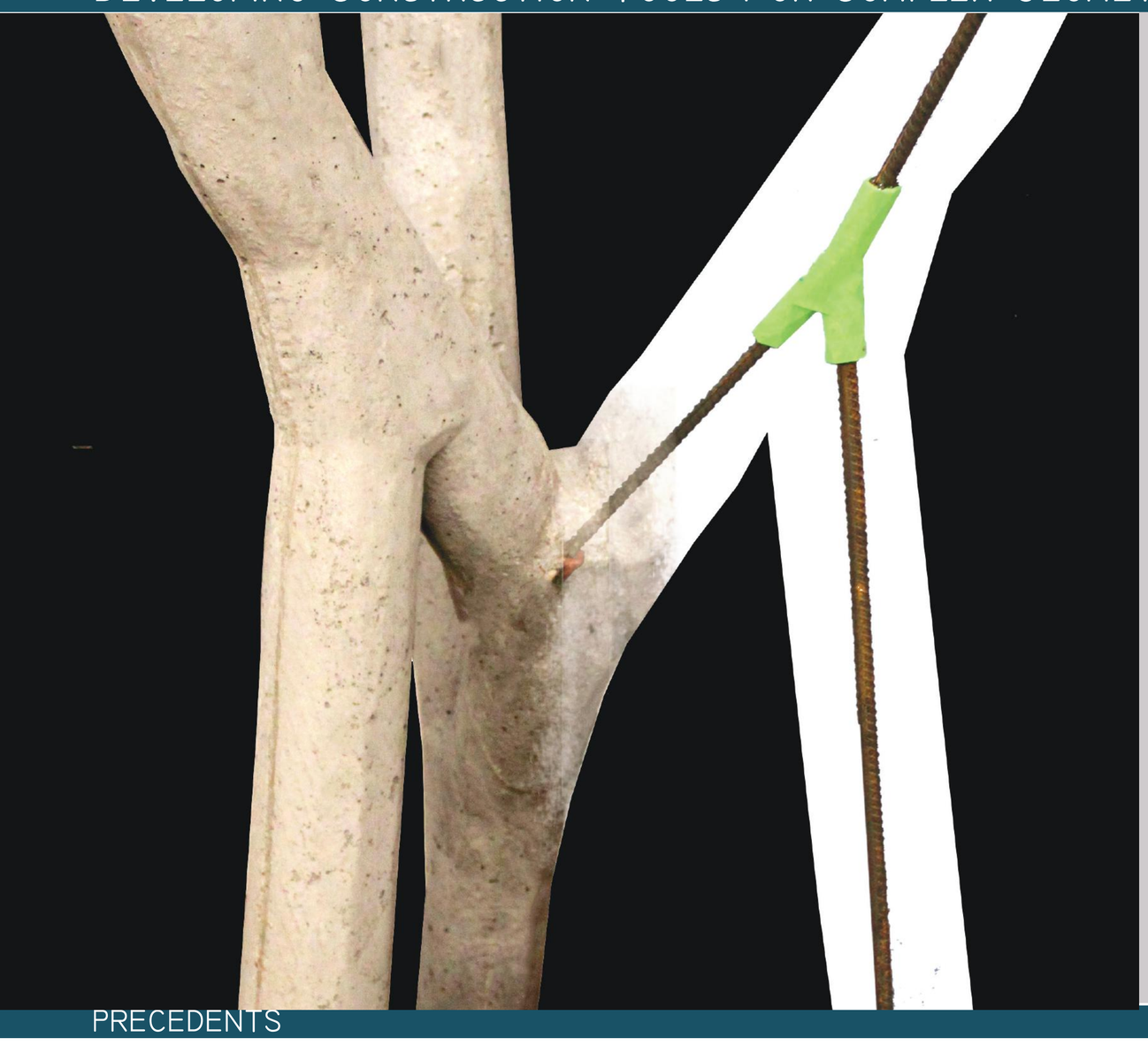
# Digitally Sculpted Branching Manifold Structures

## Developing Construction Tools For Complex Geometries



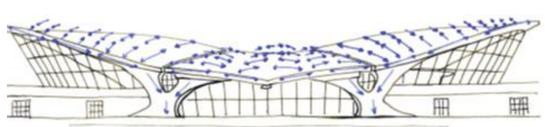
Formwork is the most expensive part of most concrete construction projects. According to "Building Construction: Principles, Materials and Systems" written by Dr. Madan Mehta, formwork for site cast concrete projects costs 50-55% of the total budget and can cost 75% or more for structures with complex geometries. Therefore, form reusability is vital, making it necessary to use materials with high durability that are easy to reutilize.

The previous methods of multi-nodal columnar branching structural formwork was attempting to solve issues related to form, structure, and formwork, and it is the starting point of the current research. The prior formwork strategy encountered challenges when casting the final structure, which has provided insight into issues to consider in the current research. The fabric formwork used was labor intensive, inconsistent from one cast to the next, questionable quality, and was difficult to reuse. Similiarly, the plastic formwork was difficult to utilize in a timely and efficient manner. The plastic used did not properly support the weight of the concrete in order to reduce expansion of the mold, and extensive use of reinforced tape and rope latice-work added a total of 48 hours to mold assembly time.

We will determine if a consistent formwork for casting a high performance concrete branching manifold structure can be efficient, reusable and economical when built out of high density foam. We propose that using a digitally sculpted high density foam formwork would provide consistency in form, eliminate tedious formwork assembly, reduce time between castings and provide a reusable system for casting multiple structures. We will explore this through a series of material, digital and method testing with the intention of developing a more advanced method of formwork.

## Precedents

Branching Columns

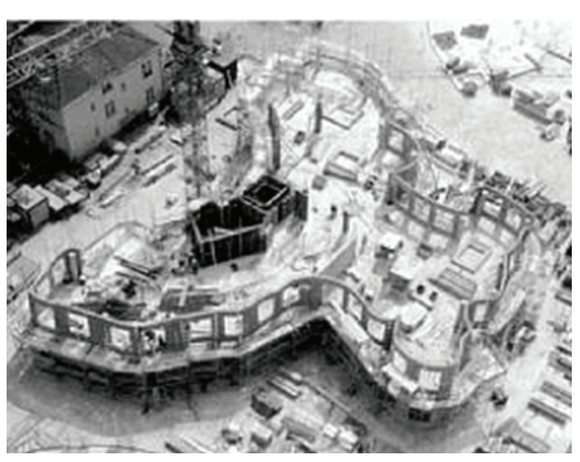


1962

### TWA Terminal | Eero Saarinen

Hundreds of drawings were required to determine the form work for the four curvilinear Y-shaped poured in place reinforced concrete columns that support the concrete shell roof of the TWA Terminal. The columns were shaped to emphasize an upward or soaring quality and a feeling of airiness, and also aid in the transfer of the loads from the roof and allow for large column spacing.

Foam Formwork



2000

### Zollhof Towers | Frank Gehry

The undulating forms of the load-bearing external wall panels made of reinforced concrete were precast in 355 different CNC-milled light weight polystyrene (Styrofoam) molds. The molds were linked together using PVC pipes running through the forms and could be reused for a small number of casts.

Adjustable Formwork

2001

### Milwaukee Art Museum | Santiago Calatrava

Cast using Peri Formwork RundFlex forms for the museum's curved walls. forms gave the ablity to easily and inexpensively adjust the radii. To achieve a smooth concrete finish, 3/4" thick birch cabinet plywood (MDO) had to be attached to the form face. Joints were sealed with fiberglass filler, sanded and painted with epoxy paint. surfaces with irregularities (reveals or chamfers) required additional pieces to be attached to the forms. Because the forms were so heavy, it was necessary to use 100-ton cranes to move them.

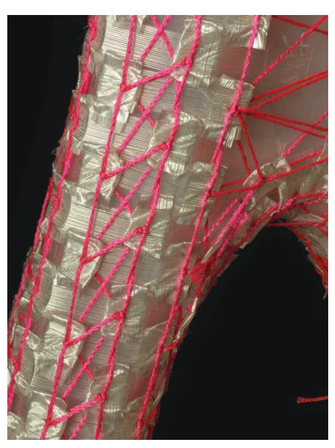
Latex Mold Formwork

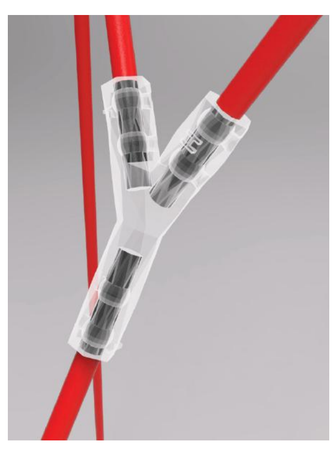
2012

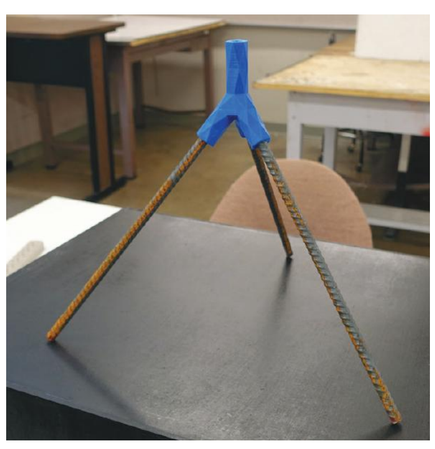
### Perot Museum | Morphosis

Project done by Gate Precast using latex molds that were re-usable and reconfigurable. the molds were Used in The casting of the facade panels. The production of the mold required less than ten variations of geometries that could be reconfigured to make the seemingly individualized facade panels.

## Previous Research







### Branching Manifold Formwork - Fabric Research Conducted By: Halima Arevalo, AnnRuth Warwinu & David Pacheco Garcia

By using fabric as formwork for concrete construction, this project sought to expand on the research done by Mark West at the University of Manitobas Centre for Architectural Structures and Technology (C.A.S.T.) and generate a multi-nodal pre-cast concrete structure with multi-nodal 3D printed steel reinforcement.

Research focused on 1.) defining the role and implication of the precast process on the multi-nodal branching structure, 2.) refining the use of bulge wall casting to provide multi-trajectory outcomes, and 3.) include structural enhancements through digitally fabricated production of internal structural networks.

### Branching Manifold Formwork- 2D Plastic

Research conducted at the University of Texas at Arlington in the Summer of 2014. The project explored the utilization of CNC milled 2D plastic as formwork for casting branching structures. The 2D plastic pieces were secured together by intricate rope lattice work running the entire legth of the column. Scaffolding for the column provided additional structural stability and braced the column to facilitate the pouring of concrete.

Though the project proved successful in producing very smooth casts, it was time consuming in the assembly of the form and the plastic began to stretch due to concrete pressure. The lattice work took many hours to tediously assemble and dissassemble, and the 2D plastic had to be reinforced with tape to withstand the pressure of concrete.

### 3D Printed NodalJoints for Manifold Structure reinforcement GH Definition Author: Josh Hallet

limb constitutes a continuation of research initiated in the Spring of 2014 that sought to discover new and exploratory methods for reinforcing precast concrete panels with non-uniform porosity. It was determined during the course of this research that steel reinforcing rebar could be accurately and effectively located within a panel by utilizing 3D printed nodes with interior "slots" whereby the rebar could be inserted and then fixed via wire-tie. these nodes were generated in the parametric plug-in tool grasshopper, which enabled complete control over the nodes' geometric properties.

This allowed not only for a vast amount of flexibility in terms of configuration and scale, but rapid alterations in the geometry as a response to changing design criteria and testing. The drawbacks of this particular GA (Grasshopper) definition was multifold, however. Where the node could be 3D printed reliably, and was somewhat sturdy, each node had to be manually adjusted to account for each nodal centroid. Furthermore, the node could only account for strut orientations in the X and Y Axis.

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# Digitally Sculpted Branching Manifold Formwork Development

## Material Research

### Factors affecting lateral pressure on forms:

- Weight of concrete
- Rate of placing (the average rate of rise in the form)
- Vibration
- Temperature (affecting the set time)

*Other variables*

- Consistency of concrete
- Ambient temperature
- Amount and location of reinforcement
- Maximum aggregate size (MSA)
- Cement type

### Formwork Performance Criteria

- Reusability
- Price
- Ease of construction
- Adaptablility

### Considerations

- minimize Mold Parts
- Mold Should have a Feeder for concrete
- consider easy mold release in mold design by adjusting drafting angles

### Formwork Development

1. select/obtain test material foams and coatings to be run through a series of test casts.
2. Cast each configuration of coating and foam molds with concrete and record variable results such as surface quality, workability, ease of release and formwork reusability.
3. From these material tests, select the appropriate materials for prototype casting.
4. Design formwork keeping in mind material compressive properties, given geometry, and machining capabilities.
5. Using the given geometry, cast column prototype with foam mold and structural reinforcement

### Nodal Joint Development

1. 3D Print a test nylon node for tensile tesing in the engineering lab.
2. conduct Tensile test and gather data
3. Adapt Nodal grasshopper definition to given geometry.

