

CYCLOPEAN

cyclopean concrete noun
: concrete with large embedded stones

SPOLIA

(lat. spoils) noun
: architectural fragment from a past
structure, embedded in a new building

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**From Concrete Rubble To
Precast Load-Bearing Walls**











Spolia (lat. Spoils)



Spolia



Parikia Tower, Paros (13th Century)

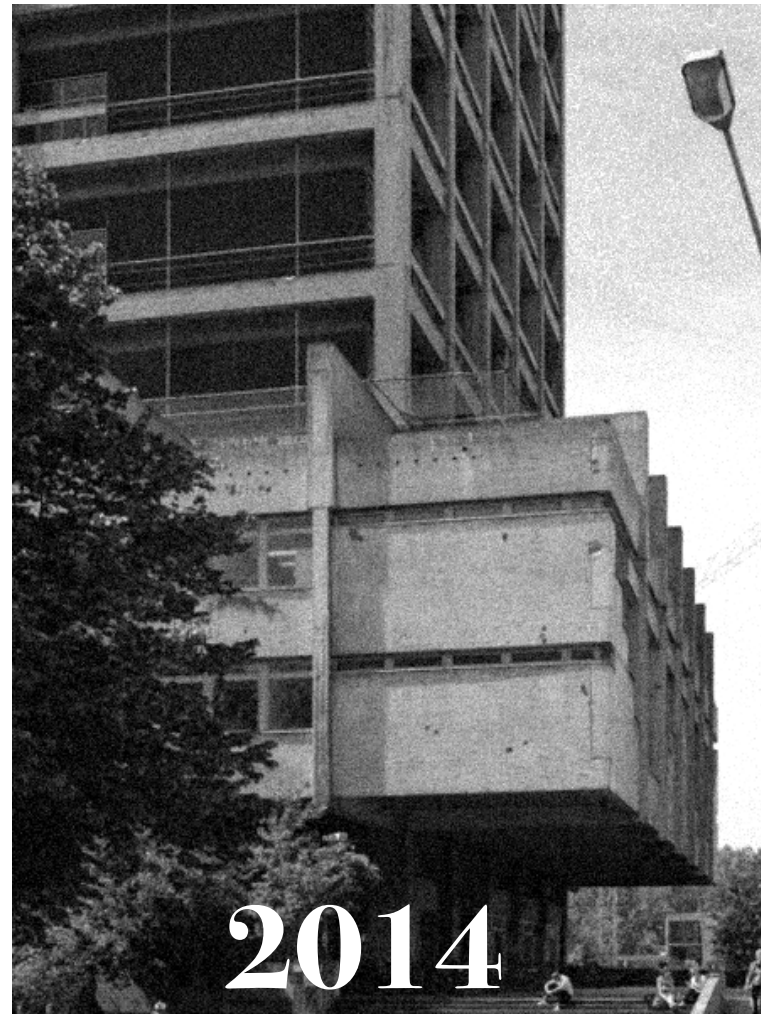


Mezquita-Catedral, Cordoba (8th Century)



What is modern day spolia?

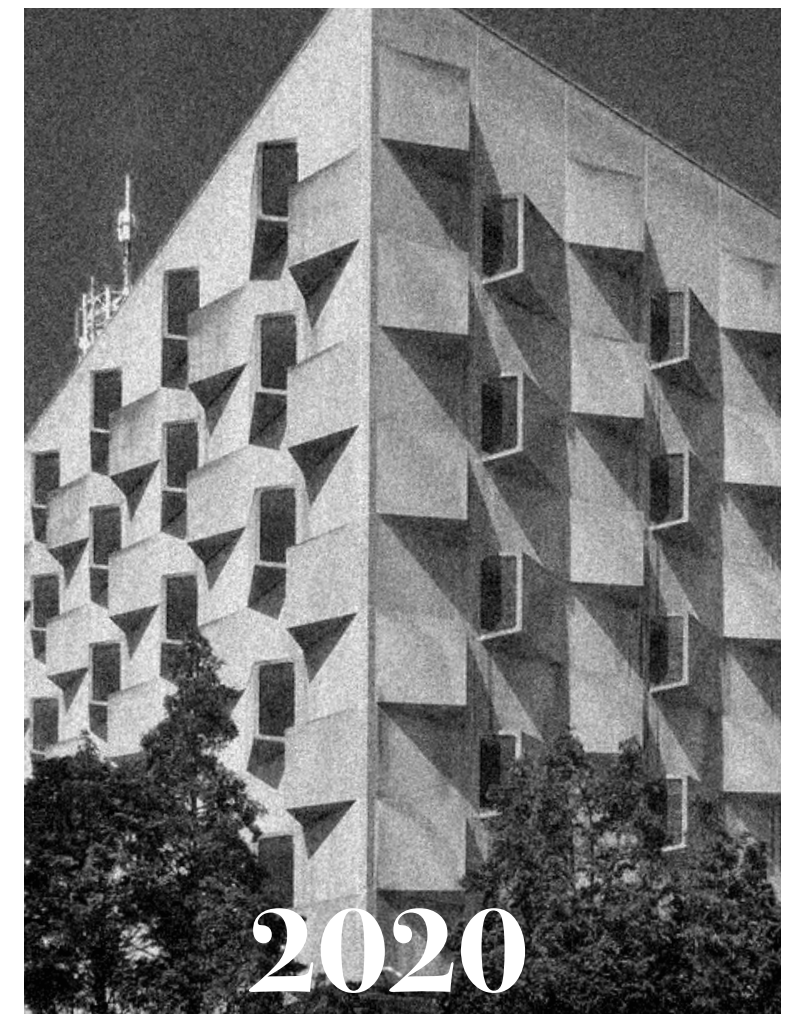
1972



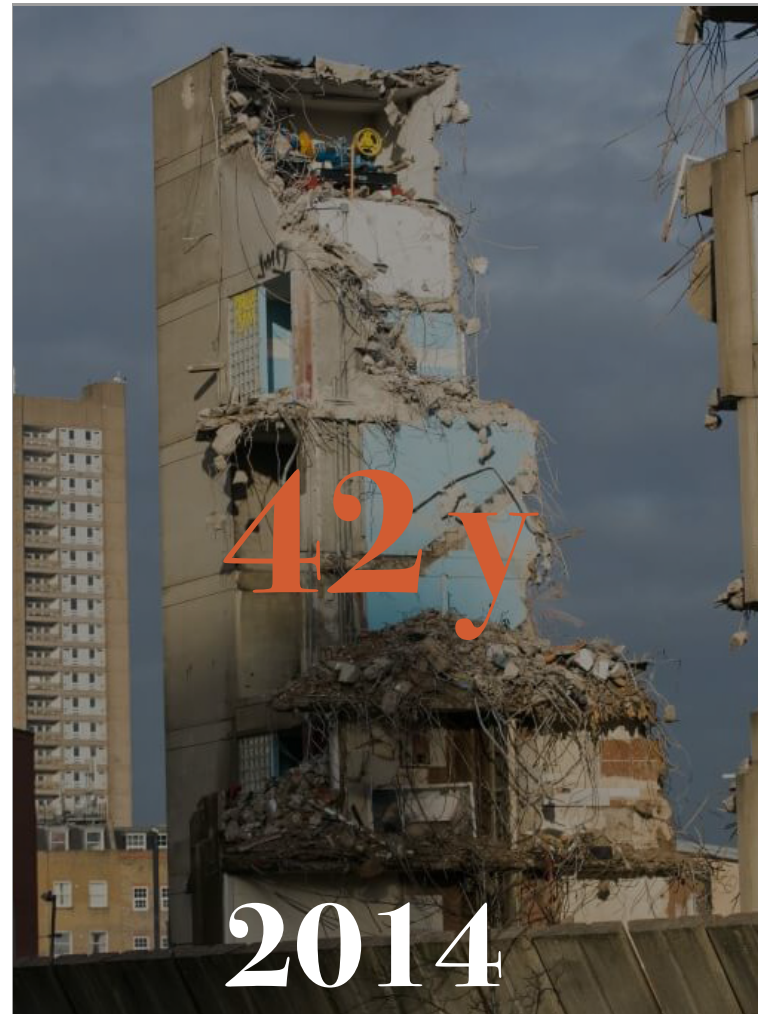
1977



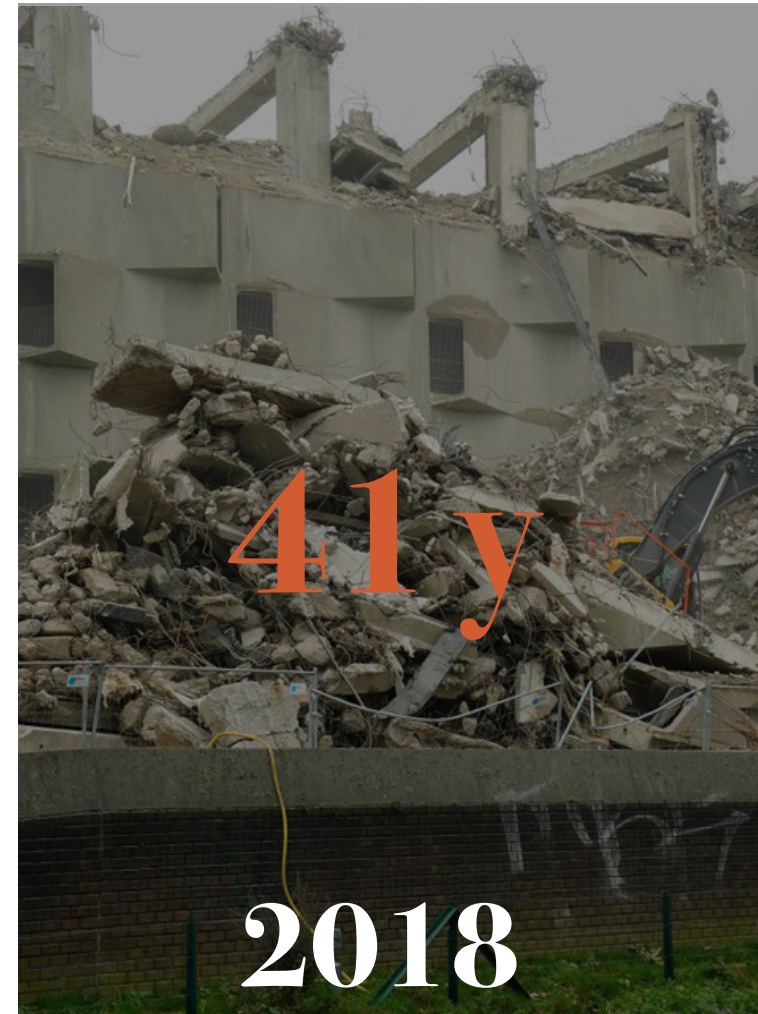
1980



1972



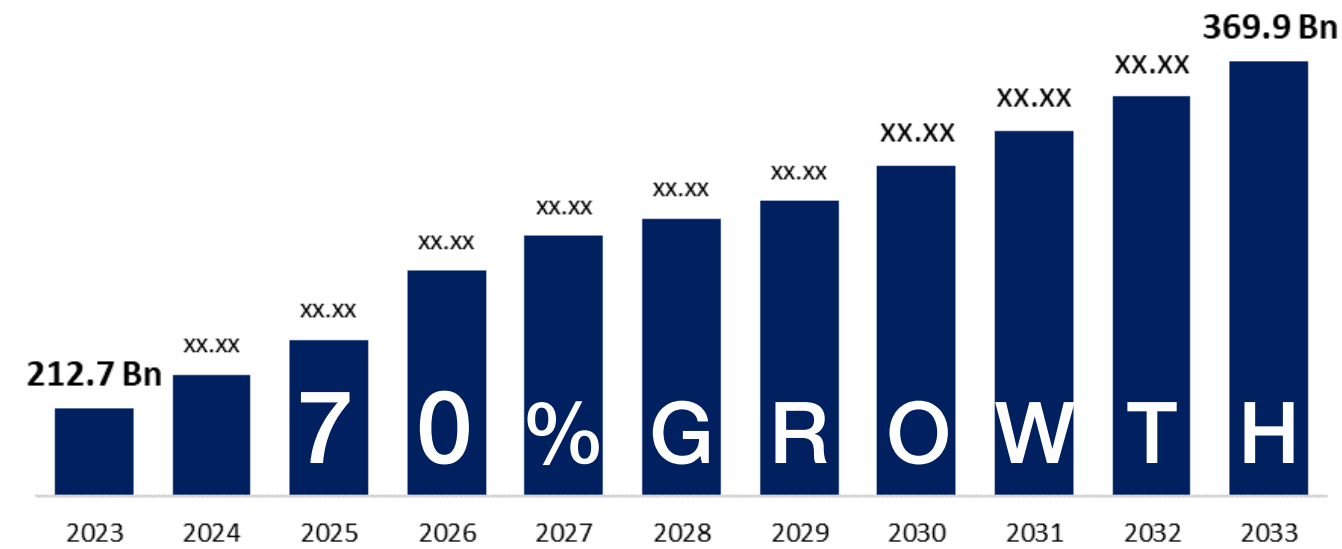
1977



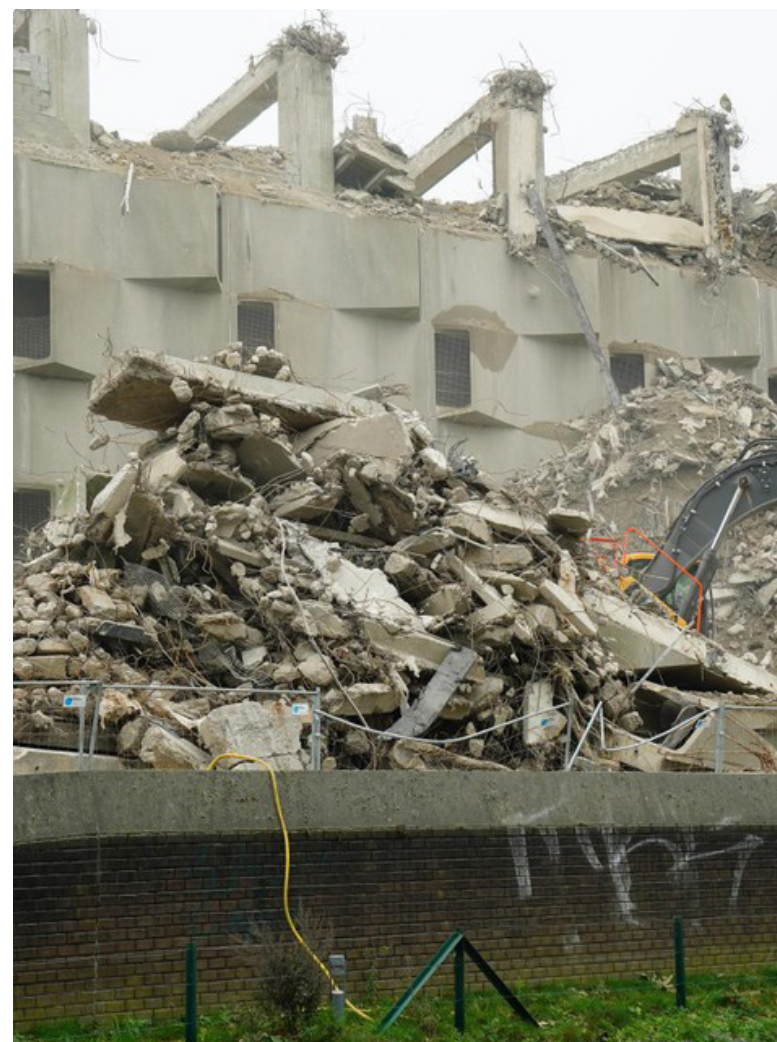
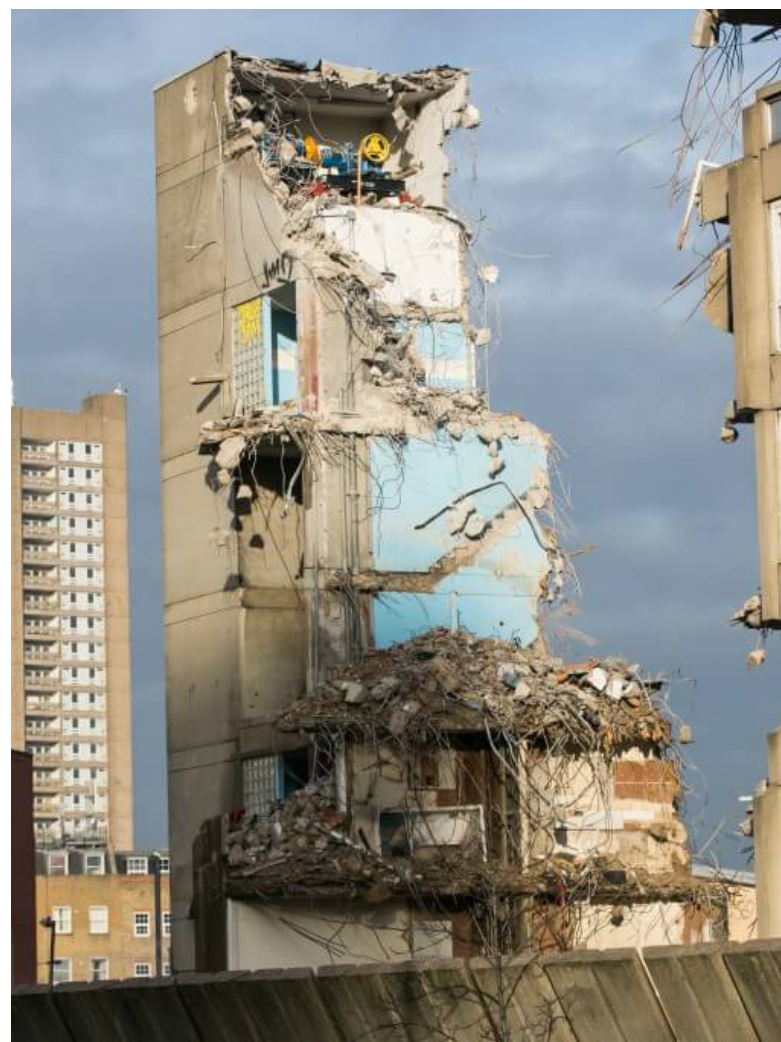
1980



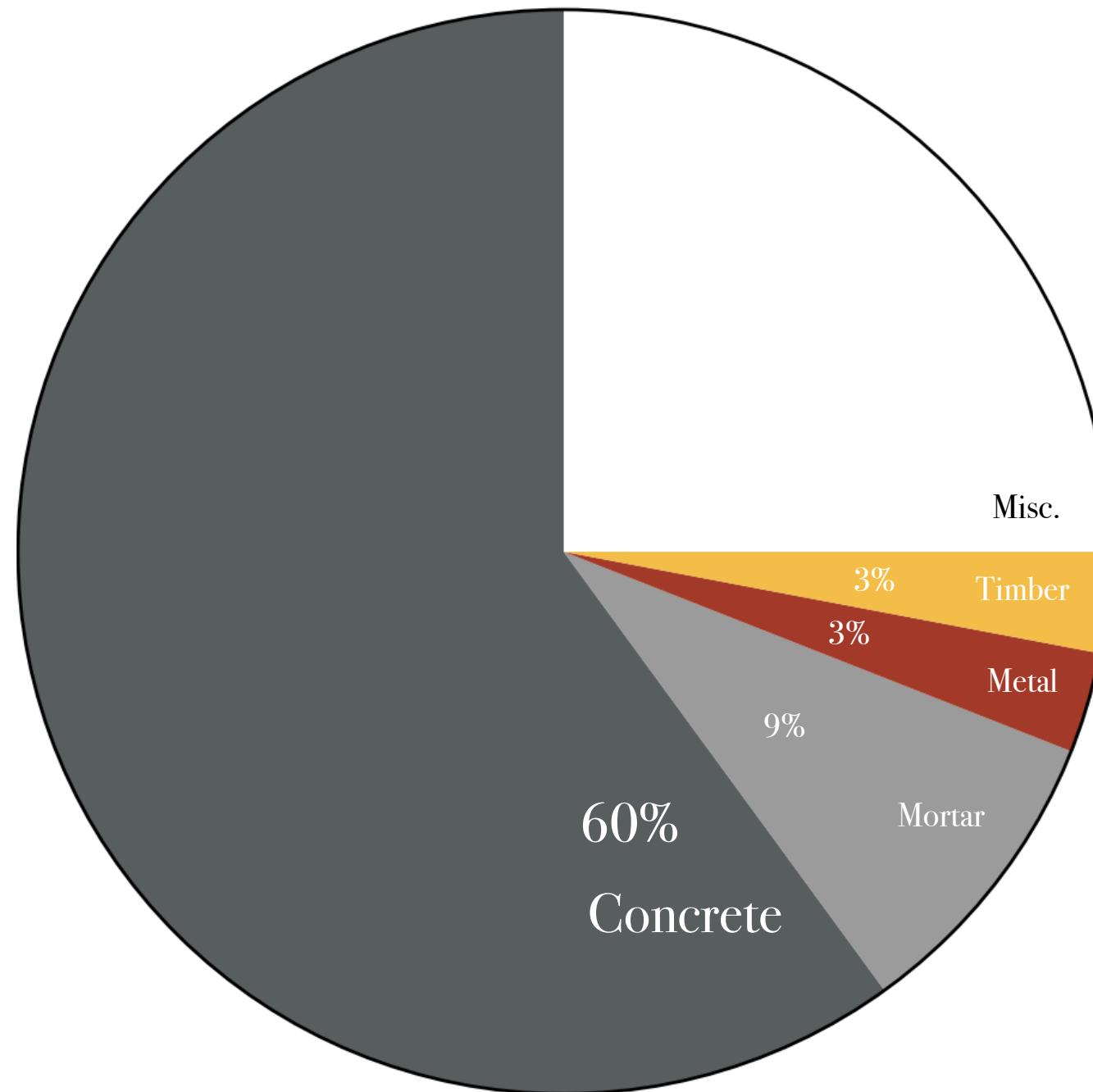
Future Growth



Global Construction & Demolition Waste Management Market



CCDW



Crushing



Backfill





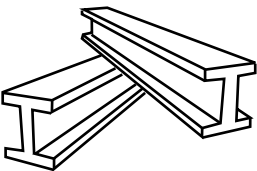
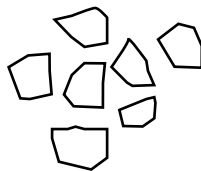
What if we changed our perception of waste?

What if we gave value to Concrete Demolition Waste?

Modern Spolia



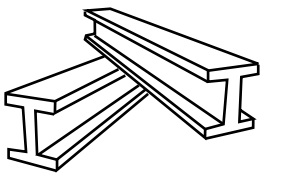
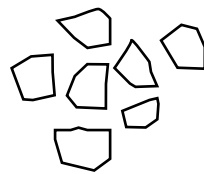
Modern Spolia



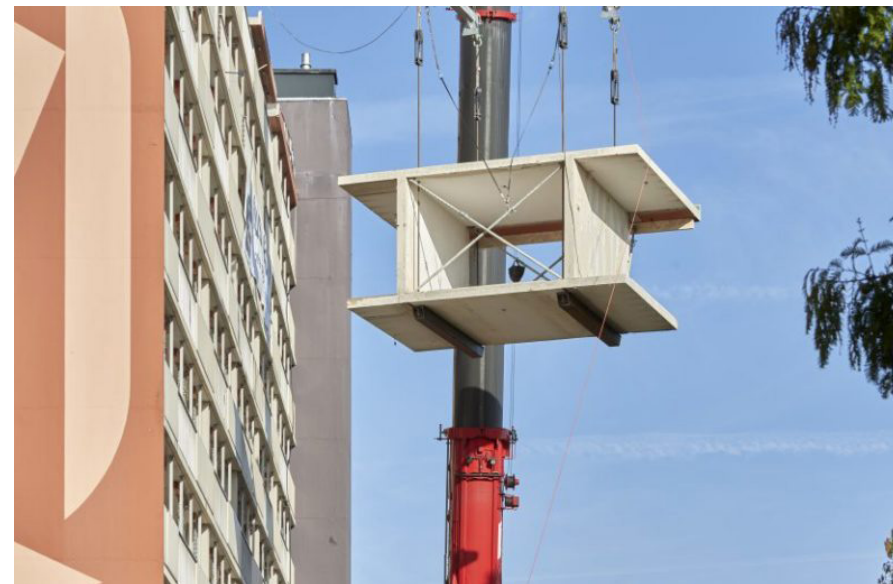
RCA



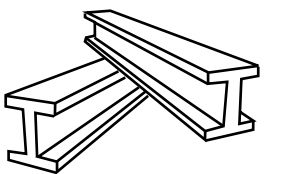
Recycled Concrete
Aggregates



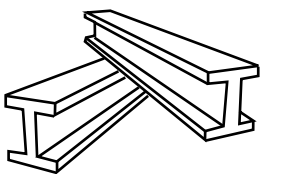
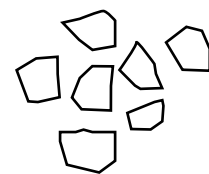
PRECS



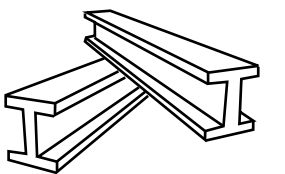
Piecewise Reuse of Extracted Concrete
in new Structures



Rubble Fragments



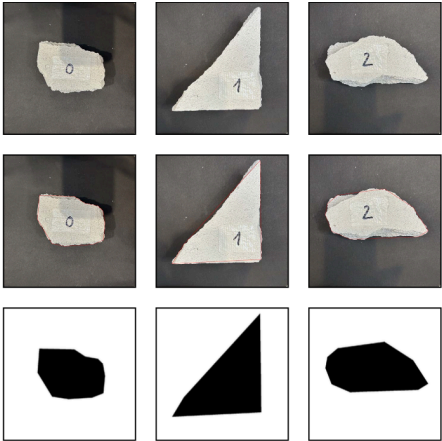
Rubble Fragments



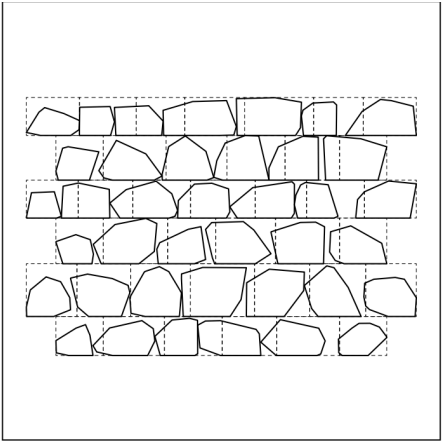
Mosaic Walls



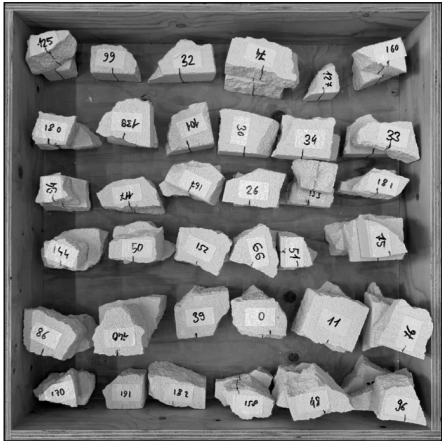
broken rubble stones



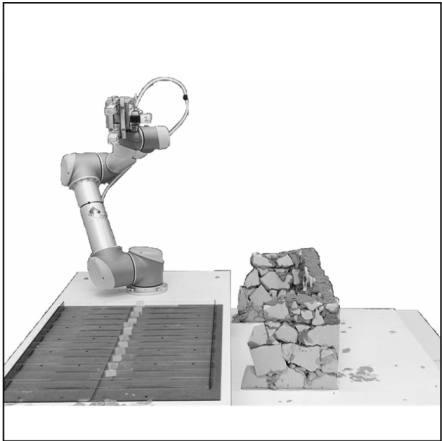
scanning & translating into vector geometries



packing algorithm



selected stones organised in rows



robotic assembly



final prototype

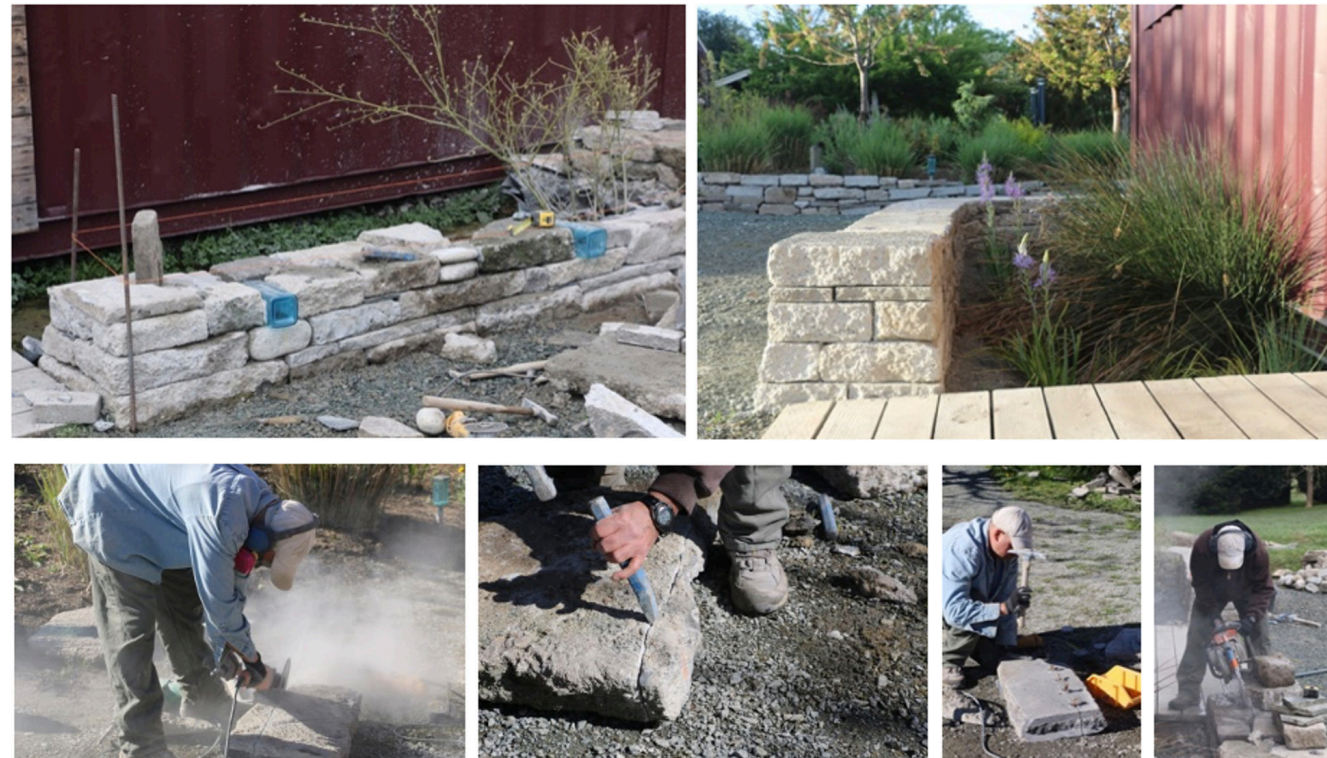


Load-Bearing Rubble Atlas

	Year	Place	Author	Method	Stone Preparation	Scale	Rubble Weight	Rubble Source	Algorithm	Database Size (multiplier)	Prefabrication
Masonry Walls from Reclaimed Concrete Demolition Waste	2024	Lausanne CH	Oreb et al.	Structural tests of horizontally stacked rubble masonry walls and weaker mortar	none	1:1	<50kg	Local Waste Treatment Plant	2D - Image Convolution Based (Wang et al., 2024)	3	ND
From Concrete Waste to Walls	2024	Lausanne CH	Grangeot et al.	Robotic stacking of vertical raw concrete rubble elements with mortar	none	1:1	>100kg	Local Waste Treatment Plant	2D - Image Convolution Based (Wang et al., 2024)	3	yes, vertically
Cyclopean Cannibalism	2017	Boston USA	Clifford & McGee	Revival of ancient masonry methods with CDW and computational methods	precise carving of the stones	1:1	>300kg	Local Waste Treatment Plant		ND	prefabricated stone preparation
Mosaic Walls	2024	Delft NL	Hany et al.	Robotical stacking of large stones with manual placement of infill stones and mortar	none	1:5	>2kg	Broken aerated concrete blocks	2D - Tessellation Based, Stacking and Nesting (Hany et al., 2024)	2	no
Cyclopean Spolia	2024	Delft NL	von Kardorff	Horizontal prefabrication of load bearing elements	none	1:5	>2kg	Self-made	Nesting (tbd) & Stacking (Wang et al., 2024)	3	yes, horizontally
Missing Pieces	2023	Cape Cod, USA	Ensamble Studio	Creation of an art piece made of large vertically stacked concrete rubble elements connected with steel	none	1:1	>100kg	Self-made	NA	NA	yes, but not in controlled environment
Urbanite	NA	USA	Various	Remanufacturing of concrete rubble elements for landscaping into pathways and retaining walls	sometimes	1:1	<100kg	Local Waste Treatment Plant	NA	NA	no

Table 3 Current Methods of Load Bearing Parallel Sided Concrete Rubble

Local Methods



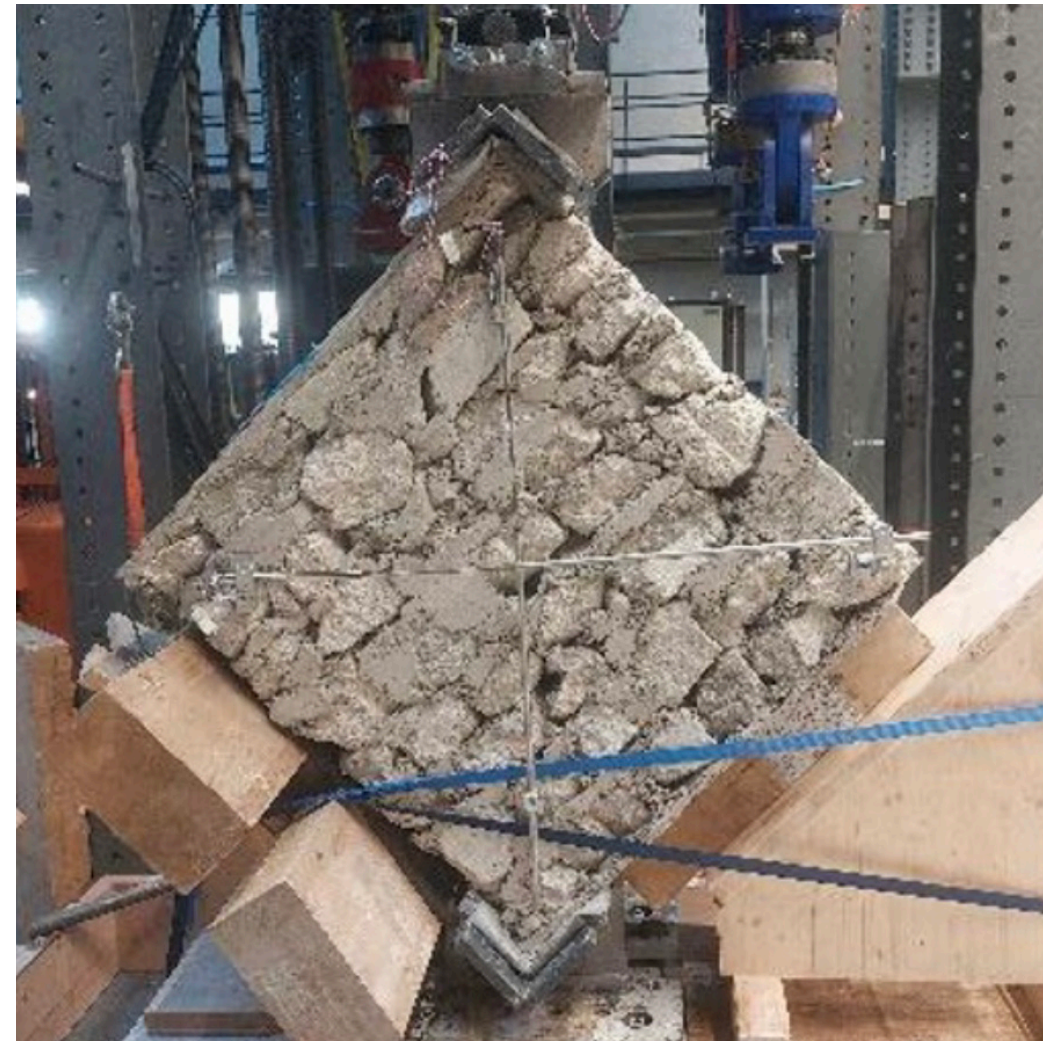
Load-Bearing Rubble Atlas



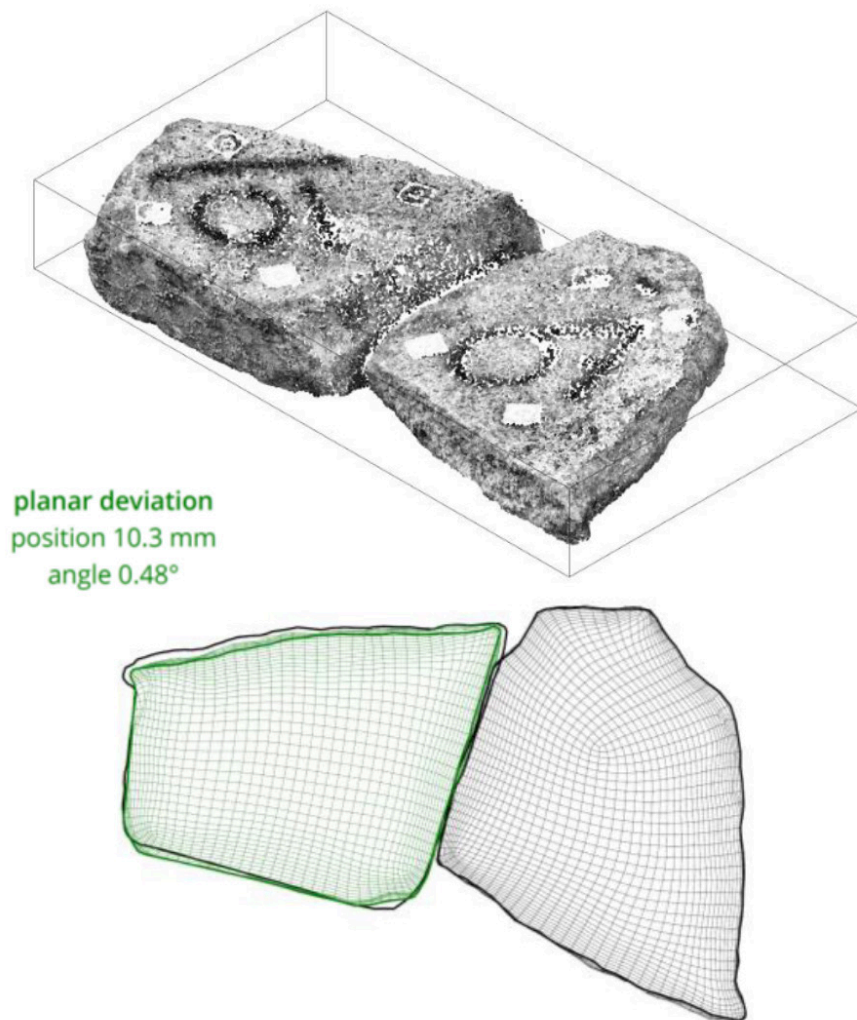
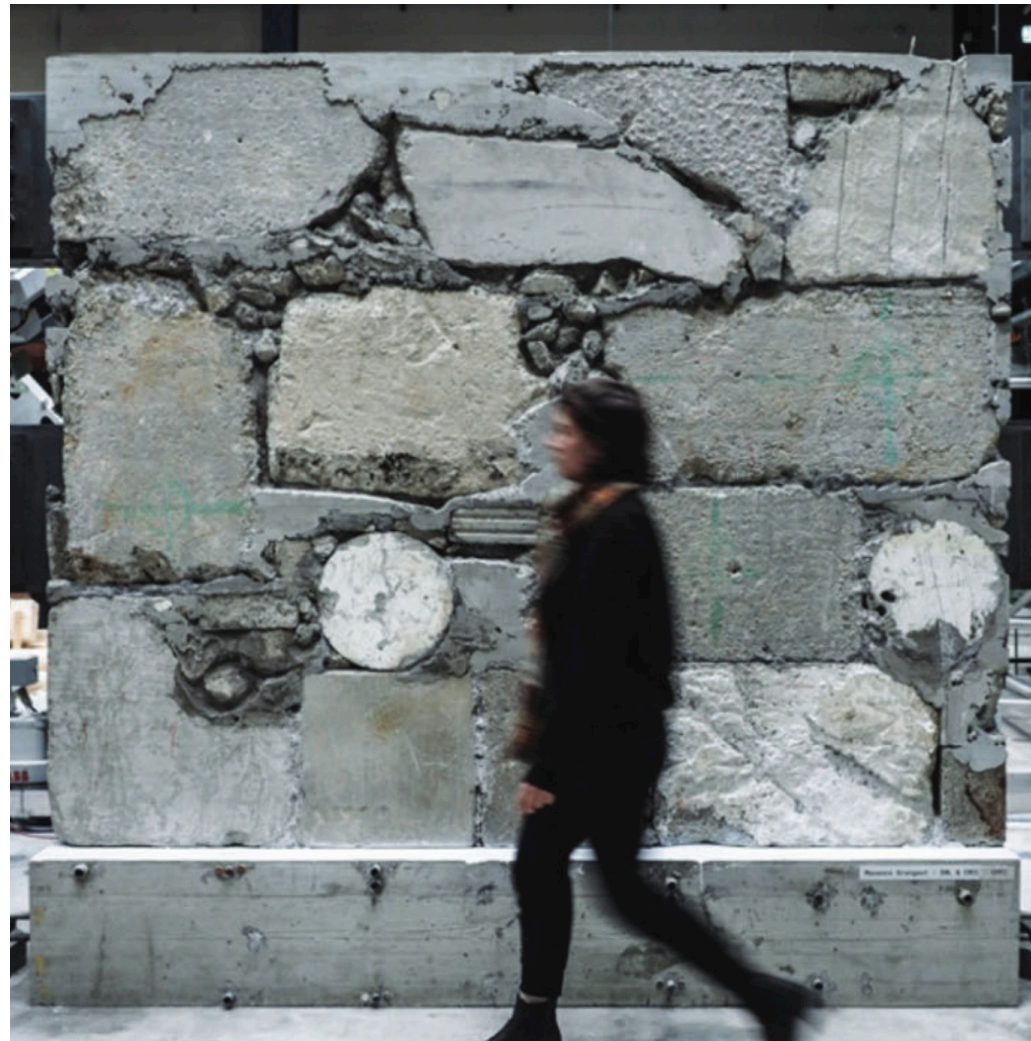
Load-Bearing Rubble Atlas



