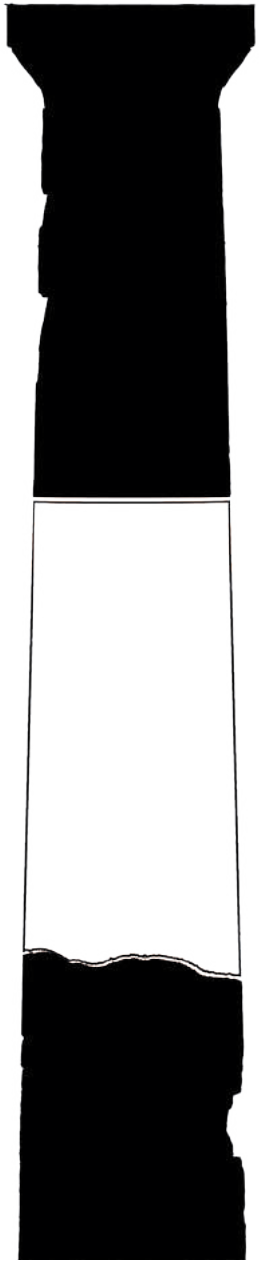
P5 PRESENTATION
2 JULY 2020

CAST GLASS RESTORATION OF MARBLE MONUMENTS



BART VAN NIMWEGEN - 4484770

MENTORS:
DR. IR. FAIDRA OIKONOMOPOULOU
DR. ING. MARCEL BILOW

CONSULTANT
LIDA BAROU

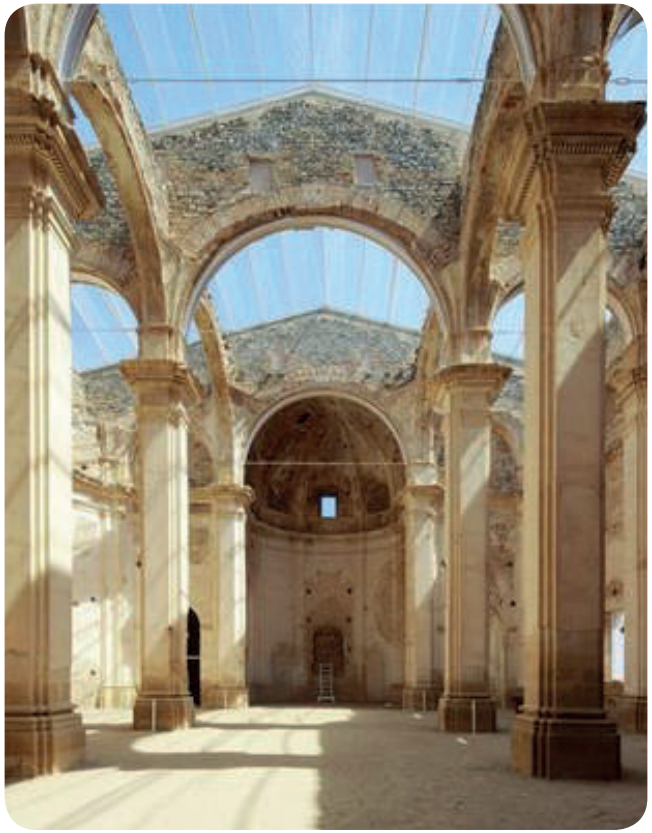
EXTERNAL EXAMINER
PROF. DR. P.W. CHAN

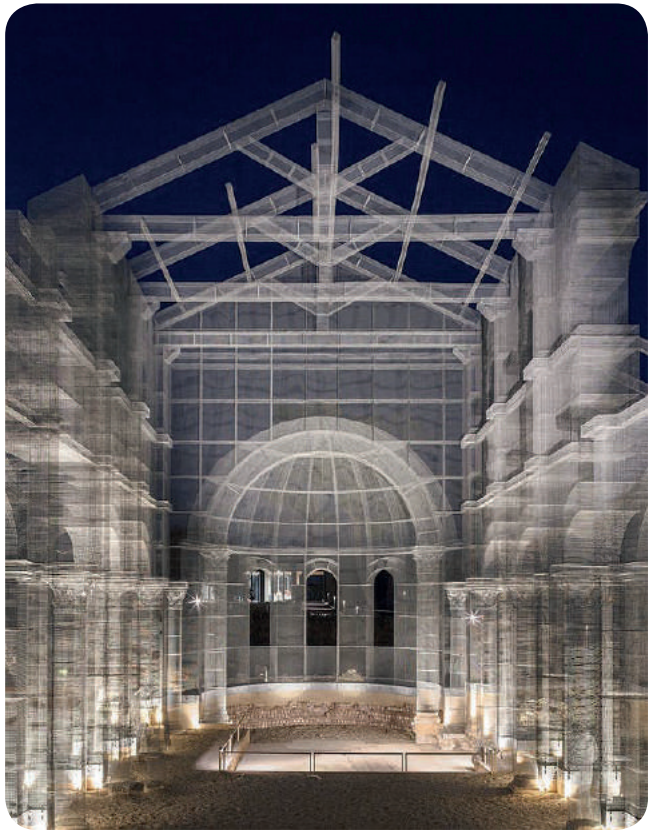
TOPIC

HOW CAN ONE, IN CASE OF CONSERVATION, RESTORE THE MONUMENT STRUCTURALLY AND AESTHETICALLY, BUT SIMULTANEOUSLY PRESERVE THE TRACES OF THE PAST AS WELL?

TOPIC

TRANSPARENT RESTORATION: A POSSIBILITY TO SIMULTANEOUSLY SHOW THE CURRENT AND ORIGINAL CONDITION OF A HISTORIC MONUMENT





PRINCIPLES OF CONSERVATION

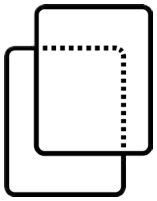
VENICE CHARTER - BURRA CHARTER - NARA DOCUMENT - RIGA CHARTER

conservation:

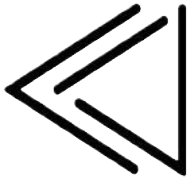
"all the processes of looking after a place so to retain its cultural significance"

PRESERVE AUTHENTICITY

MINIMISE VISUAL IMPACT



REVERSIBILITY



CONTEMPORARY CONSERVATION

ANCIENT TECHNIQUES ARE OFTEN STILL STANDARD IN RESTORATION PROJECTS

EXPENSIVE AND TIME-CONSUMING

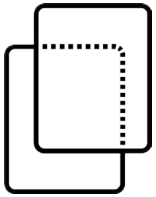
WHY GLASS?

CONFORM THE GUIDELINES

SHAPING POSSIBILTIES

MECHANICAL PROPERTIES

AESTETICAL APPEARANCE

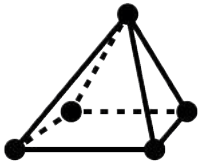


FIELD OF RESEARCH

"TO WHICH EXTENT CAN *MONOLITHIC CAST GLASS COMPONENTS OF A SUBSTANTIAL MASS* BE USED TO *RECONSTRUCT STRUCTURAL ELEMENTS IN MARBLE MONUMENTS*, WHILE SIMULTANEOUSLY *COMPLYING WITH THE INTERNATIONAL CONSERVATION GUIDELINES*?"

HERITAGE AND CONSERVATION

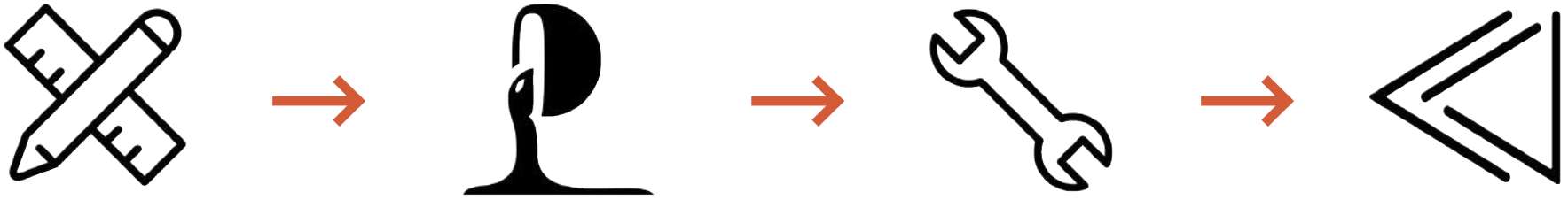
GLASS AS STRUCTURAL MATERIAL



PRODUCTION OF CAST GLASS

FOUR PRODUCTION PHASES

1 DESIGN → 2 PRODUCTION → 3 ASSEMBLY → 4 REVERSE



IS IT ALLOWED ACCORDING TO INTERNATIONAL GUIDELINES?

IS GLASS STRUCTURALLY AND MECHANICALLY SUITABLE FOR THIS APPLICATION?

CAN IT BE PRODUCED WITH EXISTING MANUFACTURING TECHNIQUES?

CASE STUDY ANALYSIS

CASE-STUDY ANALYSIS

PARTHENON

ATHENS, GREECE

500 B.C

DRY ASSEMBLY STRUCTURE

MONOLITHIC PENTELIC MARBLE

CASE-STUDY ANALYSIS

PENTELIC MARBLE

DIONYSSOS QUARRIES

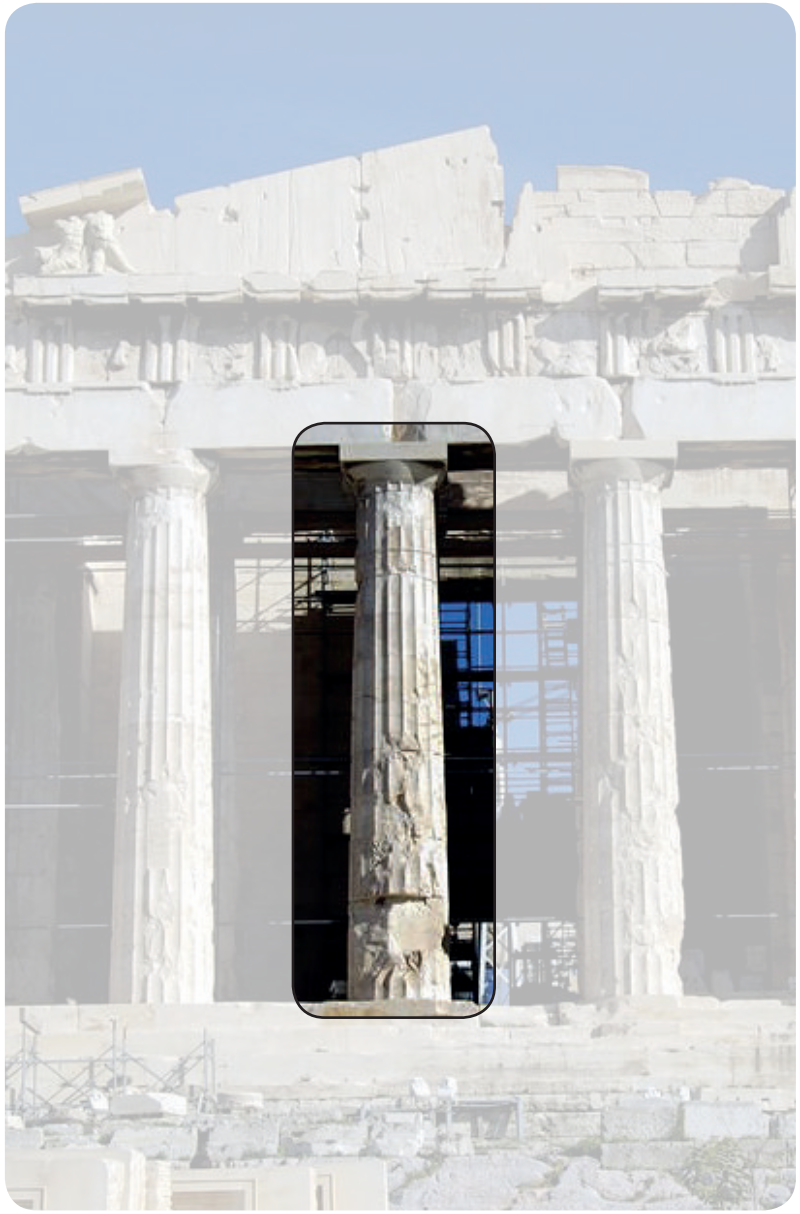
WOODEN JOINTS

CONIFERIOUS AND
OLIVE TREES

METAL CLAMPS

IRON PROFILES
CAST IN LEAD

INTERVENTION

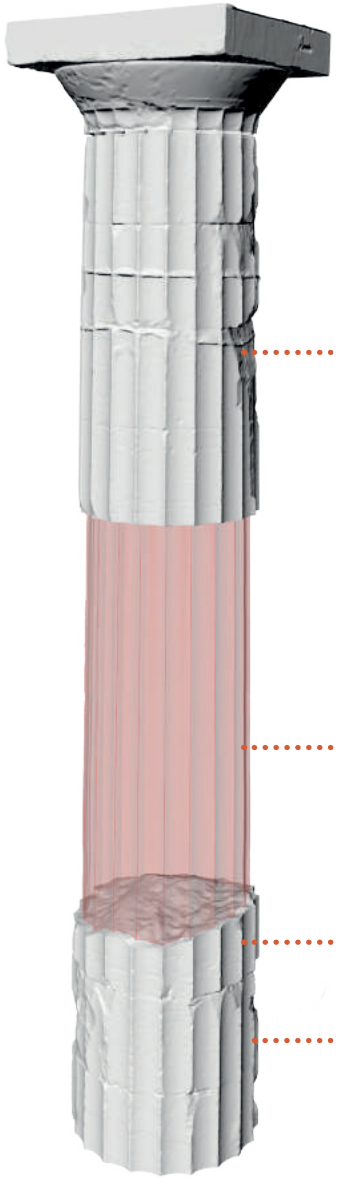


- 3D SCAN MODEL

- WESTERN COLLONADE

- 10 MARBLE DRUMS

INTERVENTION



DRUM 7,8,9 & 10 INTACT

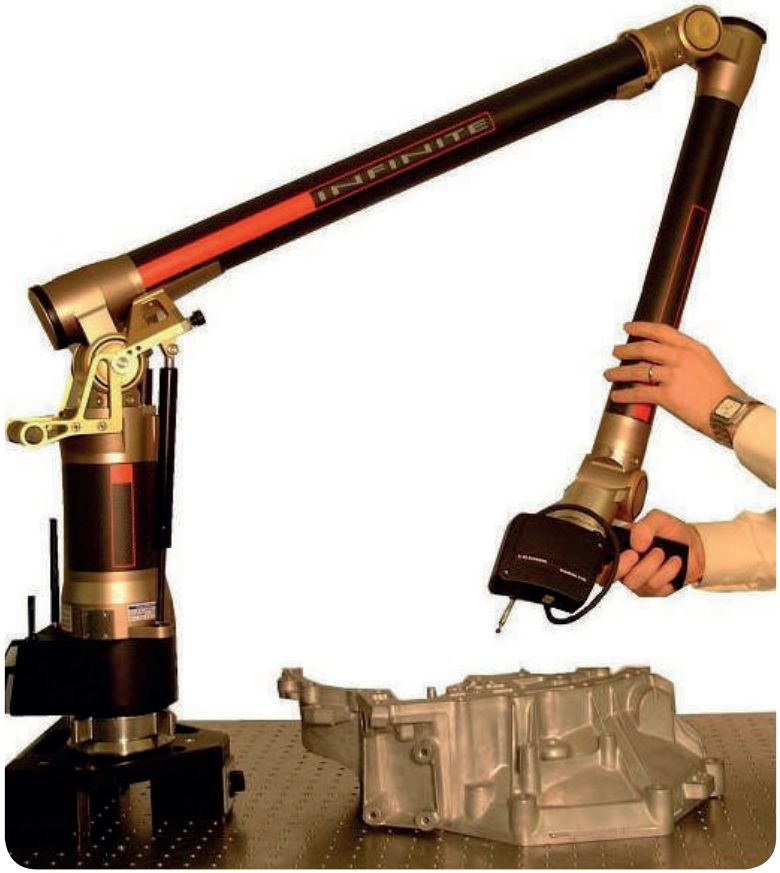
DRUM 4,5 & 6 MISSING

DRUM 3 FRACTURED

DRUM 1 & 2 INTACT

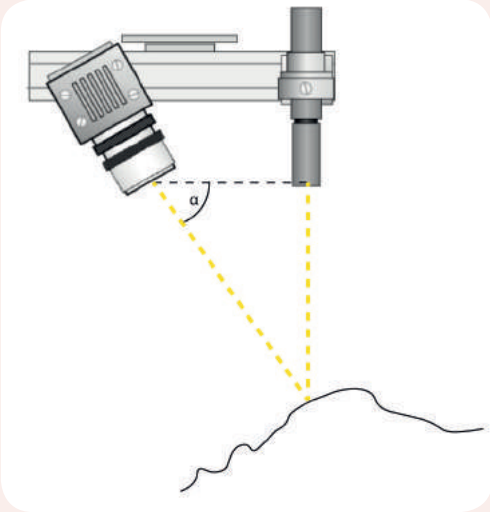
SCANNING THE SURFACE

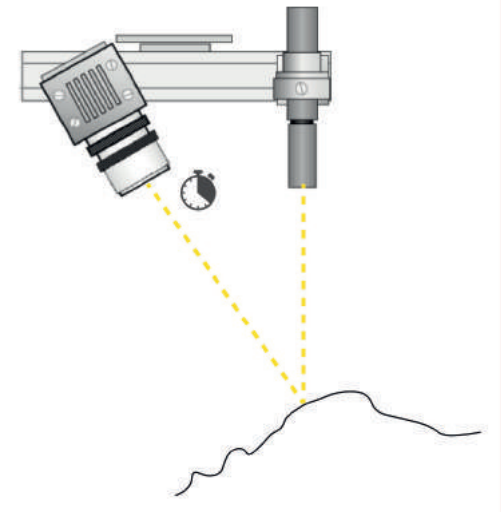
GEOMETRY OF THE LOWER PART OF THE DAMAGED COLUMN.

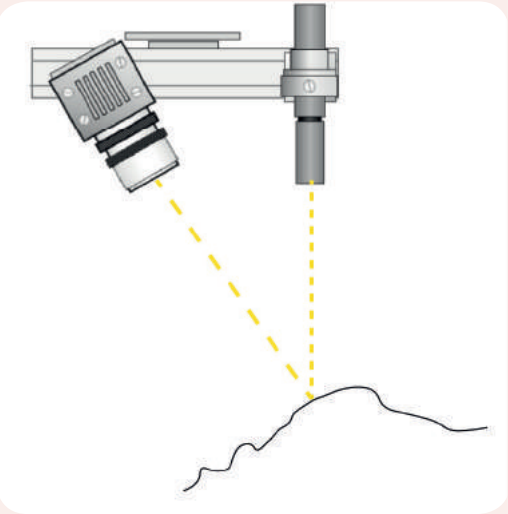


EXAMPLE OF A CONTACT SCANNER WHICH IS USED TO DOCUMENT THE SHAPE OF A STEEL ELEMENT.

SCANNING THE SURFACE







01 TRIANGULATION

ANGLE OF IMPACT

0.01 - 0.1 [MM]

02 TIME OF FLIGHT

TIME DIFFERENCE

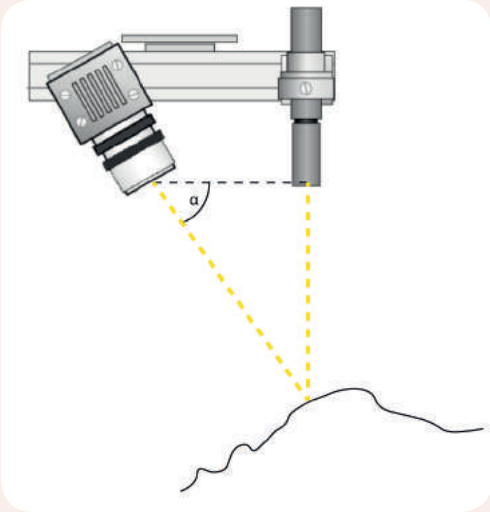
1 - 6 [MM]

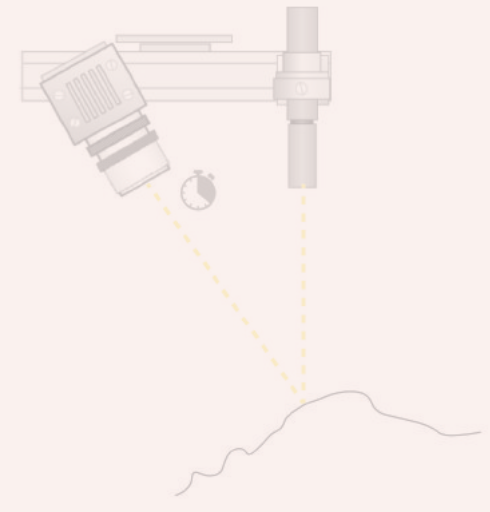
03 PHASE COMPARISON

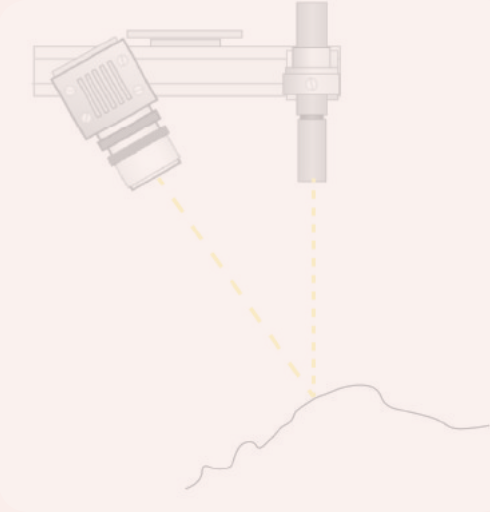
WAVE ENERGY DIFFERENCE

2 - 10 [MM]

SCANNING THE SURFACE







01 TRIANGULATION

ANGLE OF IMPACT

0.01 - 0.1 [MM]

02 TIME OF FLIGHT

TIME DIFFERENCE

1 - 6 [MM]

03 PHASE COMPARISON

WAVE ENERGY DIFFERENCE

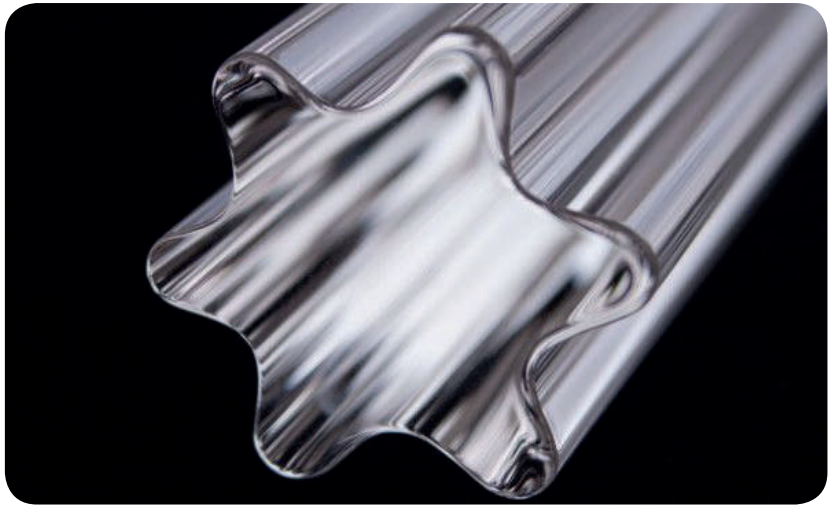
2 - 10 [MM]

MATERIALS

GLASS TYPES

01 FLOAT GLASS

03 3D PRINTED GLASS



02 EXTRUDED GLASS

04 CAST GLASS

WHY CAST GLASS?

