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Exploring the Use of Re-Forming Concrete

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EXPLORING THE USE OF RE-FORMING CONCRETE

Non-Rigid Materials for Sustainable Concrete Formwork Applications

By Moritz Meditz

EXPLORING THE USE OF RE-FORMING CONCRETE

Thesis Proposal is Presented to the
Faculty of the Department of Architecture
College of Architecture and Construction Management

Giovanni Loreto
and
Dr. Arash Soleimani, Thesis Coordinator
Kathryn Bedette, Interim Chair of Department

By

Moritz Meditz

In partial fulfillment of the requirements for the Degree
Bachelor of Architecture

Kennesaw State University
Marietta, Georgia

May 2022

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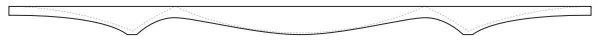

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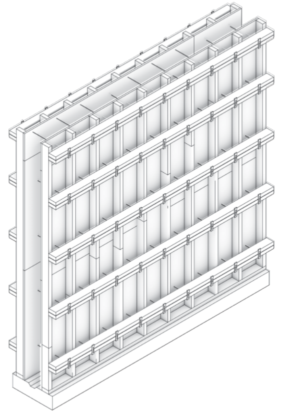

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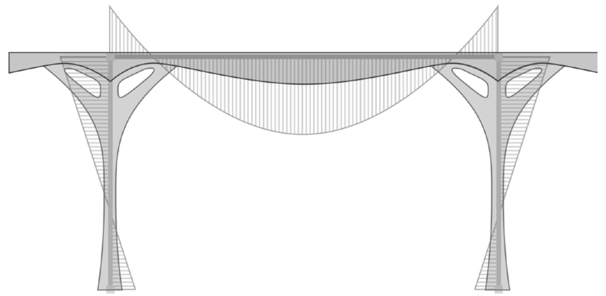

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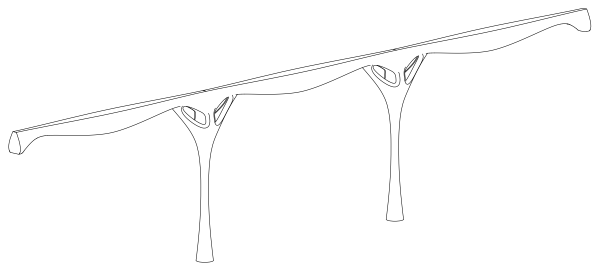

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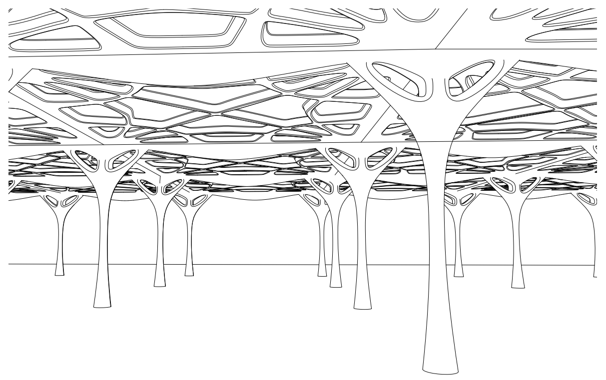

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CHAPTER 1

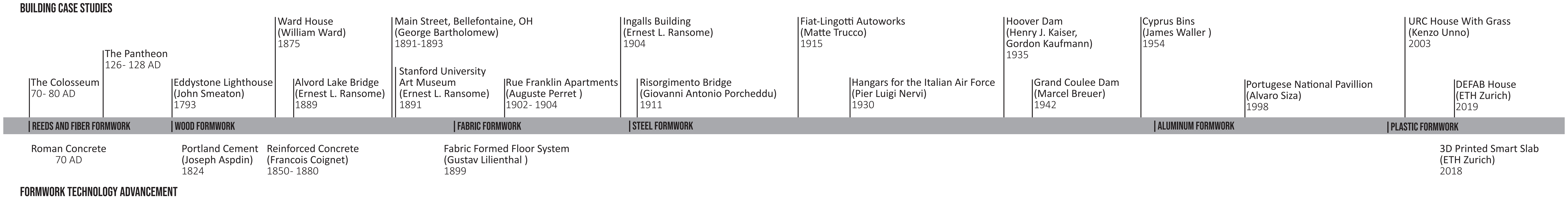
1.1 BACKGROUND

This thesis takes a closer look at concrete construction in the modern era and, more specifically, the use of formwork to shape the built environment.

Traditional rigid concrete formwork has been optimized for buildability while serving structural needs. This mentality means simple prismatic elements that are entirely overbuilt for the task, stacked on top or next to one another. The idea that these elements are the peak of efficiency in concrete production has informed virtually all modern concrete construction. Any shapes that vary from the simple prismatic volumes are seen as challenging to build and expensive. For the most part, this is true if traditional methods of constructing formwork are used to create those shapes, but what if that did not have to be the case?

Over the last 100 years, several alternative methods of building formwork have been suggested, but almost all of them have stayed almost entirely in the academic realm. The major categories of these technologies include flexible formwork, such as fabrics; Folding formwork, using materials such as fiberglass; 3D printing formwork, using plastics; and even Knitted formwork. The major challenge that most of these technologies face is that they only propose formwork to replace select elements needed to construct a building, and this leads to a strange mix of architectural languages that is not desirable. Even if they include multiple elements, they often use vastly different systems and materials to create the framework, making them not viable at larger building scales.

1.2 TIMELINE



1.3 THESIS INQUIRY

This thesis looks at the use of structurally optimized formwork systems in architectural buildings. The aim is to combine math, material science, and architectural design in an interdisciplinary effort to better the built environment. In part motivated by the artwork of Mark West and informed by structural engineering concepts, this thesis aims to advance the fundamental understanding of concrete formwork systems in an effort to marry architectural form and structural design by creating a new design language for concrete construction. Stemming from the architectural, structural, and construction considerations, this thesis will investigate the use of different formwork systems in concrete structures to achieve:

1. More economical construction practices while improving sustainability and resilience of concrete structures.
2. Nontraditional and varying architectural forms using parametric design solutions.
3. The adoption of new applications for advanced concrete materials such as engineered cementitious composites.

The objective is to define an architectural language for concrete structures that will introduce a new design for formwork systems as well as explore solutions to minimize the use of reinforcement without sacrificing structural integrity. The goals is to evaluate the new design strategies and computational tools so that they can seamlessly integrate architectural forms with structural needs. Based on previous research, this approach could lead to an approximately 40% reduction in concrete usage, dramatically affecting the sustainability of such a building. In order to achieve these results, individual structural elements and their formwork systems will be analyzed and evaluated for their strengths and weaknesses, followed by an investigation of how these different systems can be combined into one unified language using one type of formwork.

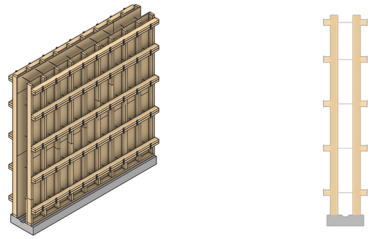
Nevertheless, why is any of this relevant for the future? Well, despite the inefficiencies associated to traditional formwork, concrete remains one of the most widely used manufactured materials globally, with the global production of cement reaching 4.1x10^9 t in 2017. According to data, concrete use has become so prevalent that it is now the second most consumed commodity after water. Although concrete has a relatively low embodied energy, its rate of production and uses account for almost 9% of total global anthropogenic greenhouse gas emissions.

1.4 DEFINING FORMWORK

As one of the most widely used construction material, concrete has many exceptional properties. However, in order to create any building element out of concrete, it must be poured into a specifically designed mold. These molds are commonly referred to as formwork.
Formwork holds the concrete in the desired shape until it achieves the required strength to support itself. The different types of formworks can be classified in three main ways: type of material used, by building element created, and if it is removable or permanent.
Formwork is an essential part of concrete construction and can often account for 20% to 25% if a structures cost.

1.5 MOST COMMON FORMWORKS

TIMBER



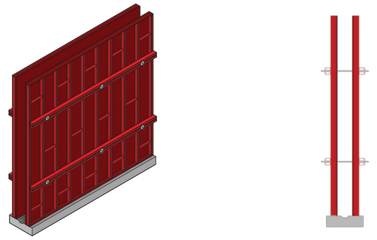
Construction Const	●●●○○○○○○○
Ease of Assembly	●●●●●○○○○○
Reusability	●●●●○○○○○○
Material Optimization	●●●●●○○○○○
Flexibility in Shapes	●●●●○○○○○○

Timber formwork was one the first types used in construction industry. It is assembled on site and is the most flexible type, bringing the following advantages:

- Easy to produce and remove
- Lightweight, especially when compared with metallic formwork
- Workable, allowing any shape, size and height
- Economical in small projects
- Allows the use of local timber

However, before using timber its condition must be checked carefully, making sure it is free of termites. Timber formwork also has two limitations that must be considered: it has a short life span and is time consuming in large projects. In general, timber formwork is recommended when labor costs are low, or when complex concrete sections require flexible formwork. Plywood formwork has similar properties as timber formwork, including strength, durability and being lightweight.

METAL



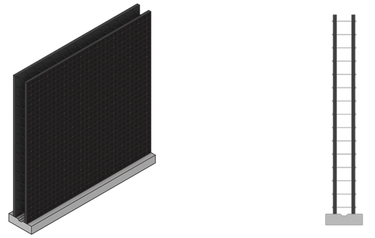
Construction Const	●○○○○○○○○○
Ease of Assembly	●●●●●●●●○○
Reusability	●●●●●●●●●●
Material Optimization	●●●●●○○○○○
Flexibility in Shapes	●●○○○○○○○○

Steel formwork and steel hardware is becoming more popular due to its long service life and multiple reuses. Although it is costly, steel formwork is useful for multiple projects, and it is a viable option when many opportunities for reuse are expected.
The following are some of the main features of steel formwork:

- Strong and durable, with a long lifespan
- Creates a smooth finish on concrete surfaces
- Waterproof
- Reduces honeycombing effect in concrete
- Easily installed and dismantled
- Suitable for curved structures

Aluminum formwork is very similar to steel formwork. The main difference is that aluminum has a lower density than steel, which makes formwork lighter. Aluminum also has a lower strength than steel, and this must be considered before using it.