Load-Bearing Rubble Atlas



Load-Bearing Rubble Atlas

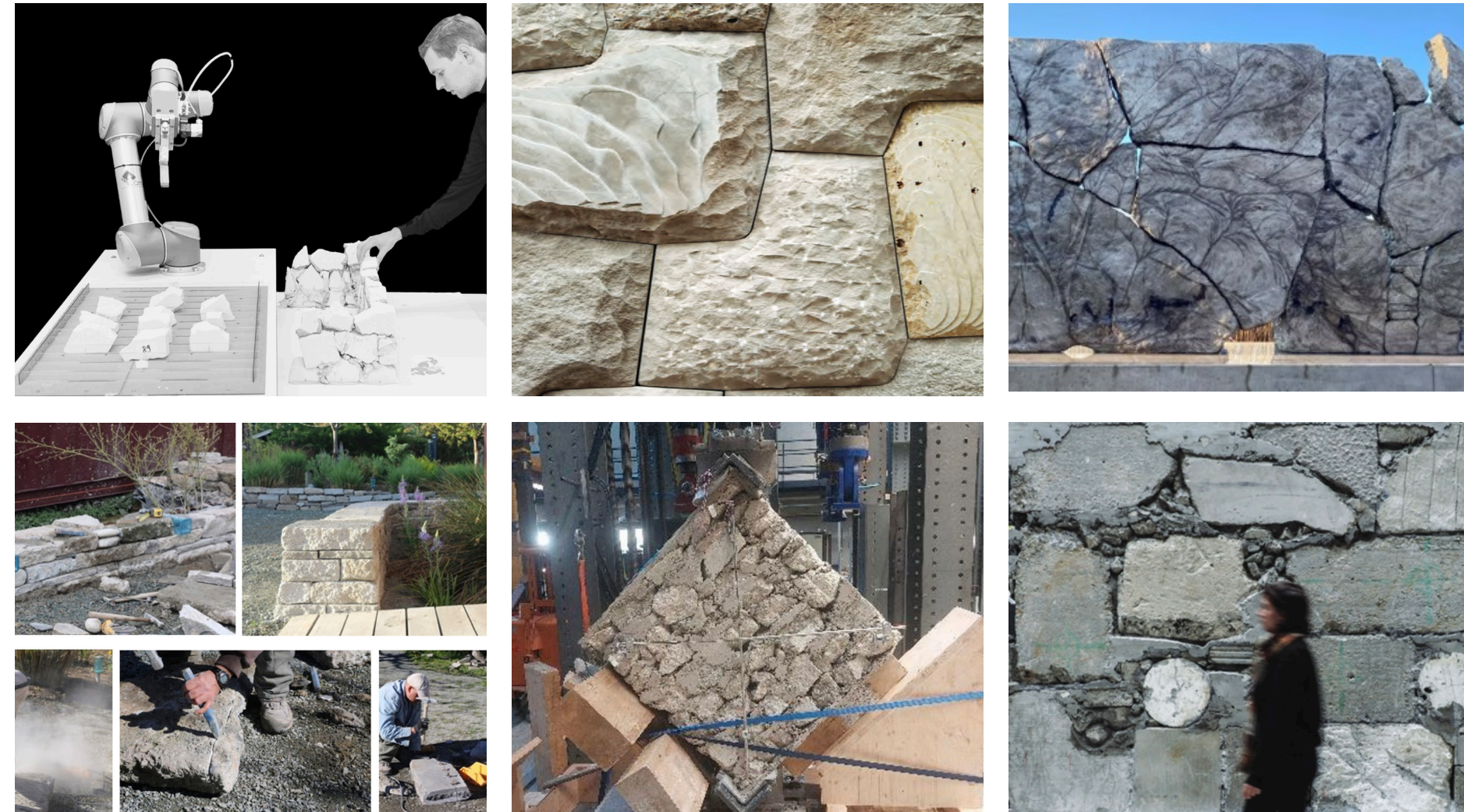


Scaling Rubble Walls



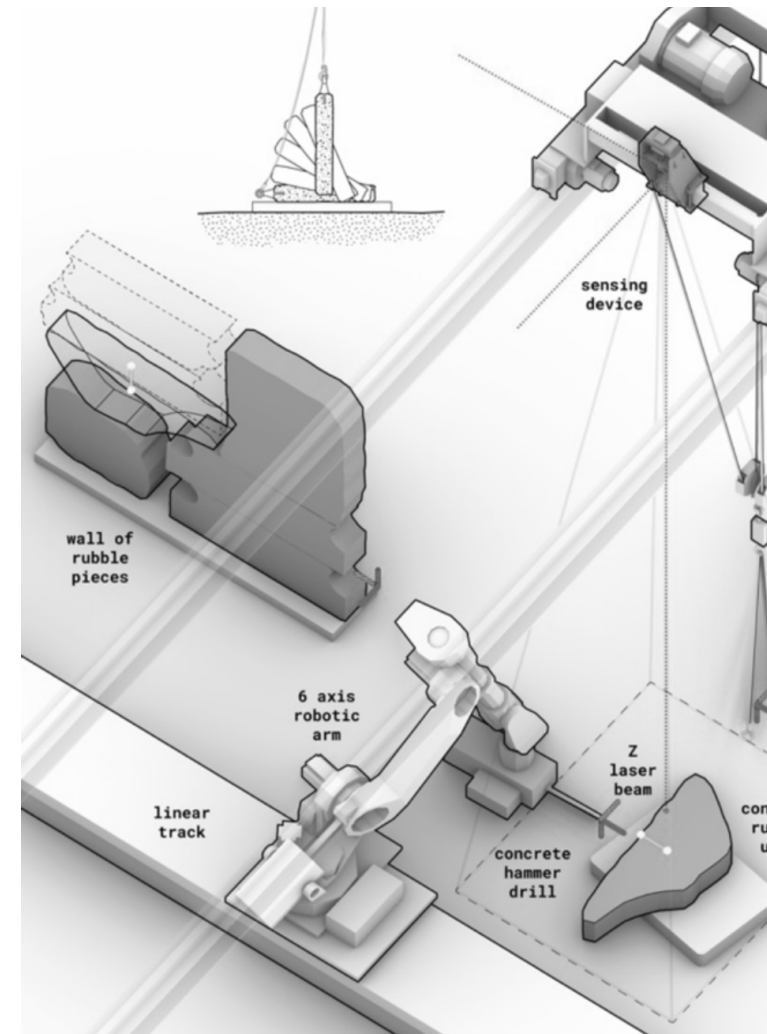
Grangeot et. al (2024)
Clifford (2018)
Taproot (n/d)
Oreb et al., (2024)
Ensamble (2023)

Scaling Rubble Walls



Grangeot et. al (2024)
Clifford (2018)
Taproot (n/d)
Oreb et al., (2024)
Ensamble (2023)

Challenges

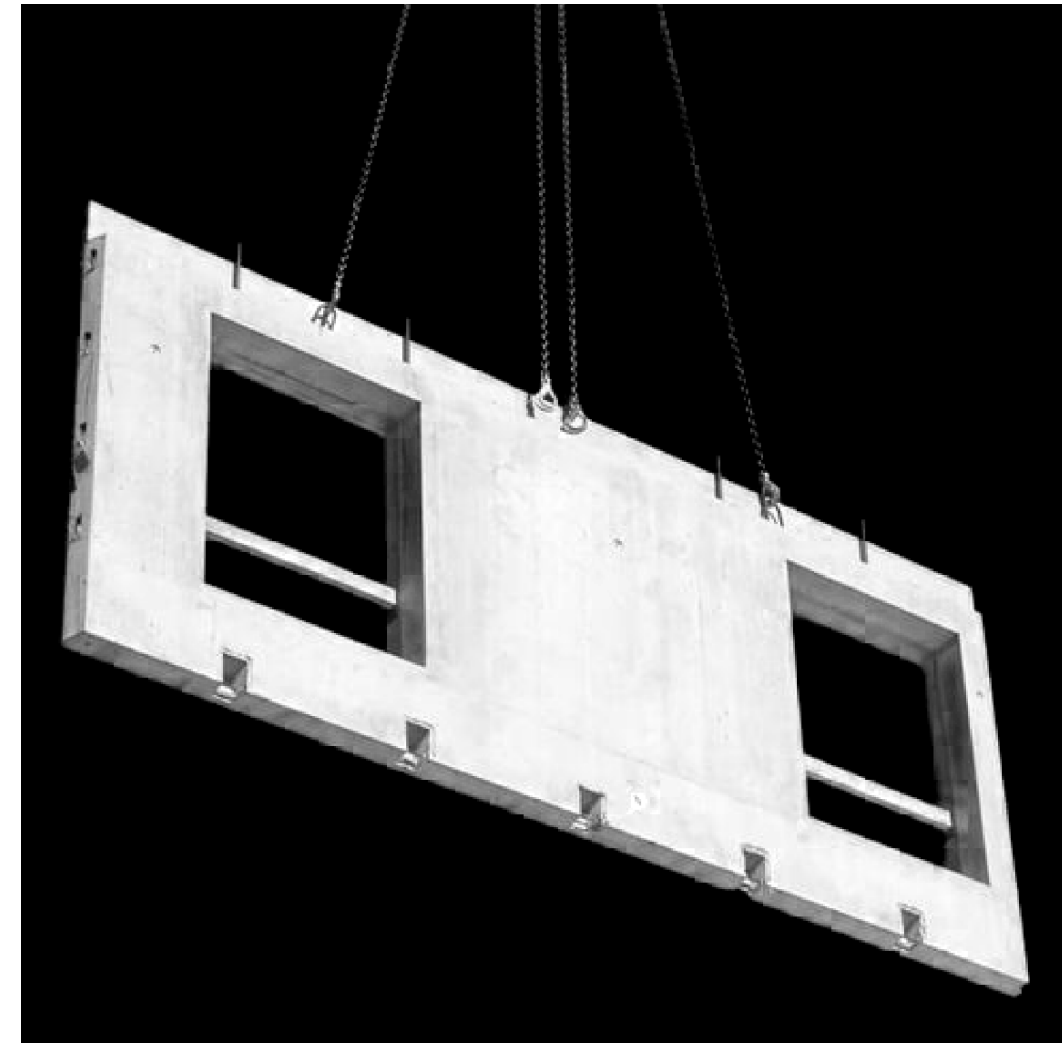




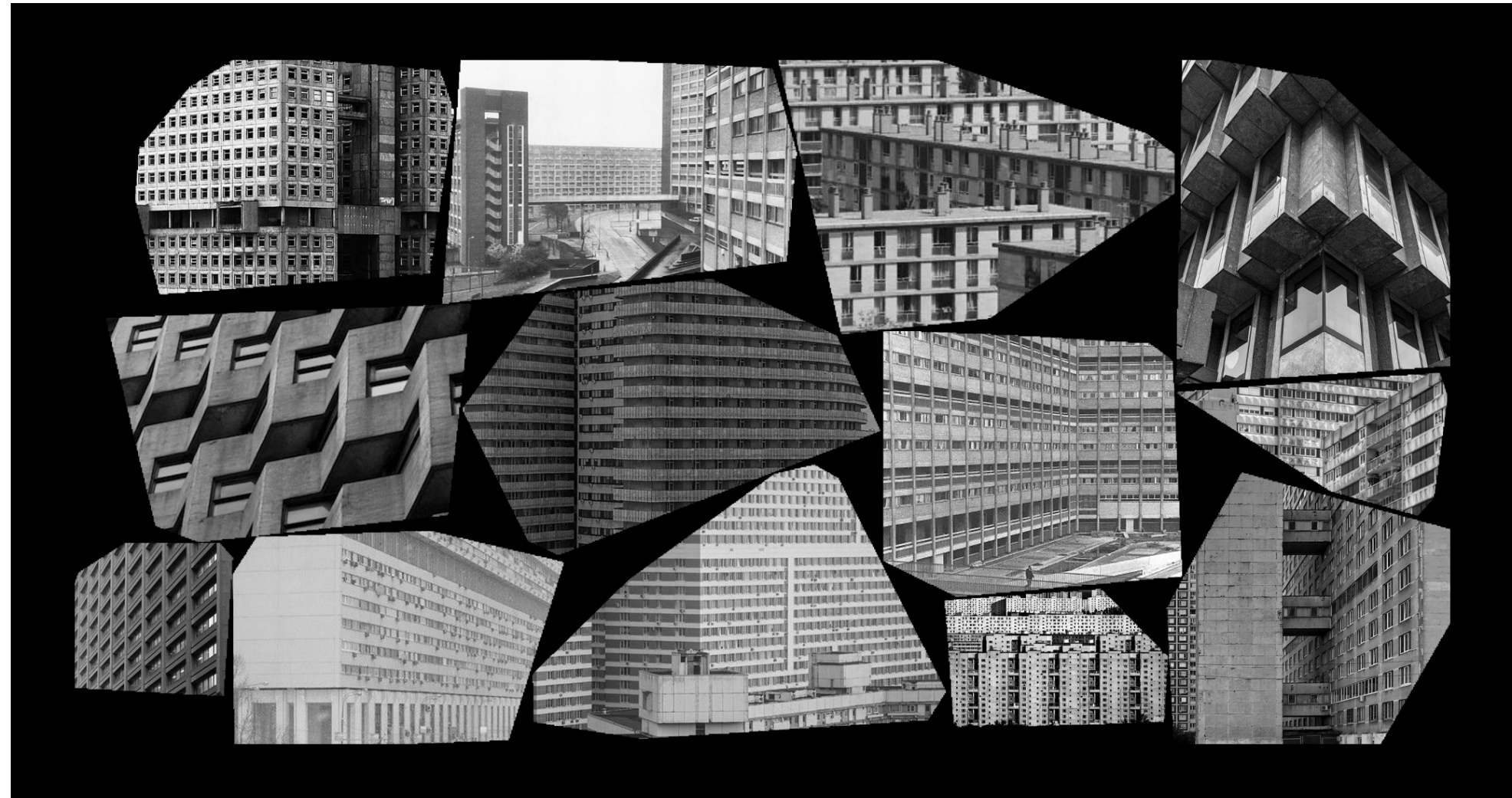
Precast Walls



A Bridge Between Irregularity And Repetitiveness



A Bridge Between Irregularity And Repetitiveness



‘[The] act of reconsuming becomes a character trait in the resultant architectures’





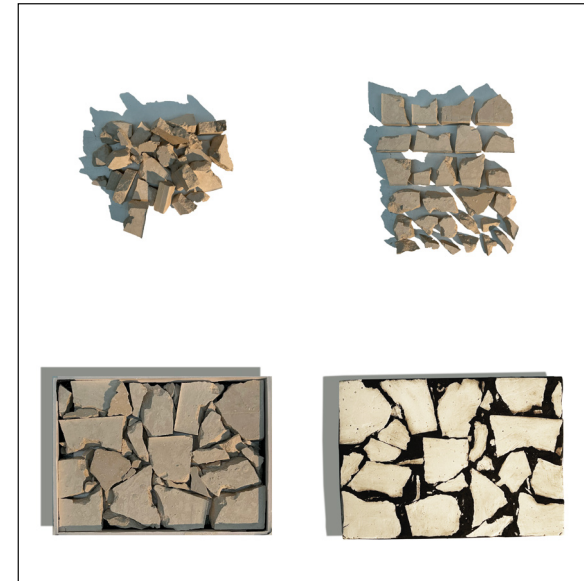
Inspiration



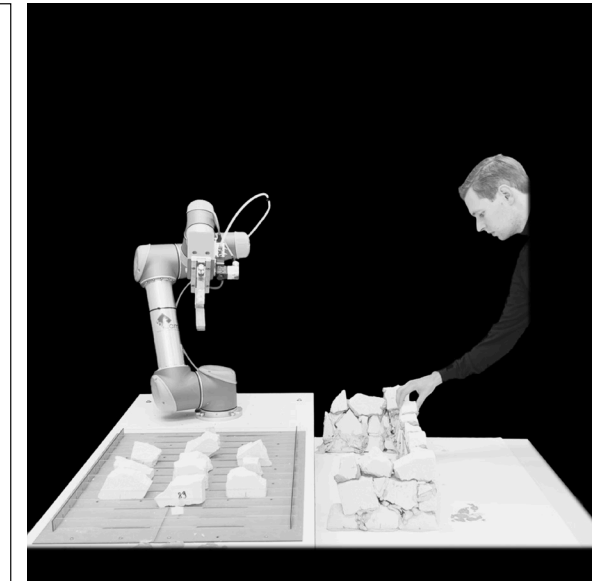
Advantages Horizontal



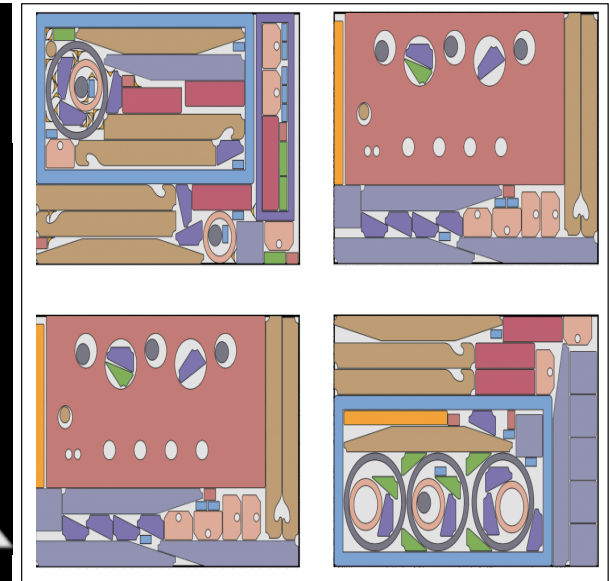
Vibration



Air Tightness

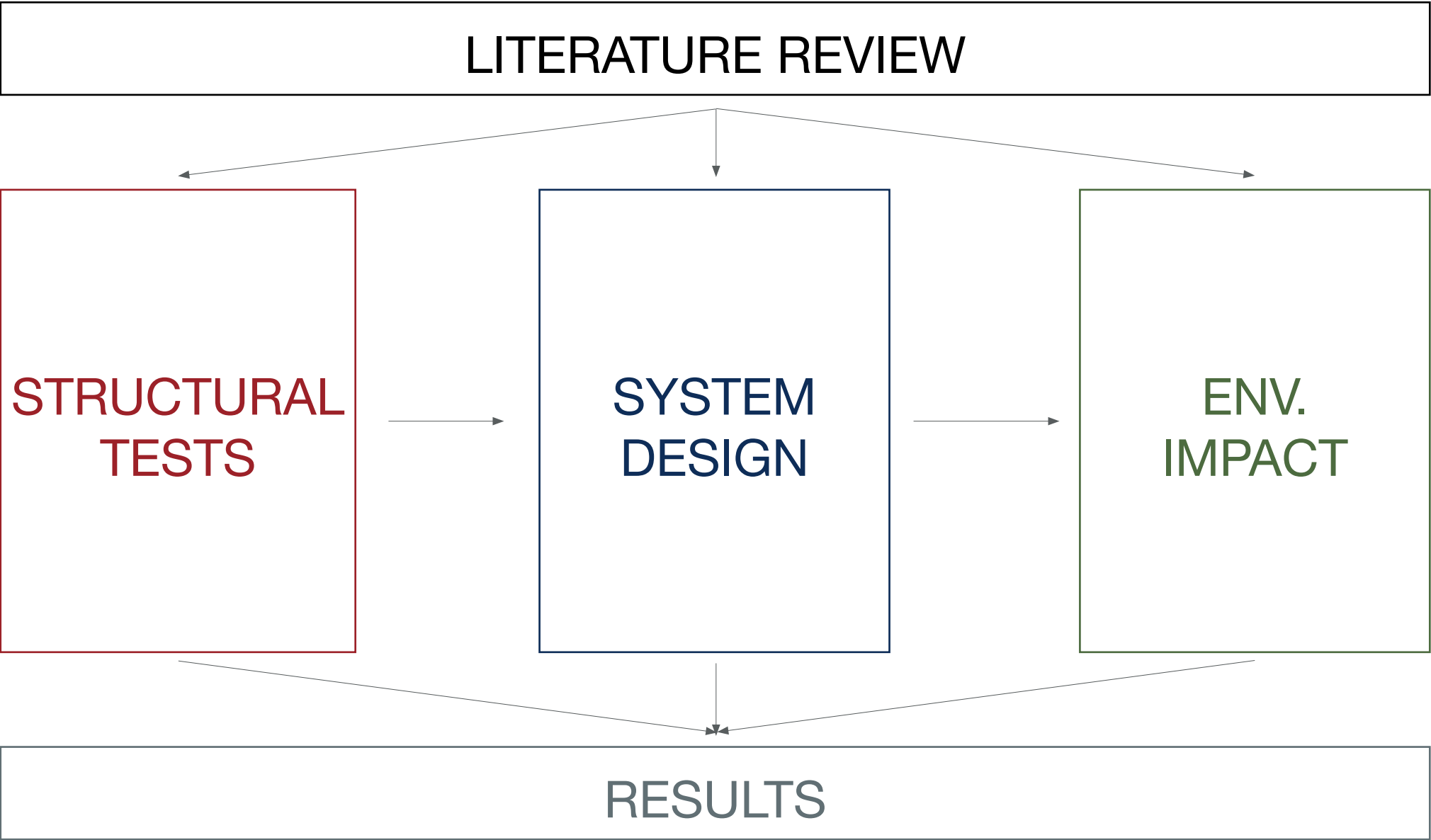


No Str. Integrity

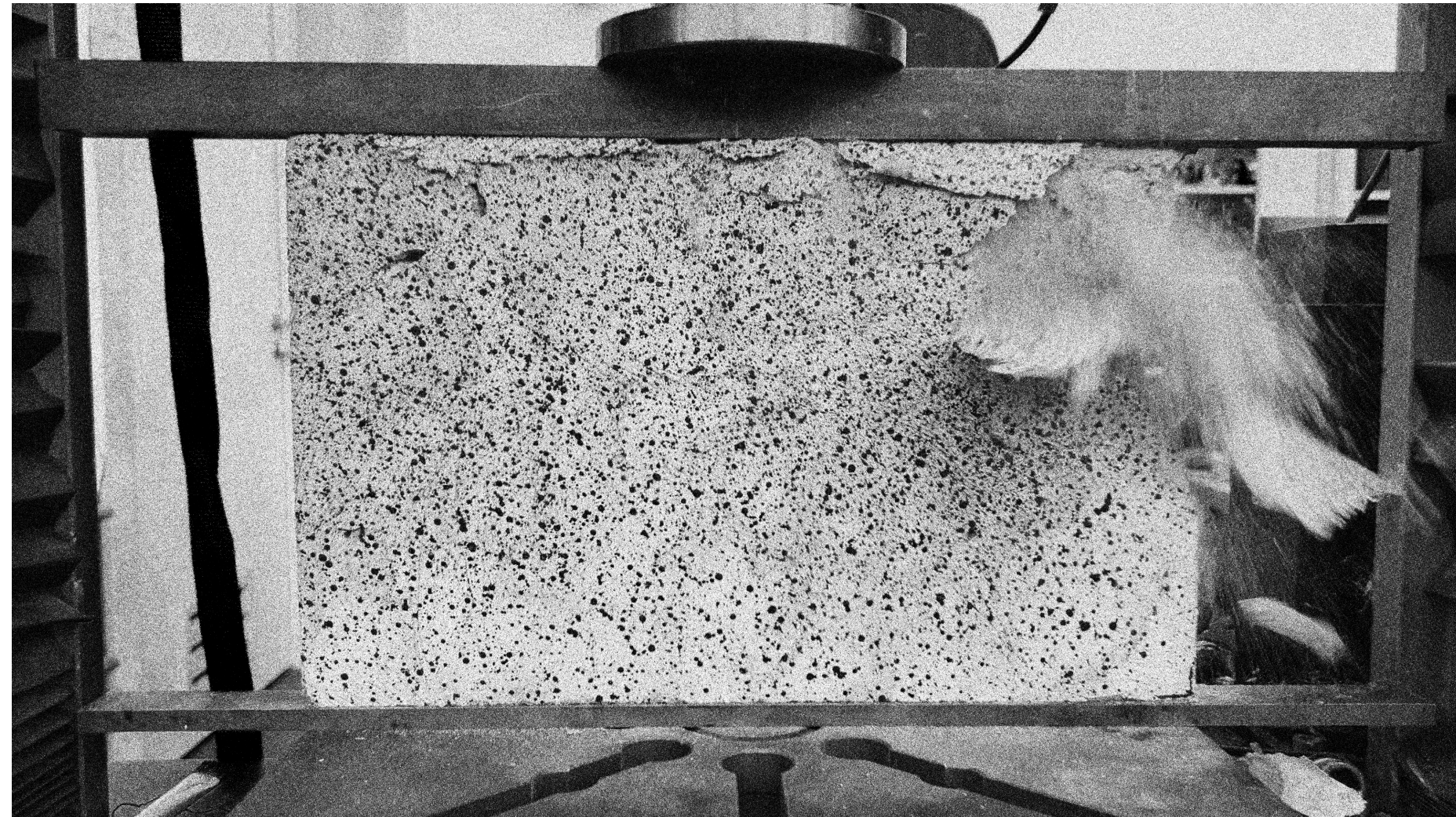


Freedom Of Placement

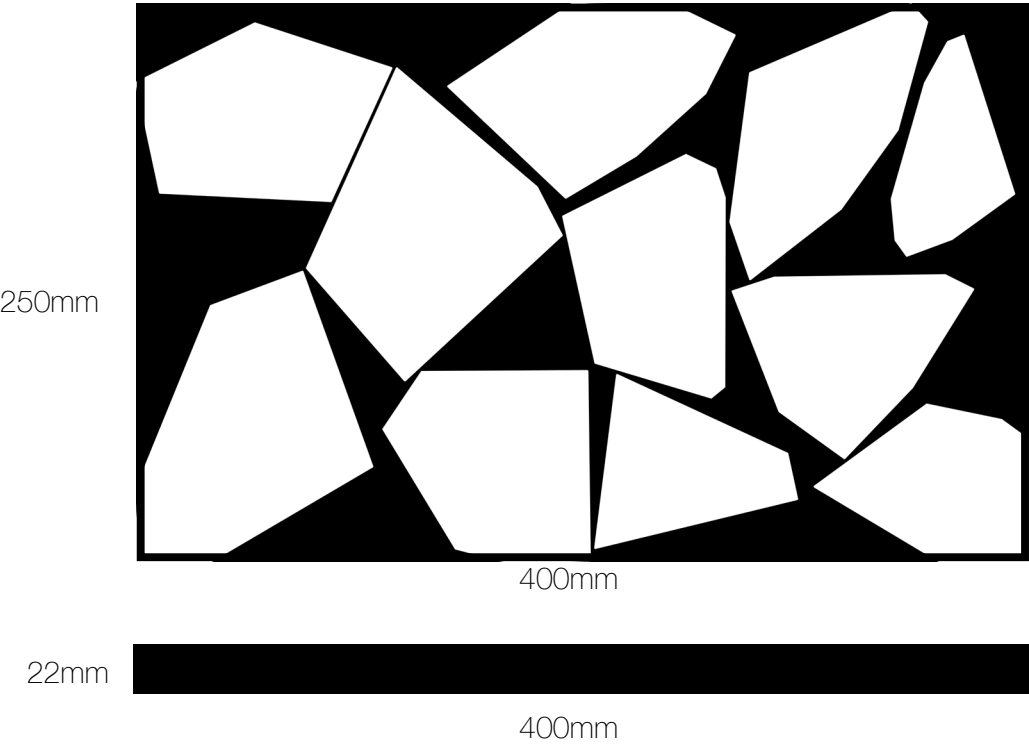
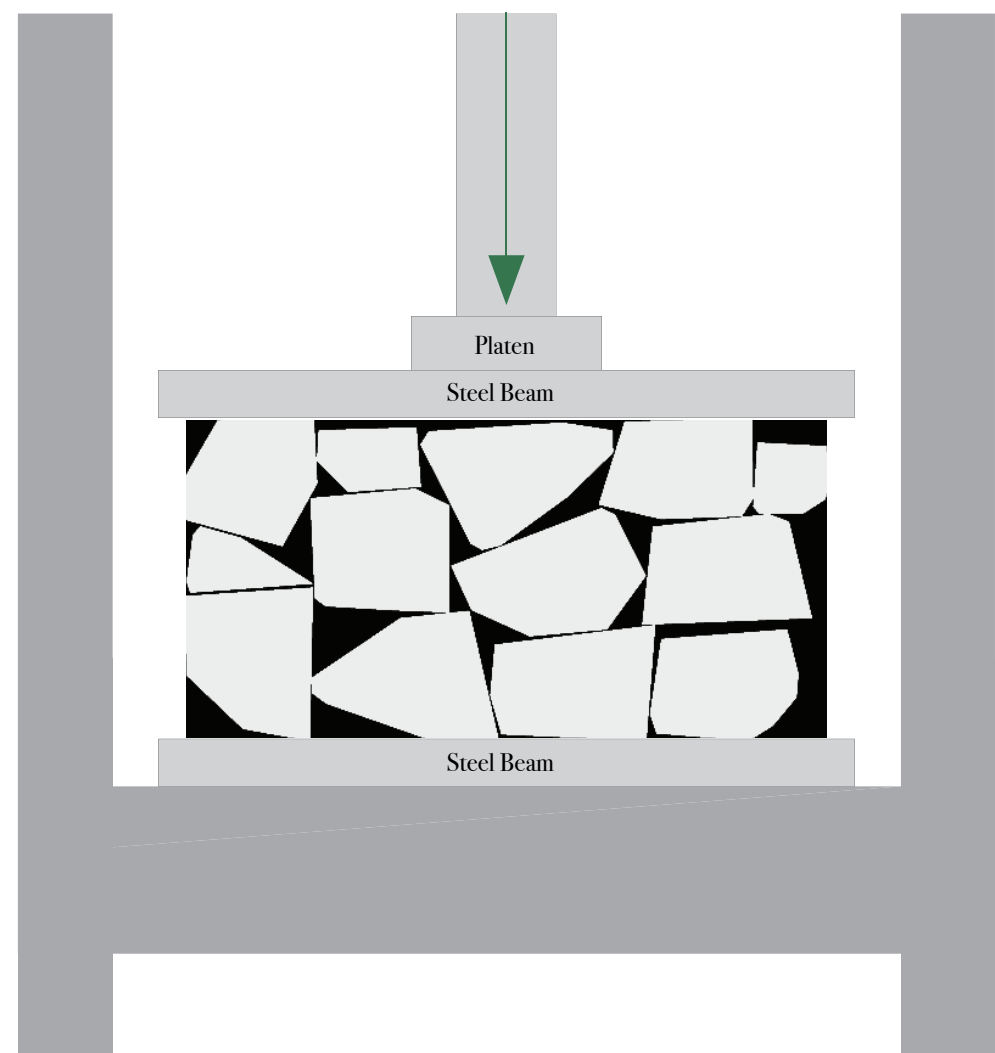
Research Pillars



Structural Tests



1:10 Compression Tests



Sample Production



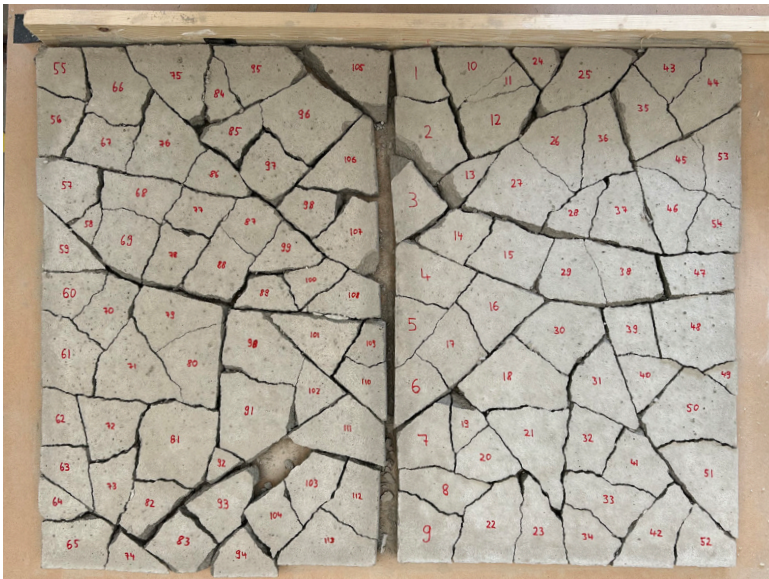
Step II



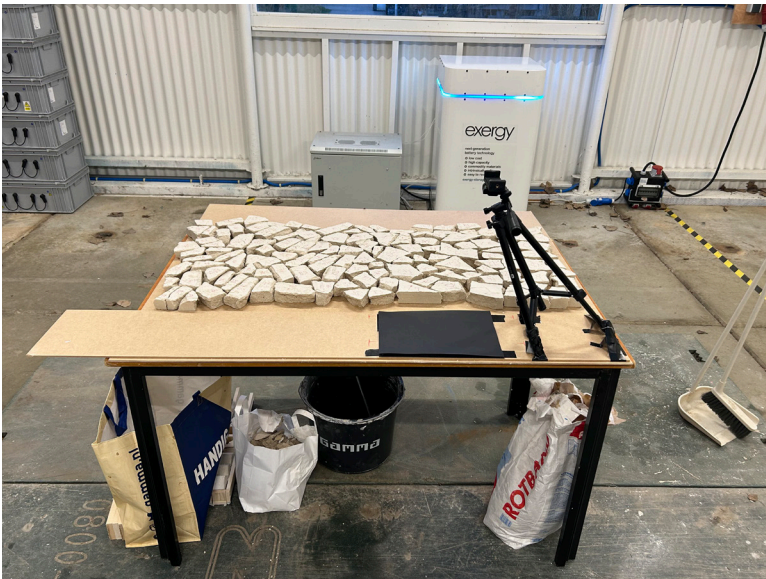
Step IV



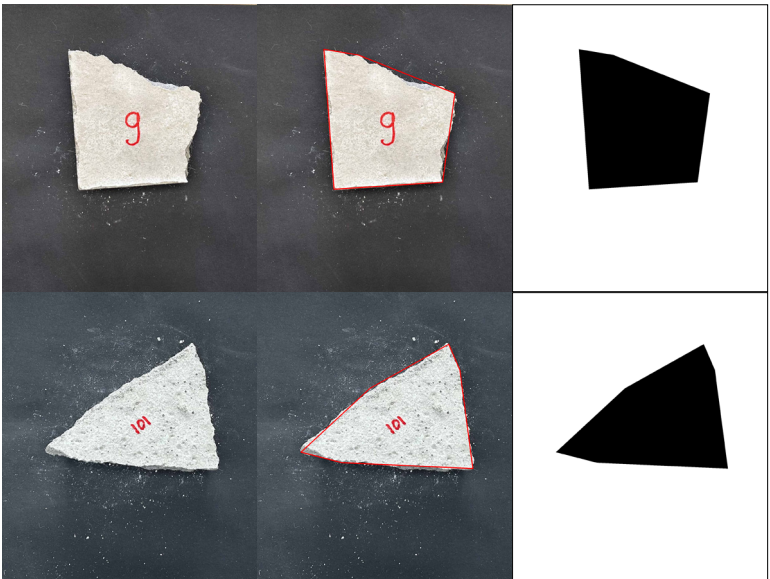
Step V



Step VI

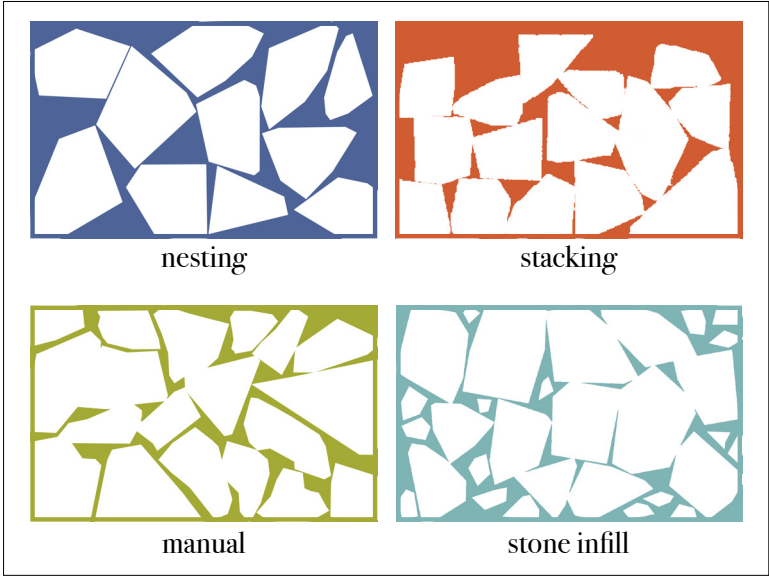


Step VII



Step IX

Sample Production



Step X



Step XI



Step XIII



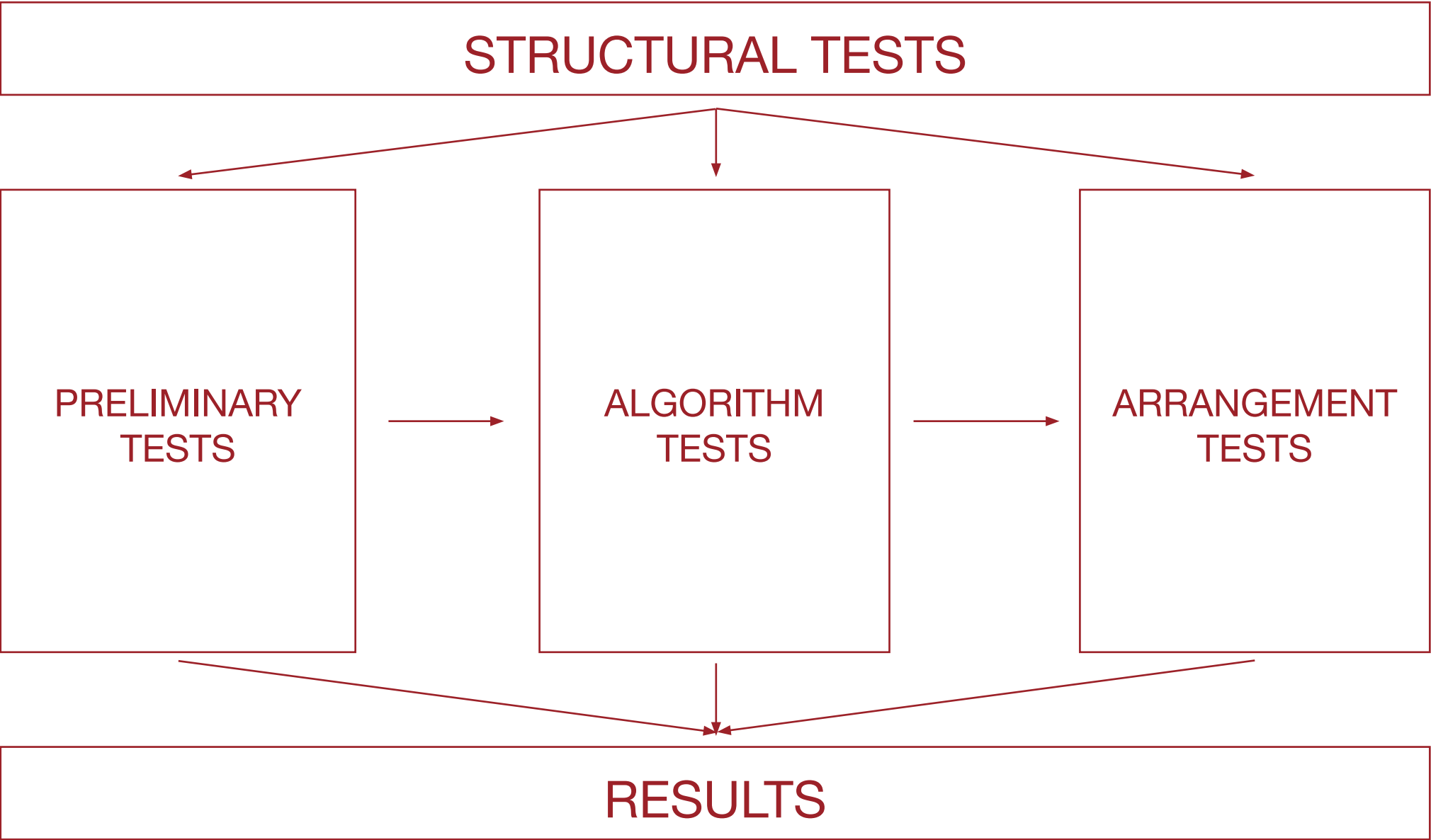
Step XIII

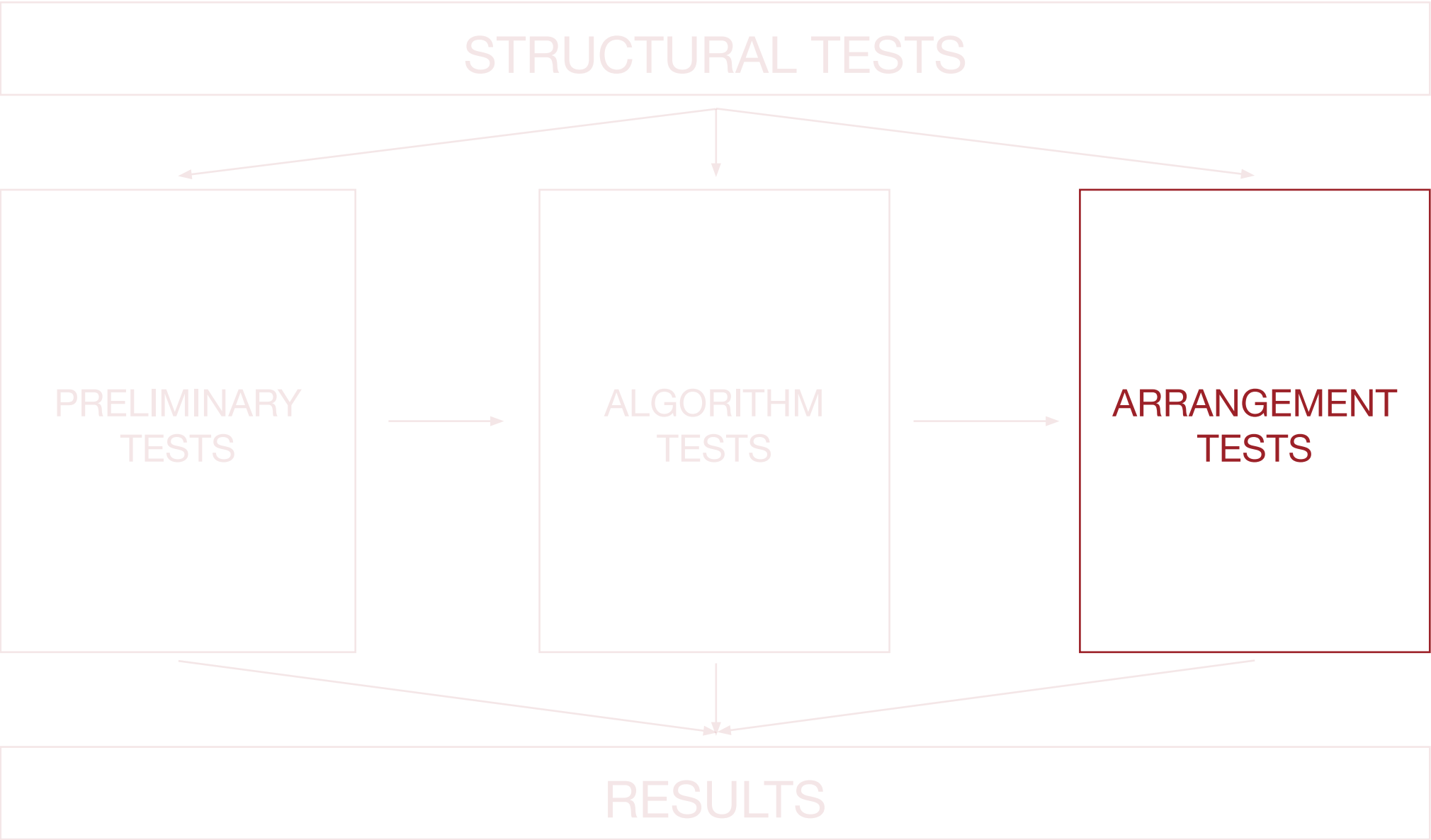


Step XIV



Step XV

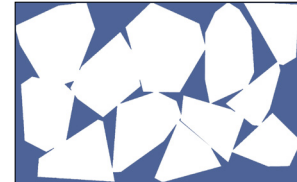




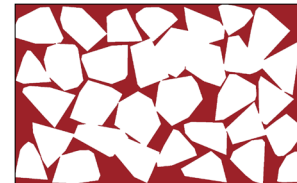
Arrangement Tests

Arrangement (17-04-25)