THREE DIMENSIONALITY

SHAPING POSSIBLITIES

GLASS COMPOSITIONS

	SODA-LIME	BOROSILICATE	MARBLE	TITANIUM
MEAN MELTING POINT [°C]	1350 - 1400	1450 - 1550		
SOFTENING POINT [°C]	730	780		
ANNEALING POINT [°C]	548	525		
STRAIN POINT [°C]	505	480		
DENSITY [kg/m3]	2460	2230	~2600	4500
TH. EXPANSION COEFF [E-6/°C]	8.5	3.4	~5.5 - 14.1	8.9
YOUNG'S MODULUS [GPa]	69	63	40.1	116

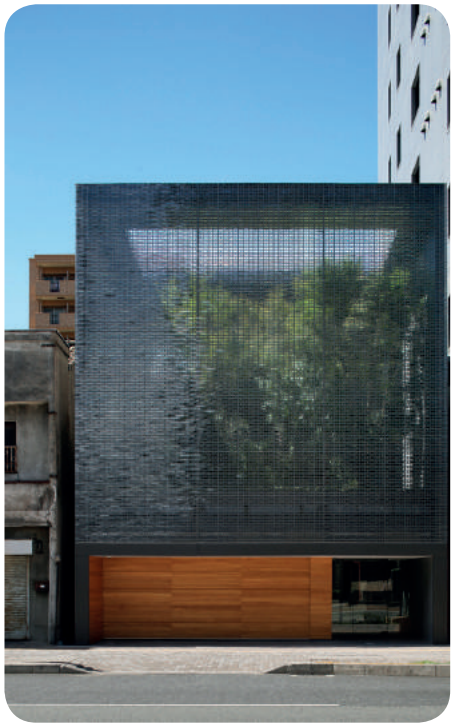
PENTELIC MARBLE:

THERMAL EXPANSION: **9*E-6/°C**
YOUNG'S MODULUS: **40.1 GPA**
COMPRESSIVE STRENGTH: **77.8 MPA**
BENDIGN STRENGTH: **18 MPA**

SODA-LIME GLASS

THERMAL EXPANSION: **8.5*E-6/°C**
YOUNG'S MODULUS: **69 GPA**
COMPRESSIVE STRENGTH: **300 MPA**
BENDING STRENGHT: **30 MPA**

APPLICATIONS OF CAST GLASS

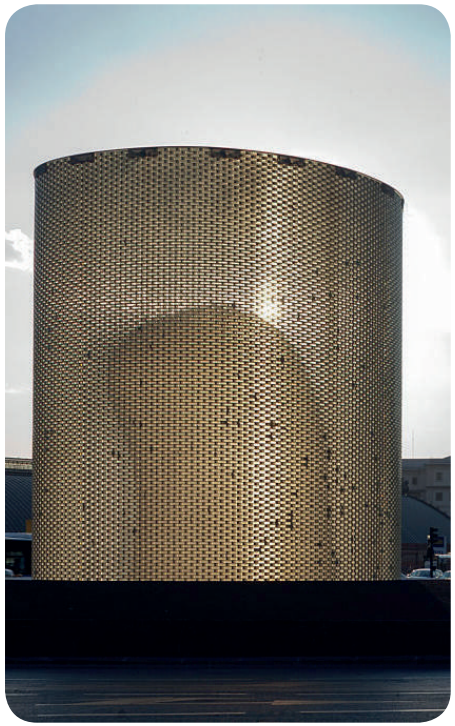


OPTICAL HOUSE

HIROSHIMA, 2012

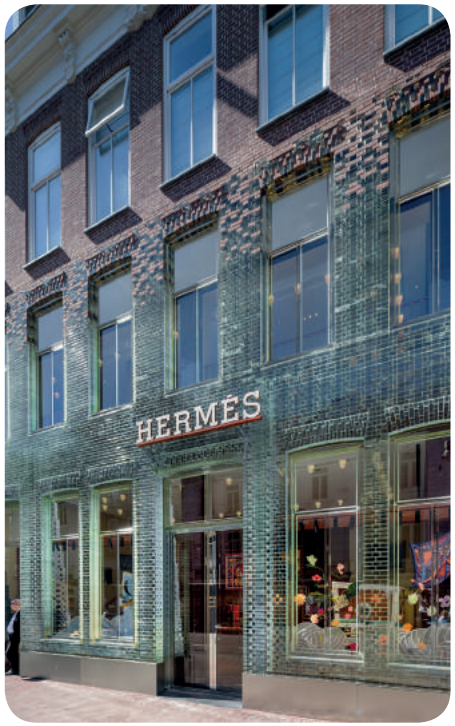
CROWN FOUNTAIN

CHICAGO, 2004



ATOCHA MEMORIAL

MADRID, 2007

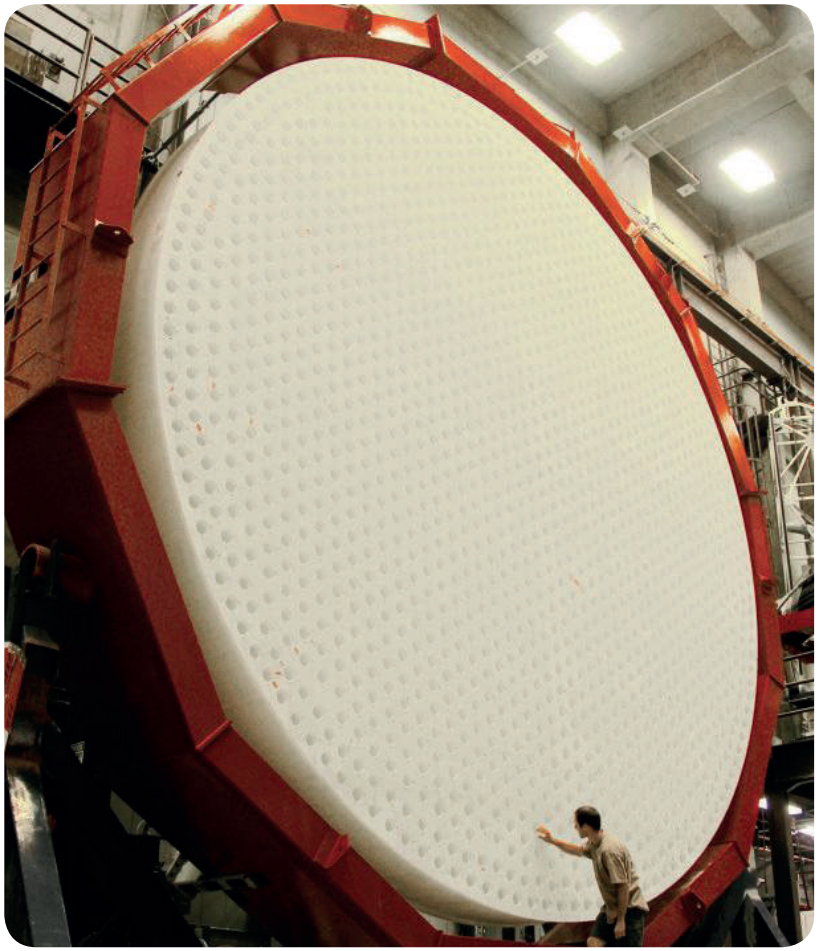


CRYSTAL HOUSES

AMSTERDAM, 2016

APPLICATIONS OF CAST GLASS

CAST GLASS ART



TELESCOPE MIRRORS

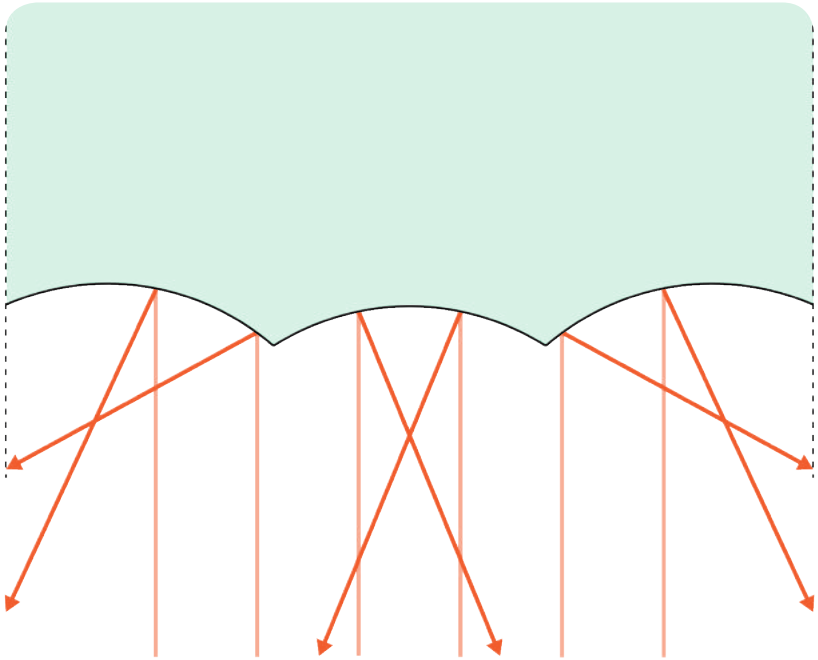
APPEARANCE OF GLASS

INFLUENCE OF THE VIEWING ANGLE

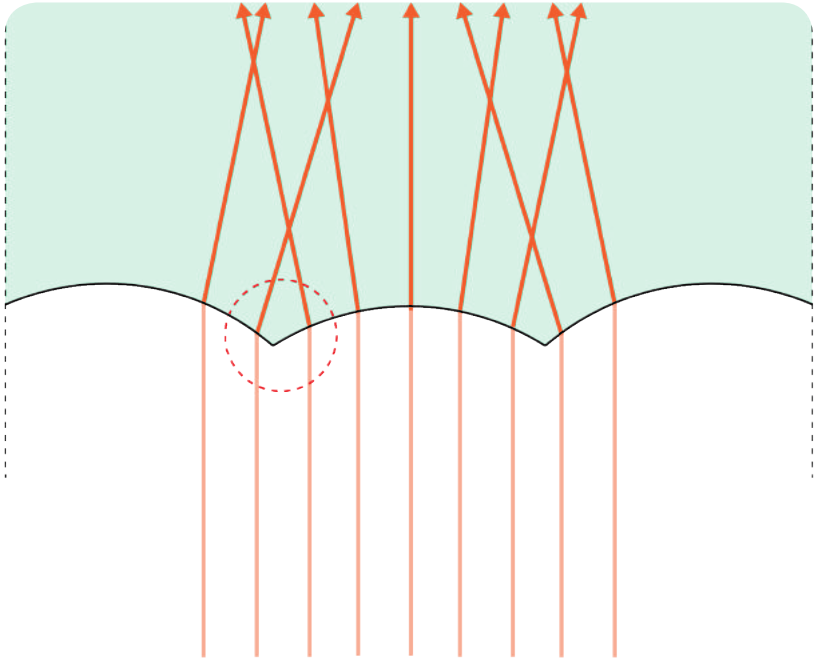
CRYSTAL HOUSES GLASS FROM PERPENDICULAR ANGLES

CRYSTAL HOUSES FACADE FROM OBLIQUE ANGLES

INFLUENCE OF THE GEOMETRY

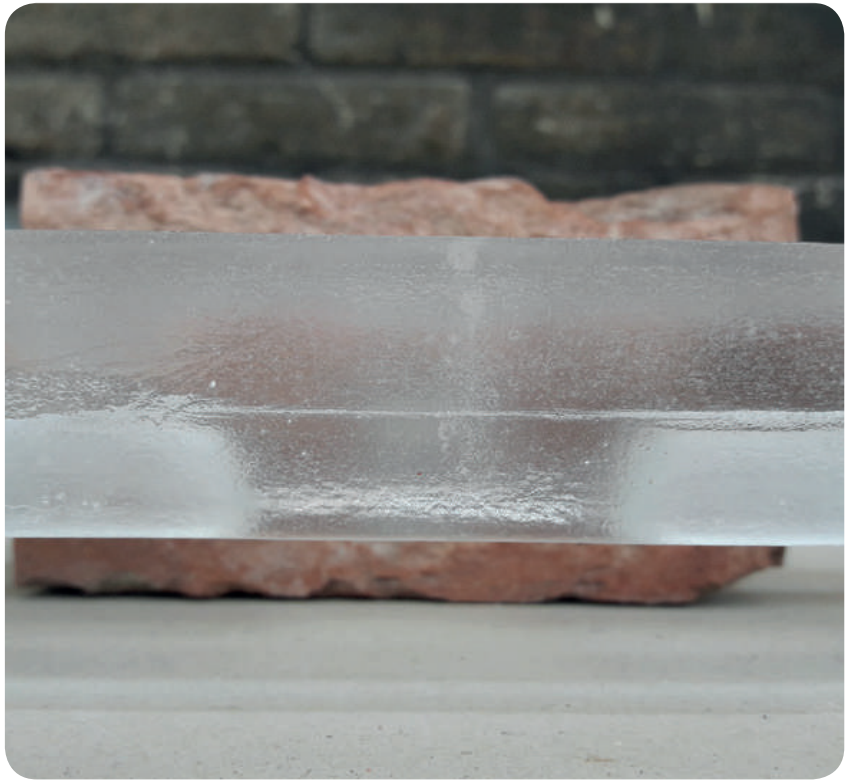


INFLUENCE OF THE GEOMETRY OF A GREEK DRUM ON THE REFLECTION OF LIGHT



INFLUENCE OF THE GEOMETRY OF A GREEK DRUM ON THE REFRACTION OF LIGHT

TRANSPARENT OR TRANSLUCENT

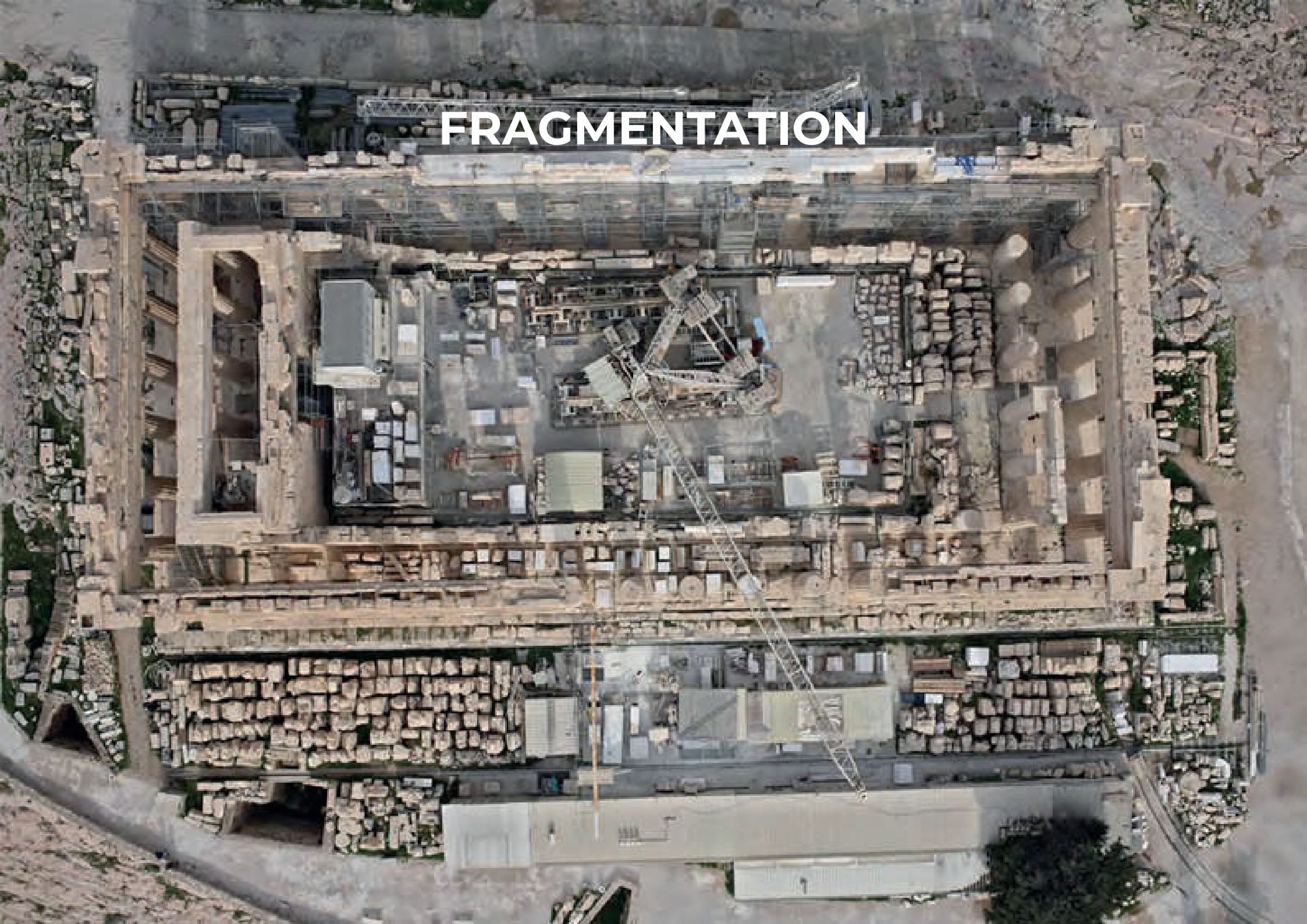


CAST GLASS SPECIMEN WITH A TRANSLUCENT APPEARANCE AND ROUGH SURFACE

CAST GLASS SPECIMEN WITH A MORE TRANSPARENT APPEARANCE AND A GLOSSY SURFACE

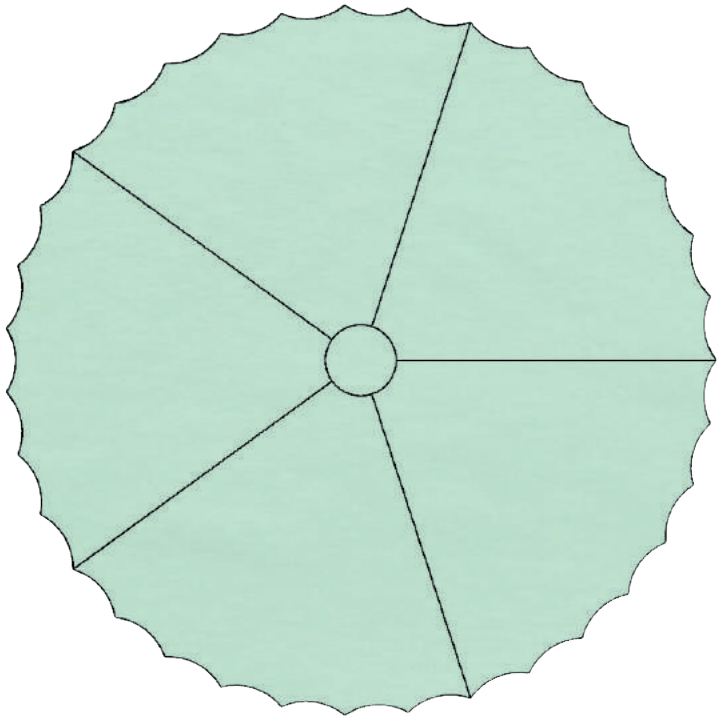
COLOURED AND TEXTURED CAST GLASS

FRAGMENTATION



FRAGMENTATION

HORIZONTAL FRAGMENTATION:
SPLITTING THE DRUMS



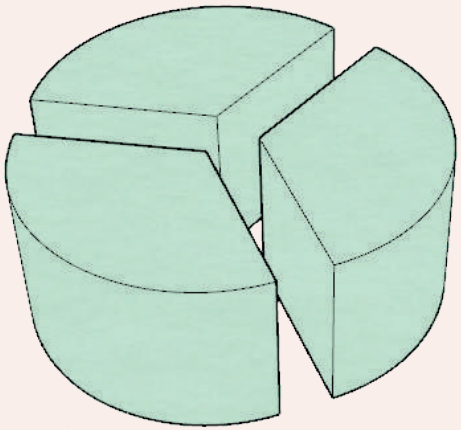
VERTICAL FRAGMENTATION:
BASED ON DRUM HEIGHT

