ZERO-WASTE, FLAT-PACKED, TRI-CHORD TRUSS:
CONTINUED INVESTIGATIONS OF STRUCTURAL EXPRESSION IN PARAMETRIC DESIGN

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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 design investigation focused on a single structural component: the truss.

Using folding methodologies and sheet steel to create a truss, the 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 made 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.

This paper will expand (greatly) upon previous research into bi-chord truss designs, developing a tri-chord truss, which is parametrically linked to its structural moment diagram. The cross-section of each truss is formed based on the loading condition for each beam. This truss design has been developed through a thorough series of analytical models and tests performed digitally, to scale and in full scale. The tri-chord truss is capable of resisting rotational failures well beyond the capacity of the bi-chord designs previously developed. The results are complex and elegant expressions of structural logics embodied in a tightly constrained, functional design.

figure 1

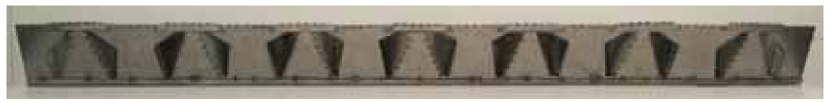


figure 2

figure 1

Bi-chord to tri-chord evolution.

figure 2

The original test for the bi-chord truss.

1 INTRODUCTION

This paper will expand upon previous research done into the fabrication of flat-pack, three-dimensional trusses. Through this research, parametric structural members are defined by linkages to their loading and moment diagrams. Variable loading creates shifts in these diagrams, defining changes in the cross-section of each relative truss design. This truss design has been developed through a thorough series of digital and analog tests, performed at full scale and with scaled models.

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. Through a series of assumptions about materiality and fabrication techniques, we were able to develop a comprehensive analysis of profiles, thicknesses, offsets, and diagonal fold patterns, which were analyzed to conclude in an optimized truss design within these parameters. These variables created a taxonomy that recombines zero-waste goals, flat-packing potential, structural expression, and computational processes.

2 PREVIOUS RESEARCH: BI-CHORD TO TRI-CHORD

The process of investigating material properties is based on the conditions of the structural members being recreated and reinvented in this system. The work of Mark West (C.A.S.T.) and others provides a benchmark of how this exploration leads to a process of form finding. Using the method of structural expression coupled with material constraints, the definition of our process starts to take form.

Previous research into the zero-waste, bi-chord, flat-packed truss provided the premise for this new research into the tri-chord truss. The bi-chord was so named because of the enclosed top and bottom chords (as seen in Figure 2). The shape of the bi-chord was based on the proportions of an I-beam, making the width of the upper and lower chords and depth of the truss match that of the I-beam. This research was based on the basic intersection of form and structural expression, and led to folding patterns that defined the web of the truss. As the moment diagram is based directly on the loads applied to the truss, it allowed for the web pieces to grow where the moment diagram was higher. As an example, in Figure 2, a uniform load was input into the truss to define the cut pattern.

Since the bi-chord was based on an I-beam, it was designed to resist vertical forces. However, because of the thin-gauge steel used, it could not behave like an I-beam in material strength. This undercompensation in material led to failures in rotation, typically due to a lack of material thickness in the cross-section of the beam.

2.1 Current Investigation

The tri-chord truss created an opportunity for the placement of more steel in the flange of the truss, and thus allowed the geometry to resist the rotational failures of the bi-chord truss. Additional shifts in the geometry of the truss included analysis into appropriate thickness of sheet steel. The use of 22-gauge mild steel was proven to create the correct balance of strength and simple fabrication. Other materials, such as concrete or wood, have very limiting uses when placed into a truss configuration. The use of a CNC plasma cutter afforded us the appropriate amount of precision and speed in the production of variable iterations of the design.

The move to a tri-chord truss also required a deeper understanding of the forces moving through the variable sections of the truss. These understandings come from a thorough investigation of all the cut-and-fold variables that make up the truss. These included the chord offset distance (thickness), web stiffener size and orientation, and folding gussets.

3 PROFILE SHAPE

"... 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"" (Beorkrem 2011).

