Topology Optimization Based Additive Construction

ACI Convention Spring 2024

03-24-2024

Jenna Migliorino[1], Aly Ahmed[1], Anthony Mackin[1], Zaid Hanoun[1], and Islam M. Mantawy[2]

[1]Graduate Research Assistant
[2]Assistant Professor

Civil and Environmental Engineering
Henry M. Rowan College of Engineering
Rowan University

Acknowledgement

This work was made possible by a U.S. Department of Education Graduate Assistance in Areas of National Need (GAANN) Grant Number P200A210109.

Acknowledgement

Graduate Students

RU Undergrads Clinic Students

Conventional Construction vs Hybrid Construction vs Additive Construction

Construction industry over the last decades

Comparison of construction techniques between 1950s (left) and 21st century (right).

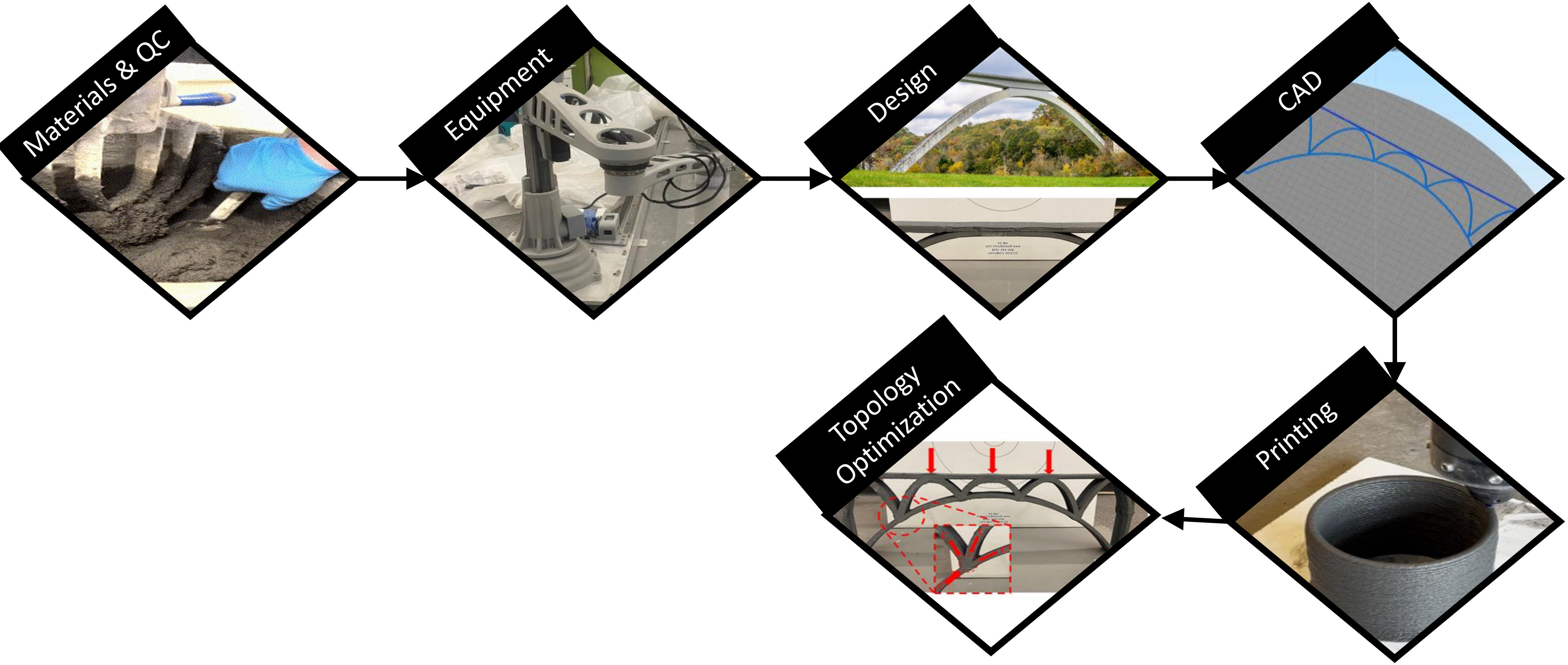
Conventional Construction vs Hybrid Construction vs Additive Construction

Conventional Construction
(forming, reinforcement placement & casting)

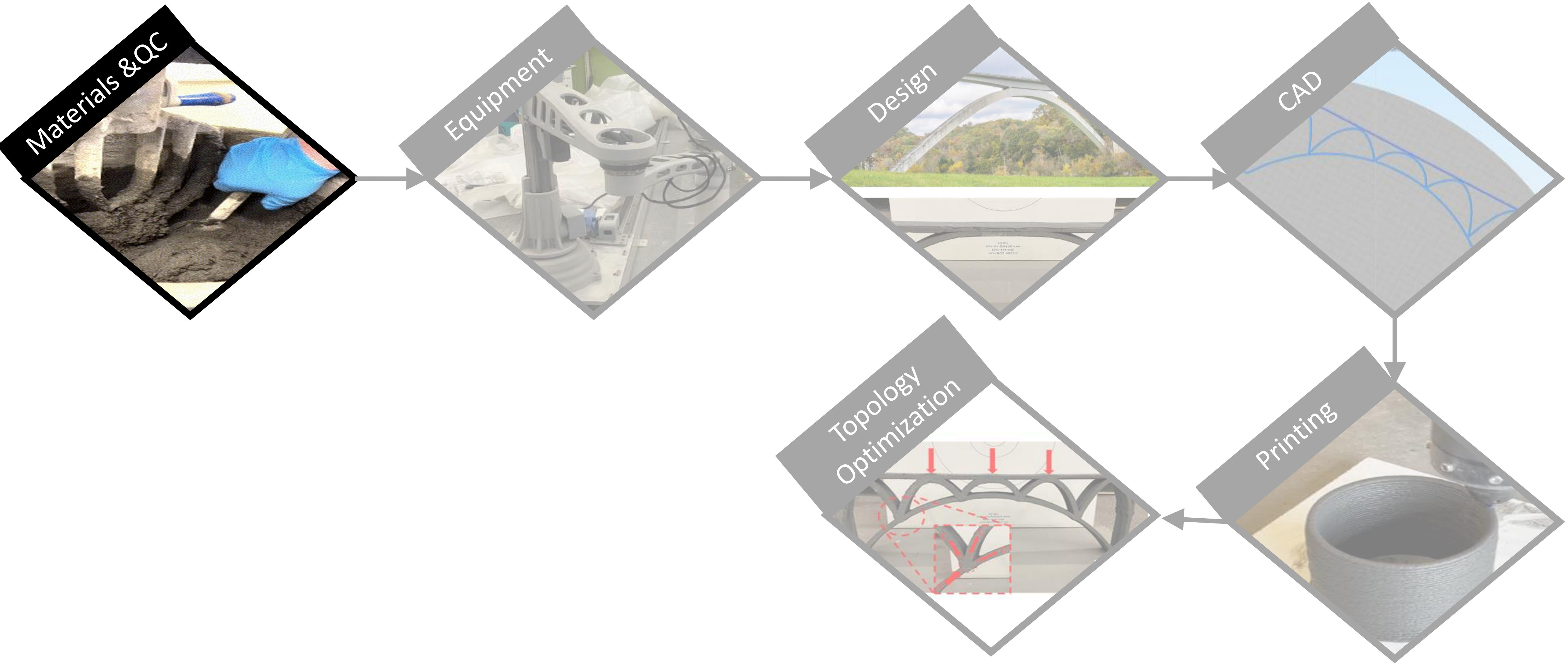
Hybrid Construction
(printing formwork, reinforcement placement & casting)

Additive Construction
with Topology Optimization

Outline of the Presentation



Materials and QC



Materials and QC

Mixes for Additive Construction

- Printability
- Fresh and Hardened Properties
- Shrinkage

Chronology

October 2022

Feb 2023

Oct. 2023

March 2024

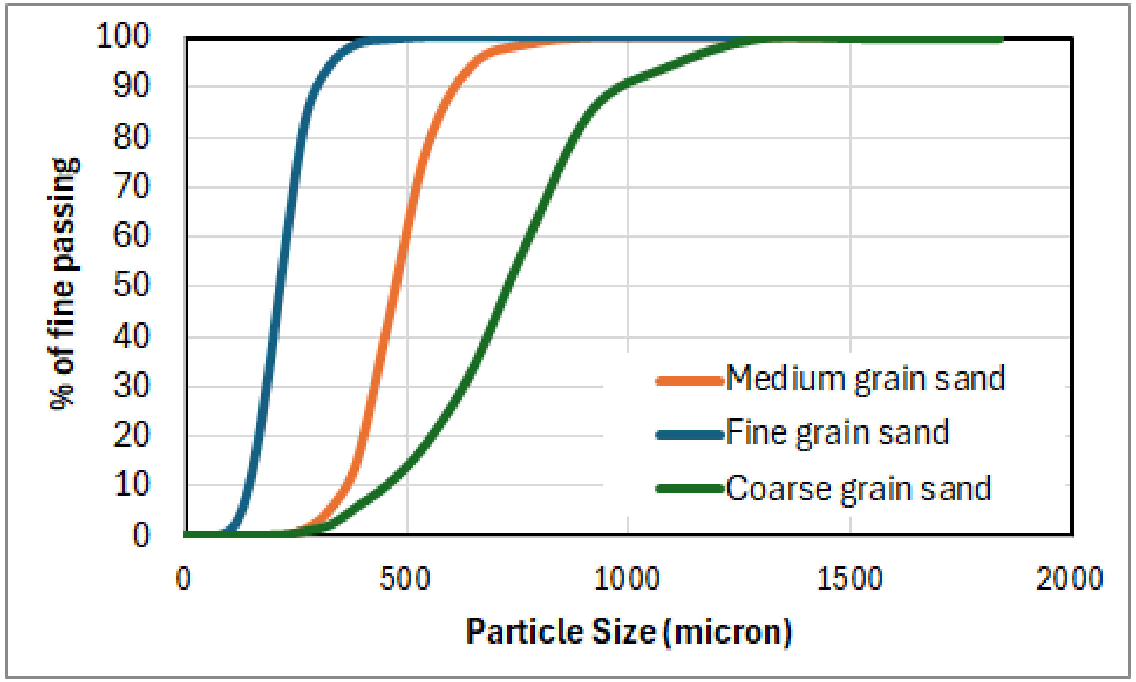
Materials and QC

Mix Ingredients for cementitious based-materials

Element	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3	K_2O	LOI
OPC (%)	16.12	3.58	5.08	65.92	2.85	4.32	1.36	0.77
Fly Ash (%)	15.23	2.90	5.30	66.40	2.90	5.07	1.38	0.82
Silica Fume (%)	96.29	0.133	0.37	1.10	0.26	0.18	0.62	1.05
Type 1 Sand (%)	99.11	--	0.714	0.047	--	0.08	0.04	0.01
Type 2 Sand (%)	95.0	0.09	4.50	0.10	--	--	0.30	0.01