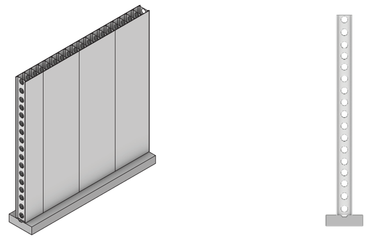
PLASTIC



Construction Const	●●○○○○○○○○
Ease of Assembly	●●●●●○○○○○
Reusability	●●●●●●●○○○
Material Optimization	●●●●●○○○○○
Flexibility in Shapes	●●●○○○○○○○

This type of formwork is assembled from interlocking panels or modular systems, made of lightweight and robust plastic. Plastic formwork works best in small projects consisting of repetitive tasks, such as low-cost housing estates. Plastic formwork is light and can be cleaned with water, while being suitable for large sections and multiple reuses. Its main drawback is having less flexibility than timber, since many components are prefabricated.

STAY-IN-PLACE



Construction Const	●●●●●●○○○○
Ease of Assembly	●●●●●●●●○○
Reusability	●○○○○○○○○○
Material Optimization	●●●●●○○○○○
Flexibility in Shapes	●○○○○○○○○○

This formwork is designed to remain fixed after the concrete has set, acting as axial and shear reinforcement. This formwork is made on-site from prefabricated and fiber-reinforced plastic forms. It is mainly used in piers and columns, and also provides resistance against corrosion and other types of environmental damage.
Another type of stay in place formwork is called coffor, which can be used in any type of building:

- It is composed of two filtering grids, reinforced by stiffeners and linked with articulated connectors.
- Thanks to its construction, it can be easily transported from a factory to the point of use.

CHAPTER 2

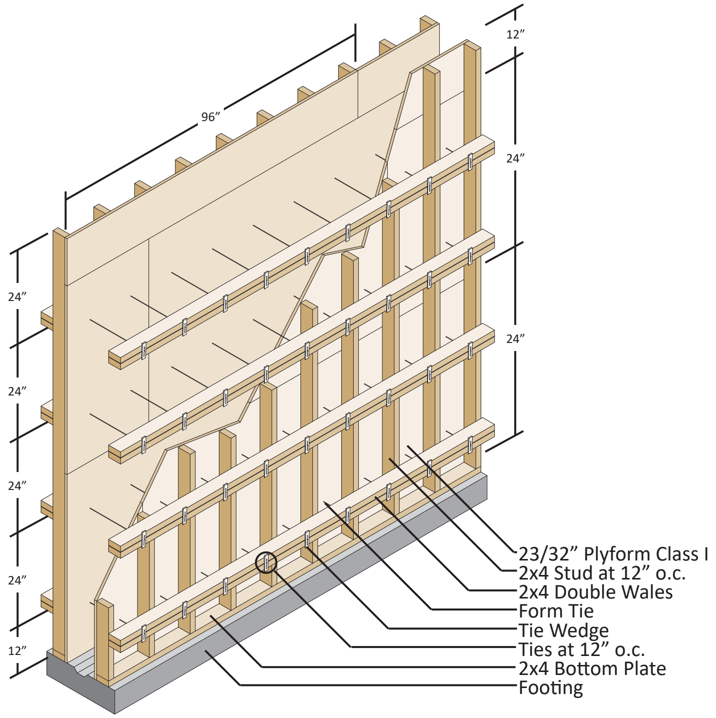
2.1 PRECEDENT ANALYSIS

TRADITIONAL - Rigid Formwork

Traditional Formwork is usually comprised of a variety of rigid materials such as wood, steel, aluminum, and plastic. The nature of the material lead to the optimization of prismatic elements for all structural components. This development means that in most areas the structural elements are significantly overbuilt for the task they are performing, in order to fit within the prismatic shapes. Traditional Formwork methods are by far the most common in the construction industry today as they are made from abundant materials and can be procured extremely easily. With the advancement of CAD modeling and computational design this type of formwork has been pushed to its limits as more organic shapes start to pop up more and more. To create these forms using traditional rigid methods is extremely time consuming and very expensive to do as you are working against the strengths it naturally presents.


Figure 1: Traditional Wooden Formwork


Figure 2: Traditional Wooden Formwork Outcome



Construction Const	●●●○○○○○○○
Ease of Assembly	●●●●●○○○○○
Reusability	●●●●○○○○○○
Material Optimization	●●●●●○○○○○
Flexibility in Shapes	●●●●○○○○○○

STAY IN PLAY THIN SHELL CONCRETE FORMWORK - Pier Luigi Nervi

Pier Luigi Nervi created a very unique system for creating concrete formwork, using concrete as the formwork. His designs, especially his domes utilize a strategy that used precast ferrocement panels that create a sort of coffered ceiling, which he holds in place using scaffolding. After the pre-cast panels are in place concrete is poured on top of the panels, but specifically in between the panels, which then created a kind of rib system that supports most of the structural load. Using this method Nervi ensures that the visible ceiling is a consistent color and texture while the concrete behind it really carries most of the load. Due to the nature of this system, very little resources are wasted on the formwork that won't be visible later.

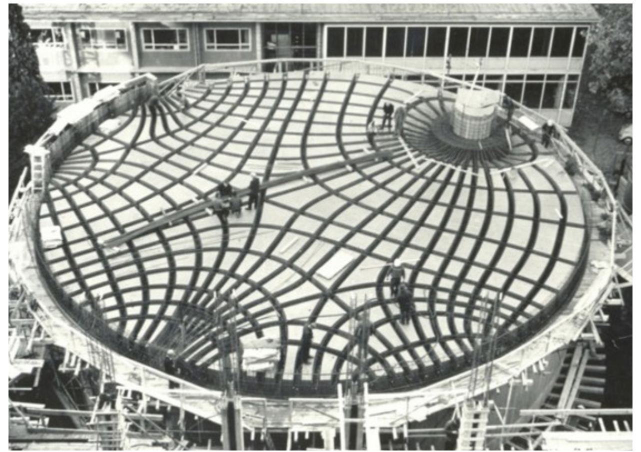


Figure 3: Ceiling of the zoology lecture hall at the University of Freiburg

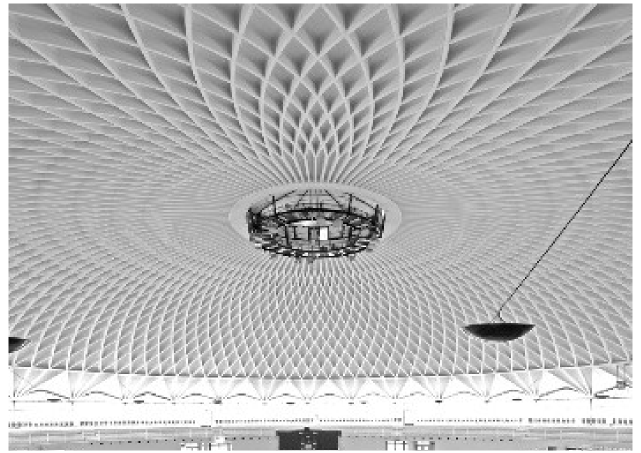


Figure 4: The Palazzetto dello Sport. Nervi

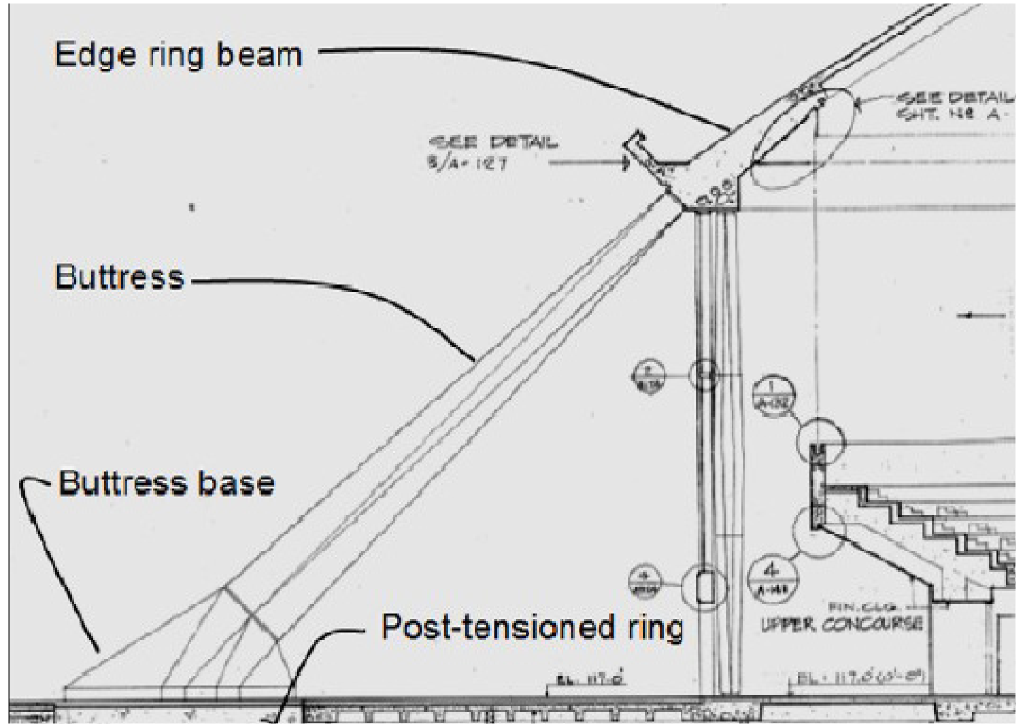


Figure 5: The Palazzetto dello Sport. Nervi Section

Construction Const	●●●○○○○○○○
Ease of Assembly	●●●●●○○○○○
Reusability	●●●●○○○○○○
Material Optimization	●●●●●○○○○○
Flexibility in Shapes	●●●●○○○○○○

FLEXIBLE STAY-IN-PLACE FORMWORK - ETH KnitCrete

KnitCrete is a novel, material-saving, labor-reducing and cost-effective formwork system for the casting of doubly curved geometries in concrete. KnitCrete formworks use a custom, 3D-knitted, technical textile as a lightweight, stay-in-place shuttering, coated with a special cement paste to create a rigid mold, and supported by additional falsework elements such as a tensioned cable-net or bending-active splines. Compared to conventional weaving, knitting minimizes the need for cutting patterns to create spatial surfaces, allows for the directional variation of material properties, and simplifies the integration of channels and openings, for example, for the insertion of additional formwork elements, insulation, reinforcements, electrical components and technical systems for heating and cooling.