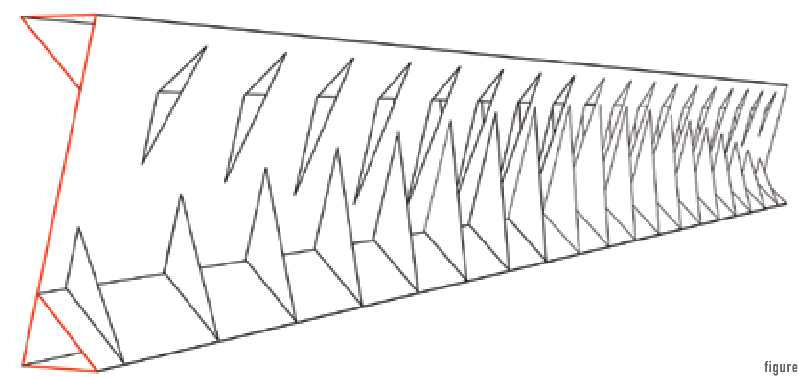


figure 3

figure 4

figure 3

Localized failure of the top chord of the bi-chord truss.

figure 4

Tri-chord profile and defined geometry.

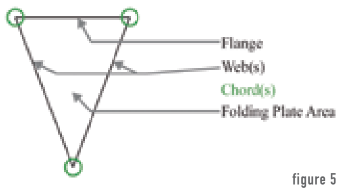
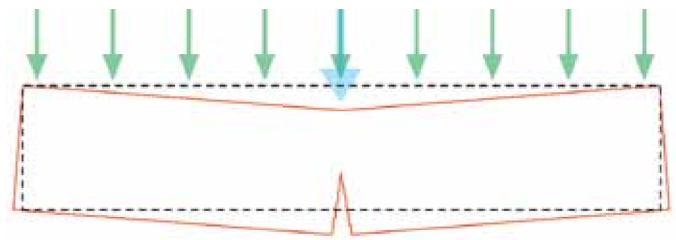


figure 5



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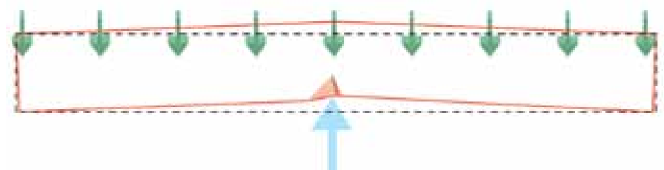


figure 7

3.1 Tri-Chord

The investigation of the bi-chord showed that additional material was required on the flange, which would give this truss more lateral strength. Instead of modifying the bi-chord, a new direction was taken. A triangulated form defined by a horizontal flange provided enough additional material to significantly reduce, if not eliminate, the chance of failure through rotation. The triangulated profile also created two webs to support each side of the flange. These webs folded together also create a bottom fold or chord. Having three chords, two on top and one on the bottom (Figure 4), helps stabilize the form in normal loading conditions.

3.2 Profile Optimization

As the shape of a triangle could vary from an obtuse, equilateral, or acute triangle, an optimum profile form had to be established. The process of finding the optimized profile originated with an equilateral triangle. With each iteration, a deeper profile was used until the beam began to weaken. Using a uniform load, the first set of experiments kept the beam length at a scaled 7'-6", and the total width of the steel before folding at 23". The 23" includes a 1" wide overlapping fold which, when welded, completes the profile of the truss. The type of failure and the load the beam carried as it failed were used to evaluate each cross-section. These failures occurred in two different types, which stayed consistent through all the testing.

These failure types are:

1) Failure in bending, tension side: Failing on the tension side is not something the optimized truss should do. This would mean there is too much material on the flange, which causes the web to become weaker than the flange, creating a tear or deformation in the bottom chord and resulting in local crippling. Tension-side failure occurs at the center of the truss and/or where the moment of load is greatest.

