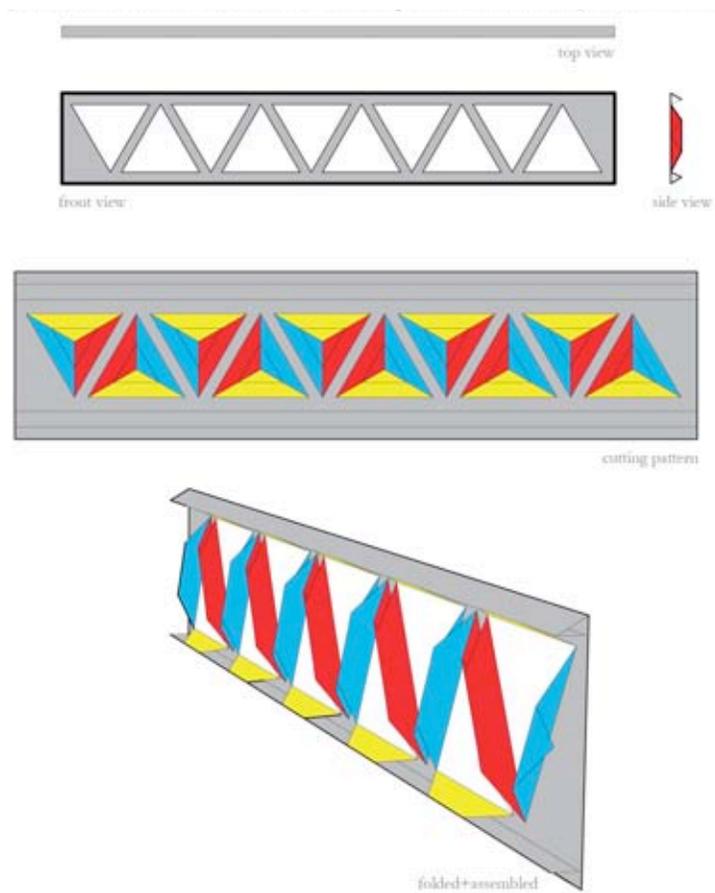


Figure 3. The second preliminary exploration of a flat truss.