Materials and QC

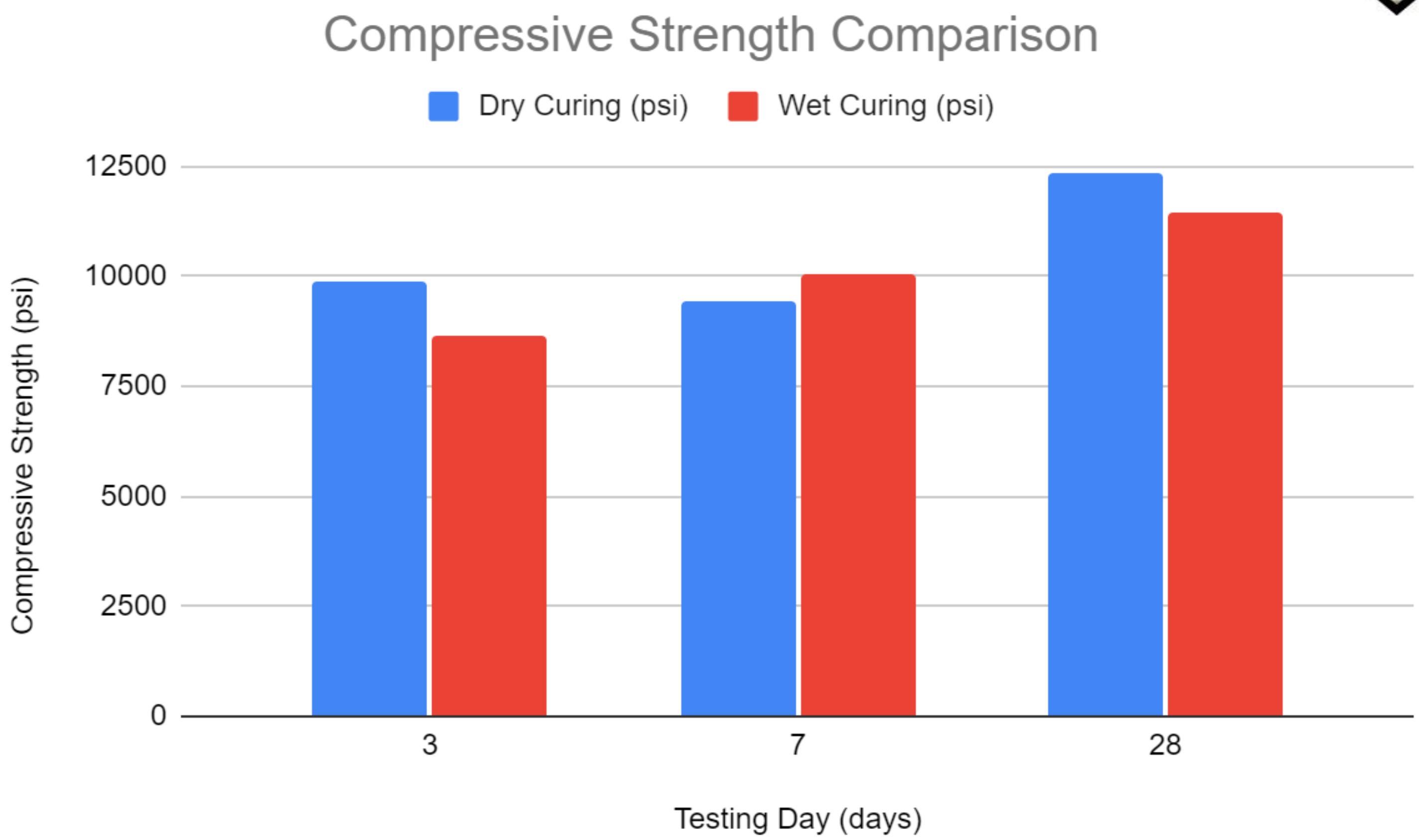
Mix Ingredients for cementitious based-materials



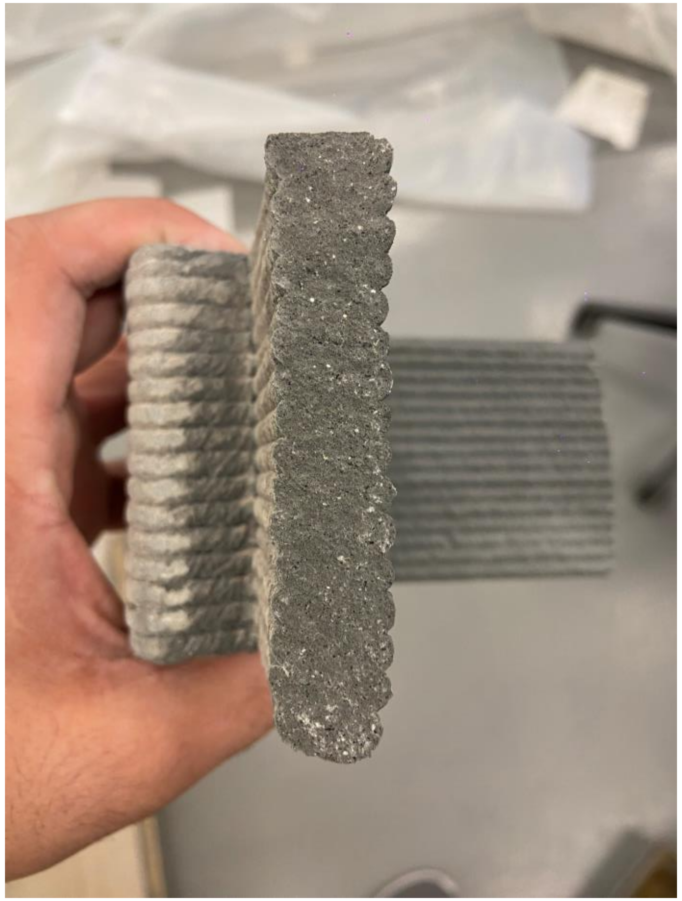
Material Development and QC

Hardened Properties

Compressive Strength
(ASTM C109)

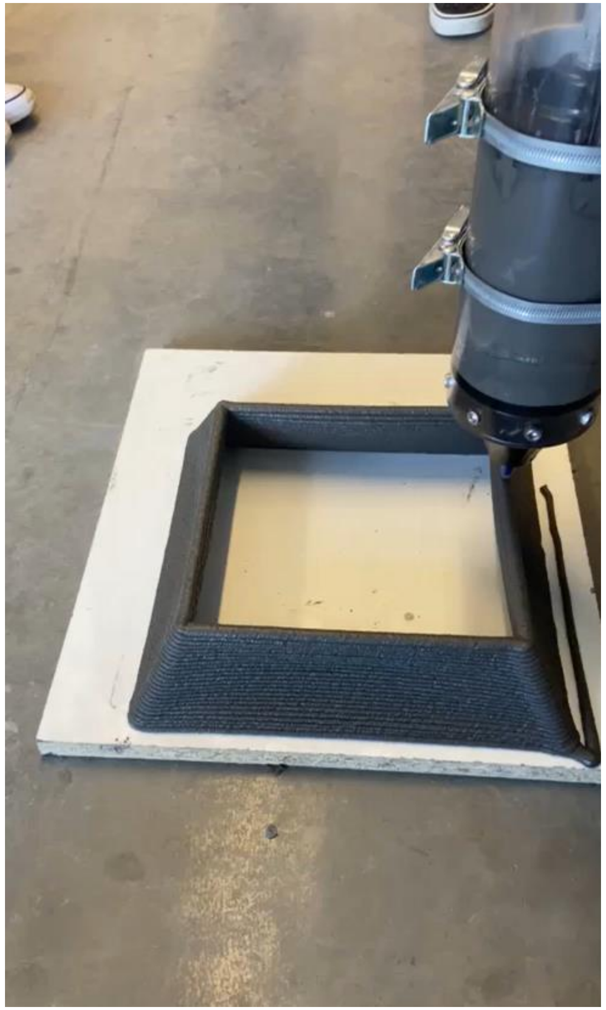


Hardened Properties



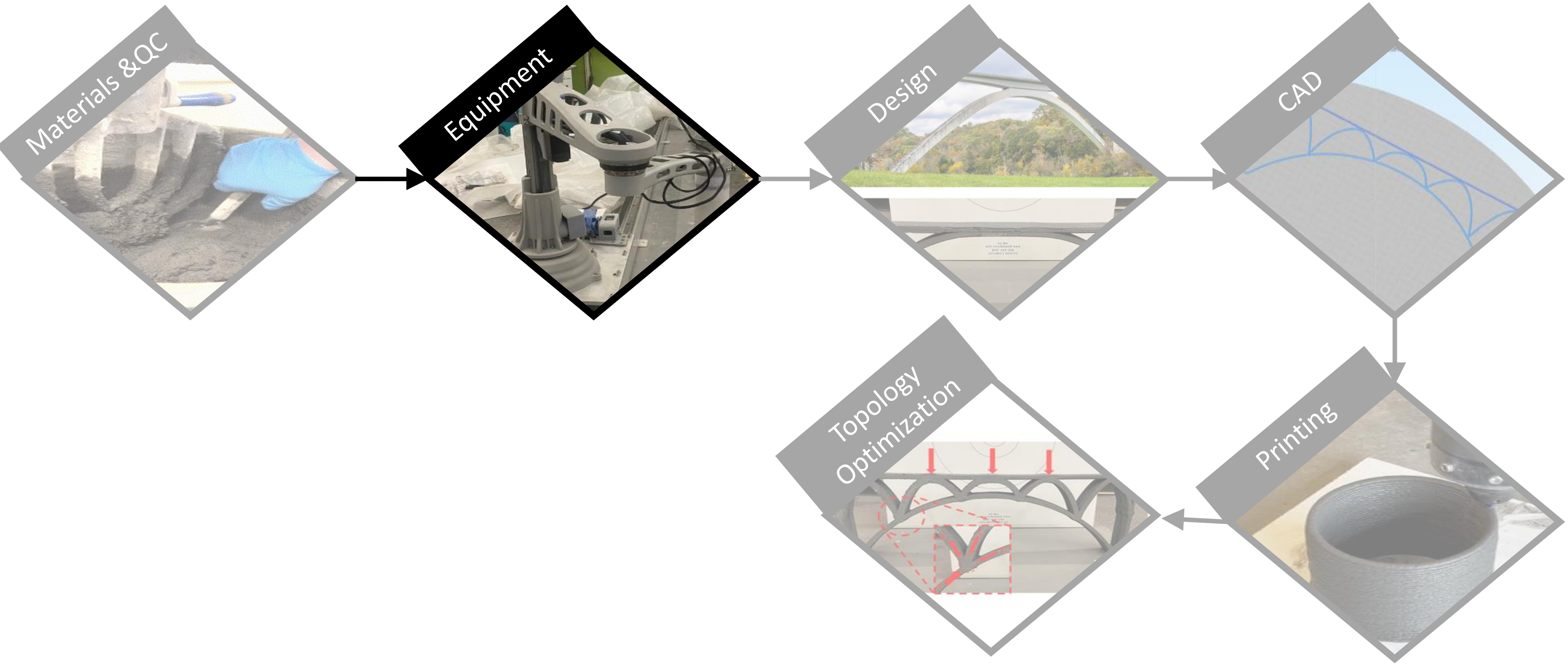
Interlayer Bond

Printability Requirements



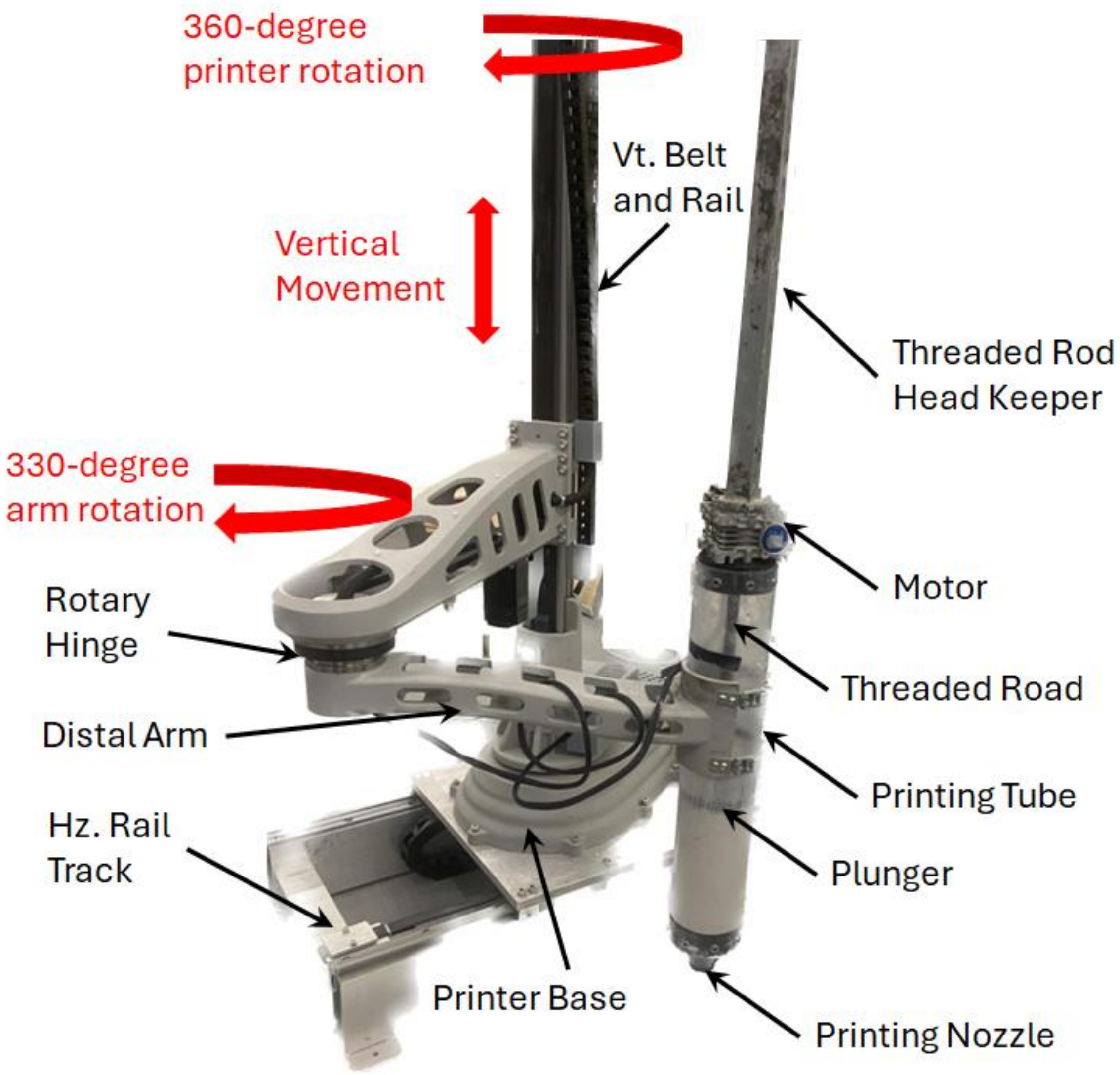
Successful Extrusion and Buildability Failure