5x



5x



5x



5x



5x



Objectives

- I. Compare rubble diameters
- II. Compare infill types
- III. Benchmark with unreinforced wall

Arrangement Tests

30% Infill

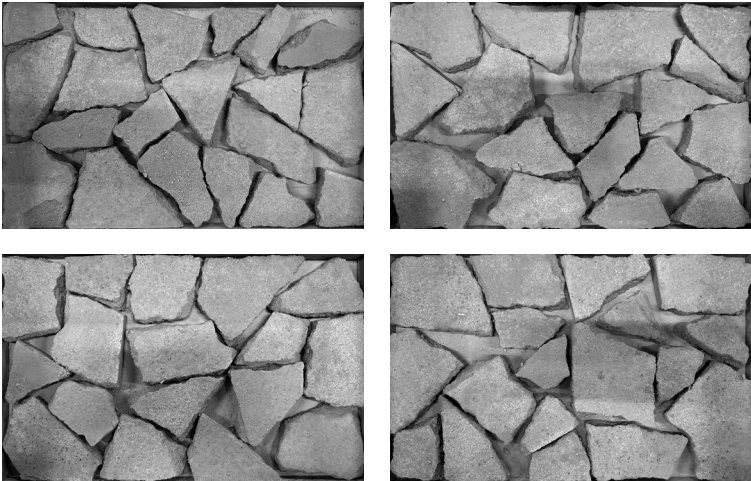


Large Stones

Small Stones

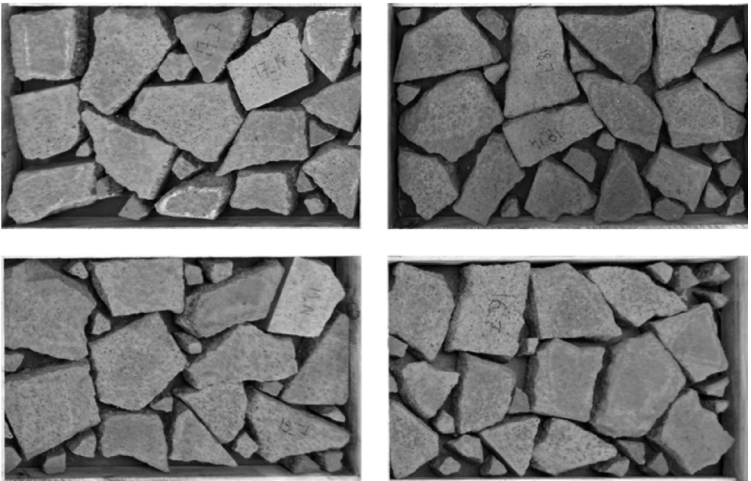


20% Infill



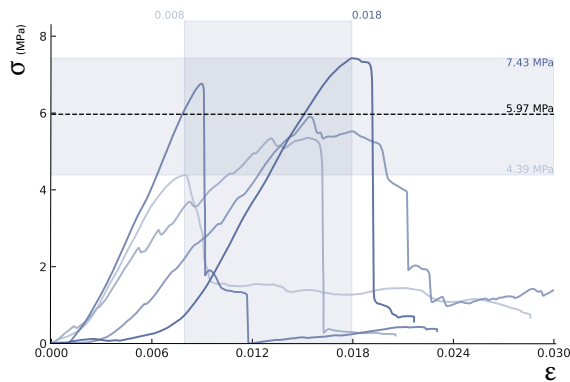
Manual

Stone Infill

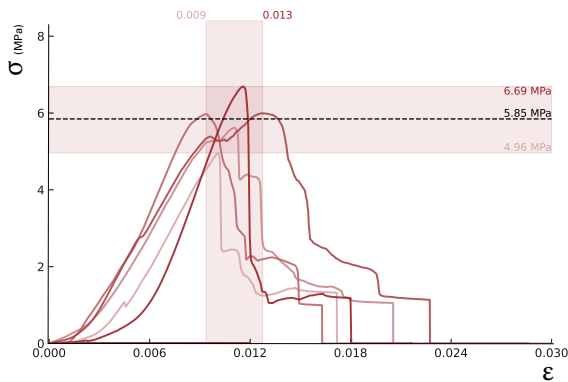


Arrangement Tests

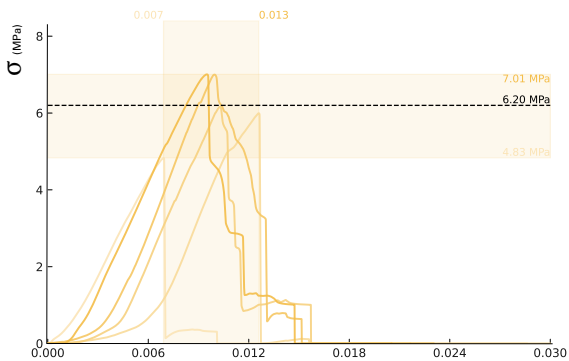
Large Stones (W01-05)



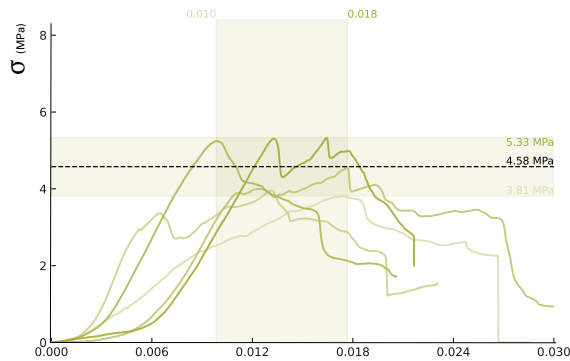
Small Stones (W06-10)



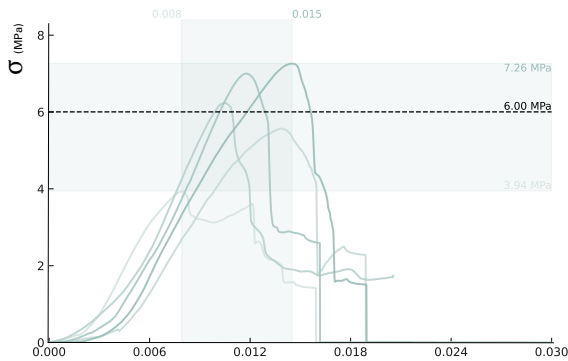
No Rubble (W21-25)



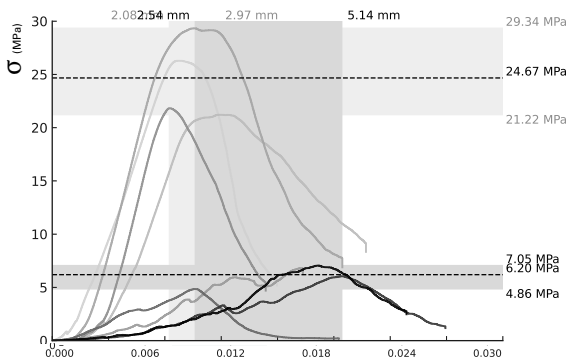
Manual (W11-15)



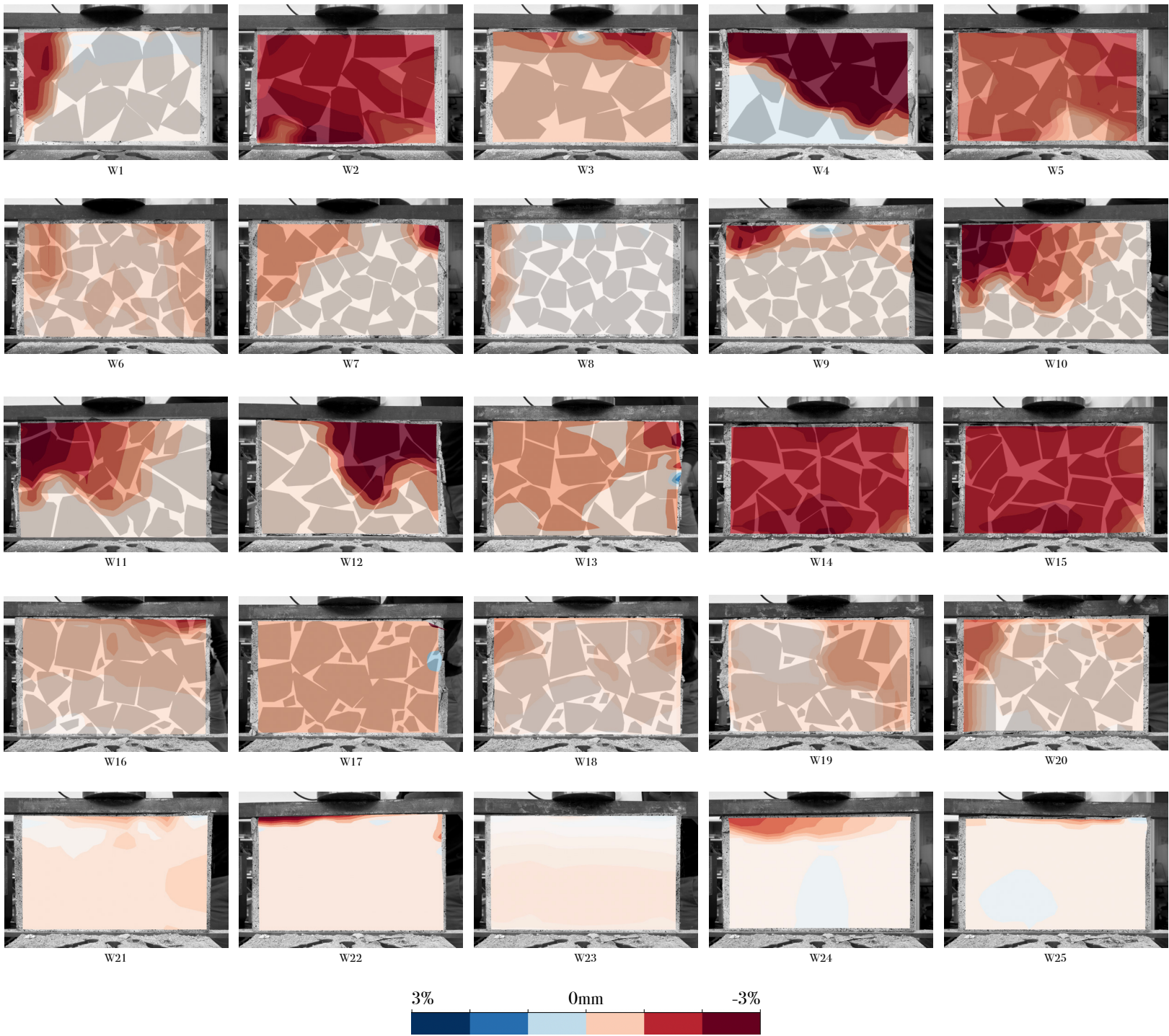
Stones Infill (W16-20)



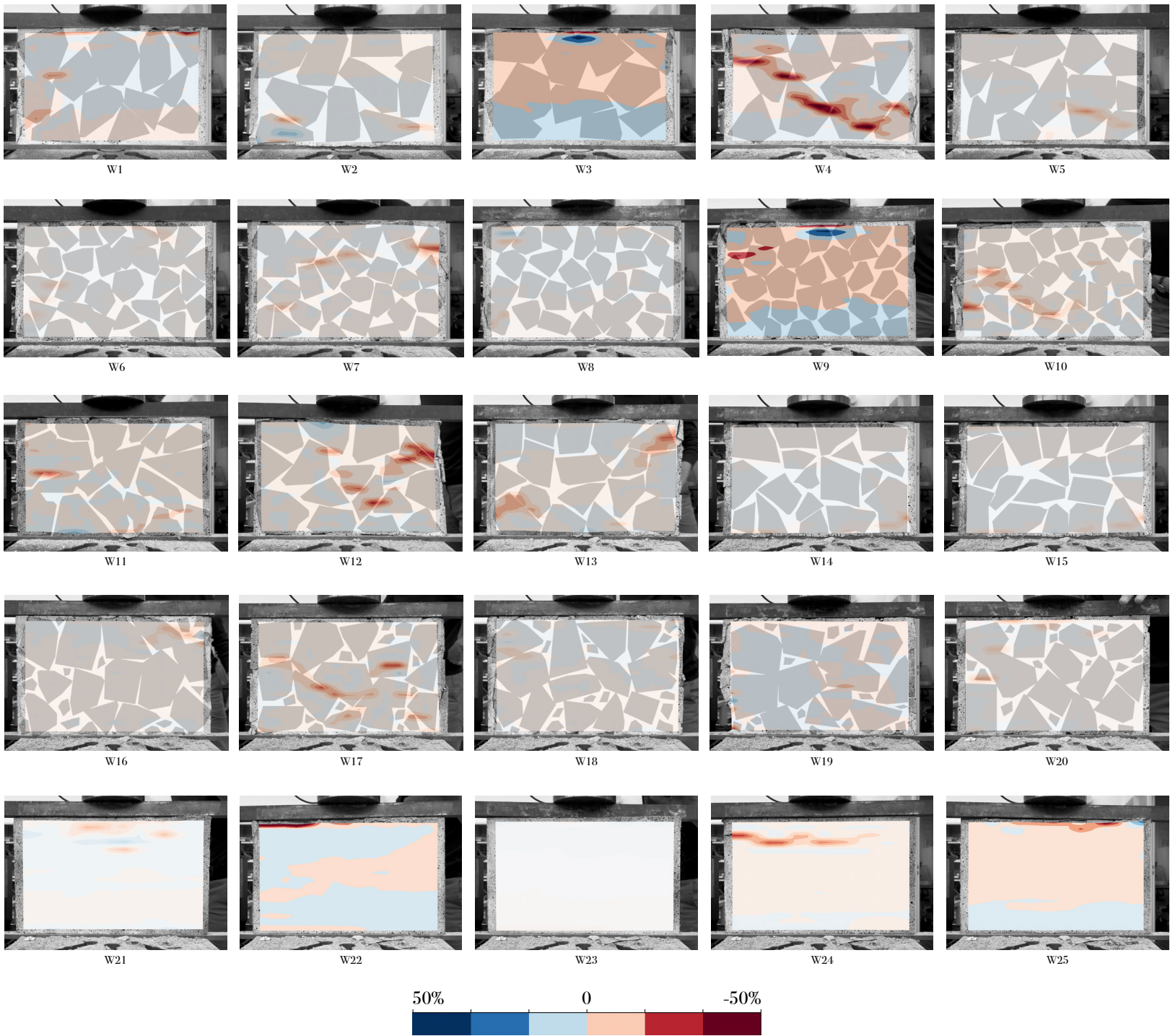
Rubble / Infill



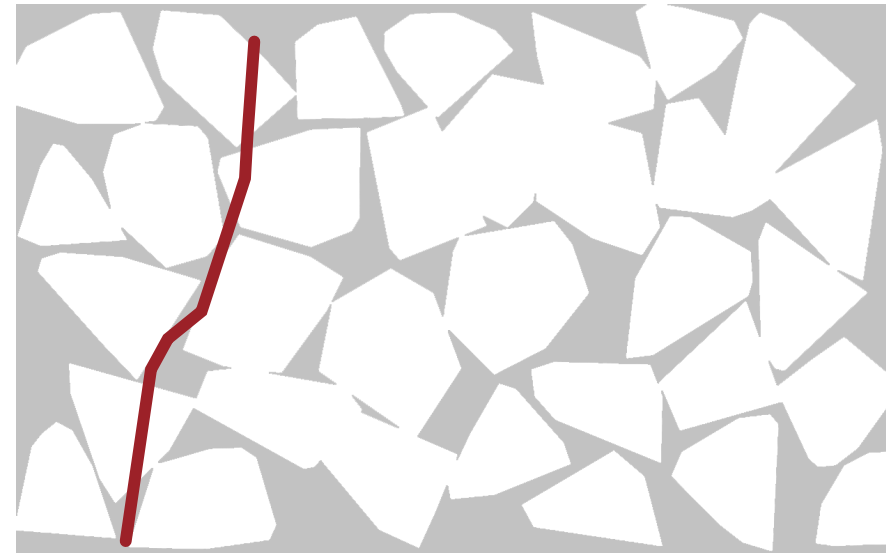
Displacement



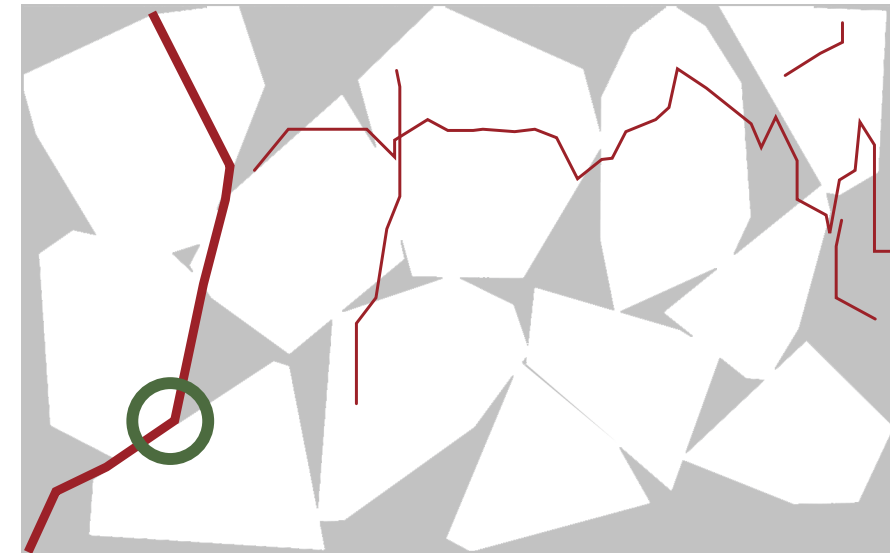
Strain



Conclusion



W6 - Small Stones



W1 - Large Stones

Conclusion



W14 Top



W14 Bottom

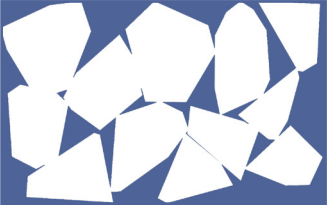
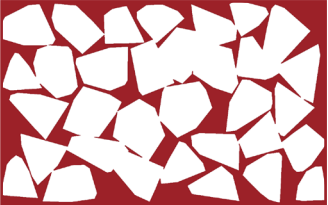


W19 Top

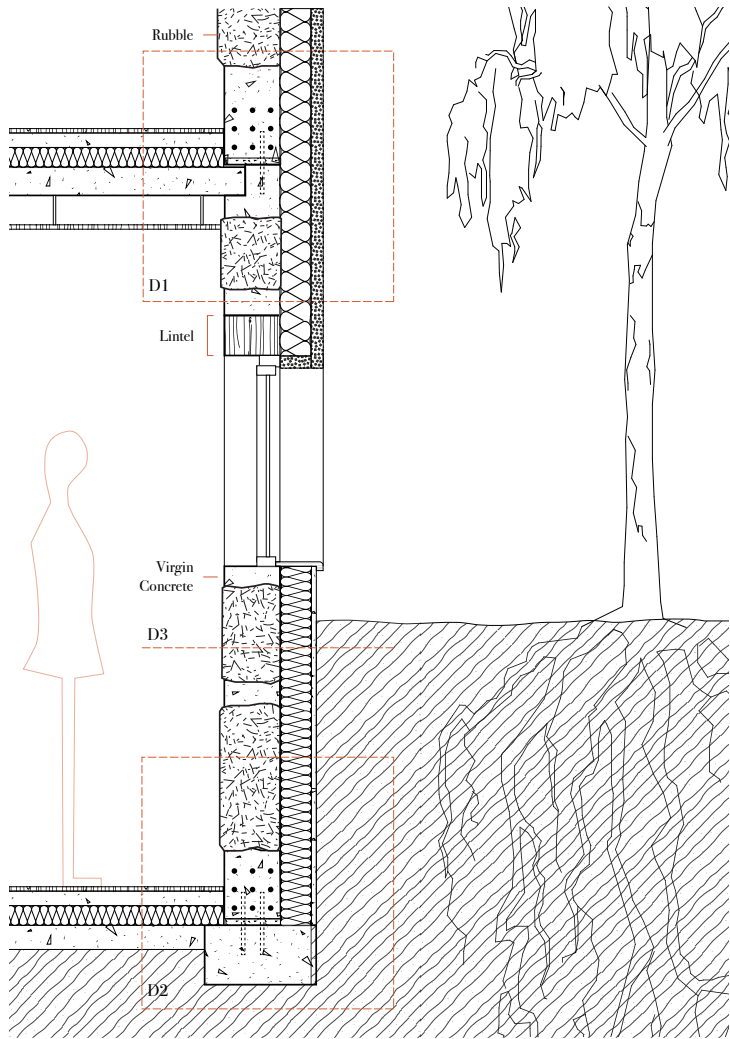


W19 Bottom

Conclusion

	Large Stones	Small Stones	Manual	Stone Infill	No Rubble
					
Failure Behaviour	Quasibrittle	Quasibrittle	Showed Compaction	Quasibrittle	Brittle
Disadvantages	Less Predictable High Weight	More Labour	Gap Filling Problem	Manual Labour	-
Advantages	Less Labour	Reliable Less Weight	More Rubble	Strong + More Rubble	-

System Design



Compressive Strength

~ 5 MPa

Applications

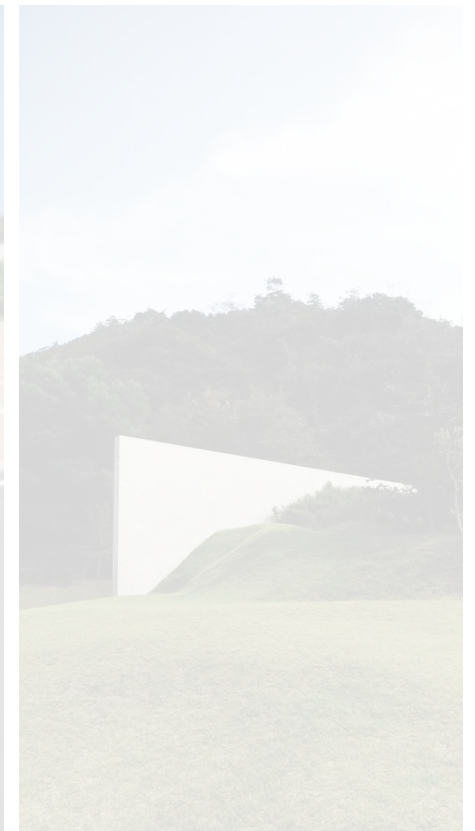
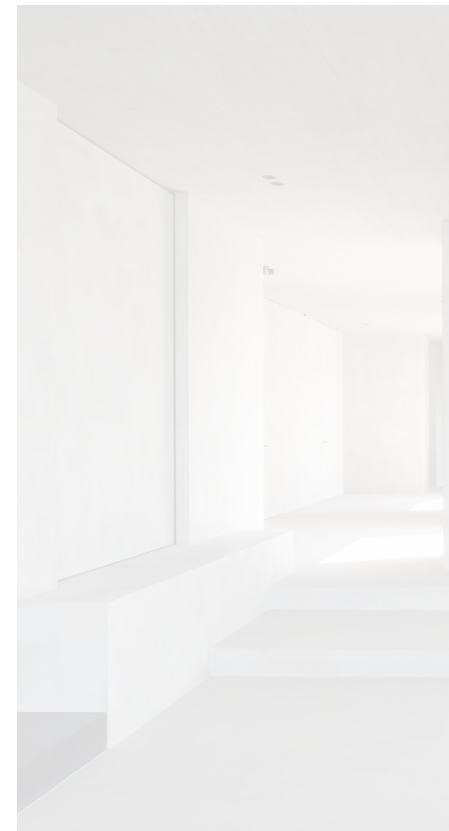