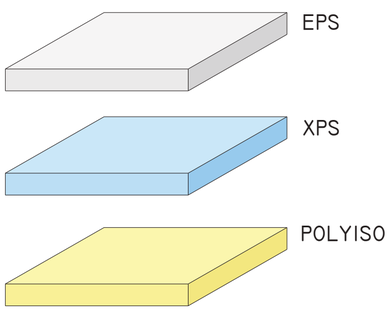
### Testing Factors

**Surface Quality**
Smoothness
Material texture cast on concrete
foam adherence on cast form

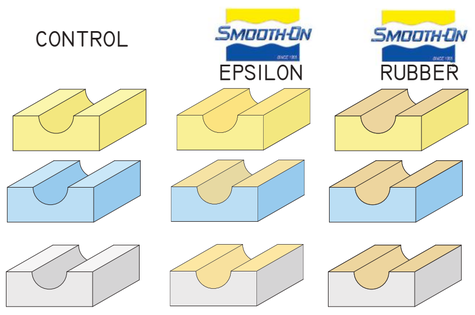
**Ease of Release**
Time to detach cast form from form work

**Formwork reusability**
Formwork damage
Compressive strength of concrete
Surface quality of foam after casting

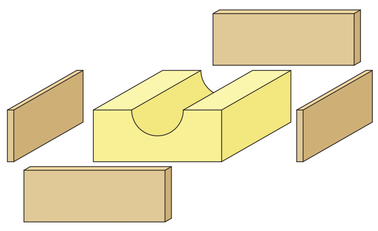
**Coatings**
improvements on mold release
improvements on surface quality
improvements on foam deterioration
effect on foam/concrete
time required in addition to concrete casting
number of additional procedures required prior to casting
difficulty of application



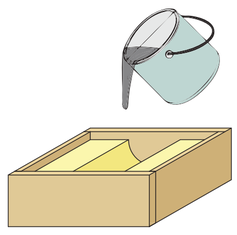

FOAM SELECTION
STRENGTH & SURFACE QUALITY



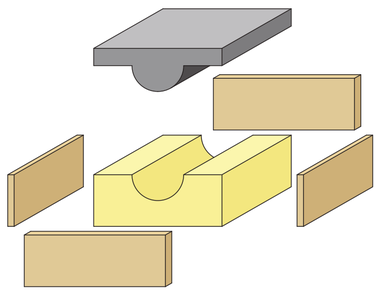

COATING SELECTION
REUSABILITY & RELEASE AID



PLYWOOD SCAFFOLDING
FOAM PROTECTION



CONCRETE CASTING



CAST / FORMWORK ASSESSMENT
DURABILITY & CAST QUALITY

## Foams

### Polyisocyanurate (polyiso)

Also Known as Rigid Polyurethane Foam. offers higher compressive strength and better solved resistance than polysterene foam board, used with polyester resin and fiberglass.

### Expanded Polystyrene (EPS)

less dense, small white beads, low surface quality, needs to be coated with more rigid materials

### Extruded Polysterene Foam Board (XPS)

close cell foam, can be cut/routed/sanded without a coat, vulnerable to denting, vulnerable to solvents (acetone, xylene, toluene, MEK fiberglass polyester resin), can be coated with epoxy.

| | Cost (/ft³) | Max Compressive Strength (psi) | Max Flexural Strength (psi) | Least Water Absorption (% by volume) | Density (lbs/ft³) | Able to Hot Wire Cut | Max Dimensions |
|---|---|---|---|---|---|---|---|
| Expanded Polystyrene Foam (EPS) | $7.60 | 60.0 | 75.0 | 2.0 | 0.75 - 2.85 | Yes | 48.0" x 54.0" x 216.0" |
| Extruded Polystyrene Foam (XPS) | $5.85 | 100.0 | 140.0 | 0.1 | 1.3 - 3.0 | Yes | 4.0" x 48.0" x 96.0" |
| Polyisocyanurate Foam (Polyiso) | $10.68 | 16.0 | 40.0 | 0.1 | 2.0 - 6.0 | No | 4.5" x 48.0" x 120.0" |
| Polymethacrylimide Foam (Rohacell) | $221.70 | 435.0 | 348.0 | 2.5 | 2.0 - 7.0 | Yes | 4.75" x 49.0" x 98.0" |

## Coatings


### Smooth-on Epoxy Resin Epsilon

Advantages:
- No mother mold needed
- Quick application
- no additional support parts
- Protects foam mold for multiple casts

Disadvantages:
- Strong chemical reaction, safety equiomment is required
- Shorter pot life, must work quickly
- Re-application in between casts is required


### Brush-on Polyurethane Rubber Mold

Advantages:
- Very durable mold material that is reusable
- Very abrasion resistant and generally has a long life
- Flexible
- Fairly easy to work with
- Can create highly accurate molds
- longer pot life, more workable time

Disadvantages:
- Cost
- Needs a mother mold
- Precise measurement and thorough mixing for proper reaction
- Multiple Coats and cure time make casting process longer

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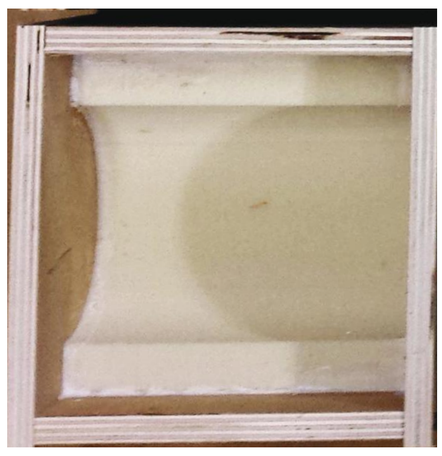
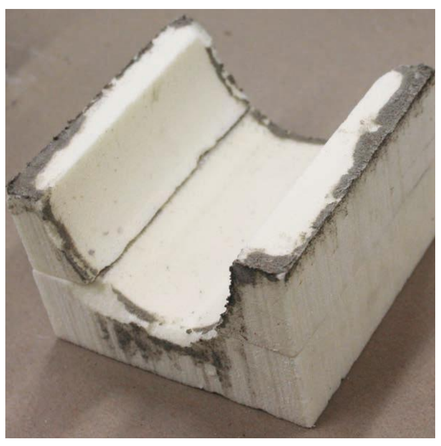
# Digitally Sculpted Branching Manifold Formwork Materials

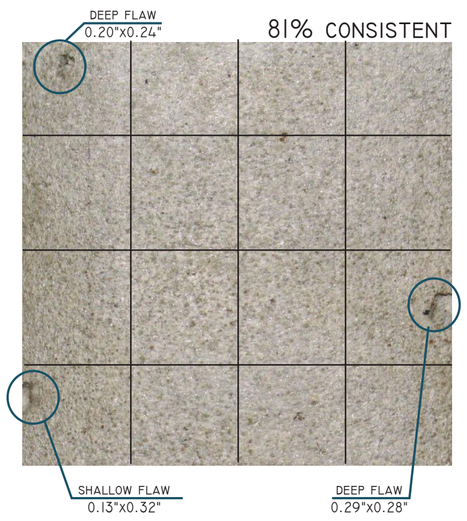
## Material Research

## Control Tests: No Coating

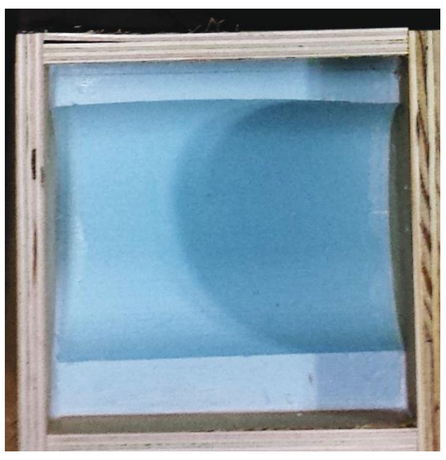
### Polyiso

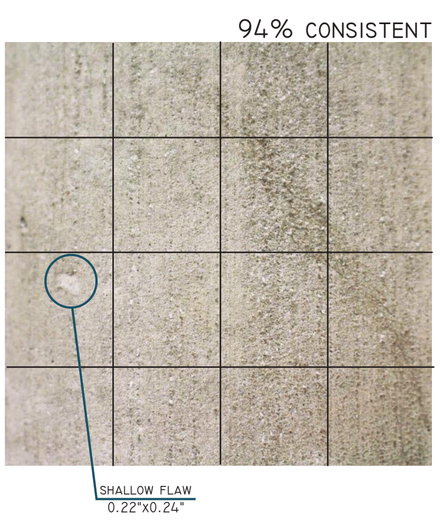




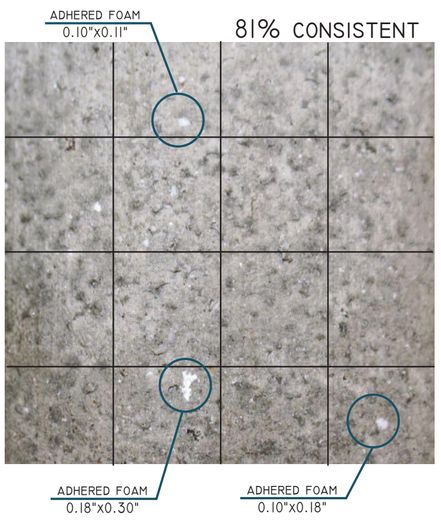



### XPS






### EPS




Original Molds

Post-Casting

Surface Texture

### Polyisocyanurate (Polyiso)

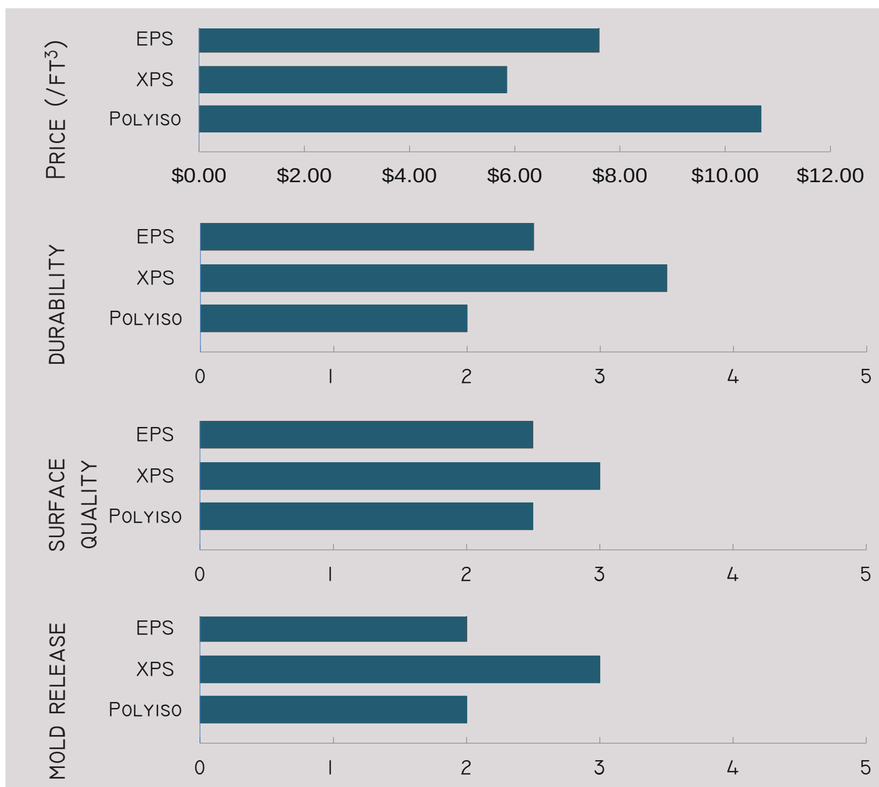
When testing the release of the Polyiso mold, the bond between the foam and the concrete cast was strongest at the edges. The exterior edge of the mold began to deform under the force of pulling to release it from the concrete. Ultimately, it broke along the seam where the two 2-in. sheets were flushed together with an aerosol adhesive. The formwork was deformed and not able to be reused for a second cast. Dime sized pieces of Polyiso remained stuck to the concrete cast as well as a thin layer of foam particles.

### Extruded Polystyrene (XPS)

Release from the XPS mold was not any easier in regards to force applied for separation but it did not adhere to the concrete at all and the form was still intact once isolated. It is reusable for at least one more cast.

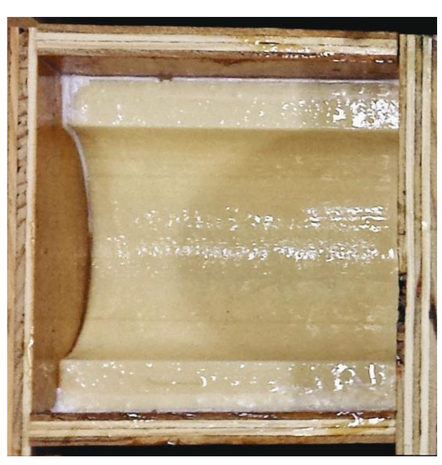
### Expanded Polystyrene (EPS)

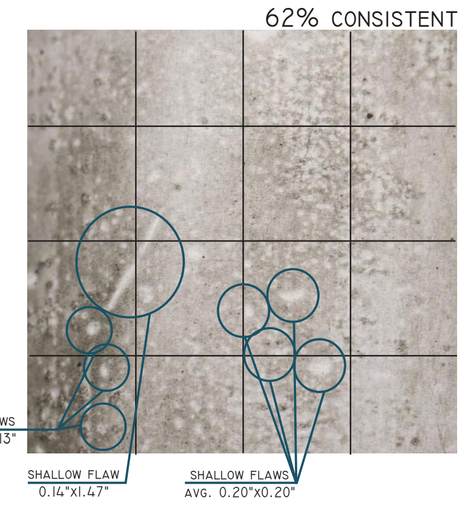
The EPS control test remained more intact during release. One corner of the mold broke off under the force of release. Small expanded cell pieces remained on the surface of the concrete cast and the surface quality also retained the cellular texture of the EPS foam