Equipment

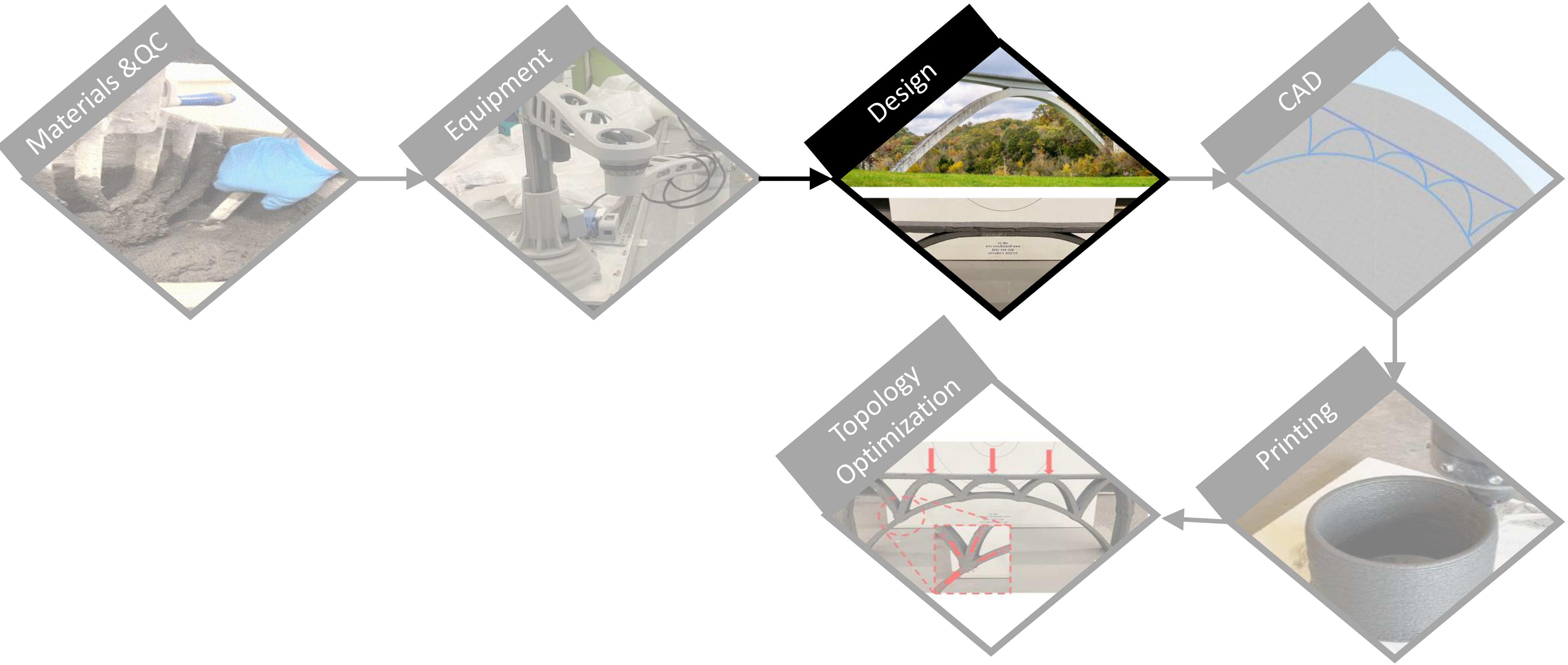

Materials &QC
Equipment
Design
CAD
Topology
Optimization
Printing

Equipment


Equipment

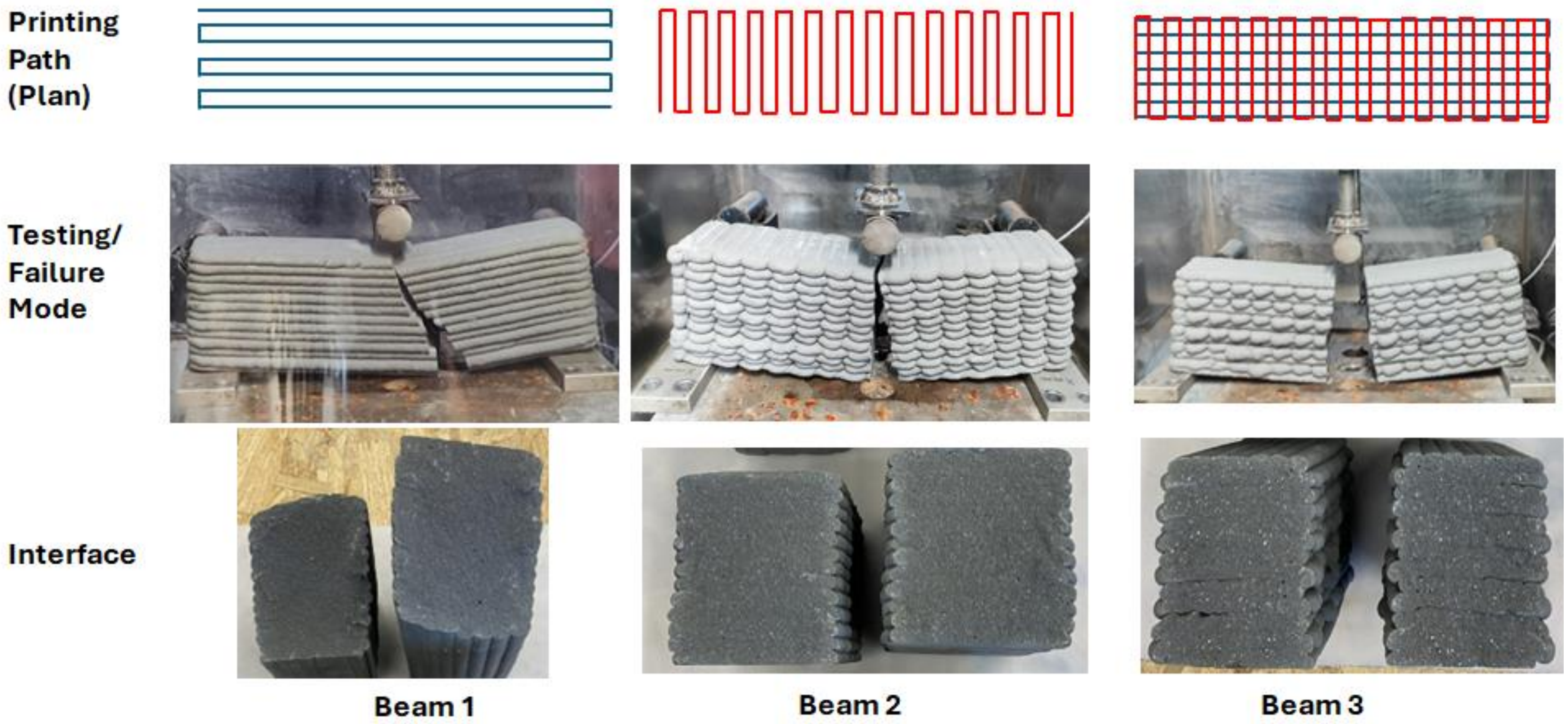

360-degree
printer rotation
Vt. Belt
and Rail
Vertical
Movement
Threaded Rod
Head Keeper
330-degree
arm rotation
Motor
Rotary
Hinge
Threaded Road
Distal Arm
Printing Tube
Hz. Rail
Track
Plunger
Printer Base
Printing Nozzle

Design



Materials &QC
Equipment
Design
CAD
Printing
Topology Optimization

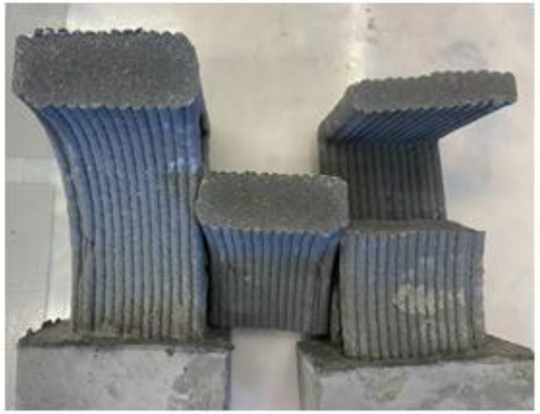
Design Process



ID	Force		Span (L)		Depth (d)		Width (b)		Modulus of Rupture (R)	
	(kips)	kN	inch	mm	inch	mm	inch	mm	ksi	mpa
Beam 1	2.460	10.943	9.25	235.0	3.50	88.9	3.00	76.2	0.929	6.404
Beam 2	2.000	8.896	9.00	228.6	3.50	88.9	3.25	82.6	0.678	4.676
Beam 3	2.880	12.811	9.13	231.8	3.75	95.3	3.00	76.2	0.934	6.442