Load-Bearing



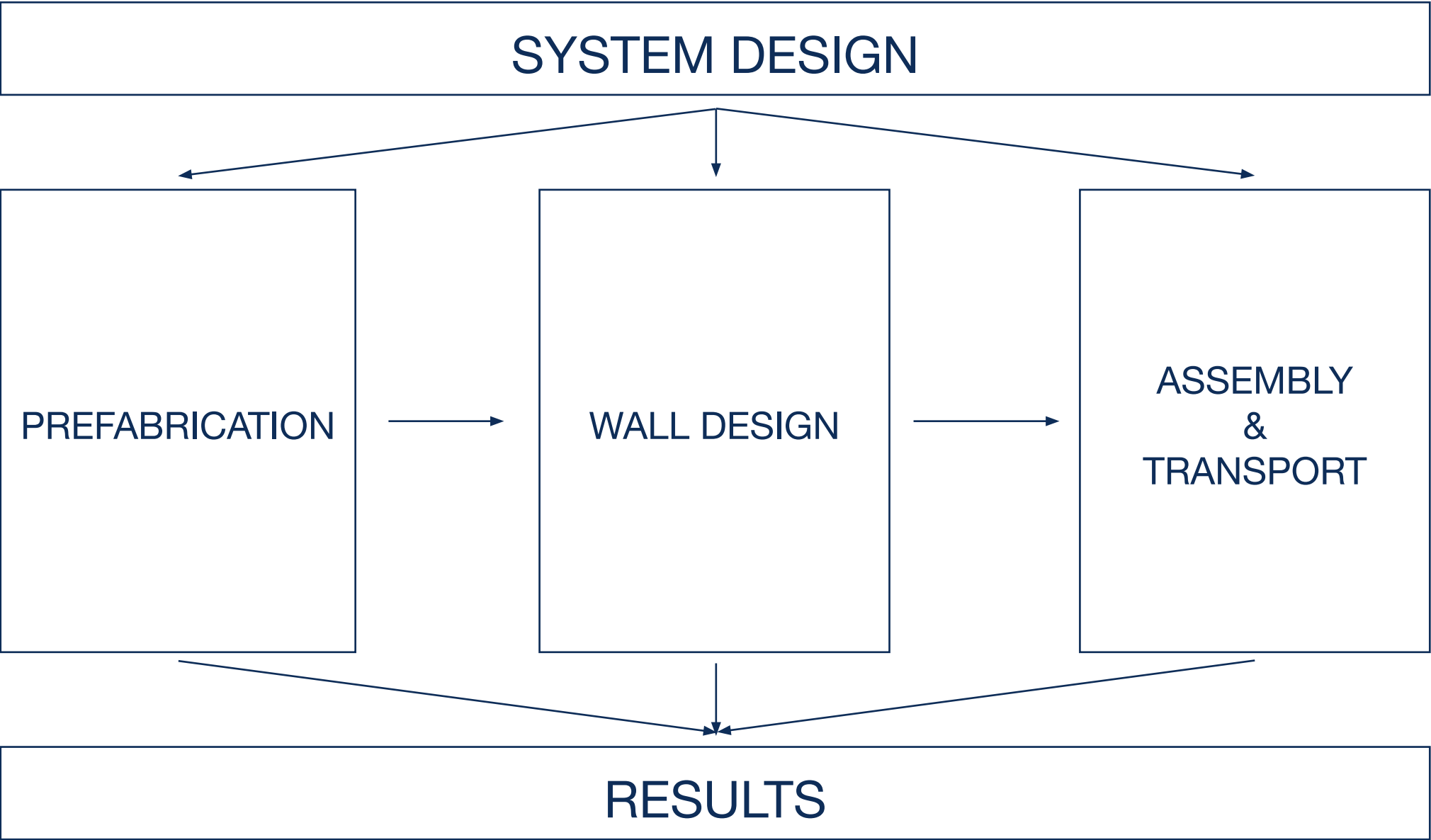
Self-Weight Only

Applications

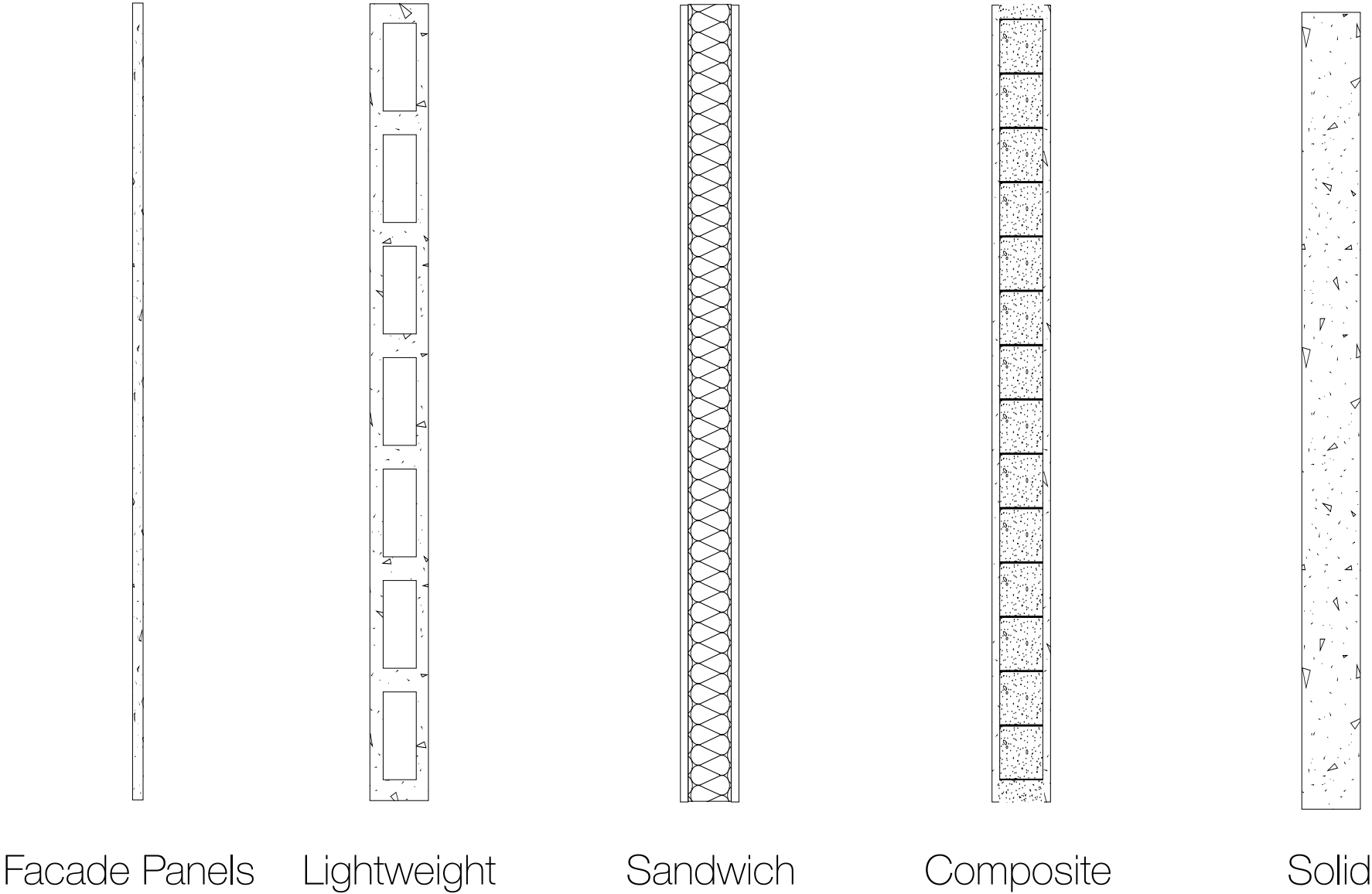


Load-Bearing

Self-Weight Only



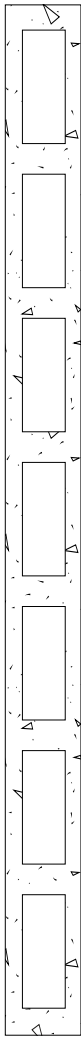
Precast Walls



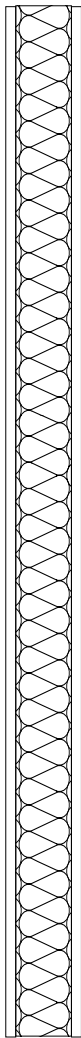
Precast Walls



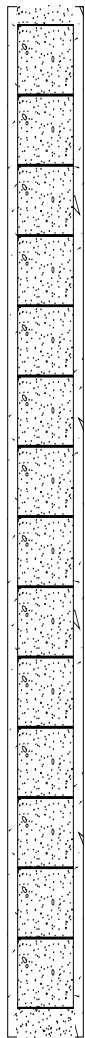
Facade Panels



Lightweight



Sandwich



Composite



Solid

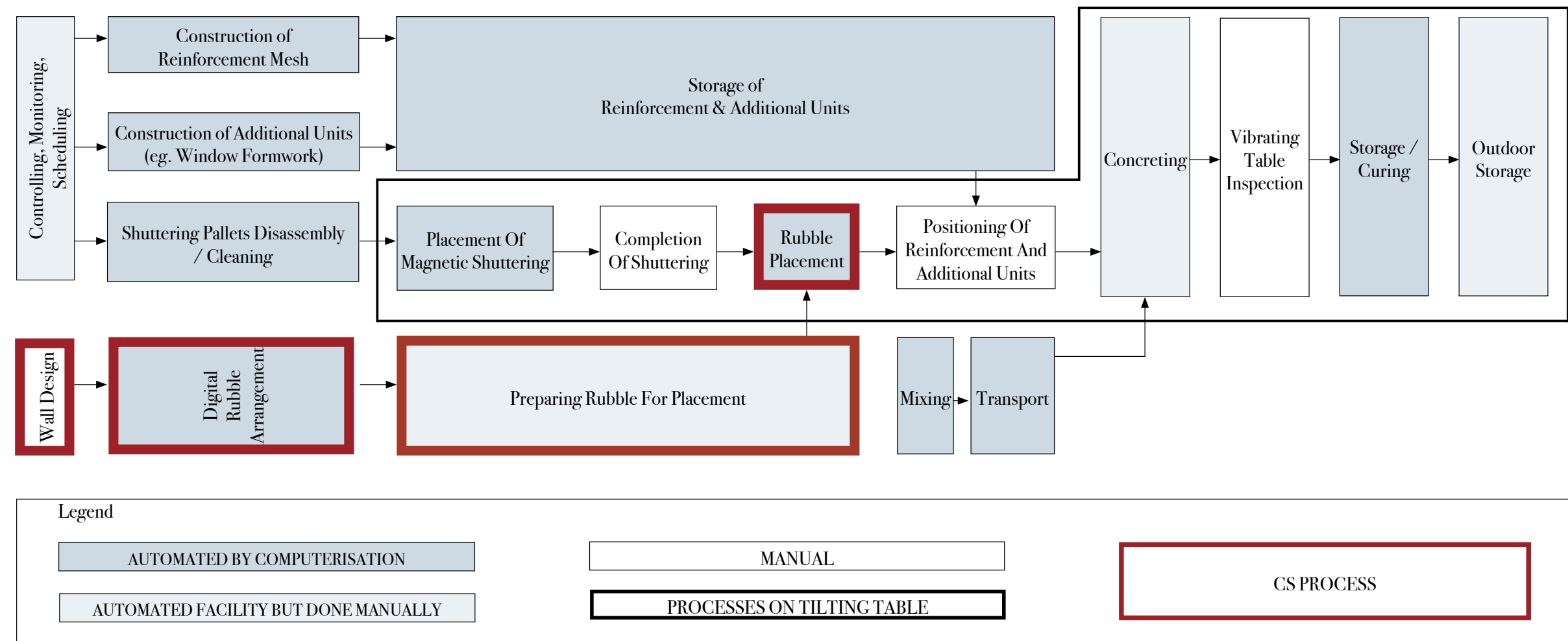


Cyclopean
Spolia

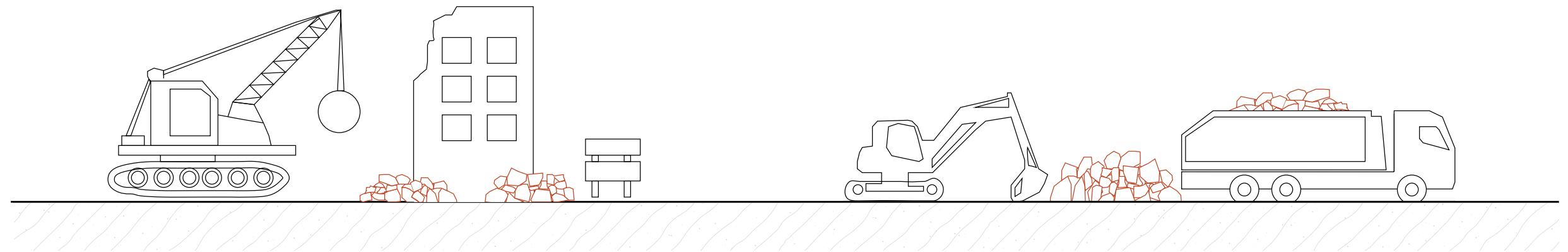
Stationary System



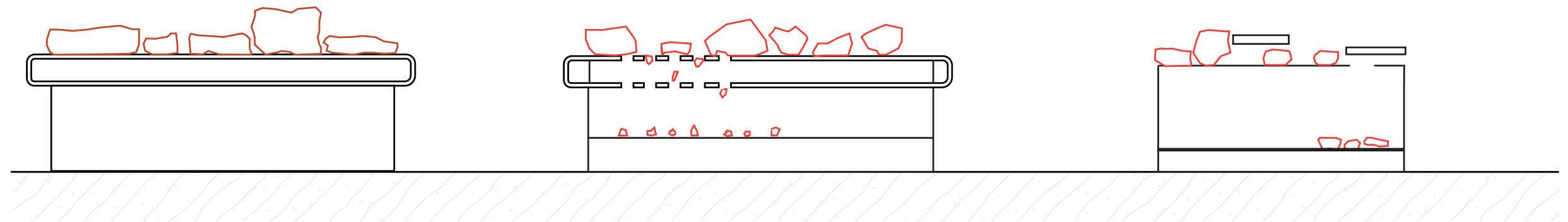
Automation



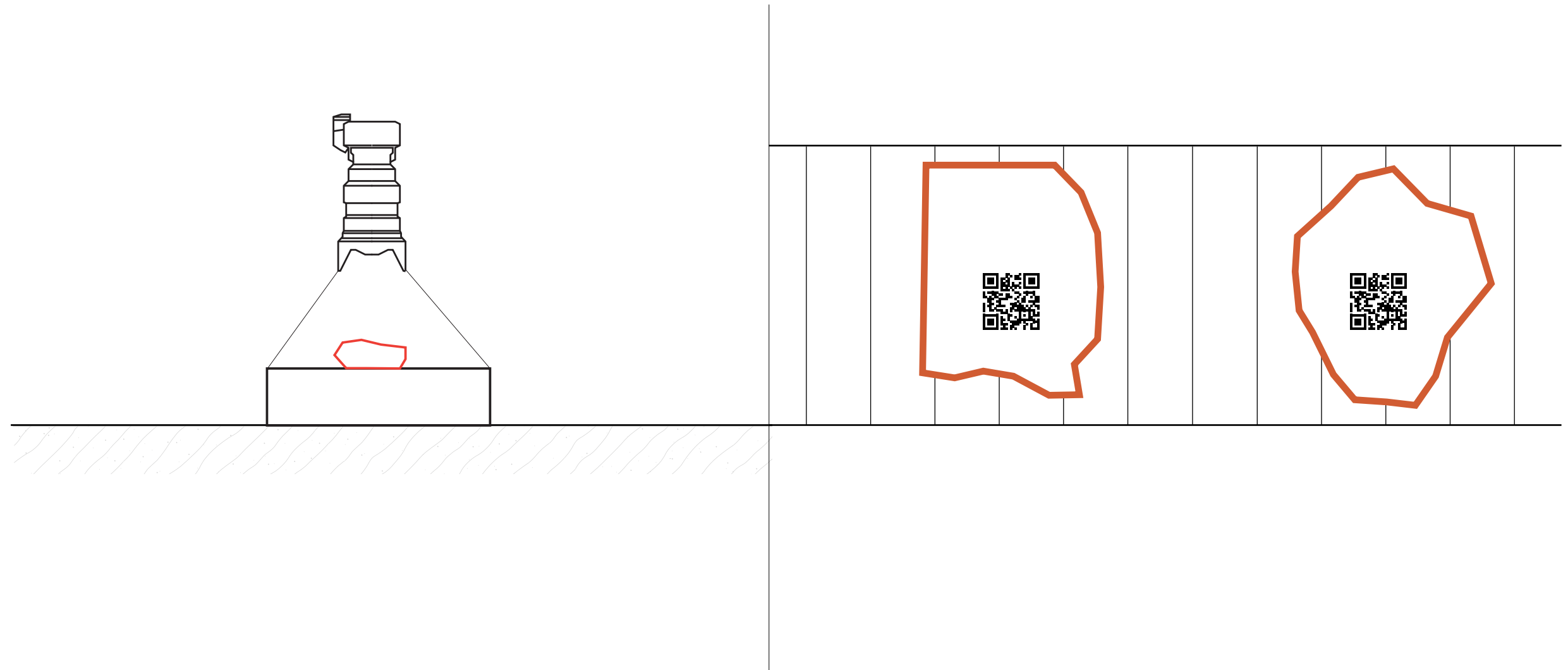
Cyclopean Spolia Precast Process



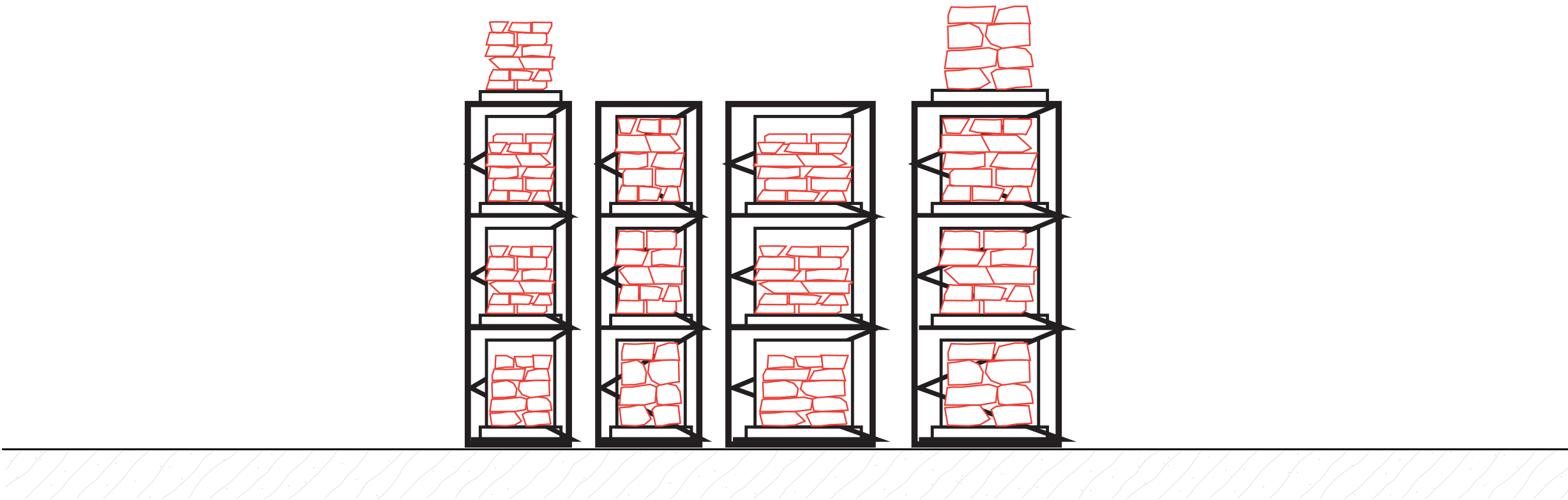
Cyclopean Spolia Precast Process



Cyclopean Spolia Precast Process

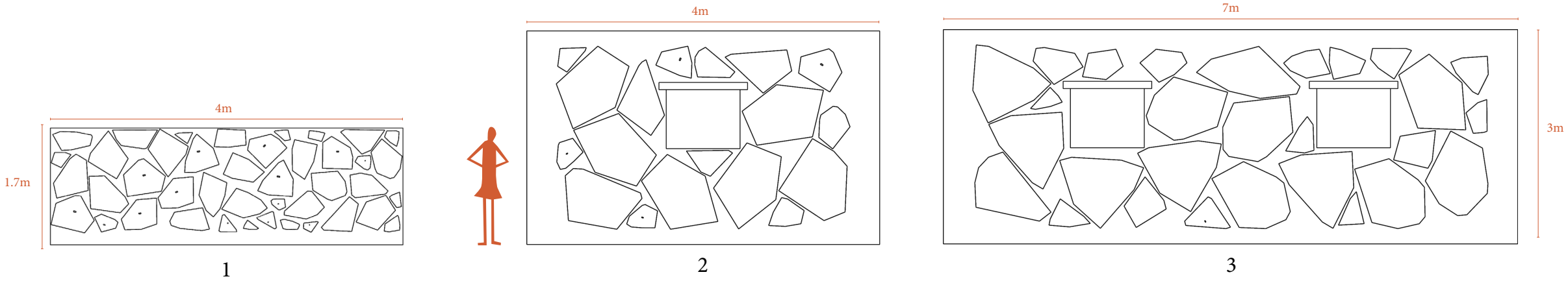


Cyclopean Spolia Precast Process

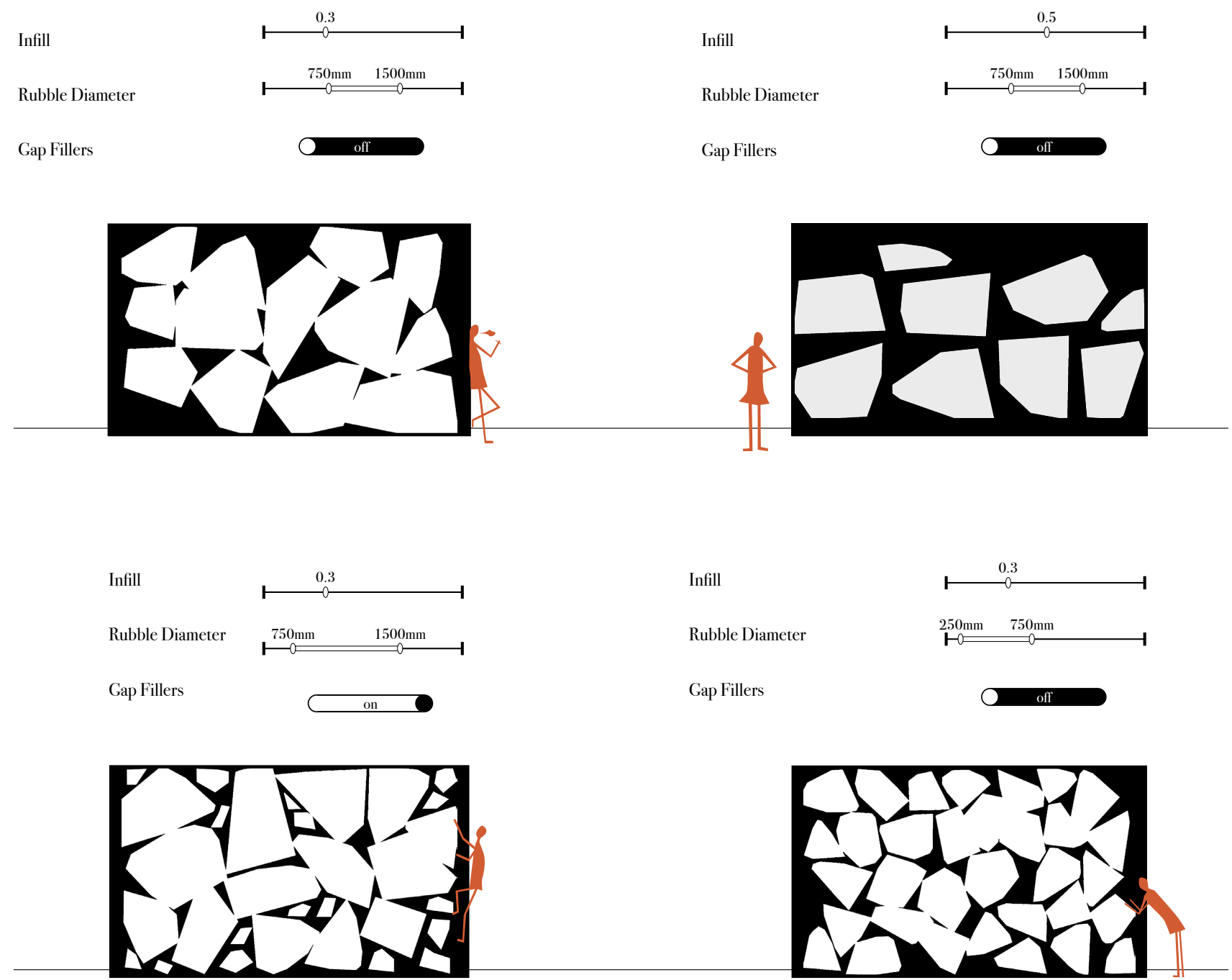


Thickness	Thickness	Thickness	Thickness
< 200 mm	> 200 mm	< 200 mm	> 200 mm
Diameter	Diameter	Diameter	Diameter
< 750 mm	< 750 mm	> 750 mm	> 750 mm

Wall Sizes



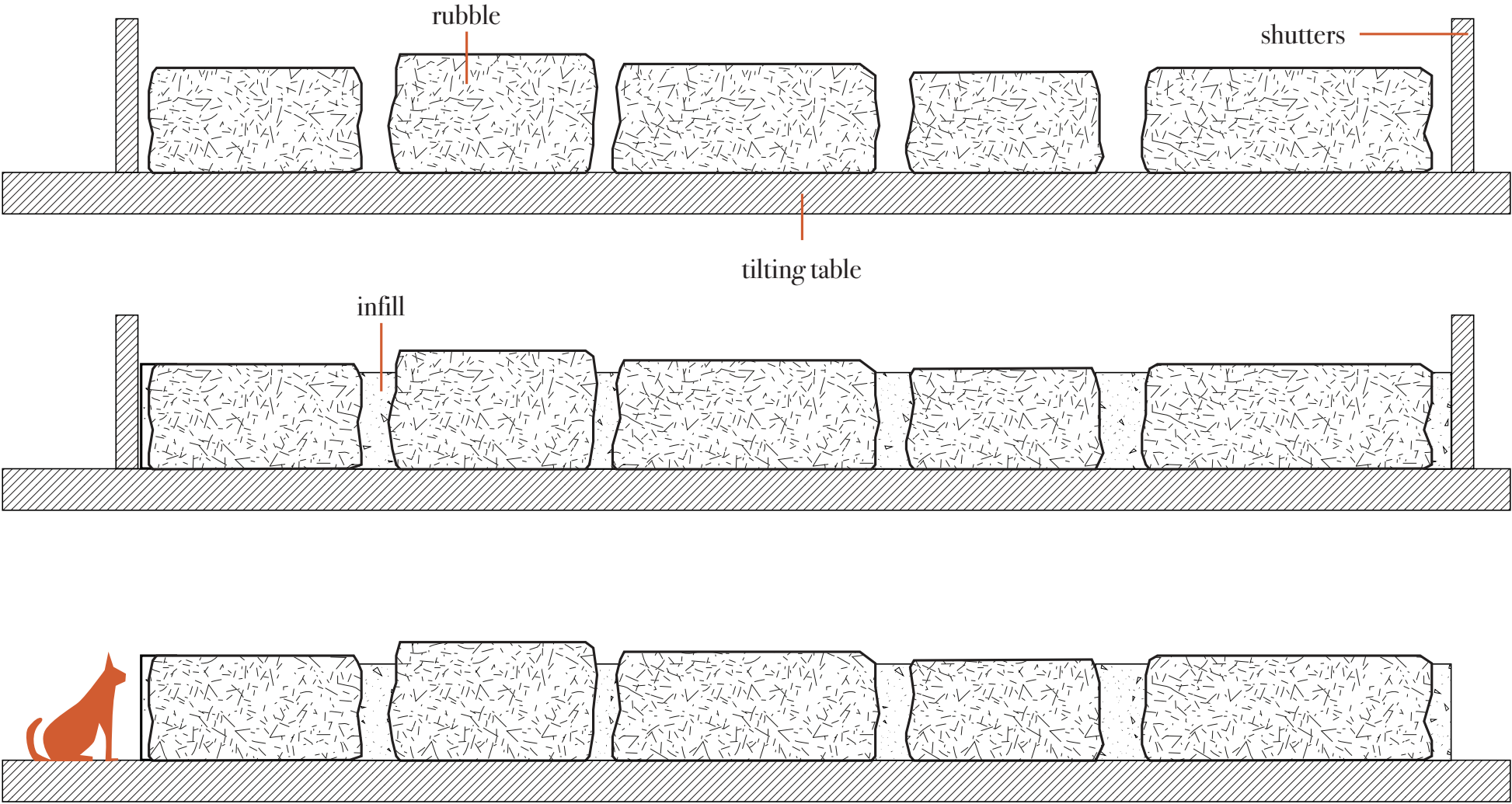
Cyclopean Spolia Precast Process



Cyclopean Spolia Precast Process



Rubble Thickness



Wall Design





Large Stones Smooth Surface



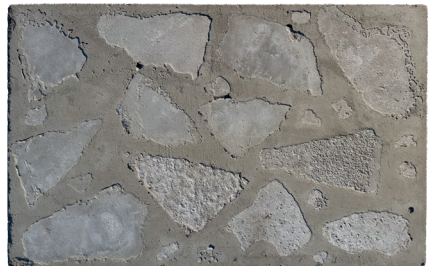
Gradient Smooth Surface



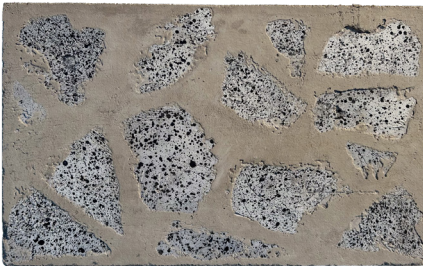
Small Stones Smooth Surface



Sand Tone Filler Smooth Surface



Stone Infill Smooth Surface



CS Rubble² Smooth Surface



Large Stones Rough Surface



Gradient Rough Surface



Small Stones Rough Surface



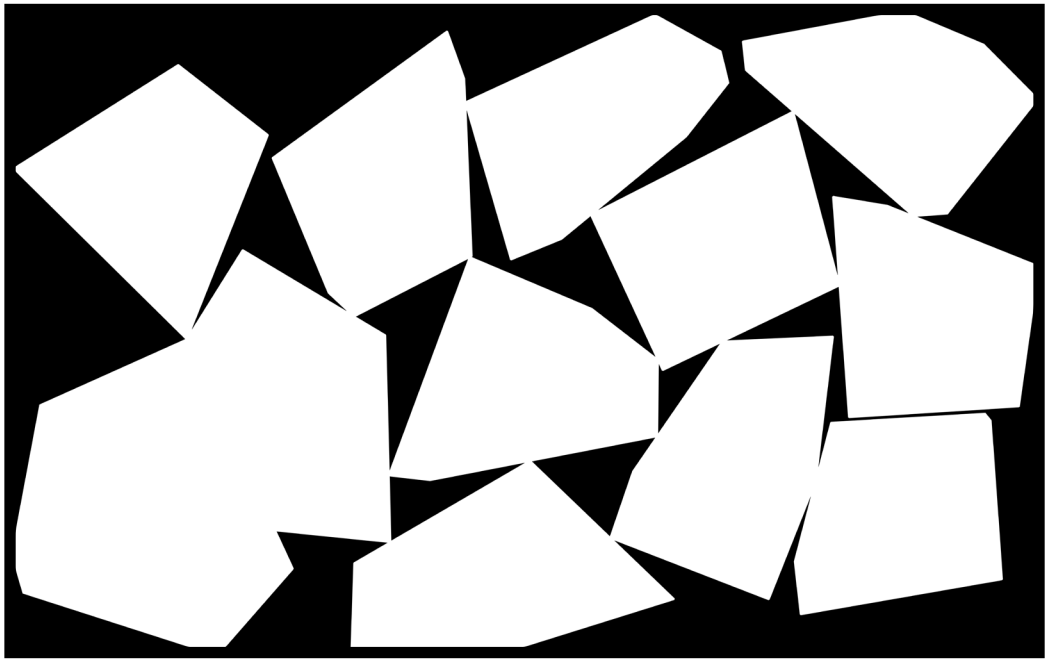
Sand Tone Filler Rough Surface



Stone Infill Rough Surface

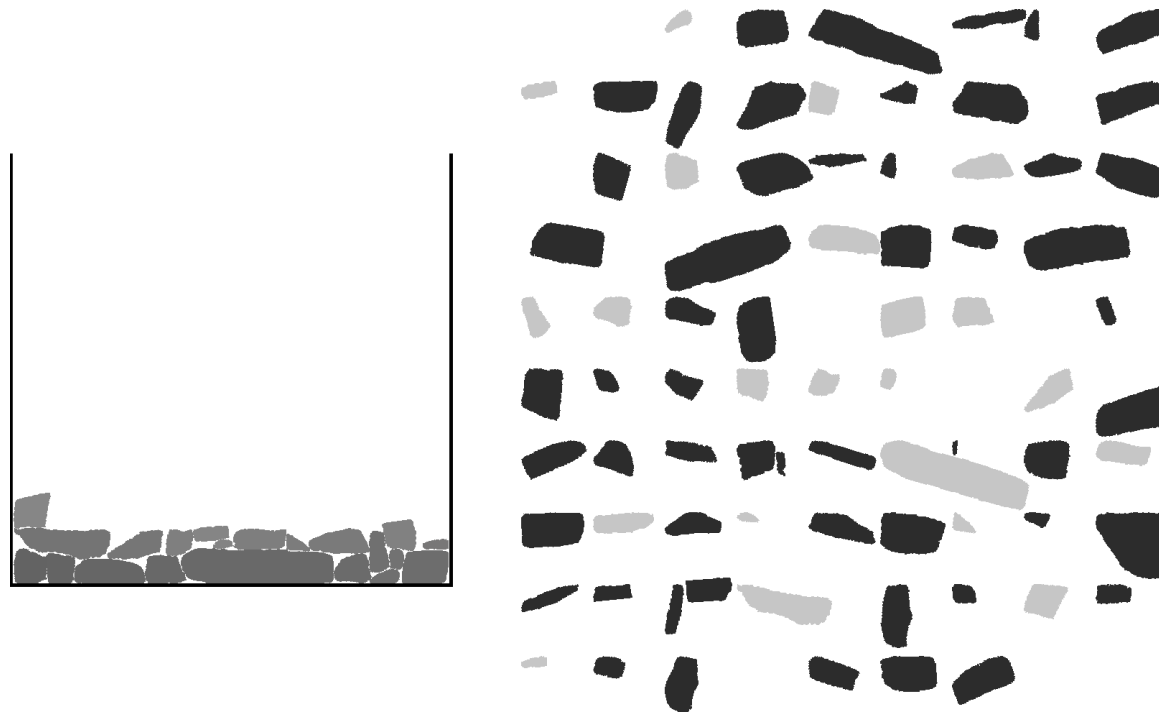


CS Rubble² Rough Surface

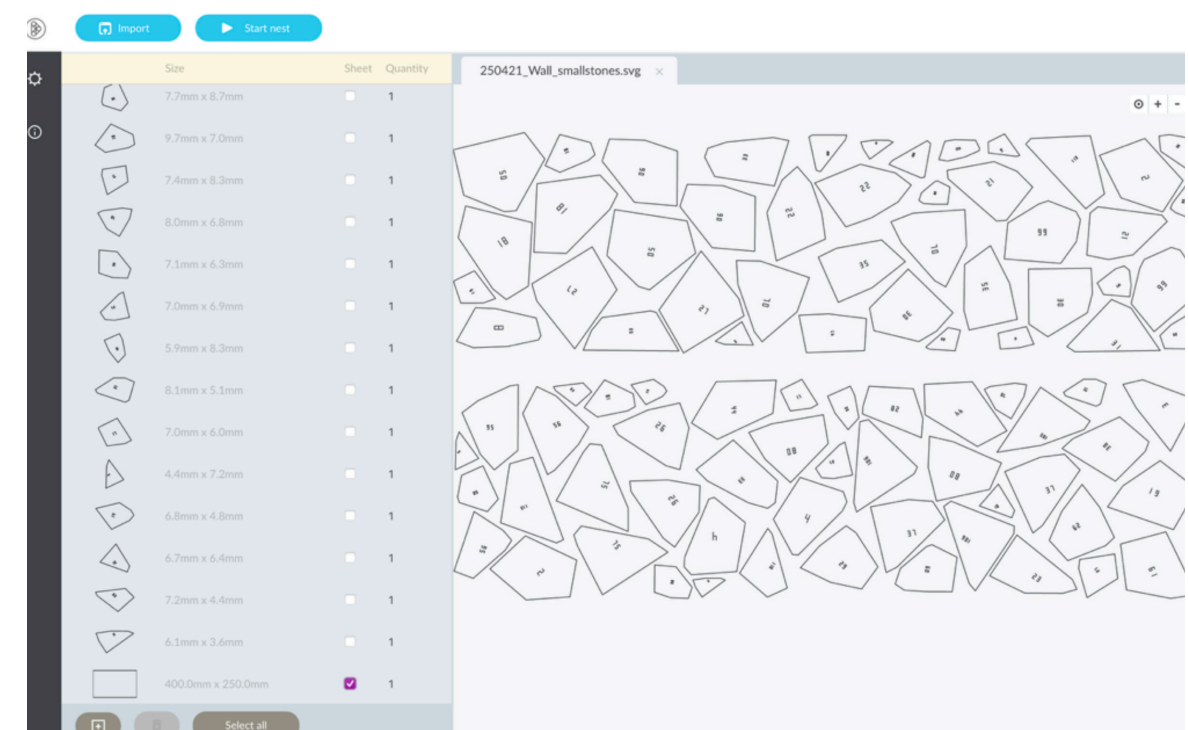


Cyclopean Spolia Precast Process

Stable Packing 2D

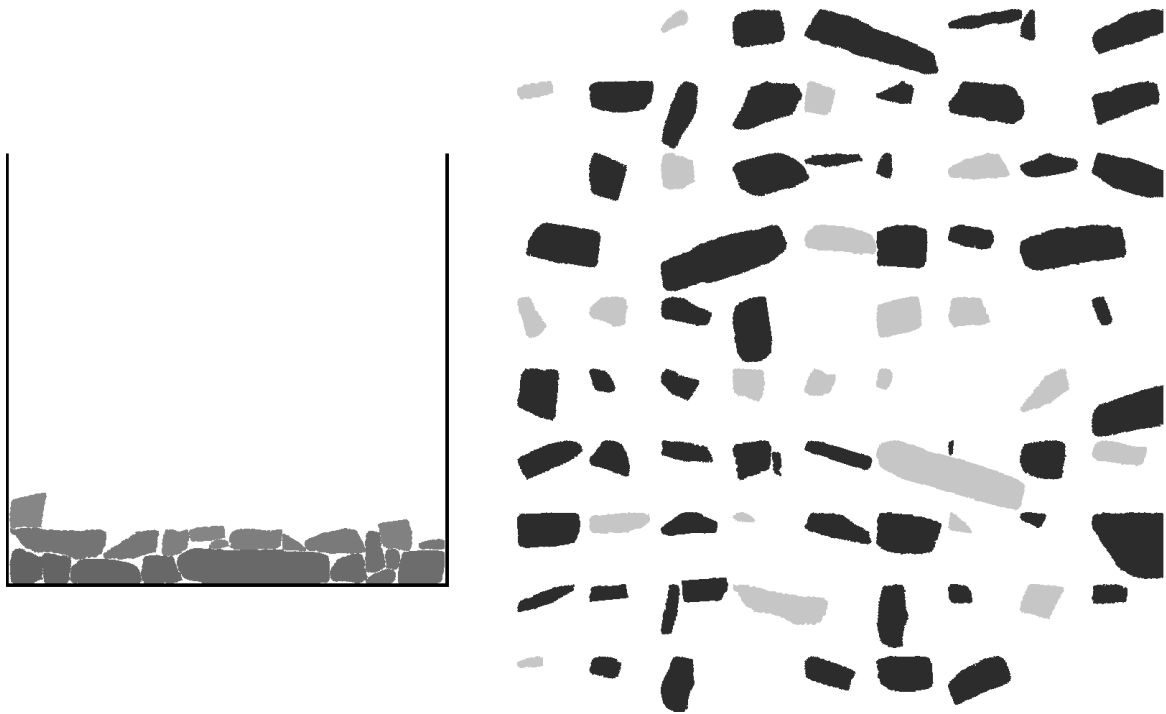


DeepNest



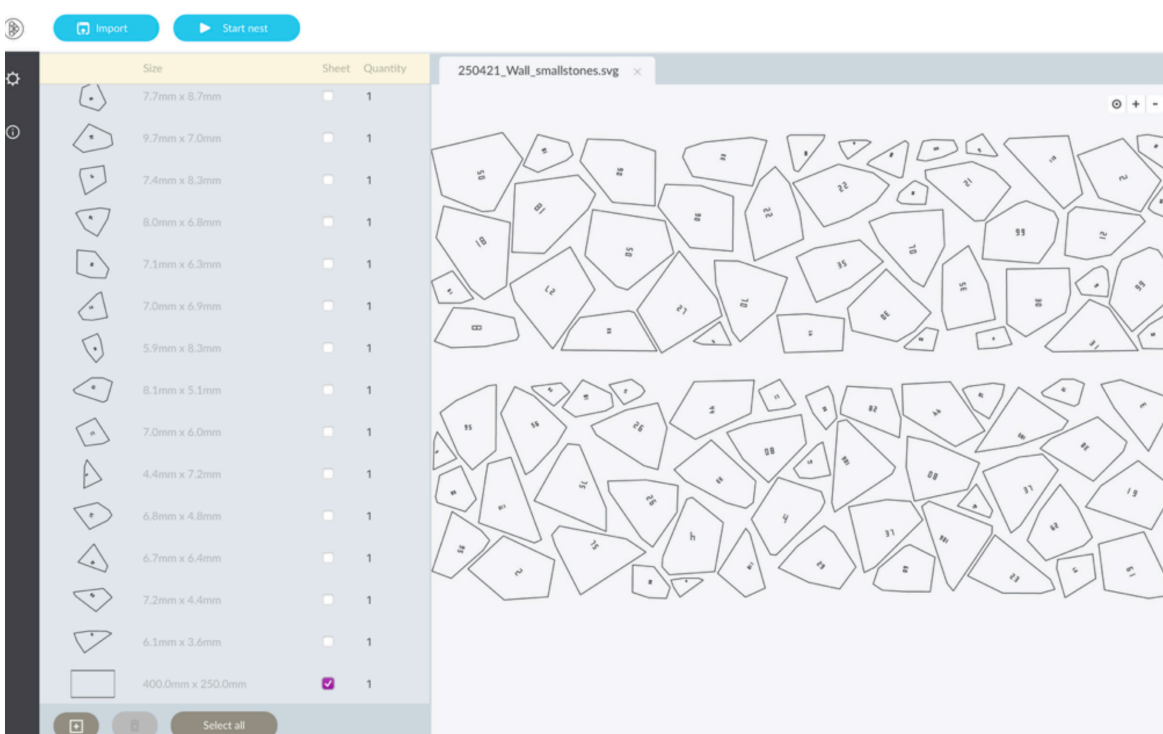
Cyclopean Spolia Precast Process

Stable Packing 2D



Structural Verifications

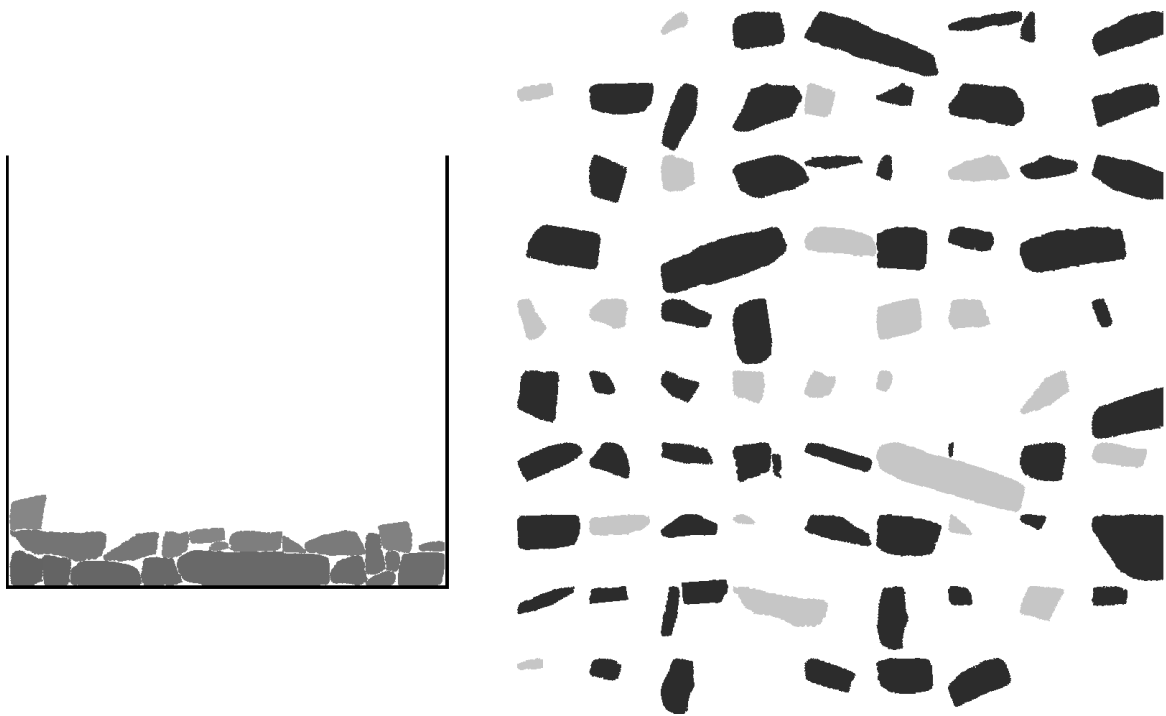
DeepNest



No Structural Verification

Cyclopean Spolia Precast Process

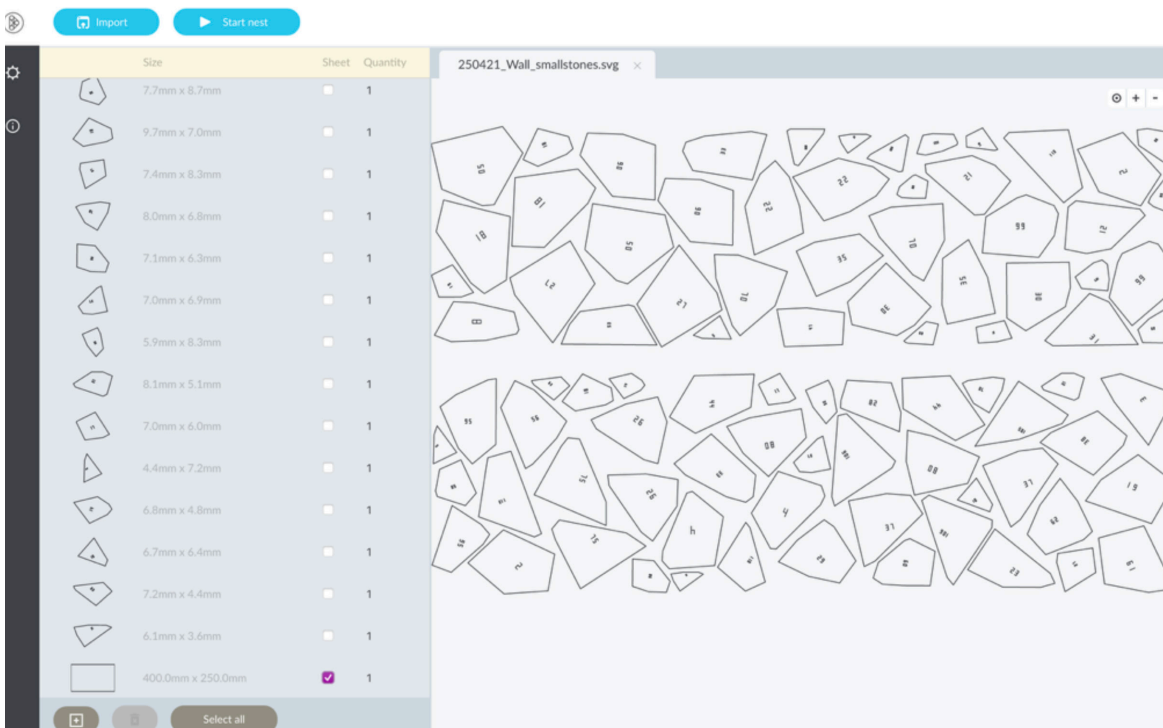
Stable Packing 2D



Structural Verifications

Large Database needed

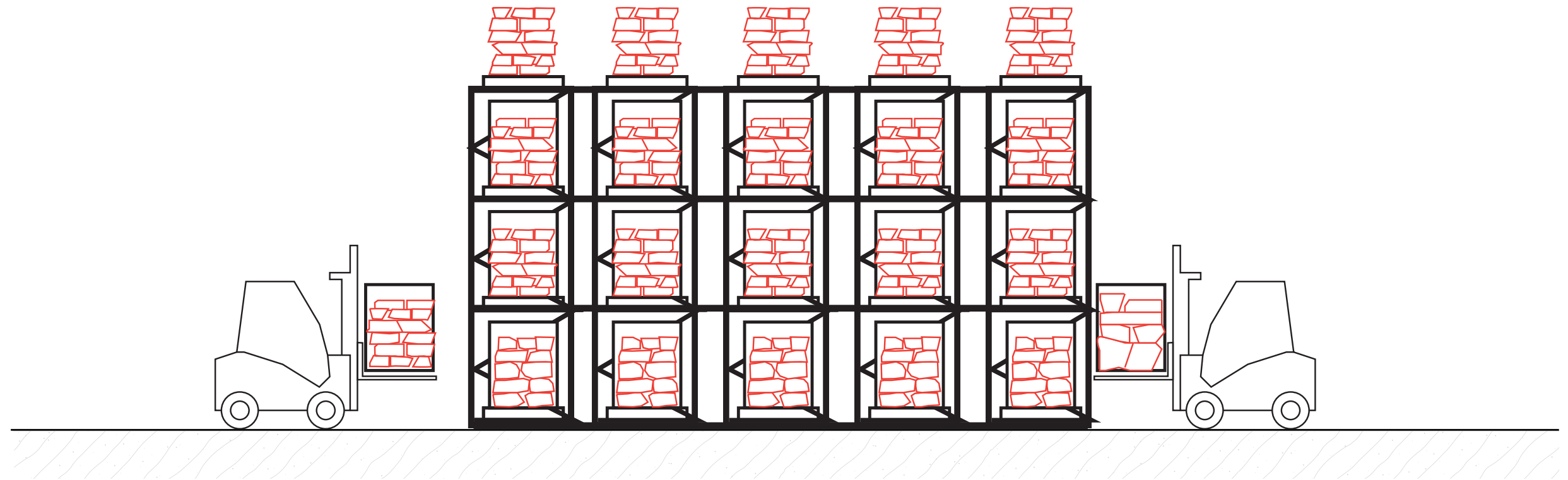
DeepNest



Small Database
Equal Spread

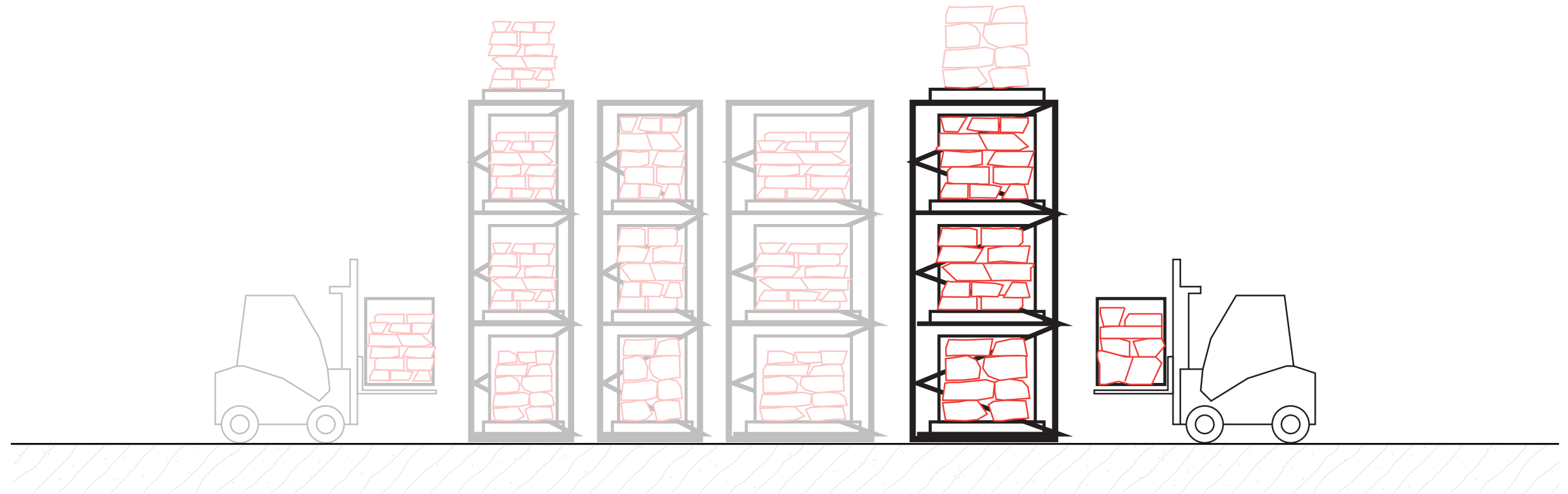
No Structural Verification

Cyclopean Spolia Precast Process

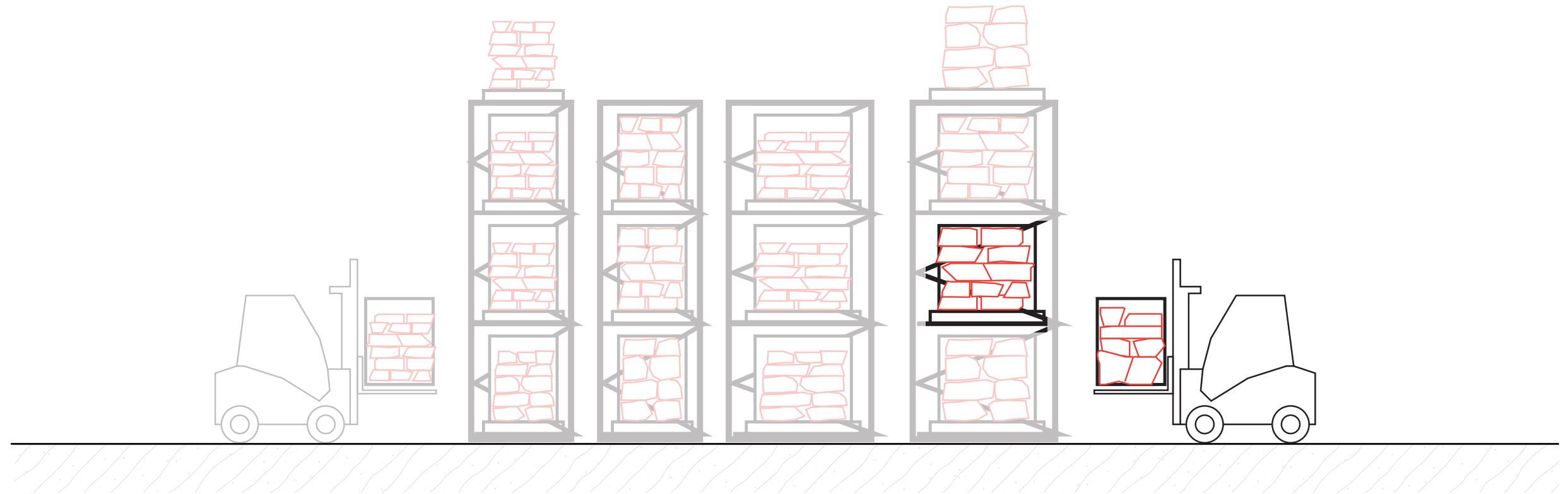


FIFO

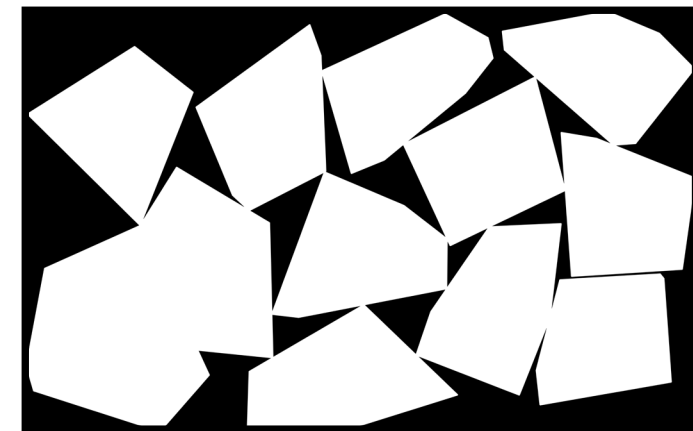
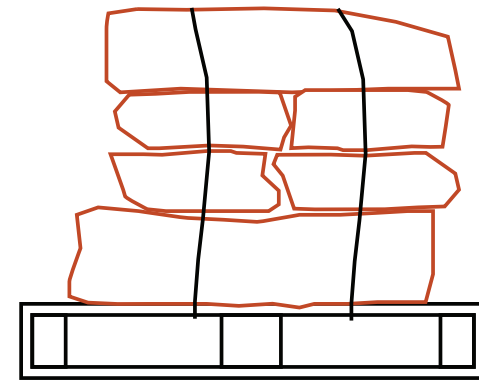
Cyclopean Spolia Precast Process