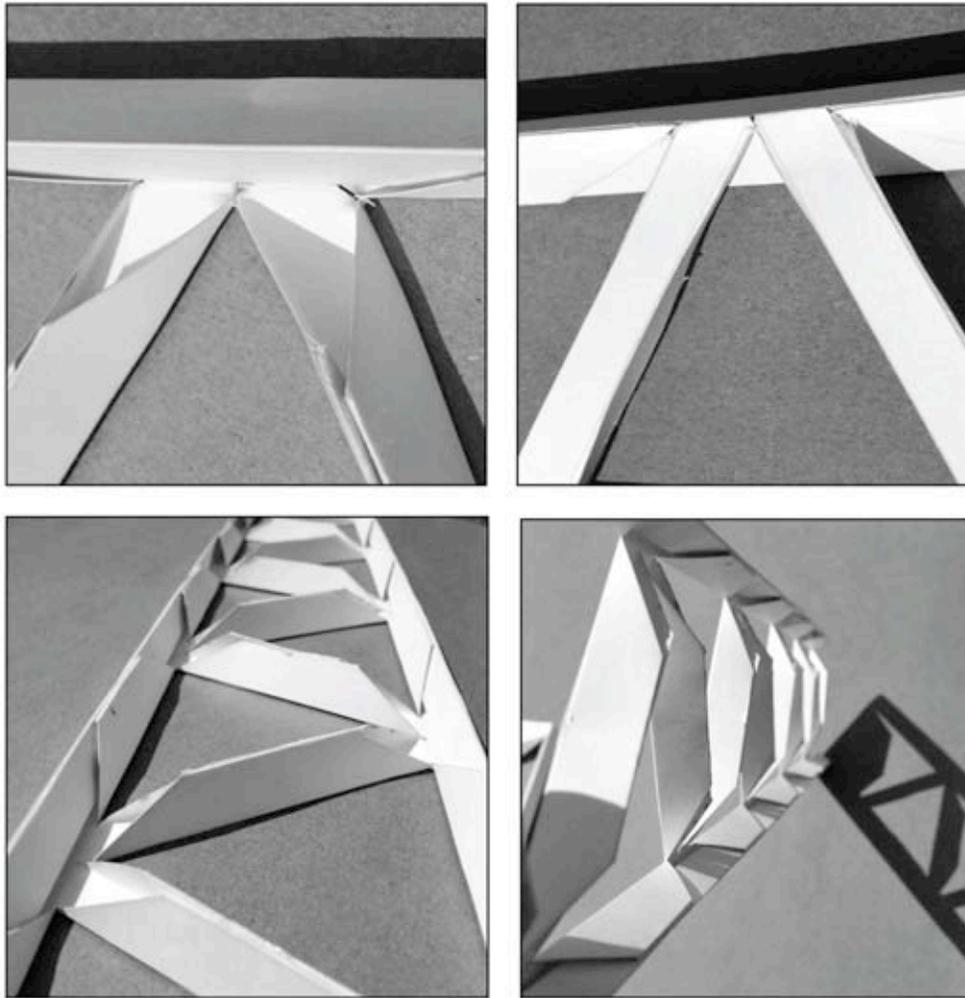


Figure 4. Paper model of the second exploration.

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.

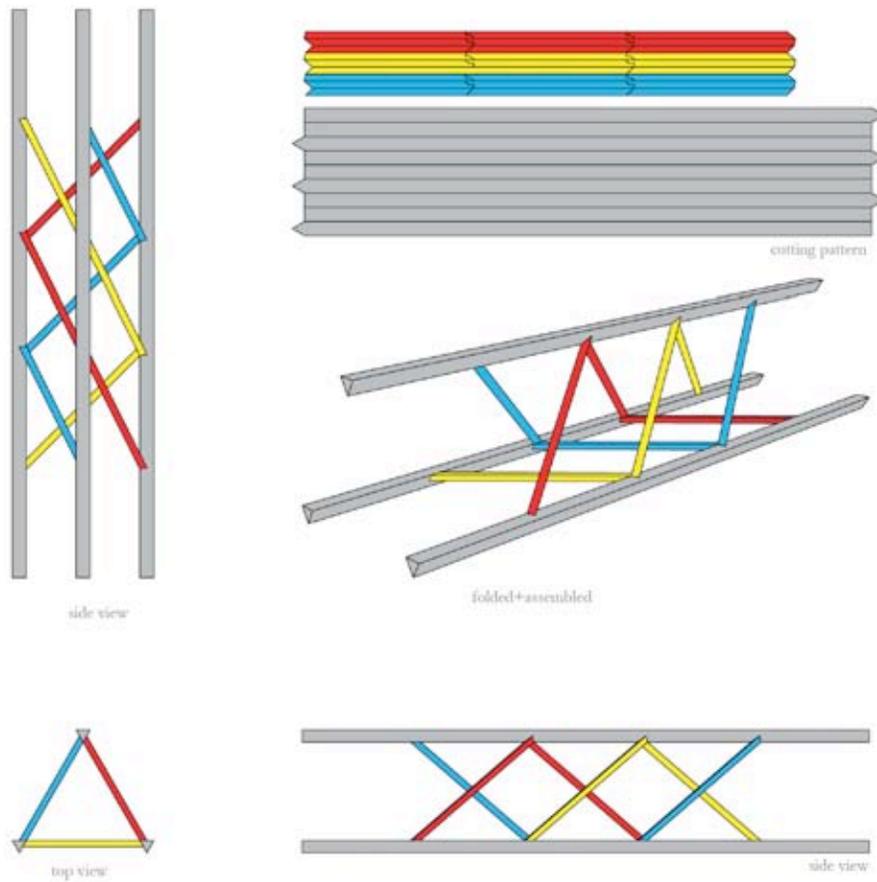


Figure 5. A preliminary exploration of folding methods with a prismatic, tri-chord truss.