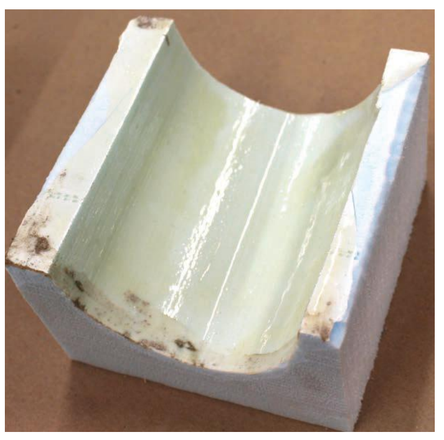

## Brush-on Epsilon: Impact Resistant Foam Coating

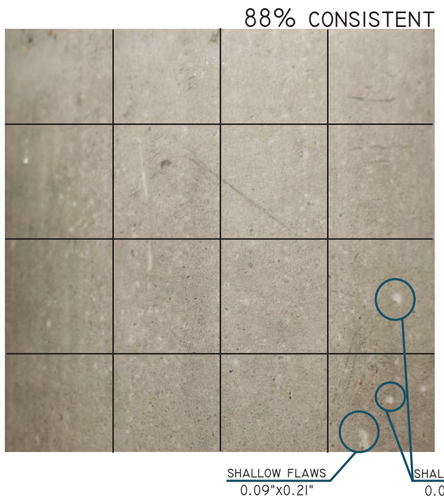
### Polyiso



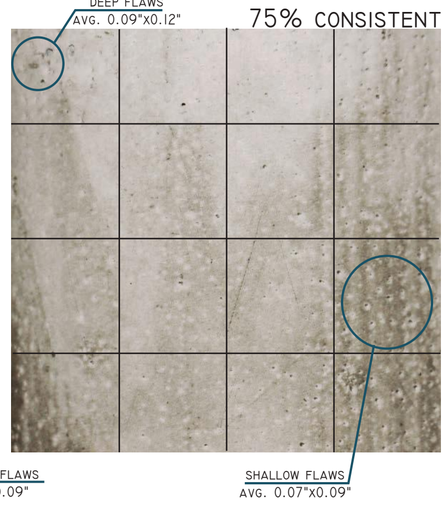



### XPS






### EPS




Original Molds

Post-Casting

Surface Texture

### Polyisocyanurate (Polyiso)

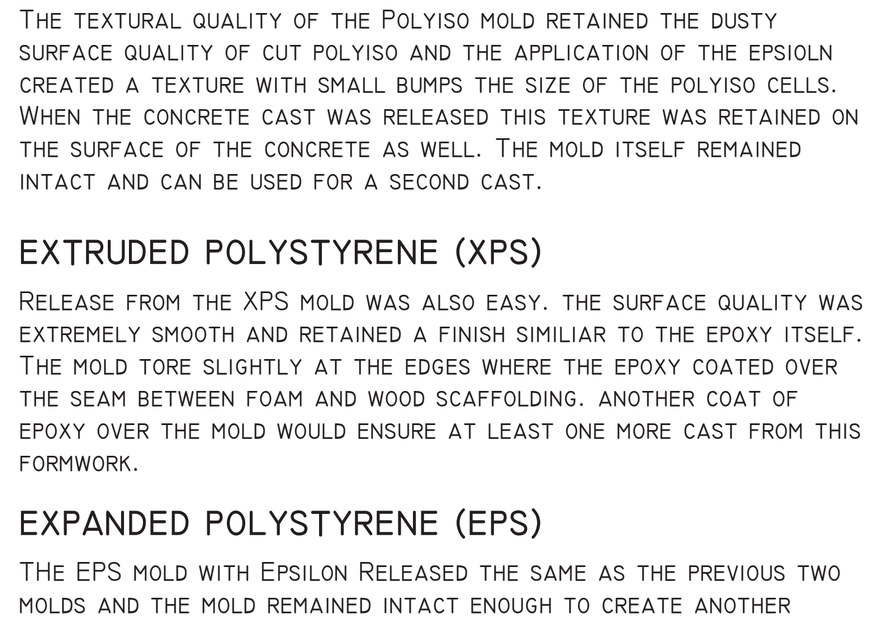
The textural quality of the Polyiso mold retained the dusty surface quality of cut polyiso and the application of the epsioln created a texture with small bumps the size of the polyiso cells. When the concrete cast was released this texture was retained on the surface of the concrete as well. The mold itself remained intact and can be used for a second cast.

### Extruded Polystyrene (XPS)

Release from the XPS mold was also easy. the surface quality was extremely smooth and retained a finish similiar to the epoxy itself. The mold tore slightly at the edges where the epoxy coated over the seam between foam and wood scaffolding. another coat of epoxy over the mold would ensure at least one more cast from this formwork.

### Expanded Polystyrene (EPS)

The EPS mold with Epsilon Released the same as the previous two molds and the mold remained intact enough to create another cast.
The surface Quality of the concrete cast was similiar to the EPS foam and there were several cellular holes along the surface that match in size to the cellular components of EPS foam.




Out of the three foams, XPS worked best in terms of price, durability and surface quality. The epsilon coating worked well not only in mold release but also as a mold protective shell

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# MATERIAL RESEARCH

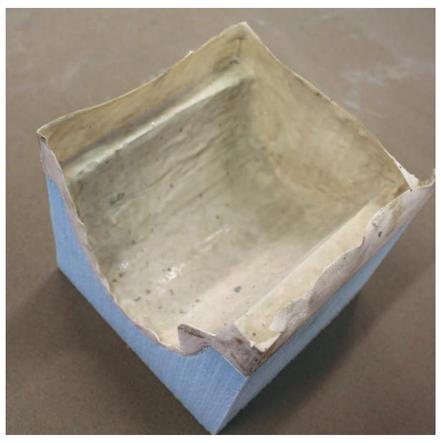
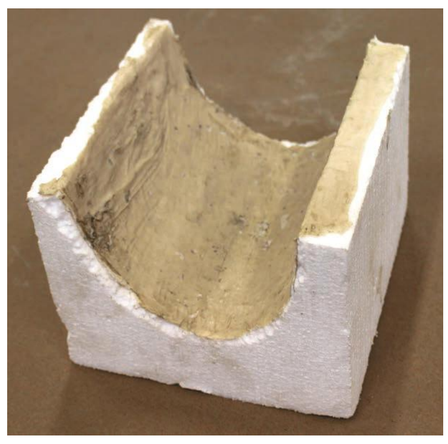
## BRUSH-ON POLYURETHANE RUBBER COMPOUNDS

POLYISO | XPS | EPS

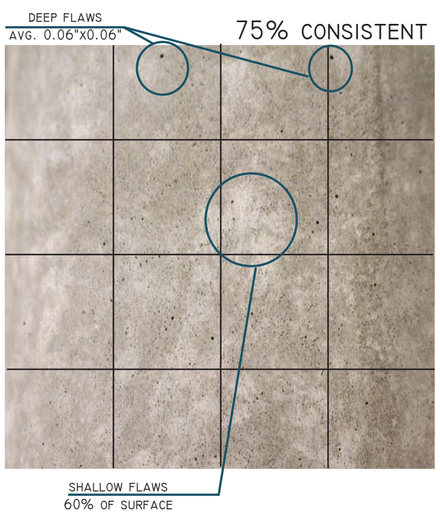
ORIGINAL MOLDS

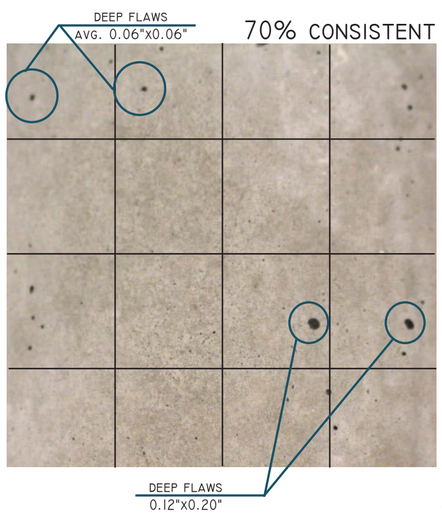


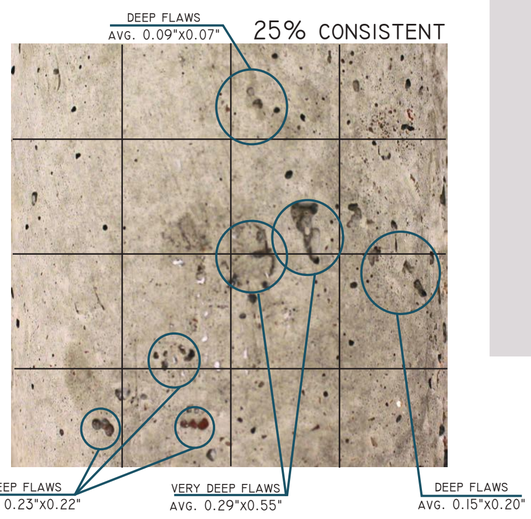
POST-CASTING

SURFACE TEXTURE








### POLYISOCYANURATE (POLYISO)

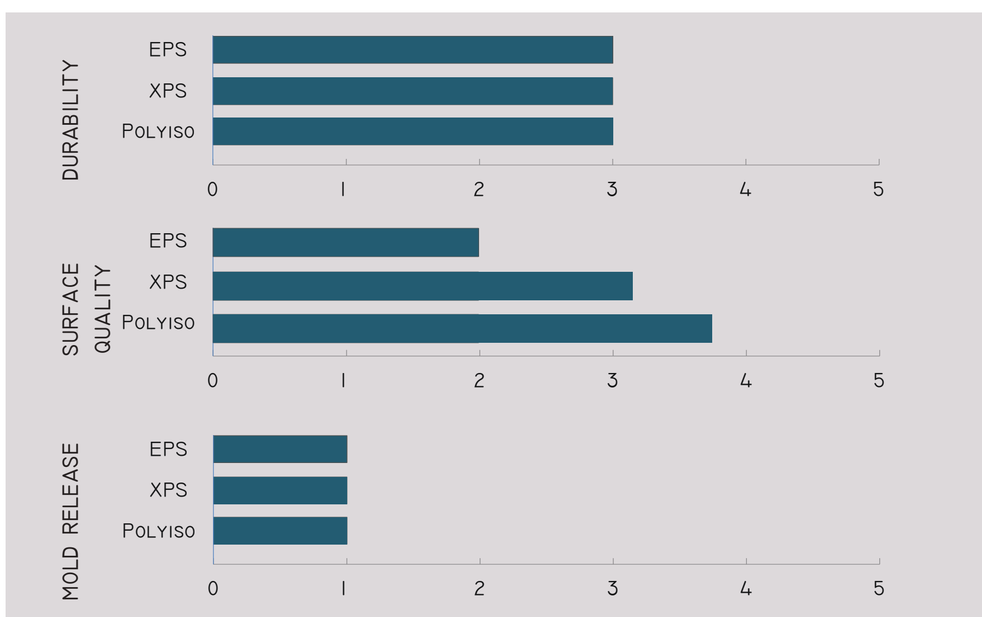
THE POLYISO MOLD REMAINED ADHERED TO A PORTION OF THE FOAM AND THE WOOD FRAME BECAUSE OF THE BRUSH ON RUBBER'S BOND. THE CONCRETE SURFACE WAS SMOOTH WITH ONLY A FEW AIR BUBBLE HOLES AND BRUSH STROKE INDENTIONS FROM THE APPLICATION OF THE RUBBER ONTO THE FOAM. UPON CLOSER SURFACE ANALYSIS, MOST OF THE SURFACE IS FREE OF IMPERFECTIONS WITH ONLY MINOR FLAWS.

### EXTRUDED POLYSTYRENE (XPS)

THE XPS MOLD BONDED TO THE FOAM STRONGER THAN THE WOOD AND REMAINED ABOUT 60% INTACT AFTER THE CONCRETE WAS EXTRACTED. THE CONCRETE WAS EQUALLY SMOOTH TO THE POLYISO MOLD AND HAD A FEW AIR BUBBLE HOLES.

### EXPANDED POLYSTYRENE (EPS)

THE EPS MOLD DID NOT REMAIN INTACT AND THE BRUSH ON RUBBER ONLY REMAINED INTACT TO THE CONCAVE SECTION OF THE FOAM. THE CONCRETE WAS BUMPY AND CONTAINED SEVERAL LARGER AIR BUBBLE HOLES.



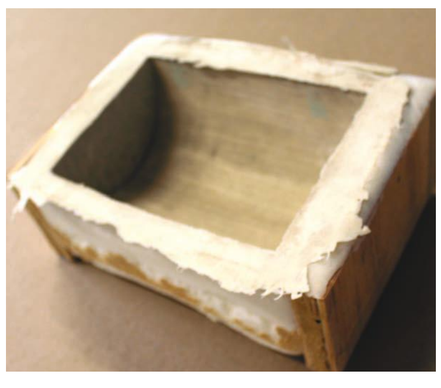
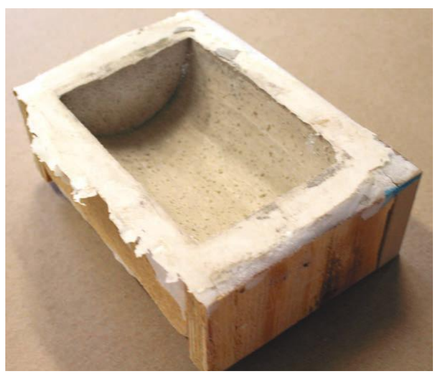

## ADDITIONAL RUBBER TESTING

POLYISO | XPS | EPS

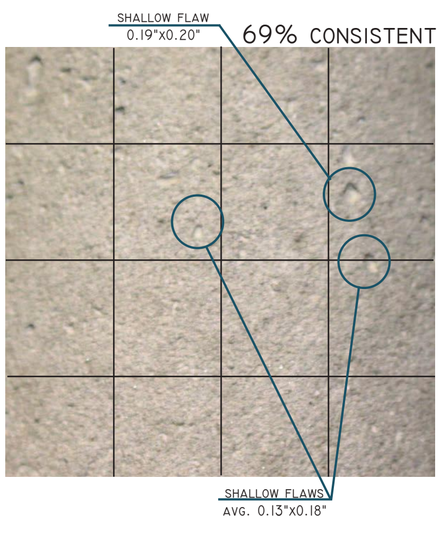
ORIGINAL MOLDS

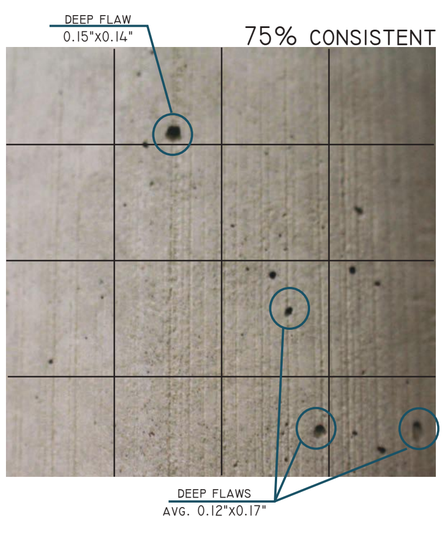


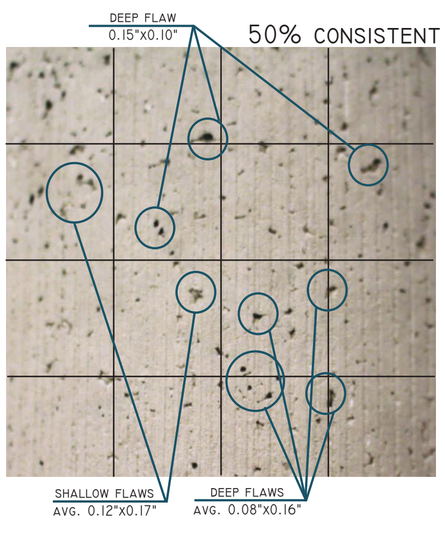
POST-CASTING

SURFACE TEXTURE








A SECOND CASTING TEST WAS COMPLETED TO UNDERSTAND THE MOLD RELEASE FROM A SEMI- CYLINDRICAL FORM AND THE SURFACE QUALITIES CREATED FROM A SOURCE FORM METHOD USING BRUSH-ON RUBBER.