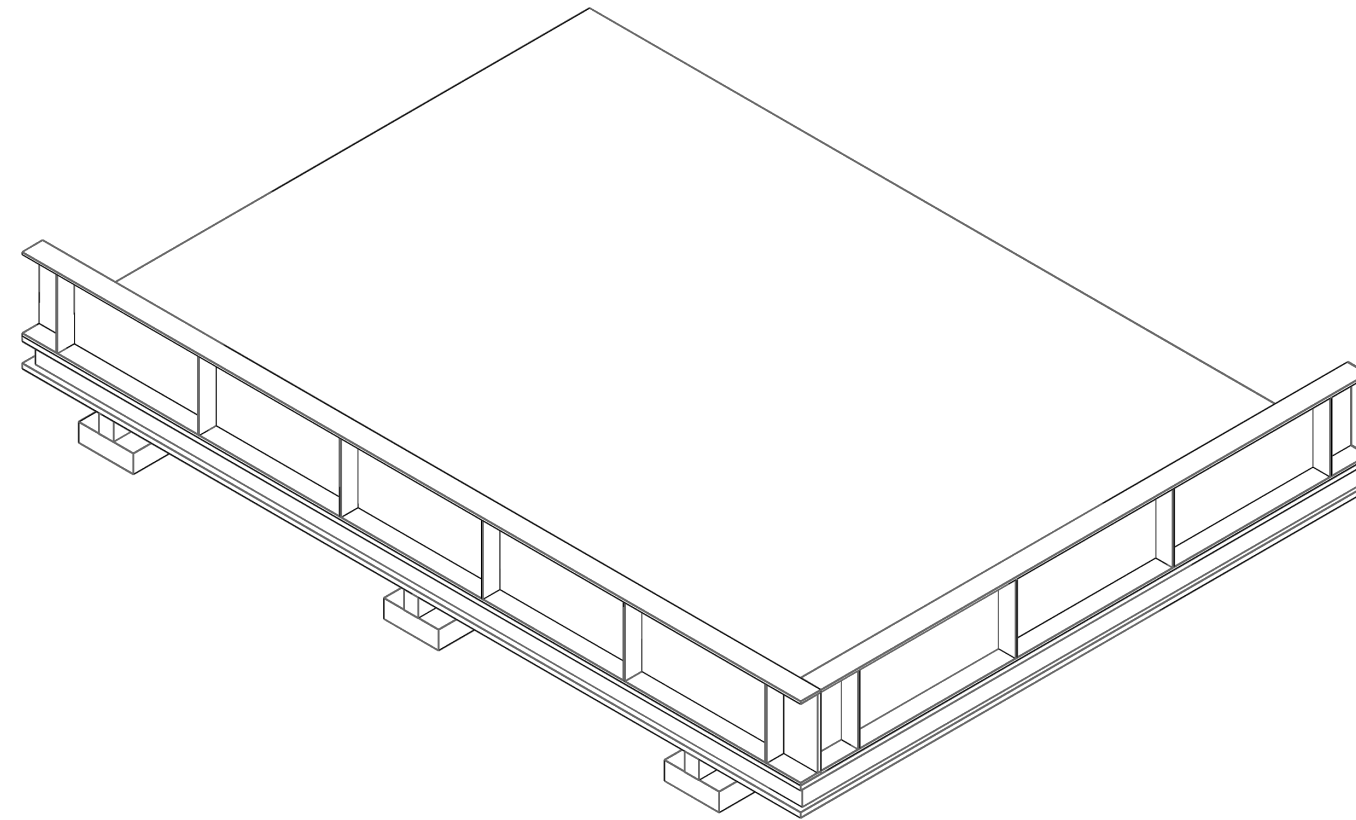
Cyclopean Spolia Precast Process



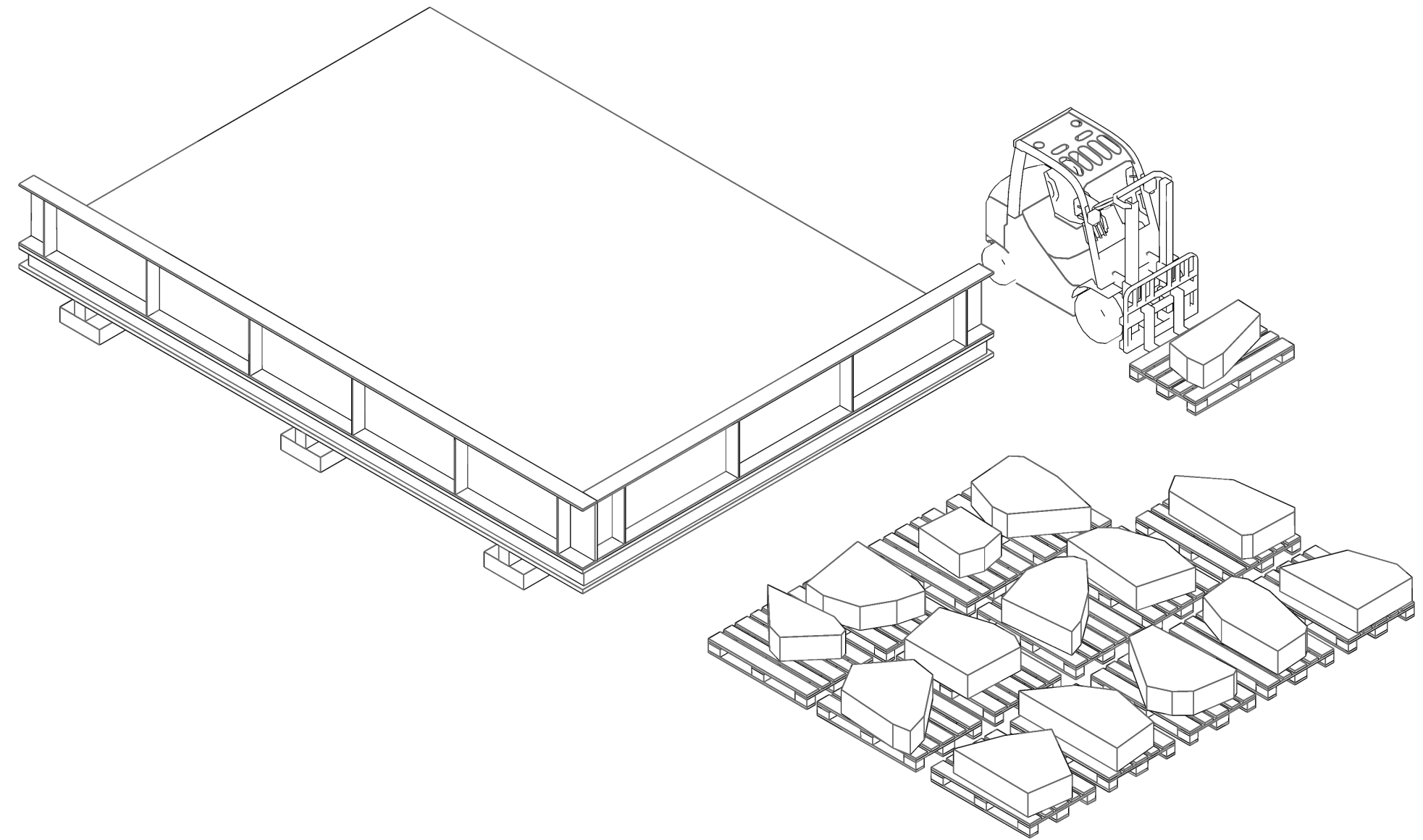
Cyclopean Spolia Precast Process



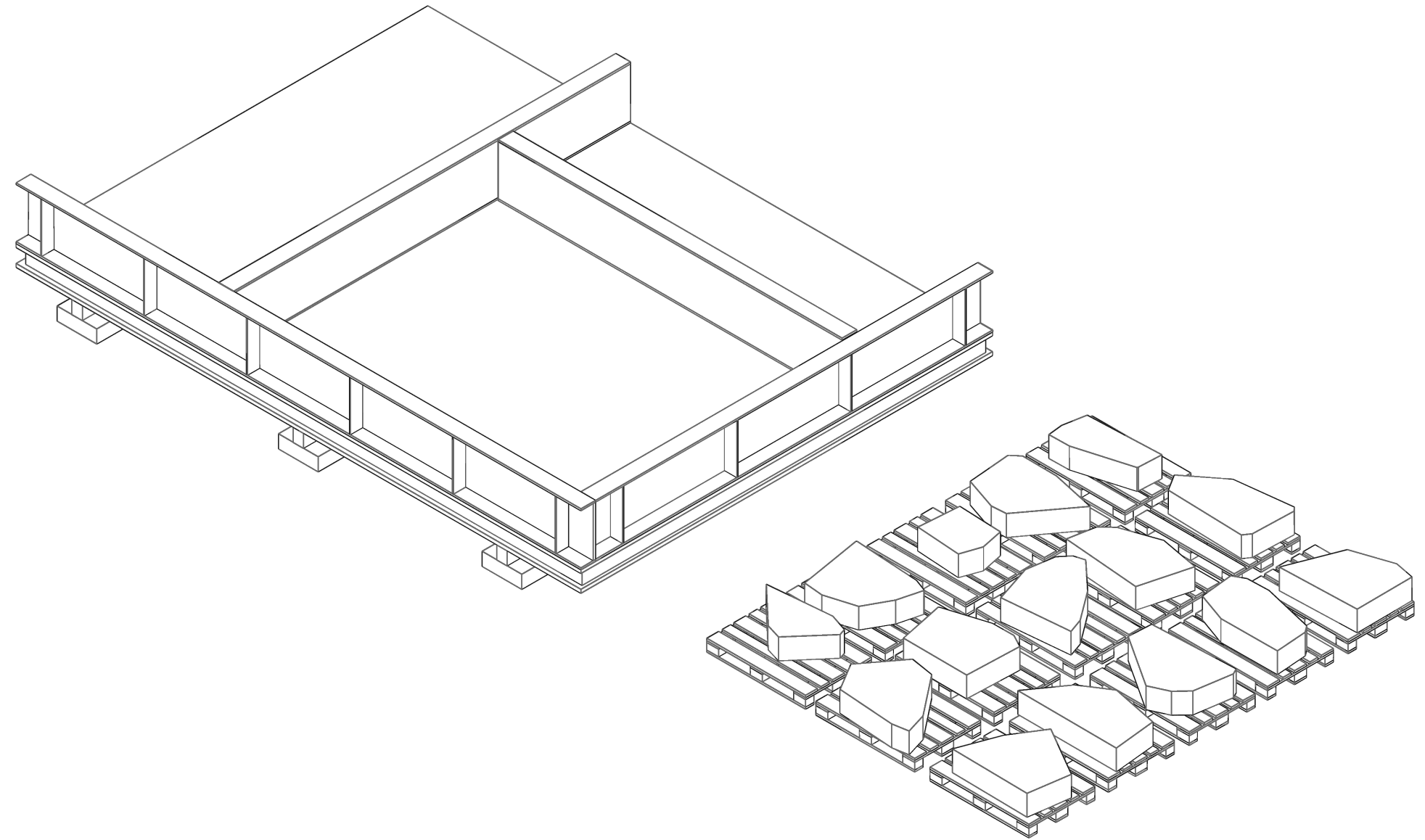
Cyclopean Spolia Precast Process



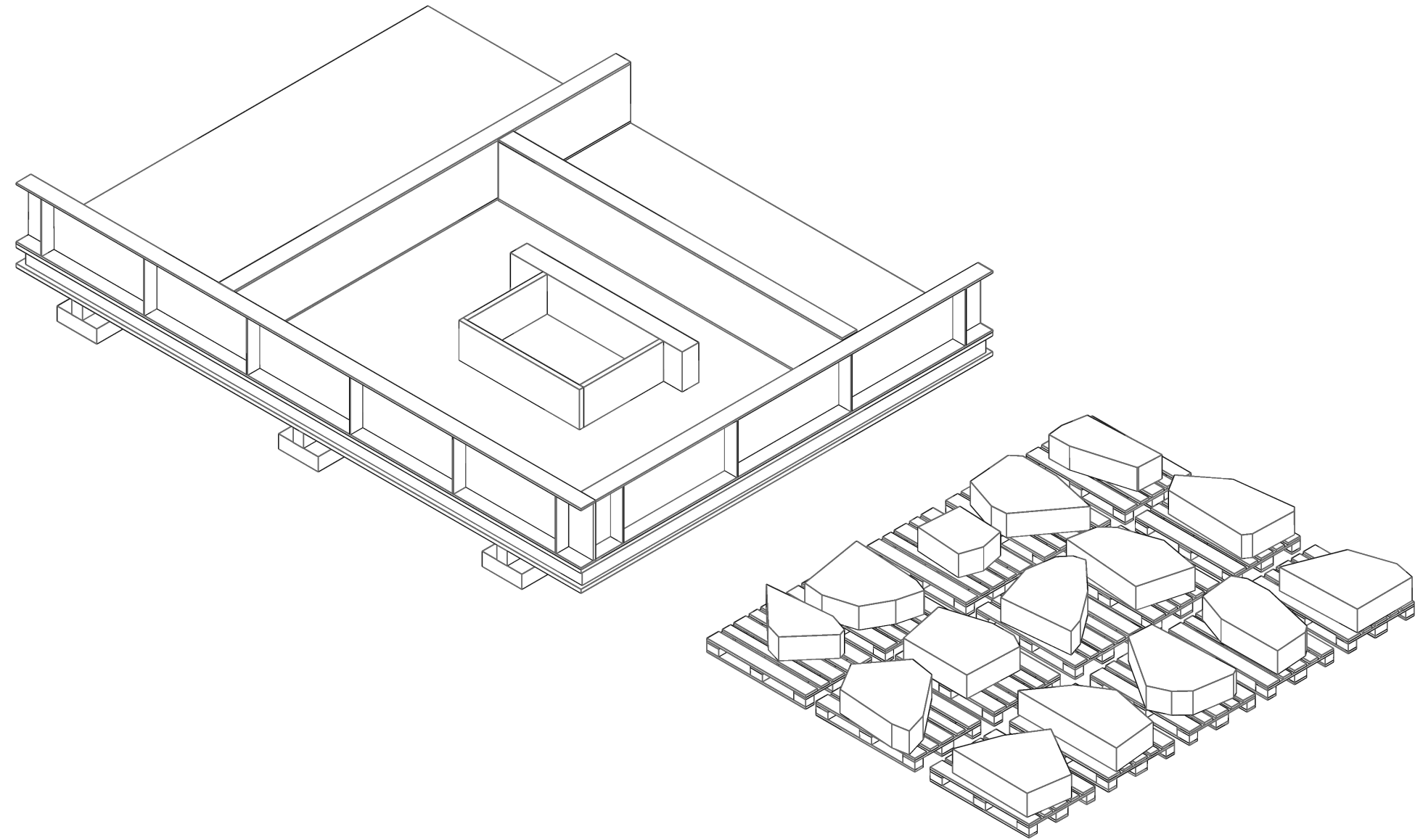
Cyclopean Spolia Precast Process



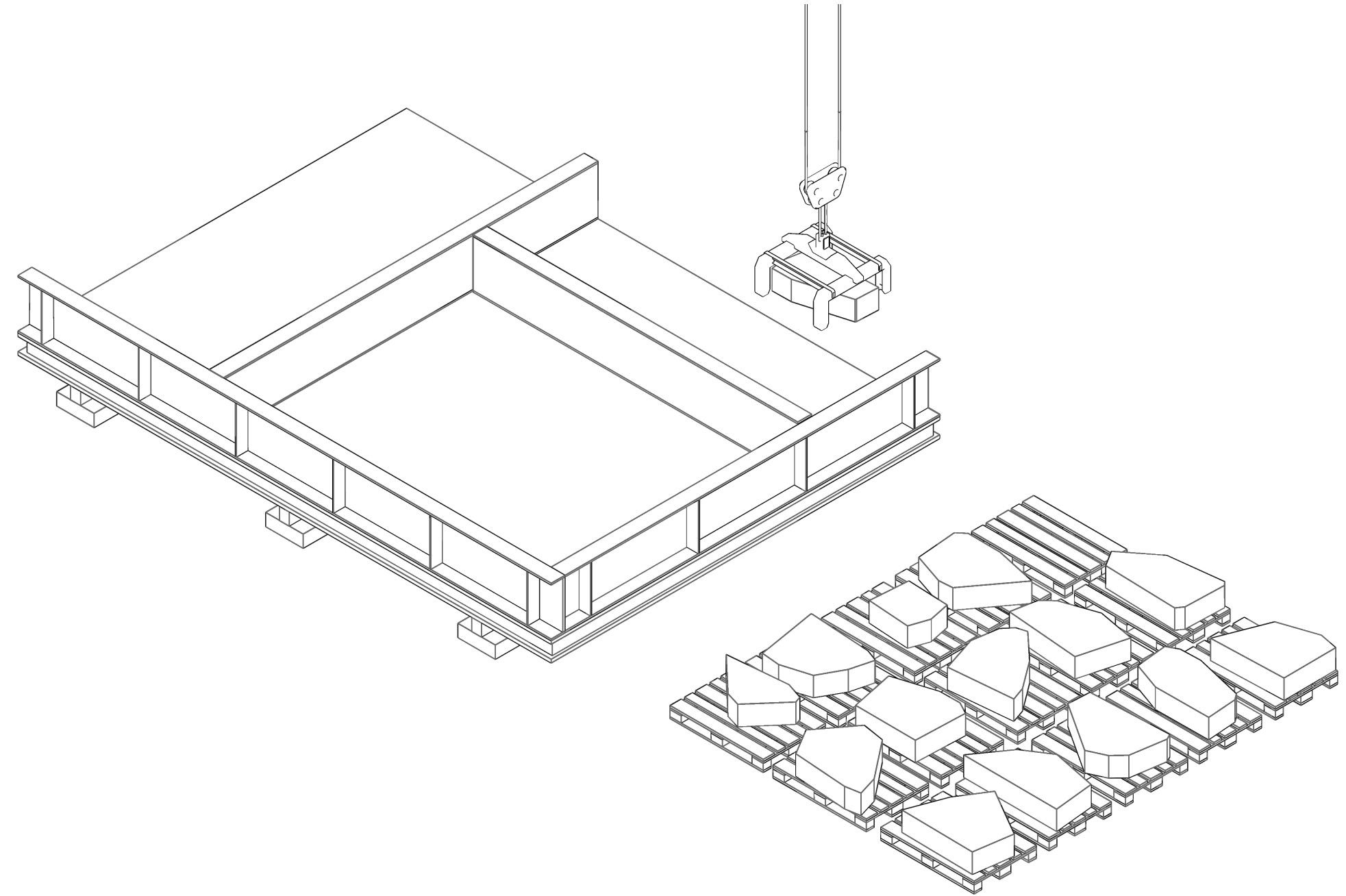
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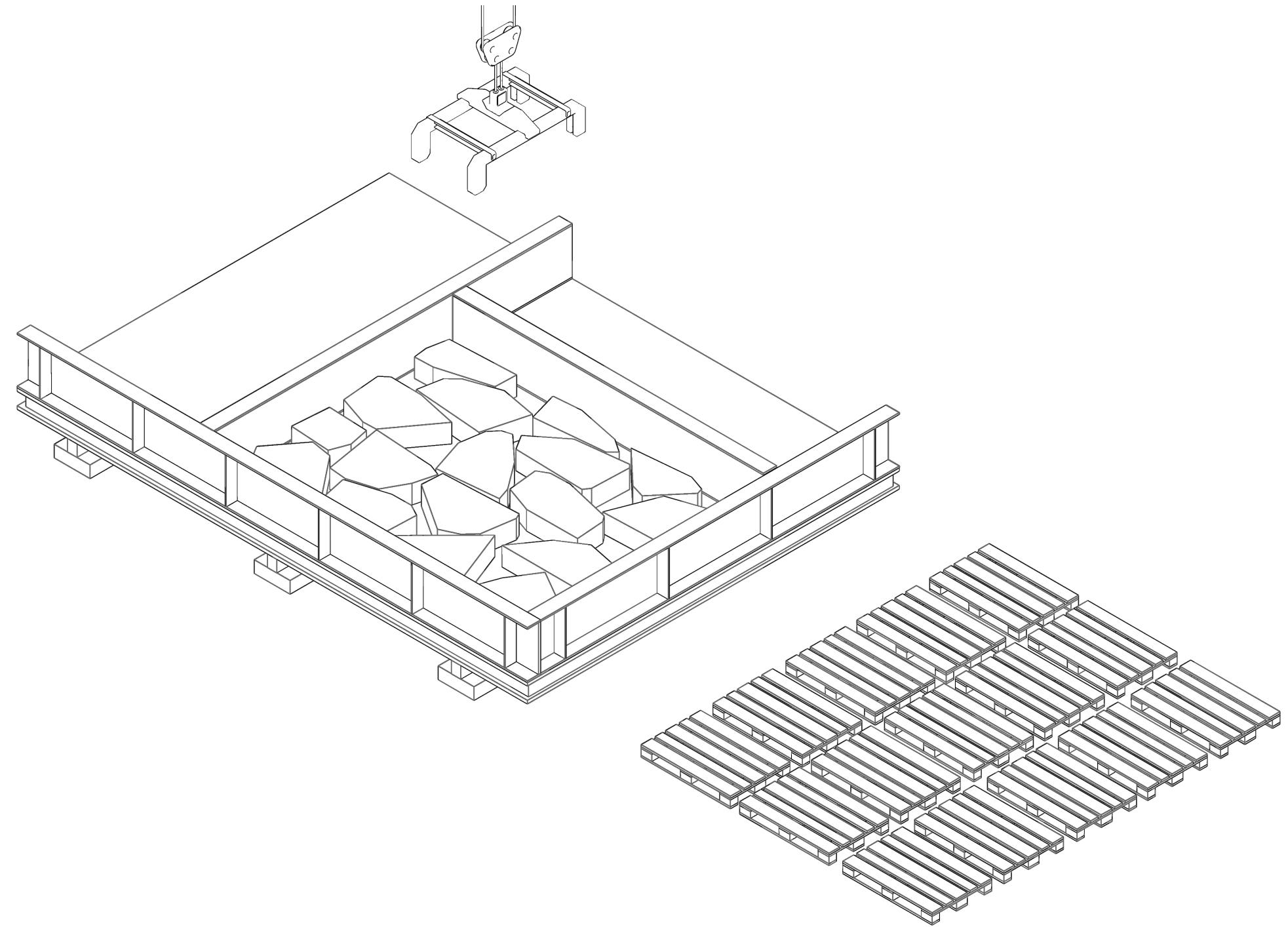
Cyclopean Spolia Precast Process



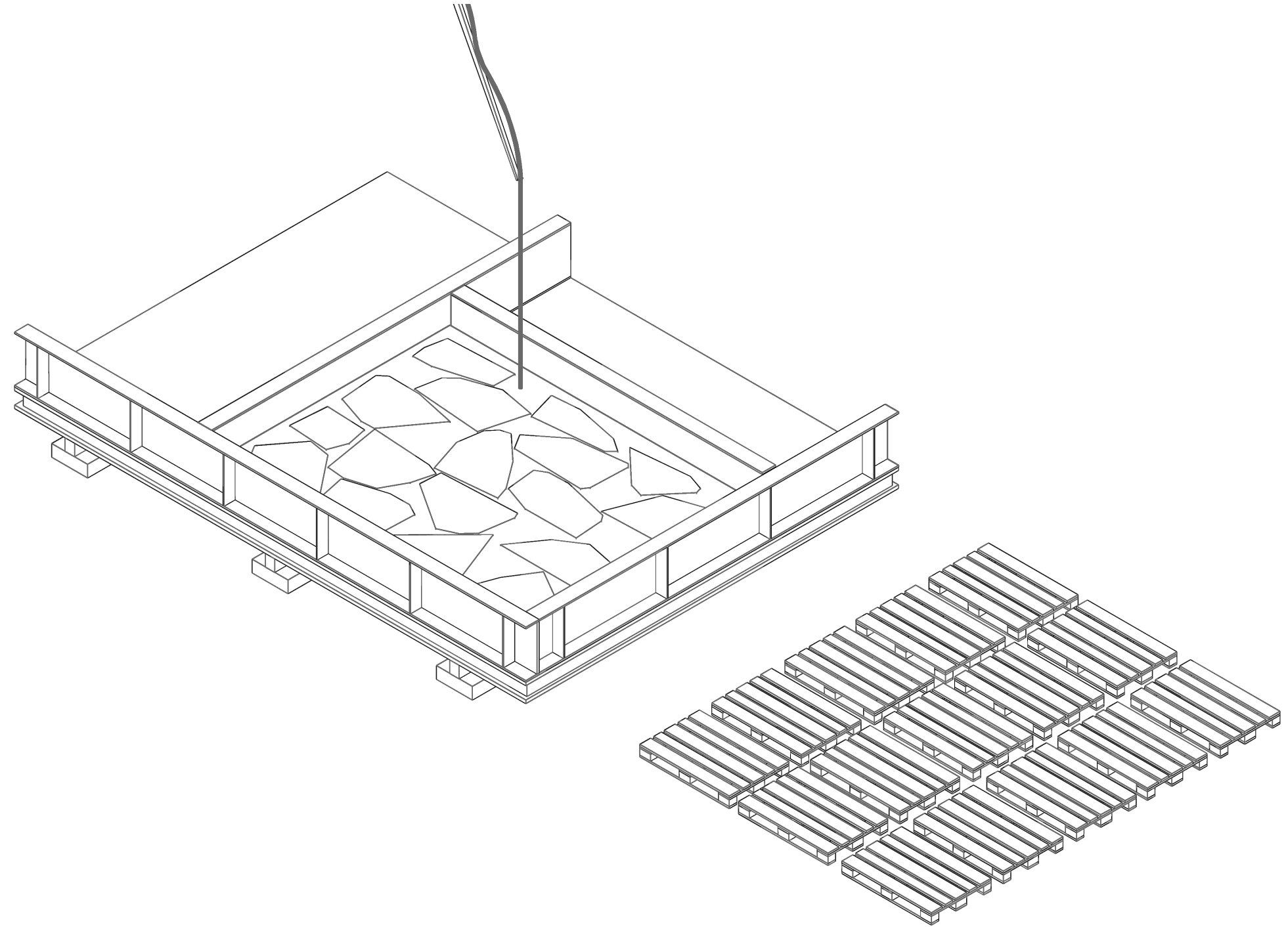
Cyclopean Spolia Precast Process



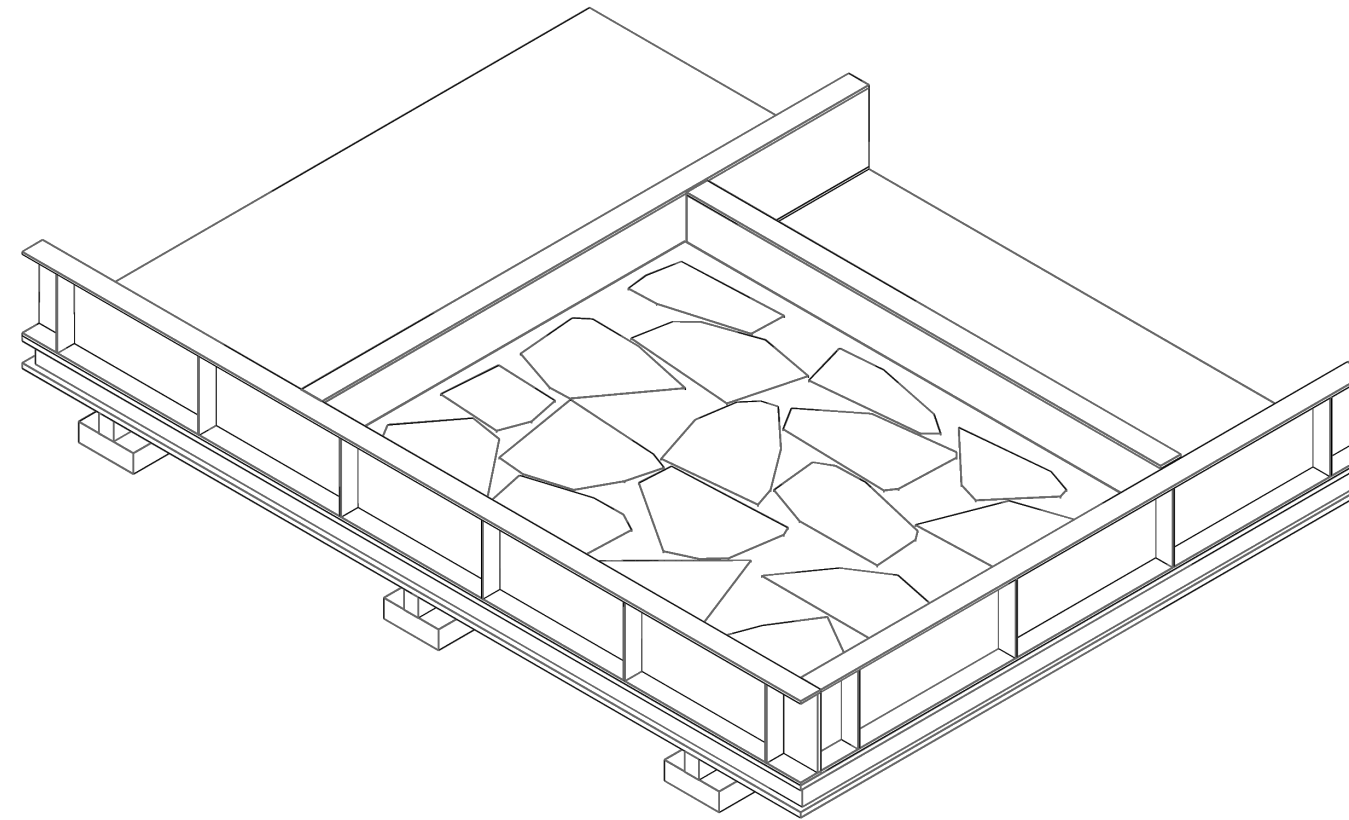
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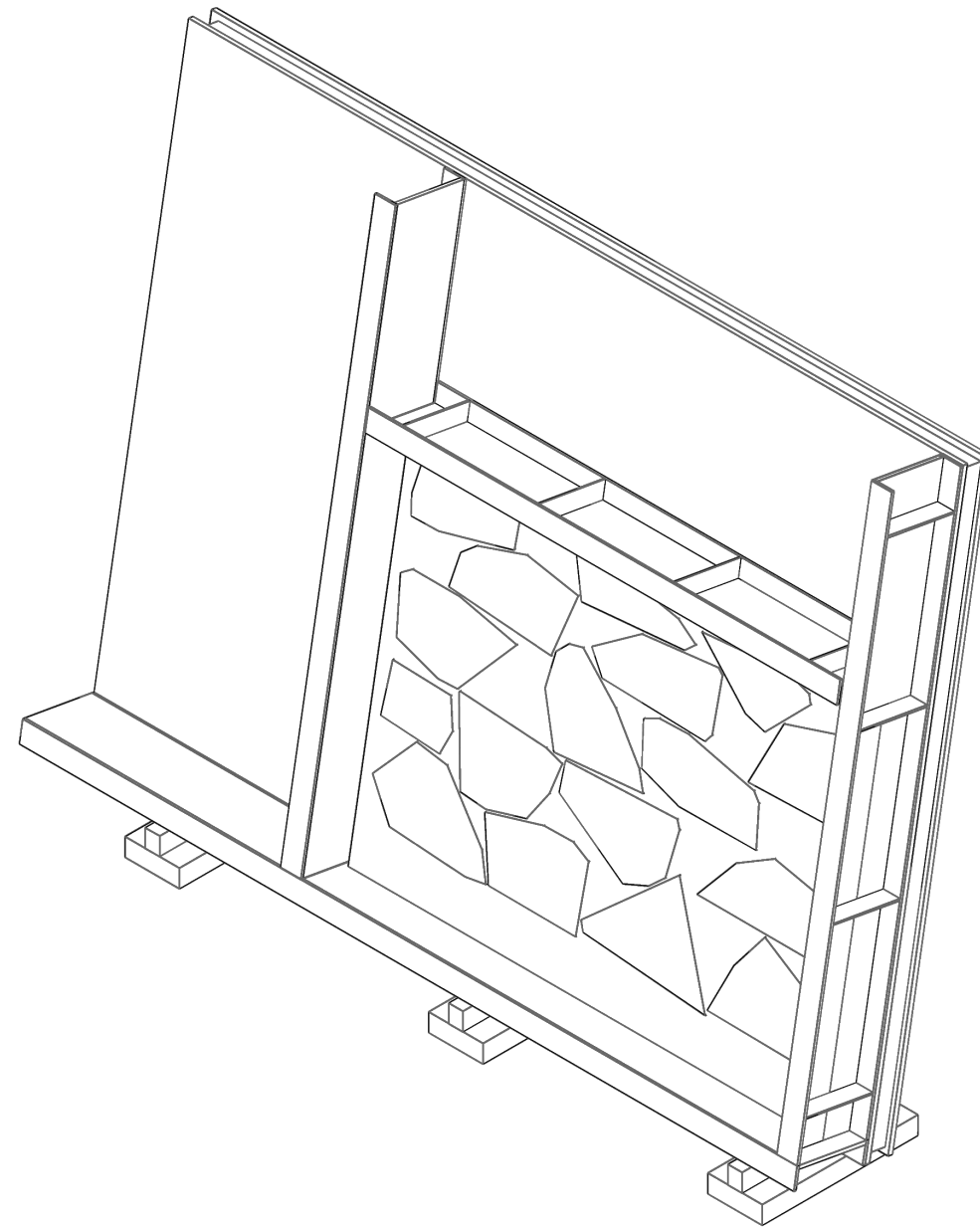
Cyclopean Spolia Precast Process



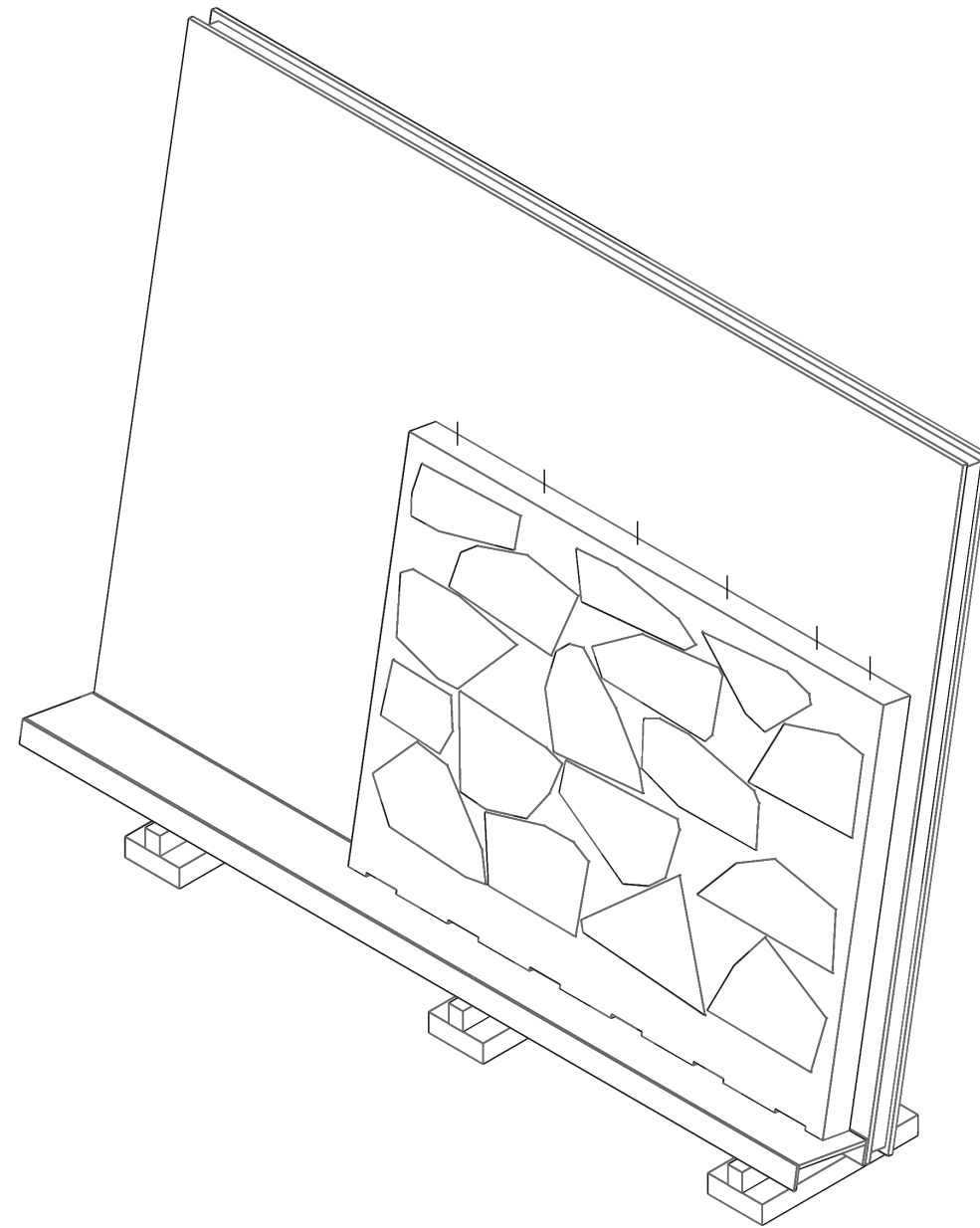
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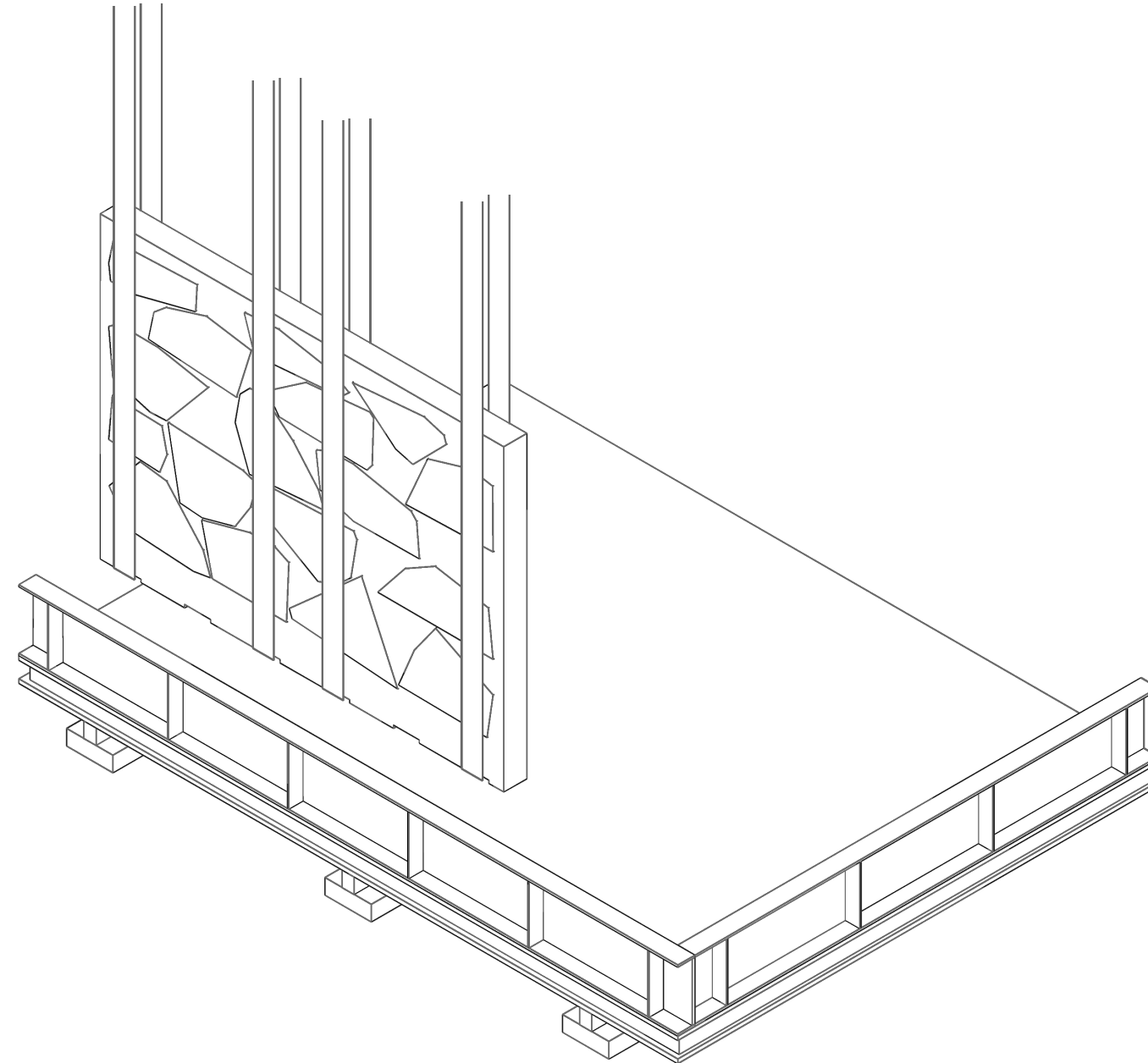
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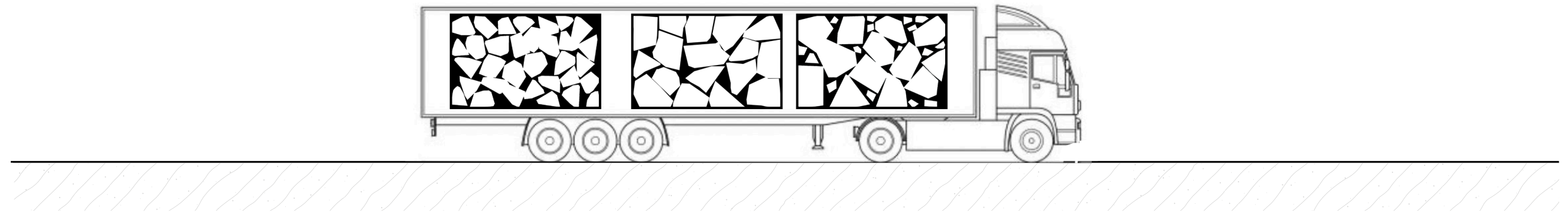
Cyclopean Spolia Precast Process



