STATIC - AND FABRICATION - AWARE CONCRETE SHELLS SEGMENTED INTO FLAT TILES

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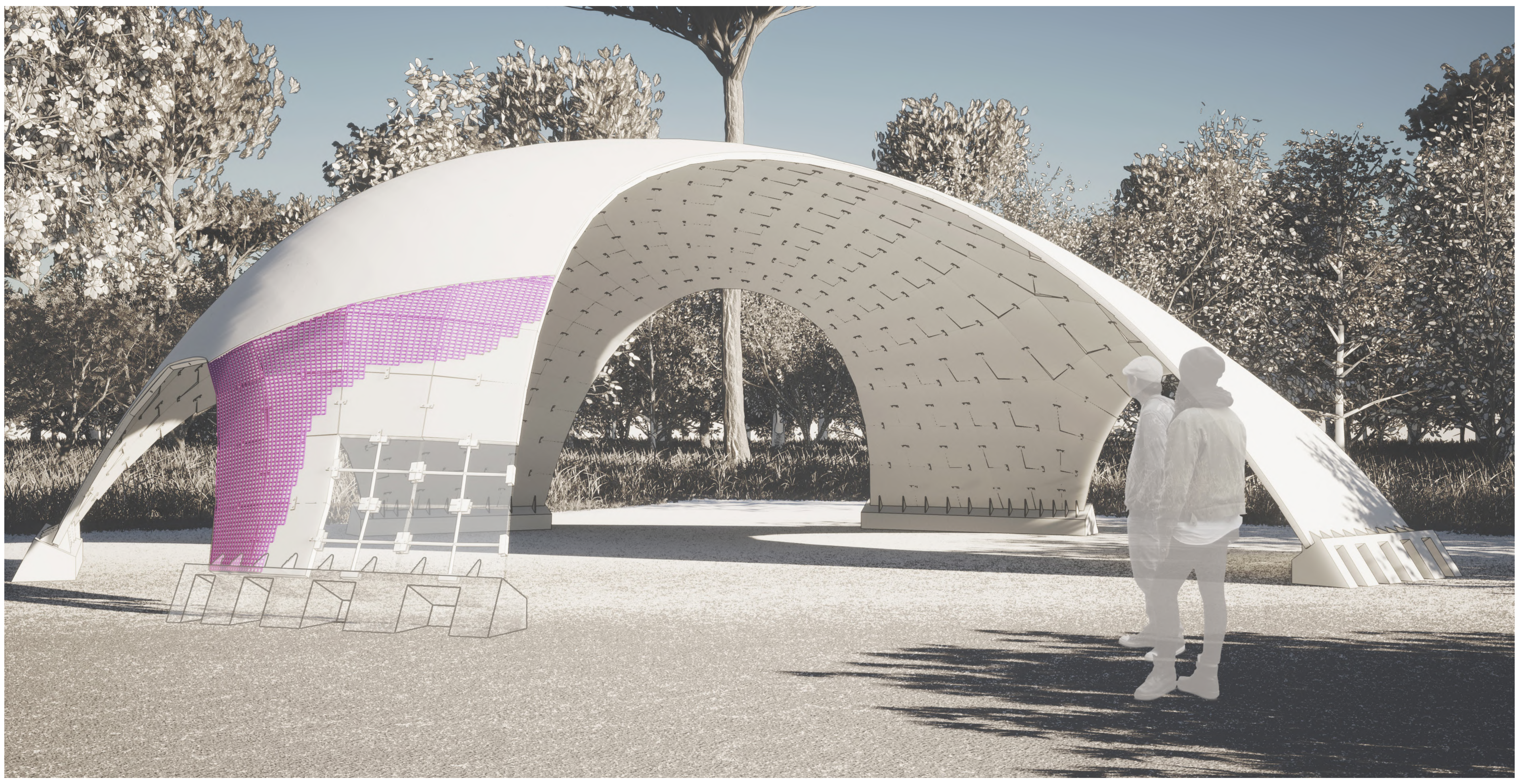
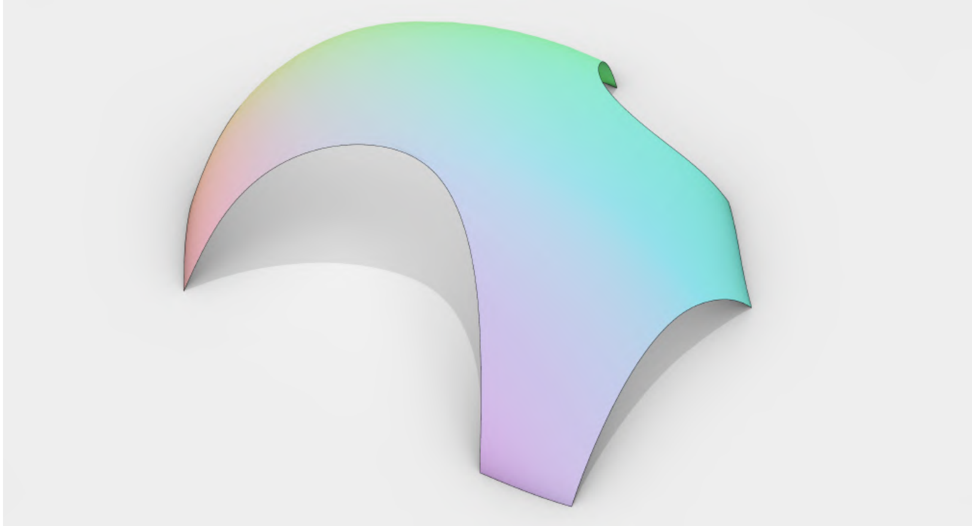