The hybrid and ultra-lightweight KnitCrete formworks are thus easily transportable, reduce the need for additional supporting structure and scaffolding, and simplify the logistics on the construction site.

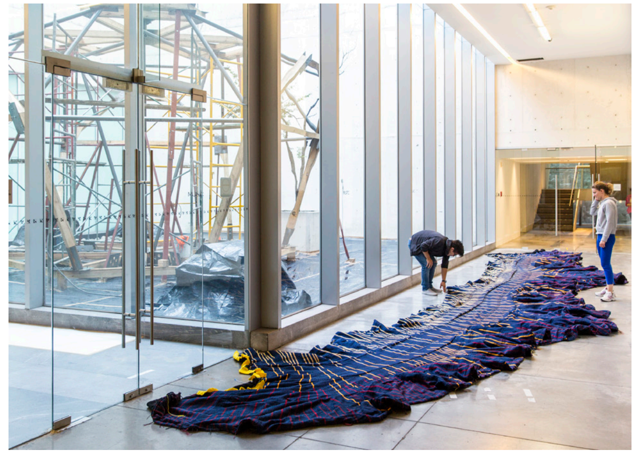
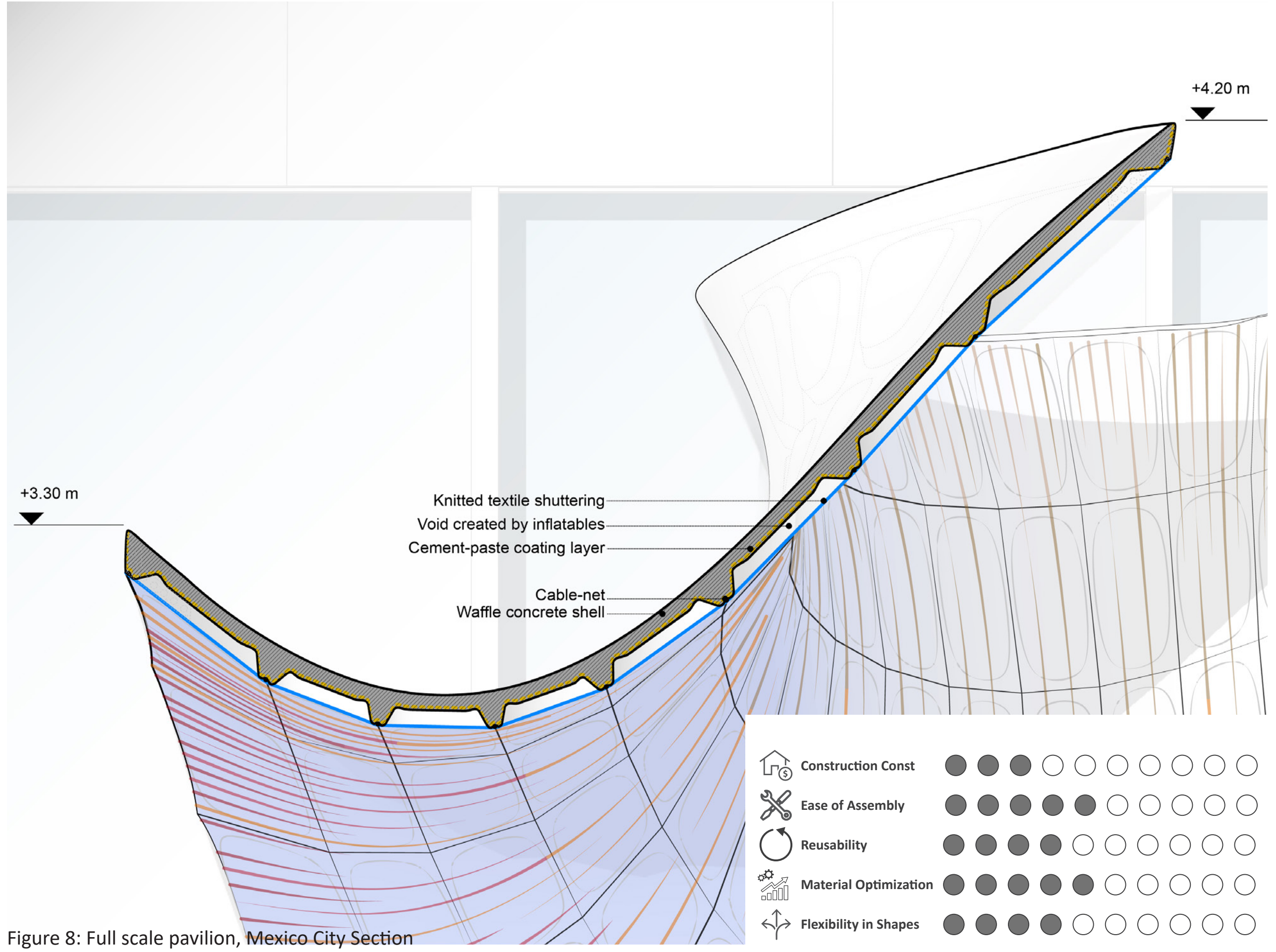


Figure 6: Full Formwork laid out

Figure 7: Full scale pavilion, Mexico City



Construction Const	●	●	●	○	○	○	○	○	○	○
Ease of Assembly	●	●	●	●	●	○	○	○	○	○
Reusability	●	●	●	●	○	○	○	○	○	○
Material Optimization	●	●	●	●	●	○	○	○	○	○
Flexibility in Shapes	●	●	●	●	○	○	○	○	○	○

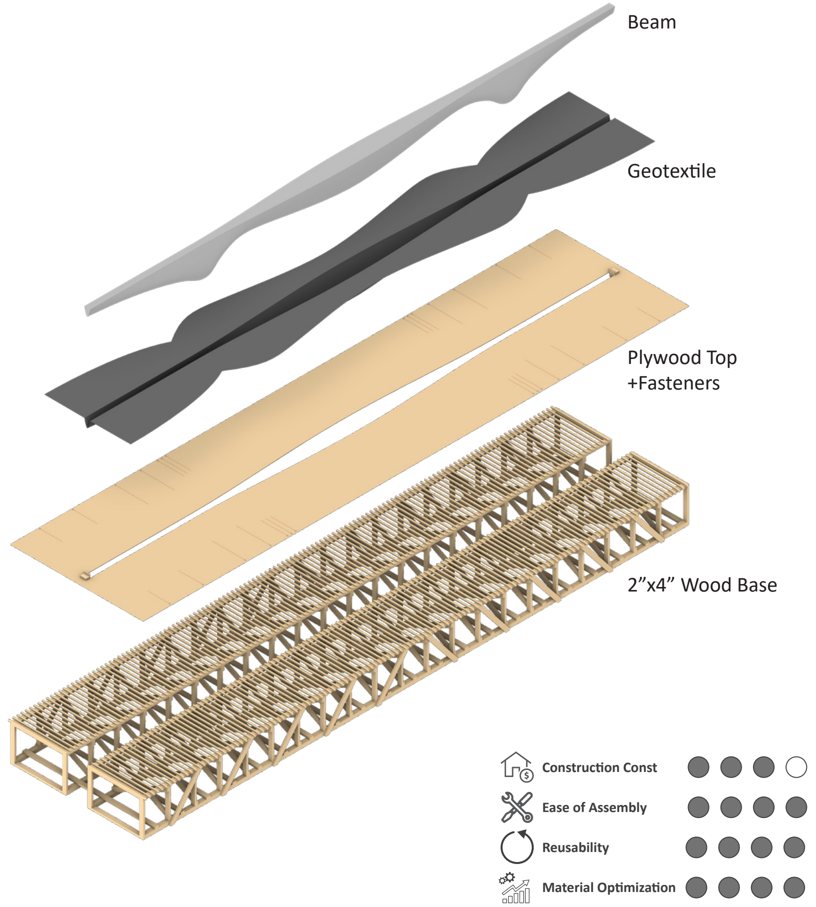
Figure 8: Full scale pavilion, Mexico City Section

FLEXIBLE FORMWORK - Mark West

The Flexible formwork explored by mark west, focuses on the use of geotextile in order to create a more optimized beam shape that allows for massive savings in material, while maintaining close to the same strength as a traditional beam. The method he explored focused on pre-casting a bream with a shape that is heavily influenced by the shape of the moment diagram for the desired load. The theory is that using this method, concrete is focused around those areas that need it most and saved in areas that do not. The result is a very organically shaped beam that saves up to 40% of the material that would be used in a traditional beam. The total fabric used for the full-scale beam only weights 10 Kg and can be easily folded up into a nice small bundle (as seen in the image to the right). Besides the savings in material the beam also tries to radically change the formwork construction with its lightweight design and relatively easy set up this method of formwork construction could save enormous amounts of money while also providing a visually more interesting outcome. West also experimented with the creation of columns using this same method, but with less success at optimizing the structural element, since the material does not hold its shape very well when placed in a vertical tube.