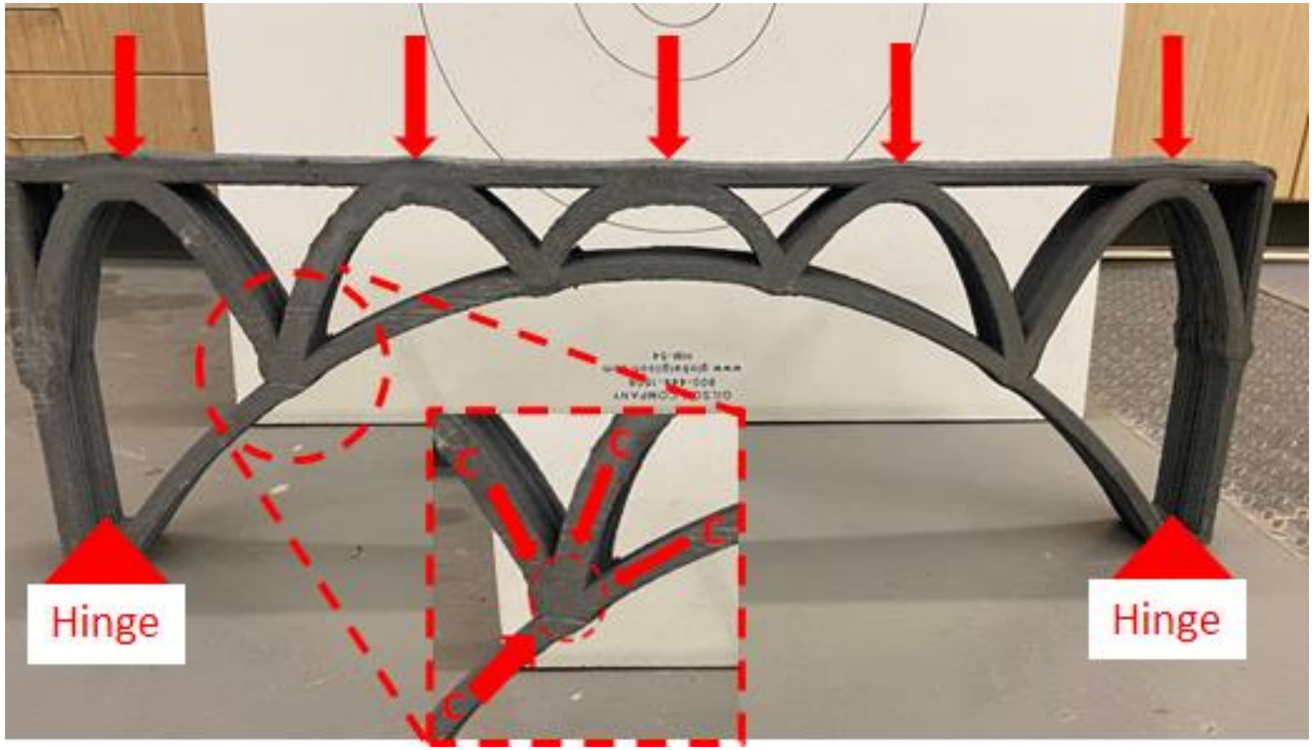
Equivalent Beam

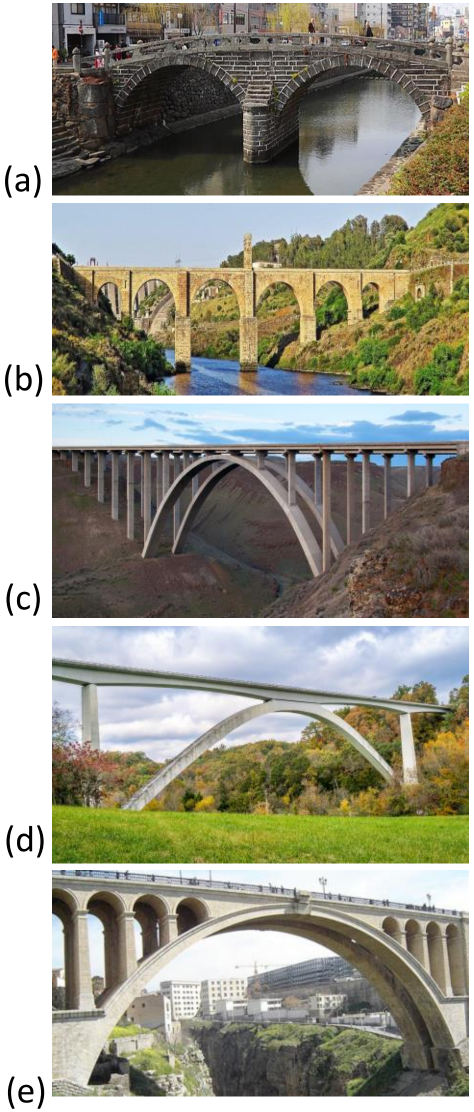
Arch



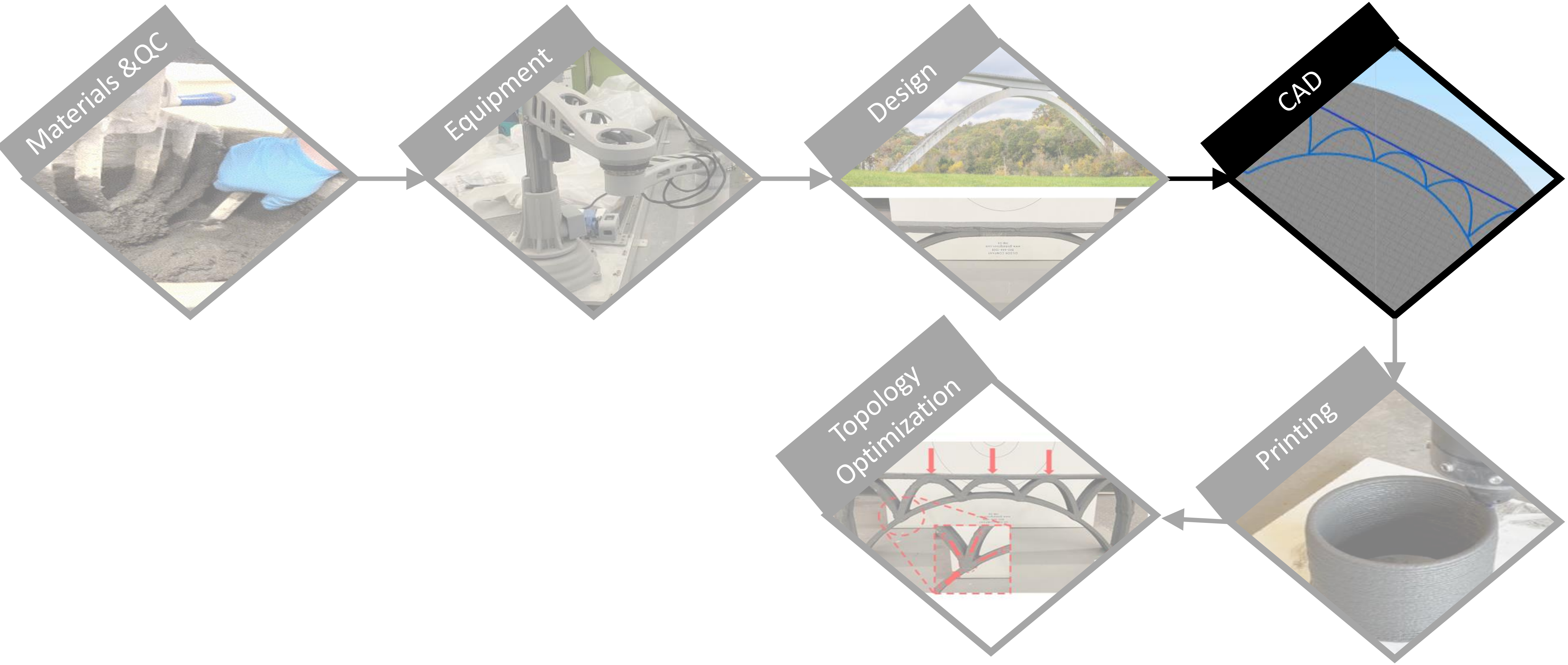
	ID	Force		Span (L)		Depth (d)		Width (b)		Modulus of Rupture (R)	
		(kips)	kN	inch	mm	inch	mm	inch	mm	ksi	mpa
Calculated	Equivelant Beam	0.135	0.602	9.00	228.6	0.75	19.1	3.50	88.9	0.929	6.404
Tested	Arch	1.349	6.000								
	Ratio	10.0	10.0								

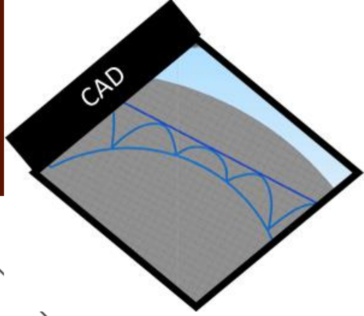
Compression Only Structures



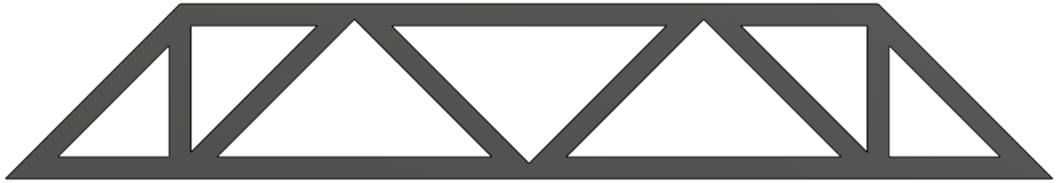


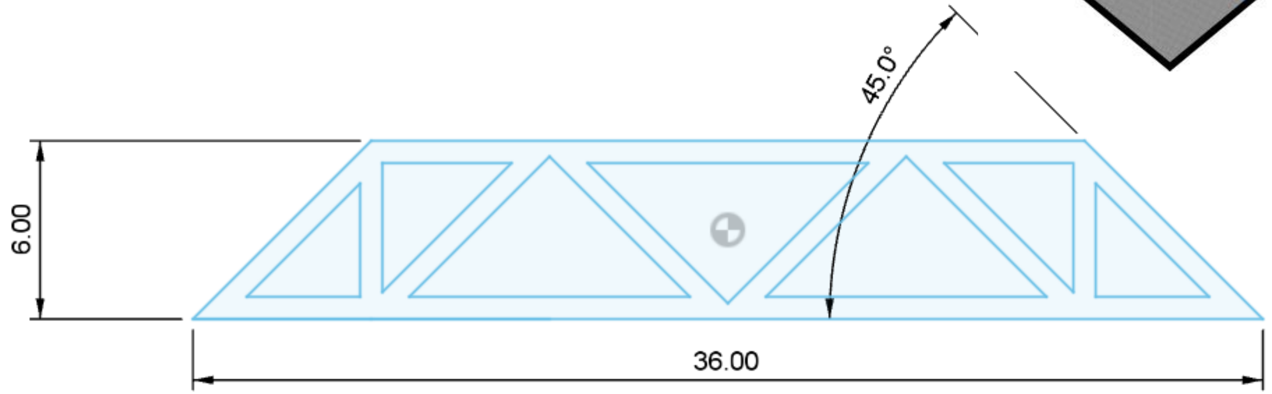
Computer-Aided Design





Computer-Aided Design (CAD)

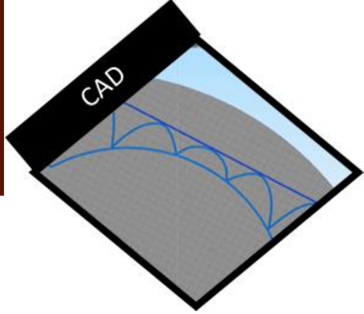




Optimized Flexural Design

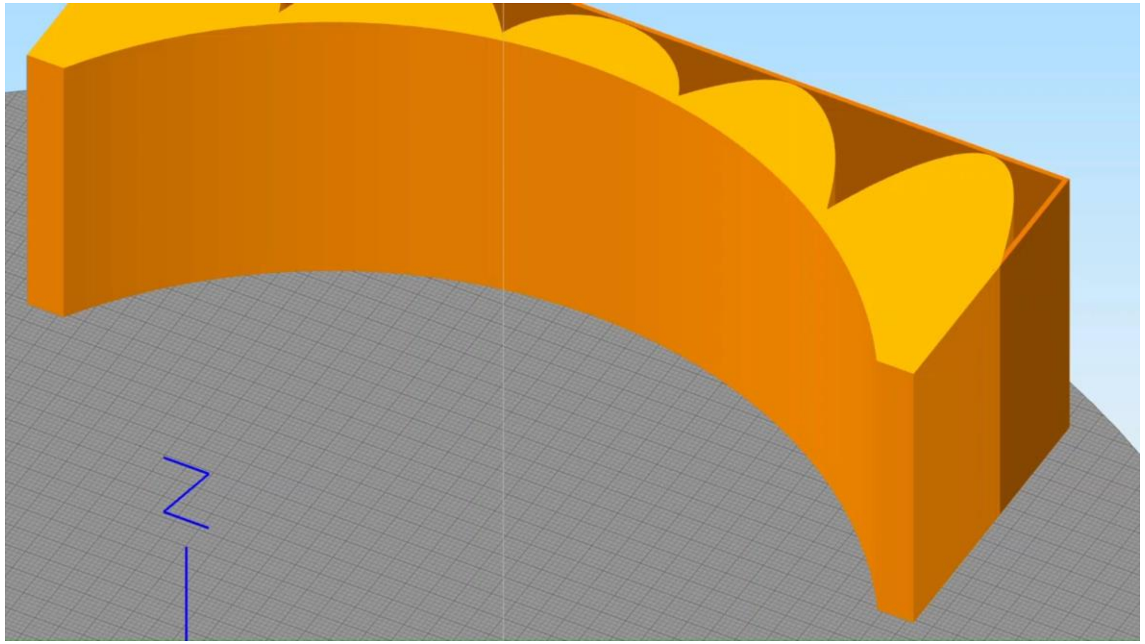
Optimized Compression-Only Design (Arch Structure)