### POLYISOCYANURATE (POLYISO)

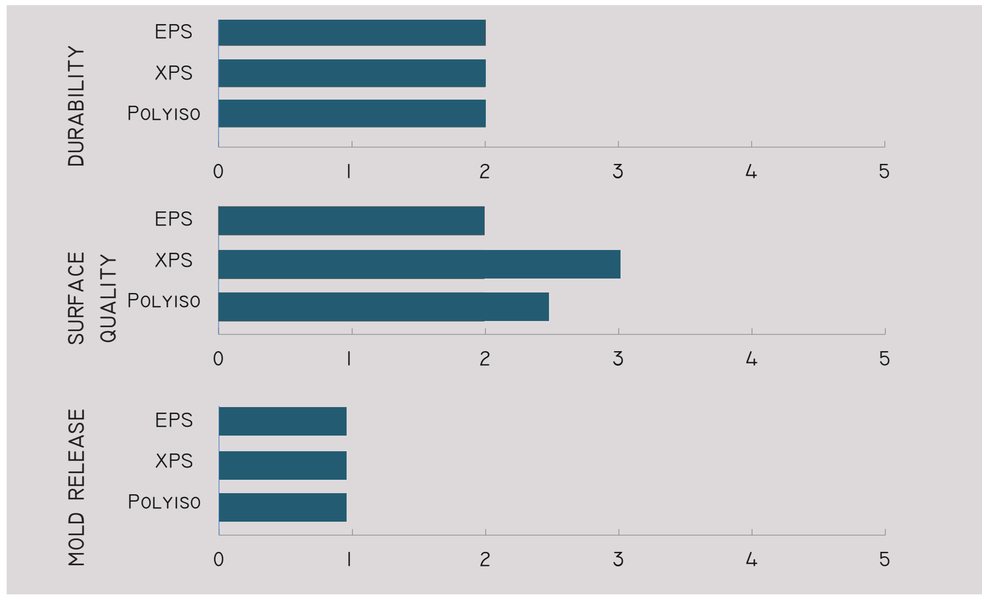
A THIN LAYER OF THE POLYISO FOAM REMAINED ATTACHED TO THE INTERIOR SURFACE OF THE MOLD AND WAS ADHERED SECURELY ENOUGH THAT IT COULD NOT BE WASHED OFF. THAT, IN ADDITION TO THE TEXTURE THE RUBBER ITSELF CAPTURED, RESULTED IN A CONCRETE SURFACE THAT WAS ROUGH WITH VERY SMALL CELLULAR POCKETS THAT COMPOSE POLYISO FOAM.

### EXTRUDED POLYSTYRENE (XPS)

THE XPS FOAM RELEASED FROM THE RUBBER MOLD VERY EASILY, AND SINCE XPS FOAM HAD A MORE SOLID CELLULAR MAKEUP, THE RUBBER MAINTAINED A SMOOTH SURFACE THAT SHOWED ONLY THE CUT LINES FROM THE BAND-SAW USED TO CUT THE FOAM SEMI-CYLINDRICAL SOURCE FORM. THE CONCRETE SURFACE MAINTAINED THE SAME TEXTURE. A FEW AIR BUBBLES MARKED THE SURFACE BUT THAT IS BELIEVED TO BE FROM NOT ENOUGH VIBRATION WHILE CURING.

### EXPANDED POLYSTYRENE (EPS)

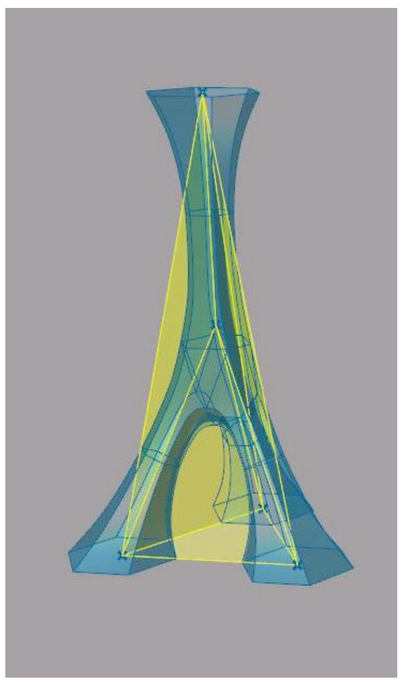
THE EPS FOAM ALSO RELEASED WITH EASE. THE MOLD CAPTURED THE LARGE CELL TEXTURE OF THE EPS FOAM AND THE CONCRETE SURFACE ALSO MAINTAINED THE TEXTURE. WHERE HOLES APPEAR TO BE AIR BUBBLES AT FIRST GLANCE, ACTUALLY ARE THE NEGATIVE OF THE RUBBER CAPTURING THE INTERIOR OF THE OPEN CELLS FROM THE EPS SOURCE FORM.

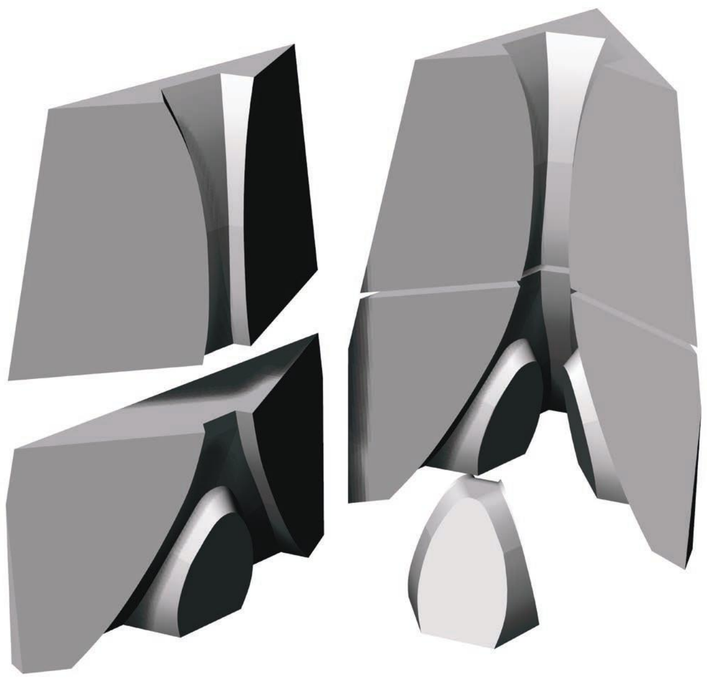



MOLD RELEASE WAS MORE DIFFICULT THAN THE RELEASE FROM THE EPSILON. DUE TO THE ADDITIONAL TIME AND PROCESSES REQUIRED FOR RUBBER COATINGS, AS WELL AS COST AND RELEASE DIFFICULTY, THIS METHOD PROVED TO BE LESS EFFECTIVE THAN USING EPSILON AS A COATING.

# FORMWORK DEVELOPMENT - PROTOTYPE I

## DIGITAL FORMWORK FABRICATION



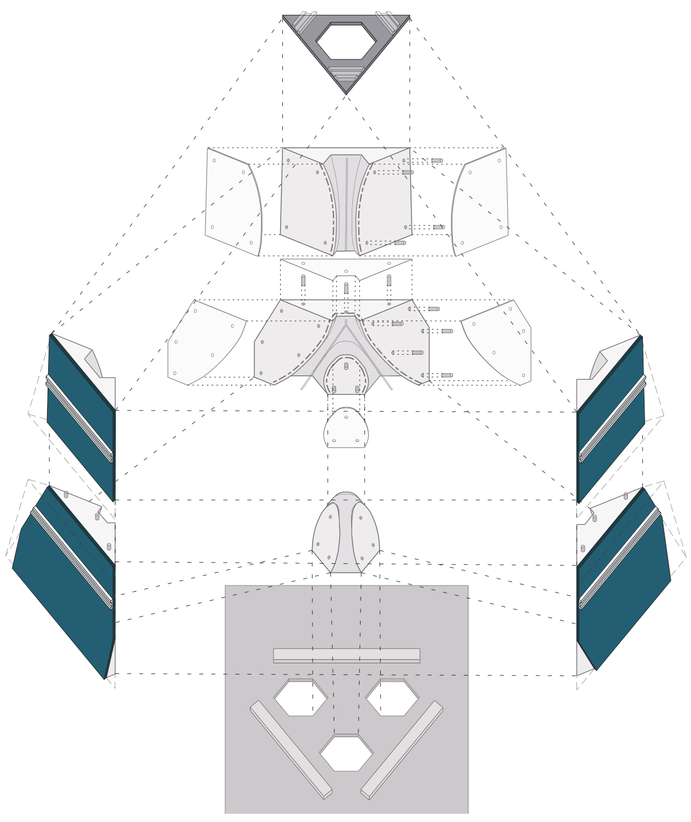


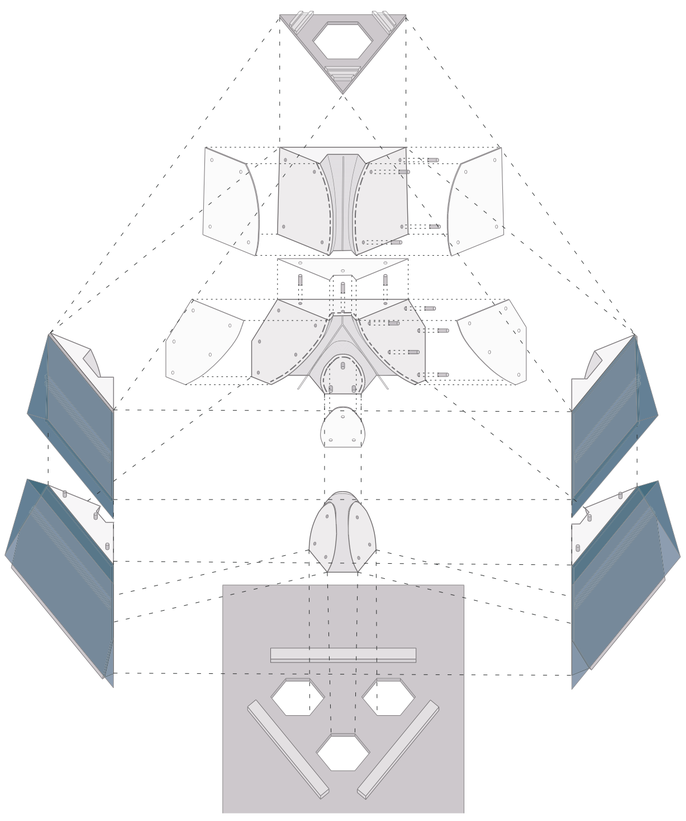
THE FORMWORK DESIGN WAS A COMPLEX MULTI-STEP PROCESS THAT TOOK INTO ACCOUNT ISSUES ENCOUNTERED IN PREVIOUS PROJECTS, SUCH AS CROWDING AND BLOCKAGE AT THE CENTRAL JOINT, TIME REQUIRED FOR SET-UP, ALIGNMENT OF NODES AND REBAR WITHIN THE FORM, AND SURFACE QUALITY INCONSISTENCIES. ADDITIONAL CONSIDERATIONS WERE REQUIRED FOR THE DIGITALLY SCULPTED FORMWORK, INCLUDING MATERIAL STRENGTH (FOAM), CNC MILLING LIMITATIONS AND MILLING DIRECTION AND TEXTURE. UTILIZING THE GIVEN GEOMETRY OF A TRIFURCATED COLUMN, A GRASSHOPPER DEFINITION WAS DEVELOPED TO CREATE PRECISE FORMWORK THAT COULD THEN BE ADAPTED TO MORE ELABORATE GEOMETRIES.

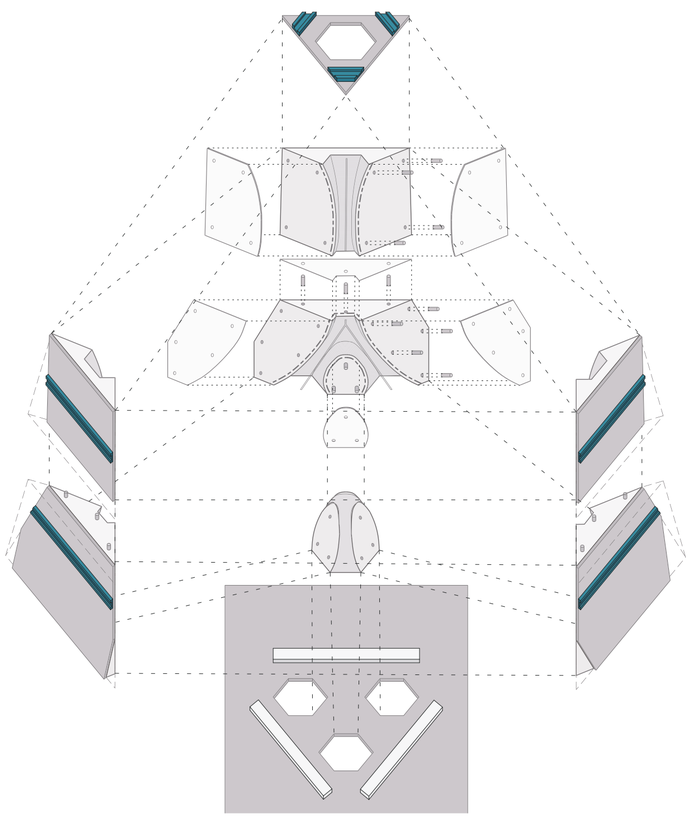
A KEY PARAMETER WAS DETERMINING A MINIMUM THICKNESS OF FOAM REQUIRED FOR CASTING CONCRETE. THROUGH AN ANALYSIS OF THE XPS FOAM'S COMPRESSIVE STRENGTH, DURABILITY AND MATERIAL TESTING, IT WAS CONCLUDED THAT THE MINIMUM THICKNESS OF THE FOAM AROUND THE GEOMETRY SHOULD BE 1.25" TO 1.50" IN ORDER TO CAST CONCRETE WITHIN IT. THE FORMWORK'S EXTERIOR GEOMETRY WAS DESIGNED TO ALLOW FOR PLYWOOD REINFORCING THAT WOULD WORK AS SCAFFOLDING, A STRONG SURFACE TO APPLY EVEN PRESSURE ONTO, AND AID FOAM DURABILITY.