Figure 9: Mark West Full Scale Optimized Flexible Formwork Beam

Figure 10: Mark West Full Scale Beam Formwork Bundled up



Mark West Full Scale Formwork Axon

Construction Const	●	●	●	○	○	○	○	○	○	○
Ease of Assembly	●	●	●	●	●	○	○	○	○	○
Reusability	●	●	●	●	○	○	○	○	○	○
Material Optimization	●	●	●	●	●	○	○	○	○	○
Flexibility in Shapes	●	●	●	●	○	○	○	○	○	○

3D PRINTED FORMWORK - ETH Zurich DFAB House

The geometry of the Smart Slab is structurally optimized for its challenging load-case, involving cantilevers of up to 4.5 meters. The material is distributed in a hierarchical grid of curved ribs, which vary between 30 and 60 centimeters in depth. The 1.5-centimeter-thick concrete fields between these ribs are domed to maximize stability and to minimize the amount of material needed. Consequently, the slab only weighs 15 tons, almost 70% less in comparison to a conventional solid concrete slab. The Smart Slab utilizes 3D printing as a way to automate and optimize the most labor-intense process in concrete construction: fabricating the formwork. Through 3D-printed formwork, Smart Slab takes full advantage of the plasticity of concrete to create a highly optimized building component featuring intricate ornamental structures which create a rich architectural experience. The 3D-printed parts are assembled to form the lower part of a formwork segment, then sealed and treated with paint for spraying concrete; A thin (20mm thick) fiber-reinforced concrete layer is sprayed on the surface; pre-assembled timber formwork modules, integrating the building services voids and reinforcement bars, are installed above the sprayed layer; The upstand ribs are cast inside the plywood formwork. In Smart Slab, details for the façade interface and for technical installations such as sprinklers and lighting are embedded into the prefabricated elements to reduce construction height and to avoid complexity on the construction site.


Figure 11: Mold release applied to formwork


Figure 12: 3D printed floor slab assembly

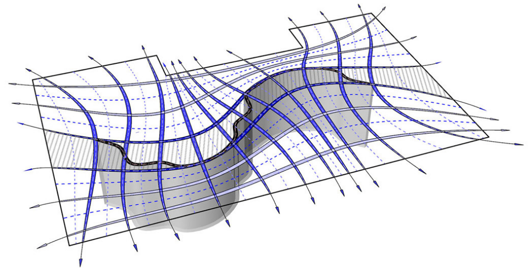


Figure 13: Structural Diagram

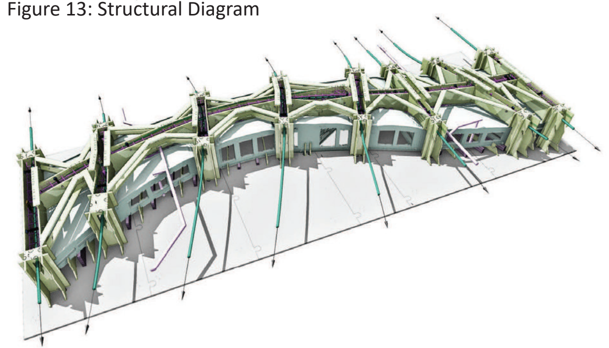


Figure 14: Reinforcement Diagram

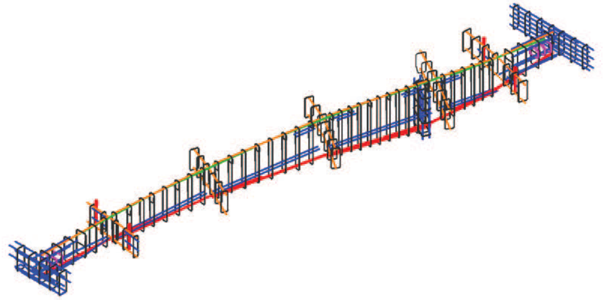


Figure 15: Rebar Diagram

Construction Const	● ● ● ○ ○ ○ ○ ○ ○ ○
Ease of Assembly	● ● ● ● ● ○ ○ ○ ○ ○
Reusability	● ● ● ● ○ ○ ○ ○ ○ ○
Material Optimization	● ● ● ● ● ○ ○ ○ ○ ○
Flexibility in Shapes	● ● ● ● ○ ○ ○ ○ ○ ○

FOLDING FORMWORK - Joseph Choma

"Folding" architecture has been seen in many places over the years, but it is rarely truly folding related when it comes to the formwork or construction of the formwork. Most structures that currently are considered folding architecture are mostly plate structures that are designed to look like they are folded. One of the architects that are trying to create true folding architecture is Joseph Choma. His approach is based in crease patterns that can fold flat for easy transport. His material of choice is fiberglass with reading, in order to create the harder surfaces in between the folds. By basing the form on a cease pattern, rather that assembling plates, he creates a chance to use the inherent strength of geometry and folding in order to maximize the capabilities of the material he is using. While not many tests have been done to check the viability of the system as a concrete formwork system, he is definitely interested in pursuing the idea of it more. This could come in especially handy for elements such as columns since the rigid portions of fiberglass will be able to resist the hydrostatic forces of the concrete much better than just a fabric, while preserving many of the advantages of fabric use, such as light weight and easy of assembly.


Figure 16: Resin on fiberglass masked off using tape


Figure 17: Large scale floor slab formwork

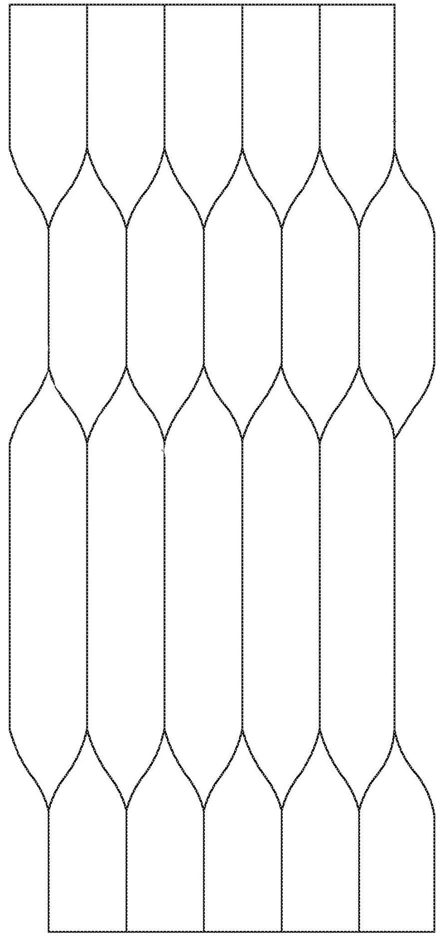


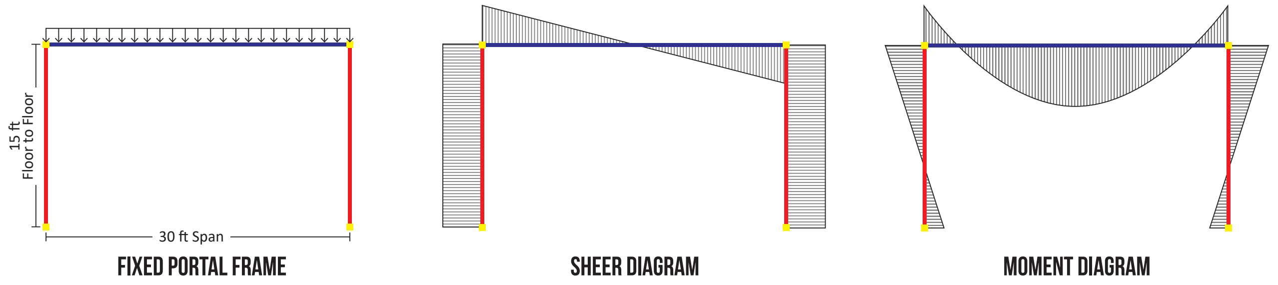
Figure 18: Column Crease pattern

Construction Const	● ● ● ○ ○ ○ ○ ○ ○ ○
Ease of Assembly	● ● ● ● ● ○ ○ ○ ○ ○
Reusability	● ● ● ● ○ ○ ○ ○ ○ ○
Material Optimization	● ● ● ● ● ○ ○ ○ ○ ○
Flexibility in Shapes	● ● ● ● ○ ○ ○ ○ ○ ○