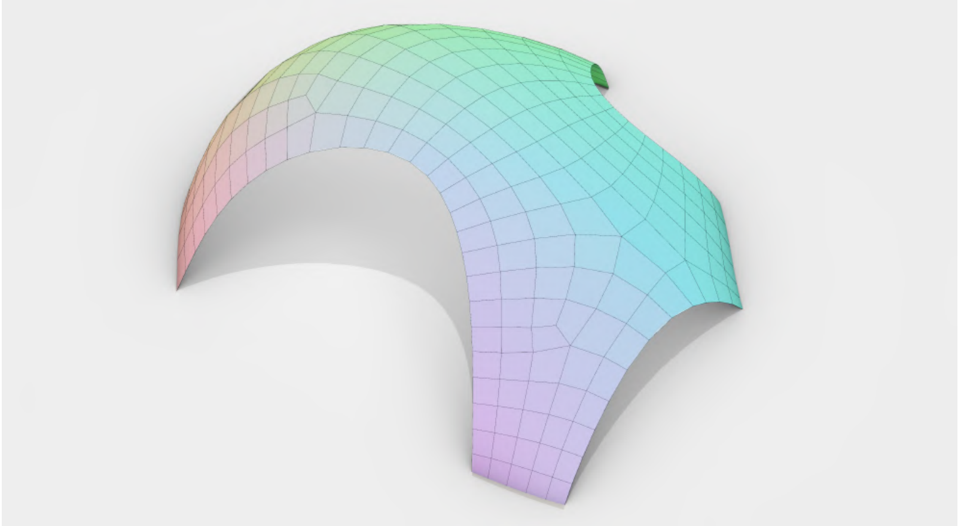
MOTIVATION AND CONCEPT

The design of freeform concrete shells has gained popularity recently, pushed by computational tools that allow manipulating and exploring complex shapes interactively. However, their actual fabrication, even on a small scale, still poses challenges of feasibility and cost. Continuous shells require accurate and dense formworks, while segmented shells offer a low prefabrication rate, especially in the case of variable curvature. We propose a novel structural concept for freeform shells, in which the shape is decomposed into flat tiles, touching each other at the midpoint of the edges. Once assembled, the tiles are post-tensioned to minimize the resulting tension on the structure under service load. The outer surface is finally completed with an in situ cast that fills the gaps and activates the entire shell behavior. The bottom surface presents a jagged aesthetic due to gaps and misalignments at the seams. We developed an automatic pipeline to manage the design process from a general input shape to fabrication. The input shape is segmented based on a field-aligned quad mesh computed from the principal stress of the thin shell. The flat tiles are obtained by extruding each face along the normal of the associated checkerboard mesh, i.e., a mesh whose 'solid' parts are the planar rhomboids with vertices on each quad edge's midpoint. The contact between adjacent tiles is ensured only at their edge midpoints so that forces can flow along the cross directions, namely the principal directions. Candidate post-tensioning paths are found by clustering the segments linking pairs of opposite midpoints of the tiles' edges. We discard paths that do not terminate on the boundary, closed loops, or paths with significant kinks, to avoid localized shear on the surface.