2) Failure in lateral buckling: Failing in buckling has been the more common type of failure in the overall scheme of testing. Buckling occurs where the forces on the flange are too great, and the web is too strong. This makes the truss start to rotate and move horizontally around one of the top chords, causing the material to warp from its normal position and resulting in beam failure. Lateral buckling failure occurs at the center of the truss and/or where the moment of load is greatest.

With these two failure types established, the profiles were tested against one another in scaled models. The optimum profile shape tested at the top of both failure types (Figure 7) generated an optimized profile having sides that were 120 percent of the width of the flange.

figure 5

Failure in bending, tension side (elevation).

figure 6

Failure in lateral buckling (plan).

figure 7

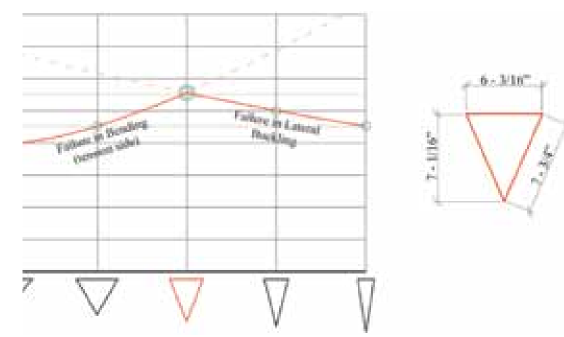
Profile optimization graph and selected shape.

4 WEB STIFFENER TYPE

Using this optimum profile shape, the next layer of investigations explored how to create web stiffeners through triangulated folds from the webs and flange. The initial tests used perpendicular folds from length to create these plates, as seen on the left of Figure 8. A second set evolved into a diagonal fold, which increased the strength and efficiency of each cross-section. This process involved identifying the weakest spots in each of the 45 to 50 physical iterations of the truss. Each design was an adjustment of its predecessor, correcting flaws and using parametric linkages to adjust the web stiffeners within each design.

4.1 Perpendicular Folds

The perpendicular fold typology was used in the original bi-chord truss. The system was successful in the bi-chord, as the linear design was not intended to resist external rotation, so the geometry was not needed. To define the perpendicular fold to length means the web stiffener plates are folded perpendicular to the truss chords. This type of folding pattern was originally created to keep the top and bottom chords in place. These folds were tested here using a tri-chord design (Figure 8). However, perpendicular folding types did not perform as well as the optimized profile without cuts in the web. Folds from the web were compromising the strength of the folded chords, allowing for localized buckling, which was often lateral to the plane of the truss.



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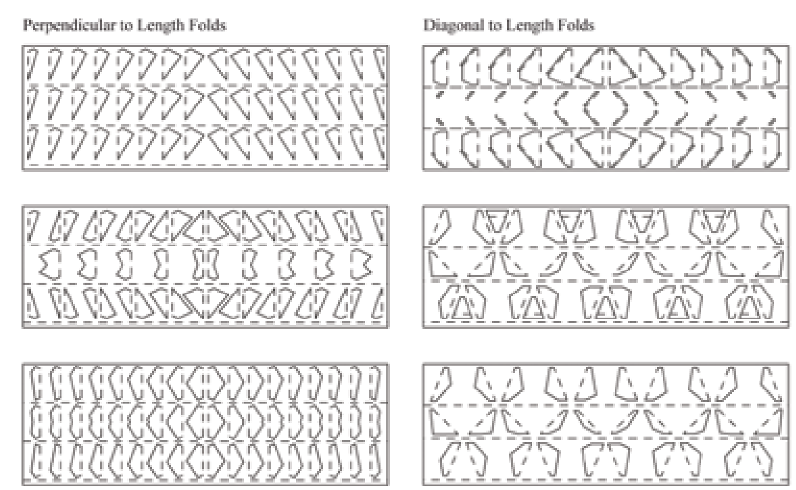


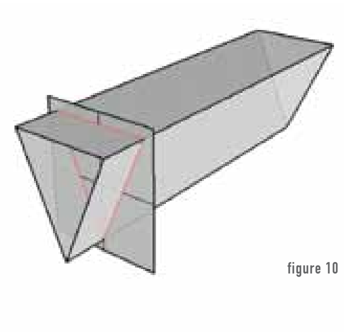
figures 9

figure 8

Examples of web stiffener folding-sheet types.