Design Process



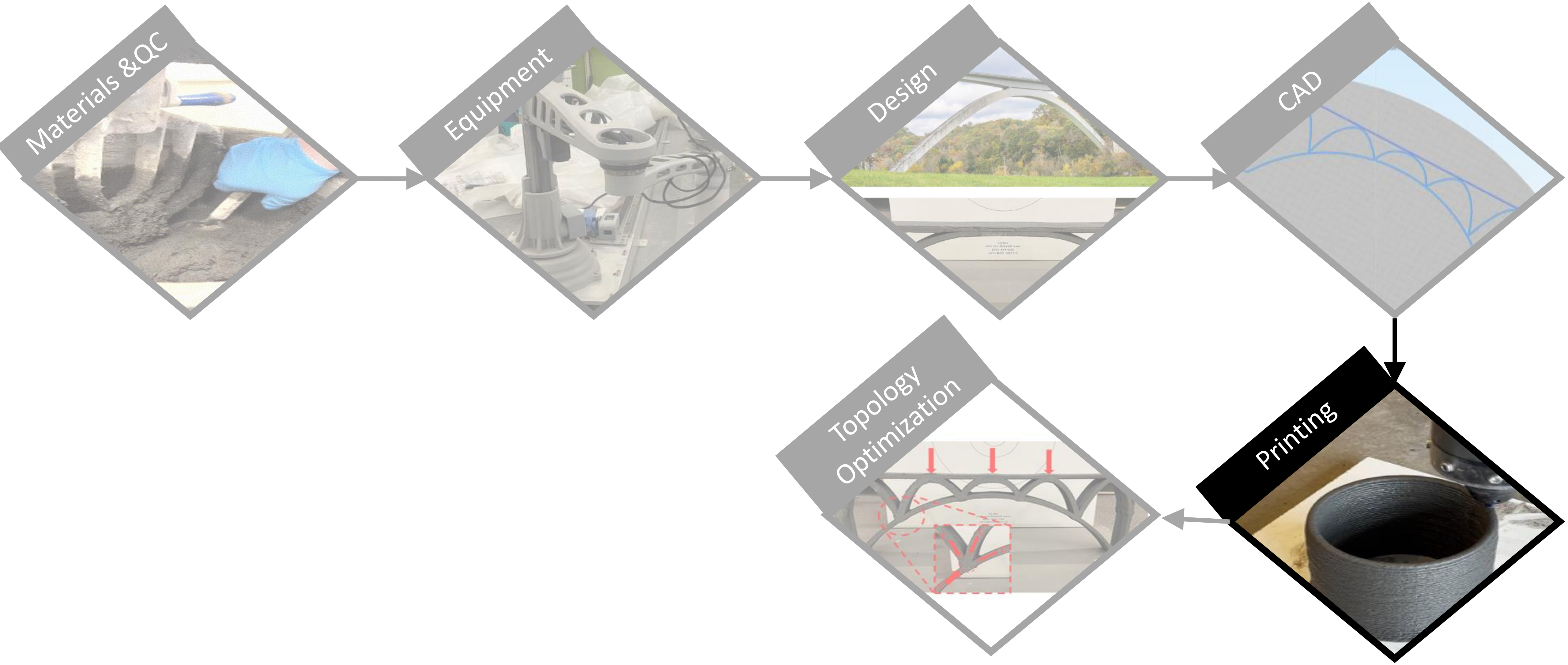
onshape → SIMPLIFY3D →

- Floor- Lines V1.gcode
- Optimized Beam V2 New Plan.gcode
- Optimized Beam V2 Special.gcode
- Optimzed beam V3 New Plan.gcode
- Scara Printer Eagle Extra Large.gcode



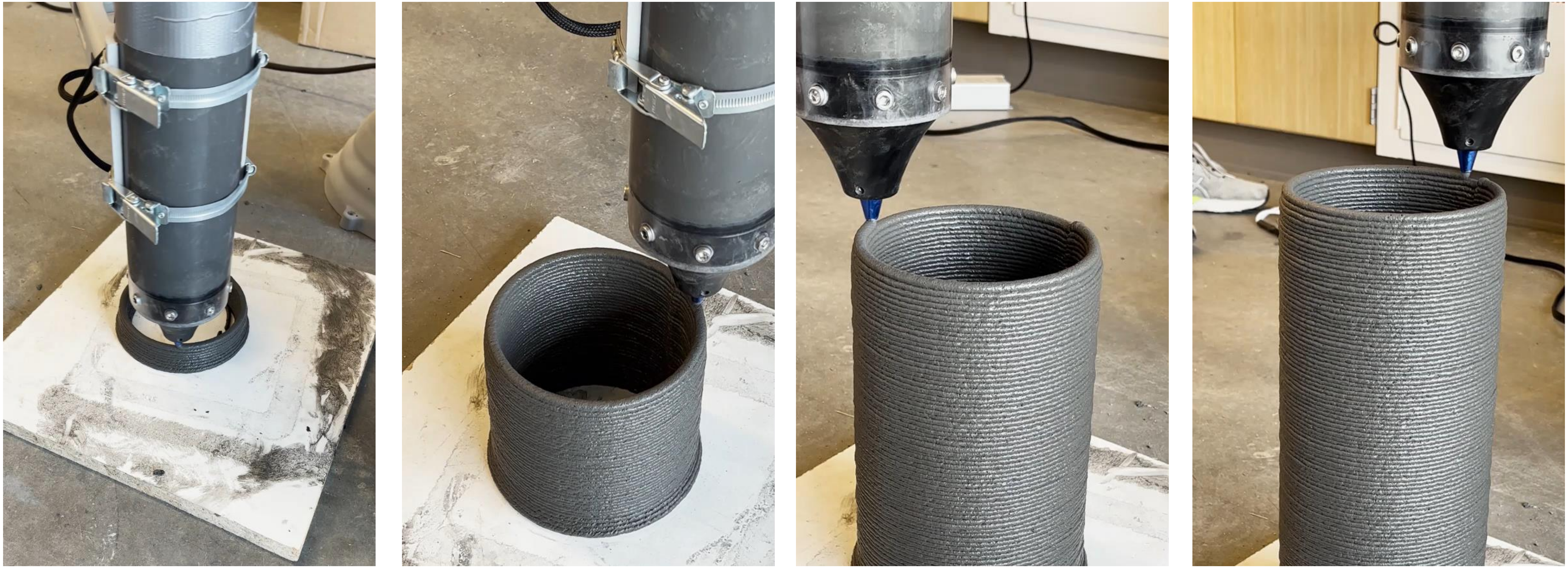
Typical Printing Parameters		
Nozzle Diameter	Layer Height	Printing Speed
5 mm	3 mm	60 mm/sec

Concrete 3D Printing



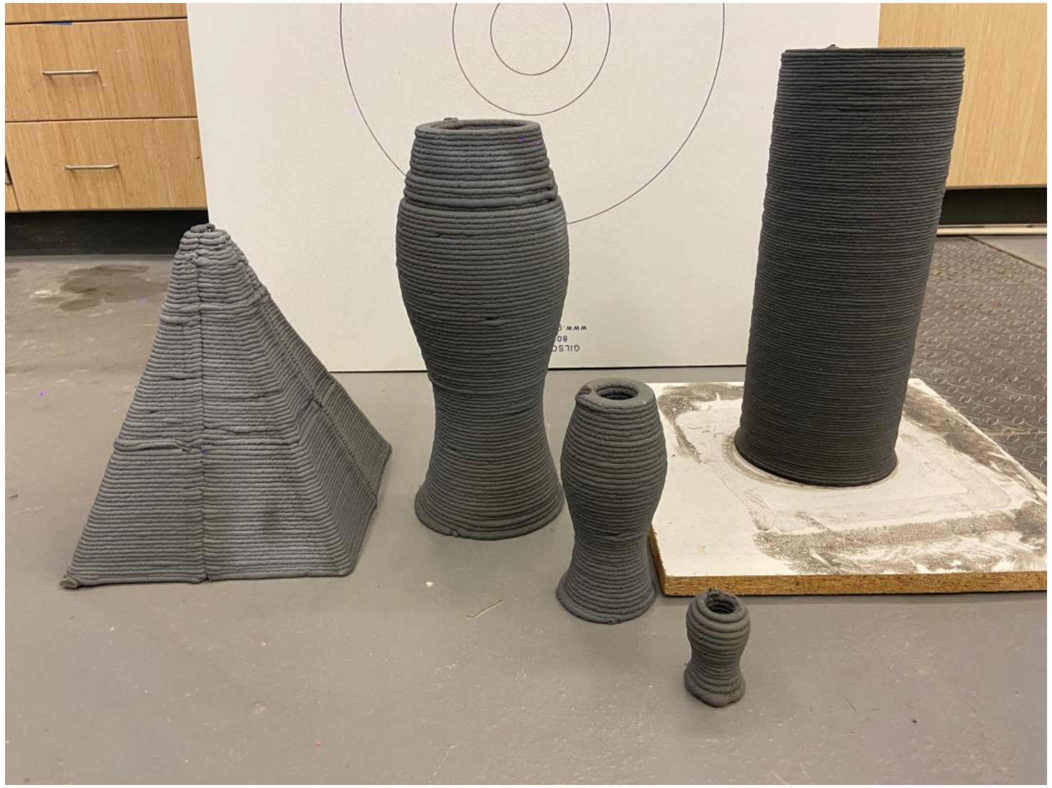
Concrete 3D-Printing

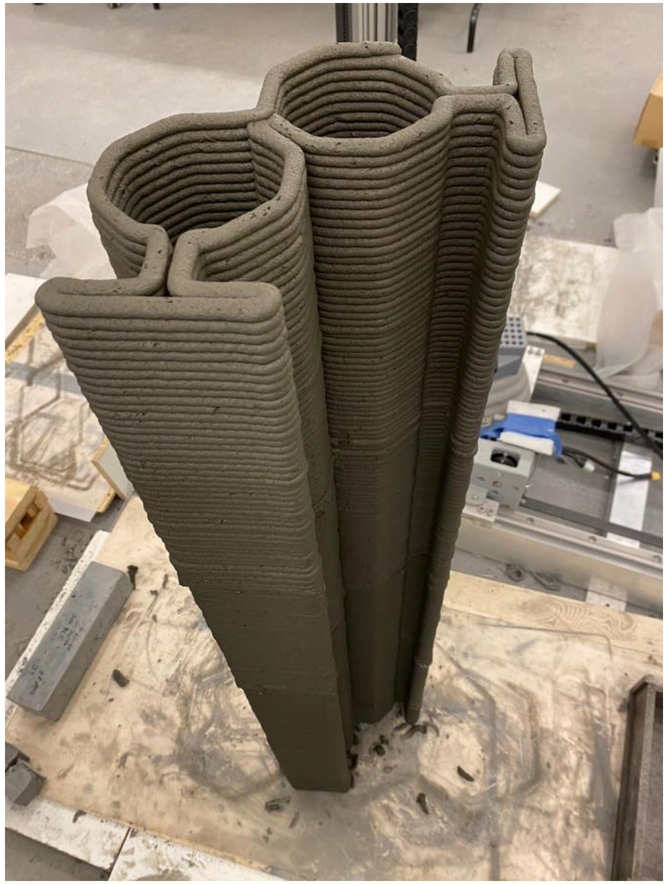
Printability Properties



Successful Extrusion and Buildability (Cementitious Materials)

Concrete 3D-Printing





Successful Extrusion and Buildability (Cementitious Materials)