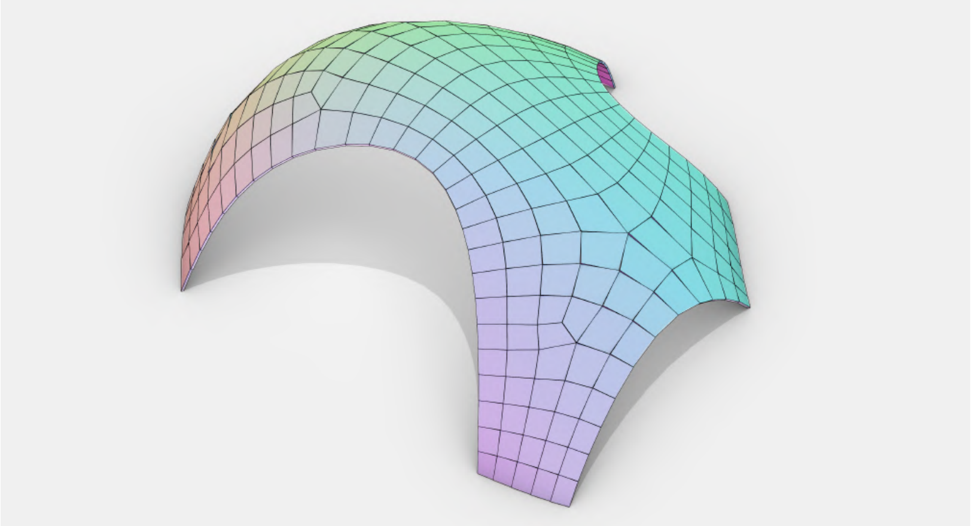
1. INPUT SHAPE



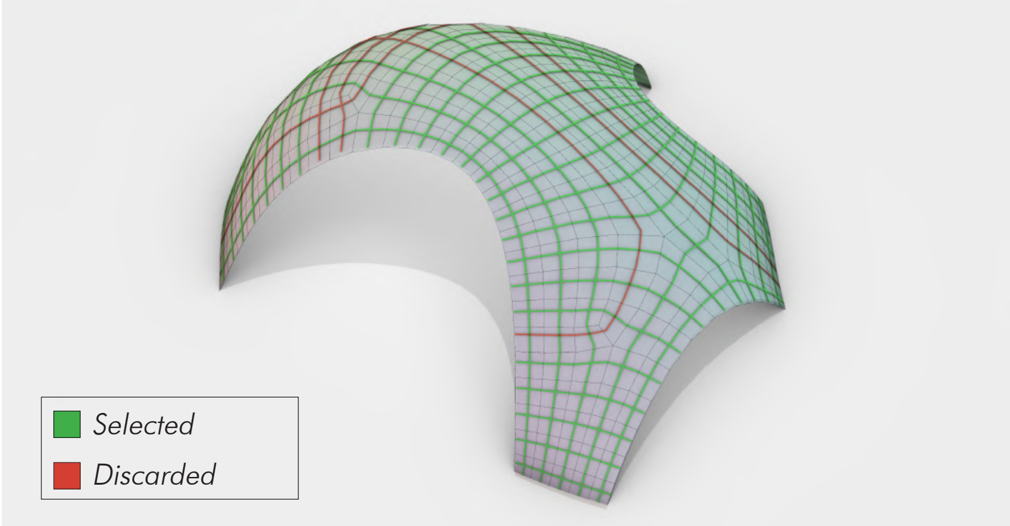
2. QUAD MESH



3. RIGHT PRISMS FROM FLAT QUADS



4. POST-TENSIONING PATHS



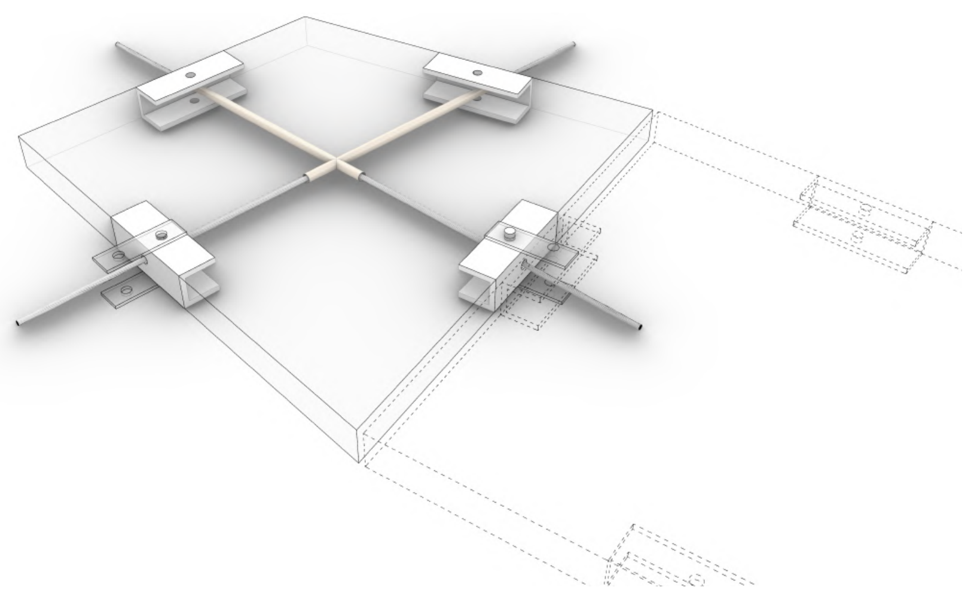
MODELING AND OPTIMIZATION

The adopted meshing guarantees contact at the midpoint of each tile edge. We incorporate C-post steel segments at these contact interfaces to avoid local failure due to force transfer. These steel components serve two other functions of (a) restraining the ducts during the fabrication of the tiles and (b) accommodating the connectors of the tiles in the assembly phase. All tiles can be prefabricated in the shop by means of an adaptable and reusable molding system. The mold walls can be altered to form any angle and edge length. Also, singular tiles, like triangles and polygons, can be formed with this system. Since the mesh faces are aligned with the principal stress directions, and the adopted detail enforces punctual force transfer, the tiles show a strut-and-tie behavior along the two crossing directions (the tile shear is negligible). Therefore, the structure can be modeled as a net of beams for optimization purposes. We model the cable effect as an equivalent load that can be superimposed on the results of a linear analysis under service load. Because of the linearity, the cable effect can be scaled by a factor (i.e., its pre-load). We select appropriate cables and their accompanying pre-load by formulating a bounded minimization problem:

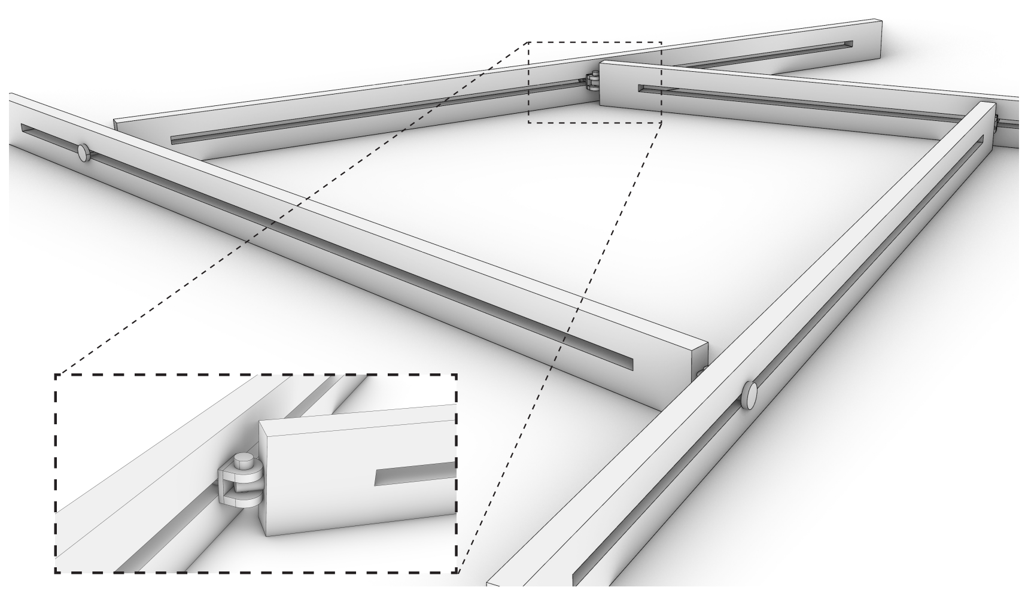
$$
\begin{aligned}
& \min(\Sigma f_t) \\
\text{s.t.}\quad & 0 \leq \Sigma f_t \\
& 0 \leq p_j \leq p_{max}
\end{aligned}
$$

In which Σf_t is the sum of tension forces among all beams, and p_j is the pre-load of the j-th cable.