figure 9

Perpendicular fold direction.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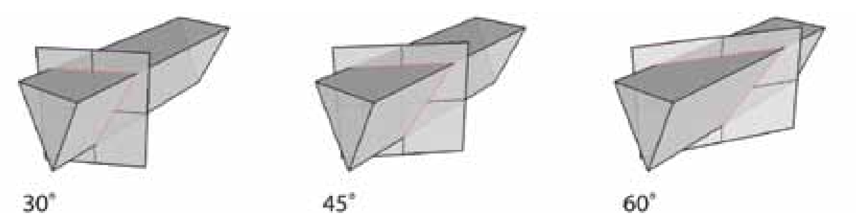


figure 11


figure 12

figure 10

Diagonal fold angles.

figure 11

Small set of paper models, which were tested under uniform loads.

Figure 12

Chord offset on diagonal folds.

4.2 Diagonal-to-Chord Folds

As a response to lateral buckling failures, a new set was developed to attempt a diagonal folding method. These web stiffeners are drawn at an angle across the inner volume of the truss. The goal of these folds is to create one solid plate across the depth of the truss. Cut profiles for the geometry are relational to the previous iterations, but also are responsive to the truss profile. This design results in a plate of steel that creates a structural member capable of transferring loads evenly to the webs and down to the lower chord. Previous experiments left holes in the connection plates, allowing for the inner material to rotate out of correct placement. Internal plate rotation was caused by a lack of connection in the center of the plates. Creating a full-plate connection allowed them to act as a single unit, adding strength and rigidity to the truss. The first outline of the plate was created through a series of section cuts rotated 45° from the flange. A resultant profile was split evenly into three pieces, and rotated back to the flange and webs (Figure 8).

As with previous iterations, once the prototype proved to have more consistent results we returned to the angle definition, attempting other alternatives including the original 45° fold and added tests for 30° and 60° folds (Figure 9). The 60° angles created long fold lines (Figure 10). As such, it was determined that the angle was too great and used steel inefficiently. Additionally, the folds could not create adequate plates for connection; the flange and web faces were also too small for those folds.

The 30° test yielded similar results. Although 30° was small enough to allow multiple diagonal folds, the geometry of the plate was larger than the angles could support. This made it difficult to place the folded plate onto the web shape effectively, which directly correlated with the lack of sheet steel remaining on the webs for transferring loads downward and through the truss.

The 45° angle was the most efficient fold type of the three tests. It allowed for ample space for the cuts, nested them very efficiently in the flange and webs, and had the best bearing capacity of the three tests. However, the beam was still experiencing localized failures occurring at the center of the truss.

5 DIAGONAL FOLD ITERATIONS

5.1 Chord Offset

To help with these localized failures, variations in the distance between the chord fold and the start of the cuts for the diagonal folds were further investigated. This distance determines the balance between the material available for the chord and the material that makes up the diagonal folding plates. Initial tests began with a base standard for the chord-side dimension set at 3/4". That distance was determined to be close to the minimum distance possible, due to fabrication, cut, and fold constraints. Increasing incrementally, we tested 1", 1-1/8", and 1-1/4" offsets for their relative strength capacities, to locate the optimized offset for chord strength and plate strength.

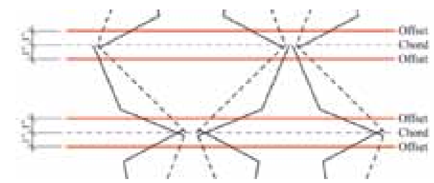
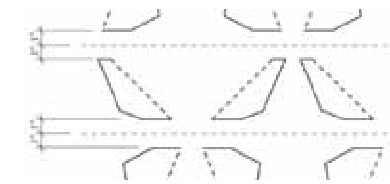


figure 13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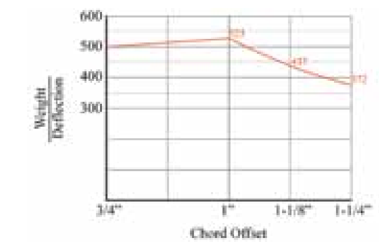