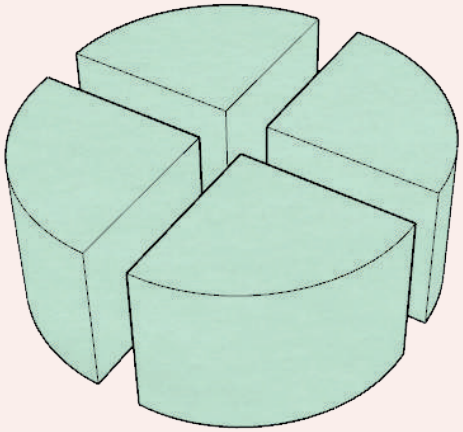
ORIGINAL SYSTEM

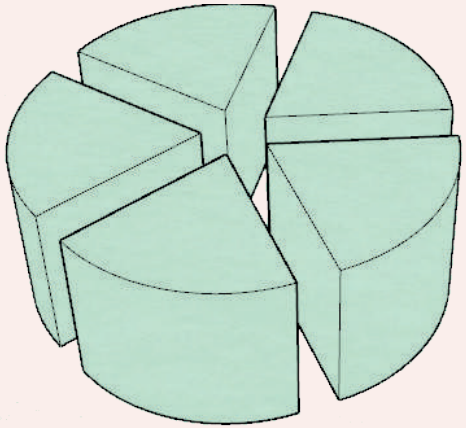
ANNEALING

SAFETY

FRAGMENTATION

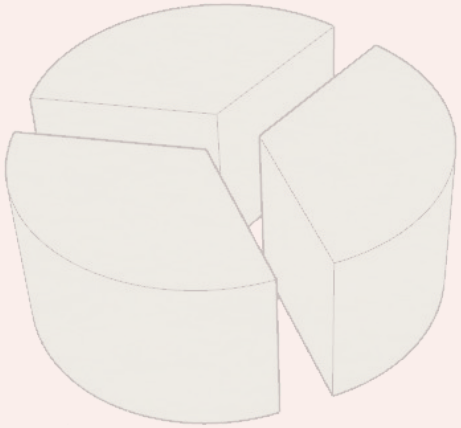


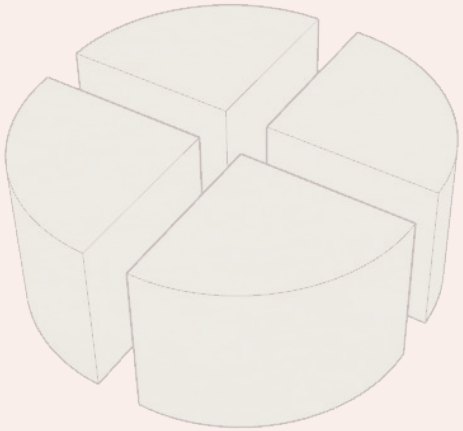


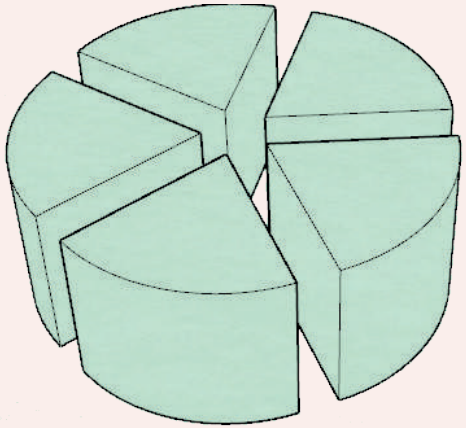


	3 - PIECE	4 - PIECE	5 - PIECE
COMPATIBILITY	-	+	+
STABILITY	+	-	+
SOLID MASS	-	+ -	+
ASSEMBLY	+	+ -	-

FRAGMENTATION

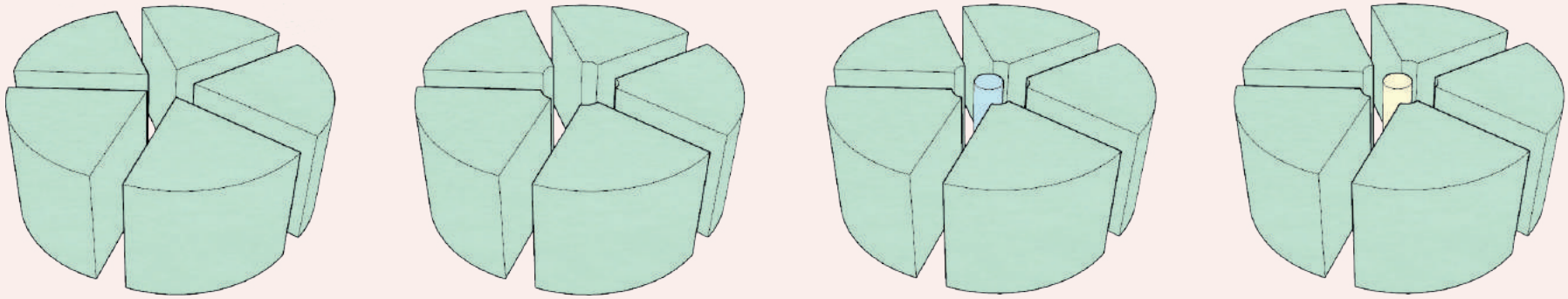






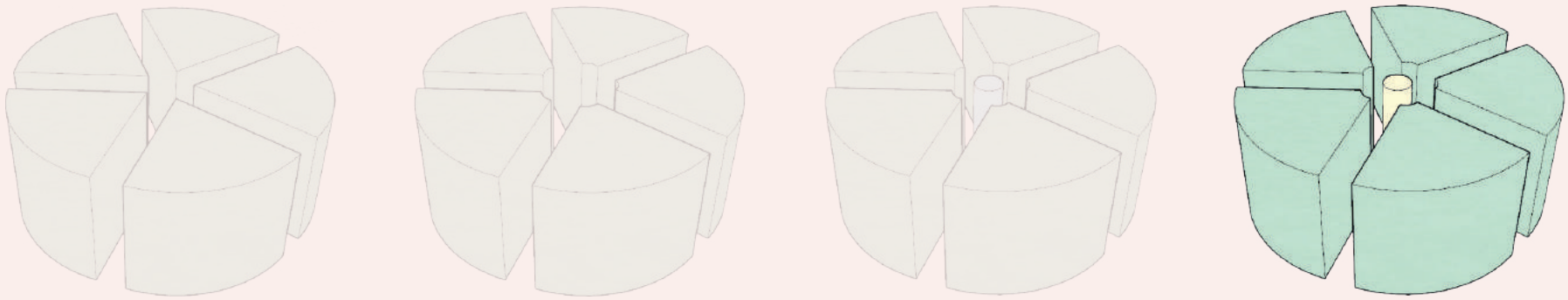
	3 - PIECE	4 - PIECE	**5 - PIECE**
COMPATIBILITY	–	+	+
STABILITY	+	–	+
SOLID MASS	–	+ –	+
ASSEMBLY	+	+ –	–

CORE SOLUTION



	NO CORE	HOLLOW	GLASS	MARBLE
COMPATIBILITY	-	-	+ -	+
ANNEALING	-	+	+	+
TOLERANCES	-	+	+ -	+ -
VISIBILITY	+	+ -	+	-

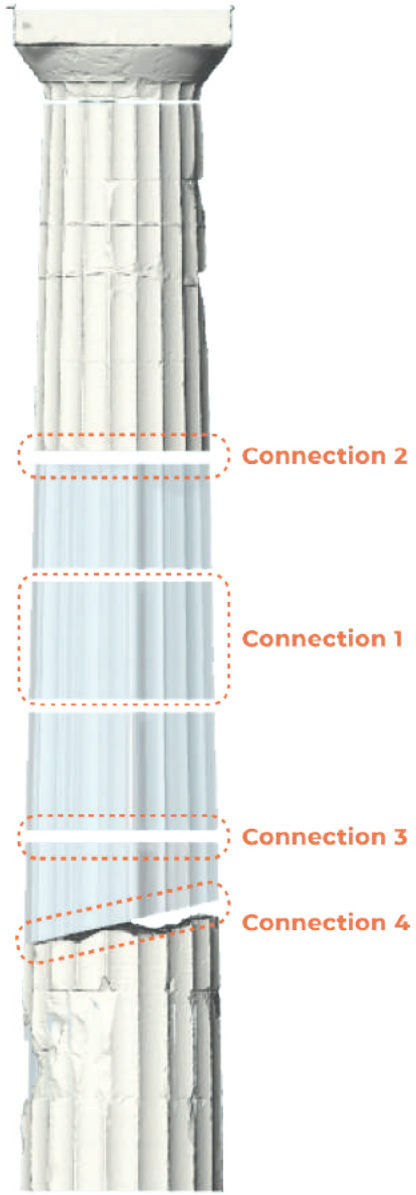
CORE SOLUTION



	NO CORE	HOLLOW	GLASS	**MARBLE**
COMPATIBILITY	-	-	+ -	+
ANNEALING	-	+	+	+
TOLERANCES	-	+	+ -	+ -
VISIBILITY	+	+ -	+	-

CONNECTIONS

CONNECTIONS



SAFETY

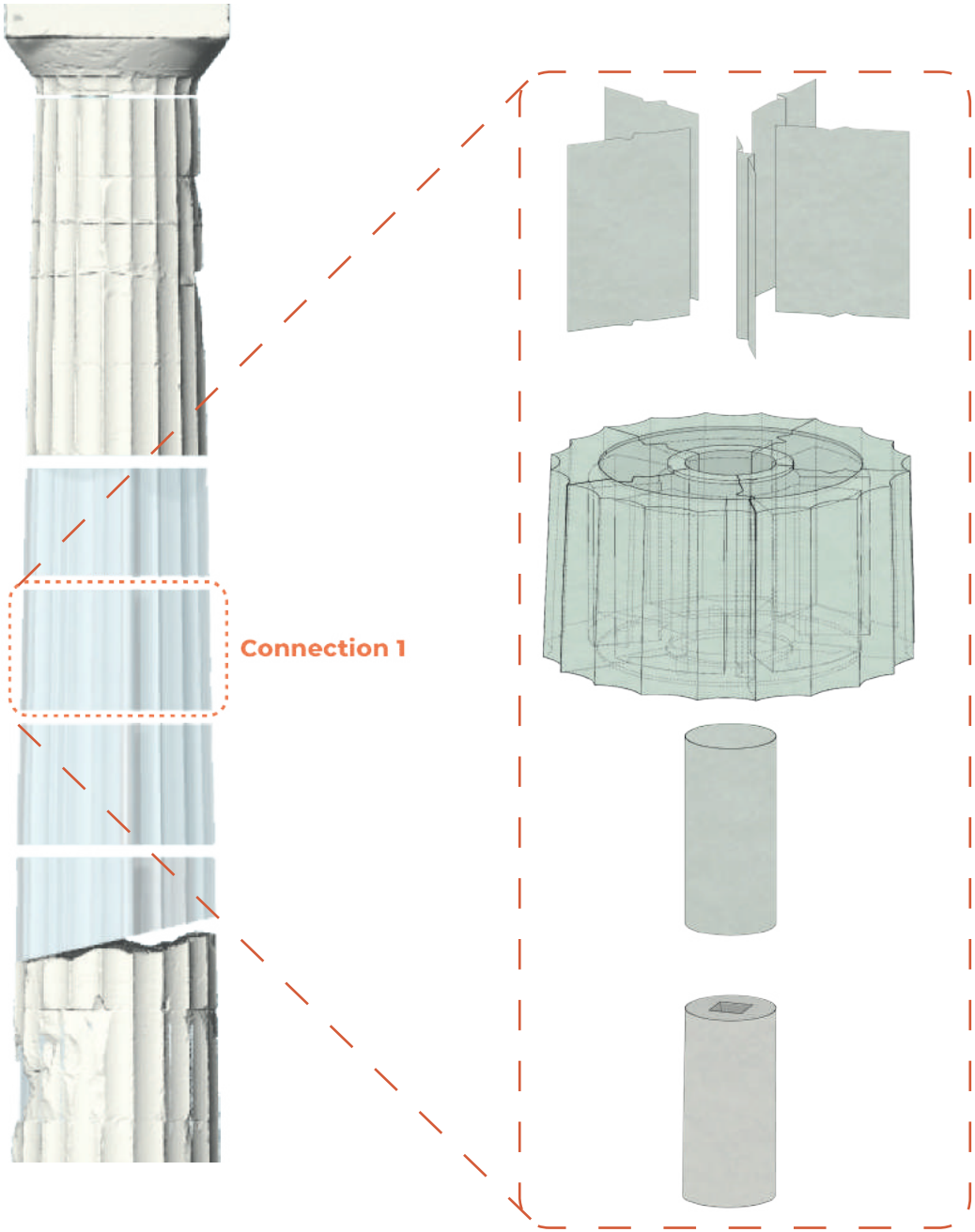
RESPECT TO ORIGINAL SYSTEM

REVERSIBLE

ASSEMBLY

MANUFACTURING

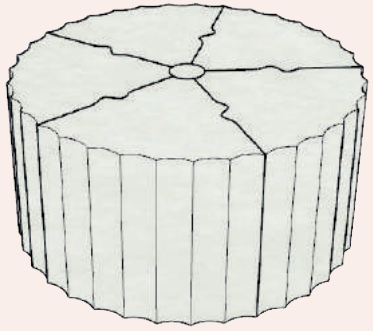
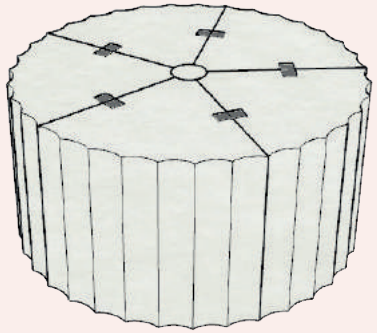
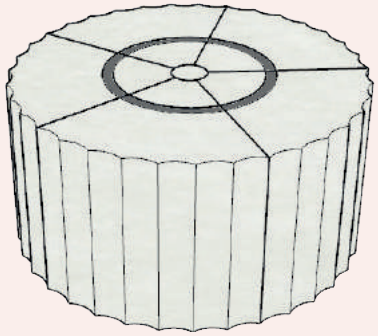
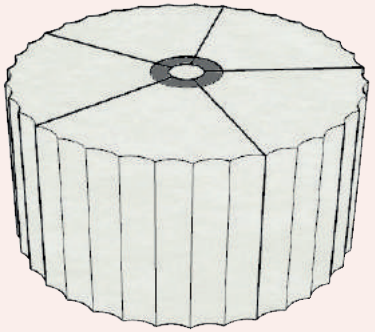
CONNECTION 1



STRUCTURAL PRINCIPLE:

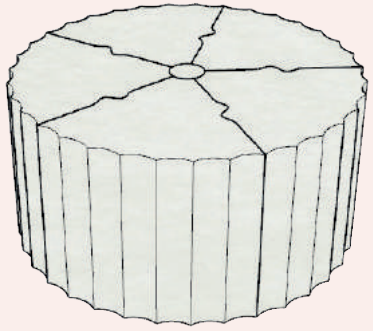
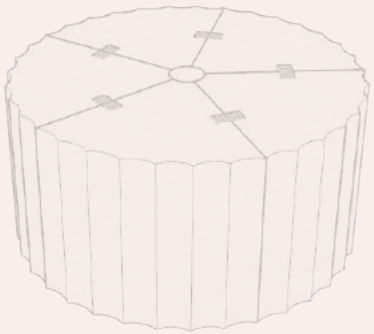
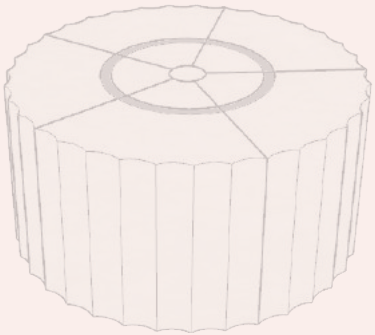
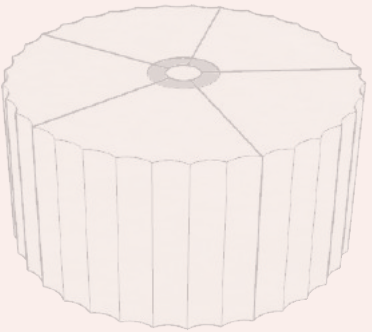
APPROACH MONOLITHIC BEHAVIOUR

1.8 - CONNECTION 1 - ALTERNATIVES

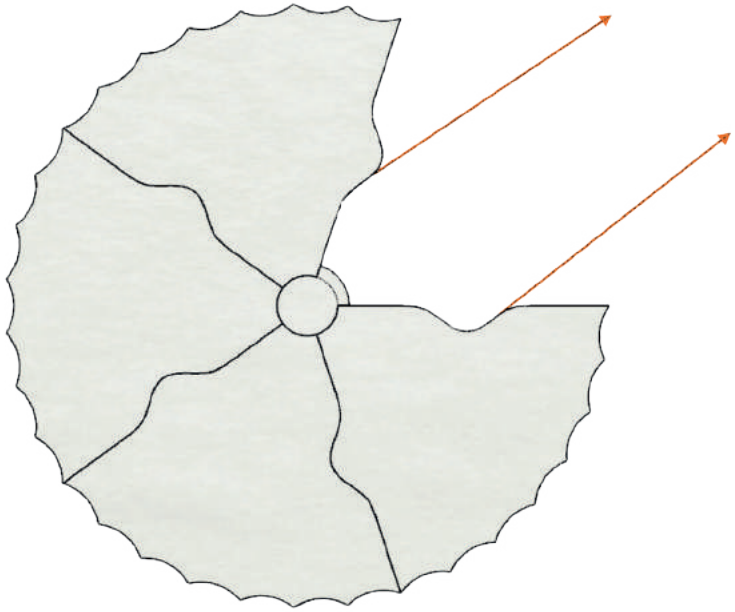
	INTERLOCKING	EMBEDDED JOINTS	COMPRESSION RING	TITANIUM CORE
COMPATIBILITY	+	-	+ -	-
ANNEALING	+	-	+ -	+ -
STABILITY	-	+ -	+	+ -
PEAK STRESS	+	-	+ -	-
VISIBILITY	+	+ -	-	+ -

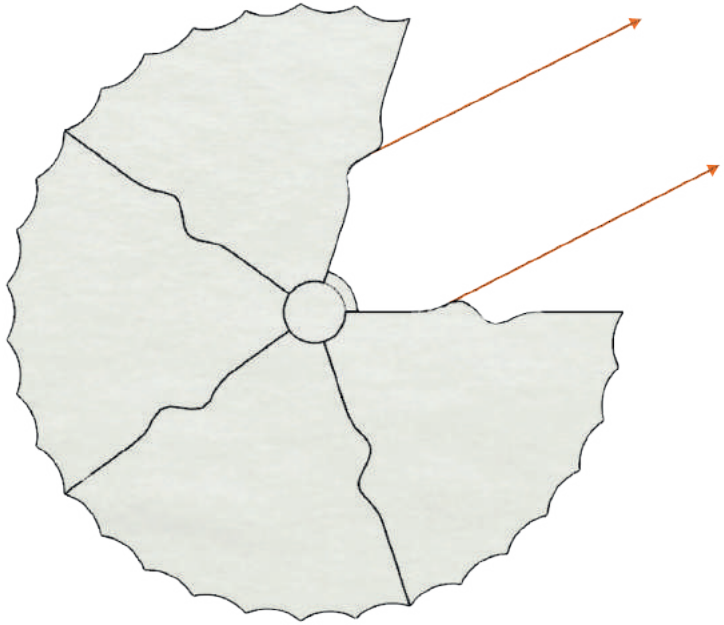
CONNECTION 1 - ALTERNATIVES

	INTERLOCKING	EMBEDDED JOINTS	COMPRESSION RING	TITANIUM CORE
COMPATIBILITY	+	-	+ -	-
ANNEALING	+	-	+ -	+ -
STABILITY	-	+ -	+	+ -
PEAK STRESS	+	-	+ -	-
VISIBILITY	+	+ -	-	+ -

1.8 - INTERLOCKING GEOMETRY

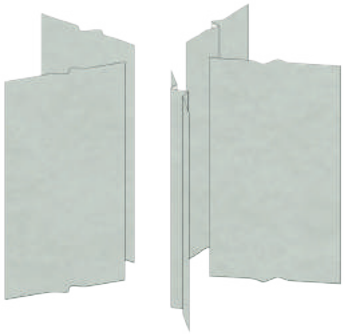




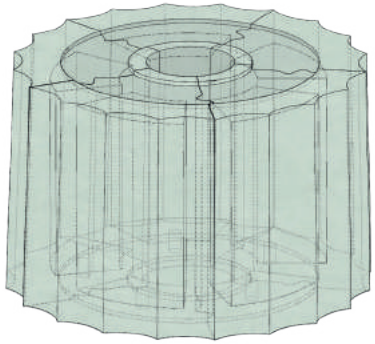
FULL SINUSOID ALLOWS FOR A SMALLER AMPLITUDE, WHICH IS BETTER ANNEALABLE

DOUBLE CURVED SURFACE LOCKS IN 3 DIMENSIONS, BUT IS HARD TO ASSEMBLY

CONNECTION 1



VIVAK - INTERLAYER

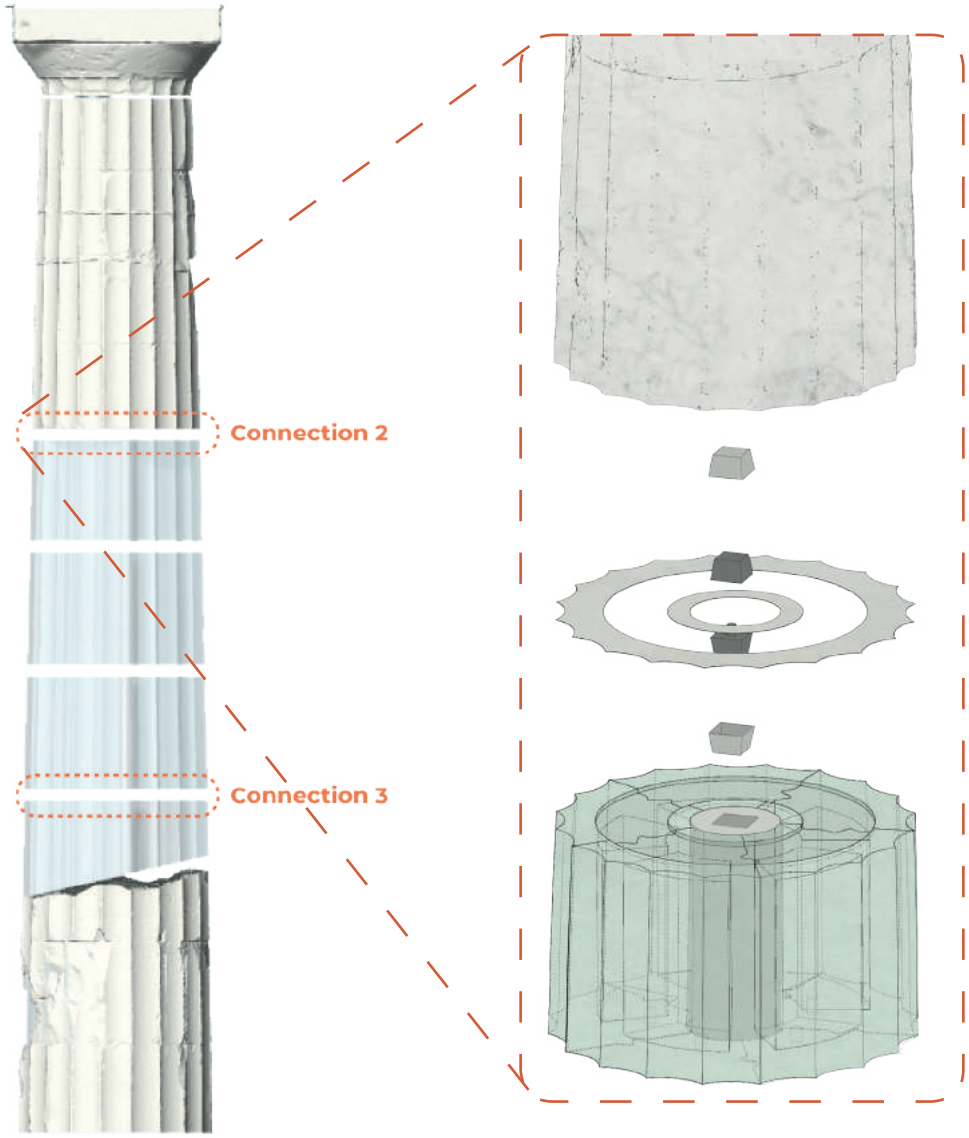


INTERLOCKING GLASS

VIVAK - INTERLAYER

MARBLE CORE

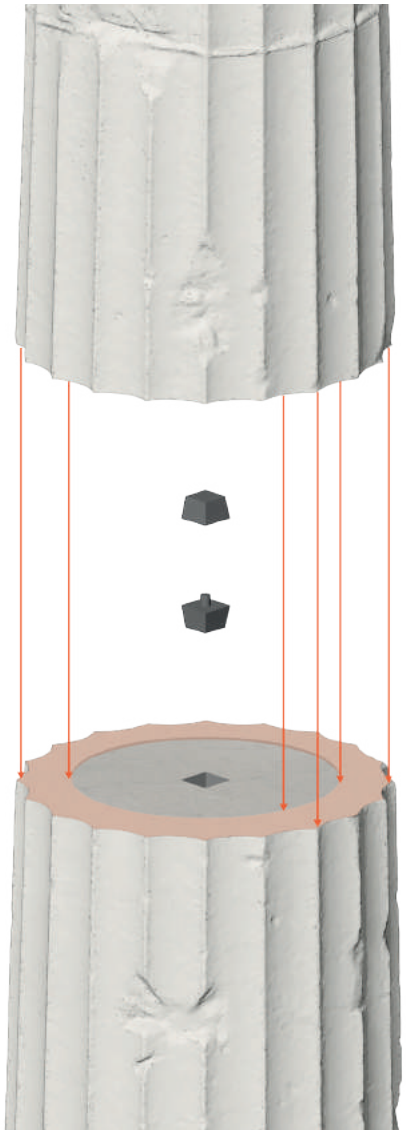
CONNECTION 2 & 3



STRUCTURAL PRINCIPLE:

- MAINTAIN INDEPEDENCY OF THE DRUMS
- EVENLY SPREAD LOAD TRANSFER
- ALLOW FOR EASY ASSEMBLY

BASED ON TRADITIONAL CONNECTION



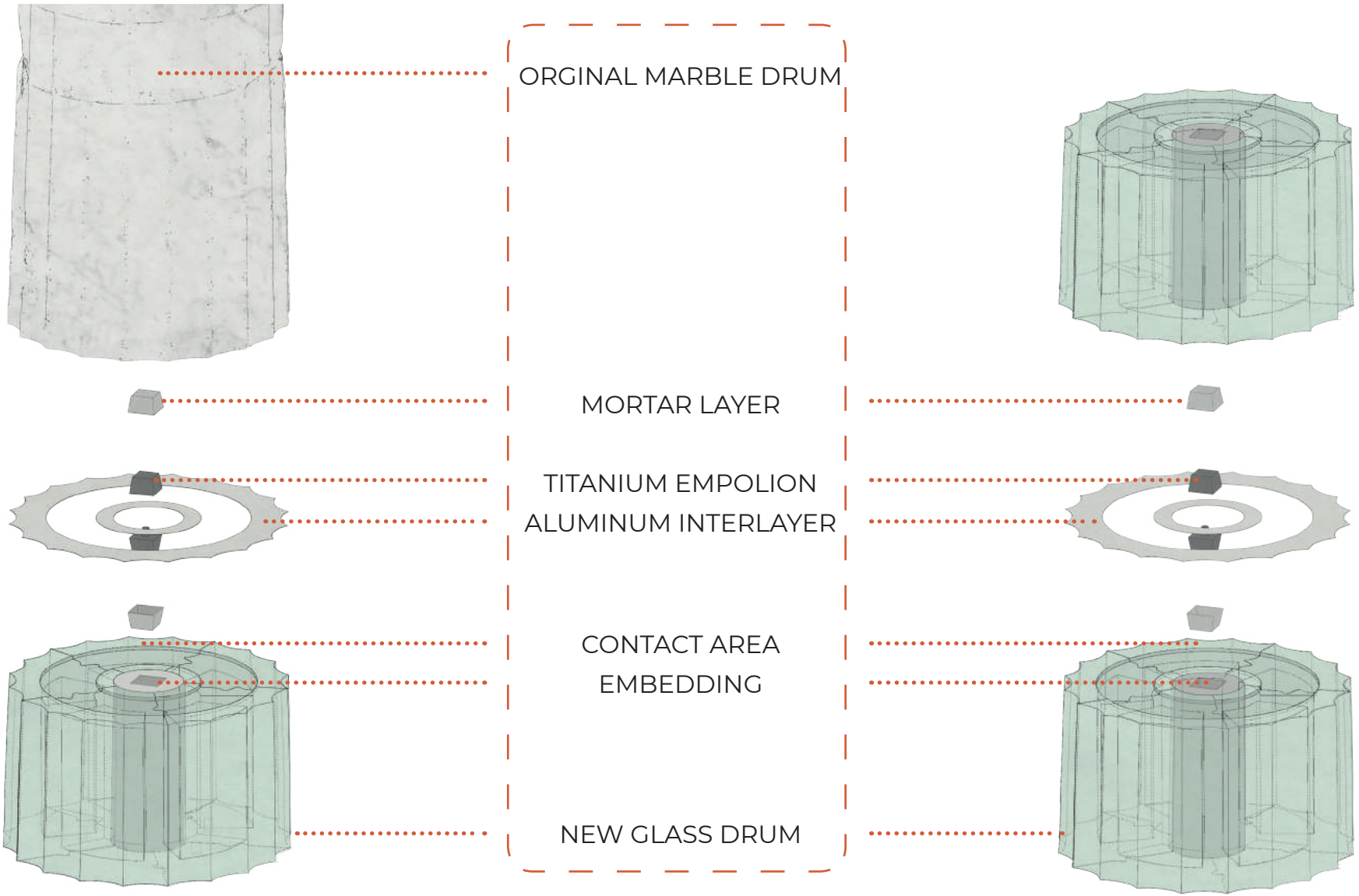
STRUCTURAL PRINCIPLE:

CONTACT AT THE PERIPHERY, ROUGH IN THE CENTRE

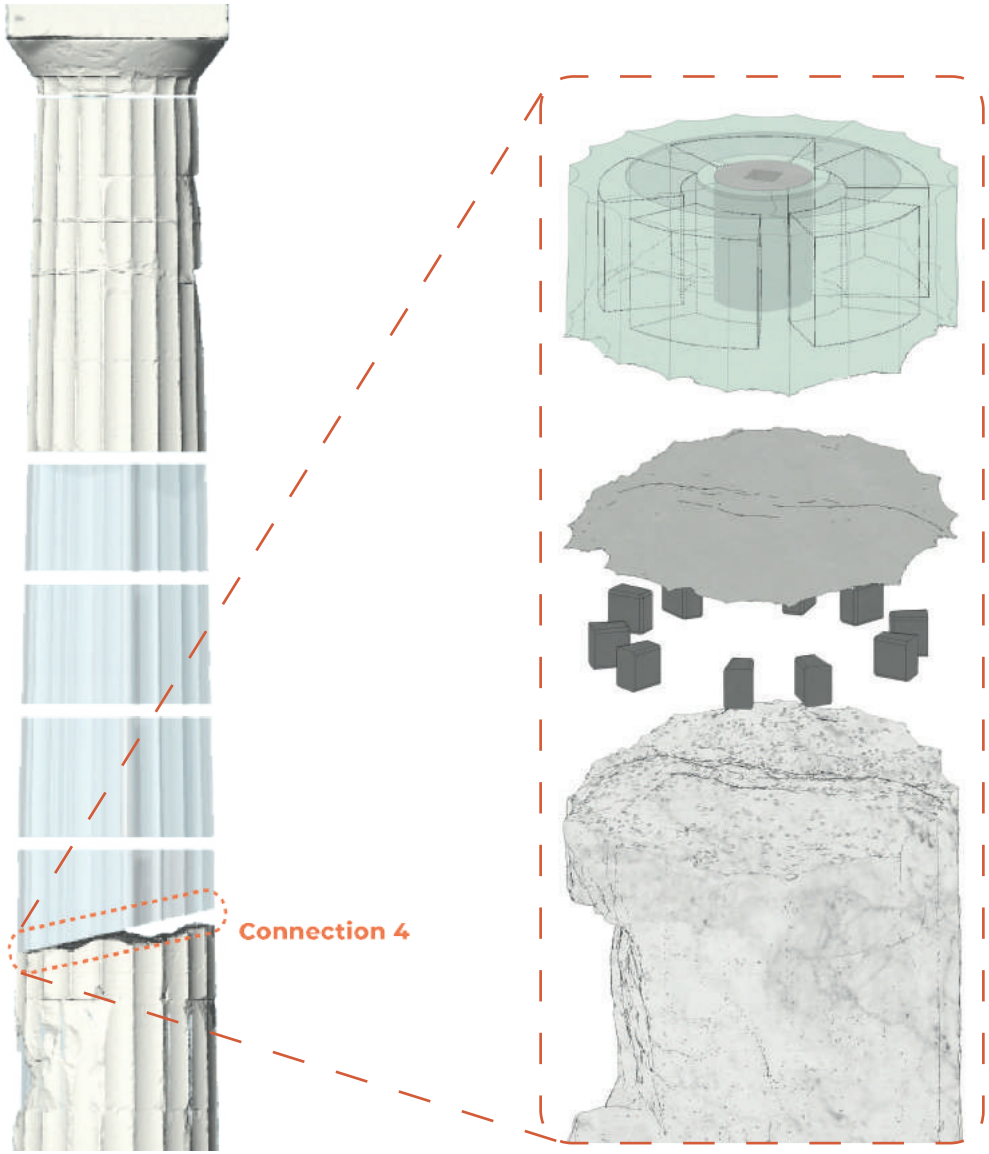
EVENLY SPREAD LOAD TRANSFER

EMBEDDING IN THE CORE FOR THE EMPOLION

CONNECTION 2 & 3



CONNECTION 4



STRUCTURAL PRINCIPLE:

ACHIEVE MONOLITHIC BEHAVIOUR

PERMANENT BINDING

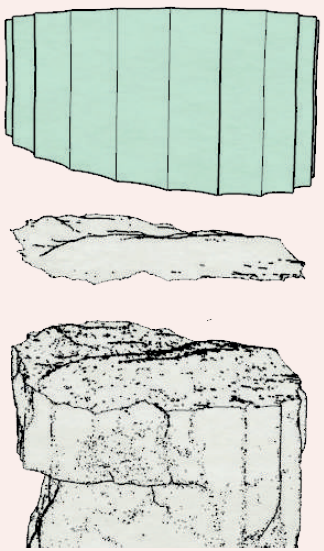
DISTRIBUTED LOAD TRANSFER

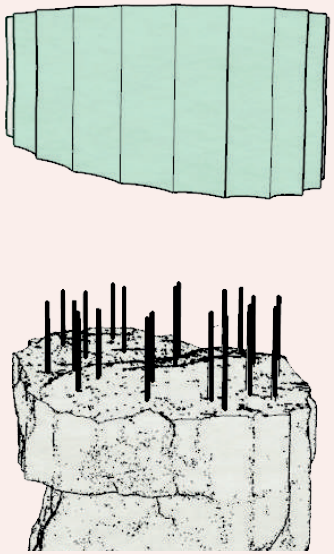
CURRENT APPROACH

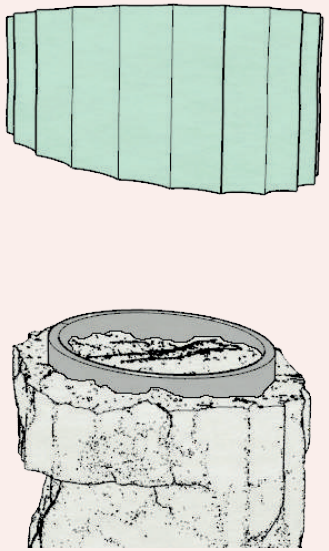
TITANIUM BARS TAKE UP THE SHEAR FORCE

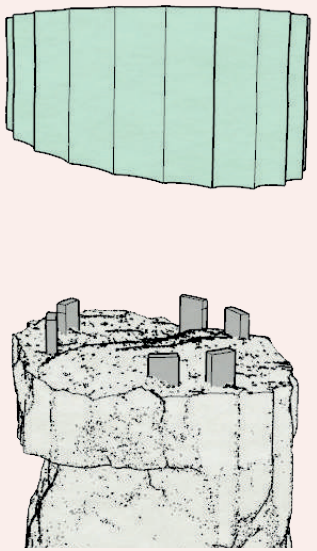
MORTAR IS USED TO SEAL GAPS, ALLOW FOR TOLERANCES AND EQUAL LOAD TRANSFER

CONNECTION 4 - ALTERNATIVES



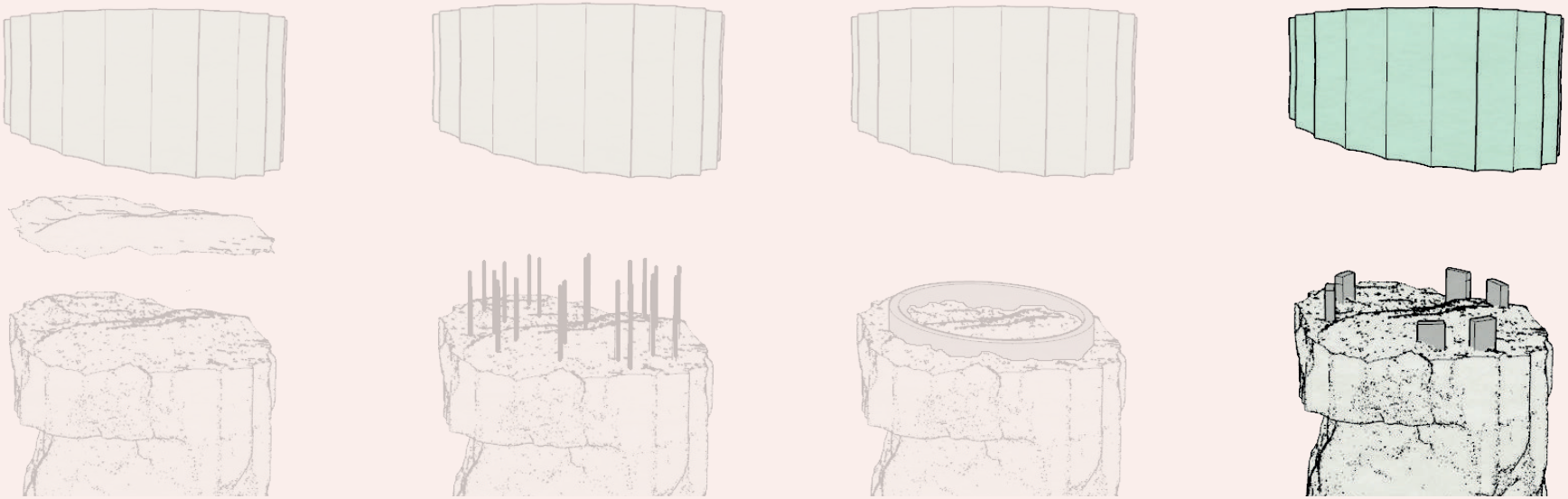






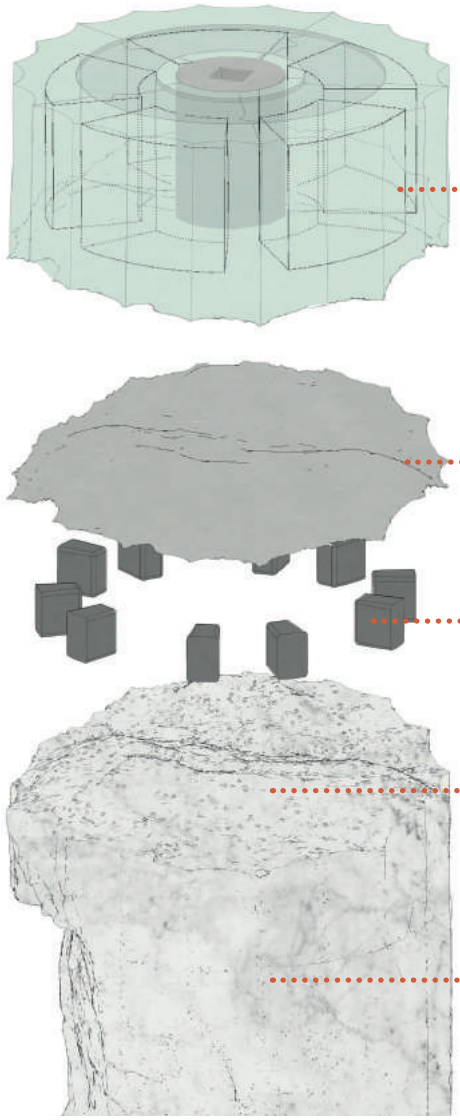
	MORTAR	TITANIUM BARS	TITANIUM RING	TITANIUM TEETH
COMPATIBILITY	+	+ -	+ -	+ -
INTRUSIVENESS	+	-	-	+ -
STABILITY	-	+	+	+
PEAK STRESS	+	-	+	+ -
VISIBILITY	+	-	-	+ -

CONNECTION 4 - ALTERNATIVES



	MORTAR	TITANIUM BARS	TITANIUM RING	TITANIUM TEETH
COMPATIBILITY	+	+ -	+ -	+ -
INTRUSIVENESS	+	-	-	+ -
STABILITY	-	+	+	+
PEAK STRESS	+	-	+	+ -
VISIBILITY	+	-	-	+ -

CONNECTION 4



NEW GLASS DRUM

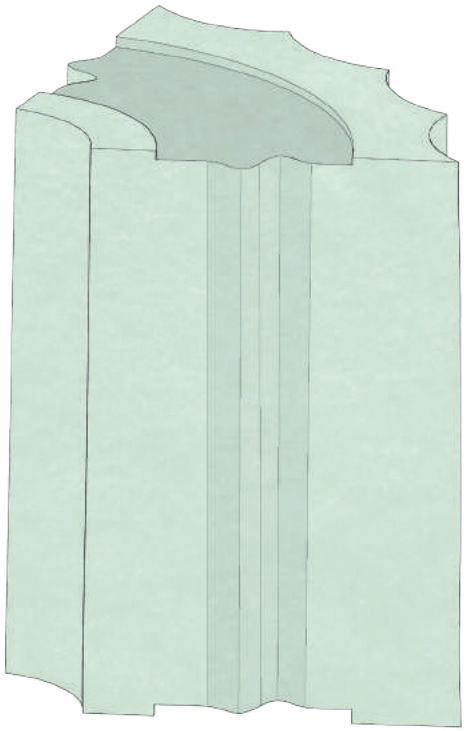
MORTAR LAYER

TITANIUM JOINT

BROKEN MARBLE DRUM

INTACT ORIGINAL DRUM

REDUCING THE MASS



SAFETY

20 % OF THE TOTAL LOAD

ORIGINAL SYSTEM

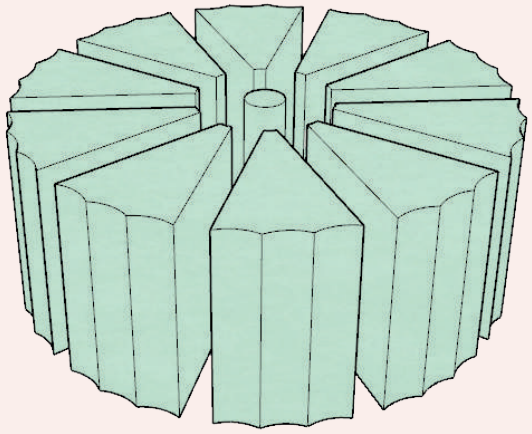
SPLIT IN DRUMS

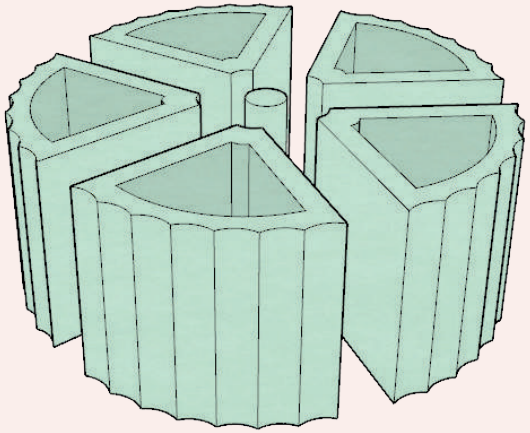
ANNEALING

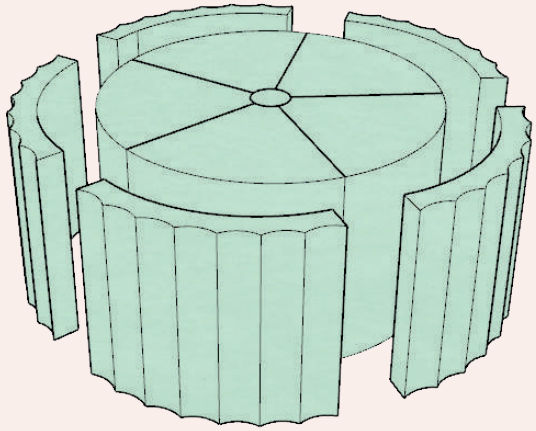
MINIMISE THE SHARP ANGLES

WEIGHT: 1,5 TONS

REDUCE THE MASS

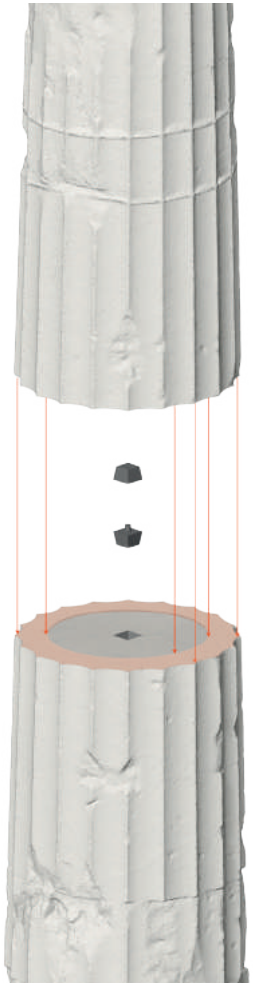




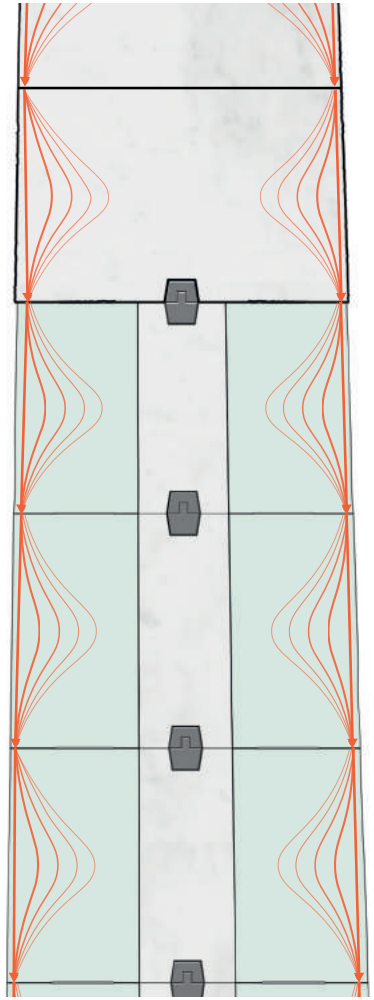


	SMALLER PIECES	HOLLOW PIECES	SEPARABLE SKIN
COMPATIBILITY	-	+	-
STABILITY	+ -	+ -	+ -
TOLERANCES	-	+	+
EFFECTIVENESS	+	+	+ -