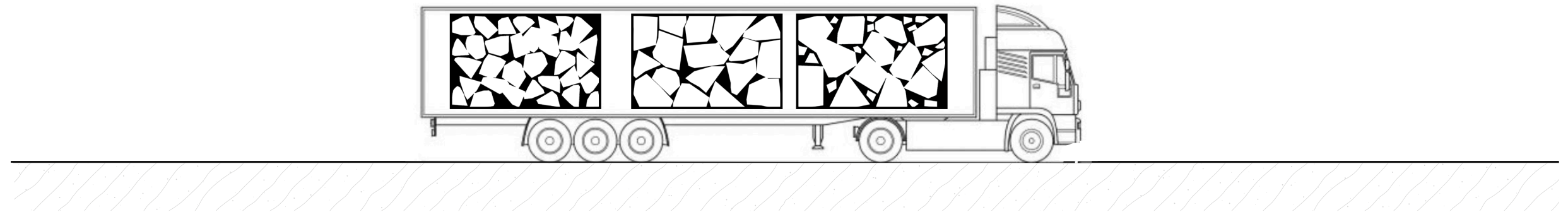
Cyclopean Spolia Precast Process



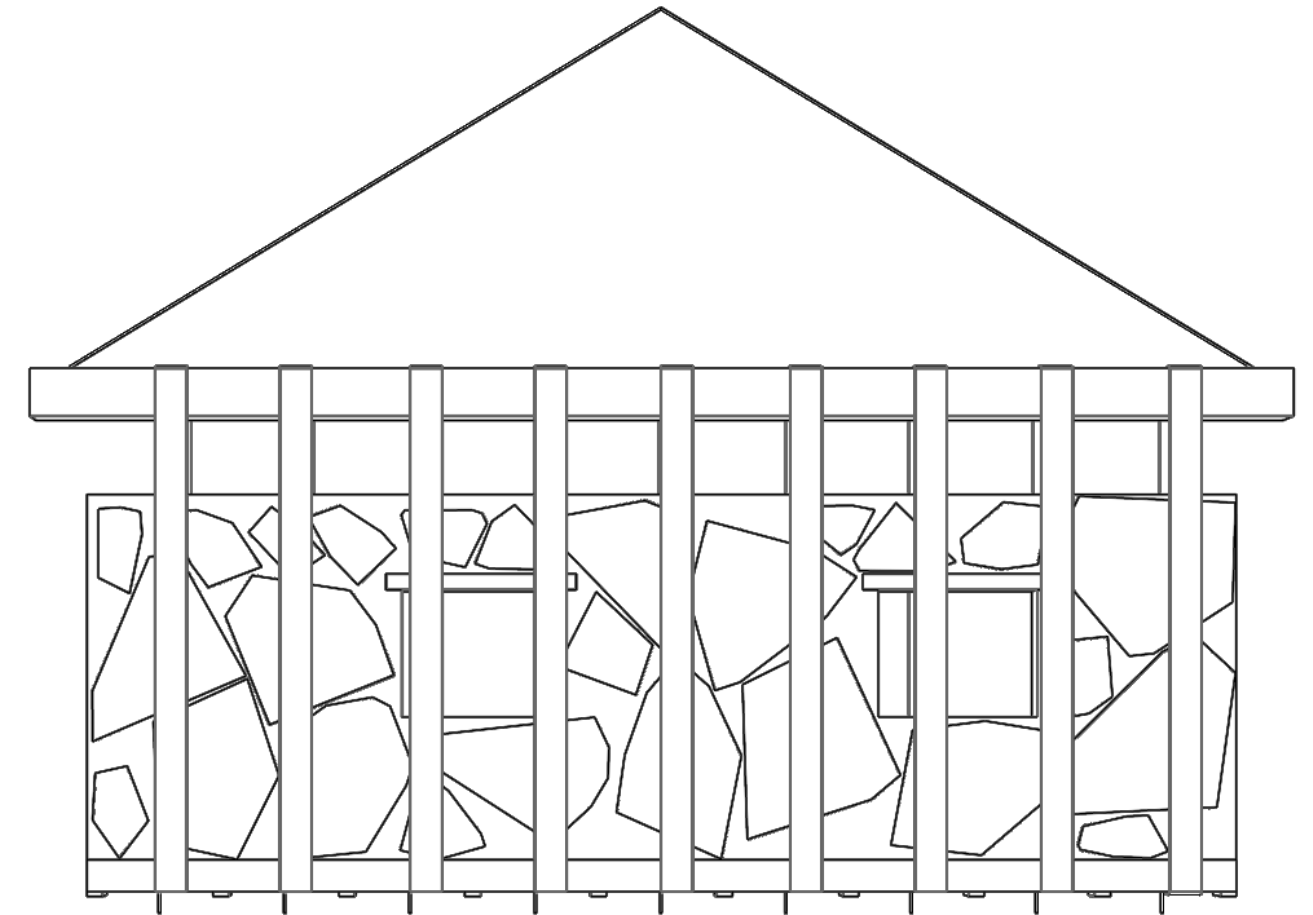
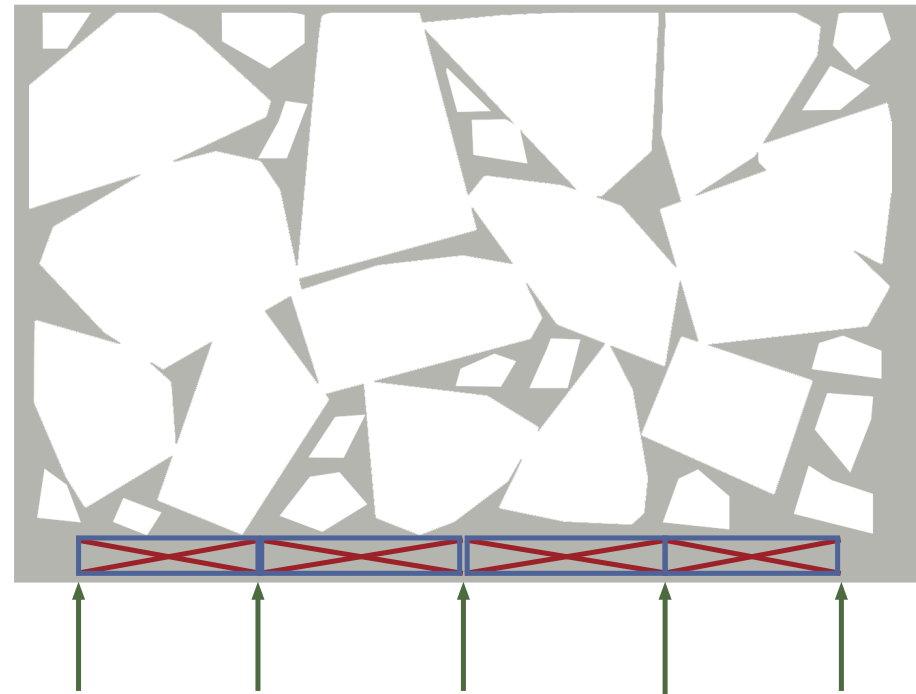
Cyclopean Spolia Precast Process



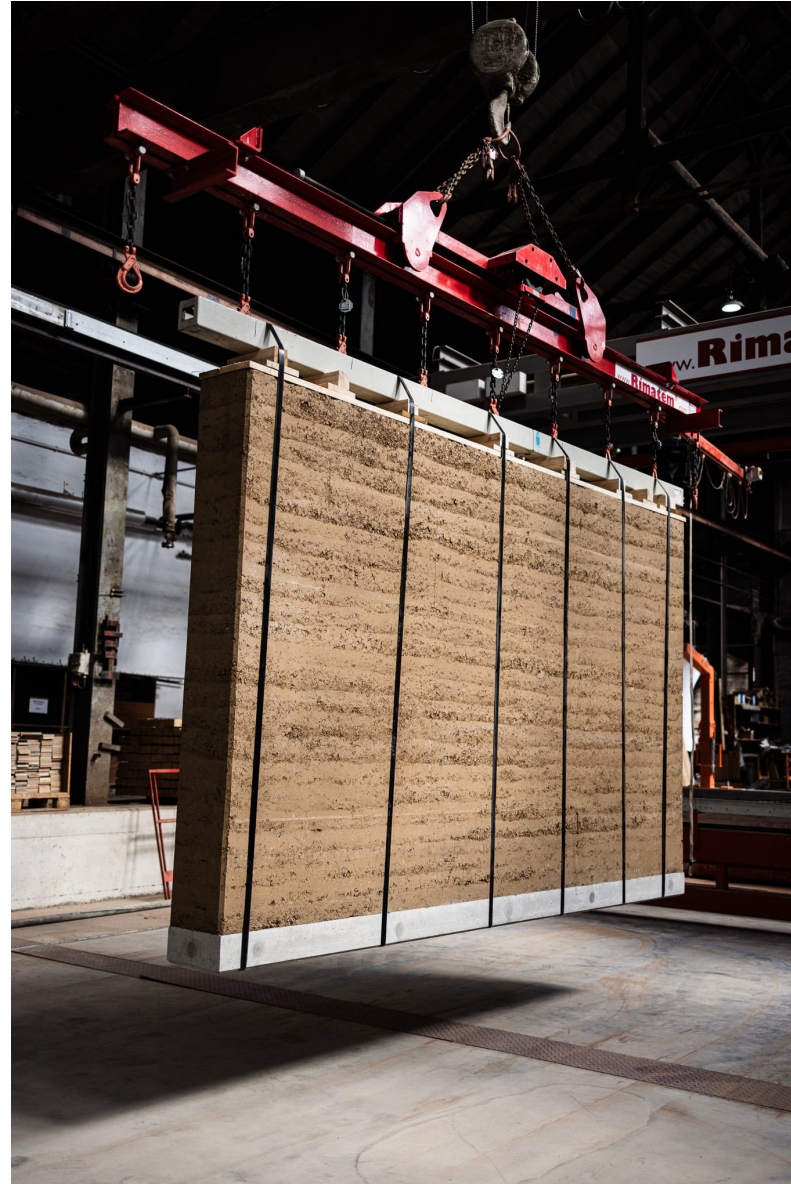
Challenge 1



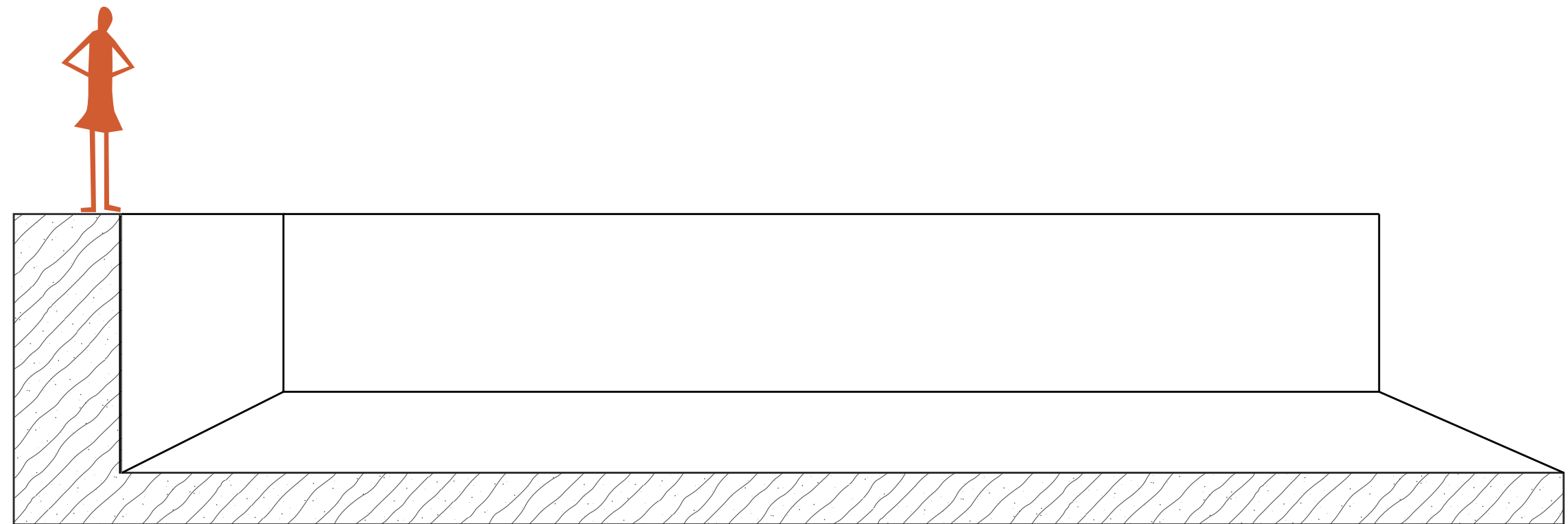
Wall Transport



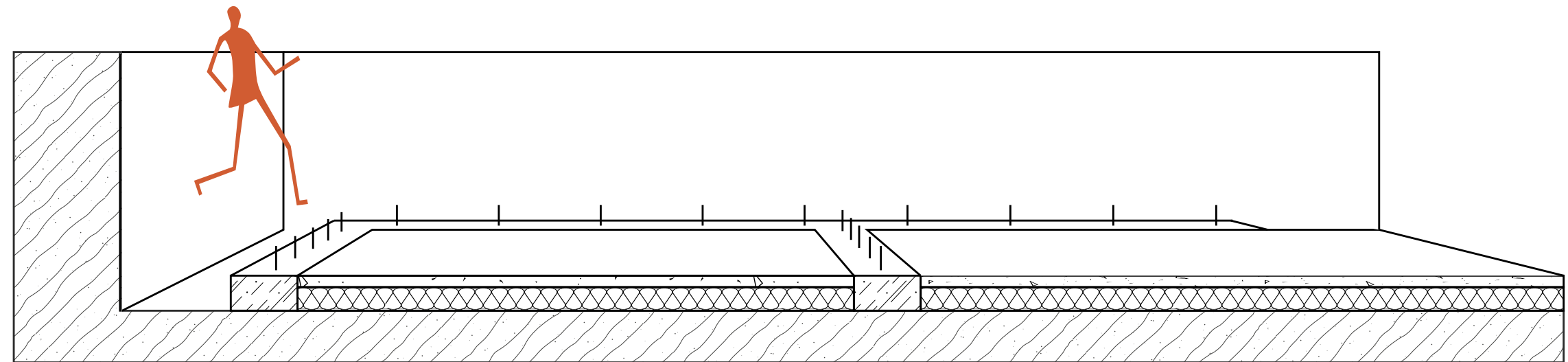
Wall Transport



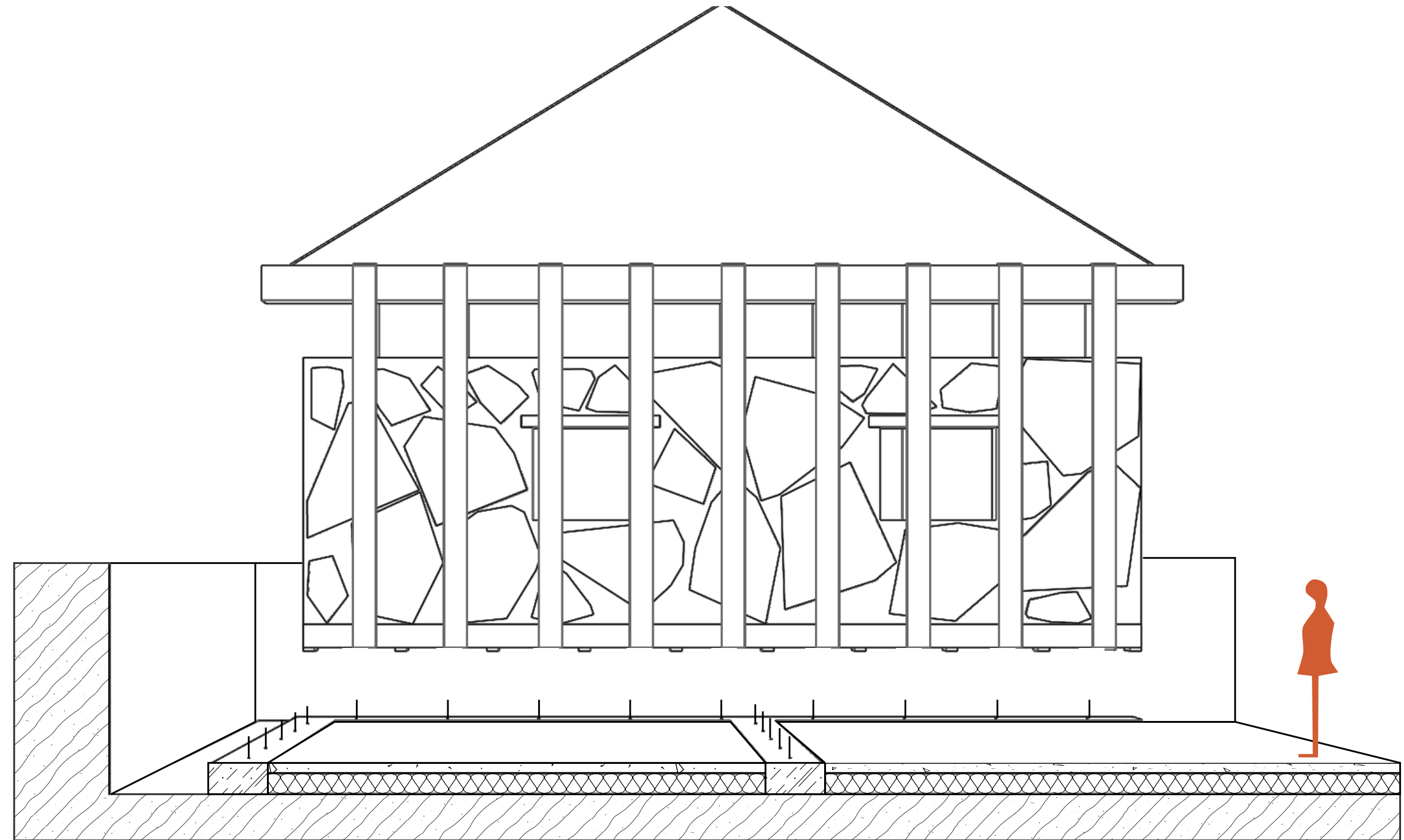
Assembly



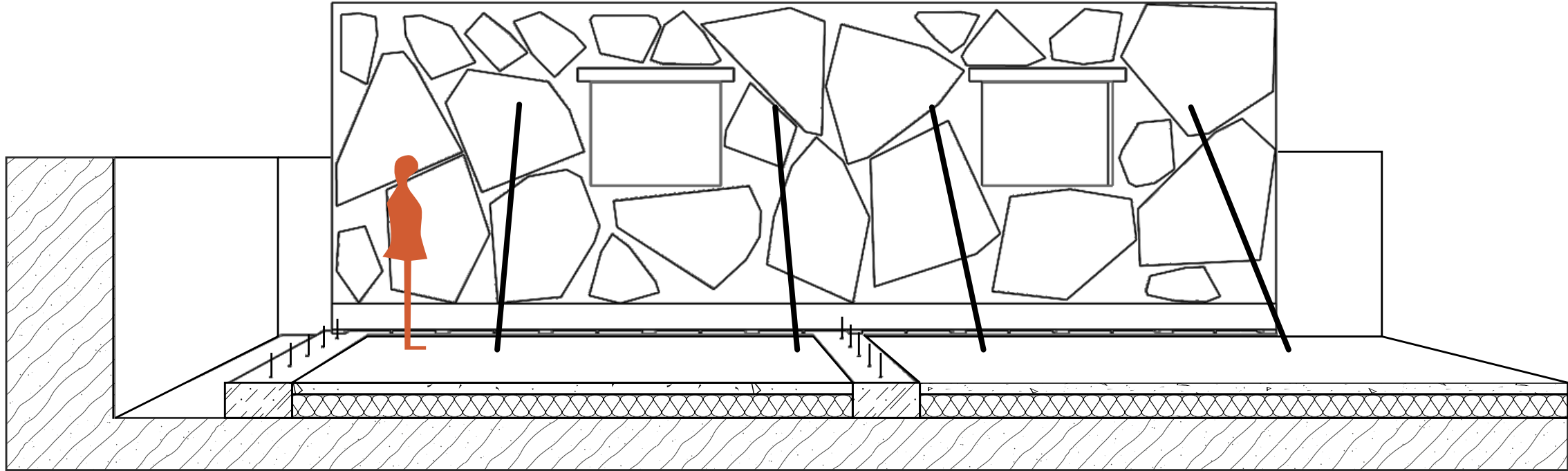
Assembly



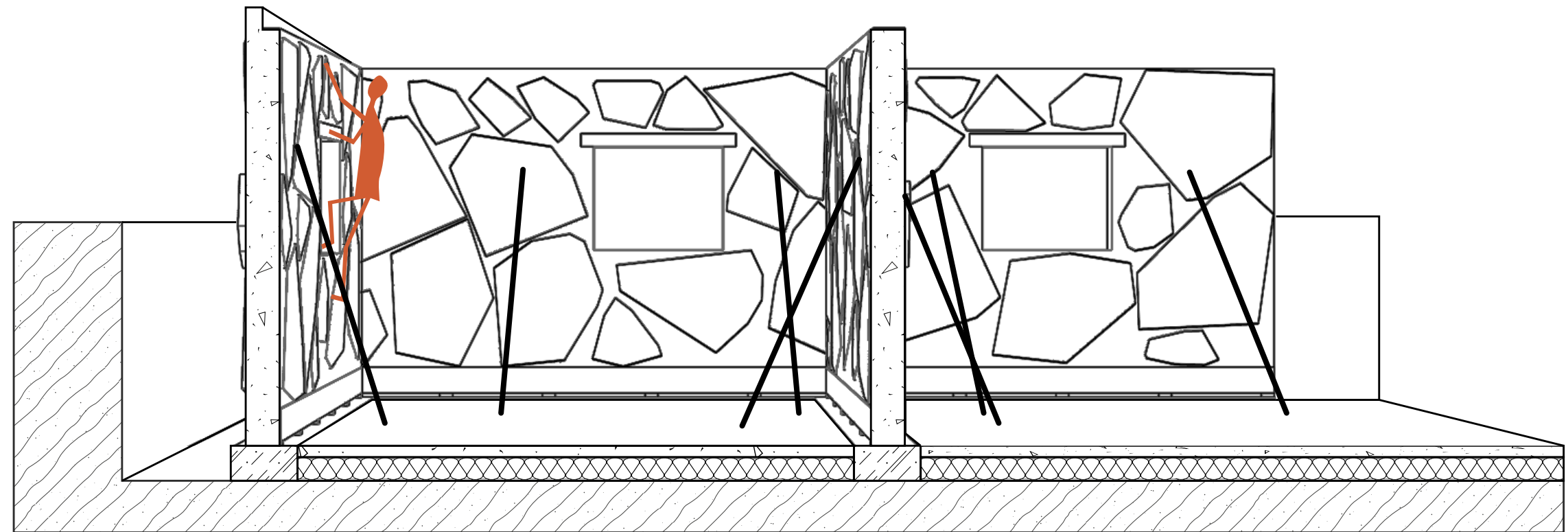
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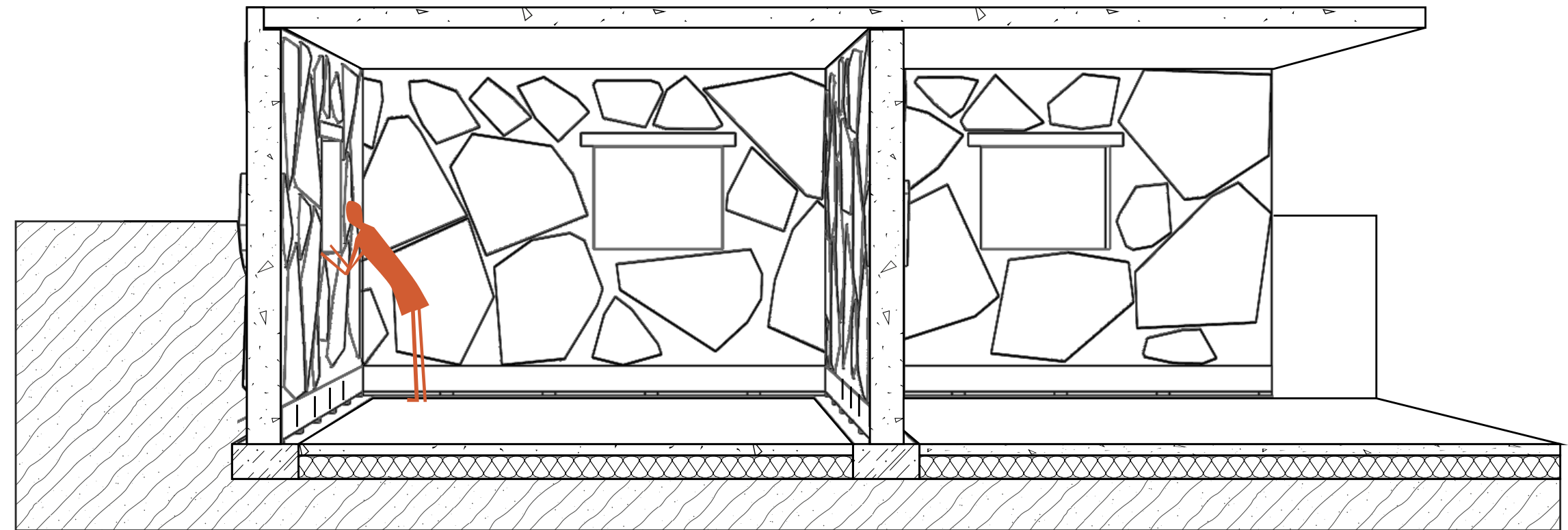
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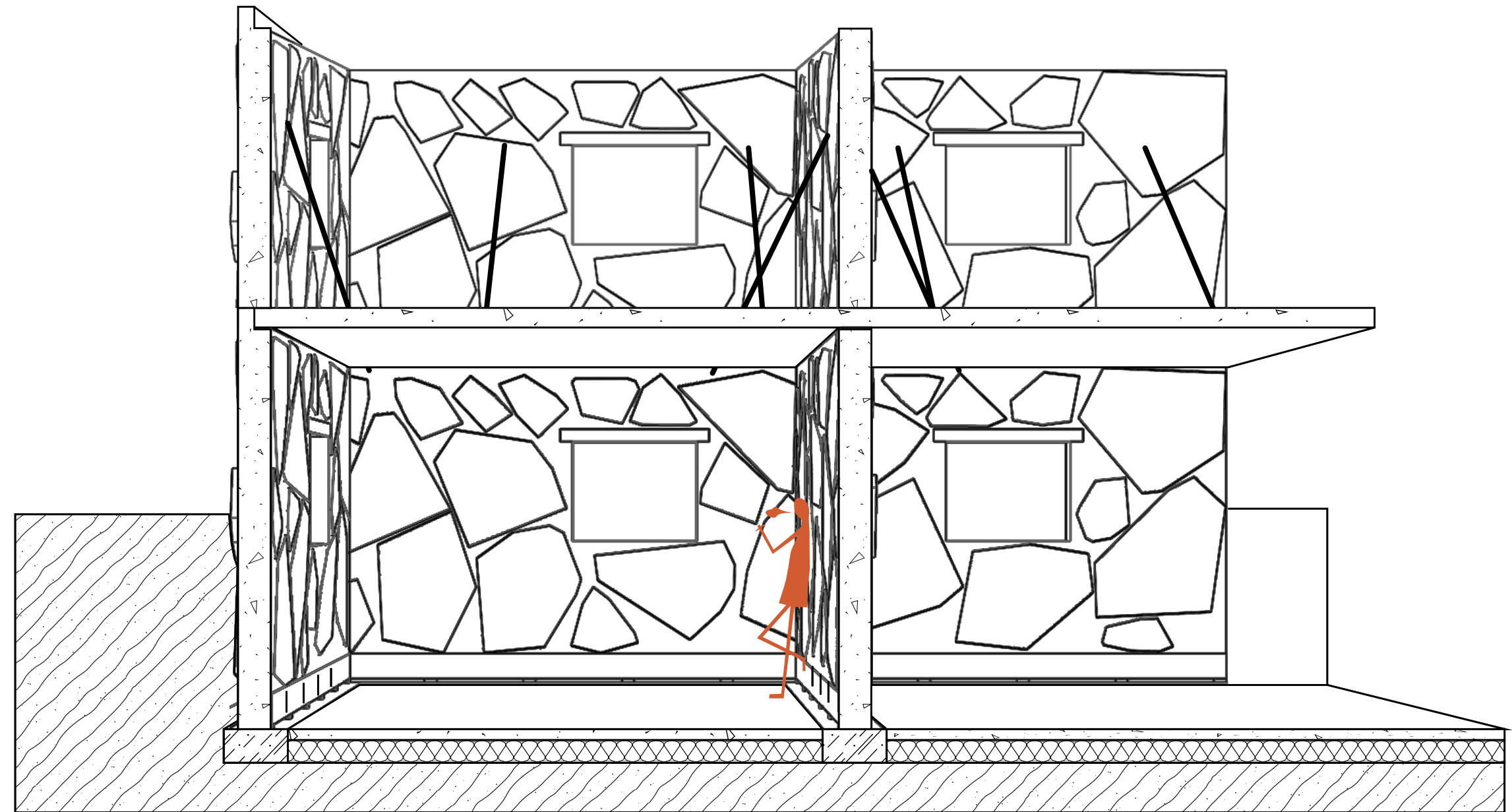
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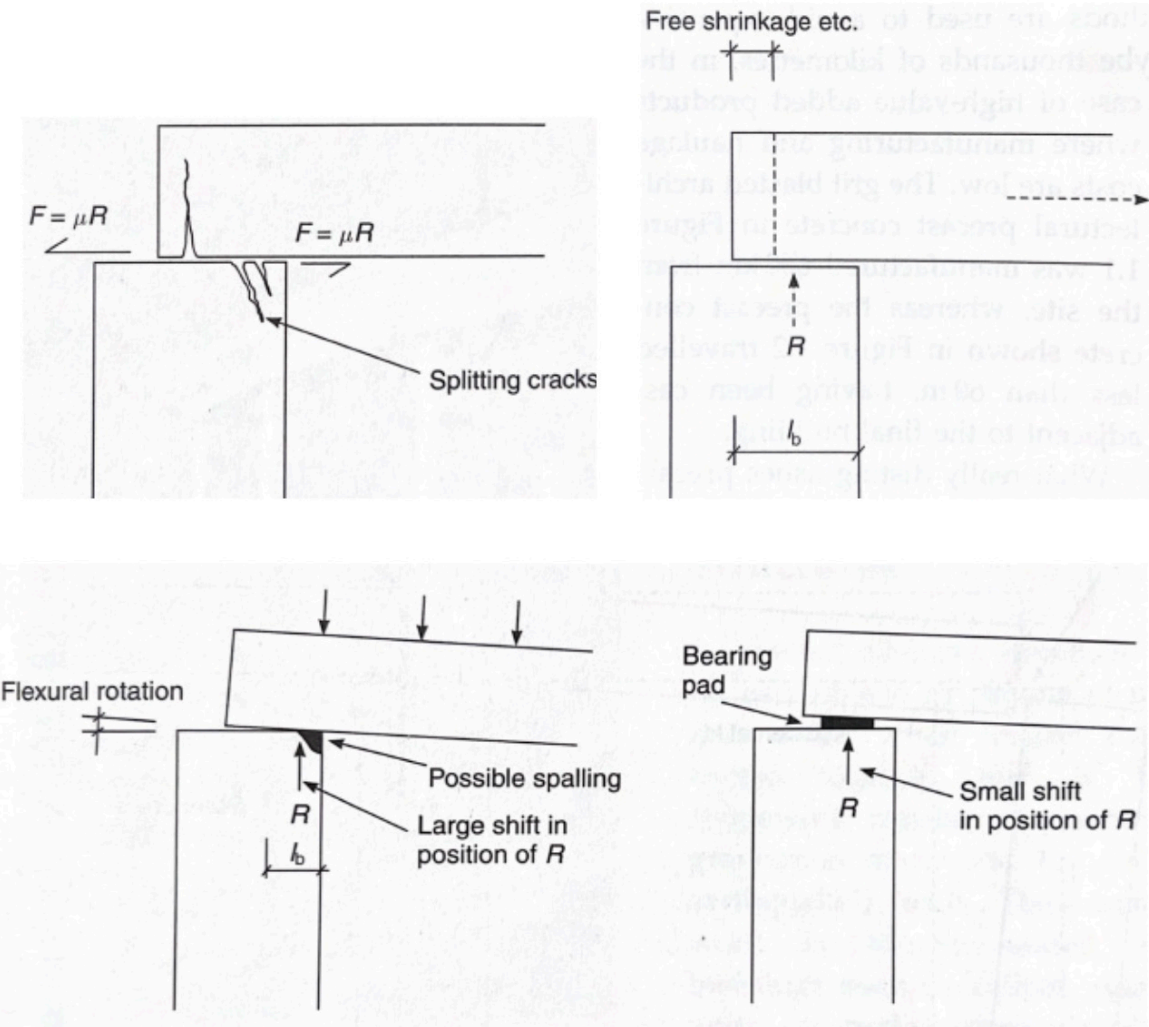
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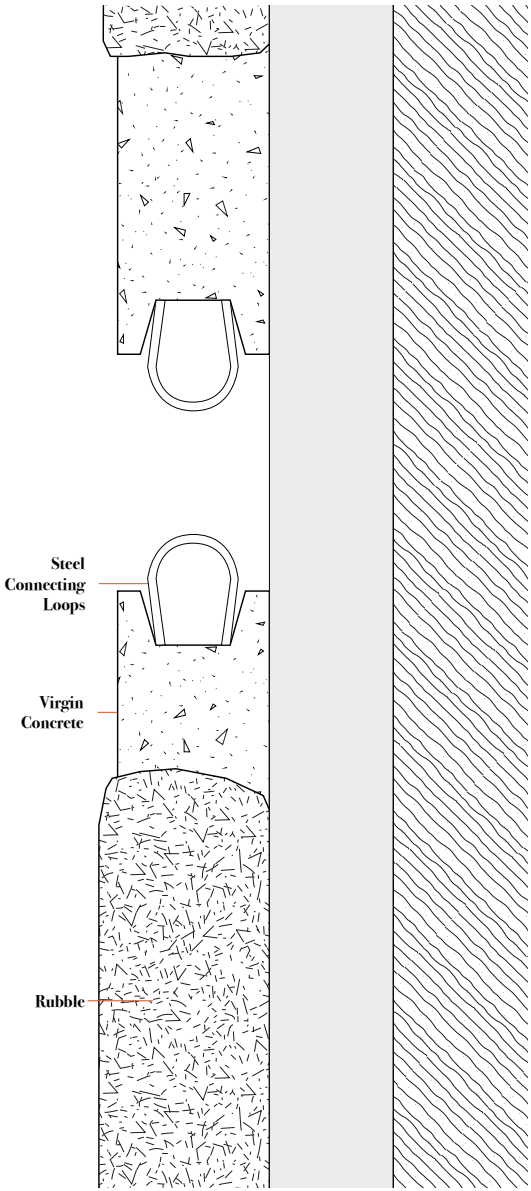
Assembly