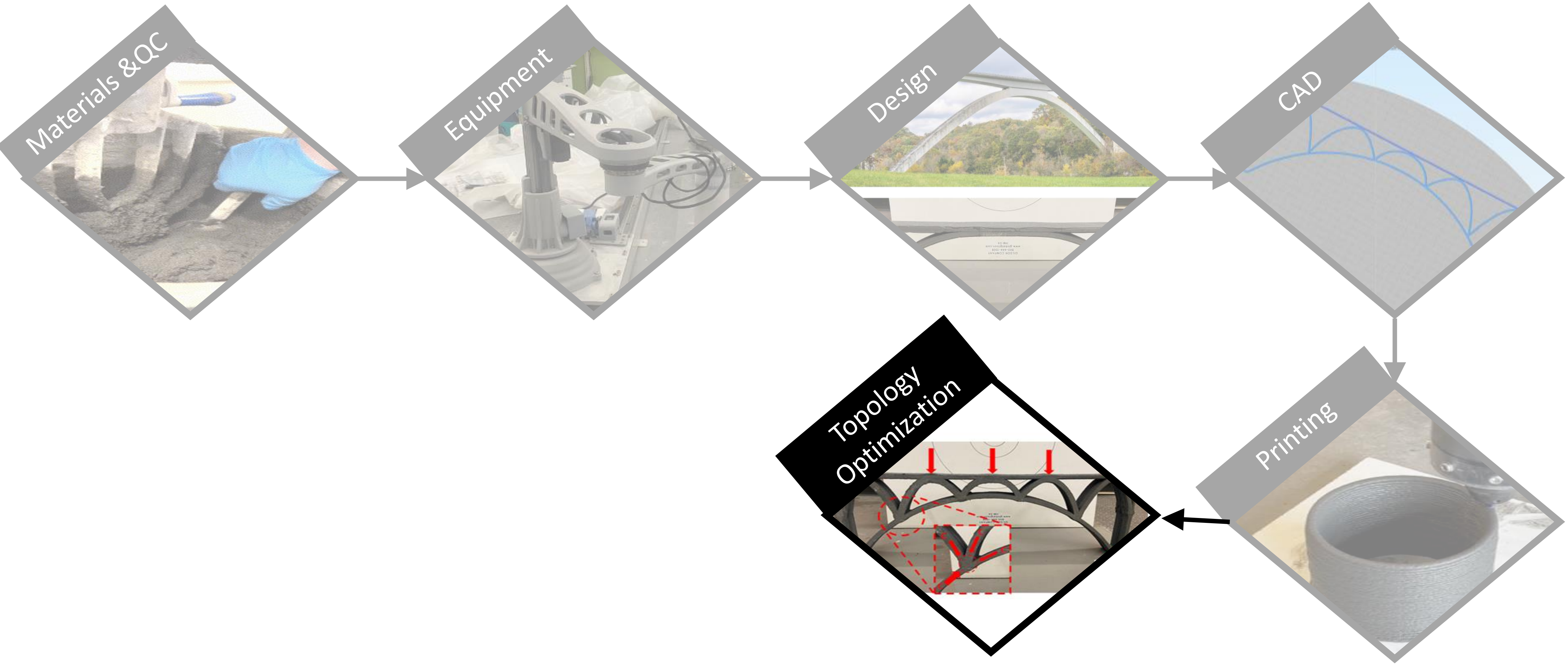
Concrete 3D-Printing

Low Embodied Carbon Mixes (Geopolymer Concrete)



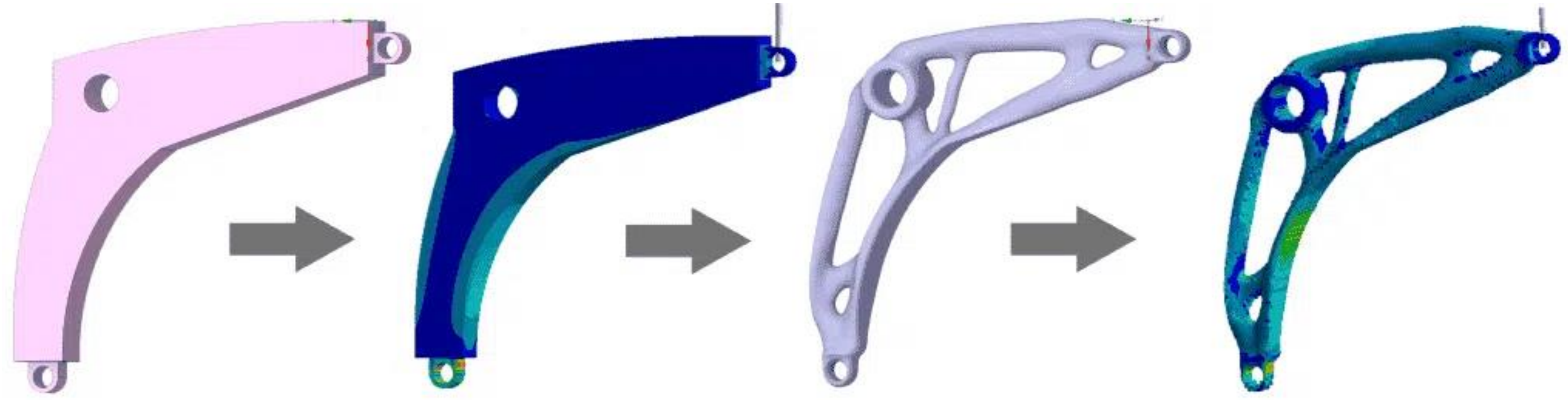

In-house printable Geopolymer Concrete developed at ARC lab, Rowan University.

Topology Optimization

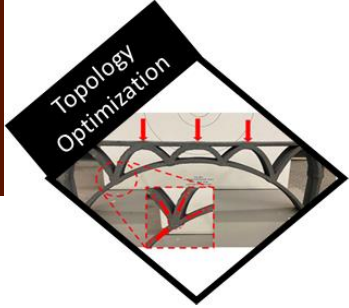


What is TO?

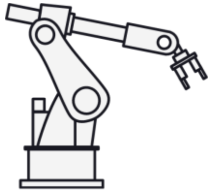
Topology optimization (TO) is a **shape optimization** method that uses algorithmic **models** to optimize **material layout** within a **user-defined space** for a given **set of loads, conditions, and constraints**. TO maximizes the performance and efficiency of the design by removing redundant material from areas that do not need to carry significant loads to reduce weight or solve design challenges like reducing resonance or thermal stress.



Topology Optimization of a Bell Crank (ANSYS Innovation Courses)



Benefits of TO in Additive Construction for Concrete



Overcoming labor shortage and development of skilled labor.

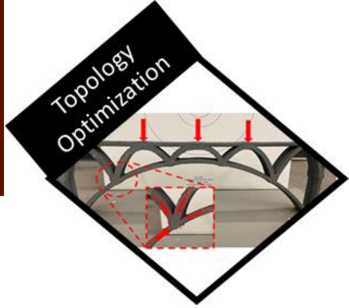
Construction time and cost saving.

Reduction of material wastage.

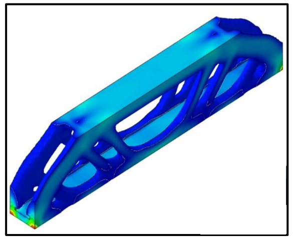
Reduction of carbon footprint of construction industry.

Broadens design creativity & problem-solving ability.

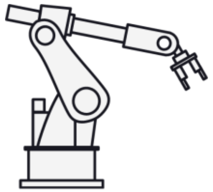
Lighter Structures (structural benefits)



Barriers for TO in Additive Construction for Concrete

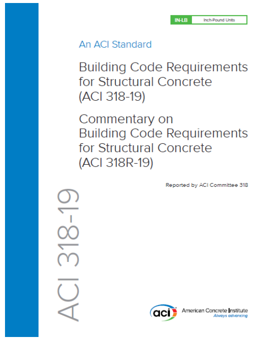


TO is often computationally expensive until achieving the correct model



Expensive Additive Construction Equipment (Print Area)

Reinforcement


An ACI Standard

Building Code Requirements for Structural Concrete (ACI 318-19)

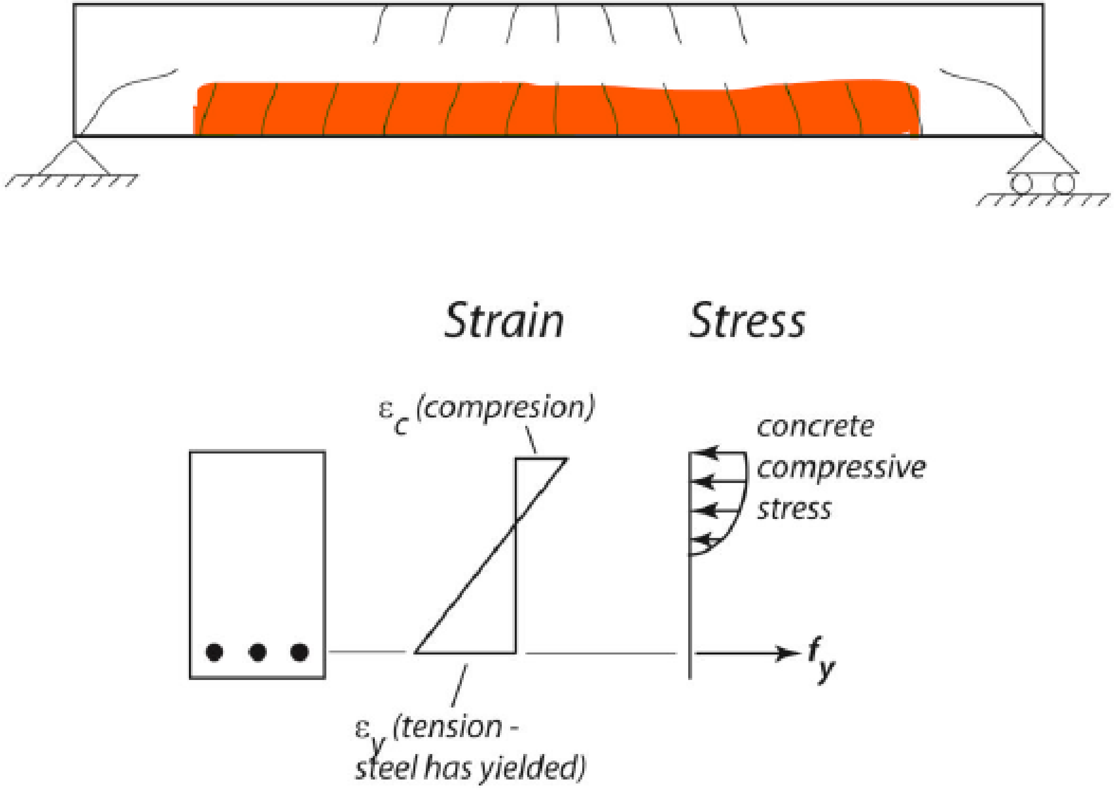
Commentary on Building Code Requirements for Structural Concrete (ACI 318R-19)

Reported by ACI Committee 318

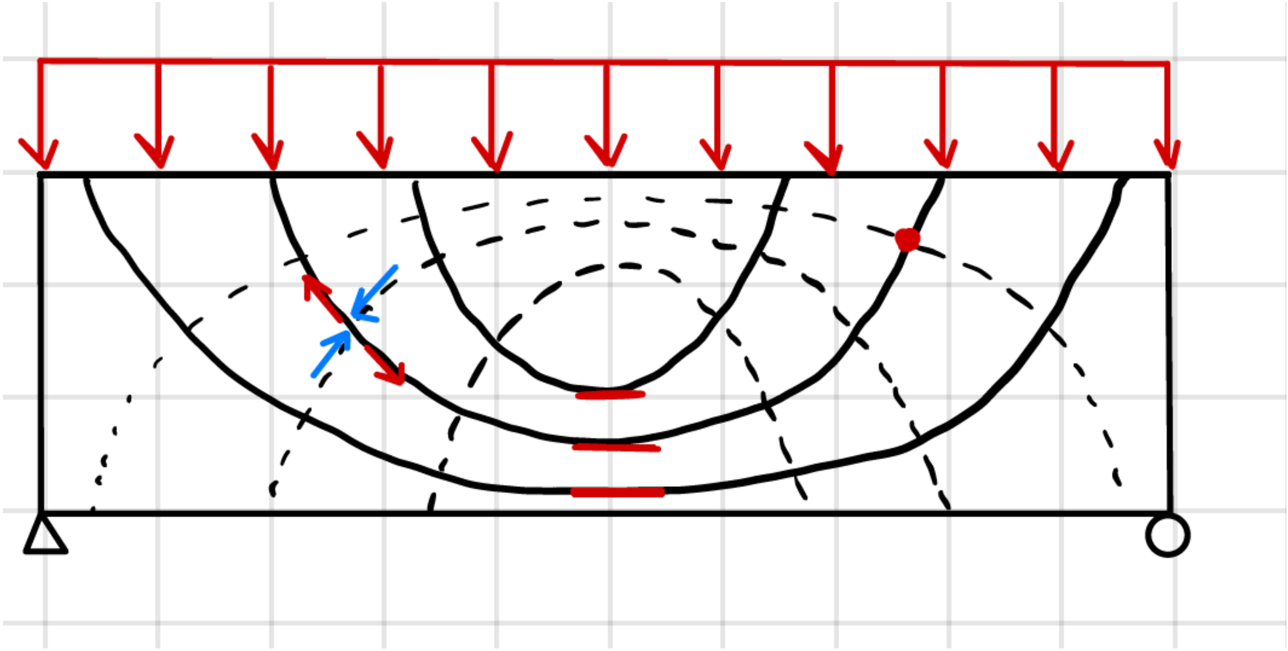
ACI 318-19

Does not Comply with codes and standards

Is TO suitable for Concrete Structures ?