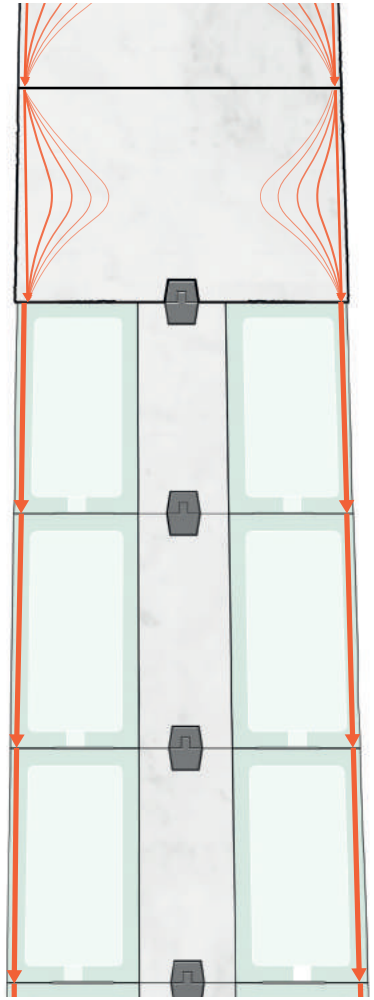
STRUCTURAL SCHEME OF A COLUMN



LOAD TRANSFER ONLY
AROUND THE PERIPHERY

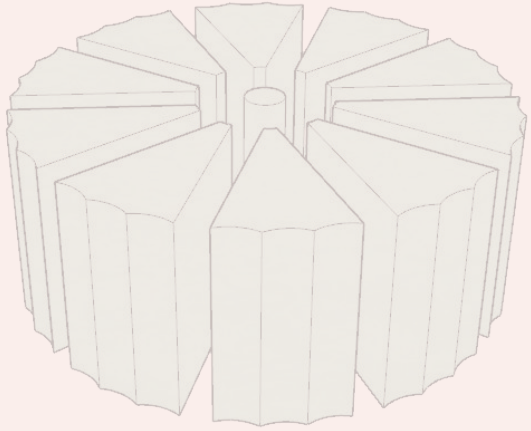


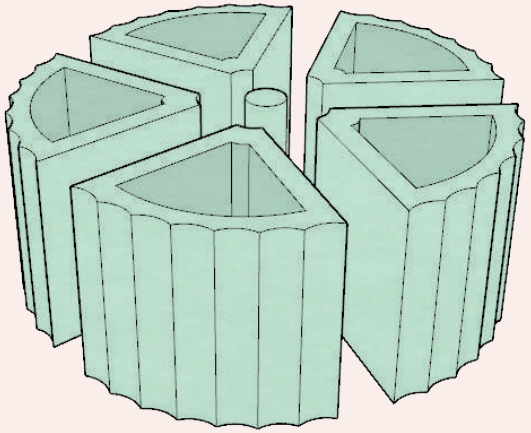
LOAD CASE IN
MONOLITHIC DRUMS

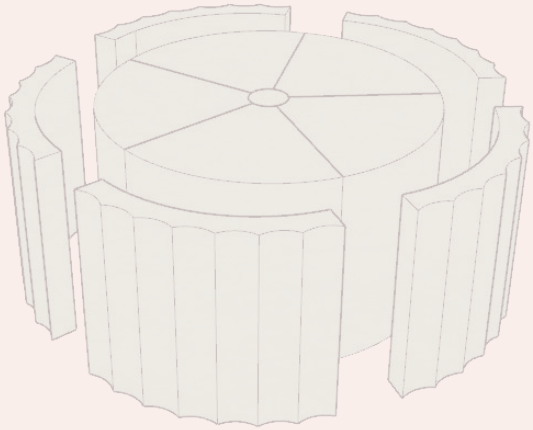


LOAD CASE IN HOLLOW
DRUMS

REDUCE THE MASS

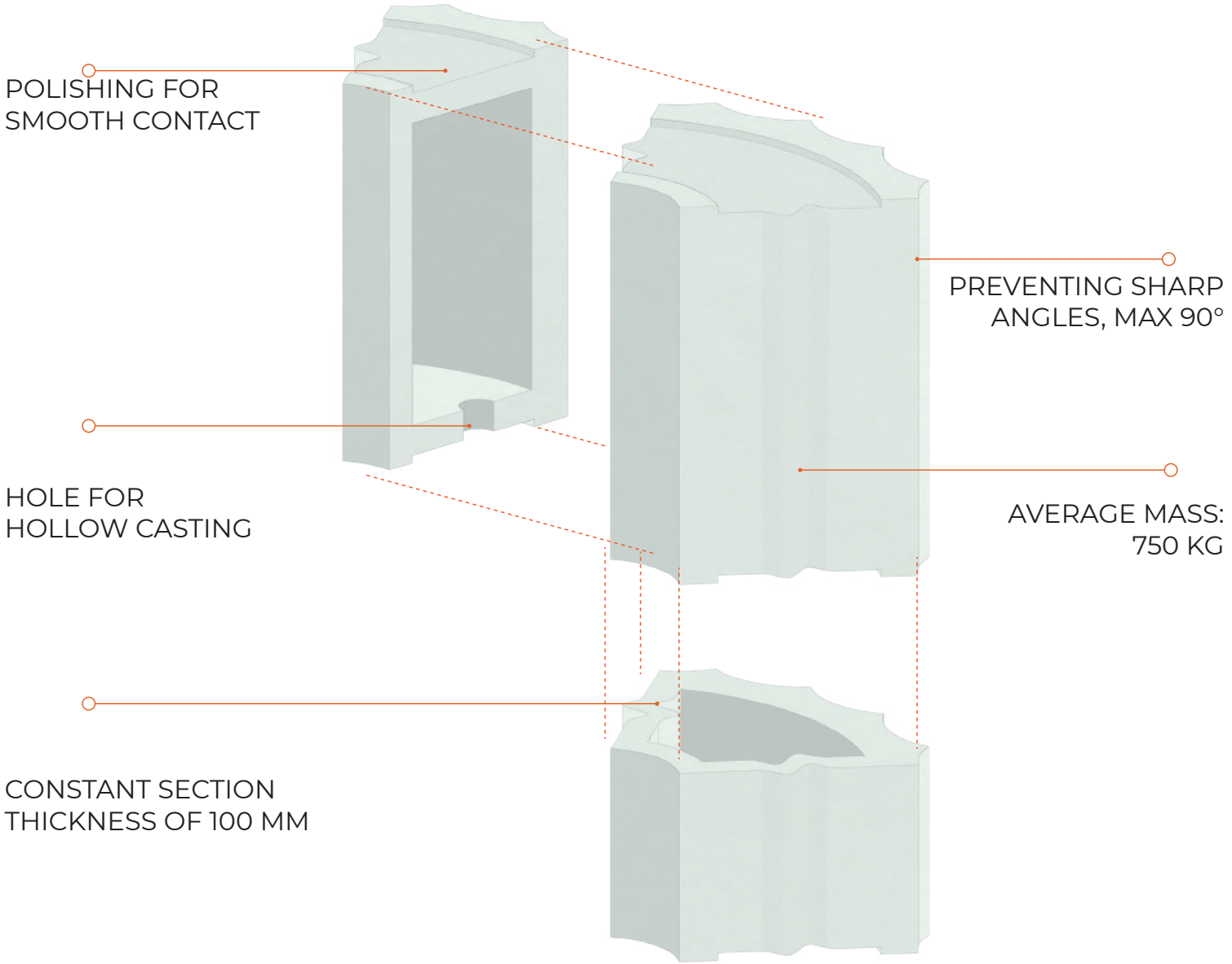




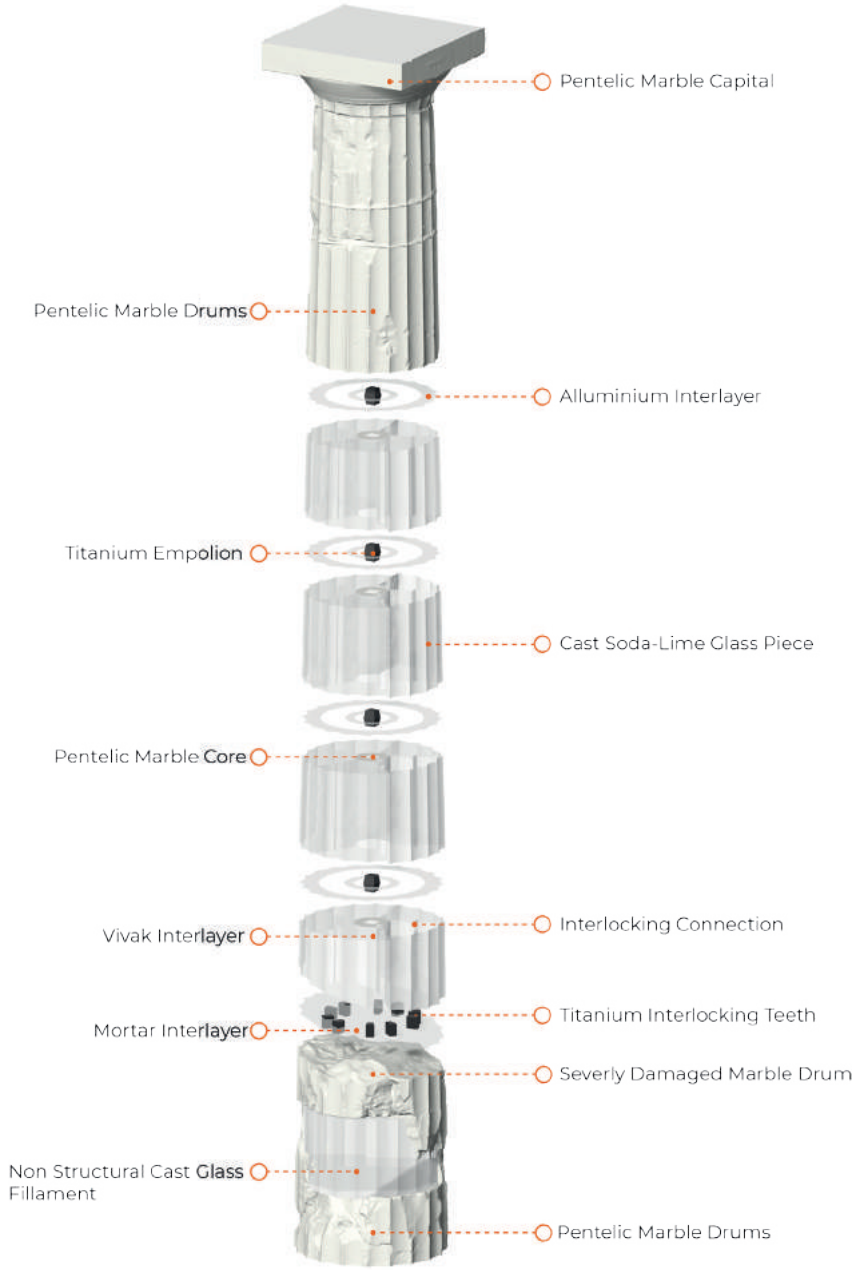


	SMALLER PIECES	HOLLOW PIECES	SEPARABLE SKIN
COMPATIBILITY	–	+	–
STABILITY	+ –	+ –	+ –
TOLERANCES	–	+	+
EFFECTIVENESS	+	+	+ –

CHARACTERISTIC PIECE



FINAL DESIGN




TRANSLUCENT GLASS


OPAQUE GLASS

PRODUCTION PHASE

MOULDS

DISPOSABLE MOULDS

NON-ADJUSTABLE

LOW ACCURACY

LOW COSTS

SINGLE USE

PERMANENT MOULDS

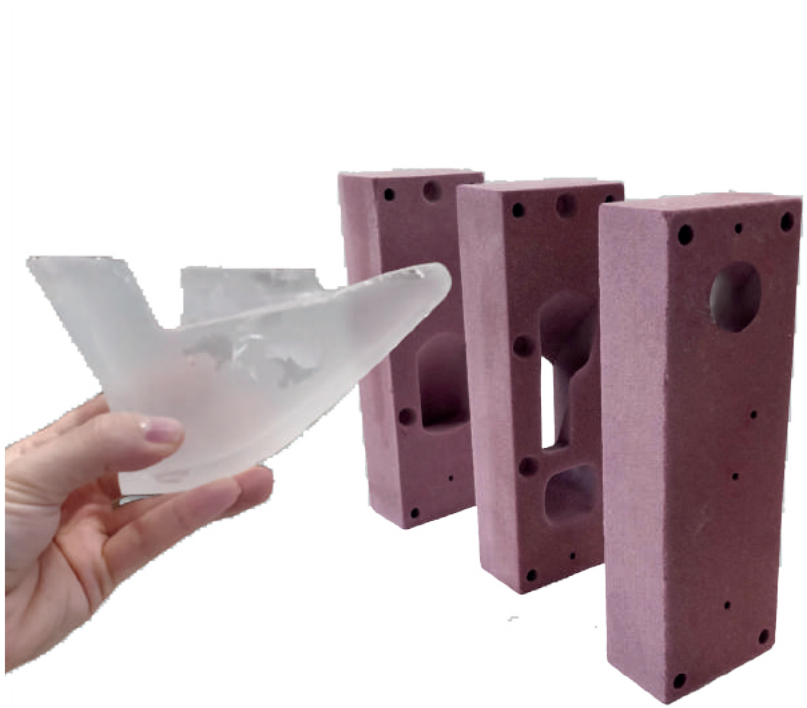
ADJUSTABLE - FIXED - PRESSED

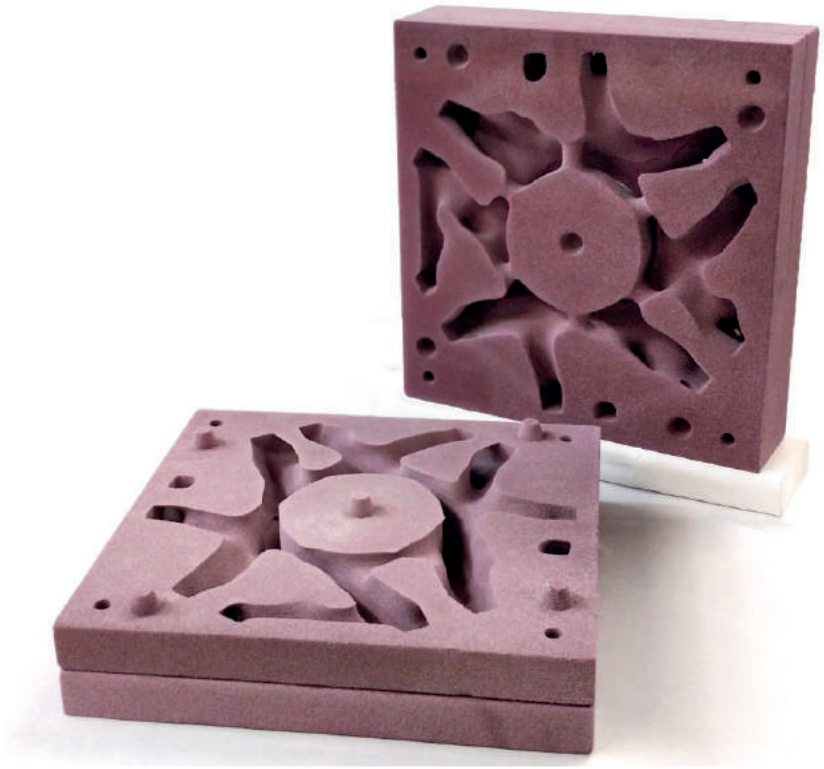
HIGH ACCURATE

HIGH COSTS

REUSABLE

3D PRINTED SAND MOULDS





- Additive manufacturing
- Single use mould
- Recylable materials
- Easy production process
- Low production costs
- High accuracy