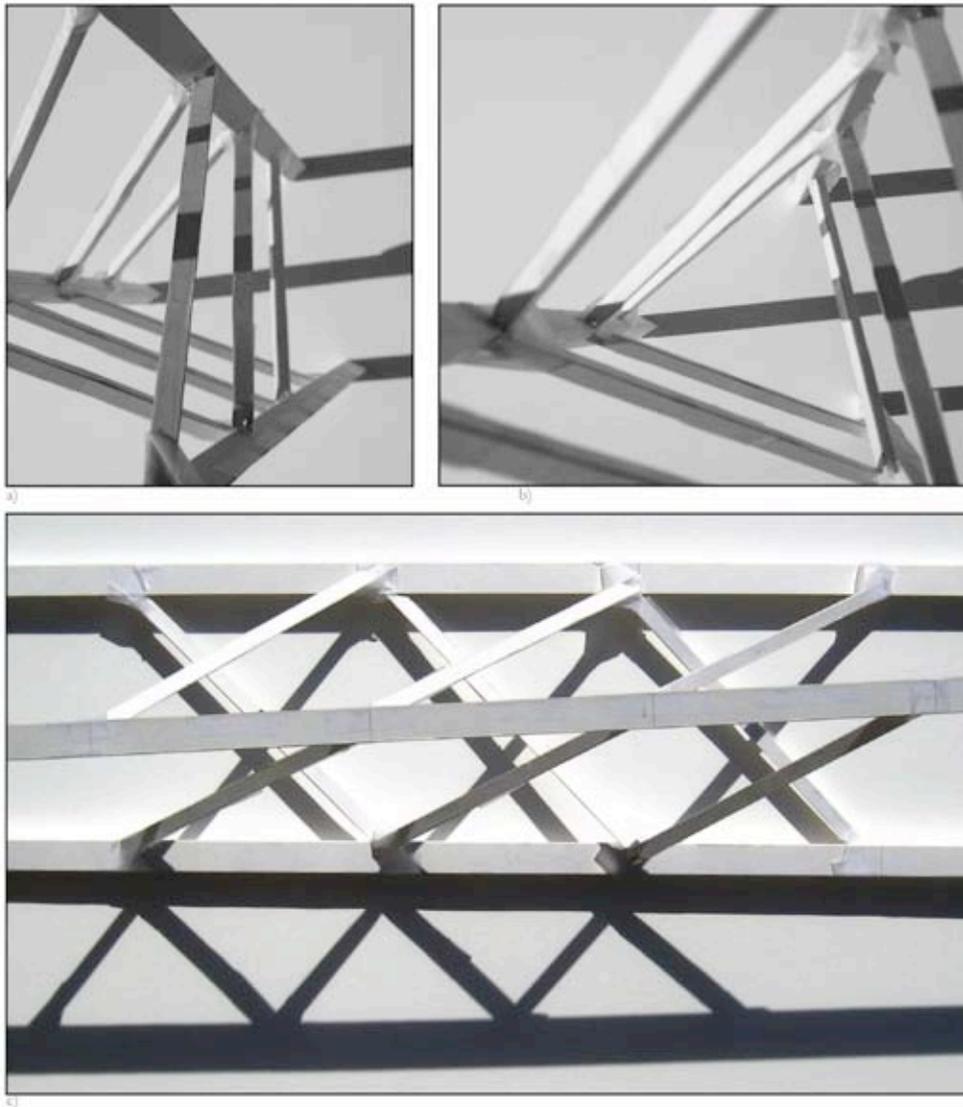


Figure 6. Paper model of an exploration of a tri-chord, prismatic truss.

2.4 Test 4: Finding a Base Model

From the two initial explorations, we identified the need to design a base model for 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 cords. 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.