figure 15

Our tests demonstrated (Figure 13) the 3/4" offset left too little material in the chord areas, allowing the diagonal fold plates to get too close to the chords and to one another. This created a vulnerable zone with a high chance of local crippling. The 1-1/8" and 1-1/4" offsets had the opposite effect. As the offset was too great, it created too much space between the chord and the fold plates. This resulted in a design with material providing no support to help carry the load. The 1" offset (Figure 12) created the correct balance of strength along the chord, through the best ratio of steel in chord to distance between diagonal folding plates.

5.2 Web Gussets

This typology is termed "web gussets" because of the additional triangulated folds that originated from each of the webs, as seen in the cut sheet on Figures 15 and 16. These triangulated pieces of geometry are folded upward, toward the top two chords, then folded over. This creates a double thickness of steel in the weakest areas of the chords. These double-thick areas help reinforce the chords, working much like a dog bone on an I-beam. Removing material from the web again required a negotiation between material advantages, as the shifting of this material resulted in a weaker web. Initial tests resulted in web deflections 75 percent more than earlier iterations. As a result, it was determined that the gusset of the truss needed a more appropriate place to find the necessary material for this reinforcement.

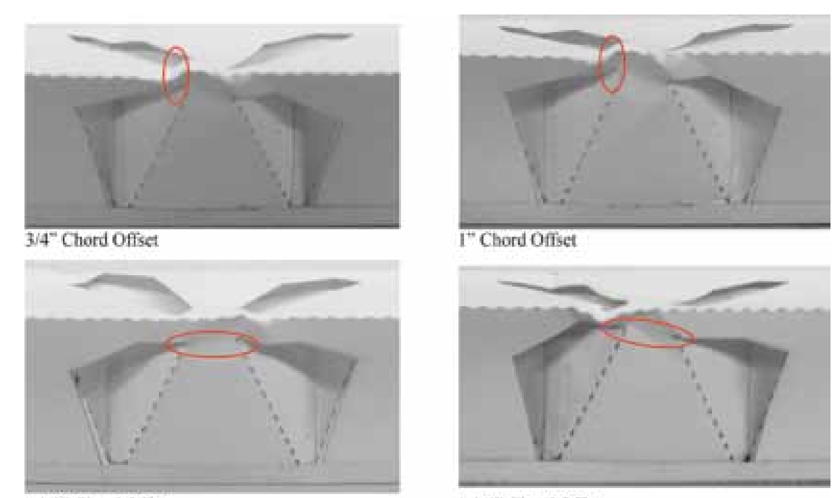


figure 16

figure 13

Graph of results from testing.

figure 14

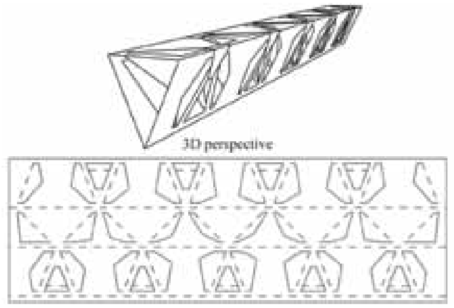
Images of result: initial failure point.

figure 15

Web gusset truss perspective, cut sheet, and results.

Figure 16

Web and flange gusset truss perspective, cut sheet, and results.



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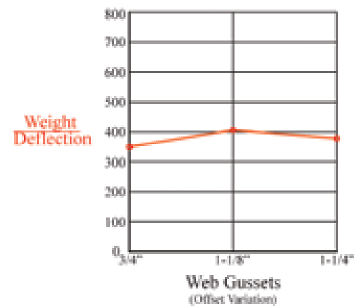


figure 18

figure 17

Variations of top fold.

figure 18

Graph of data representing all gusset truss configurations.