CASTING

HOT FORMING / QUENCHING

PRIMARY PROCESS

LARGER OBJECTS

HIGH PRODUCTION VOLUME

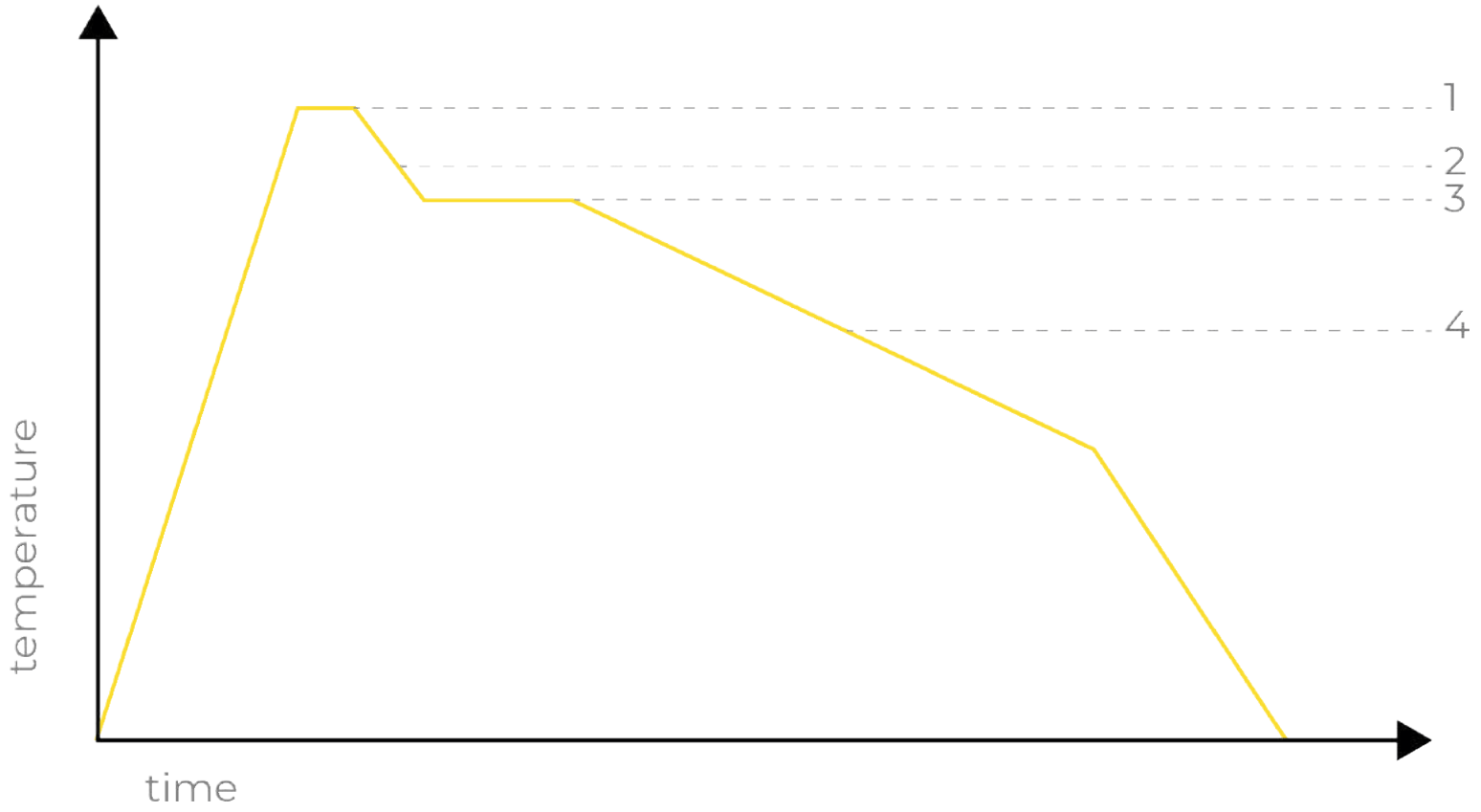
KILN CASTING

SECONDARY PROCESS

SMALL OBJECTS

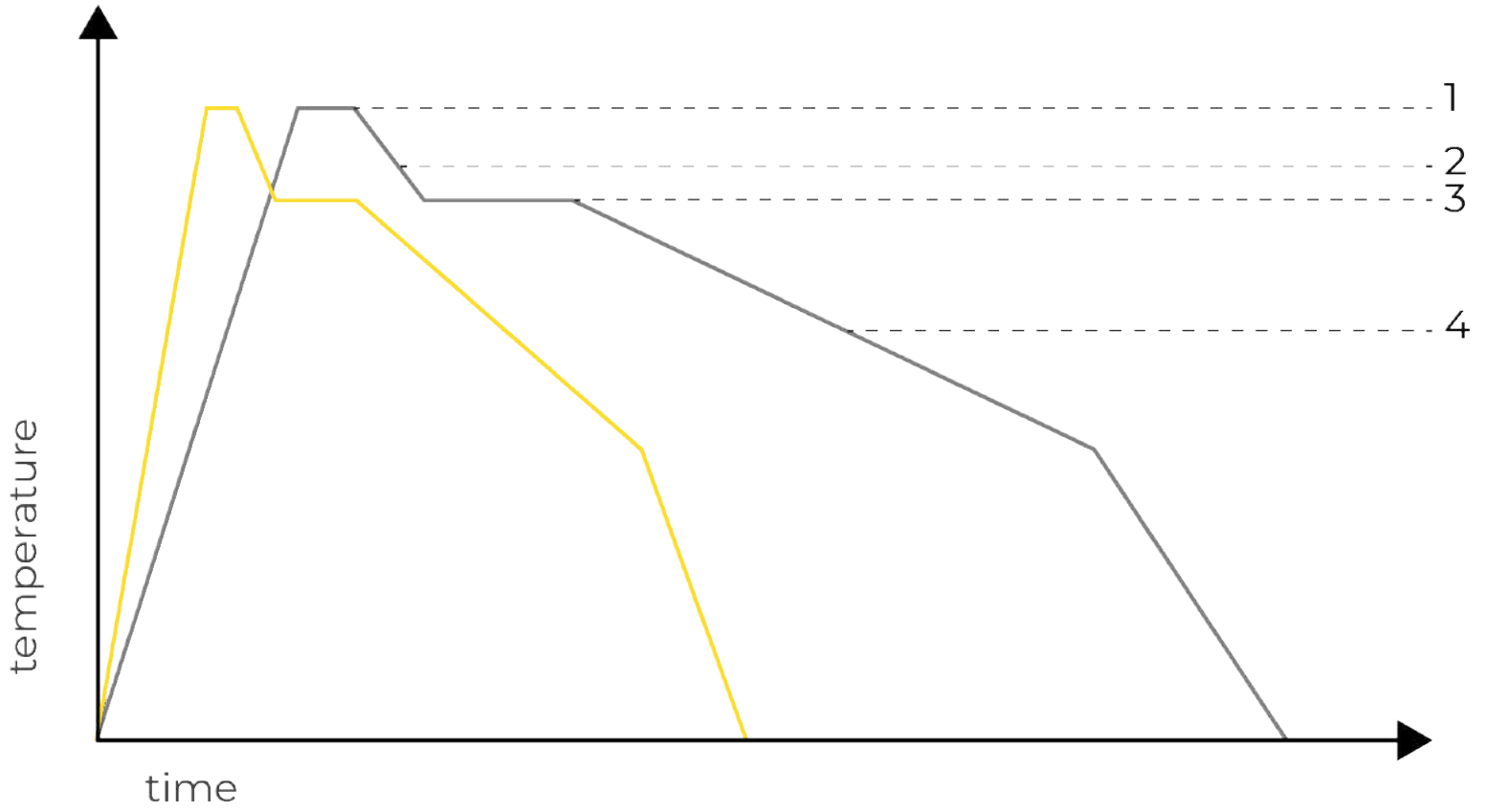
LOWER PRODUCTION VOLUME

ANNEALING



01 WORKING TEMPERATURE
02 SOFTENING TEMPERATURE
03 ANNEALING TEMPERATURE
04 STRAIN TEMPERATURE

CONTROLLING THE PROCESS

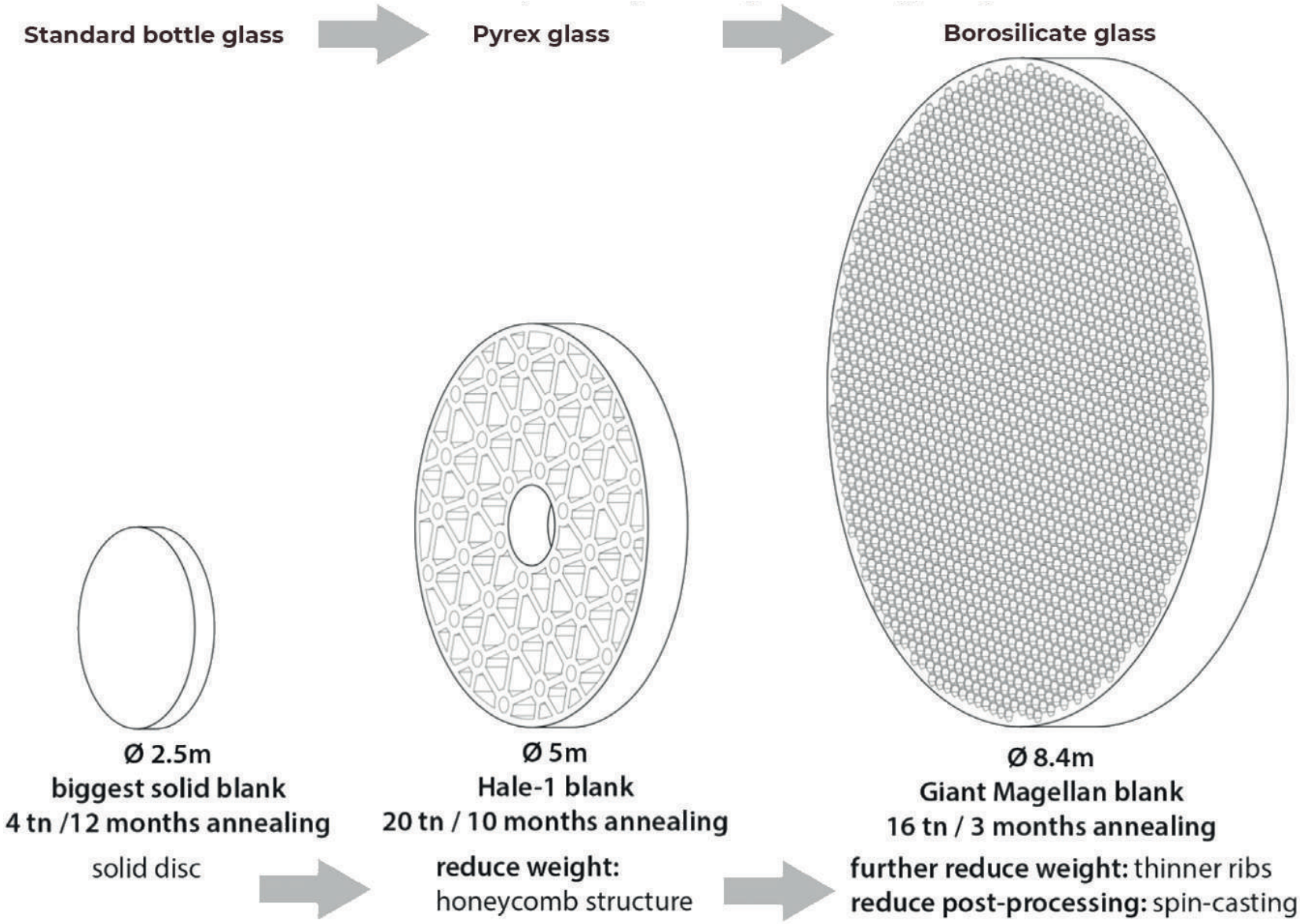


THERMAL EXPANSION OF THE GLASS

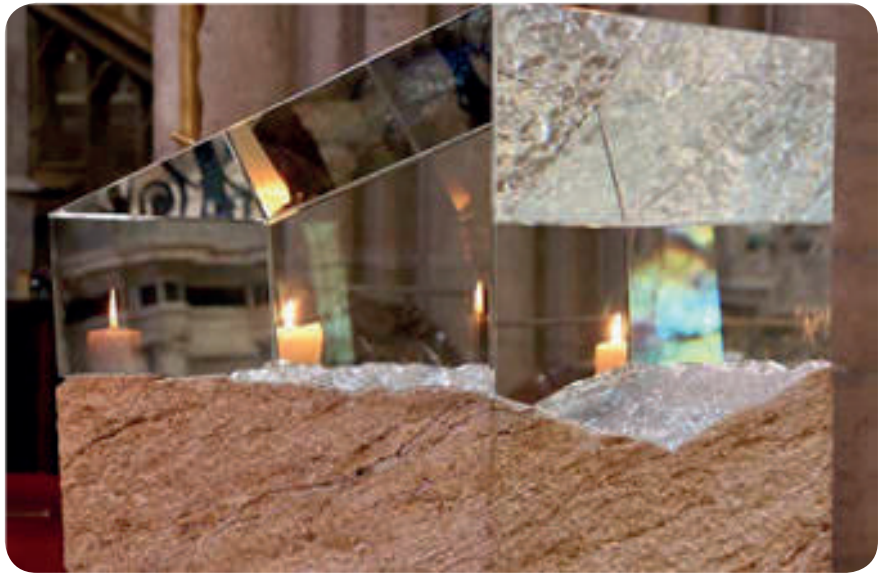
THICKNESS OF THE USED SECTION

RATE OF COOLING

ANNEALING IN TELESCOPE MIRRORS



IMPRINTING THE SURFACE



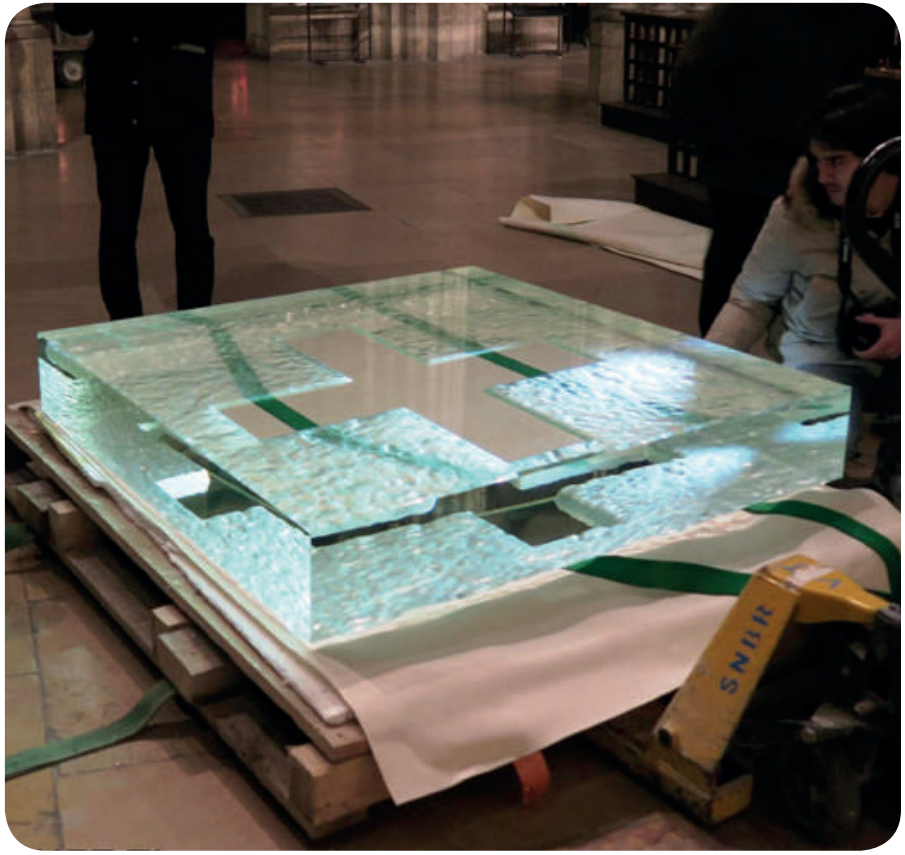
ALTAR IN ST. DENIS CATHEDRAL

1,4 TONS

1.42 * 1.42 * 0.28 METERS

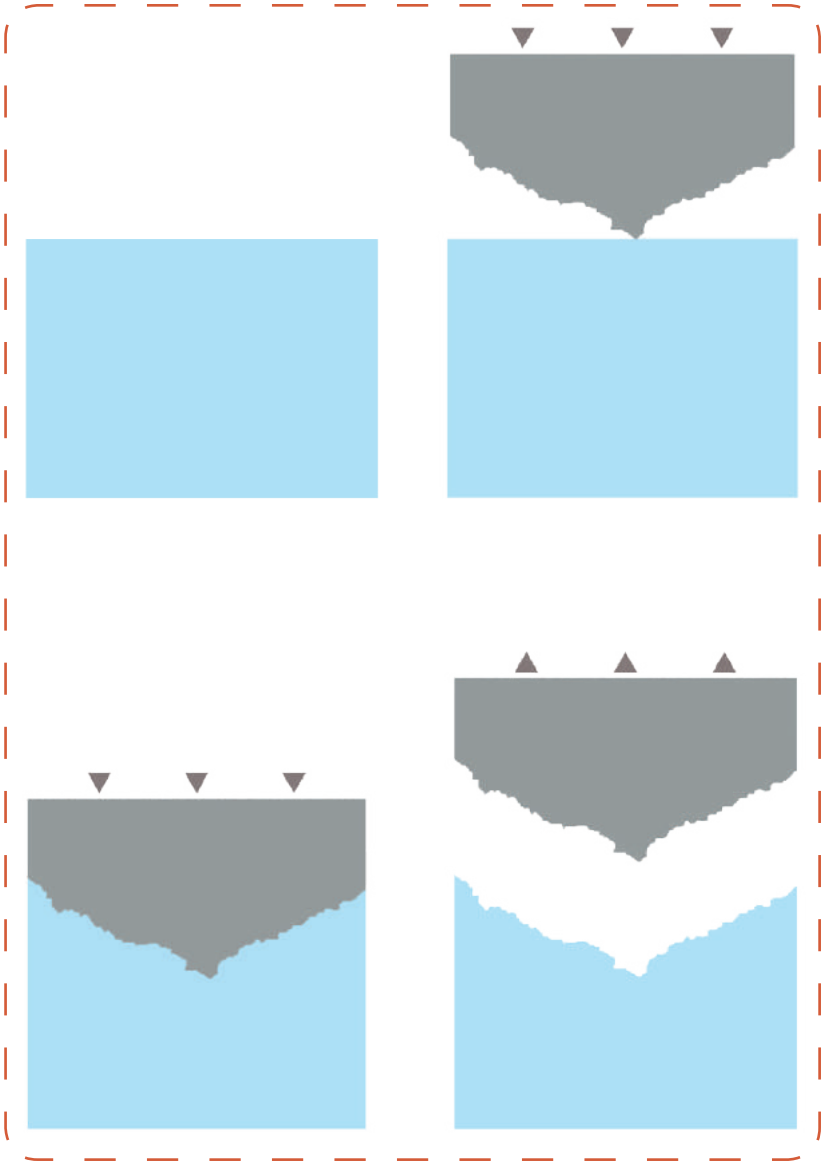
PERFECTLY FITTING GEOMETRY

IMPRINTING THE SUFACE

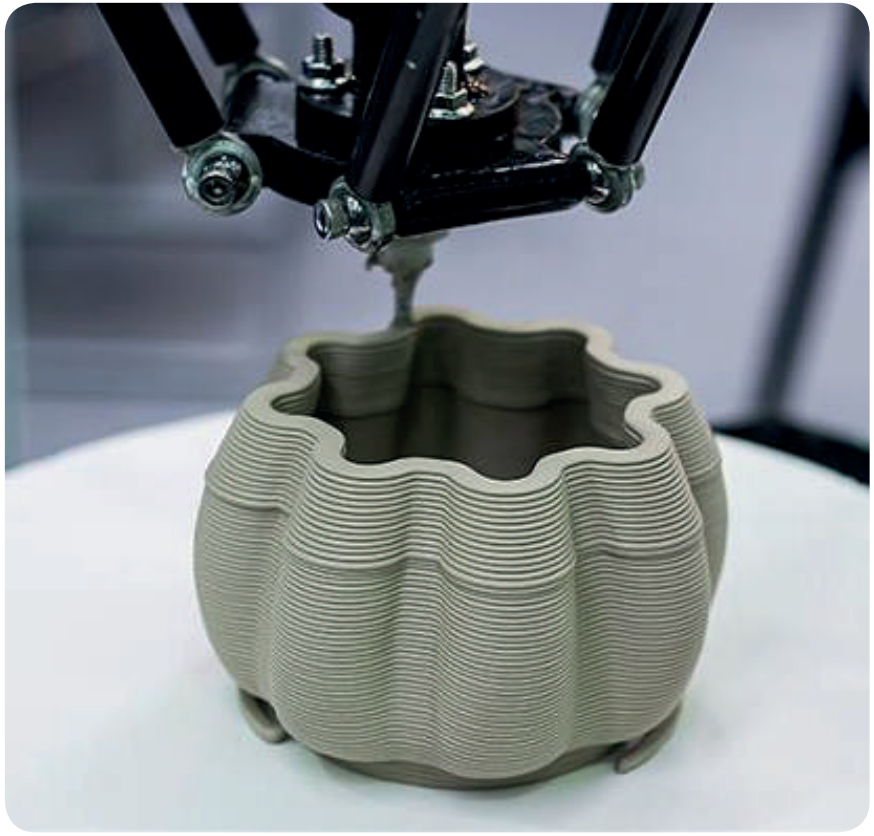


PROCESS IN THE SAINT DENIS ALTAR

1: CAST THE GLASS IN RECTANGULAR SHAPE
2: REHEAT THE GLASS TILL SOFTENING TEMPERATURE
3: PRESS THE SURFACE REPLICA INTO THE GLASS
4: REMOVE THE REPLICA FROM THE GLASS



3D PRINT FRAGMENTED SURFACE



3D PRINTED CERAMICS

STRONGER THAN SAND

LAYER THICKNESS OF 0.25 MM

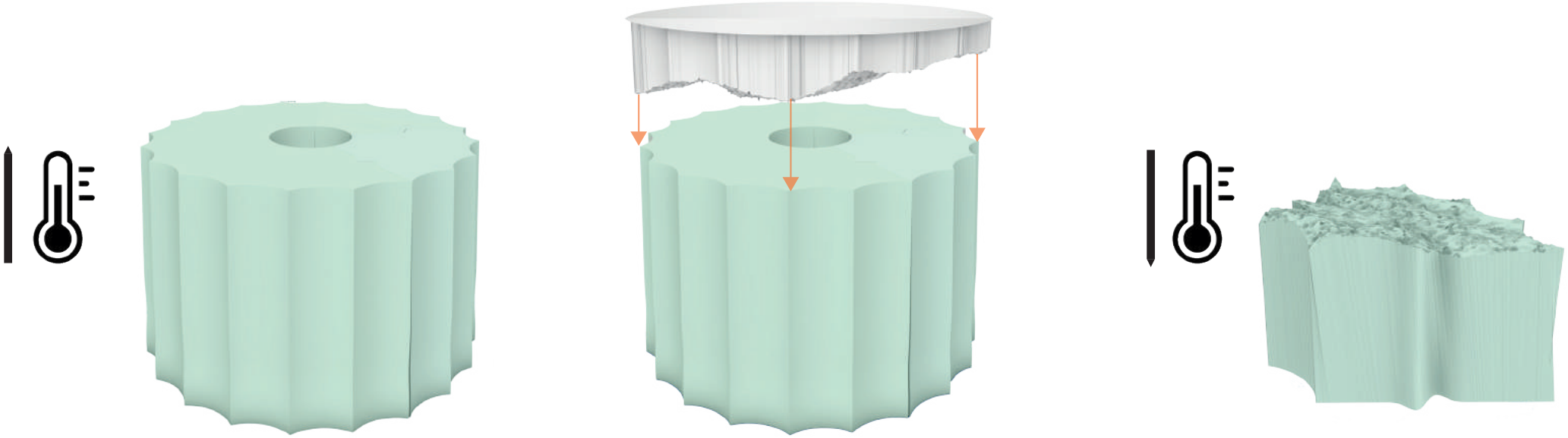
COMBINED WITH 3D SCANNING

IMPRINTING THE SURFACE

REHEAT THE GLASS

IMPRINT WITH THE CERAMIC

SECOND ANNEALING



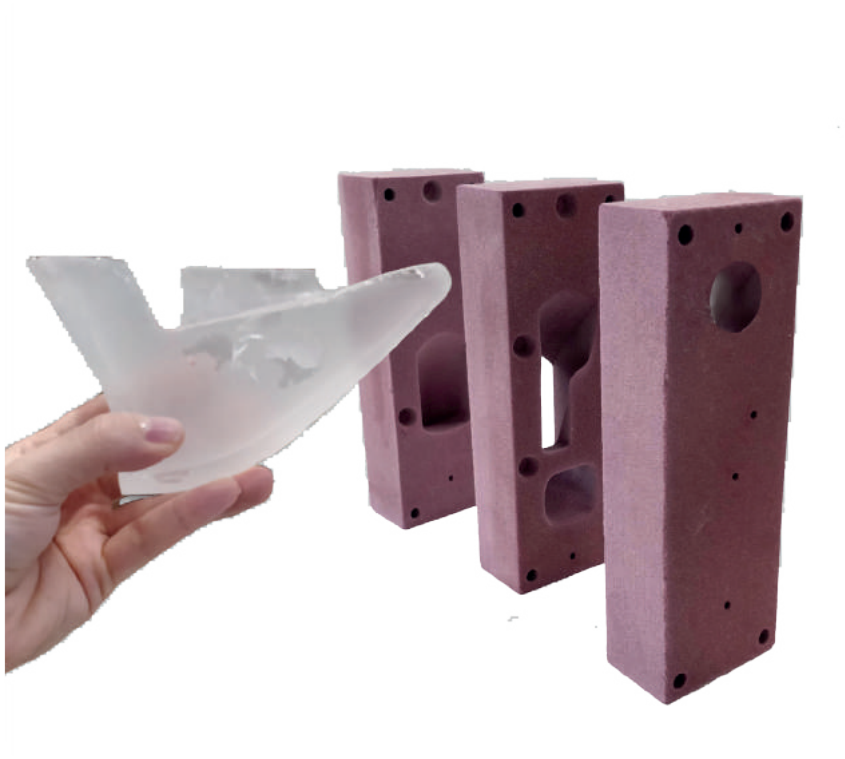
COMPARISON WITH ST. DENIS

ONE MONTH PER STEP

50 % OF THE MASS

MASS IS MORE EVENLY DISTRIBUTED

POST-TREATMENT



SAND MOULD GIVES A ROUGH SURFACE

IF WANTED POLISHING UNTIL DESIRED TEXTURE IS REACHED

CASTING COMES WITH TOLERANCES

POLISHING IS ALWAYS REQUIRED TO PROVIDE SMOOTH CONTACT BETWEEN GLASS ELEMENTS

ASSEMBLY PHASE

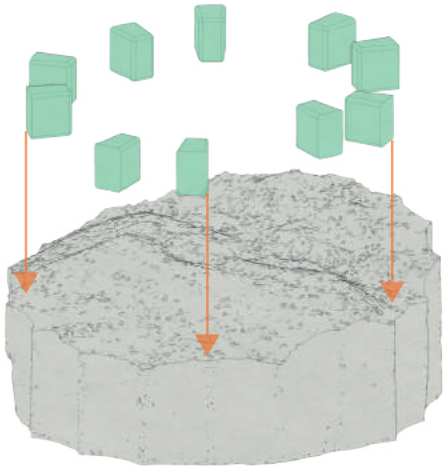
COLLECT ALL PIECES

RESTORATION OF THE PARTHENON

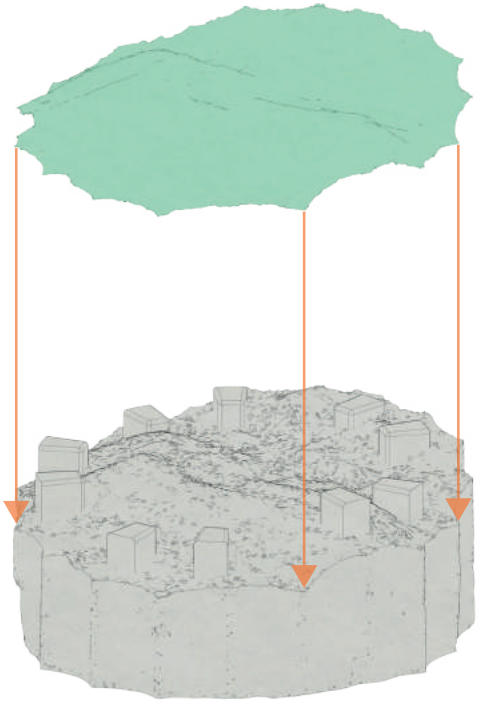
- 70.000 PIECE JIGSAW PUZZLE
- EACH PIECE IS UNIQUE
- LEARN FROM EARLIER “CONTRIBUTIONS”