CHAPTER 3

3.1 DESIGN PROCESS BEAM

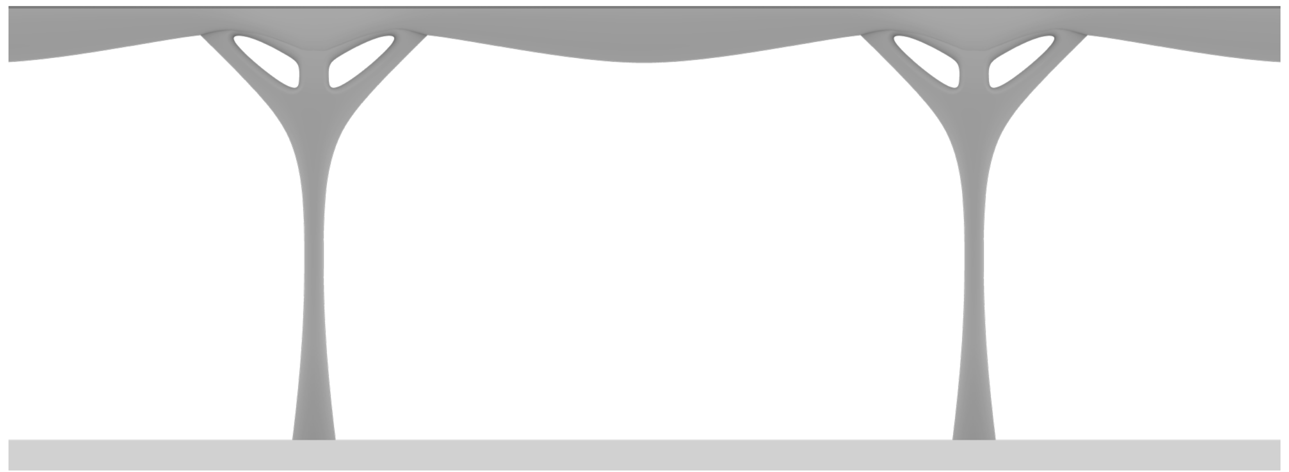
The design of the beam is based on artwork from Mark West. The design follows the moment diagram for a fixed – fixed moment frame moment diagram (seen on the right). The process is shown in the beam generation diagram below. The formwork I created to generate the desired shape consists of two main components, the scaffolding to hold the fabric itself and the flexible formwork material, in this case the tarp was used. In order to get the desired shape of the beam we CNC two pieces of plywood and clamped the tarp in between. The tarp was then clamped to the scaffolding so that it could hang freely and form naturally. The reinforcing bars where then bent to the shape of the wood pieces at the bottom and laid into the formwork.



FIXED PORTAL FRAME

SHEER DIAGRAM

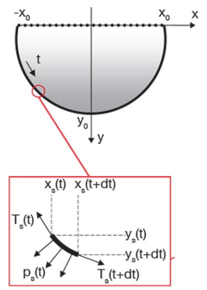
MOMENT DIAGRAM



$$\frac{x_s}{l} = \frac{E(\theta_s,k)}{K(k)} - \frac{1}{2}\frac{F(\theta_s,k)}{K(k)}$$

$$\frac{y_s}{l} = \frac{k}{K(k)}\cos\theta_s$$

$$A_c = l^2 \frac{k\sqrt{1-k^2}}{K^2(k)}$$



Where xs, ys are coordinates along the curve, l is the fabric perimeter length. F(θ,k) is the incomplete elliptical of the first kind, K(k) is the corresponding complete elliptic integral of the first kind ((k) = F(π/2,k)). E(θ,k) is the incomplete lliptic integral of the second kind.

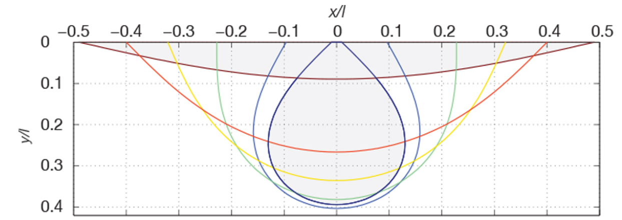
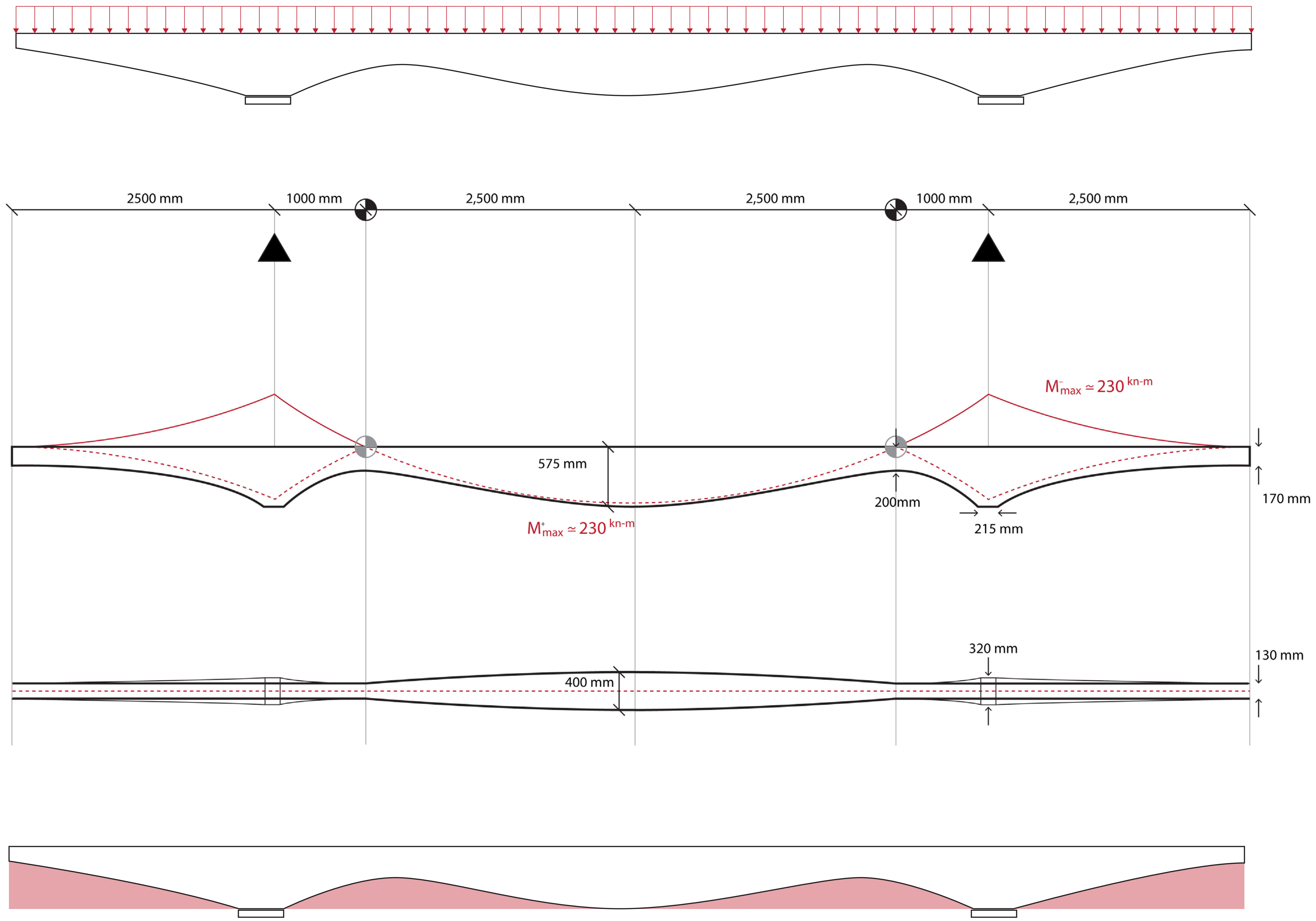


Figure 20: Equilibrium considerations (l); and cross section predictions (r)

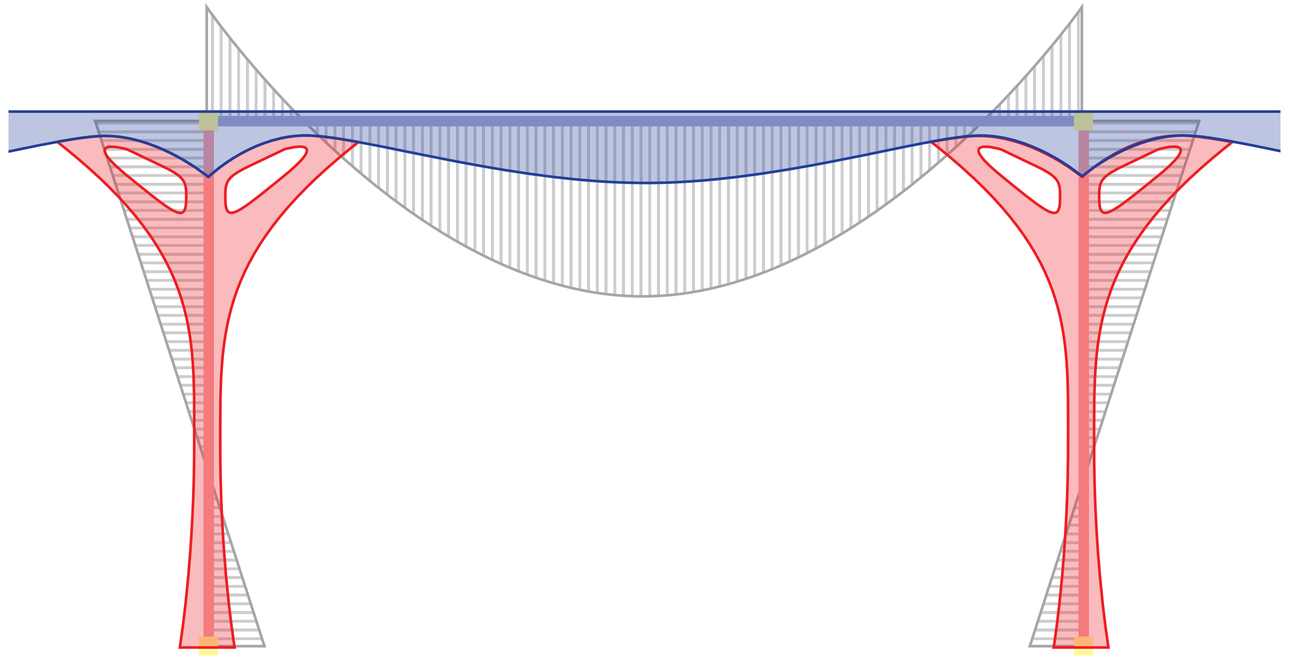
Construction Const	●	●	●	●	●	○	○	○	○	○
Ease of Assembly	●	●	●	●	●	●	●	●	○	○
Reusability	●	●	●	●	●	●	●	●	●	○
Material Optimization	●	●	●	●	●	●	●	●	●	○
Flexibility in Shapes	●	●	●	●	●	●	●	●	●	●



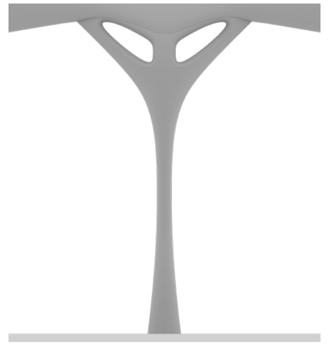
Beam Generation Diagrams

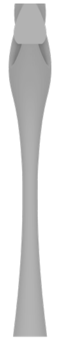
3.2 DESIGN PROCESS COLUMN

Having primarily focused on beams I believe the in future research columns should also be explored in more detail. The interplay between the column and beam is crucial to any building and the design should be inspired by each other. Using a similar method for deriving the shape of the beam, shown on the right is a possible iteration of a column design using very similar materials and processes as the beam. It also follows the moment diagram and saves material when every possible, hence the openings in the upper portion of the column.