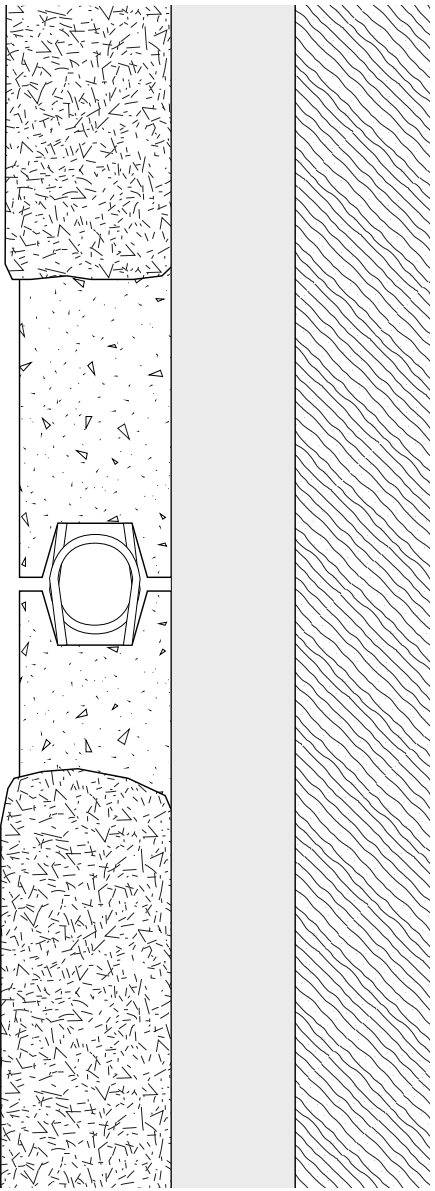
Challenge 2



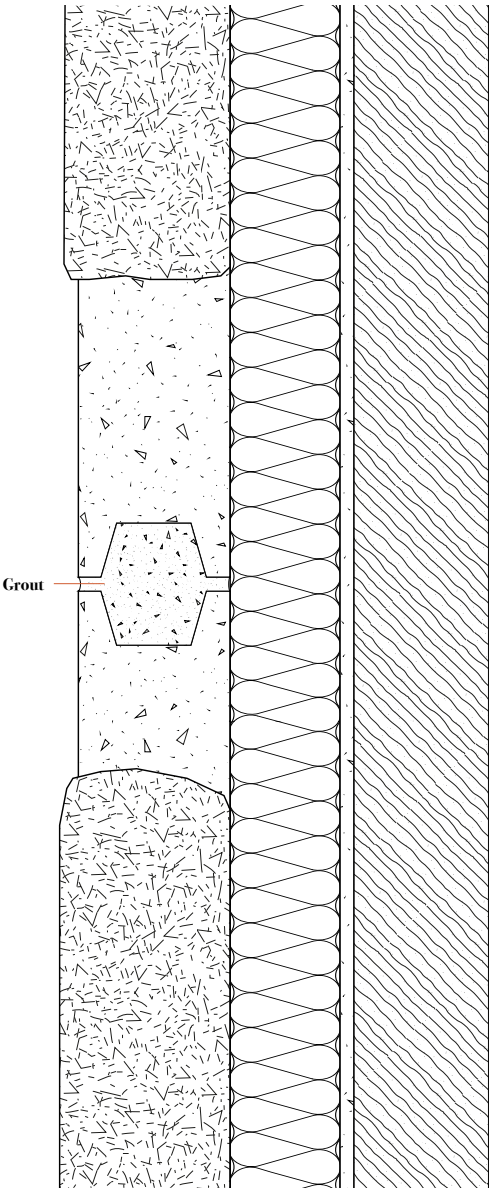
Wall Connections



Step 1

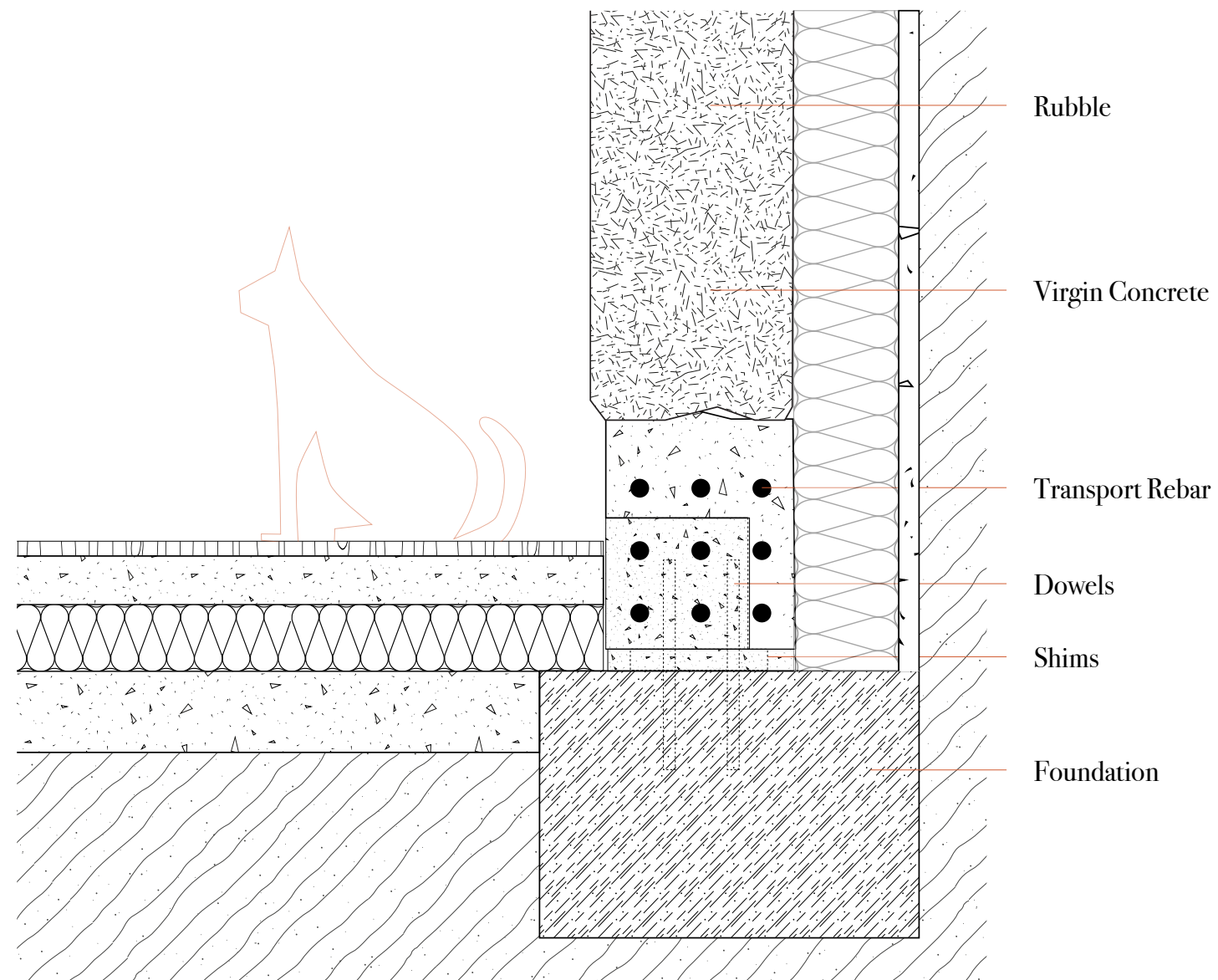


Step 2



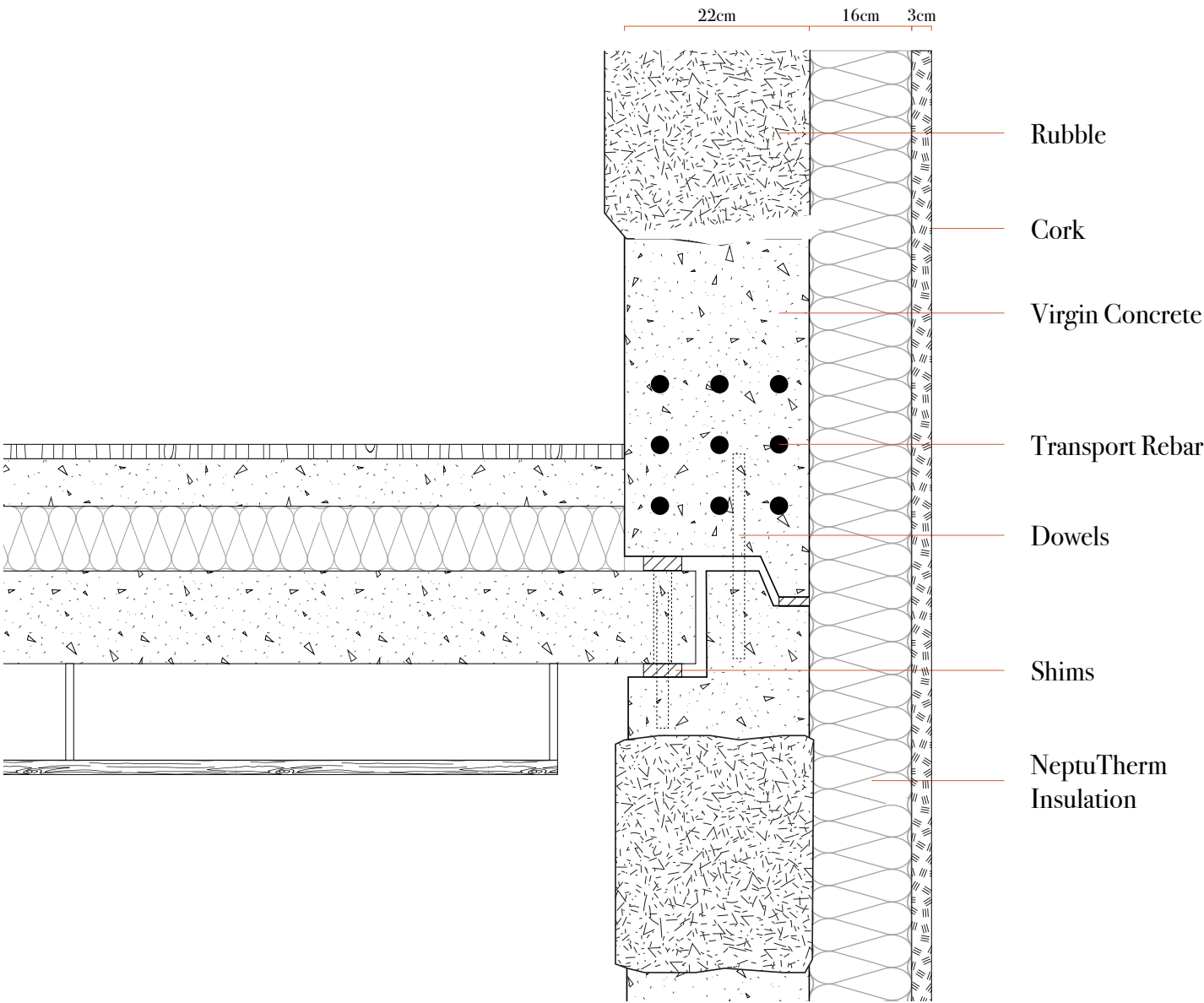
Step 3

Wall Connections



Foundation Connection

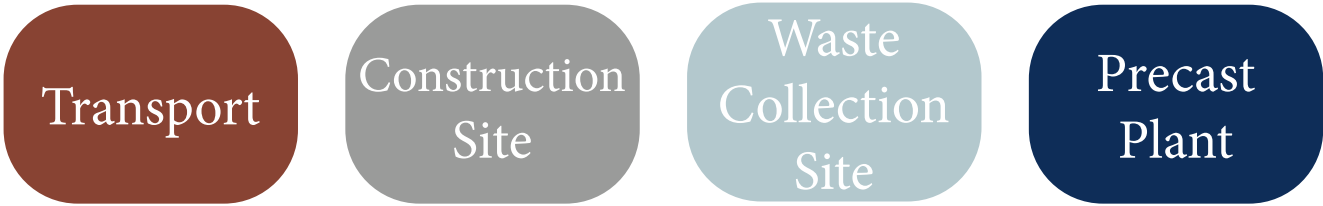
Wall Connections



Floor to Floor Connection

Actor Maps

Locations



Actors



Assets

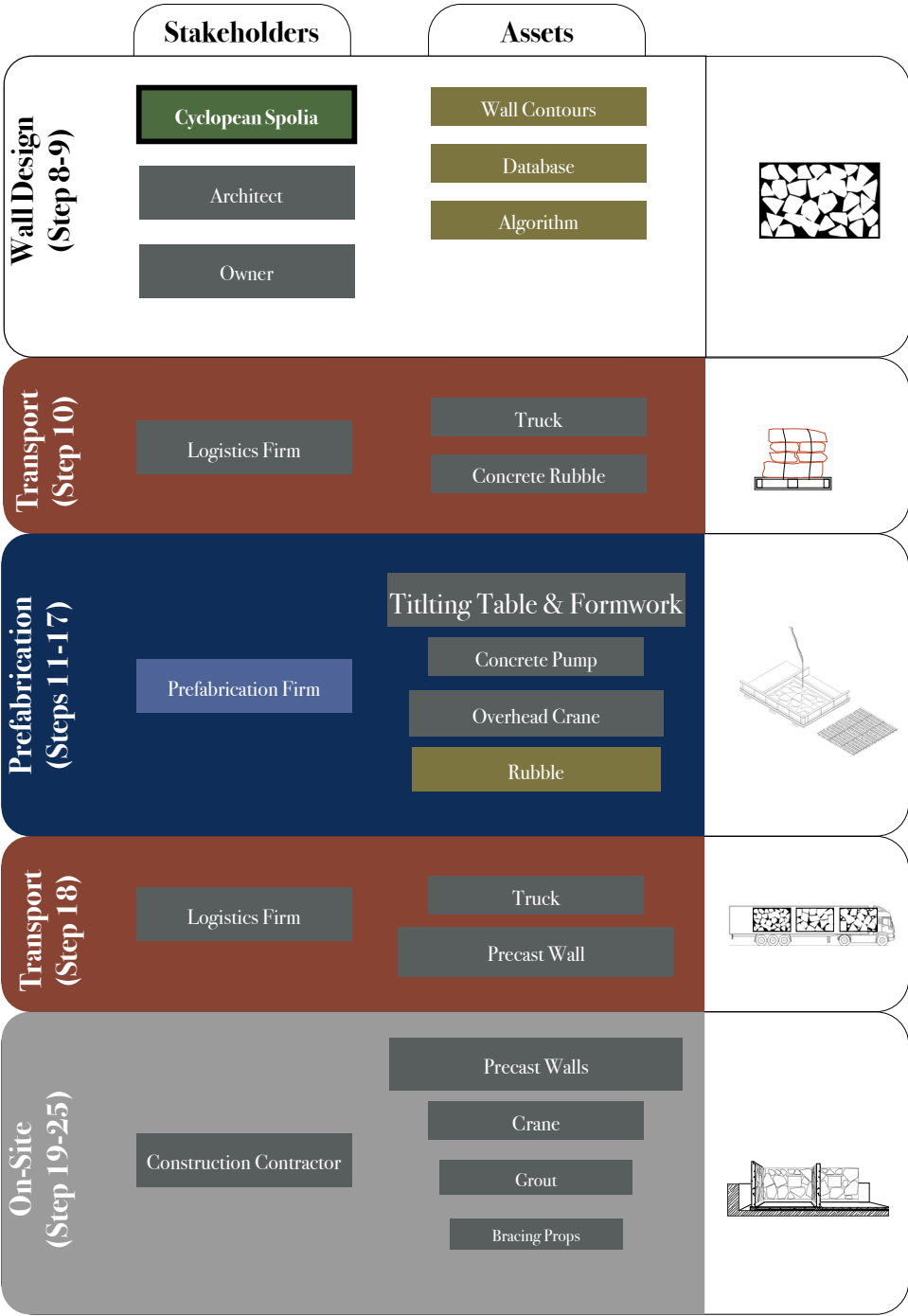
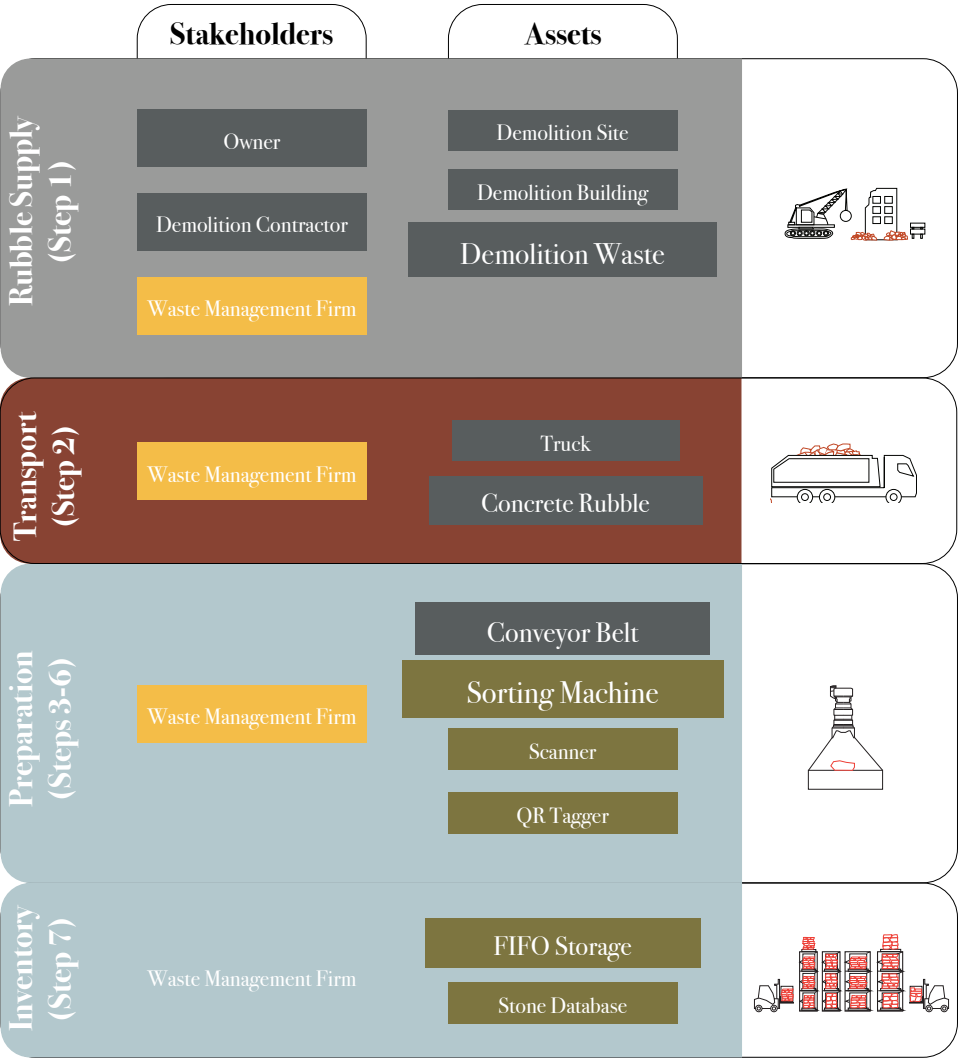




Waste Management Firm

Cyclopean Spolia

Prefabrication Firm



Transport

Construction Site

Waste Collection Site

Precast Plant

Main CS Manager

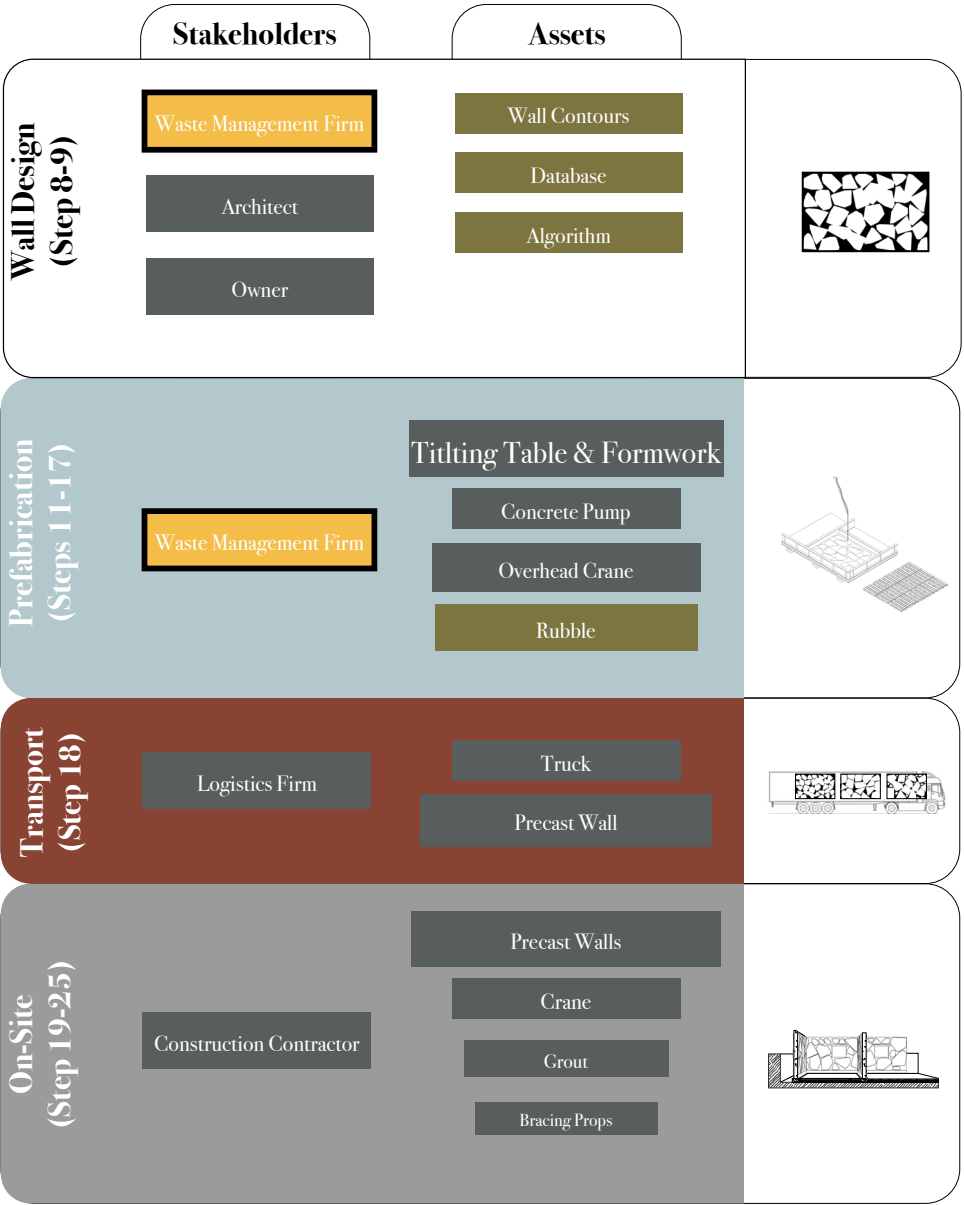
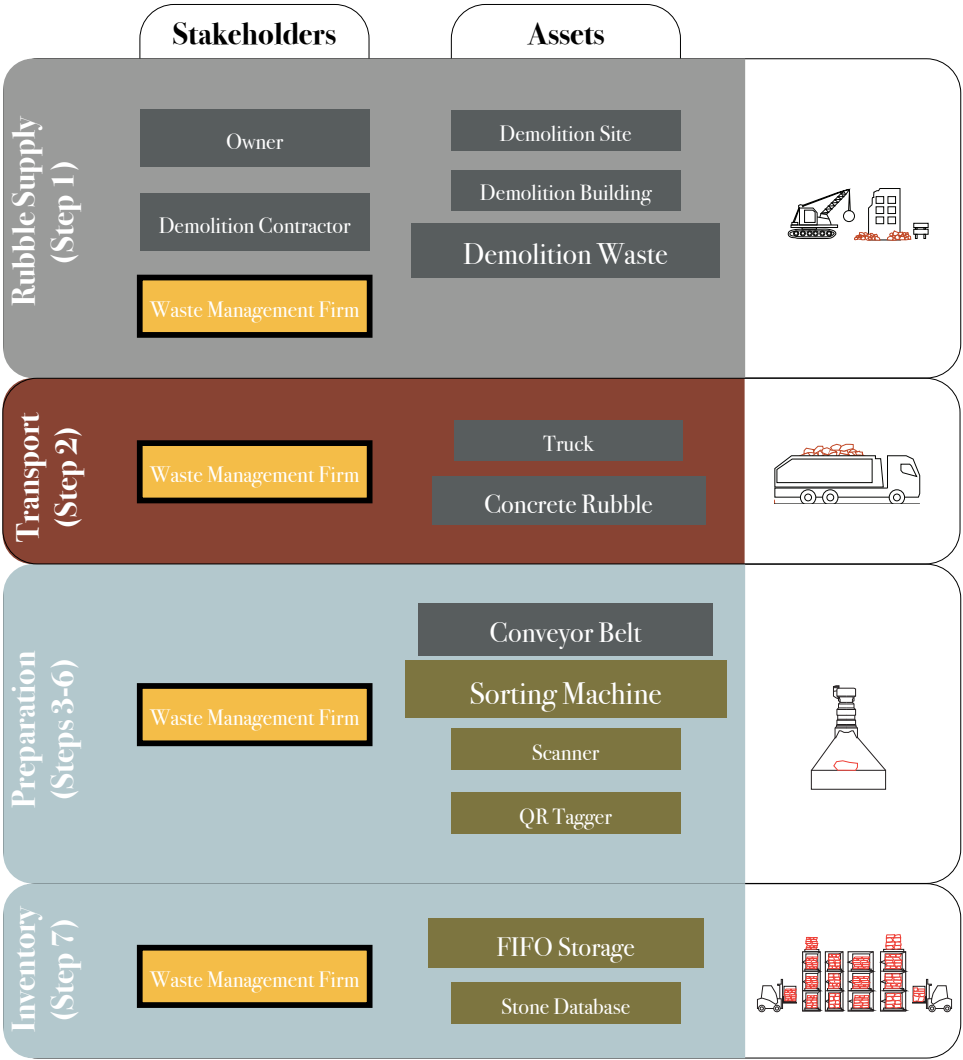
Existing

New

Heavy Asset

Light Asset

Waste Management Firm



Transport

Construction Site

Waste Collection Site

Precast Plant

Main CS Manager

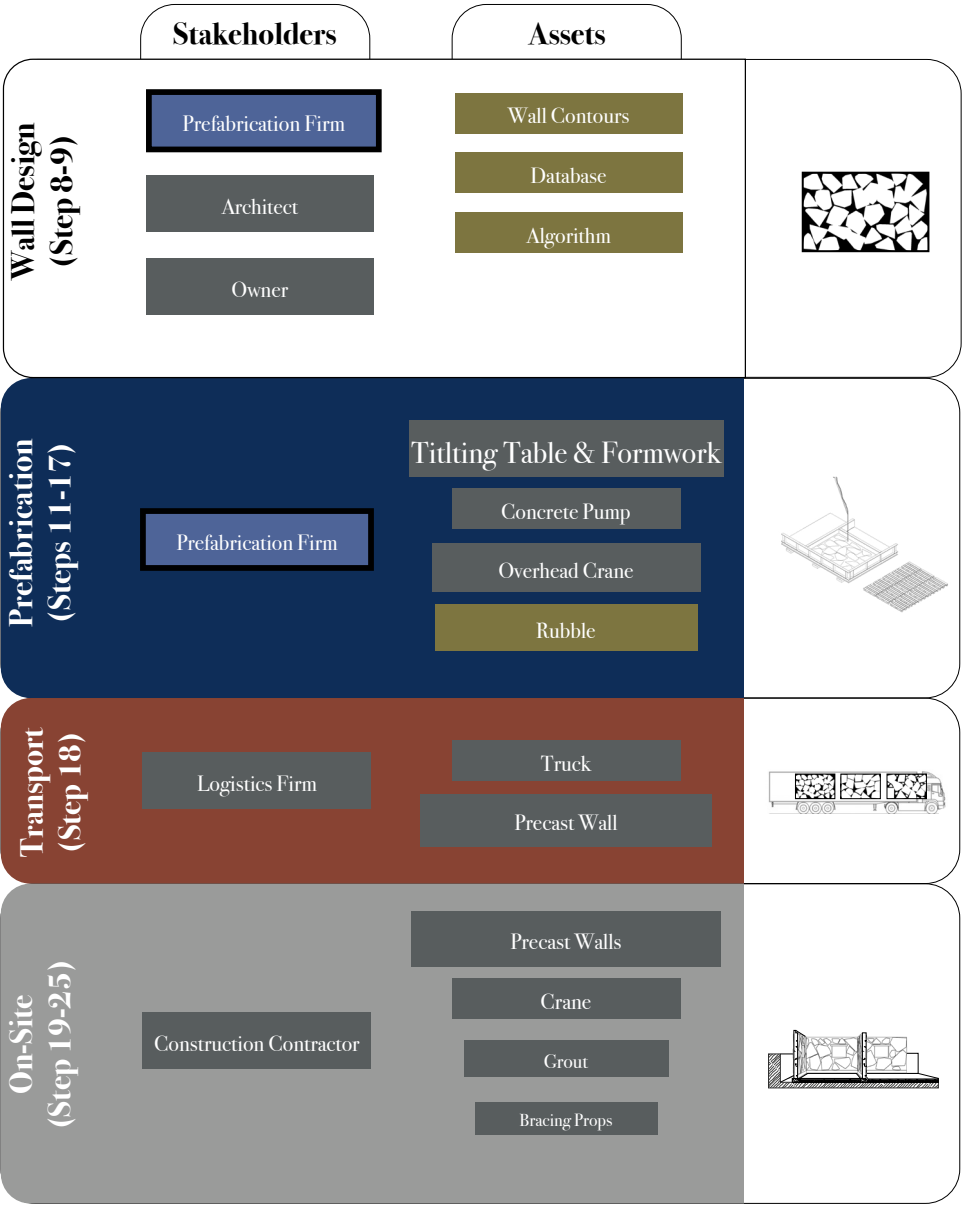
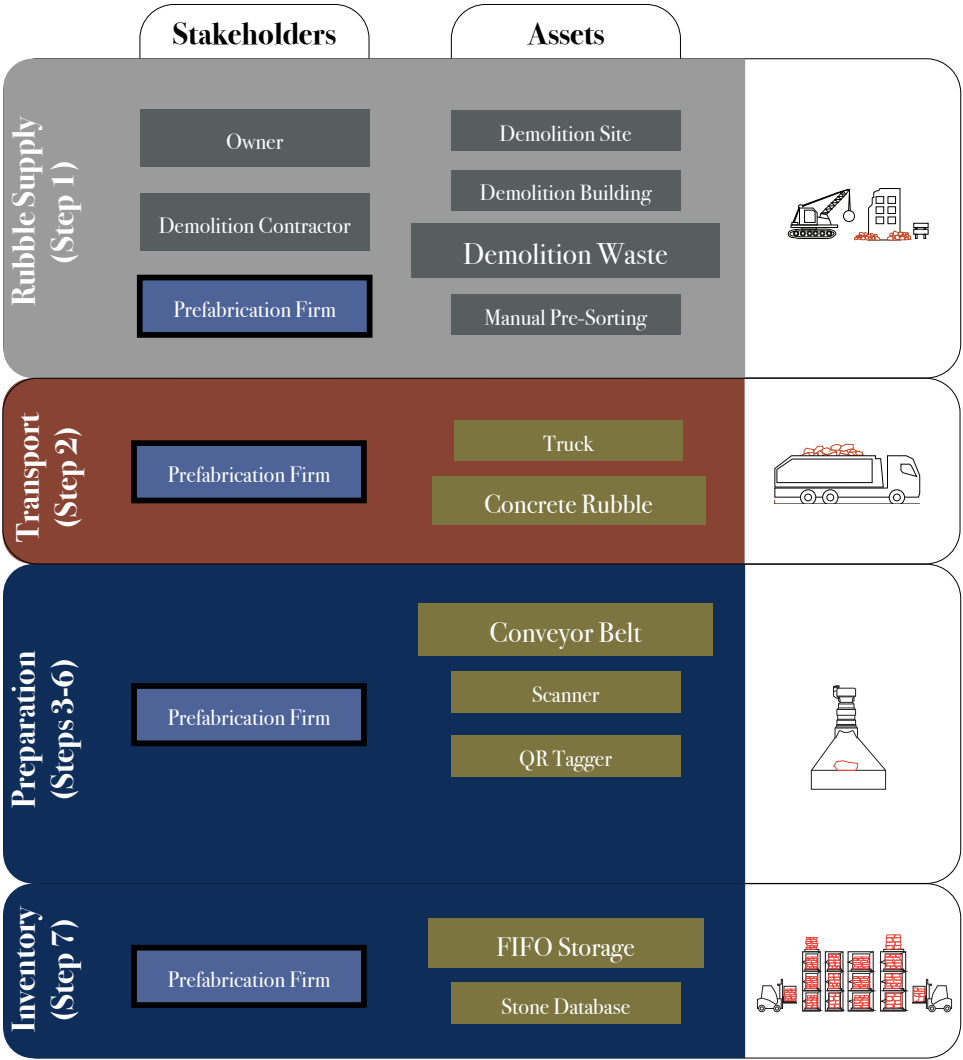
Existing

New

Heavy Asset

Light Asset

Prefabrication Firm



Transport

Construction Site

Waste Collection Site

Precast Plant

Main CS Manager

Existing

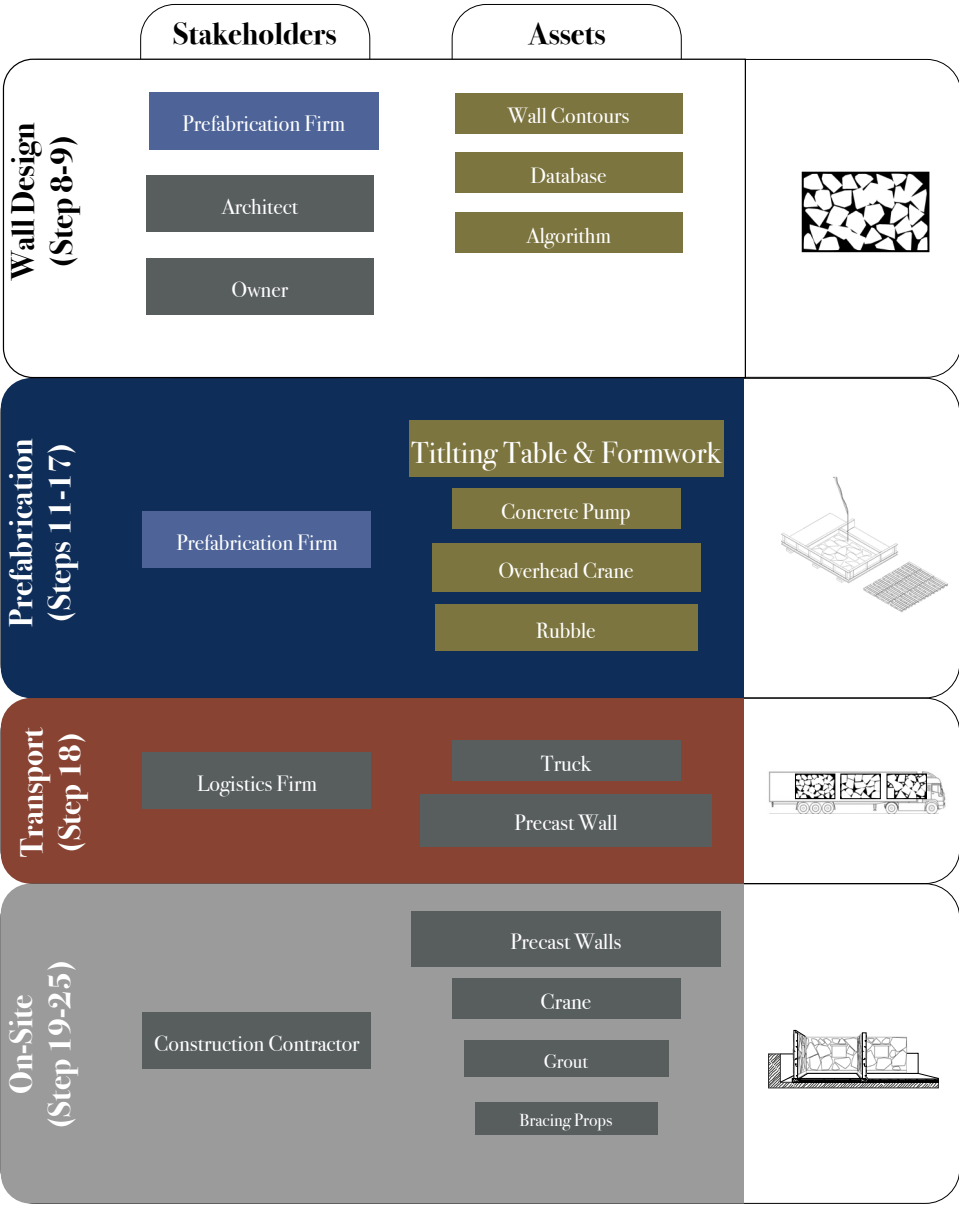
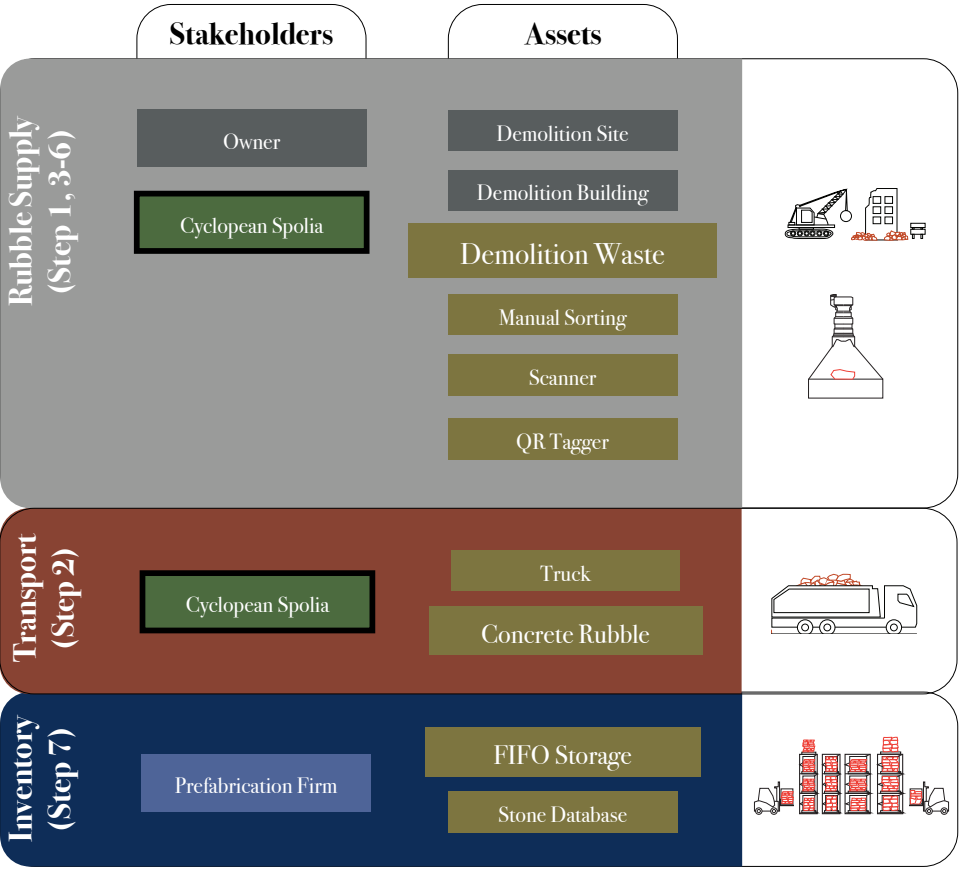
New

Heavy Asset

Light Asset

Cyclopean Spolia

Prefabrication Firm



Transport

Construction Site

Waste Collection Site

Precast Plant

Main CS Manager

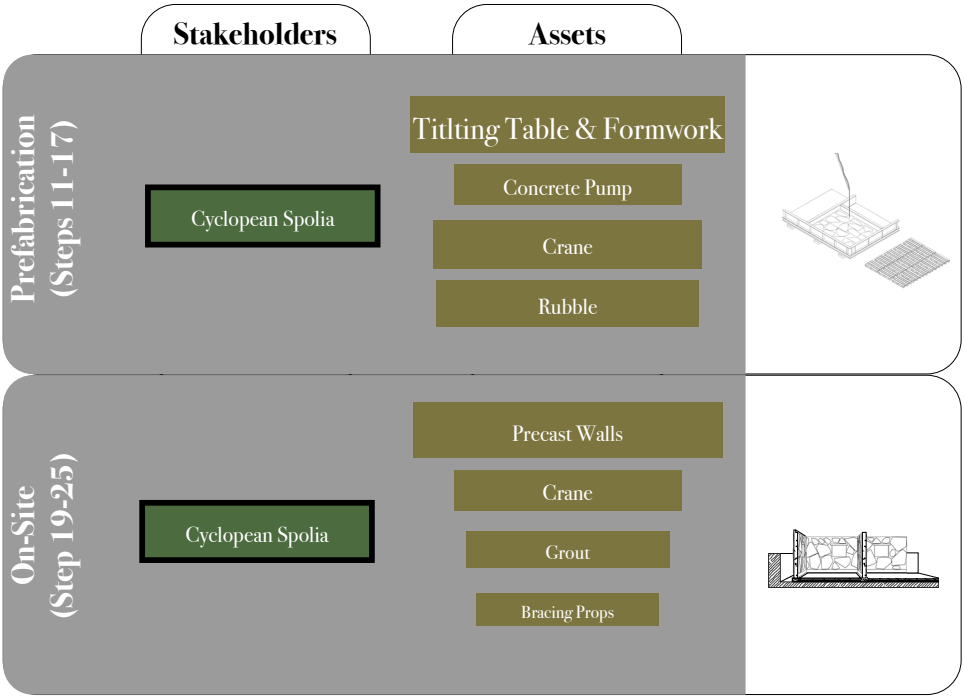
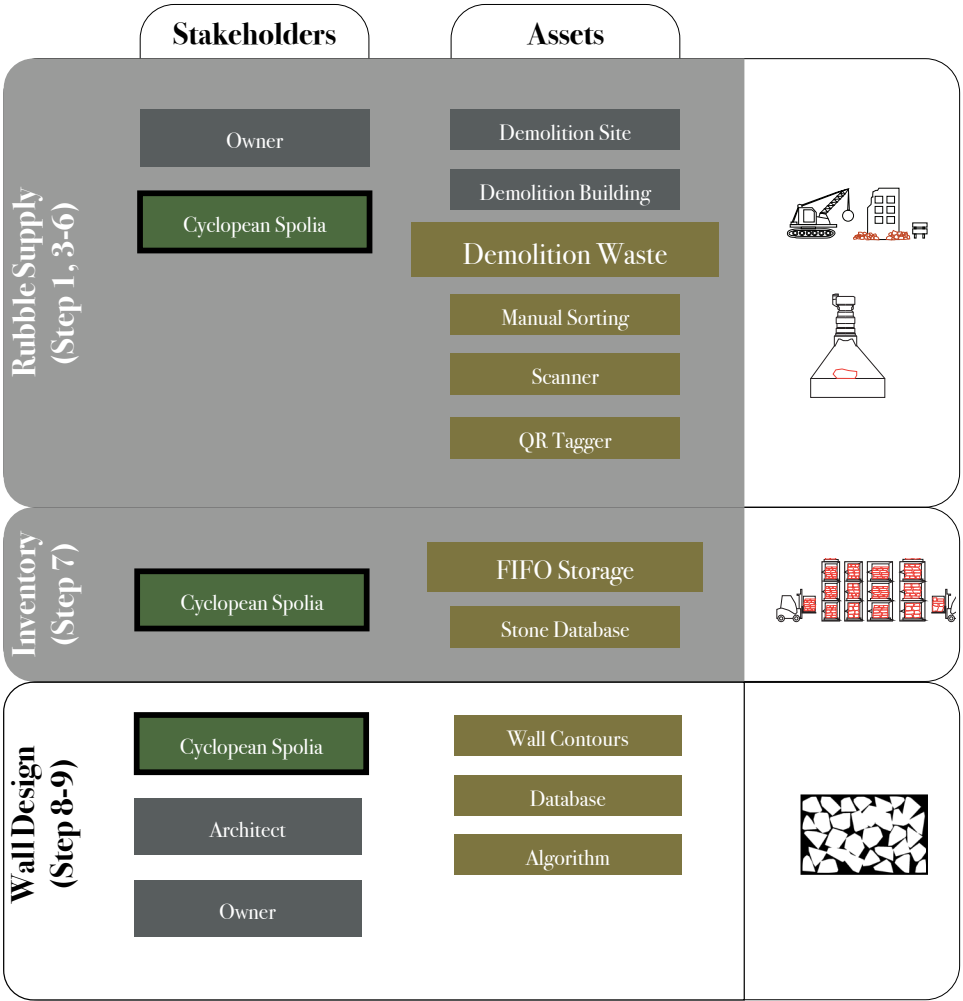
Existing

New

Heavy Asset

Light Asset

Cyclopean Spolia



Transport

Construction Site

Waste Collection Site

Precast Plant

Main CS Manager

Existing

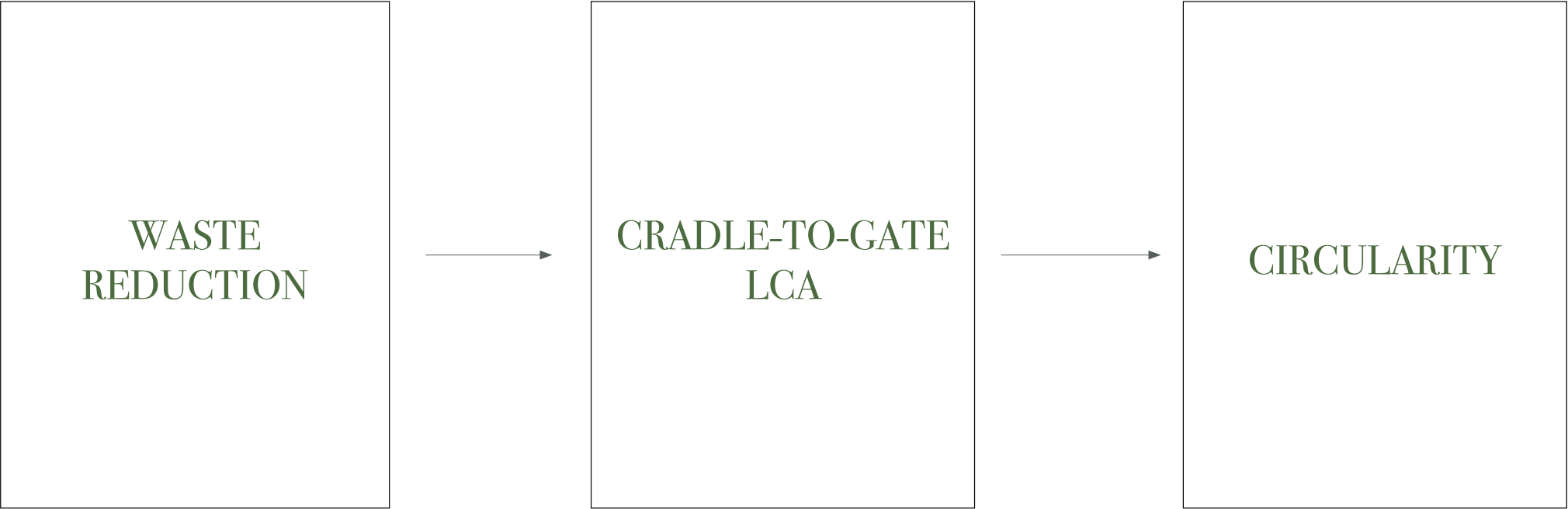
New

Heavy Asset

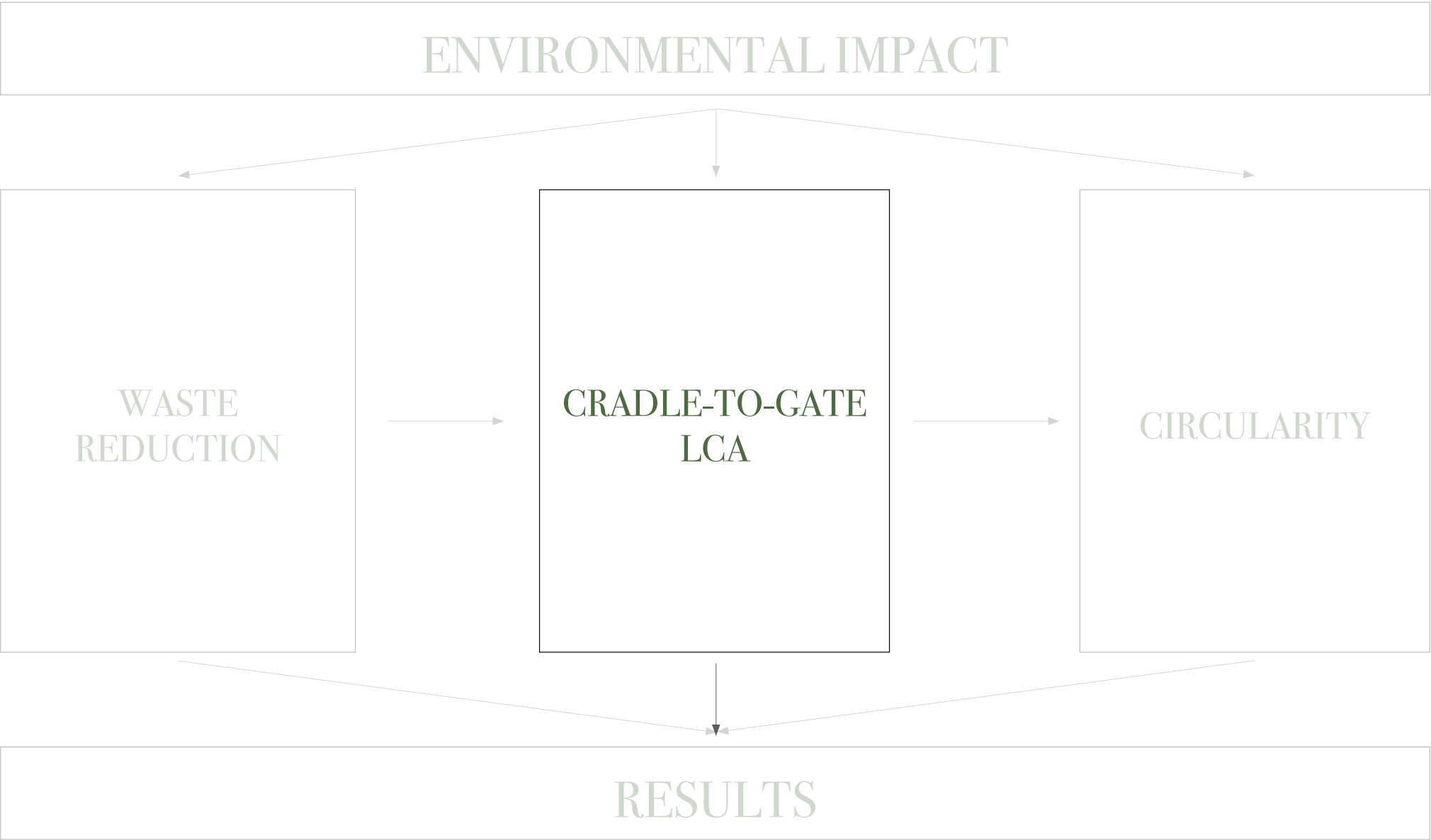
Light Asset



ENVIRONMENTAL IMPACT



RESULTS



LCA

Cradle To Gate	Product Stage	A1	Raw material extraction
		A2	Transport to manufacturing site
		A3	Manufacturing
Cradle To Practical Completion	Construction Stage	A4	Transport to construction site
		A5	Installation / Assembly
Cradle To Grave	Use Stage	B1	Use
		B2	Maintenance
		B3	Repair
		B4	Replacement
		B5	Refurbishment
		B6	Operational energy use
		B7	Operational water use
	End of Life Stage	C1	Deconstruction & Demolition
		C2	Transport
		C3	Waste processing
		C4	Disposal
Cradle To Cradle	Circularity	D	Benefits and loads beyond system boundary