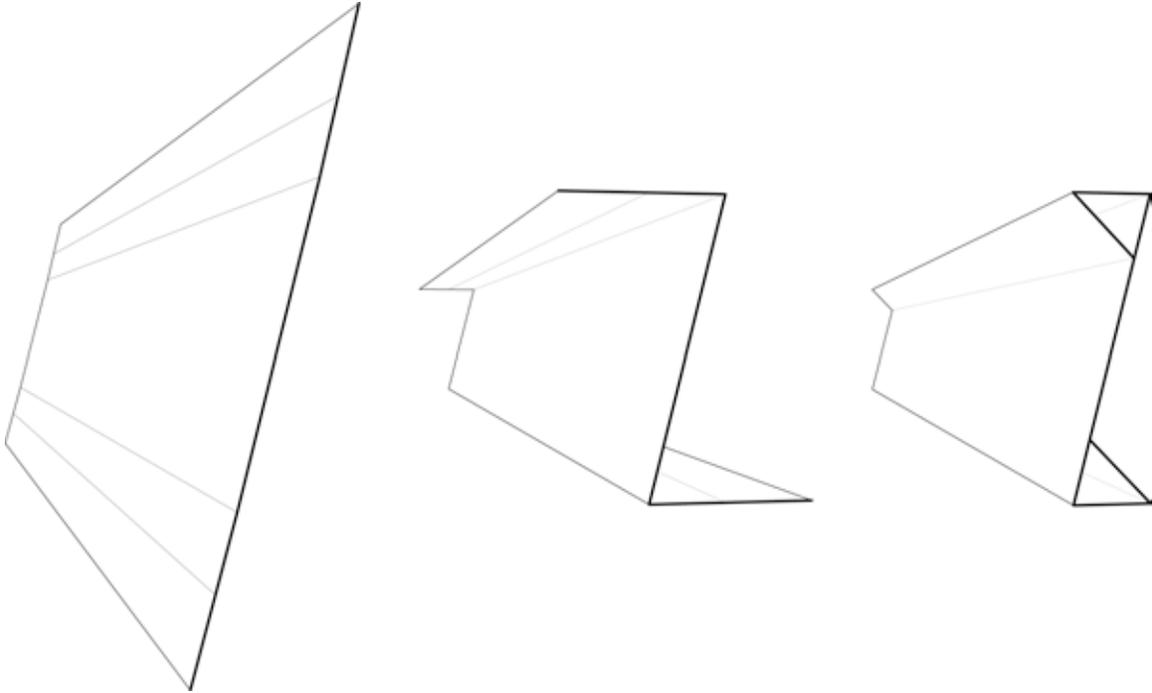


Figure 7. The base model of the truss was first designed in section with a focus on the chord profile. The sheet steel would be folded upon itself to create the chords. The image above is the folding series to create the profile.

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 and 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 differing loads.

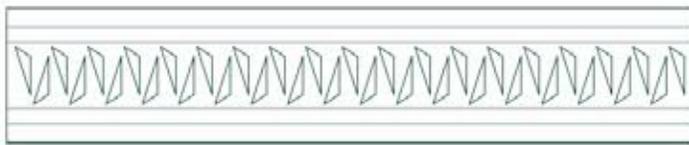


Figure 8. The cutting pattern for the base model of the truss.



Figure 9. Side elevation of folded base truss. Triangular fins (webbing waste) fold out to support the chords.

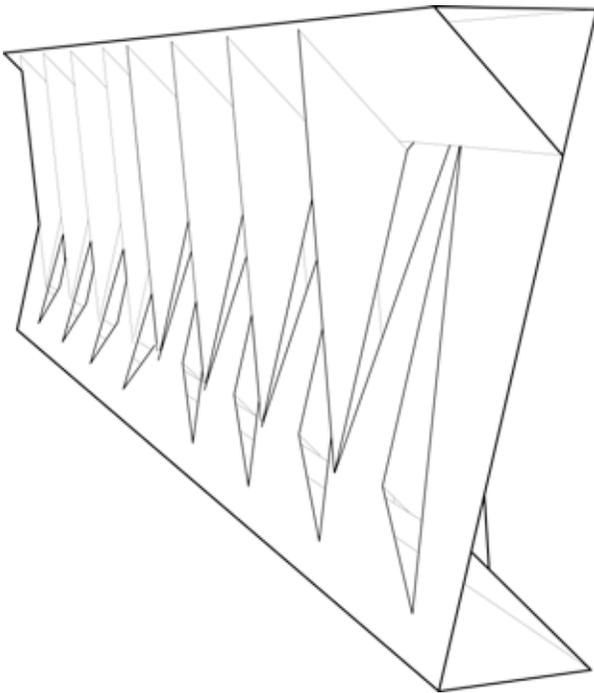


Figure 10. Folded base truss with webbing waste to support the chords.