Column -27% Volume Compared to Traditional Prismatic Column





Construction Const	●	●	●	●	●	○	○	○	○	○
Ease of Assembly	●	●	●	●	●	●	●	●	○	○
Reusability	●	●	●	●	●	●	●	●	○	○
Material Optimization	●	●	●	●	●	●	●	●	●	○
Flexibility in Shapes	●	●	●	●	●	●	●	●	●	●

3.2 DESIGN PROCESS SLAB

In order to complete the full design package, slabs should also be explored as an element to be optimized using the same methods and tools as the beam and column. While the moment diagram might not be as useful in the generation of the shape in this case, following load and stress lines similar to the work of Pier Luigi Nervi seems like the obvious choice. Dure to the flexible nature of the material used these shapes could easily be generated using a non-rigid material that gets molded from the bottom. Looking back at all there of these major structural elements a more cohesive language is clearly visible while allowing for super high customizability and reusability of each element in addition to the significant savings in material.

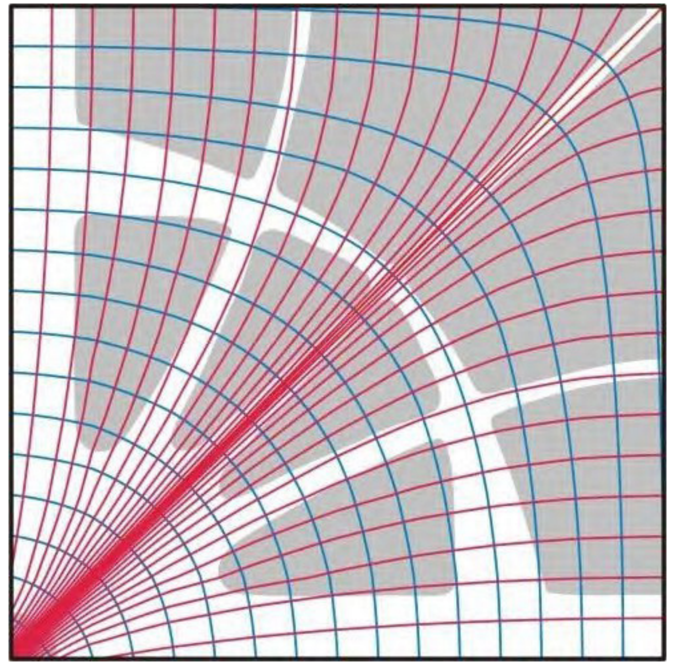
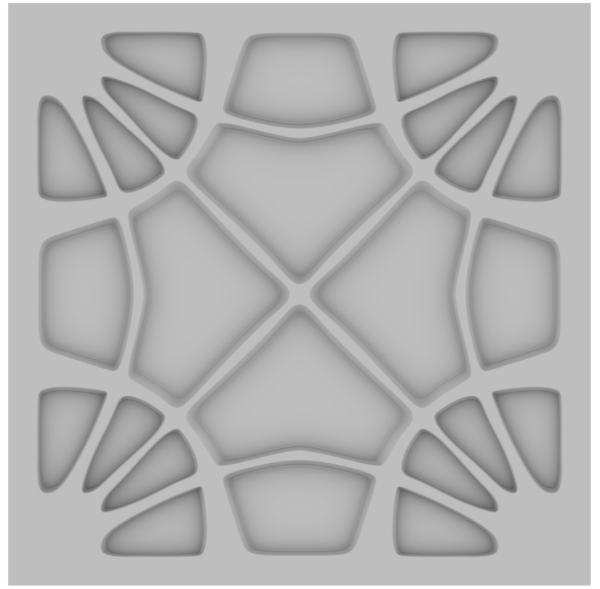


Figure 21: Pier Luigi Nervi Slab Design



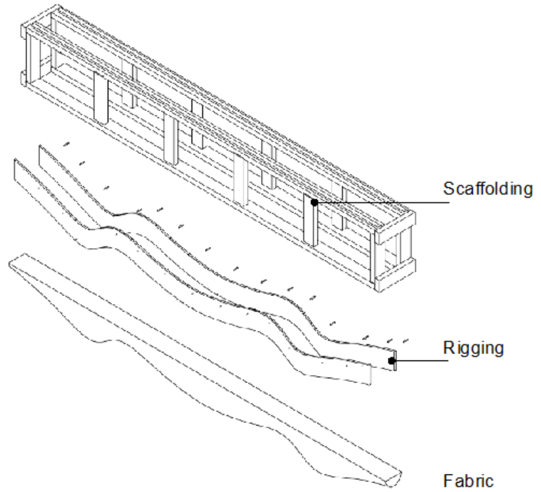
Slab -27% Volume Compared to Traditional Slab

Construction Const	●	●	●	●	○	○	○	○	○	○
Ease of Assembly	●	●	●	●	●	●	●	●	●	○
Reusability	●	●	●	●	●	●	●	●	●	●
Material Optimization	●	●	●	●	●	●	●	●	○	○
Flexibility in Shapes	●	●	●	●	●	●	●	●	●	●

CHAPTER 4

4.1 BEAM FORMWORK

In order to test my theory, I cast a series of beams that were then tested using a relatively standard four-point bending test. During the casting process it very quickly became clear that the supports will pose a problem since they are not naturally flat. In order to resolve this small "boats" were created in order to provide level support points.

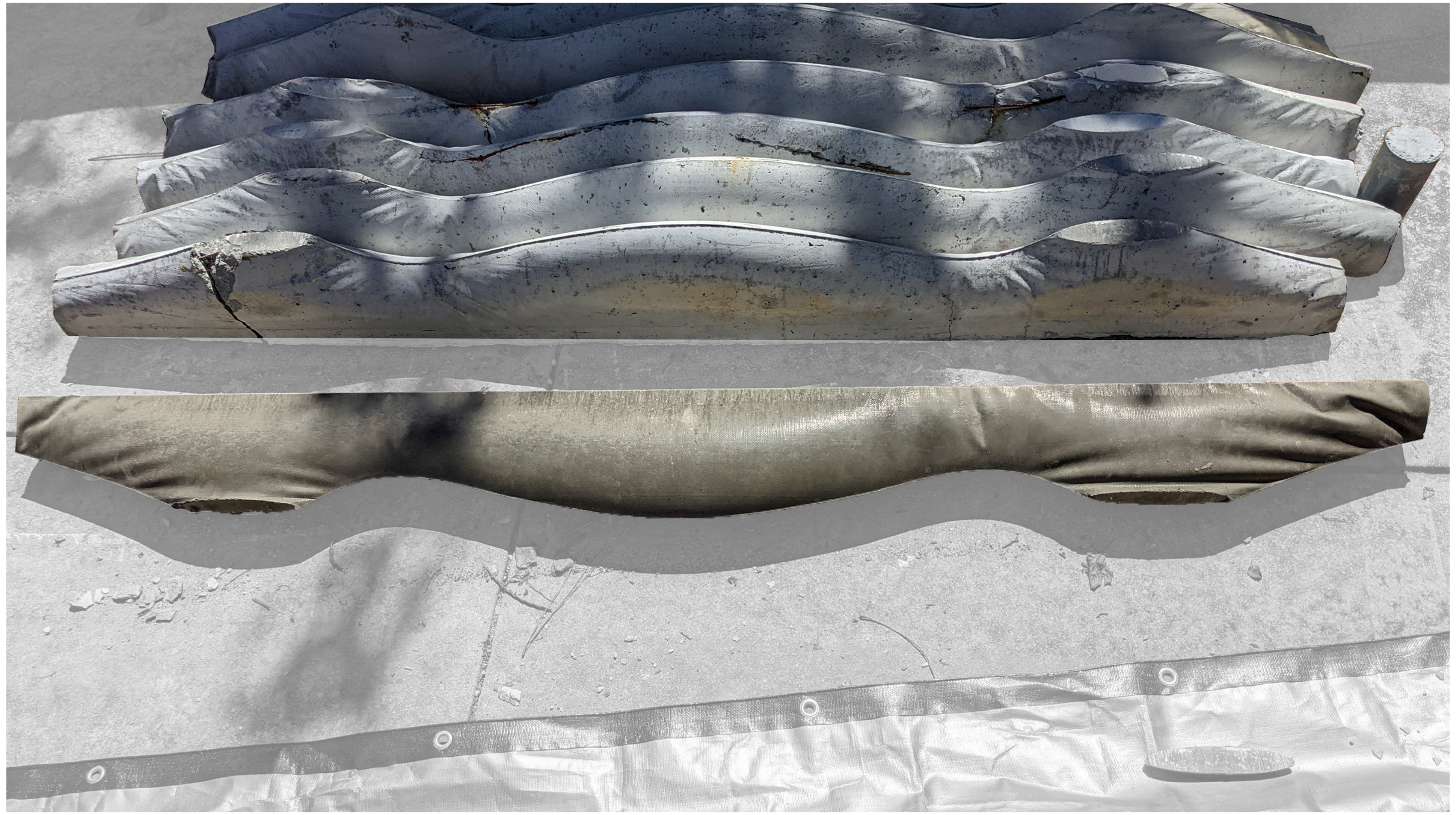


4.2 BEAM CASTING

The casting of the beams was done in the concrete lab of the civil engineering building using a drum mixer. The mix design is similar to a self-consolidating mix, since it would be difficult to properly vibrate the formwork after pouring in the concrete. In order to get the rebar into the correct place, fishing line was used to hand the rebar from the top of the formwork.