6 OPTIMIZED FORM

6.1 Final Form: Gusset Fold

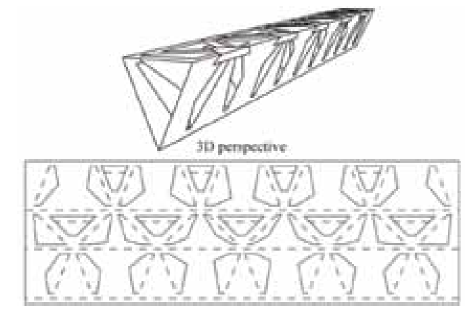
The last set of tests involved the development of a thickened chord with a gusset that was folded upon itself to create a reinforced chord. In this test, there is no additional material taken from the webs, with the exception of the diagonal fold plates. A variety of different foldover tests were developed, which varied their number along the flange, starting in the center then radiating outward (as seen on the left of Figure 17). Additionally, the size of each foldover was tested to ensure that the material removed from the gusset did not compromise the rotational resistance of the design, and to create an optimized balance between the material reinforcing, the chords, and the gusset strength. These tests began with the largest possible zone and were incrementally scaled smaller from the center out, as seen in the second and third diagrams in Figure 17. The largest possible area profile of the reinforcement proved to be the most effective. This design resulted in the best ratio of weight held/deflection, as seen in Figure 16.

6.2 Parameterization

A Grasshopper script was developed to link the variable loading conditions to the cut file. The script successfully integrated all the parameters and conclusions we had developed from the optimized design. Further, the script affords the development of variable inputs for future manipulation of the truss. Each truss variation is linked to a moment curve, which can be derived based on loading scenarios. All the variable components in the geometry move parametrically based solely on the moment curve. A graphic representation of how the Grasshopper script works is seen in Figure 19.

7 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." (Beorkrem 2011)



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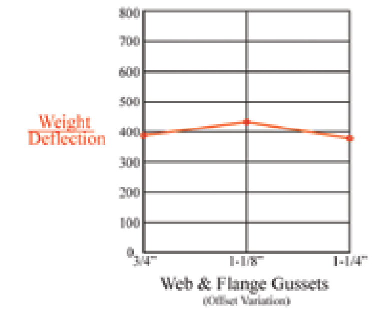

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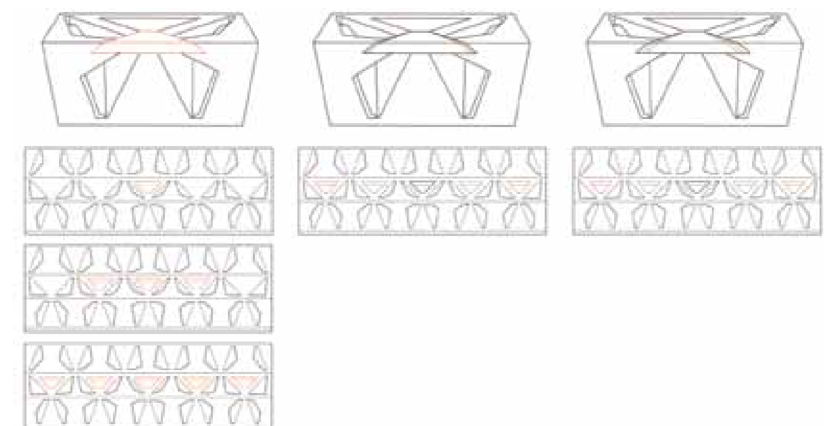

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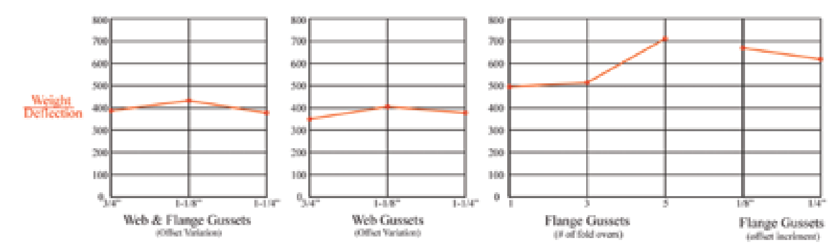