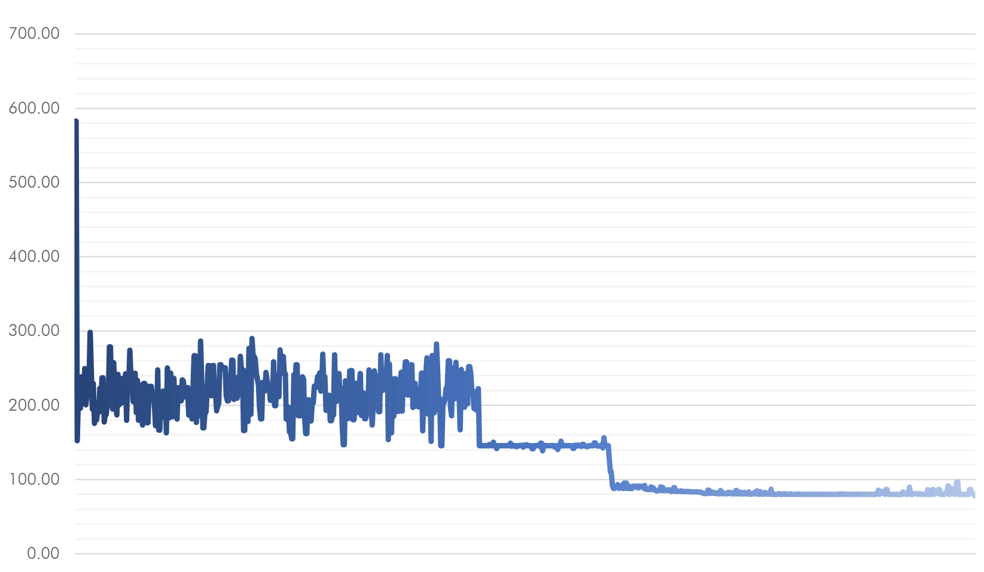
DETAILED DESIGN



ADAPTABLE MOLDING SYSTEM

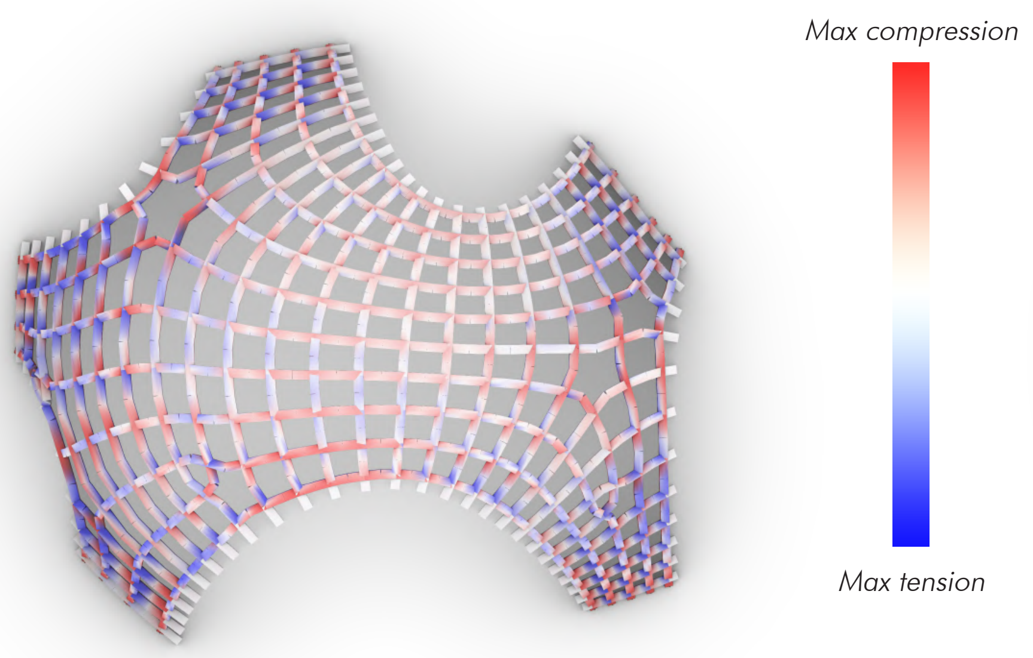


TENSION FORCE REDUCTION

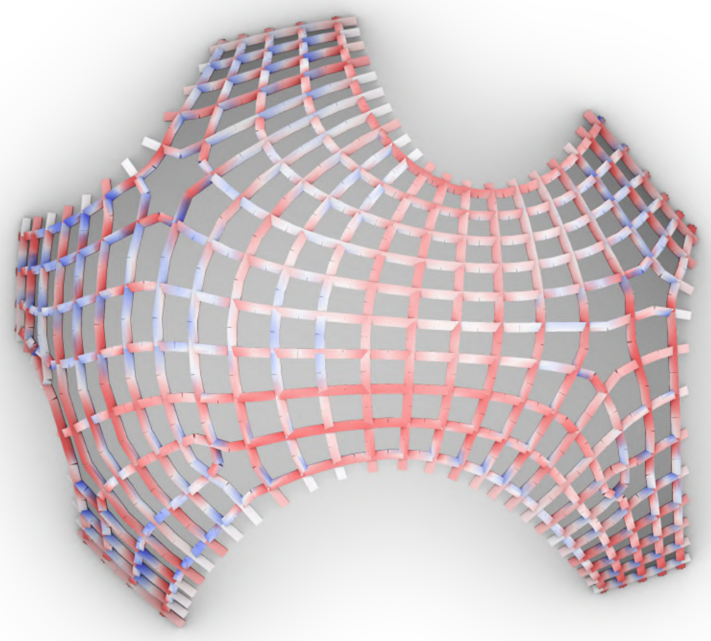


Optimization algorithms	CRS2 & BOBYQA
Pre-load range	0.00 to 50.00 kN
Max displacement (starting)	0.02 m
Max compression force f_c (starting)	35,30 kN
Max tension force f_t (starting)	8.06 kN
Sum of tension forces Σf_t (starting)	582.54 kN
Max displacement (optimized)	0.02 m
Max compression force f_c (optimized)	82.96 kN
Max tension force f_t (optimized)	6.86 kN
Sum of tension forces Σf_t (optimized)	78.07 kN