COMPLETE THE MISSING GEOMETRIES

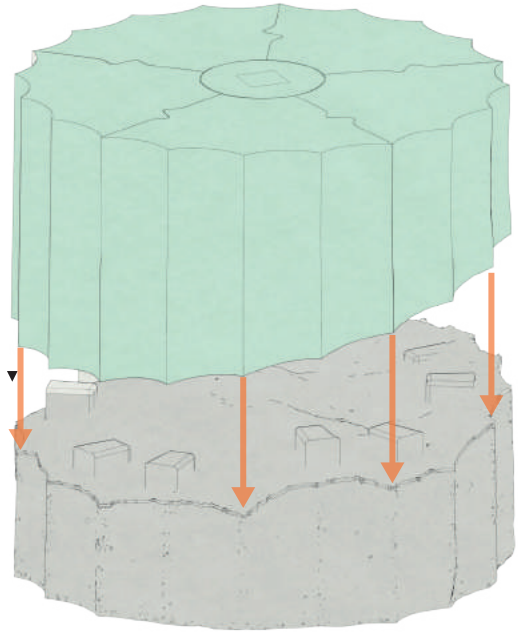
INSERT THE JOINTS



APPLY THE MORTAR

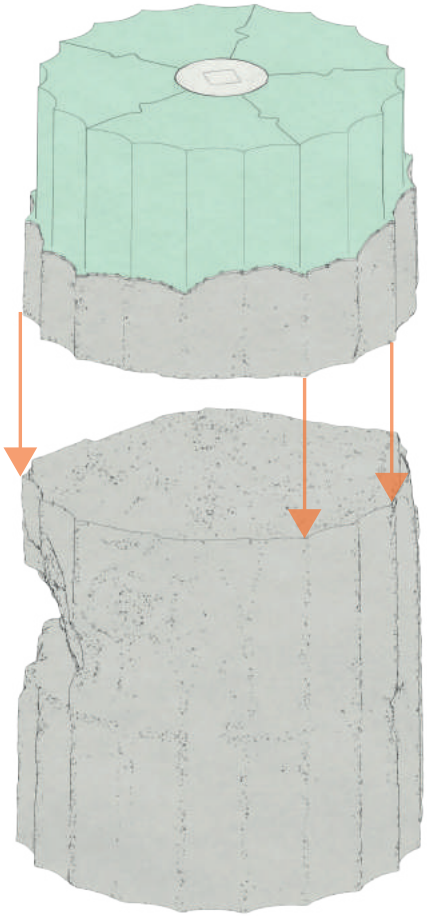


ATTACH THE GLASS

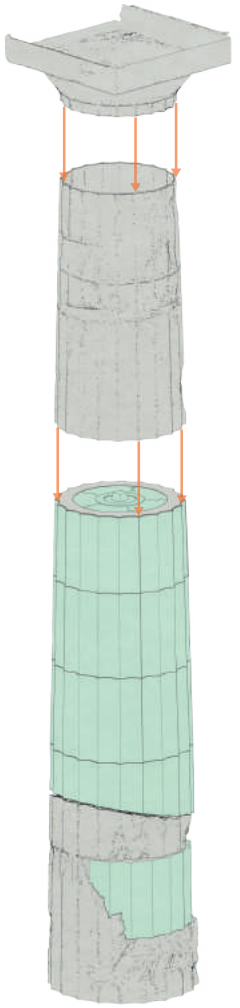


POSITION THE DRUMS

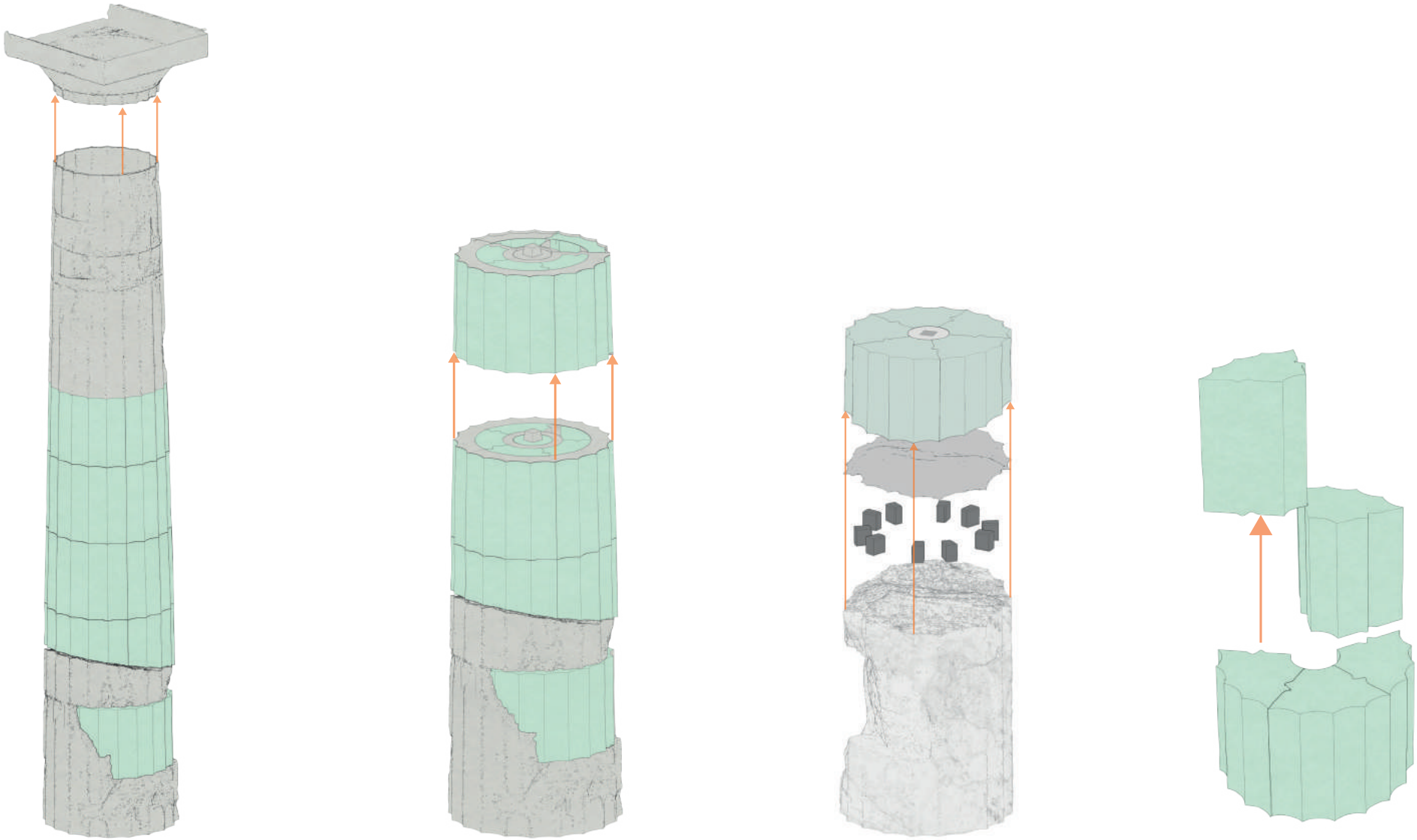
POSITION THE HYBRID DRUM



POSITION THE OTHER DRUMS AND FINISH WITH THE CAPITOL



RERVERSING THE INTERVENTION



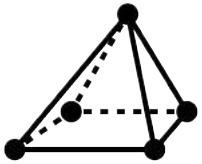
CONCLUSIONS

CONCLUSIONS

"TO WHICH EXTENT CAN *MONOLITHIC CAST GLASS COMPONENTS OF A SUBSTANTIAL MASS* BE USED TO *RECONSTRUCT STRUCTURAL ELEMENTS IN MARBLE MONUMENTS*, WHILE SIMULTANEOUSLY *COMPLYING WITH THE INTERNATIONAL CONSERVATION GUIDELINES*?"

HERITAGE AND CONSERVATION

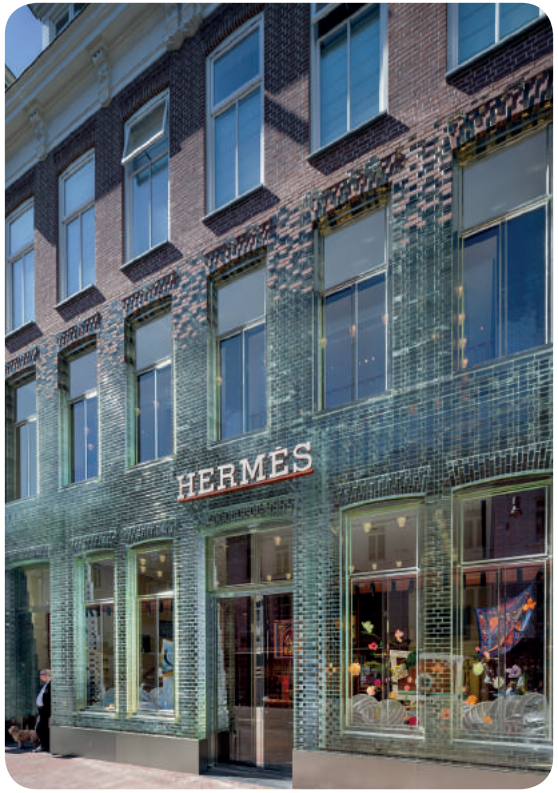
GLASS AS STRUCTRUAL MATERIAL



PRODUCTION OF CAST GLASS

CONCLUSIONS

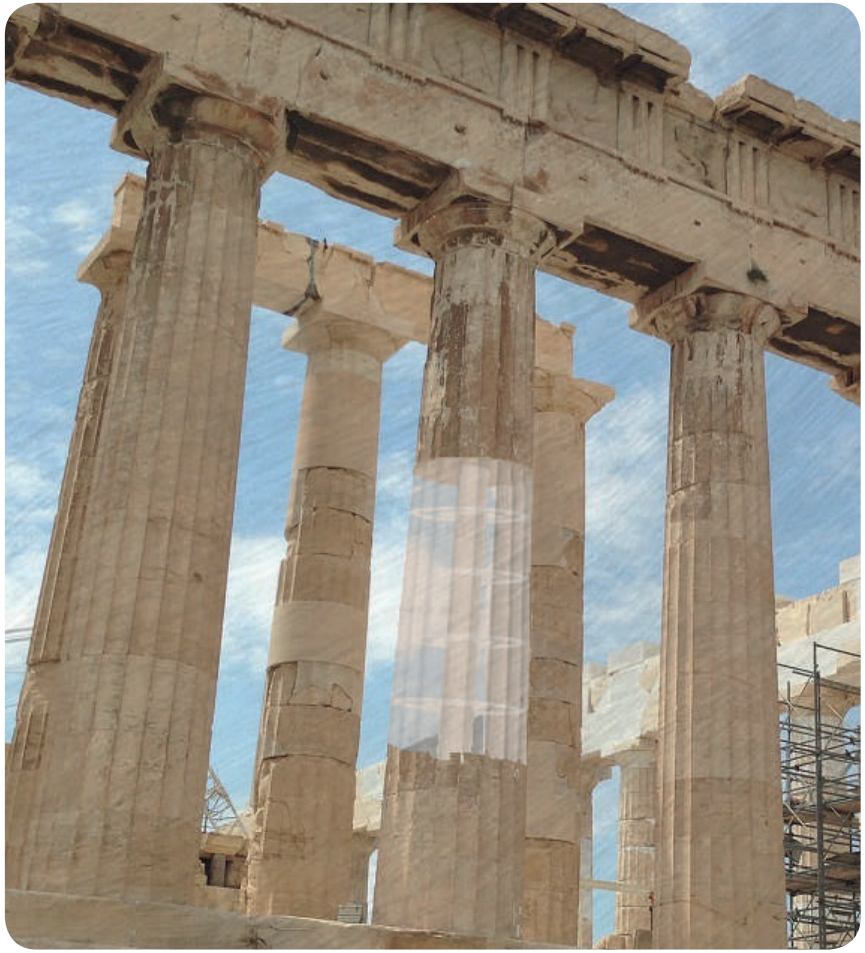
EXPENSIVE AND
TIME-CONSUMING



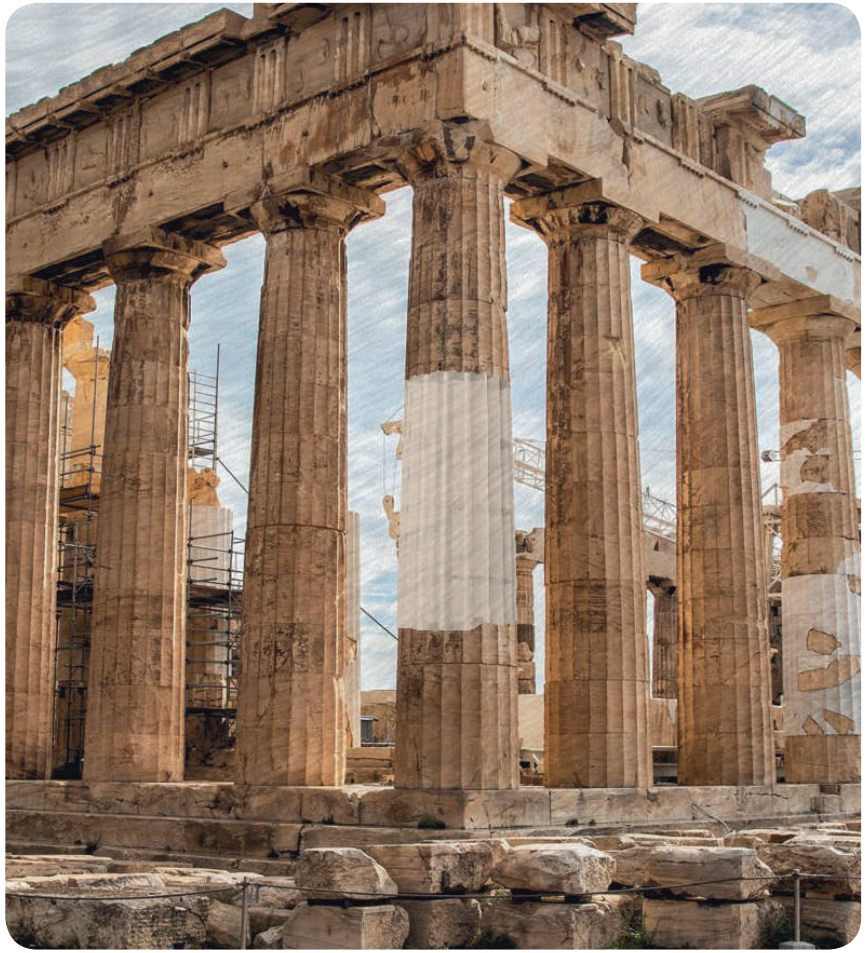
STRONG IN COMPRESSION
DRY CONNECTION POSSIBLE

3D PRINTED SAND MOULDS
ALLOW FOR EASY SHAPING

CONCLUSIONS



TRANSPARENT OR TRANSLUCENT GLASS



OPAQUE GLASS, OR
“ARTIFICIALLY PRODUCED MARBLE”

RECOMENDATIONS AND LIMITATIONS

CAST GLASS IS NOT THE ONLY OR BEST SOLUTION

CONSERVATION IS A CONSERVATIVE WORLD


THANK YOU FOR YOUR ATTENTION
ANY QUESTIONS?

REFERENCES

P2- https://en.wikipedia.org/wiki/St_Mark%27s_Campanile
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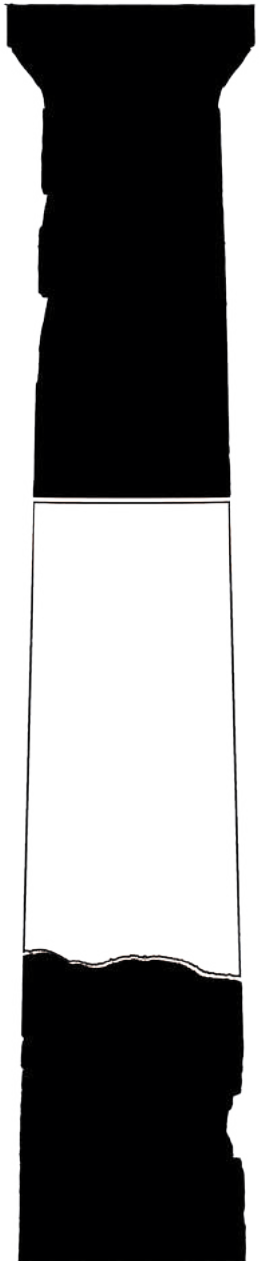
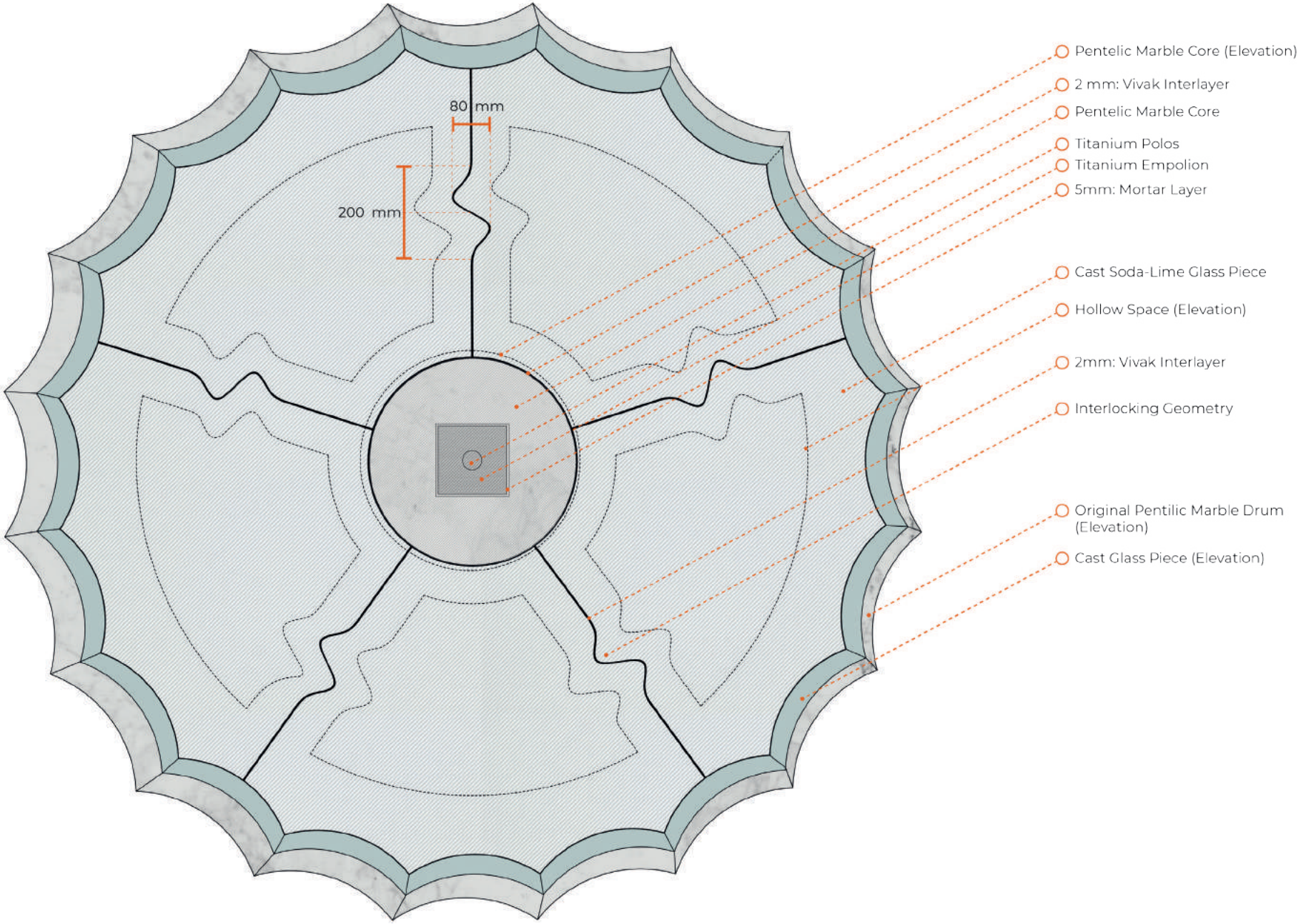
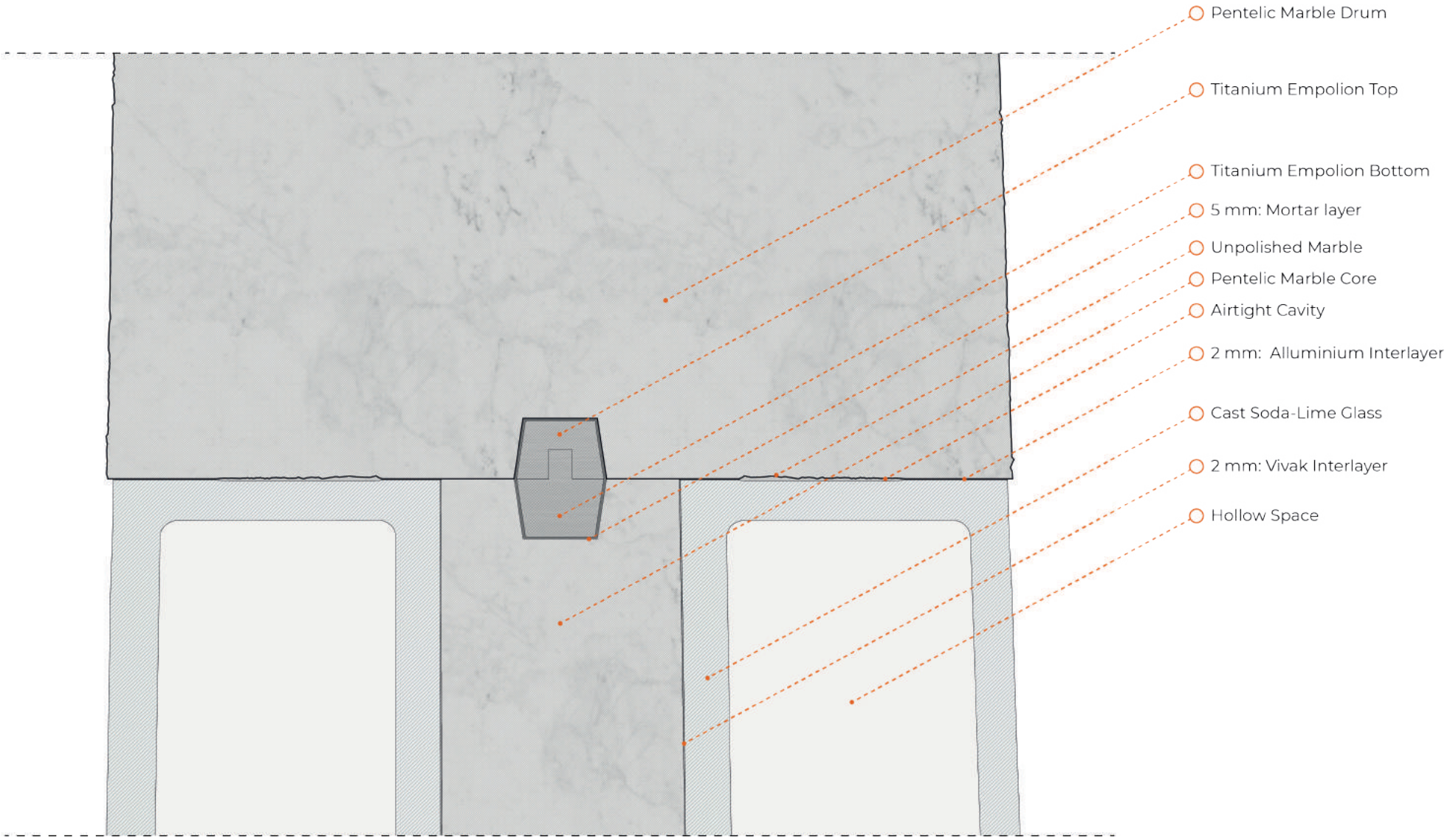
APPENDIX