Concrete Crack in Tension and Compressive Strength Block



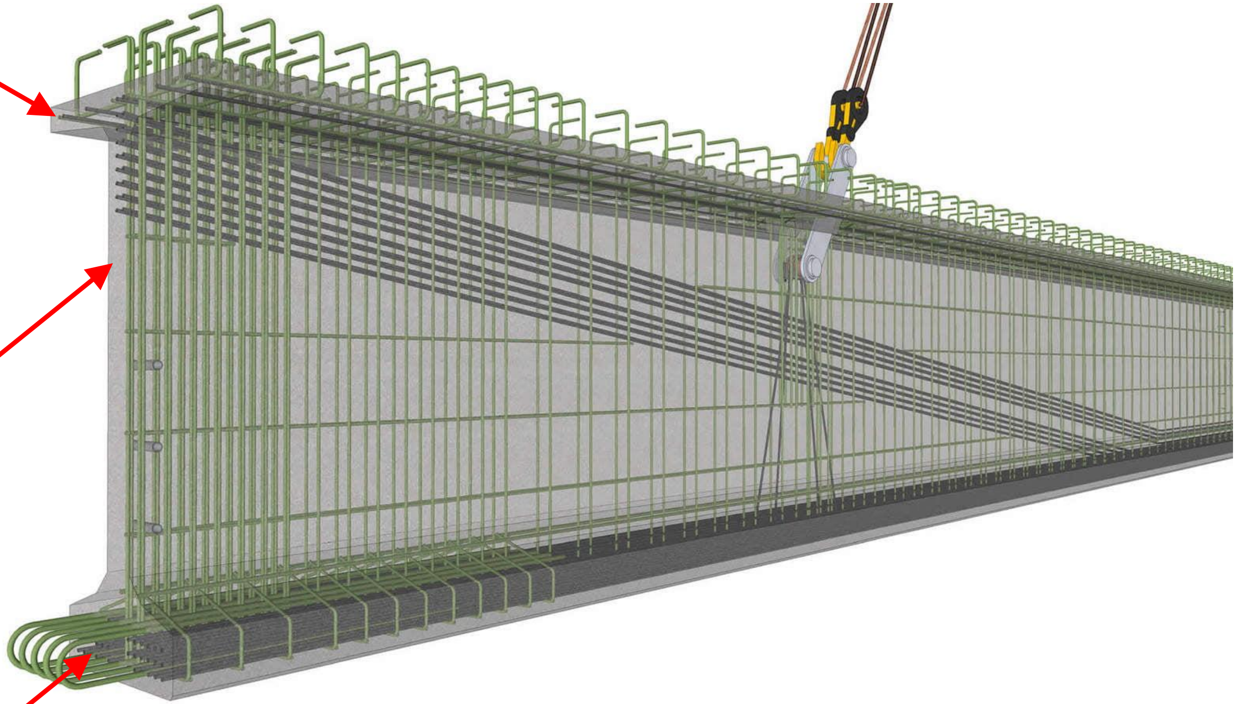
Principle Stresses in Concrete Beam

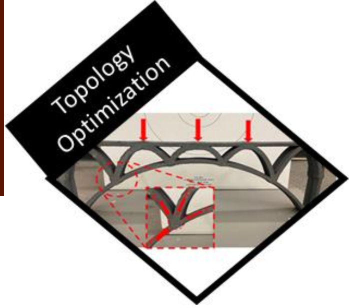
Why Topology Optimization?

Top flange to carry compression component of flexural stresses

Web to carry shear

Bottom flange to host reinforcement to carry tension component of flexural stresses

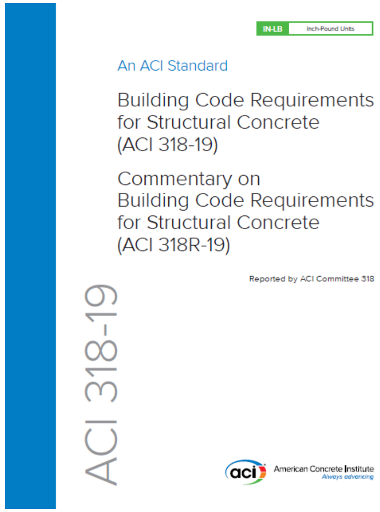




Barriers for TO in Additive Construction for Concrete

Does not Comply with codes and standards

TO is often computationally expensive until achieving the correct model


IN-LB Inch-Pound Units

An ACI Standard

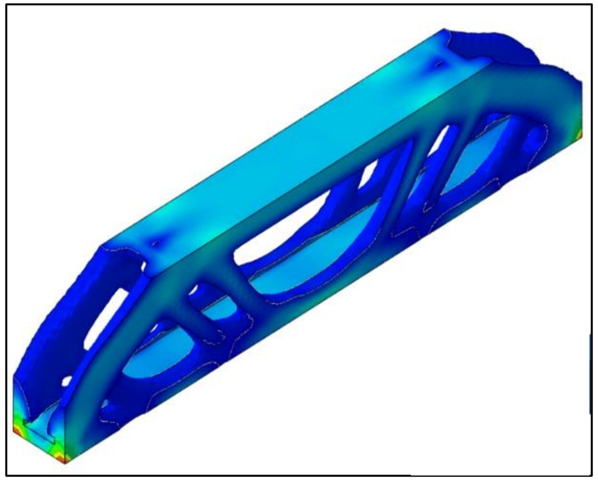
Building Code Requirements for Structural Concrete (ACI 318-19)

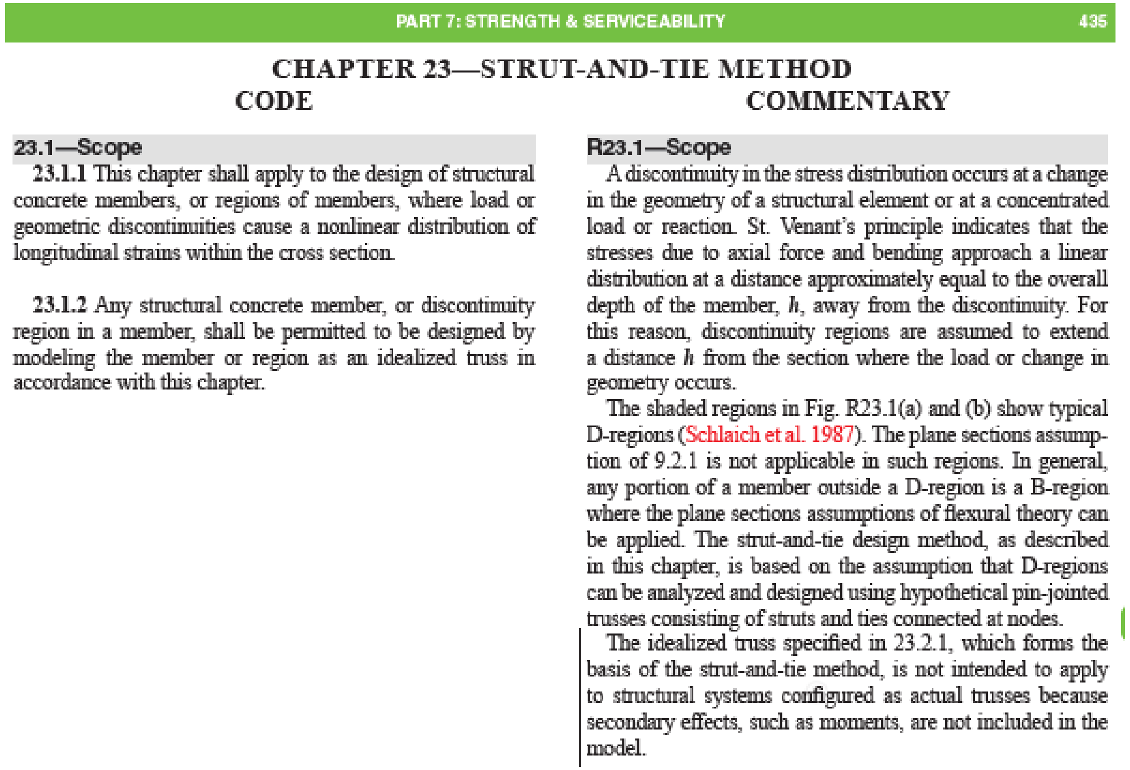
Commentary on Building Code Requirements for Structural Concrete (ACI 318R-19)

Reported by ACI Committee 318

ACI 318-19

aci American Concrete Institute Always advancing




PART 7: STRENGTH & SERVICEABILITY 435

CHAPTER 23—STRUT-AND-TIE METHOD

CODE

23.1—Scope

23.1.1 This chapter shall apply to the design of structural concrete members, or regions of members, where load or geometric discontinuities cause a nonlinear distribution of longitudinal strains within the cross section.

23.1.2 Any structural concrete member, or discontinuity region in a member, shall be permitted to be designed by modeling the member or region as an idealized truss in accordance with this chapter.

COMMENTARY

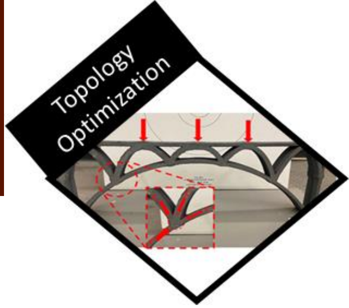
R23.1—Scope

A discontinuity in the stress distribution occurs at a change in the geometry of a structural element or at a concentrated load or reaction. St. Venant's principle indicates that the stresses due to axial force and bending approach a linear distribution at a distance approximately equal to the overall depth of the member, *h*, away from the discontinuity. For this reason, discontinuity regions are assumed to extend a distance *h* from the section where the load or change in geometry occurs.

The shaded regions in Fig. R23.1(a) and (b) show typical D-regions (Schlaich et al. 1987). The plane sections assumption of 9.2.1 is not applicable in such regions. In general, any portion of a member outside a D-region is a B-region where the plane sections assumptions of flexural theory can be applied. The strut-and-tie design method, as described in this chapter, is based on the assumption that D-regions can be analyzed and designed using hypothetical pin-jointed trusses consisting of struts and ties connected at nodes.

The idealized truss specified in 23.2.1, which forms the basis of the strut-and-tie method, is not intended to apply to structural systems configured as actual trusses because secondary effects, such as moments, are not included in the model.

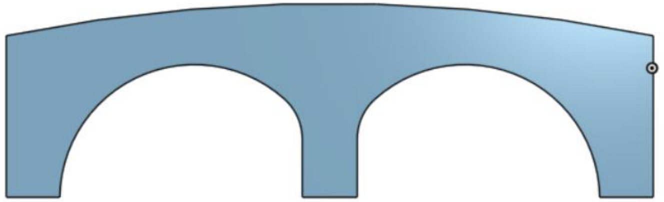
Why Topology Optimization?