figure 22

The initial stage of throwing away the bi-chord, while still attempting to keep many of its original ideas, created a chance to step back from the research, allowing for a reinterpretation of the project. Final results help compare the final bi-chord to the final tri-chord: the bi-chord weighed 7.25 pounds, held 410 pounds, and was 21" wide by 94" long. The tri-chord weighs 7.9 pounds and is 23" wide by 94" long. Although there is yet to be official testing, testing that was done in the model stage yields an estimated weight held for the tri-chord of between 1,500 and 2,000 pounds. The vast improvements are largely because of the increased flange area, which previously hindered the bi-chord's performance. The other subtle improvements, such as the gusset plates, interior diagonal folds, and chord offset amount, were made possible only because of the increased flange width.

figure 19

How the Grasshopper script functions with constraining systems.

figure 20

Construction process, cut sheet, and jig for easy construction.

figure 21

Profile folding process and final folded truss.

figure 22

Bi-chord and tri-chord, uniform loads applied.

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Zero-Waste, Flat-Packed Truss: A Continued Investigation in Structural Expressionism in Parametric Design.

A METHOD FOR THE REALIZATION OF COMPLEX CONCRETE GRIDSHELL STRUCTURES IN PRECAST CONCRETE

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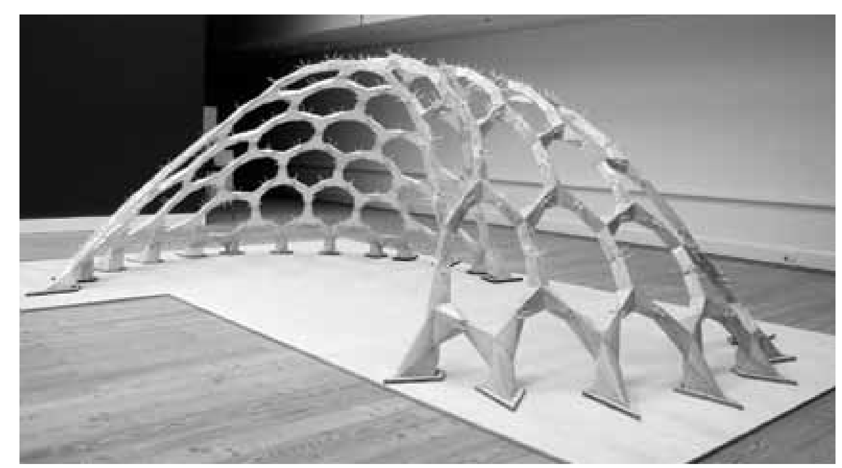
Aarhus School of Architecture

ABSTRACT

This paper describes a method for the design and fabrication of complex funicular structures from discrete precast concrete elements. The research proposes that through the integration of digital form-finding techniques, computational file-to-fabrication workflows, and innovative sustainable concrete casting techniques, complex funicular structures can be constructed using prefabricated elements in a practical, affordable, and materially efficient manner.

A recent case study is examined, in which the methodology has been used to construct a pavilion. Custom-written dynamic relaxation software was used to define the overall form and successive algorithms; it then defined each component's unique geometry, unrolled into flat shapes, and nested all parts into cut-files. PETG plastic sheets were two-dimensionally laser cut and folded to produce the unique casting molds. The case study was carried out in collaboration between the Aarhus School of Architecture and the University of Technology, Sydney (UTS). Basic research in casting techniques defined the framework for the design process, and a custom-written dynamic relaxation software application became the primary form-generating tool in the design process of a constructed pavilion. Fabrication and construction constraints were embedded within the design of both the overall structure and its components. Finite element analysis (FEA) was completed in order to verify the form-finding results, to ensure structural stability, and to direct adjustments of the structure during the design process.

The constructed pavilion case study, constructed in a very short time, for low cost and with relatively unskilled labor, demonstrates that the integration of algorithmic form-finding techniques, CNC fabrication workflows, and the use of innovative PETG folded-mold techniques enables the practical realization of freeform funicular structures in precast concrete.



figures 1

figure 1

Concrete gridshell pavilion, first installation, Aarhus School of Architecture, October 2011.