Formwork Before Casting

Formwork After Casting



Cast Beams

4.3 BEAM TESTING

In order to perform the testing on the beam I was able to use the facilities and expertise of the civil engineering department. Tests were primarily performed on the MTS machine, which allowed us to easily collect and diagram the data gathered. First the steel was tested, followed by the concrete and finally the beam. The steel was tested by pulling it apart and observing its behavior. The Concrete was tested using a crushing test. The beam was tested using a standard four-point bending test. Due to some issues with the steel, I was using I had to test a second type of steel rod which would get me closer to my desired result.

STEEL TESTIGN SET UP

Tensile testing of pieces of welded wire mesh revealed they had a high yield strength but low plasticity. The larger #2 bars have a lower yield strength but are able to deform more.

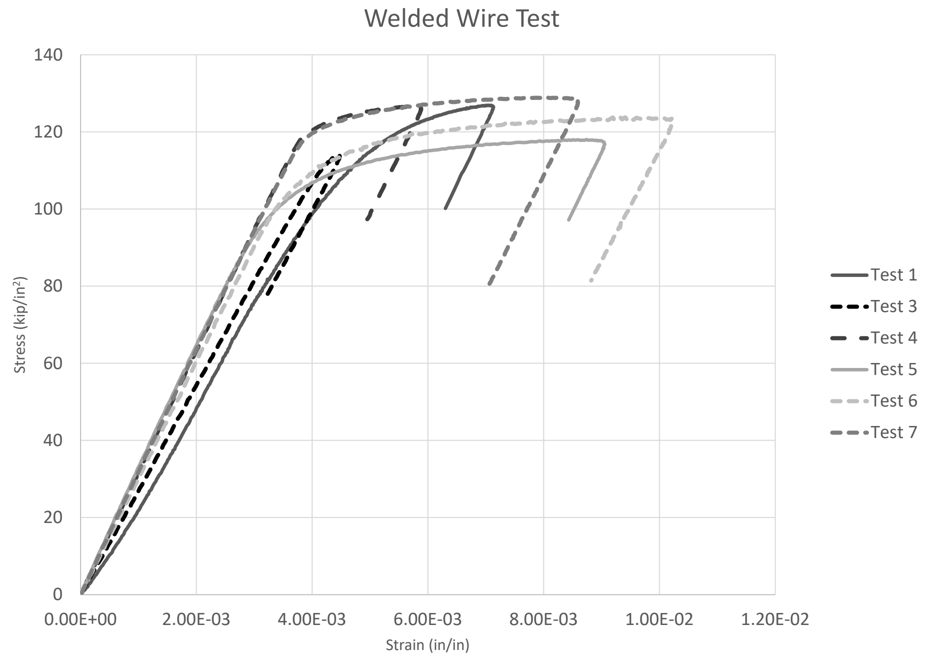
CONCRETE TESTIGN SET UP

The compressive testing of our cylinders revealed a compressive strength of at least 8,000 psi. We are using a self consolidating concrete with a water to cement ratio of 0.4 which allows the cement to flow into the complex form more easily.

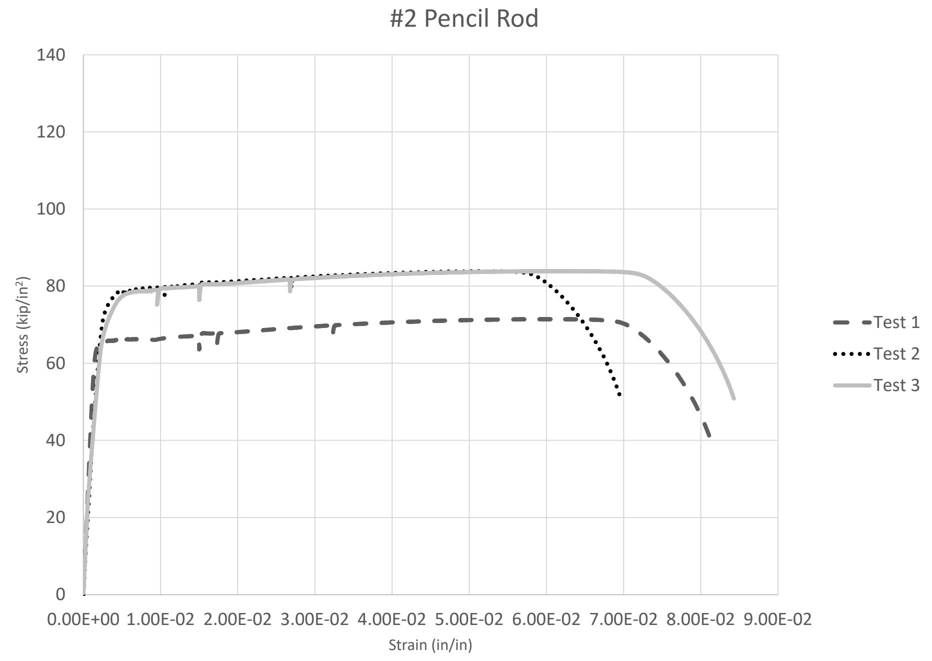
BEAM TESTIGN SET UP

Four point bending test of the fabric formed beam with a distance of 55" between supports. Our testing rig allows us to measure the displacement and force exerted of the cross-head. The overall beam is 84" from end to end. The maximum depth of the beam is in the middle where we expect it to be experiencing the largest moment forces. The largest cross-sectional area is over the supports which allows the beam to handle the sheer forces at this area.

STEEL TESTING

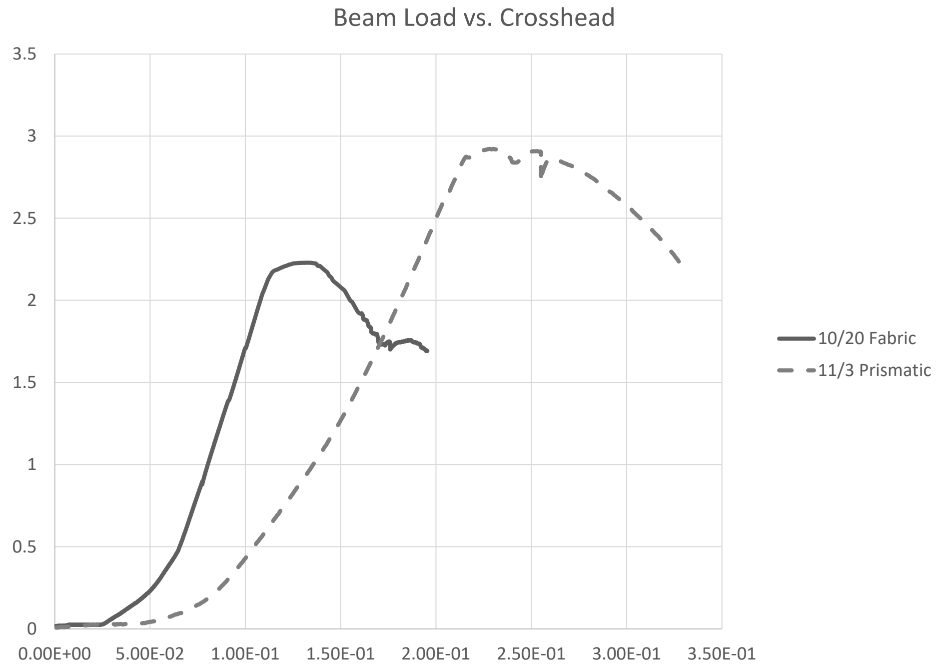


STEEL TESTING 2

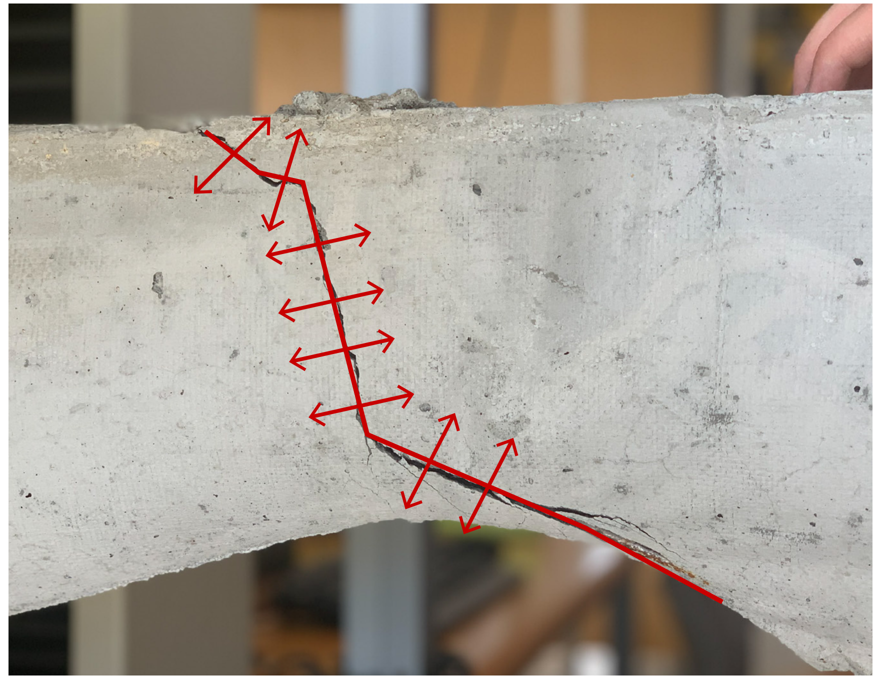


As can be seen on the initial test of the steel, the welded wire mesh I used had a fairly high yield strength for my application, but unfortunately also very low plasticity. This can be seen by the very abrupt downward lines on the graph, which represent a more brittle failure without much deformation. The #2 pencil rod, shown in the second graph had a behavior much more matching closer to what I was hoping for with unfortunately a lower yield strength, but with much better deformation.