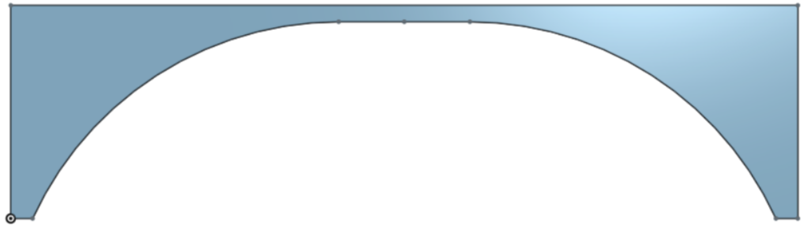


Alcántara Bridge

Meganebashi Arch Bridge

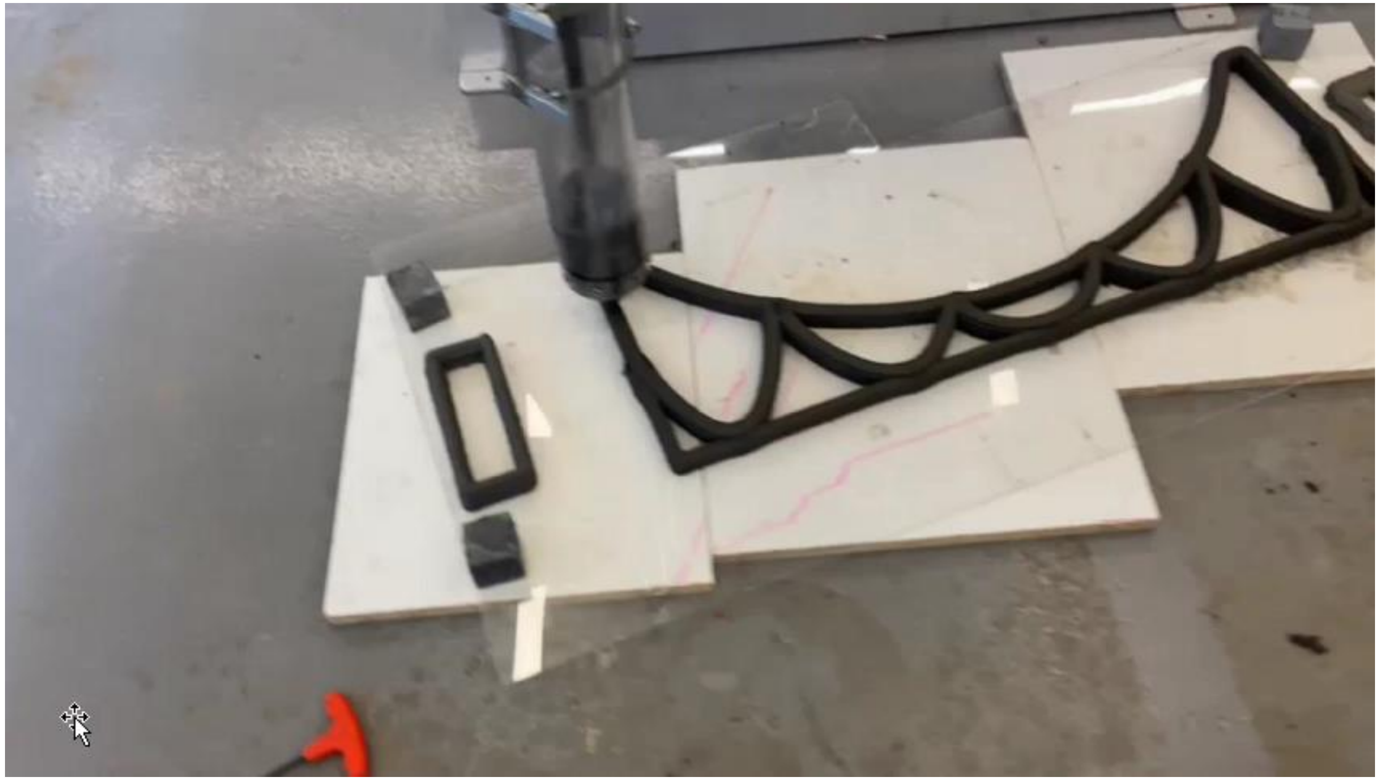
Natchez Trace Parkway Bridge

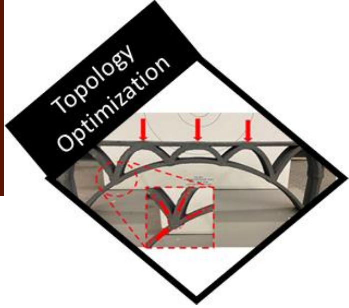




Compression Only Structures (Arch-Types) to overcome reinforcement issues

Why Topology Optimization?



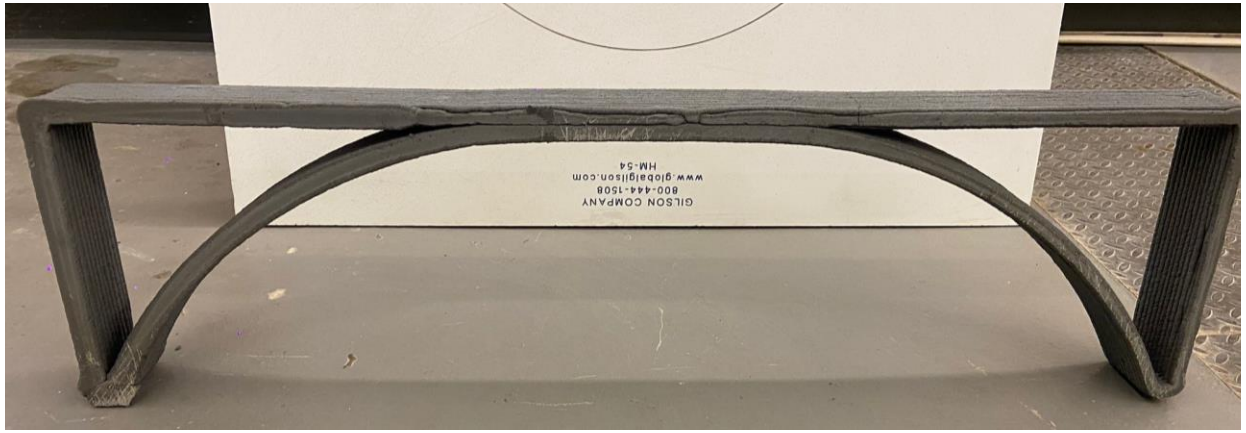


3 ft.

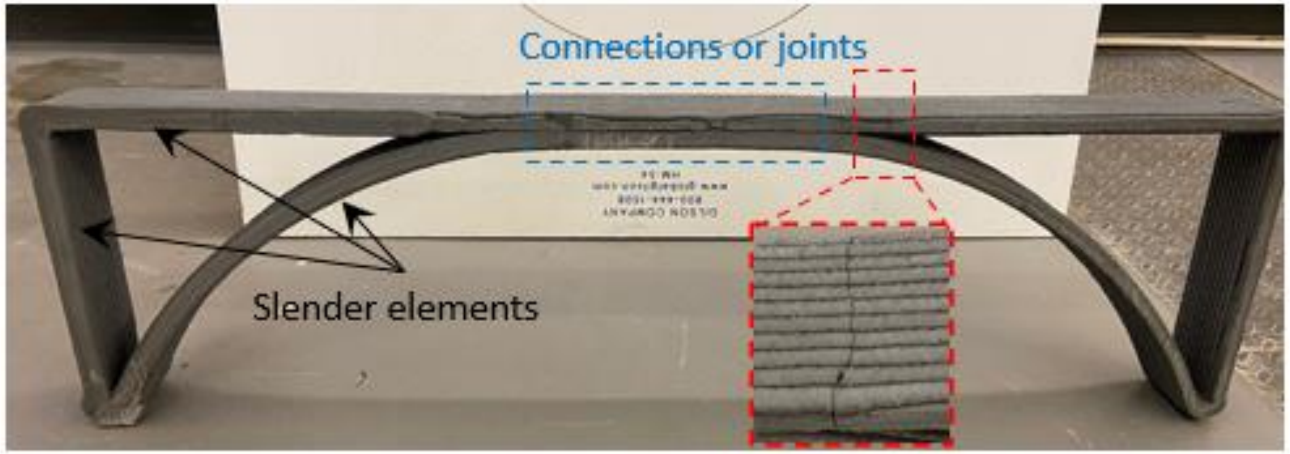
1 ft.

Why Topology Optimization?

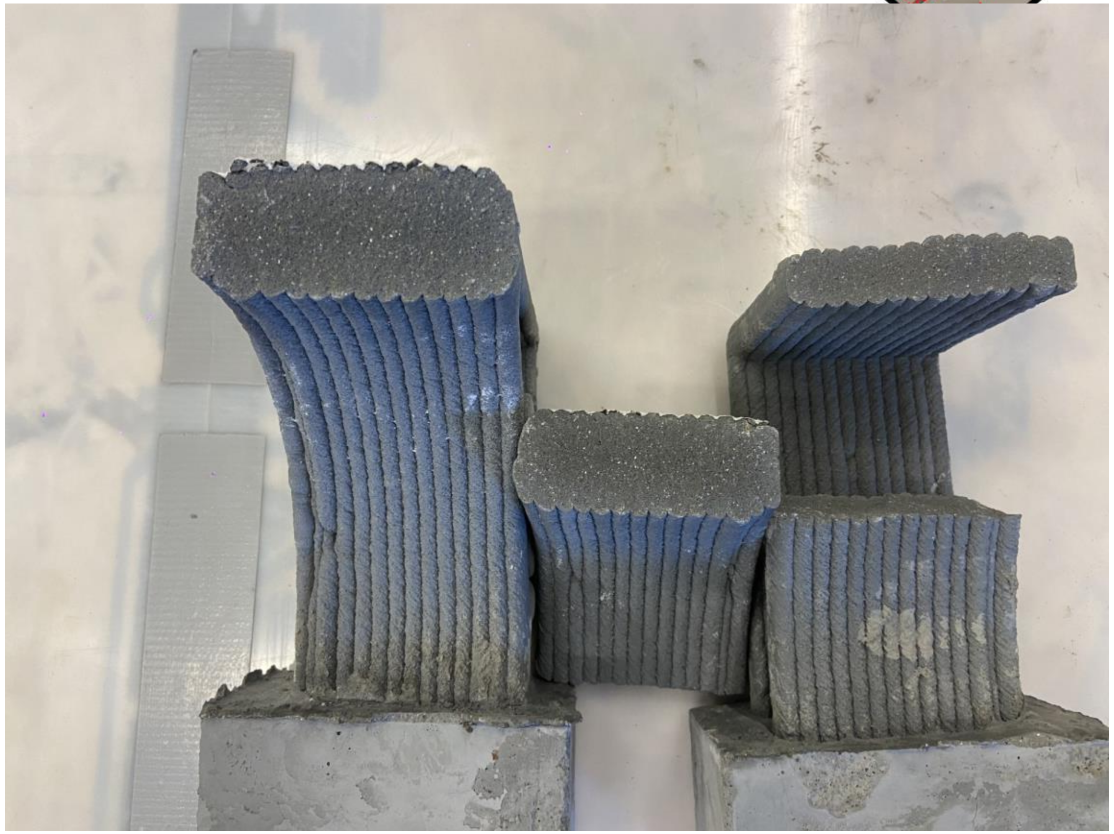
Why Topology Optimization?



Why Topology Optimization?



Shrinkage Cracks



Fused Layer and Joints

What is Next

Conclusions

- Slight variation in the printing path of the layer to be circular to form an arch resulted in a much higher capacity if compared to a straight-line printing path for the same amount of material. Therefore, the small arch-like exhibited ten times load carrying capacity compared to an equivalent beam with the same size and volume calculated based on the modulus of rupture.

- The developed in-house printable concrete mixture using locally sourced raw materials was successful based on the fresh, hardened, and printability requirement for additive construction. The developed mixture was utilized to print complex structures such as cylinders and sloped and concave surfaces through 6-millimeter and 8-millimeter nozzles.

- The selected compression-only structures scaled from historic and famous bridges provided challenges in the additive construction of C-only structures; however, all the structures were successfully printed with slender elements forming main arches, curved or straight slabs, and vertical column segments.

- One bridge showed a sign of cracking at the conjunction between the arch and the slab due to stiffening.

Thank you