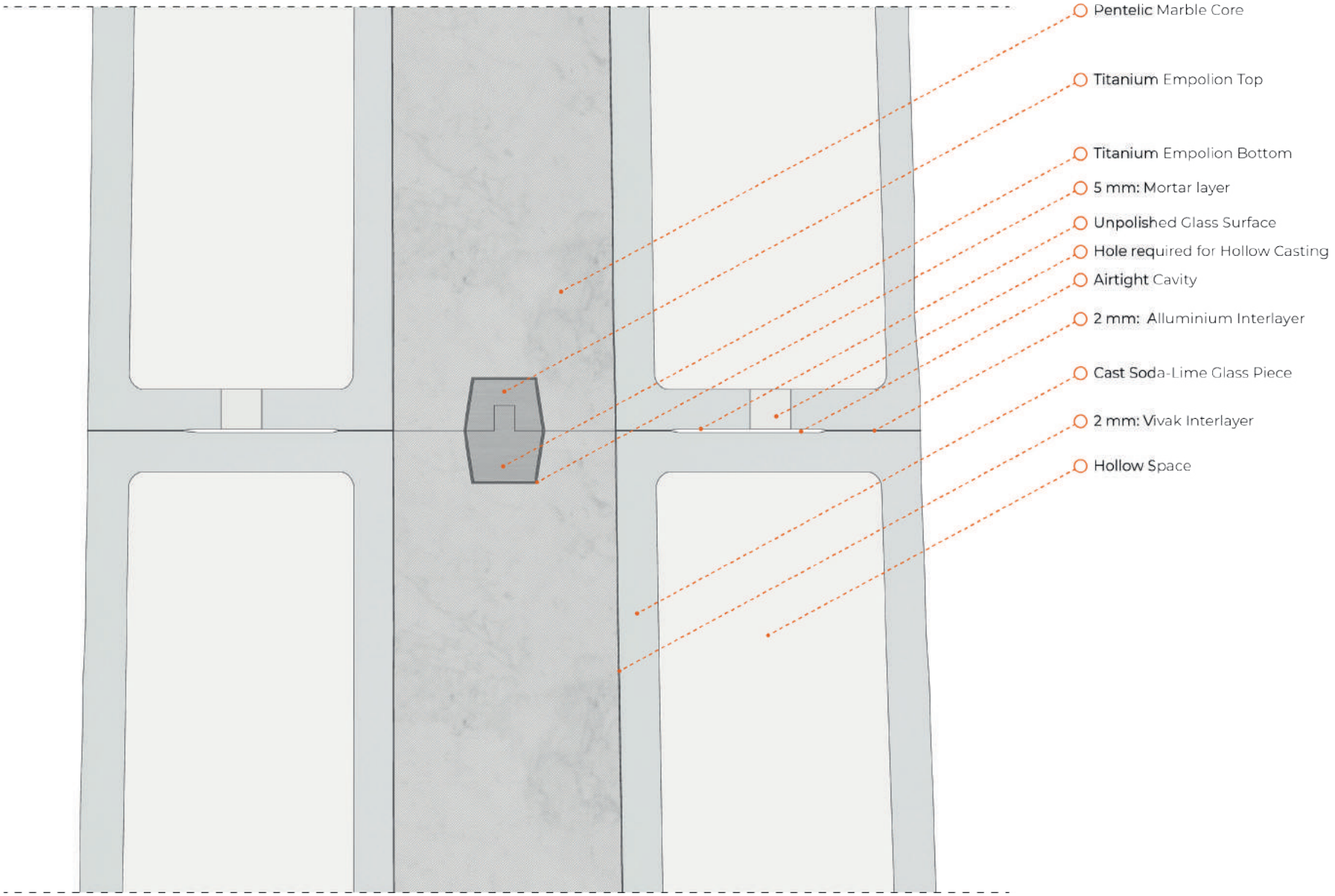
DETAIL CONNECTION 1



DETAIL CONNECTION 2



DETAIL CONNECTION 3



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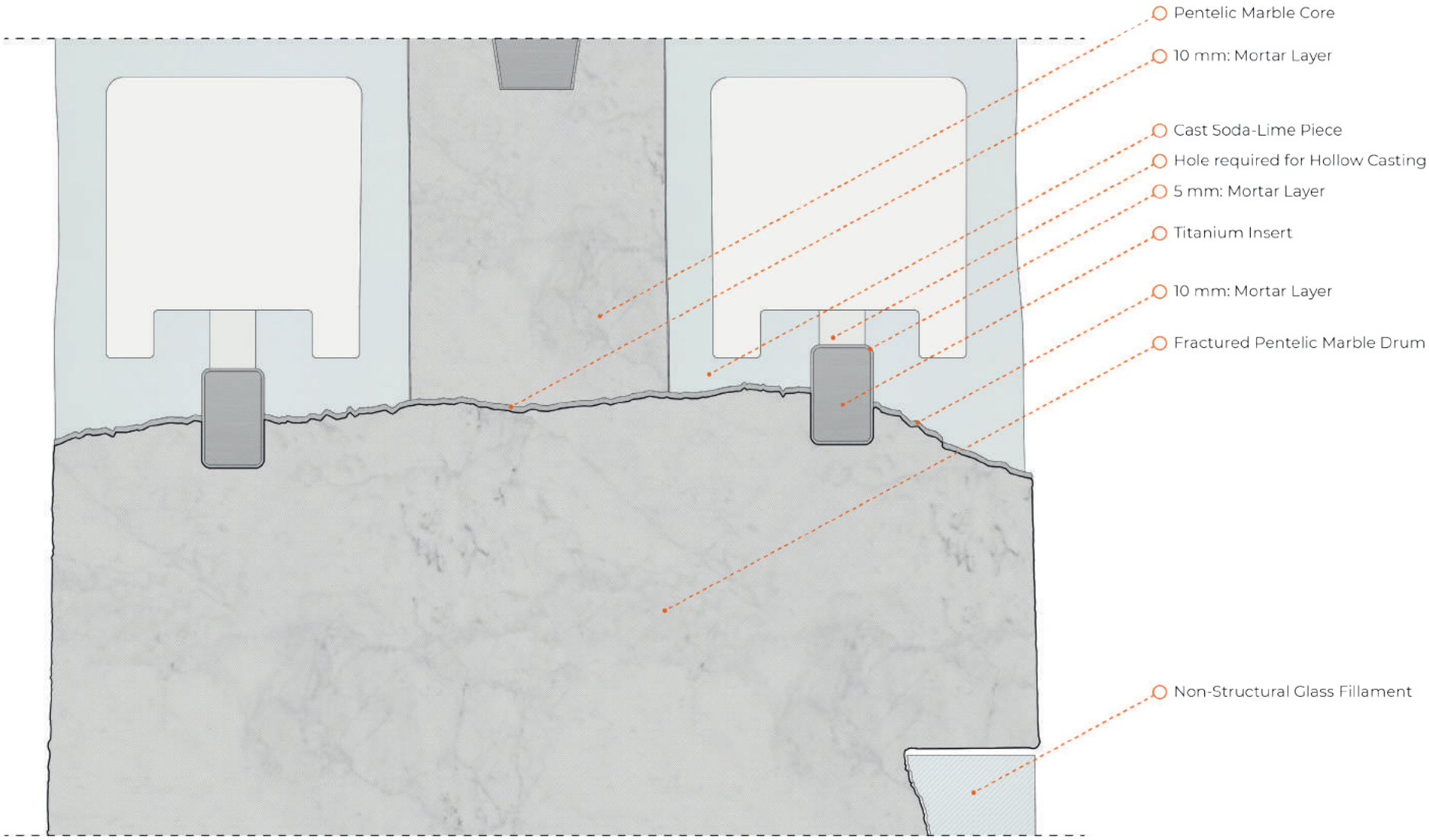
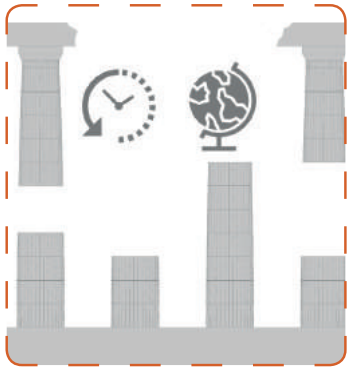
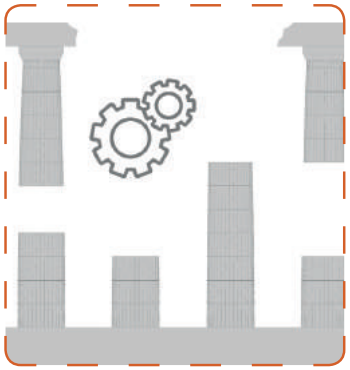


1 - DESIGN PHASE

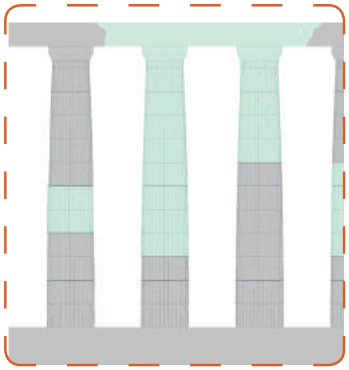
1. Case study research
Location and History



2. Case study research
Structure and mechanical behaviour

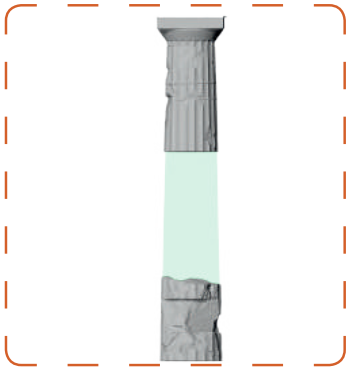


3. Determine intervention



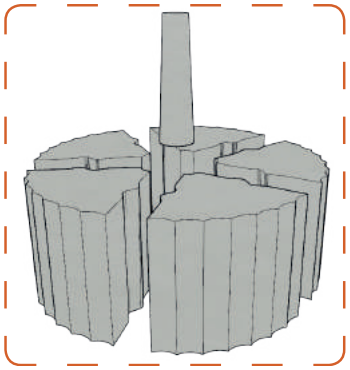
4. Surface scan

5. Determine original shape

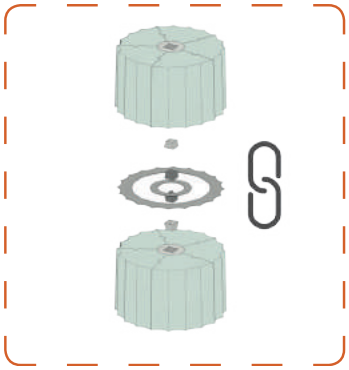


6. Choose the Materials

7. Fragment missing element



8. Design the Connections



9. Make CAD Model

AUTODESK®
AUTOCAD®

2 - PRODUCTION PHASE

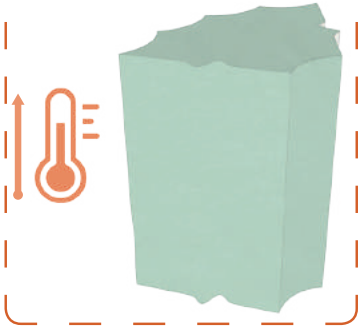
1. 3D Print the Sand Mould

2. Cast the Pie Shapes

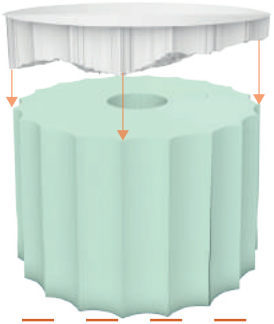
3. Let the Pieces Anneal in the sand mould

4. 3D print broken surface

5. Reheat pie pieces



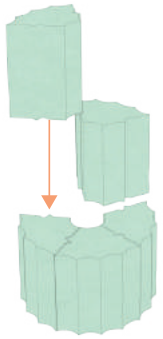
6. Imprint with a press mould



7. Anneal the imprinted pieces again

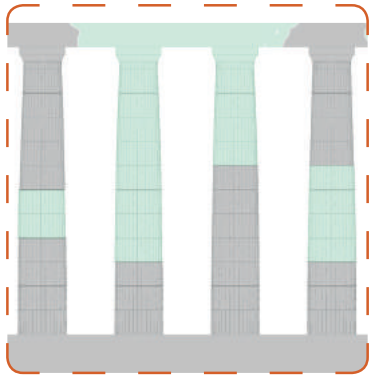
8. Post treatment of the glass

9. Assemble the drums

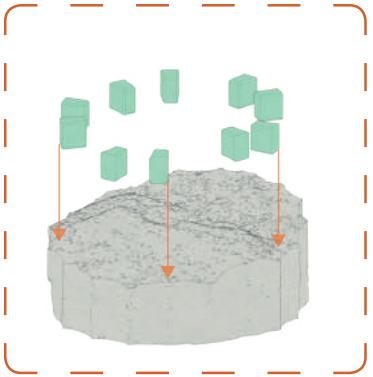


3 - ASSEMBLY PHASE

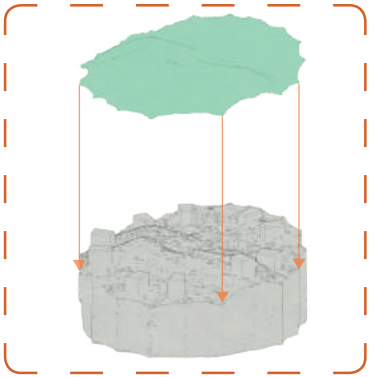
1. Collect all column pieces



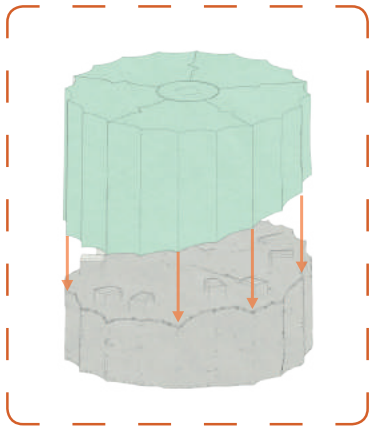
2. Insert and join metal connections in marble drum



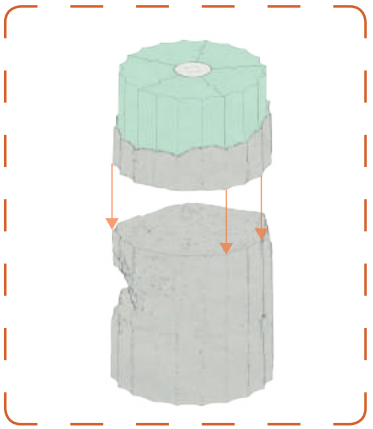
3. Apply mortar to the surface of the fractured drum



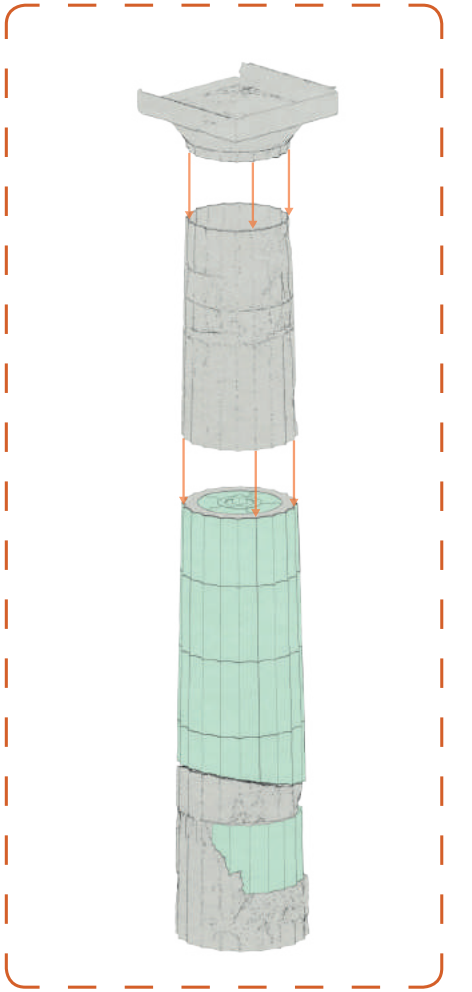
4. Bring assembled glass



5. Position the hybrid drum

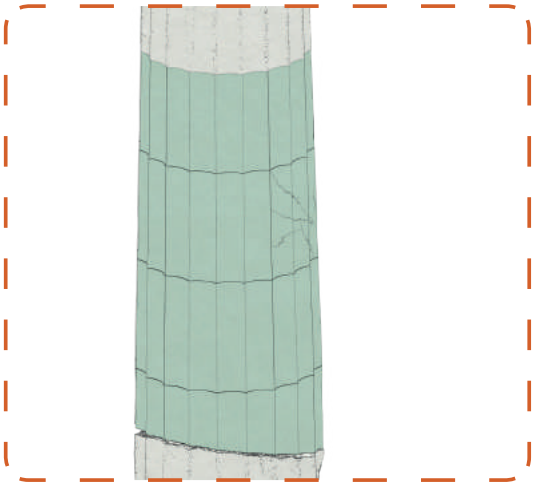


6. Repeat till column is finished

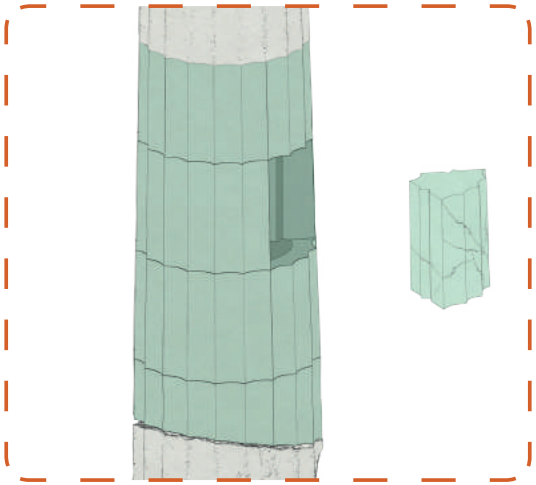


4 - REPLACING PHASE

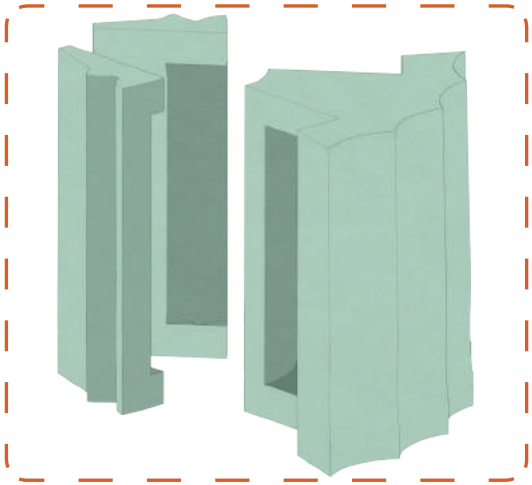
1. ONE OF THE GLASS PIECES HAS SEVERED DAMAGE, CRACKS APPEAR



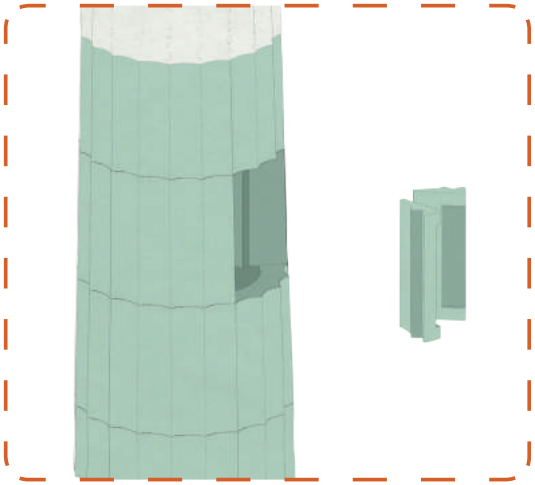
2. CAREFULLY REMOVE THE DAMAGED PIECE OF GLASS



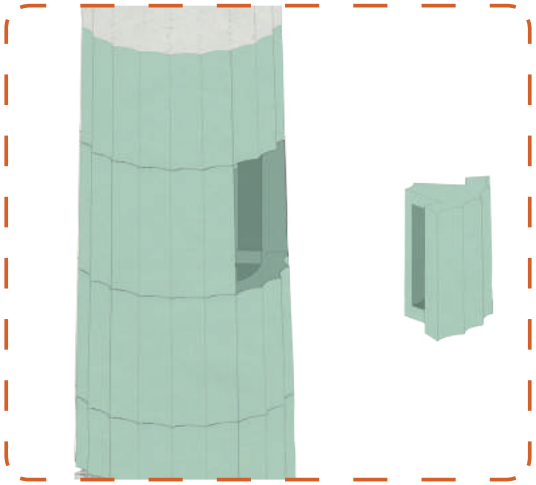
3. CAST A NEW, TEMPORARY, REPLACING PART



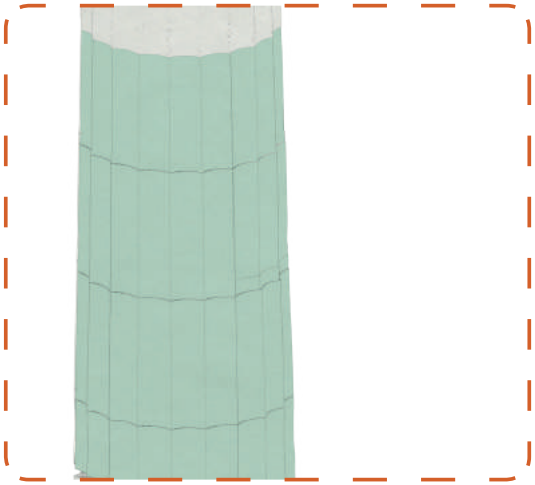
4. BRING THE FIRST TWO PIECES IN THEIR INTERLOCKING POSITION



5. PERMANENTLY JOIN THE THIRD PIECE TO THE OTHER TWO WITH AN ADHESIVE

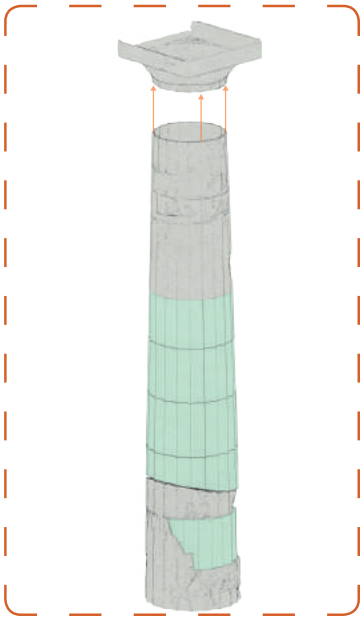


6. WITH THE ADHESIVE, THE PIECES CAN BE USED AS TEMPORARY SOLUTION

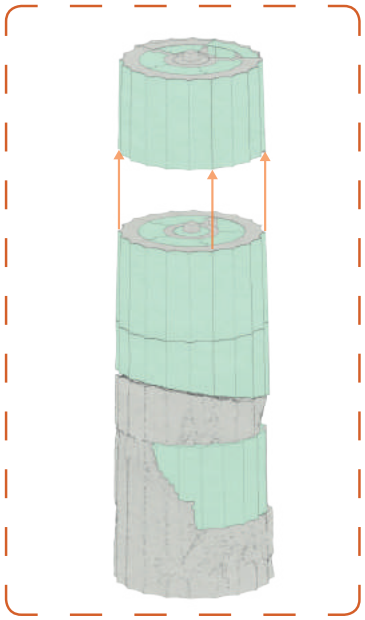


5 - DISASSEMBLY PHASE

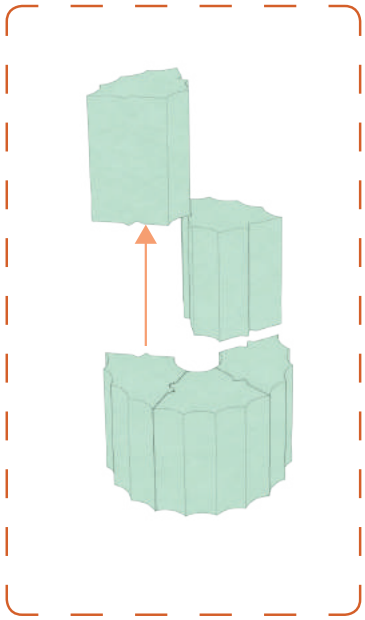
1. Remove the overlaying superstructure



2. Remove the drums one by one



3. Disassemble the glass drums off-site



4. Remove the mortar layer of the broken marble drum