WITHIN THE GRASSHOPPER DEFINITION, THE CENTER LINE GEOMETRY AND POINTS OF INTERSECTION OF THE TRIFURCATING FORM WERE USED TO CREATE IRREGULAR CUTTING PLANES THAT WERE THEN JOINED TO DISSECT THE OVERALL FOAM BLOCK. TO ACCOUNT FOR THE POTENTIAL FOR BLOCKAGE IN THE CENTER JOINT, THE FORMS WERE DESIGNED TO BE POURED IN TWO PARTS. THIS ALSO ALLOWS FOR THE NODES TO BE PROPERLY ALIGNED INSIDE THE FORMWORK AND VISUALLY INSPECTED PRIOR TO POURING. THE RESULTING FORMWORK CONSISTS OF SEVEN PARTS - SIX EXTERIOR FORMS AND ONE STATIONARY PIECE IN THE MIDDLE.

## ADDITIONAL CONSIDERATIONS







### FOAM DURABILITY AND SCAFFOLDING

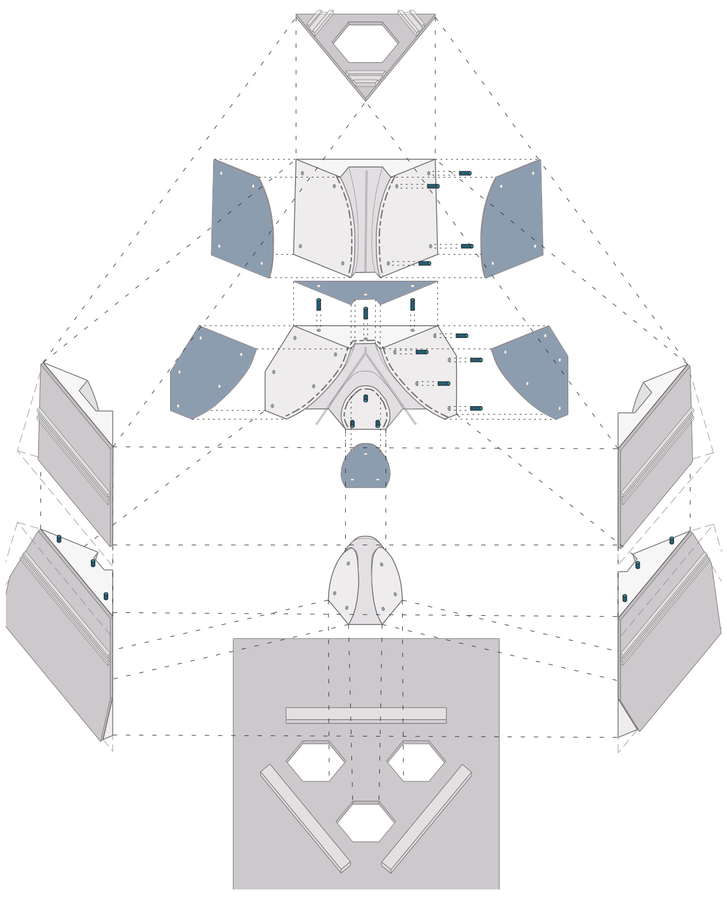
IN ORDER TO MAXIMIZE THE DURABILITY OF THE FOAM MOLDS, THE EXTERIOR OF ALL FOAM PIECES WILL BE PROTECTED WITH PLYWOOD SHEETS. THIS ALLOWS EVEN PRESSURE TO BE APPLIED TO THE FORMS TO ENSURE TIGHT SEAMS IN THE CONCRETE WITHOUT DAMAGING THE FORMS WITH THE RATCHET STRAPS.

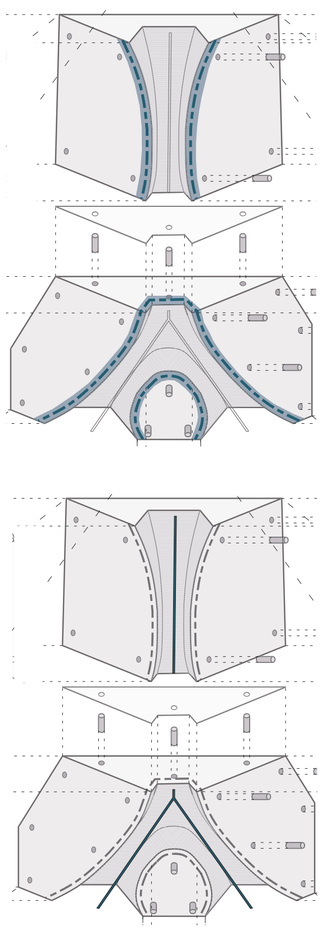
### REMOVAL OF EXCESS MATERIAL

THE SIMPLE ORTHOGONAL FORMWORK THAT RESULTED FROM THE GRASSHOPPER DEFINITION CONTAINED MANY AREAS WHERE THE HIGH DENSITY FOAM EXCEEDED THE REQUIRED THICKNESS FOR CASTING CONCRETE. TO MINIMIZE WASTE OF MATERIAL, THE FORMWORK WAS SUBDIVIDED TO CREATE CUTTING PLANES ALLOWING FOR THE REMOVAL OF EXCESS MATERIAL.

### APPLYING PRESSURE

RATCHET STRAPS ON THE EXTERIOR OF THE FORMS APPLY THE NECESSARY PRESSURE TO CAST CONCRETE. AS EVIDENT ON THE 2D PLASTIC FORMWORK, CONCRETE EXERTS A GREAT AMOUNT OF PRESSURE, PARTICULARLY AT THE BASE. RATCHET STRAPS WILL FIT ON TRACKS ATTACHED TO THE PLYWOOD SCAFFOLDING AND WILL BE TIGHTENED PRIOR TO POURING.





### CONNECTING: HOW THINGS KEY TOGETHER

DISCREPANCIES IN THE ALIGNMENT OF SEAMS CAUSED NUMEROUS PROBLEMS WHEN TESTING THE FOAM PIECES. ONE OF THE PRECEDENTS RESEARCHED, THE ZOLLHOF TOWERS, UTILIZED PVC PIPES RUNNING THROUGH THE FOAM FORMS TO PROPERLY ALIGN THE SEAMS. HOWEVER, THE TOOLS AVAILABLE TO US WERE UNABLE TO DRILL HOLES DEEP ENOUGH AND WITH THE PRECISION REQUIRED TO UTILIZE PVC PIPES, INSTEAD 1/2" WOODEN DOWELS ARE TO BE INSERTED INTO THE FOAM TO ACT AS KEYS BETWEEN THE PIECES. TEMPLATES ARE TO BE USED TO PROPERLY ALIGN ALL KEYS, AND HOLES IN THE FOAM WILL BE COATED WITH EPSILON TO PROTECT IT FROM DAMAGE. EVERY FORM WILL HAVE THREE TO FOUR KEYS ON ALL SIDES THAT CONNECT TO ANOTHER PIECE OF FOAM.

### DETERMINING WATER TIGHTNESS

ATTEMPTS TO IMPROVE THE APPEARANCE OF SEAMS BETWEEN THE FORMWORK PIECES WAS CONDUCTED USING XPS FORMS COATED WITH EPSILON. SEAMS WERE NOTICEABLE AROUND THE EDGES OF THE FORMS DUE TO POOR ALIGNMENT OF PIECES, BUT MORE IMPORTANTLY, IT WAS EVIDENT THAT THE ISSUE OF WATER TIGHTNESS NEEDED TO BE RESOLVED AS OUR FORMS WERE SEEPING WATER AT THE SEAMS. SCULPTEX MODELING CLAY WAS RECOMMENDED FOR THIS ISSUE AND WILL BE UTILIZED ON ALL SEAMS OF THE FIRST CAST.



### LOCATING REBAR

DIVIDING THE FORMS THROUGH THE CENTER OF THE GIVEN GEOMETRY PRODUCED THREE FORMS, WHICH WERE THEN SPLIT IN HALF TO IMPROVE REBAR AND NODE PLACEMENT. THE DIVISION OF FORMS ALLOWS FOR THE REBAR AND NODE STRUCTURE TO BE ASSEMBLED OUTSIDE THE FORMWORK AND THEN SECURED TO PLYWOOD "FEET" THAT CAN THEN BE ENVELOPED BY THE BOTTOM THREE PIECES OF FORMWORK. THE MIDDLE NODE AND TOP REINFORCEMENT WOULD REMAIN EXPOSED WHILE THE CONCRETE IS POURED INTO THE BOTTOM FORMS. UPON COMPLETION OF THE FIRST POUR, THE TOP FORMS CAN BE KEYED AND SECURED IN PLACE USING STRAPS TO SEAL SEAMS BETWEEN FOAM PIECES. TOP NODE AND REBAR ALIGNMENT ARE TO BE ACHIEVED USING A PIN CONNECTION BRIDGING THE TOP NODE TO THE TOP FORMS.



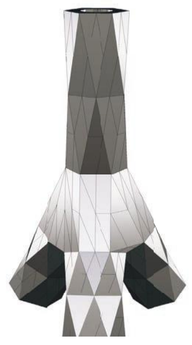
### UNDERSTANDING TEXTURE

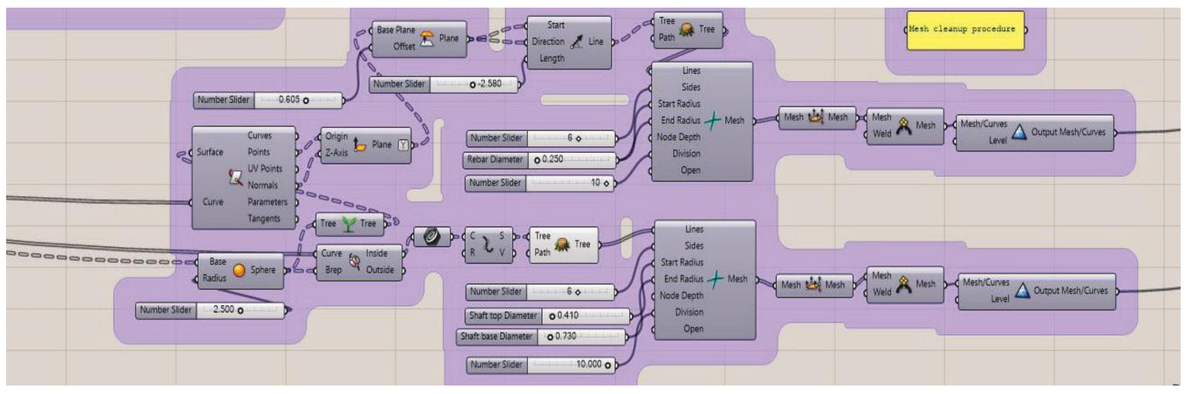
IN ORDER TO REDUCE MILLING TIME AND MASK SEAMS IN THE CAST COLUMNS, THE FORMWORK WILL BE ROUGH MILLED USING A 1/2" END MILL BIT AND FINISHED USING A 1/4" BALL NOSE BIT WITH 75% OVERLAP. HYPOTHETICALLY, THE RESULTING SURFACE TEXTURE WILL BE SUBTLE, YET ENOUGH TO HELP HIDE POTENTIAL IMPERFECTIONS.

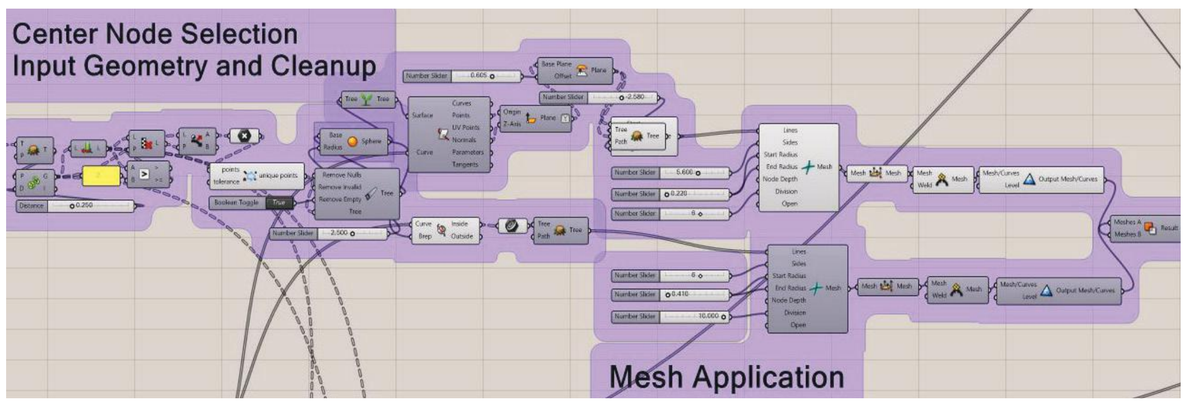
# Digitally Sculpted Branching Manifold Digital Fabricaton