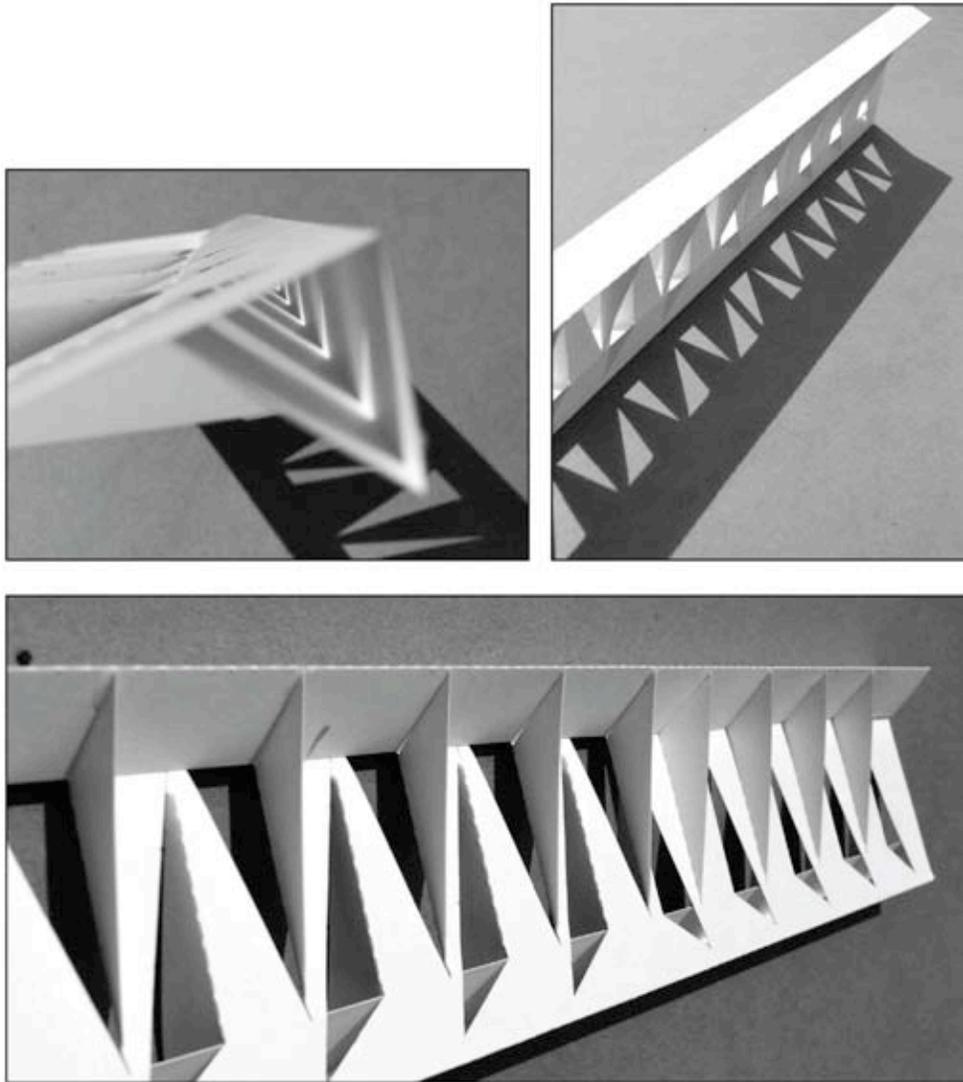


Figure 11. Images of paper base model.

3 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).