BEAM TESTING



Failure of the fabric beam was along the thinnest portion of the beam and appeared to be tensile failures. Further optimization of the reinforcement in the beam will be required in order to bring the fabric beam's strength in line with that of the standard prismatic beam.



Failure of the fabric beam was along the thinnest portion of the beam and appeared to be tensile failures. Further optimization of the reinforcement in the beam will be required in order to bring the fabric beam's strength in line with that of the standard prismatic beam.

CHAPTER 5

5.1 SUMMARY

This thesis explored the use of structurally optimized formwork systems in architectural buildings. The aim was to combine math, material science, and architectural design in an interdisciplinary effort to better the built environment. In part motivated by the artwork of Mark West and informed by structural engineering concepts, this thesis aimed to advance the fundamental understanding of concrete formwork systems in an effort to marry architectural form and structural design by creating a new design language for concrete construction.

In order to achieve this goal, I looked to the past to find how formwork had evolved over the centuries. After in-depth dive into the history of concrete formwork and the most common formwork systems currently in use in the construction industry, as well as several types of experimental systems proposed over the last 100 years, I concluded that a non-rigid formwork system would be the ideal base to build my research on. It allows for easy shaping of complex concrete elements with the main challenges arise from the scaffolding that hold the material in place. The data produced during this exploration of nonrigid formworks has led me to conclude it would be possible to consistently generate optimized structural elements, in particular beams, columns and slabs that can provide significant savings in material and formwork cost.

While my focus was mainly on beams, I believe that the same methods can be used to create columns and slabs. The flexibility of the material allows for a variety of shapes to be crated based on how the material is pulled or draped making it very versatile and reusable. Throughout several test casts the material was able to be completely reused proving that it is both strong enough to support the weight of the concrete as well as flexible enough not to break when demolding.

In the future I would like to develop these ideas further and explore the creation of a scale column and slab to go with the beams I have been working with. Now that the concept is proven I feel the with some optimization it would be possible to create a standardized system for creating these shapes based on the situation at hand, which would allow it to possibly be adopted in the wider construction field.

IMAGE INDEX

Figure 1: happhoadmin7. “What Is Formwork and Requirements of a Good Formwork.” Happho, April 28, 2020. https://happho.com/good-formwork-technical-functional-requirements/.

Figure 2: Wallender, Lee. “House Foundation Types, Uses, and Pros and Cons.” The Spruce. The Spruce, January 21, 2022. https://www.thespruce.com/types-of-house-foundations-1821308.

Figure 3: Henderson, Zoë “Nervi: The Master of Parametric Design and Construction.” Medium. The Civil Collection, February 26, 2017. https://medium.com/the-2016-civil-collection/nervi-the-master-of-parametric-design-and-construction-7e083da543cd.

Figure 4: Henderson, Zoë “Nervi: The Master of Parametric Design and Construction.” Medium. The Civil Collection, February 26, 2017. https://medium.com/the-2016-civil-collection/nervi-the-master-of-parametric-design-and-construction-7e083da543cd.

Figure 5: Adriaenssens, Sigrid. “Pier Luigi Nervi in America (Part 2) – Norfolk.” Form Finding Lab, November 15, 2018. https://formfindinglab.wordpress.com/2018/10/25/pier-luigi-nervi-in-america-part-2-norfolk/.

Figure 6: Mele, Tom Van. “Knitcandela - a Flexibly Formed Thin Concrete Shell at Muac, Mexico City, 2018.” Block Research Group. Accessed February 9, 2022. https://block.arch.ethz.ch/brg/project/knit-candela-muac-mexico-city.

Figure 7: Mele, Tom Van. “Knitcandela - a Flexibly Formed Thin Concrete Shell at Muac, Mexico City, 2018.” Block Research Group. Accessed February 9, 2022. https://block.arch.ethz.ch/brg/project/knit-candela-muac-mexico-city.

Figure 8: Mele, Tom Van. “Knitcandela - a Flexibly Formed Thin Concrete Shell at Muac, Mexico City, 2018.” Block Research Group. Accessed February 9, 2022. https://block.arch.ethz.ch/brg/project/knit-candela-muac-mexico-city.

Figure 9: “Fabric- Formed Concrete and Fabric Formwork Construction.” Surviving Logic. Accessed February 9, 2022. https://www.survivinglogic.ca/fabric-formwork-construction.html.

Figure 10: “Fabric- Formed Concrete and Fabric Formwork Construction.” Surviving Logic. Accessed February 9, 2022. https://www.survivinglogic.ca/fabric-formwork-construction.html.

Figure 11: “Smart Slab.” DFAB HOUSE. ETH Zurich. Accessed February 9, 2022. https://dfabhouse.ch/smart-slab/.

Figure 12: “Smart Slab.” DFAB HOUSE. ETH Zurich. Accessed February 9, 2022. https://dfabhouse.ch/smart-slab/.

Figure 13: “The Smart Slab - 3D-Printed Formwork for a Radical New Concrete Aesthetic.” dbt, March 1, 2022. https://dbt.arch.ethz.ch/project/smart-slab/.

Figure 14: “The Smart Slab - 3D-Printed Formwork for a Radical New Concrete Aesthetic.” dbt, March 1, 2022. https://dbt.arch.ethz.ch/project/smart-slab/.

Figure 15: “The Smart Slab - 3D-Printed Formwork for a Radical New Concrete Aesthetic.” dbt, March 1, 2022. https://dbt.arch.ethz.ch/project/smart-slab/.

Figure 16: Sloan, Jeff. “CW Talks Explores Foldable Composites with Joseph Choma.” CompositesWorld. CompositesWorld, September 12, 2017. https://www.compositesworld.com/articles/cw-talks-explores-foldable-composites-with-joseph-choma.

Figure 17: Sloan, Jeff. “CW Talks Explores Foldable Composites with Joseph Choma.” CompositesWorld. CompositesWorld, September 12, 2017. https://www.compositesworld.com/articles/cw-talks-explores-foldable-composites-with-joseph-choma.

Figure 18: Choma, Joseph. “Foldable Composite Structures.” USPTO.report. Accessed February 9, 2022. https://uspto.report/patent/grant/10,994,468.

Figure 20: Orr, John Joseph. “Flexible Formwork for Concrete Structures.” the University of Bath’s research portal. Accessed February 9, 2022. https://researchportal.bath.ac.uk/en/studentTheses/flexible-formwork-for-concrete-structures.

Figure 21: Formfindinglab. “Pier Luigi Nervi in Italy (Part 1): His Ribbed Floor Slab Systems.” Form Finding Lab, March 1, 2019. https://formfindinglab.wordpress.com/2019/01/23/pier-luigi-nervi-in-italy-part-1-his-ribbed-floor-slab-systems/.

REFERENCES

[1] USGS 2017. Cement statistics. In: KELLY, T. D., MATOS, G.R. (ed.) Historical statistics for mineral and material commodities in the United States. USGS.

[2] Van Damme, H. 2018. ’Concrete Material Science: Past, Present, and Future Innovations’, Cement and Concrete Research, Elsevier, 112, p 5-24.

[3] CDIAC.: Fossil-Fuel CO2 Emissions (online) (2005); Available from: http://cdiac.esd.ornl.gov/ trends/emis/meth_reg.html

[4] INDC. INDC - U.S. Cover Note, INDC and Accompanying Information. (2015, March 31). Retrieved October 21, 2021, from https://www4.unfccc.int/sites/submissions/INDC/Submission%20 Pages/submissions.aspx.

[5] West, M.: ‘Kenzo Unno, Fabric Formed Walls’, Winnipeg, University of Manitoba, Available from http://www.umanitoba.ca

[6] West, M., Abdelgar, H. S., Gorski, J. (2007) ‘State of the Art Report on Fabric Formwork’, Concrete: Construction’s sustainable option, Sept 4-6.

[7] Orr, J. J., Darby, A. P., Ibell, T. J. (2010) ‘Innovative Concrete Structures Using Fabric Formwork’, SEMC 2010, Cape Town, South Africa, Sept 4-8.

[8] West, M., Araya, R. (2009) ‘Fabric Formwork for Concrete Structures and Architecture’, Int. Conf. Textile Composites and Inflatable Structures, Barcelona, Spain, Oct 5-7.

[9] Bailiss, J. (2006) ‘Fabric-formed Concrete Beams: Design and Analysis’, MEng Thesis, Department of Architecture and Civil Engineering, Bath, University of Bath.

[10] Garbett, J. (2008) ‘Bone Growth Analogy for Optimizing Flexibly Formed Concrete Beams’, MEng Thesis, Dept for Architecture and Civil Engineering, Bath, University of Bath.

[11] Orr, John Joseph. “Flexible Formwork for Concrete Structures.” the University of Bath’s research portal. Accessed February 9, 2022. https://researchportal.bath.ac.uk/en/studentTheses/flexible-formwork-for-concrete-structures.