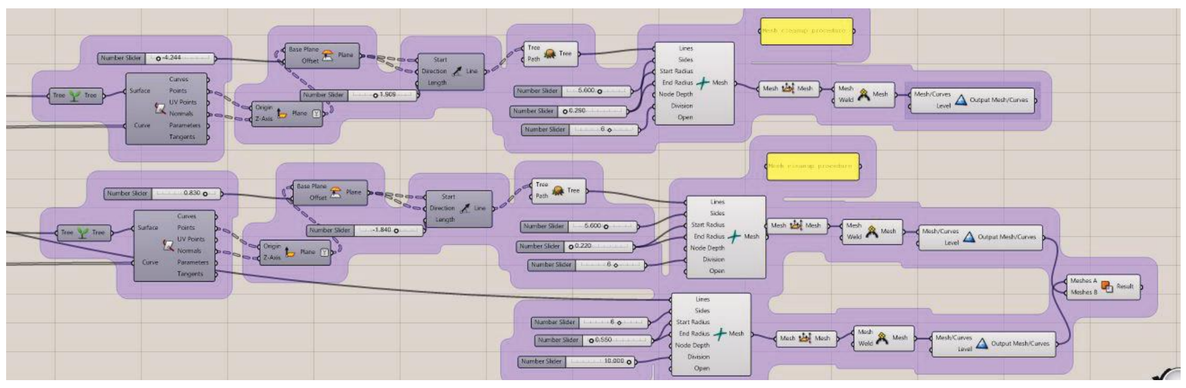
## Node Development

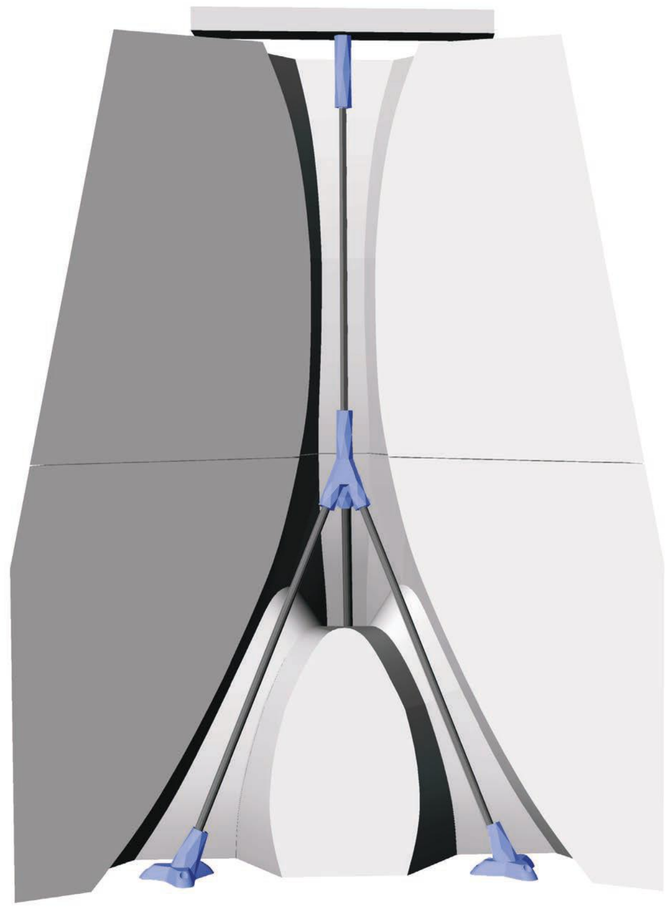
### Structural Node Fabrication







THE NODES CREATED FOR THE BRANCHING MANIFOLF FORMWORK CONTAIN THE SAME WEAVERBIRD TRIANGULATED MESH AS THE NODES DEVELOPED IN THE INITIAL RESEARCH AND DEVELOPMENT. THE DEFINITION HAS BEEN RE-WRITTEN TO ACCOMODATE VARIABLE CHANGE IN SCALE OF GEOMETRY. ADDITIONALLY, DESIGN ALTERATIONS HAVE BEEN MADE TO MITIGATE THE DIFFICULTIES FACED IN PREVIOUS RESEARCH SUCH AS A LARGE TOP NODE HINDERING A STEADY CONCRETE POUR AND INADEQUATE BOTTOM NODES FOR STABILITY.

### Node Testing Research

NYLON PLA ABS

| Material | Tensile Strength | Compressive Strength | Flexural Strength |
|---|---|---|---|
| | ASTM D638 TYPE IV | ASTM D695 | ASTM D790 |
| | STANDARD / MAX | STANDARD / MAX | STANDARD / MAX |
| | | | |
| NYLON | 5,600 PSI / 6,6550 PSI | 7,400 PSI / 7,900 PSI | 8,800 PSI / 9,700 PSI |
| PLA | 6,783 PSI / 9,531 PSI | 2,600 PSI / 13,600 PSI | 8,970 PSI / 13,731 PSI |
| ABS | 4,936 PSI / 5532 PSI | 1,100 PSI / 7,100 PSI | 5,344 PSI / 8,646 PSI |

PRINT SETTINGS
EXTRUDER TEMPERATURE: 235-270° C
BED TEMPERATURE: 60-80° C
BED ADHESION: PVA BASED GLUE

NYLON MUST BE PRINTED WITH A SPECIFIC 3D PRINTER SO PRINTING OF THE TEST NODES WAS OUTSOURCED TO TRILLIANT SYSTEMS. WE LOST EXECUTIVE CONTROL OF PRINT ORIENTATION AND SETUP.

PRINT SETTINGS
EXTRUDER TEMPERATURE: 180-220° C
BED TEMPERATURE: 20-55° C
BED ADHESION: BLUE PAINTER'S TAPE

PLA WAS PRINTED ON A FLASHFORGE 3D PRINTER AND LAMINATED WELL. THE ONLY INCONSISTENCY IS WHEN THE PRINT WAS BUILDING UNSUPPORTED DIAGONALS. BOTH NODES WERE PRINTED SUCCESSFULLY.

PRINT SETTINGS
EXTRUDER TEMPERATURE: 220-235° C
BED TEMPERATURE: 80-110° C
BED ADHESION: KAPTON/HAIRSPRAY

ABS REQUIRES HIGHER TEMPERATURE TO PRINT BOTH IN PLATE, EXTRUDER AND ROOM TEMPERATURE. ATTEMPTED ABS PRINTS FROM THE FLASH FORGE 3D PRINTER FAILED 20-45% THROUGH THE PRINT.

WE WILL BE TESTING TWO DIFFERENT MESH SCALES TO RECORD IF THEY AFFECT THE STRUCTURAL PROPERTY OF THE NODE IN ADDITION TO SAVING 30% OF 3D PRINT PRODUCTION TIME.

THE MOST COMMON TESTING MACHINE USED IN TENSILE TESTING IS THE UNIVERSAL TESTING MACHINE. THIS TYPE OF MACHINE HAS TWO CROSSHEADS; ONE IS ADJUSTED FOR THE LENGTH OF THE SPECIMEN AND THE OTHER IS DRIVEN TO APPLY TENSION TO THE TEST SPECIMEN. THERE ARE TWO TYPES: HYDRAULIC POWERED AND ELECTROMAGNETICALLY POWERED MACHINES

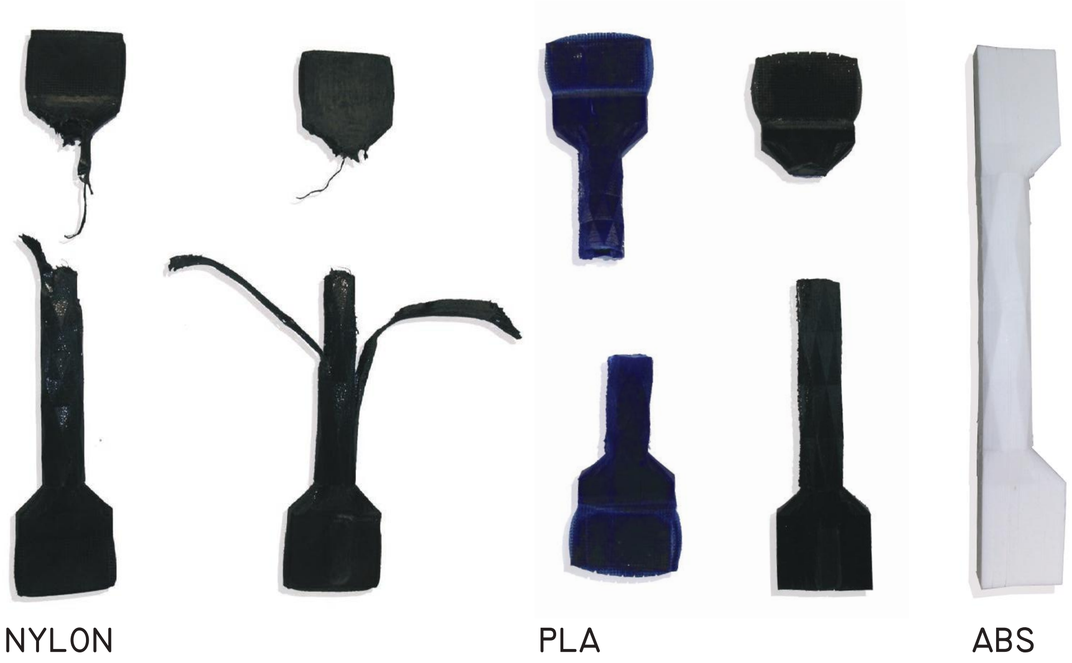
### ASTM Standards For Tensile Testing:

11.3.2 Nominal Strain: Nominal strain is the change in grip separation relative to the original grip separation expressed as a percent. Nominal strain is calculated using the apparatus described in 5.1.7.

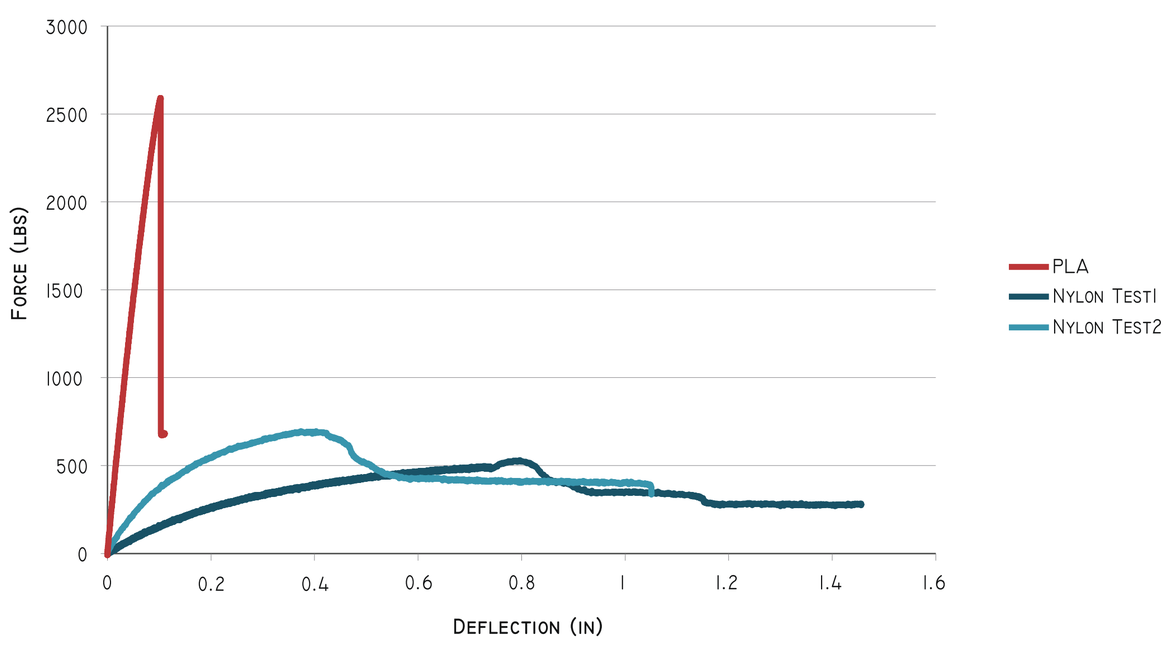
11.3.2.1 Nominal strain at break: Calculate the nominal strain at break by reading the extension (change in grip separation) at the point of rupture. Divide that extension by the original grip separation and multiply by 100.

11.4 Modulus of Elasticity: calculate the modulus of elasticity by extending the initial linear portion of the load-extension curve and dividing the difference in stress corresponding to any segment of section on this straight line by the corresponding difference in strain. All elastic modulus values shall be computed using the average original cross-sectional area in the gage length segment of the specimen in the calculations. The result shall be expressed in pascals (pounds-force per square inch) and reported to three significant figures.

### Testing Results



NYLON PLA ABS




When tensile testing the nodes, the compression caused by the clamps set to 55 Kips far exceeded the compressive strength of PLA, the force caused a break on the shaft of the PLA Test nodes and tensile data could not be collected. Adding a manual clamp to the machine allowed for a less forceful grip and the tensile data above was collected.
The nylon has a more elastic quality and stretched up to 2 1/2" before separation.

ARCH 5670-003
Cameron Martin | Miriela Rico | Renee French

Digitally Sculpted Manifold Branching Structures

# Digitally Sculpted Branching Manifold Physical Construction

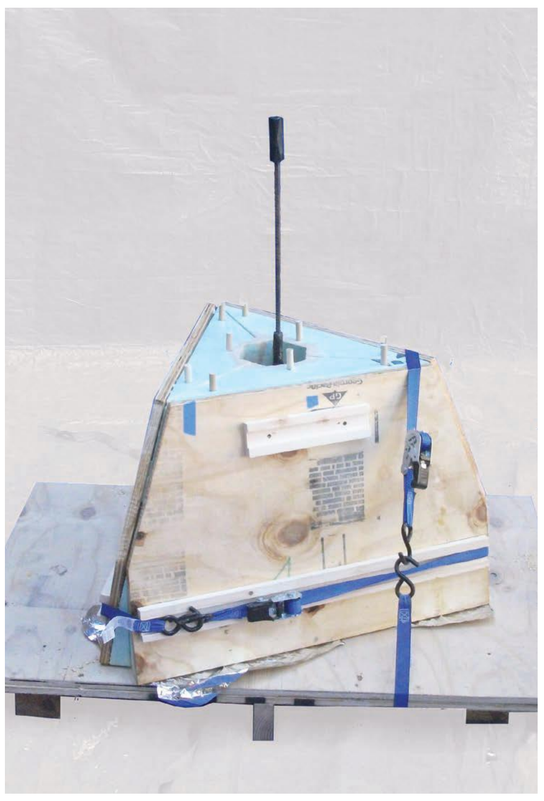
## Construction & Casting - Prototype I

### Formwork Preparation & Prototype I

POSITIONING OF REBAR AND NODES

REBAR POSITIONING IN FORMWORK

PROTOTYPE I



FIRST POUR

COMPLETE FORM ASSEMBLED & CAST

FORMWORK AFTER FIRST CAST

## Prototype I Conclusion

CASTING OF THE FIRST COLUMN IN THE FOAM FORM WAS RELATIVELY SUCCESSFUL, THOUGH THERE WERE ISSUES THAT NEED TO BE ADDRESSED FOR FUTURE CASTS TO BE IMPROVED.