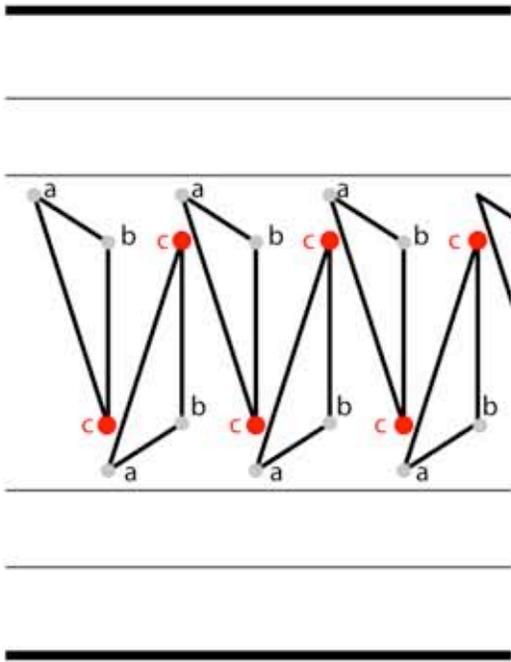
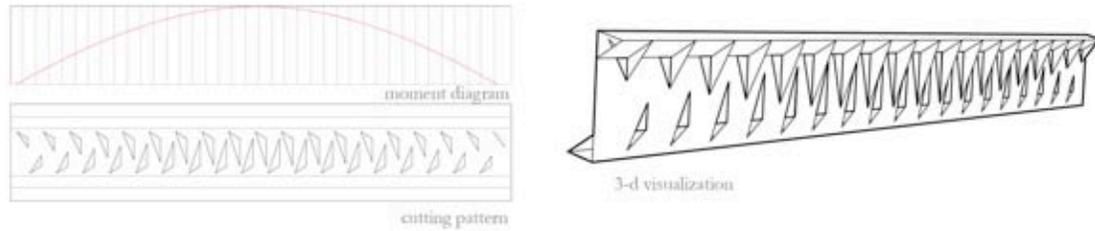


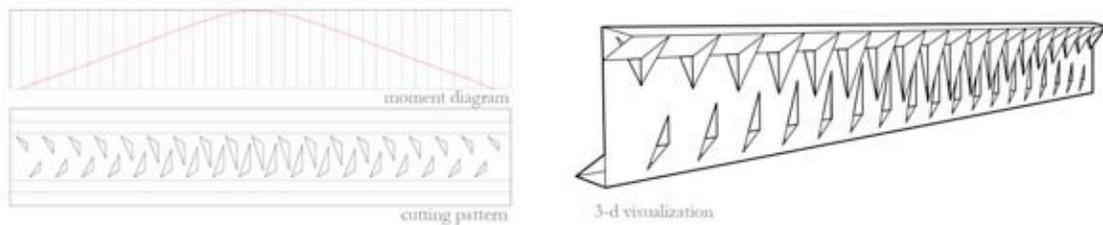
Figure 13. The cutting pattern was parameterized. The moment diagram expressed itself in moving the 'c' points. Since the 'a' to 'b' line supported the chords of the truss, they are stationary and are dependant upon dimensions of the chord folds.

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 cutting 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)

a) Uniform Load



b) Uniform load with point load



c) Uniform Load, cantilever

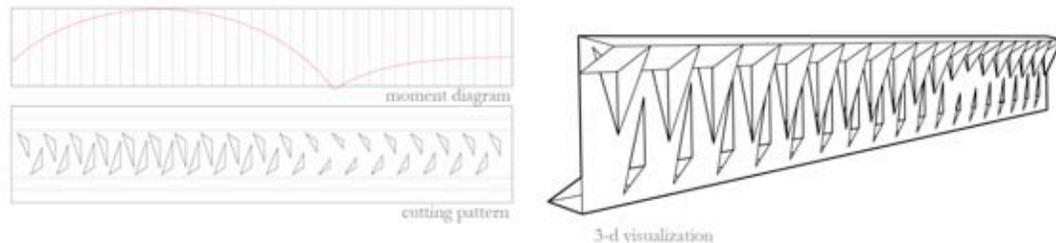


Figure 14. (a,b,c) Moment diagrams and corresponding truss cutting patterns for: (a) A uniform load supported on both ends, (b) uniform load with a single point load supported on both ends, and (c) uniform load with cantilever. The moment diagram is expressed in the webbing of the truss, revealing the structural behavior of the member.