LCA

Cradle To Gate	Product Stage	A1	Raw material extraction
		A2	Transport to manufacturing site
		A3	Manufacturing
Cradle To Practical Completion	Construction Stage	A4	Transport to construction site
		A5	Installation / Assembly
Cradle To Grave	Use Stage	B1	Use
		B2	Maintenance
		B3	Repair
		B4	Replacement
		B5	Refurbishment
		B6	Operational energy use
		B7	Operational water use
	End of Life Stage	C1	Deconstruction & Demolition
		C2	Transport
		C3	Waste processing
		C4	Disposal
Cradle To Cradle	Circularity	D	Benefits and loads beyond system boundary

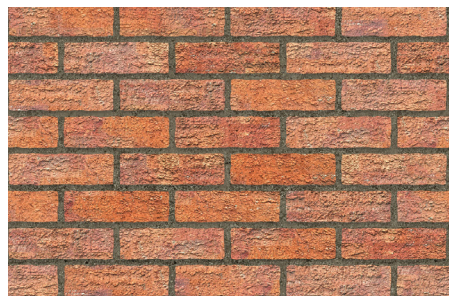
LCA



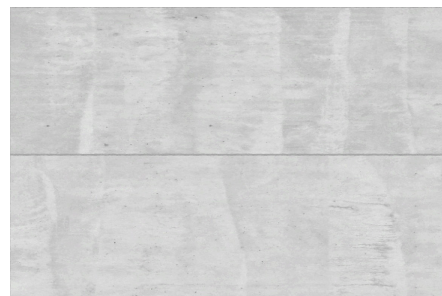
30 %



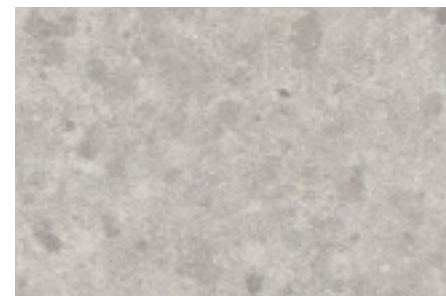
20 %



Brick



Precast Concrete



In-Situ Concrete

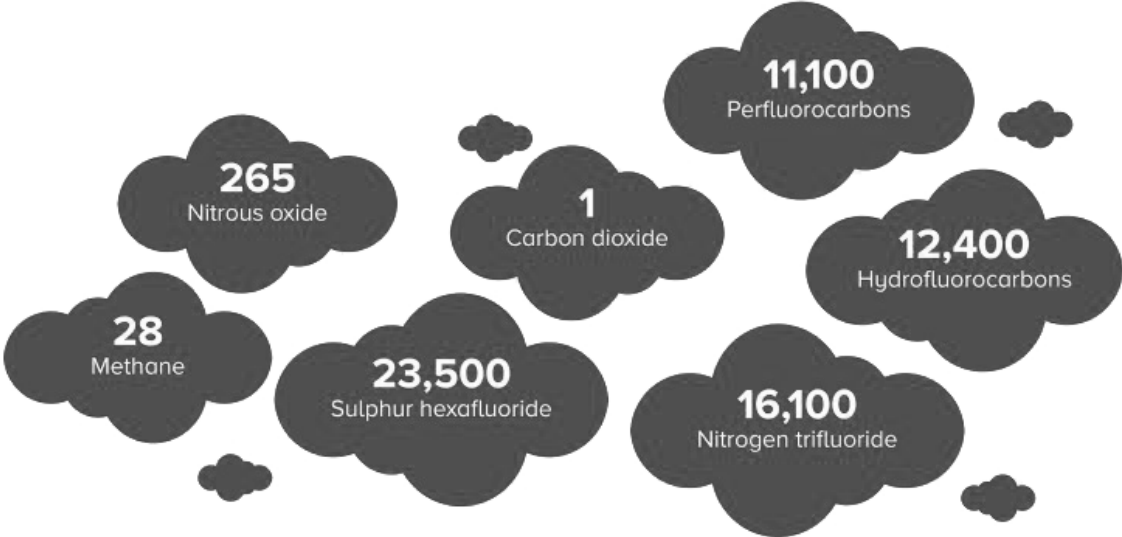


In-Situ R-Concrete

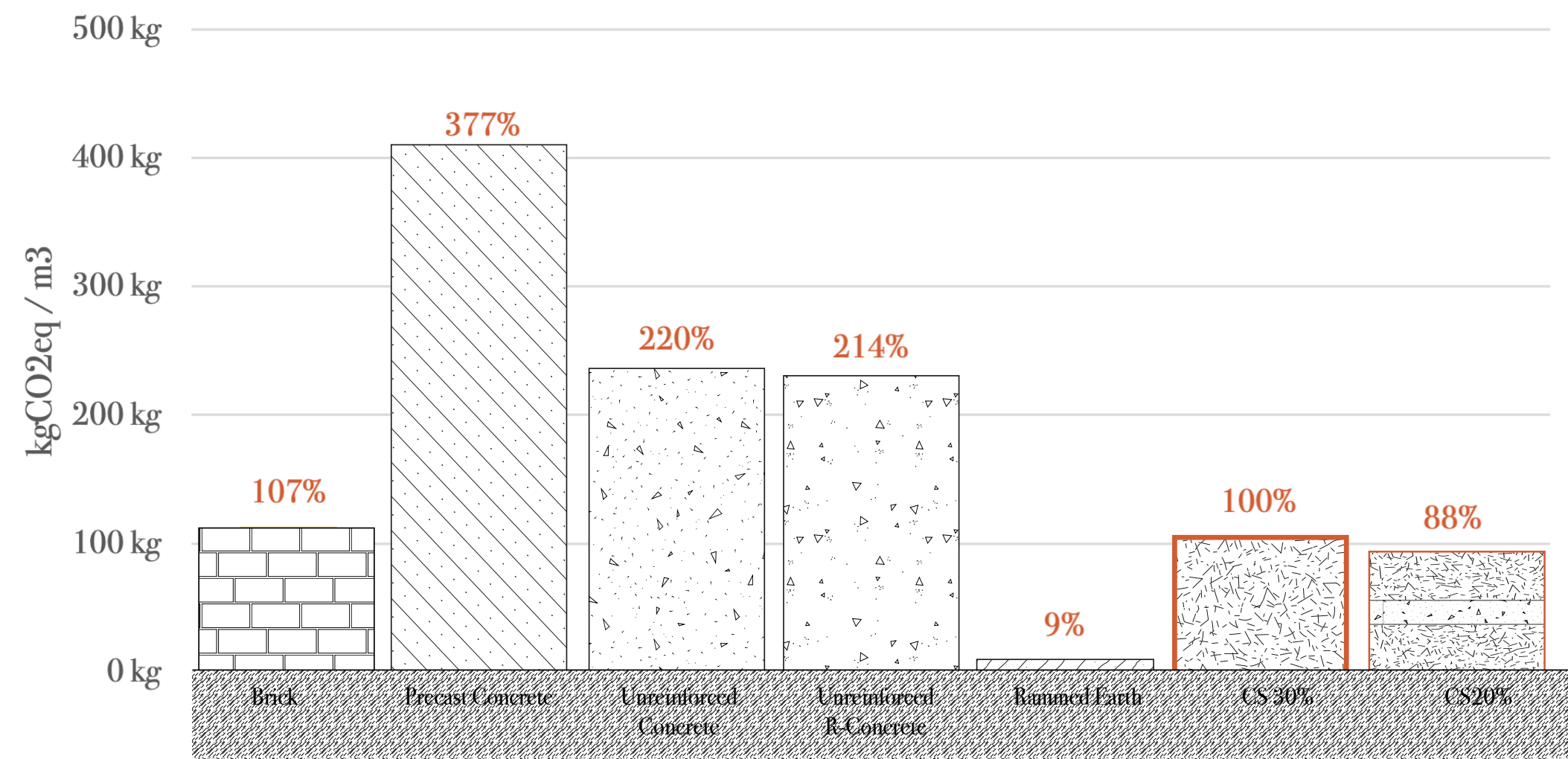


Rammed Earth

GWP



GWP / m3



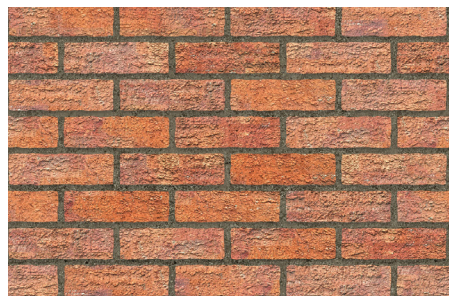
LCA



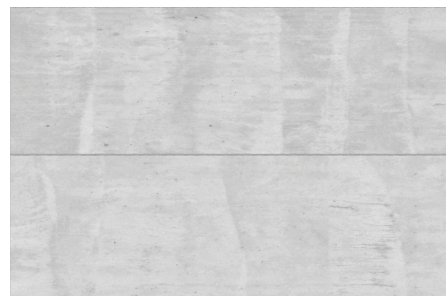
5 MPa



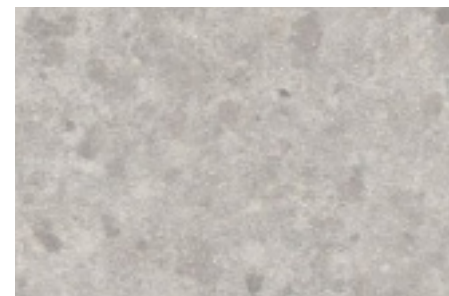
5 MPa



12 MPa



30 MPa



30 MPa

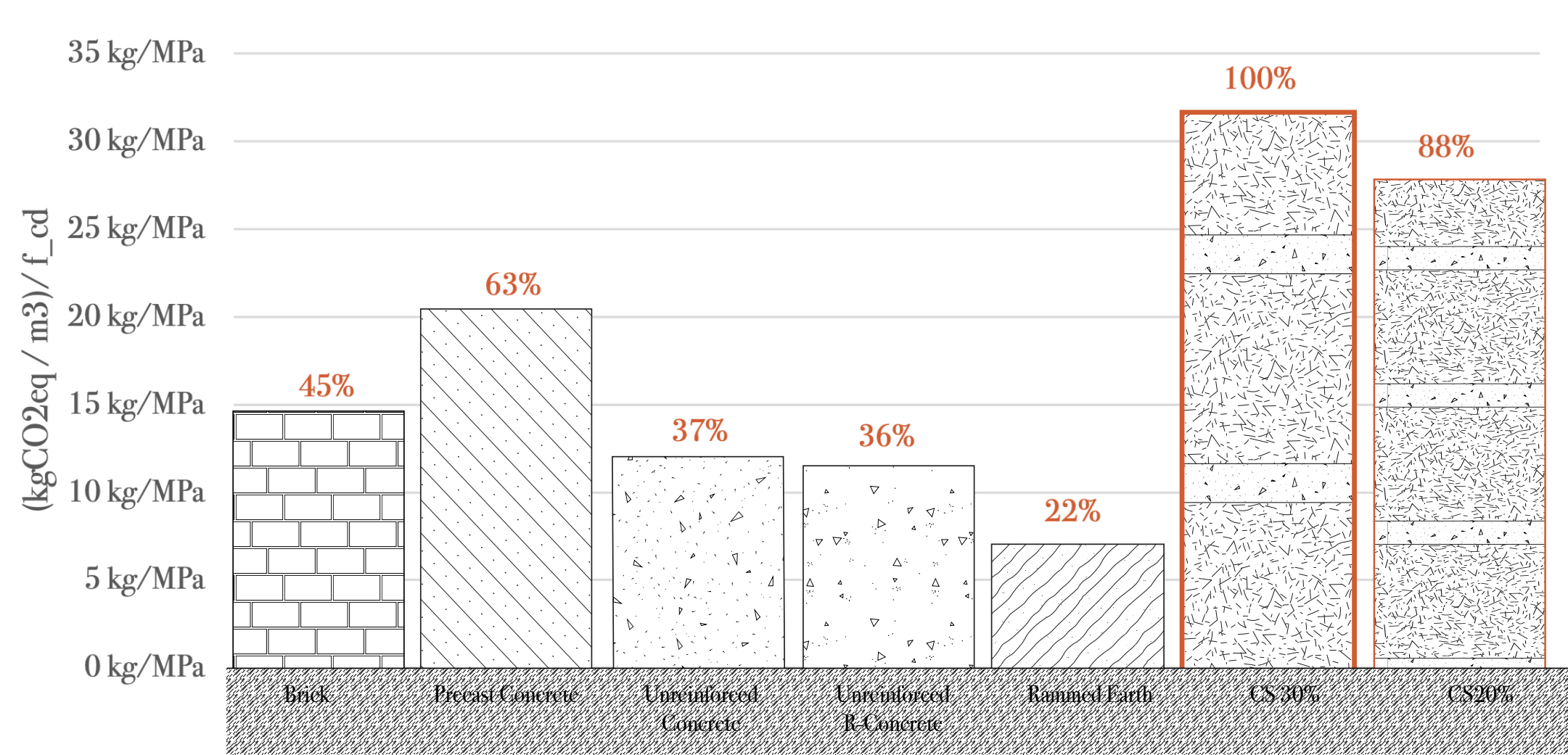


30 MPa

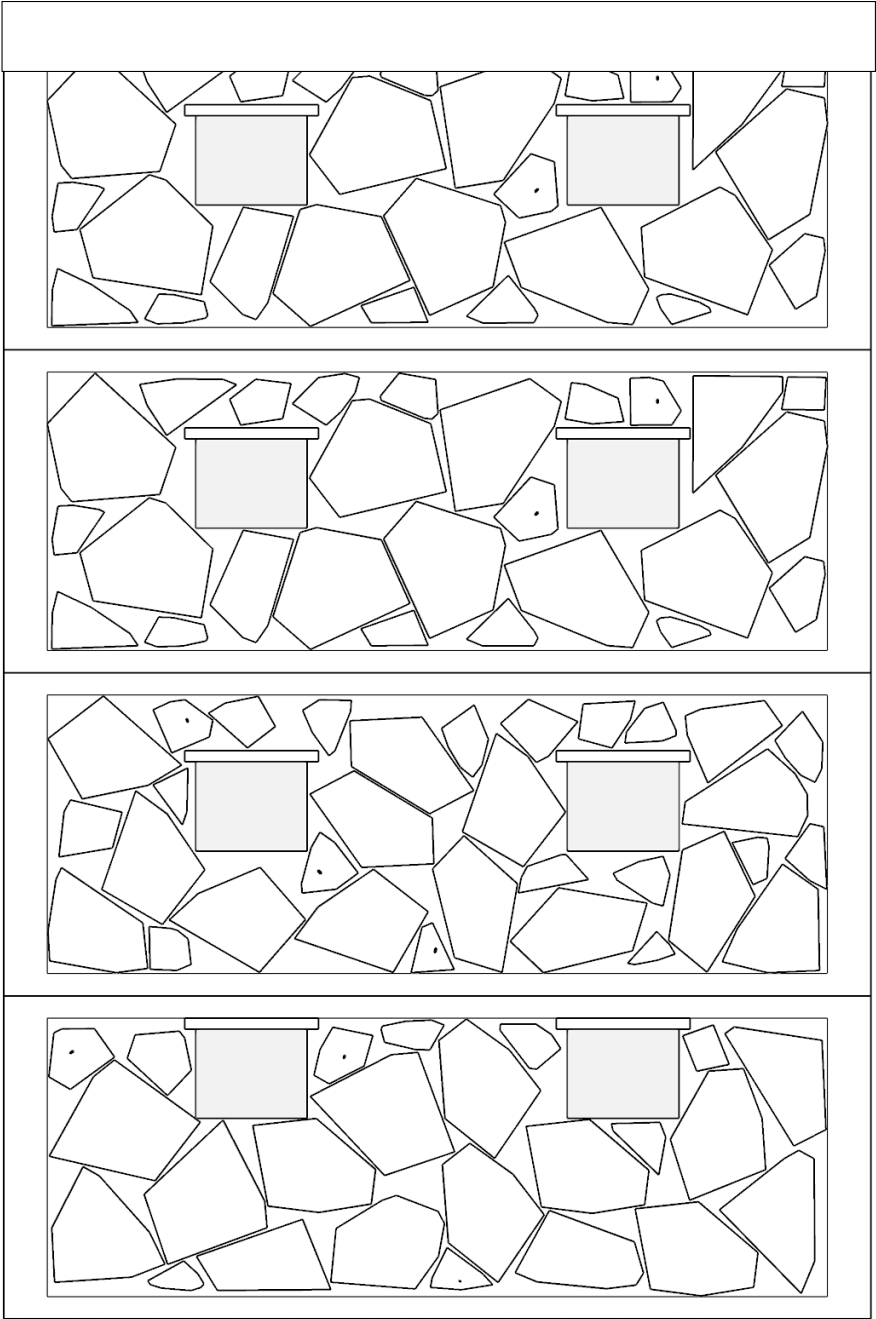


2 MPa

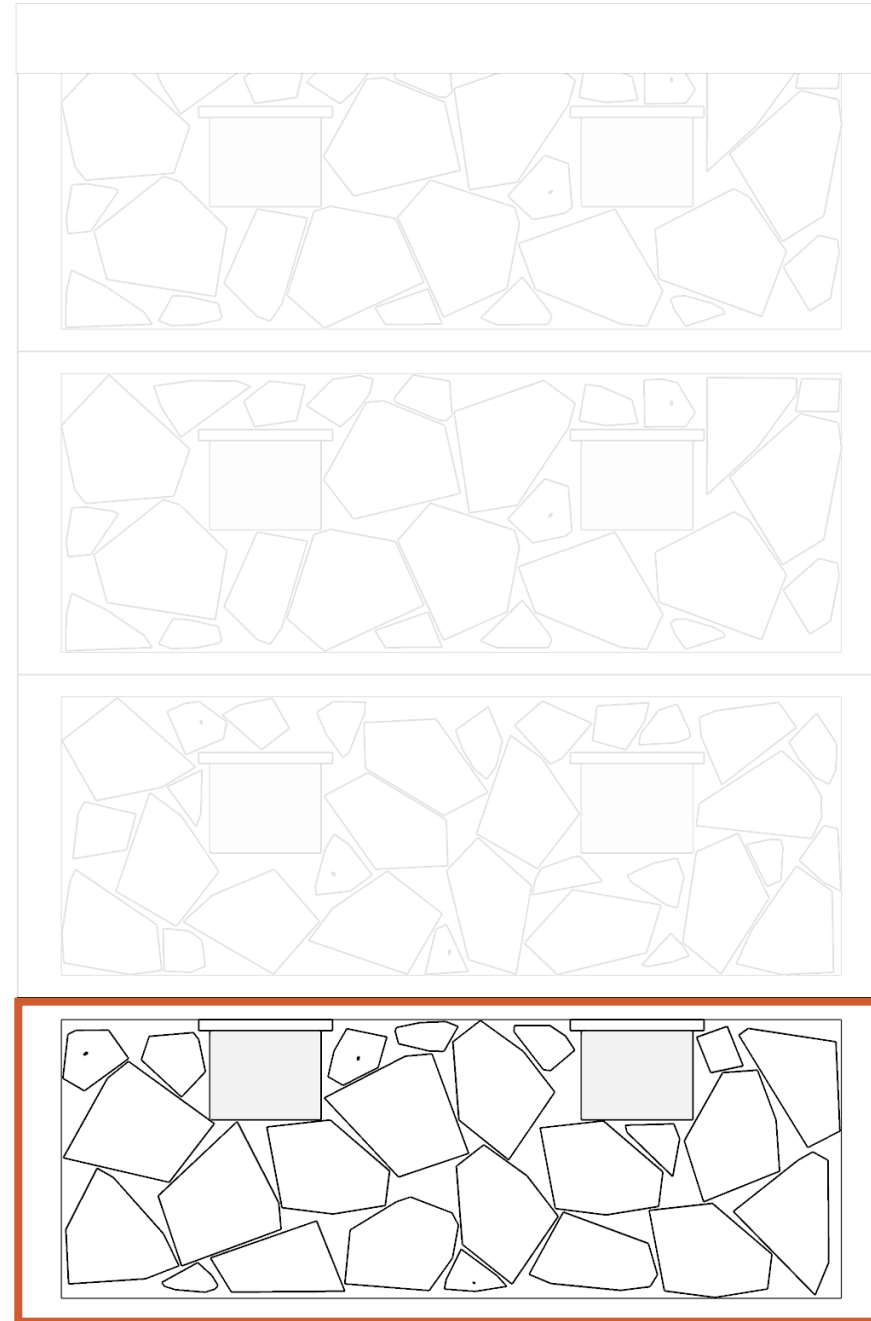
GWP / MPa



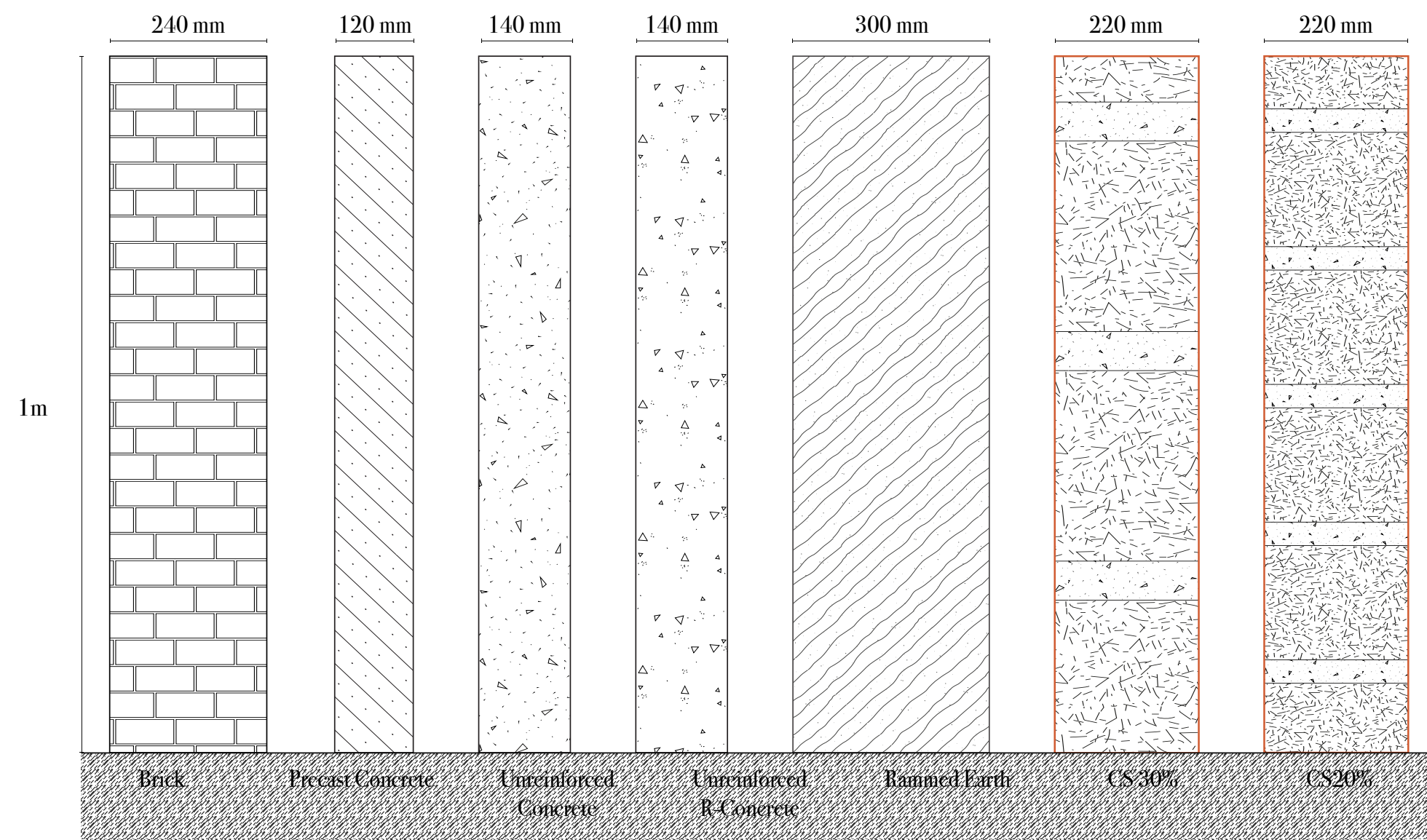
Case Study



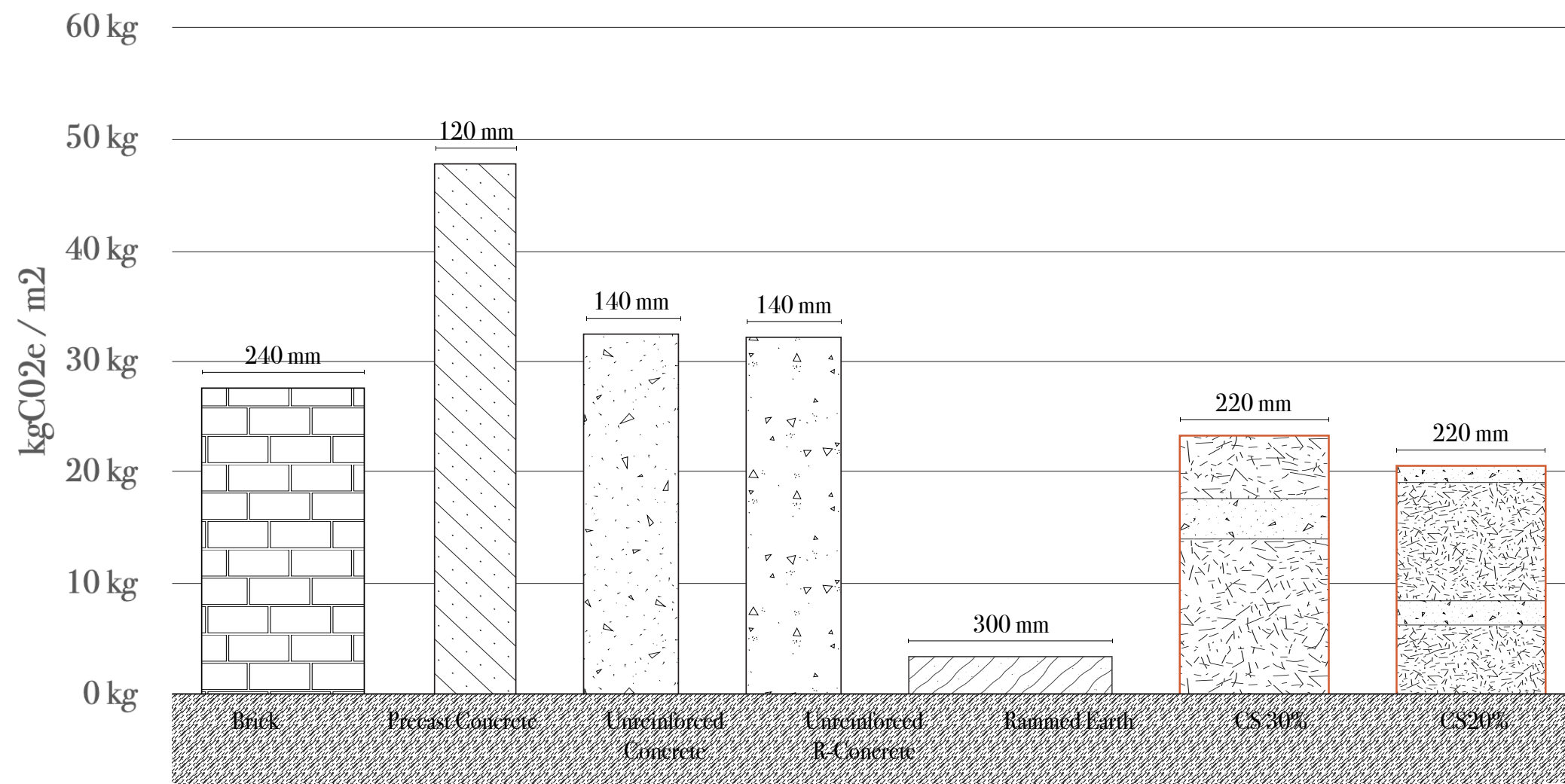
Case Study



Wall Thicknesses



GWP / m2



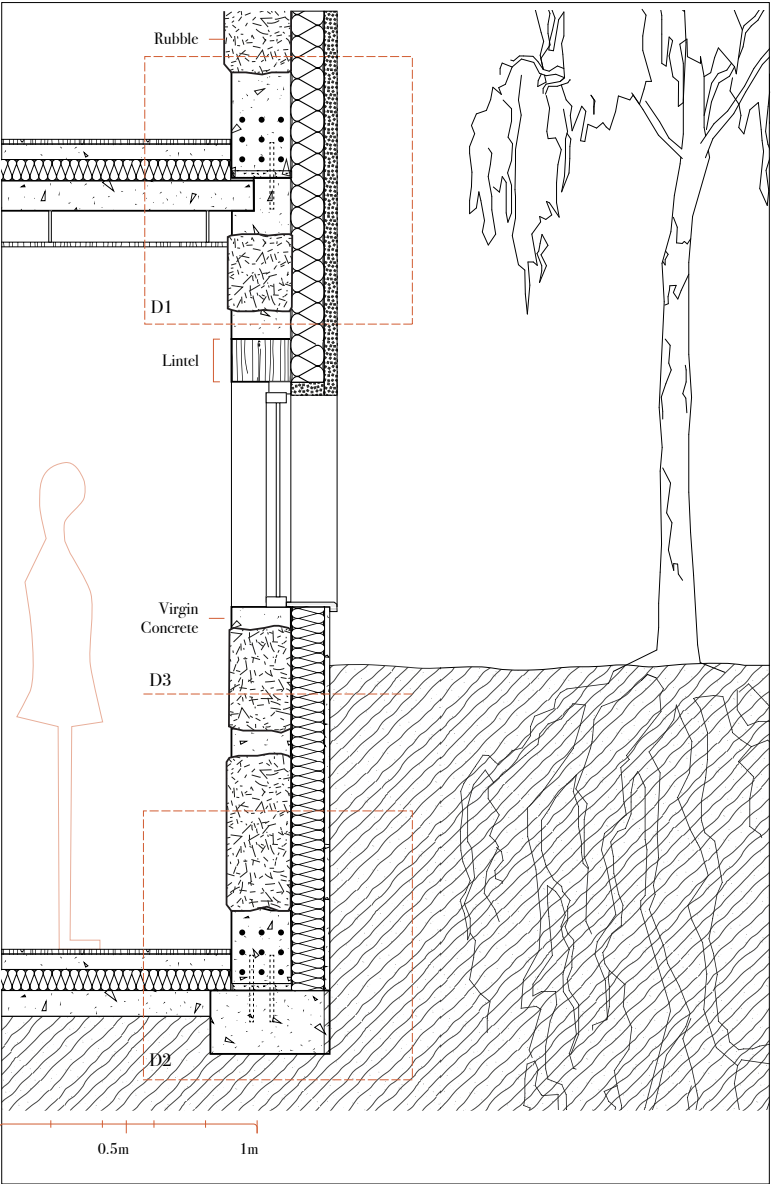
Conclusion

The Three Pillars

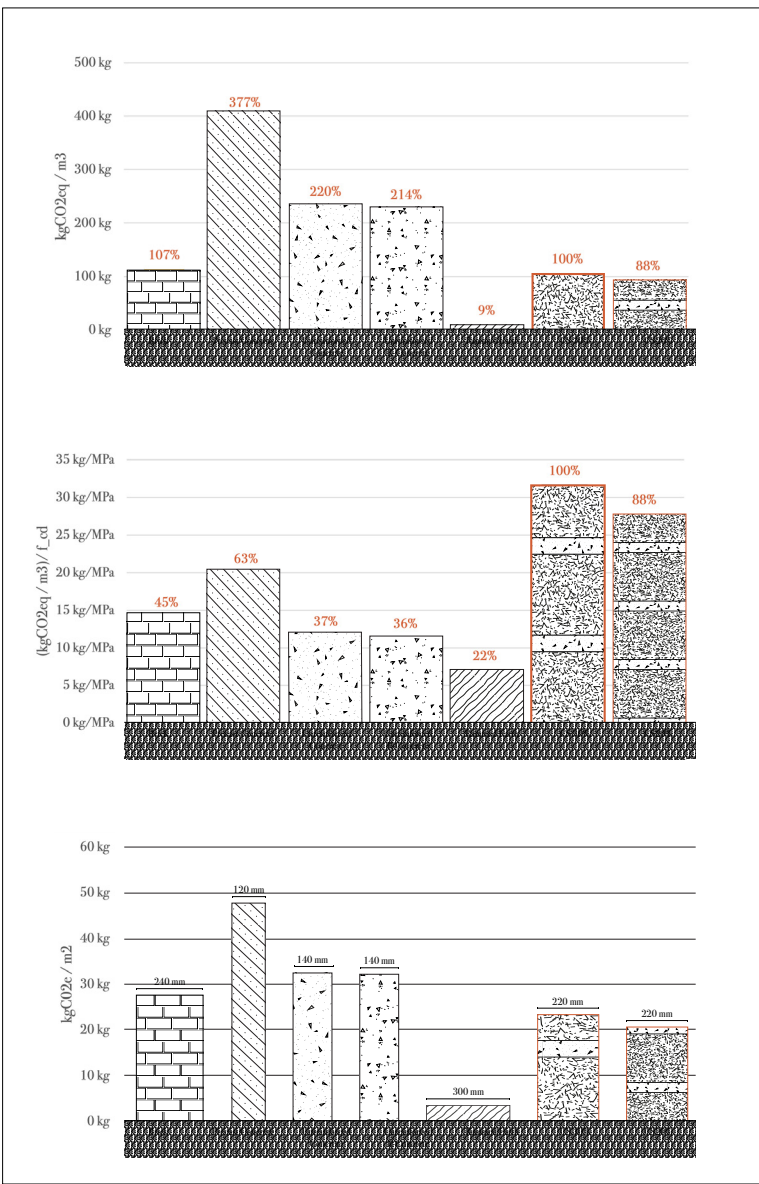
Structural Tests



System Design



Env. Impact



Further Research

Full-Scale Validation of Results (including bending & anchors)

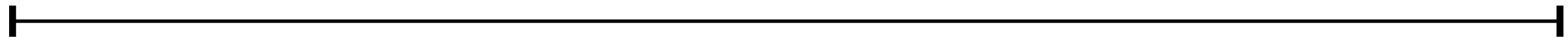
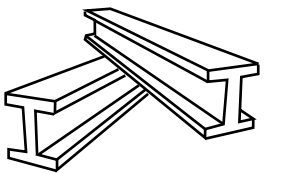
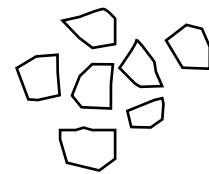
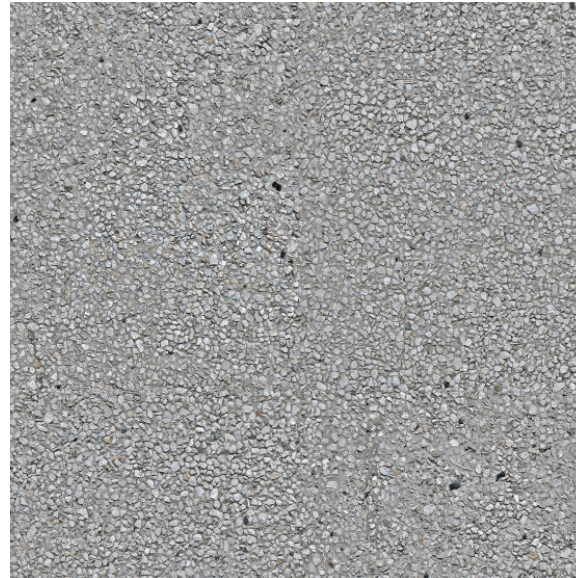
Interface Material Properties

Minimum Strength of Rubble

Explore Taller Case Studies

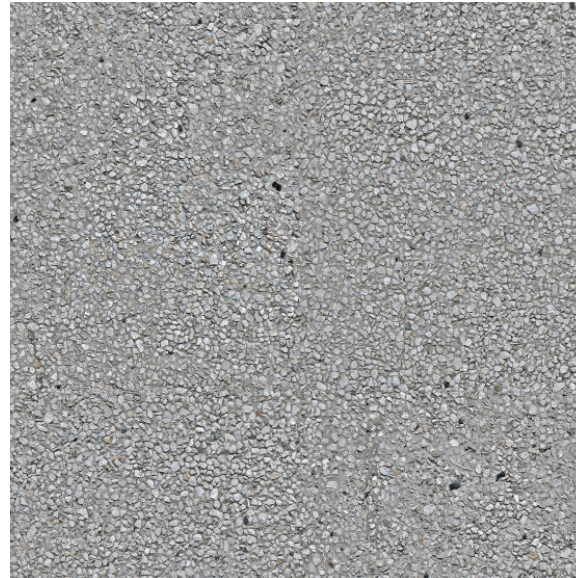
Economic Analyses

A Future For Concrete Waste?



Superuse (n/d)
Ramírez (2011)
Picharchitects (n/d)

A Future For Concrete Waste?



RCA



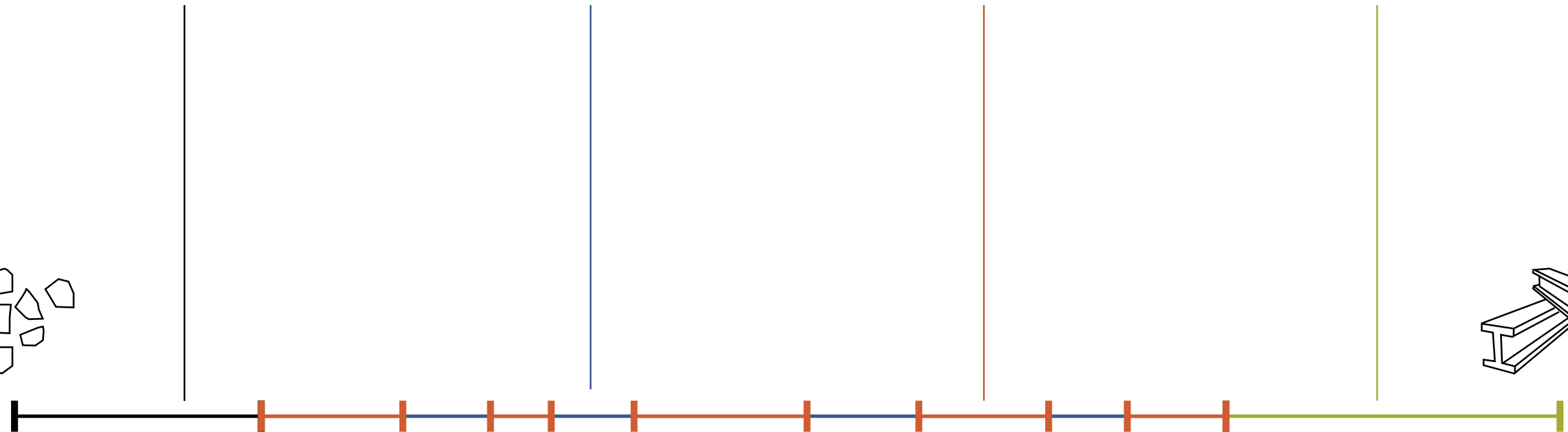
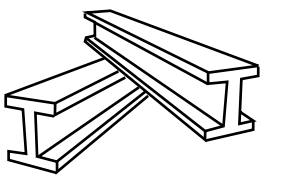
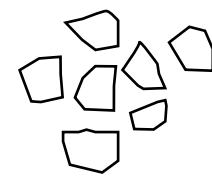
Cyclopean Concrete



Cyclopean Spolia



PRECS



A Future For Rubble?



CYCLOPEAN

cyclopean concrete noun
: concrete with large embedded stones

SPOLIA

(lat. spoils) noun
: architectural fragment from a past
structure, embedded in a new building

References

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