### Concrete Quality

REGULAR QUIKCRETE MIXED AS SPECIFIED BY THE MANUFACTURER WAS USED FOR THE CAST OF THE FIRST COLUMN BUT THE RESULTING SURFACE QUALITY WAS INFERIOR. AGGREGATE AND SAND SANK TO THE BOTTOM, AND THERE WERE A NUMBER OF AIR POCKETS THROUGHOUT THE FORM. A DIFFERENT MIX SHOULD BE USED FOR THE NEXT CAST, AND THE FORM SHOULD BE VIBRATED THOROUGHLY AFTER POURING.

### Water Tightness

WATER ESCAPED FROM THE BOTTOM AND MIDDLE SEAMS DUE TO INCONSISTENCIES IN MILLING. THESE POINTS OF INTERSECTION REQUIRE ADDITIONAL ATTENTION AND SHOULD BE BETTER SEALED FOR FUTURE CASTS.

### Form Locking/Disassembly

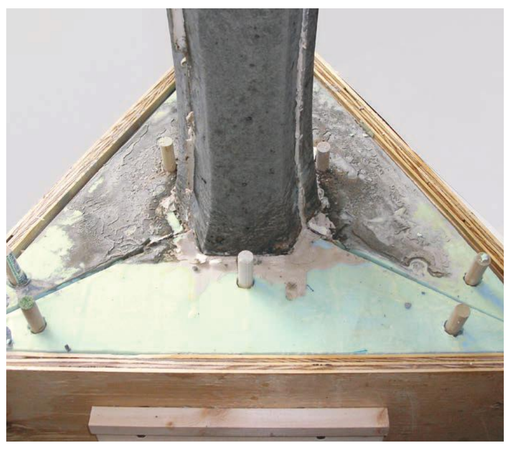
THE FORMS WERE LOCKED INTO PLACE ONCE CAST BECAUSE THE MIDDLE PEGS HOLDING THE TOP AND BOTTOM PIECES TOGETHER MADE IT DIFFICULT TO PULL THE FORMS HORIZONTALLY. HOWEVER, THE MALLEABILITY OF FOAM ALLOWED FOR THE FORMS TO BE FORCED AWAY FROM EACH OTHER.

### Pegs

THOUGH THE WOODEN PEGS WORKED WELL FOR ALIGNING ALL THE PIECES TOGETHER, THEY WERE DIFFICULT TO SET IN PLACE.

### Middle Piece Disassembly

ONCE THE FORM WAS CAST AND HARDENED, THE MIDDLE PIECE SHAPING THE INNER PORTION OF THE LEGS WAS LOCKED INTO PLACE DUE TO THE WIDENING OF THE FEET ON THE GEOMETRY. DDITIONAL CUTS WERE MADE TO THE PIECE TO DISASSEMBLE IT.



LEAKAGE AT MIDDLE SEAM

AGGREGATE ACCUMULATION AT BASE

CENTER PIECE AFTER SLICING FOR REMOVAL FROM FORM.

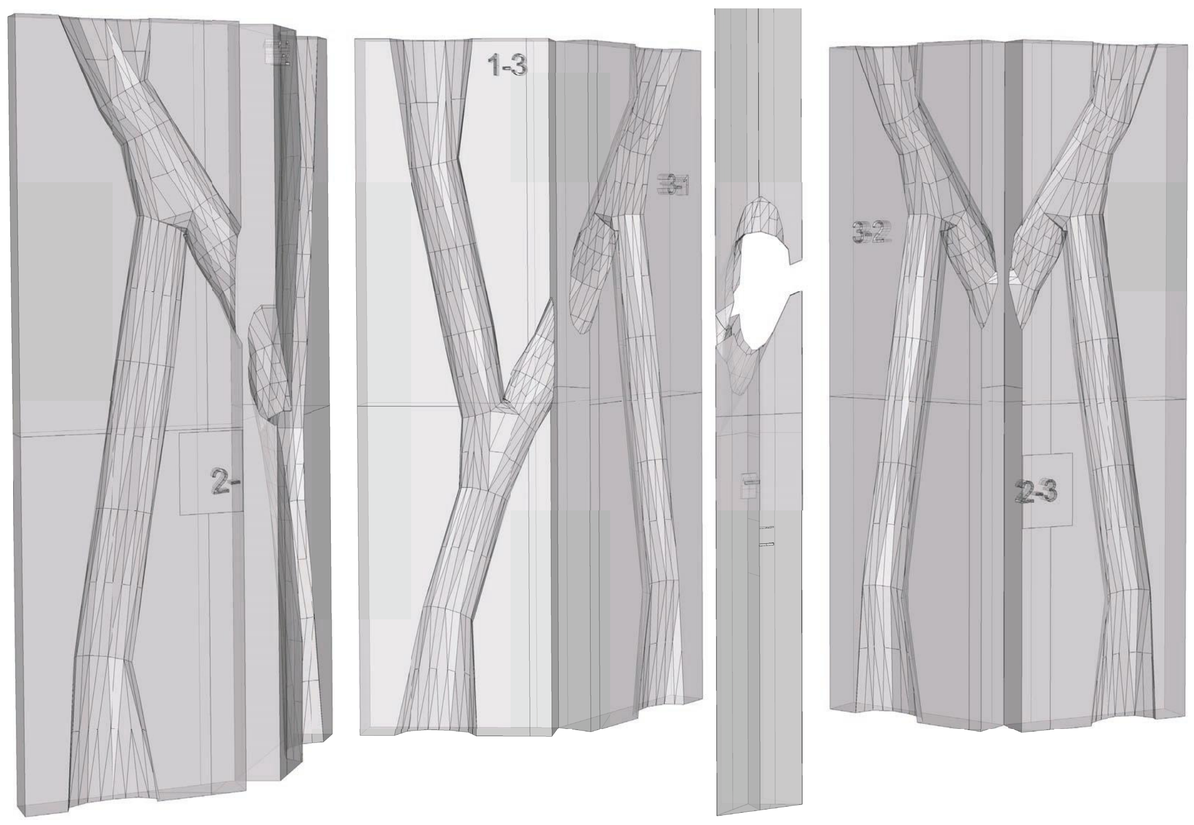
ARCH 5670-003
Cameron Martin | Miriela Rico | Renee French

Digitally Sculpted Manifold Branching Structures

# Digitally Sculpted Branching Manifold Digital Fabricaton

## Formwork Development - Prototype II

### Digital Formwork Fabrication




For Prototype II, we revisited the three-legged branching column developed during the fabric mesh formwork testing done in a prior research project. The new form had unique challenges that prototype I did not have such as additional joints, reduction in column diameter, and alignment issues between the top and bottom legs for column stacking.

Slight modifications were made to the developed geometry to address issues encountered by prior research and also to make it possible for the columns to be stacked. Column joints were widened to improve the flow of concrete around the nodes and rebar structure. The bases and tops of the columns were also modified to shift the direction of loads from one column to the other when stacked.

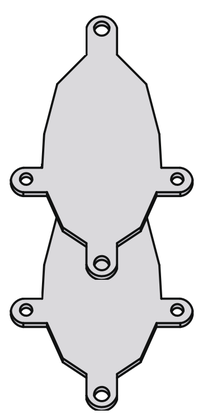
In the development of the formwork, the branching geometry was split to allow the use of rectilinear formwork that would surround each leg and be divided along a central cutting plane. Originally, the formwork consisted of six pieces, two for each leg, with a wedged end encompassing the center connection shared by all three columns. However, this design did not take into account that the formwork would be locked in place after casting because the wedge centers would not allow for the angle needed to pull off the formwork cleanly while preserving it for another cast.

The design was then modified to make the central joint its own piece split in two parts. This middle piece was then to be compressed into place by the six exterior pieces of formwork. Plywood backing was applied to the rectilinear forms but rather than relying on wooden pegs and ratchet straps for alignment and compression, bolts were used to regulate compressive force uniformly around the formwork and ensure alignment of the legs.

### Node Fabrication

#### Modification of Nodes

The node definition used on prototype I was compatible with prototype II but needed to be altered to meet the new parameters. For example, the center nodes for the new geometry did not need to have four connections intersecting like in the prototype I geometry. By altering the definition integer value to three, the three center intersections in the prototype II centerline geometry were detected and nodes were generated. Additionally, the prototype II geometry is to be cast twice not only to test the reusability of the formwork but also to test the ability of the form to be stacked. Steel plates would be used to create a level platform that the two forms could be joined and bolted together. To allow for nodal attachment to the top plates on the bottom form, a design like the one for the base nodes is needed to be applied to the top nodes but inverted. The base for the top nodes is then rotated about the centerline geometry to set the bolt holes. Both the top nodes of the first form and the adjoining base nodes from the second form coincide in alignment.



#### Connecting Plates

The steel plates are designed to create a strong and level platform so that the two cast columns can be stacked upon one another and bolted into alignment. These plates mimic the shape of both the heading and footing of the geometry. In the previous geometry developed by the fabric formwork team, the footing at the bottom of the geometry and the top of the geometry align vertically but do not align in footprint due to the relaxation mesh that was applied to replicate a fabric exterior. To address this inconsistency, the geometry needed to be altered to have the same footprint at the top and bottom of the column legs. This alteration served two purposes: to make the forms stackable, and to widen the footprint and create a larger area for the service loads to be distributed down onto. The resulting footprint resembles an egg shape, a rounded semi-circle on the exterior of the leg and a subtle transition to an ovoid that narrows to a smaller radius on the interior of the leg. These plates are to be sculpted to match the footprint of the column and align into a clean edge with each other.

#### Center Piece Development

A center form piece was developed due to an oversight in the first design of the formwork. Similar to the bottom piece of prototype I, the center piece addresses a complication in the geometry where the three legs are connected. It is a critical joint that determines the structural ability of the geometry. Casting of this joint hindered the success of this geometry in the fabric formwork research. The new central form consists of two equilateral triangular pieces meeting in the center and compressed into alignment by the flat interior ends of the three leg forms.

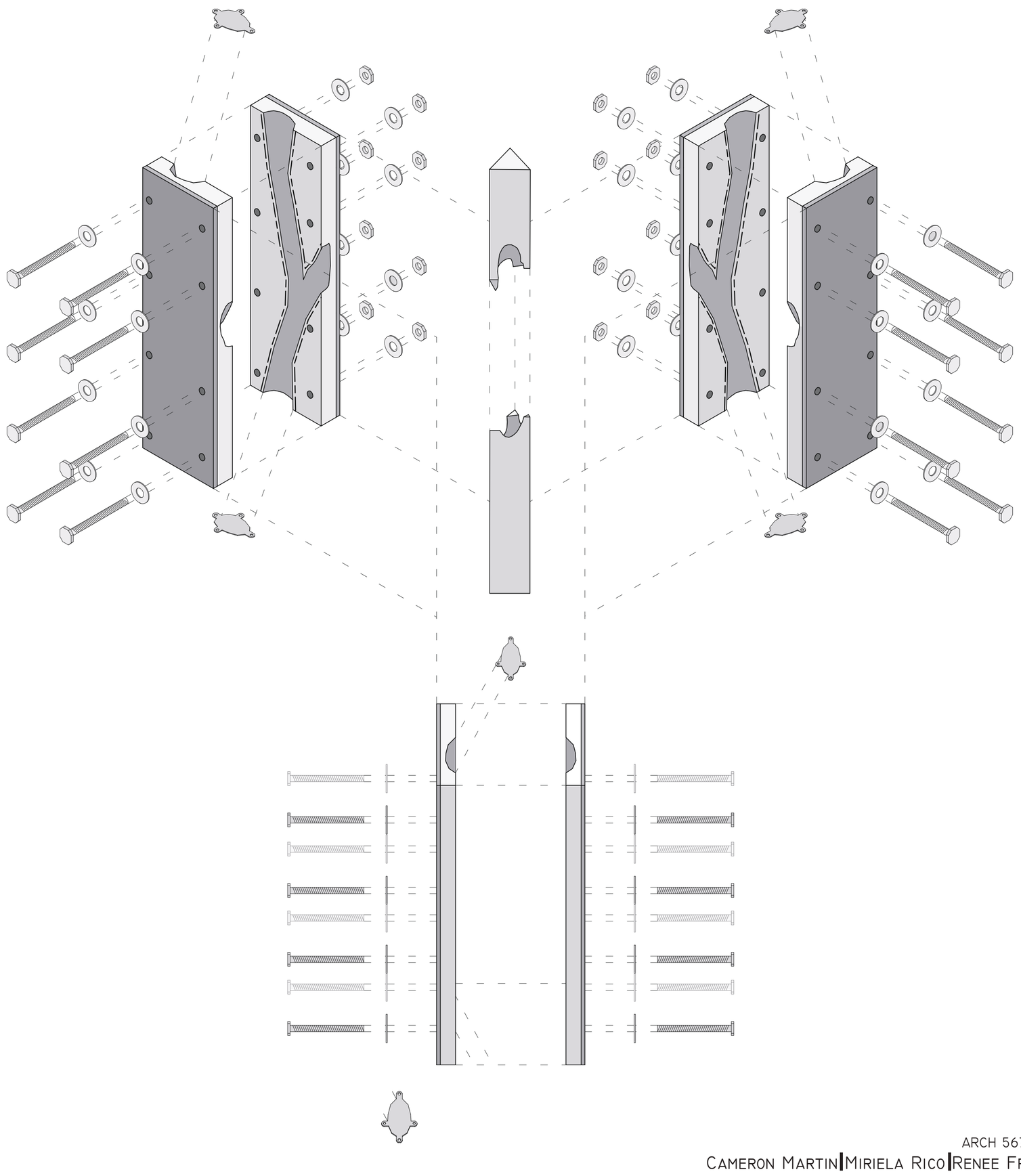
#### Seam Alterations

In the first cast of prototype I, clay was used along the foam seams to not only smooth the geometry but to provide water tightness. The bottom of the formwork did experience leakage of water and cement in spite of the clay. This resulted in exposed aggregate and rough edges around the footing of the column.

This issue is addressed in prototype II via a combination of glad press □n seal and clay that will be used to help seal the seams at the foot of the column. Not only will this strategy potentially protect the formwork from a blowout, but it will also keep the water inside the formwork.