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 (lines 'ac' and 'bc', Figure 13). 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.

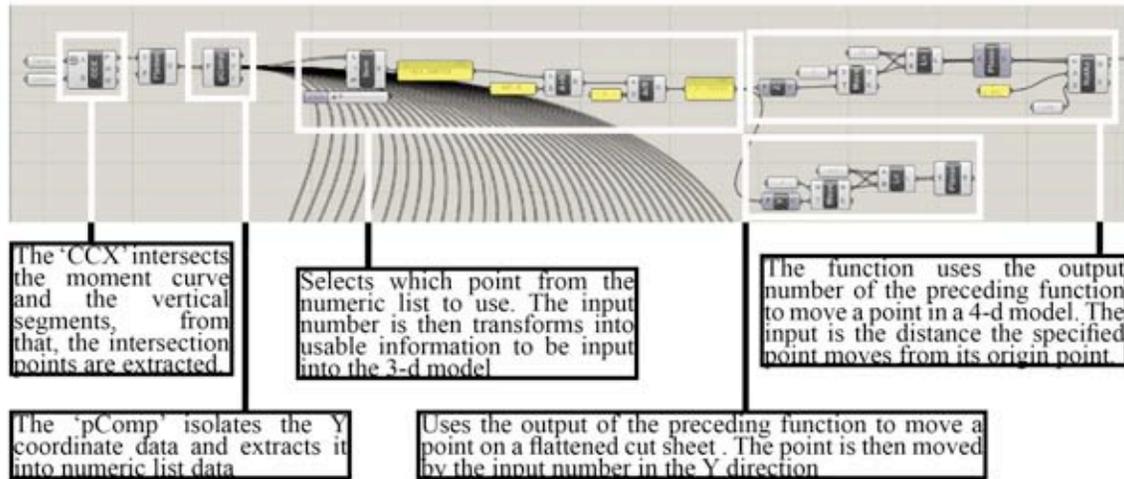


Figure 15. The Grasshopper script above allows for the moment diagram of the loads to be expressed in the cutting pattern.

4 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 cutting steel.

4.1 Full-Scale Testing

The first cut sequence began on a scrap piece of steel (16 gauge sheet, approximately an 8' x19" 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 cut would be 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 loss of some fins completely. 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.



Figure 16. The fabrication of test beam was difficult because of the heavy gauge and stitching pattern. Note the hammer.

4.2 Full-Scale Deployment

After the first test, the following trusses were cut from new pieces of sheet steel allowing for a more consistent material. In addition, 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. we tes 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 $\frac{3}{4}$ ” material in between to a “smile” 3” in length with a $\frac{1}{2}$ ” of material left because the difficulty in folding the running cords and the 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.



Figure 17. Example of a “smiley cut.” (maybe draw a white box around the smiley cut)

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)



Figure 18. An additional tack weld was necessary between webbing fins to keep the chord rigid.

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 (Figures 20, 21). 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.



Figure 19. A 1/8” steel plate was welded to the end of the truss, along with a steel angle for loading and testing.



Figure 20. After 410 pounds, the truss failed with the lower chord in tension and the upper chord in compression. (let's not acknowledge that we didn't use dead loads to do this (delete this image))



Figure 21. The deformation of the top chord of the truss.

The final truss in this investigation was 7'11.5" long, weighed 7.071 pounds and carried a load of 410 pounds. The weight of the member versus the load carried is dramatically 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 expression principles. The appearance of the truss follows its form, which in turn maps its function of carrying loads. This 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 maintain and 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 a physics machine (such as Kangaroo) or generating variations through genetic algorithms (such as Galapagos). In addition, parameterization could be extended from just controlling the webbing geometry to managing the combinations of depth and width of the truss. In the research of this investigation, the user controls the moment diagram, but the application of a physics application may allow for further automation. With the introduction of lighting and ceiling material, these structural members become an integrated part of the designed spaces' overall aesthetic.

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. 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.

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