#### Bolt Connections

The wooden pegs used in the formwork of prototype I aided in the alignment of multiple pieces of formwork simultaneously. This idea is taken a step further in prototype II by utilizing bolts instead of pegs to align the formwork and also to aid in compression to ensure water tightness and minimize seams. Bolts will be placed systematically throughout the formwork according to the individual need for compression on each leg. They will be tightened with washers and nuts to the exterior of the formwork. A plywood backing of 3/8□ will help add rigidity to the exterior face of the formwork to allow tightening of the bolts and act as a diaphragm for the distribution of the force from a point load to the entire exterior face of the formwork.



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Digitally Sculpted Manifold Branching Structures

# Digitally Sculpted Branching Manifold Physical Construction

## Construction & Casting - Prototype II

### Formwork Preparation & Prototype II





Prototype II Casting Sequence

Prototype II







Formwork After First Cast

## Prototype II Conclusion

### Water/Cement Ratio

During the first cast of Prototype II, the consistency of the concrete per gate precast's recommendations had less than 1/2" slump and it was believed that the resulting air-pockets in the surface quality of the concrete were due to a lack of fluidity in the concrete when poured. Vibration was applied but large holes are still present on the form. During the second cast, the mix ratio of cement, sand, aggregate and water was altered to produce a 3" slump. The form was vibrated similarly to the first cast. We believed the surface quality of the form would improve, but the results were very similar to the first cast. There were not any pockets that would alter the structural integrity of the column but the percentage of pockets on the surface is the same.

### Alignment of Middle Forms

The alignment of the center top and bottom pieces proved to be more difficult than anticipated. The location of joints of the top and bottom pieces to the rest of the formwork become invisible once inserted through the top of the form. Due to the small diameter of each leg, physical access to the center seam is also restricted. Because of this we had to assume that the digitally sculpted edges would match up accordingly.The release of the cast revealed that the top half of the center formwork had positioned itself too low and the center joint was smaller than intended. During the second cast it was placed 1/4" higher. The inclusion of more clay to secure the seams added to the depth of the top piece and resulted in sitting too high during the second cast.

### Plywood Thickness

The plywood used for the backing of Prototype II was 3/8" thick. The 1/2" used for protype worked well under the compressive stress of the ratchet straps. However, the 3/8" plywood used for Prototype II was subjected to point loads of compression from the washers and 3/8" was not thick enough to keep it from bowing. This did not alter the cast form in anyway but inhibits the reusability of the formwork.

Misalignment

Plywood Bowing

Bugholes

Concrete Slump

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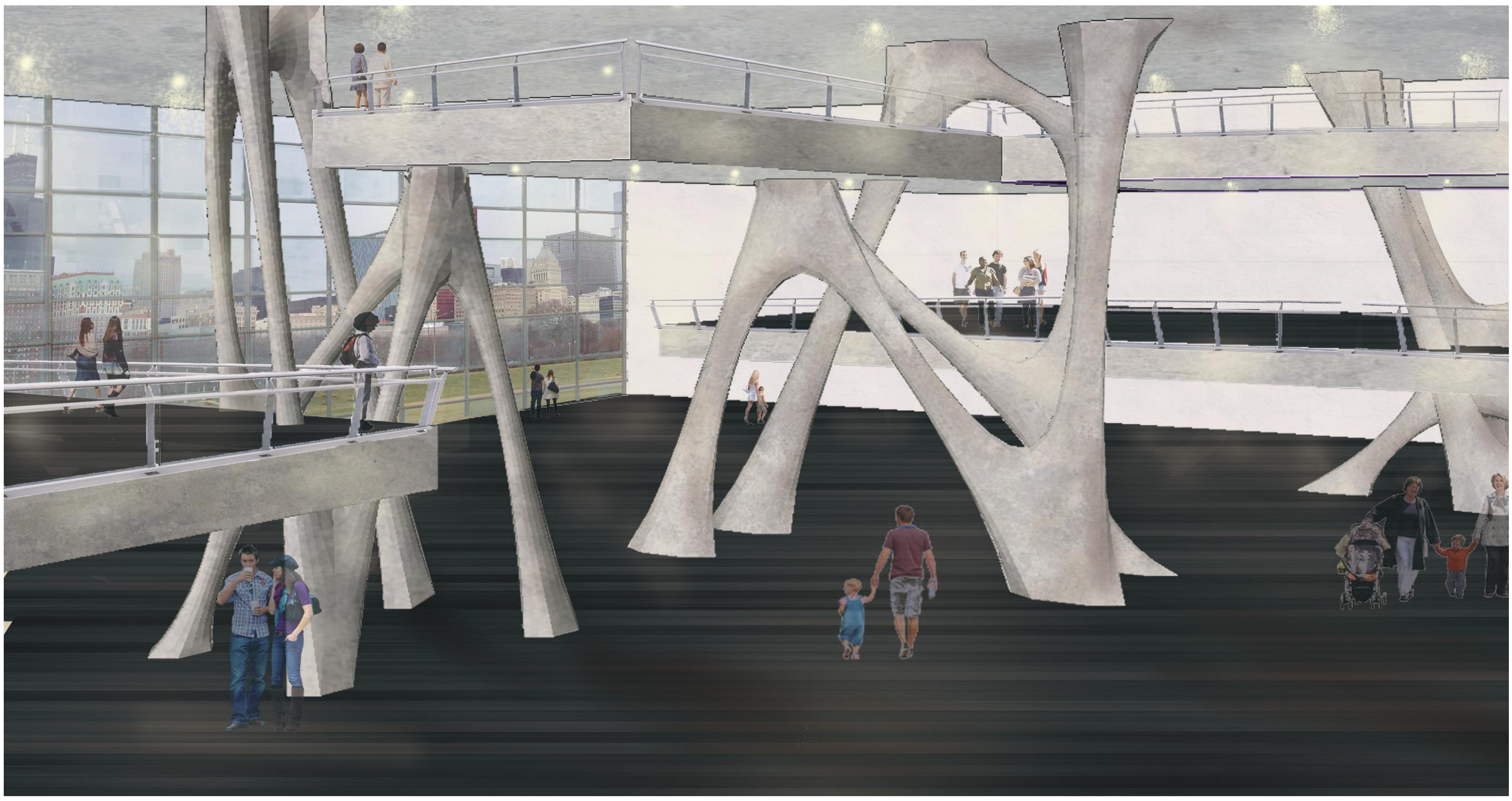
# DIGITALLY SCULPTED BRANCHING MANIFOLD APPLICATION

## ARCHITECTURAL APPLICATIONS

### BRANCHING STRUCTURES



## RESEARCH CONCLUSION

AT THE ONSET OF THIS RESEARCH AGENDA, THERE WERE SEVERAL DEFINED GOALS THAT ADDRESSED TOPICS FROM PAST ITERATIONS OF FORMWORK DEVELOPMENT. THE FIRST GOAL OF THE PROJECT WAS TO CREATE FORMWORK THAT COULD BE USED FOR MULTIPLE CASTS, CREATING CONSISTENCY AND ECONOMY IN FABRICATION AND DEPLOYMENT. THE SECOND GOAL WAS TO CREATE THE FORMWORK FROM INEXPENSIVE MATERIALS IN COMPARISON TO THE TRADITIONAL METHODS OF FORMWORK THAT ARE CURRENTLY BEING USED IN ARCHITECTURAL CONSTRUCTION. THE THIRD GOAL WAS TO SIMPLIFY FORMWORK ASSEMBLY IN ORDER TO AID IN USABILITY AND REPLICATION OF FORM. LASTLY, DIGITAL TOOLS WERE TO BE EASILY ADAPTABLE SO THAT MOST NON-EUCLIDIAN FORMS COULD BE CAST WITH MINIMAL DIGITAL WORKTIME AND EFFICIENT FABRICATION. AFTER TESTING, THE FOLLOWING ASSUMPTIONS CAN BE MADE.

**FORM REUSABILITY**

THE REUSABILITY OF THE FORMWORK WAS STILL POSSIBLE AFTER TWO CASTS AND IT CAN BE ASSUMED THAT IT WOULD BE GOOD FOR AT LEAST FOUR TO FIVE CASTS, IF NOT MORE, WITH MINIMAL FORM CLEANUP AND RECOATING.

**COST**

AFTER PRICING WAS ADDED UP, THE TOTAL COST FOR THE PROTOTYPE I FORMWORK WAS $348.60 AND THE FORMWORK FOR PROTOTYPE II WAS $240.90. IF YOU DIVIDE IT PER CAST, IT IS $87.15 FOR EACH CAST OF PROTOTYPE I AND $60.23 FOR EACH CAST OF PROTOTYPE II. THE MORE REUSABLE THE FORMWORK, THE MORE COST EFFECTIVE IT BECOMES. THIS MAY OR MAY NOT BE MORE AFFORDABLE THAN OTHER CASTING METHODS EXPLORED THROUGHOUT THE LENGTH OF THIS RESEARCH BUT IT IS MORE AFFORDABLE THAN METHODS BEING USED FOR CONSTRUCTION CURRENTLY.

**EASE OF CONSTRUCTION**

THE FORMWORK WAS QUICK TO ASSEMBLE FOR RE-CASTS, BUT THE INITIAL CONSTRUCTION TOOK 12-15 HOURS. THIS IS MUCH MORE EFFICIENT IN COMPARISON TO OTHER METHODS EXPLORED. SET UP TIME WAS CUT BY MORE THAN 65% COMPARED TO THE 2D PLASTIC FORMWORK.

FINALLY, THE DIGITAL SETUP FOR SCULPTING THE FORMWORK AND PRINTING THE CONNECTING NODES WAS APPLICABLE TO BOTH GEOMETRIES WITH MINIMAL DEFINITION ADJUSTMENTS.
THERE WERE SEVERAL IMPORTANT LESSONS LEARNED WHILE CASTING THE FORMS AND METHODS THAT WOULD BEEN DONE DIFFERENTLY IF THIS RESEARCH WAS TO CONTINUE.

**FURTHER DEVELOPMENT**

THE NEXT STEP IN THE TESTING OF THE FORMWORK WOULD BE TO CONTINUE CASTING BOTH GEOMETRIES UNTIL THE FORMWORK BEGINS TO DETERIORATE OR THE RESULTING CAST NO LONGER MAINTAINS CONSISTENT QUALITY. THIS CAN BE DONE WITHOUT RE-COATING THE EPSILON AS IT HAS BEEN DONE FOR THIS PORTION OF THE RESEARCH OR IT CAN BE RE-COATED FOR TESTING OF OPTIMUM USAGE. IT IS ESTIMATED THAT THE FORMS COULD BE USED AT LEAST 4-5 TIMES BUT COULD POTENTIALLY CAST MORE. AFTER THAT, THE DIGITAL DEFINITIONS WOULD NEED TO BE TESTED ON NOT ONLY A MORE COMPLEX GEOMETRY BUT ALSO TO ONE IN A LARGER SCALE.

CONCRETE SURFACE QUALITY OF THE CASTS PRODUCED WAS INCONSISTENT AND CONTAINED MANY AIR POCKETS, SOME OVER 1/2" IN DIAMETER. THIS ISSUE SHOULD BE EXPLORED FURTHER TO TEST WHETHER THIS WAS DUE TO RELEASE AGENTS USED ON THE FORMWORK OR IF THE INTRODUCTION OF AIR ESCAPE HOLES IN THE FORMWORK WOULD BE BENEFICIAL.

**LESSONS LEARNED**

THROUGHOUT THE DEVELOPMENT OF THIS RESEARCH THERE HAVE BEEN SEVERAL IMPORTANT LESSONS LEARNED FROM UNFORESEEN OBSTACLES. UNDERSTANDING THE LIMITATIONS OF RESOURCES AVAILABLE WAS ONE OF THE FIRST OBSTACLES FACED. THE DEPTH OF THE FIRST FORMWORK WAS PROBLEMATIC WHEN MILLED ON THE CNC AND IT WASN'T UNTIL ONE OF THE LAST PIECES WAS BEING MILLED THAT AN ALTERNATE METHOD OF MILLING WAS USED. WHEN MILLING AT A DEPTH OF THREE INCHES RATHER THAN SIX, MILLING WAS SUCCESSFUL. IF THIS DEPTH HAD BEEN IMPLEMENTED FROM THE BEGINNING, THERE WOULD HAVE BEEN LESS PATCHWORK AND PREP FOR THE FORMS OF PROTOTYPE I BEFORE CASTING. PUSHING THE LIMITS OF THE CNC MILL WAS A TIMELY SET-BACK EARLY ON.

THE NEXT OBSTACLE WE FACED WAS THE SCIENCE OF MIXING AND POURING CONCRETE. AFTER THE FIRST CAST THE DIFFERENCE BETWEEN QUIKRETE AND SELF-MIXED CONCRETE CONSISTENCIES BECAME APPARENT. MOVING FORWARD, ALL CONCRETE WAS MEASURED AND MIXED FOR EACH CAST. BECAUSE THESE FORMS ARE BEING CAST VERTICALLY, THE AGGREGATE SINKS UNEVENLY TO THE BOTTOM IF THE MIX IS TOO FLUID. SLUMP BECOMES AN IMPORTANT FACTOR WHEN CASTING VERTICALLY.

THE BASE PLATES FOR THE FIRST GEOMETRY WERE MADE ACCORDING TO THE DIGITAL FILES AND DID NOT TRANSLATE TO THE PHYSICAL MODEL ADEQUATELY. DUE TO OBSTACLES FACED WITH THE CNC MILL AND THE APPLICATION OF EPSILON, THE FORMWORK DID NOT ALIGN WITH THE SAME PRECISION AS THE DIGITAL FILE. FOR THE FOLLOWING CASTS, THE BASE PLATES WERE MADE FROM A HANDMADE TEMPLATE THAT COULD EASILY BE ALTERED TO WORK ACCORDINGLY.

THE CENTRAL PIECE OF THE SECOND PROTOTYPE WAS DIFFICULT TO WORK WITH DUE TO LACK OF VISIBILITY AND CONFIRMATION OF THE SEAM CONNECTIONS. IF THE RESEARCH WERE TO BE CONTINUED, THE ADDITION OF KEYS OR AN ALTERNATE METHOD OF FORM DIVISION WOULD BE EXPLORED TO CAST A MORE CONSISTENT FORM. DUE TO TIME CONSTRAINTS ONLY ONE VARIATION OF THE FORMWORK FOR EACH GEOMETRY WAS EXPLORED.