REDUCED-MODEL ANALYSIS



POST-TENSIONED ANALYSIS

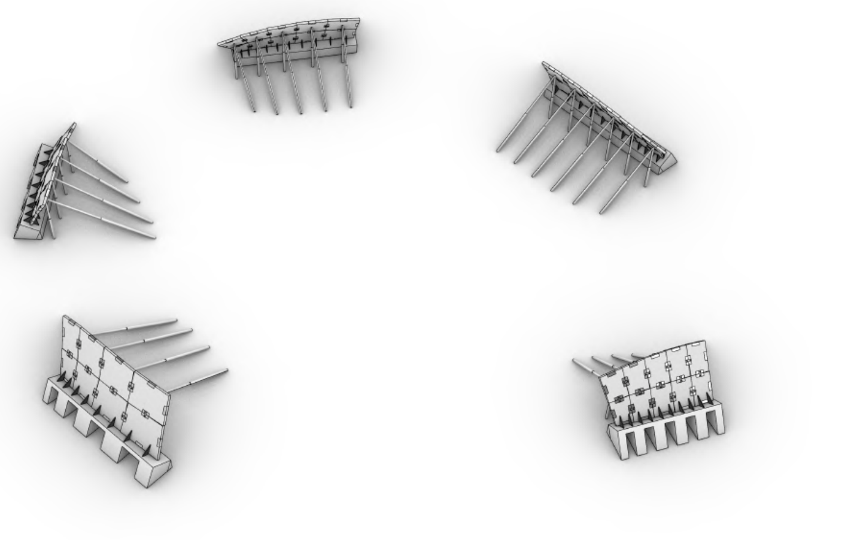


CASE STUDY DETAILS AND ASSEMBLY

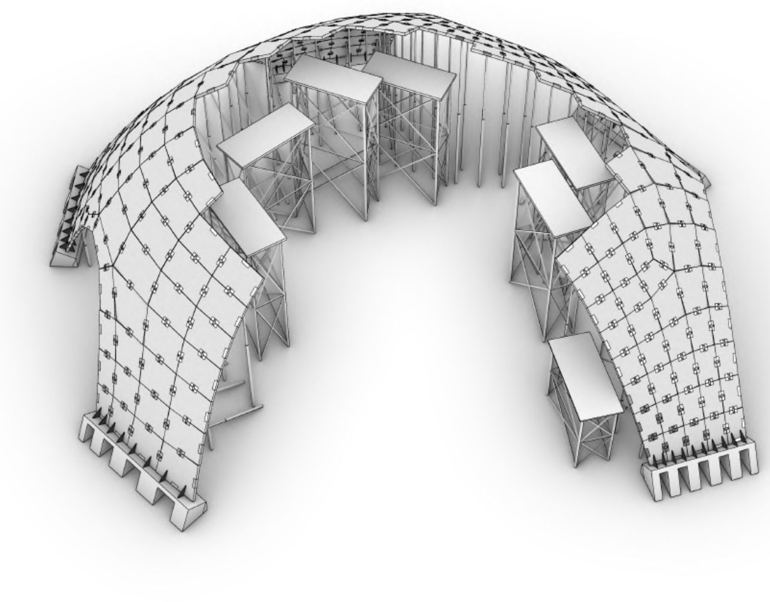
We tested our pipeline on a quasi-membrane shape with large openings and non-trivial structural behavior. Our service load is the sum of the structural weight and 1.5 x 0.5 kN/m². The reduced model analysis confirms the effectiveness of the meshing showing low bending moment and shear forces. The optimization leads to an impressive reduction of the tension on the elements. The pipeline results in a labeled set of tile shapes and cable segments, which are easily fabricable. The assembly requires a few temporary punctual supports to fulfill the stability of the tiles once they are sequentially moved to their target position. The shape's curvature and the connectors' anchoring between the tiles gradually favor the formation of stable patches. Moreover, the connectors can transfer both tension and compression. Once completed, the cables can be pushed into the ducts and post-tensioned from the boundary up to the desired pre-load. An in situ cast completes the outer surface of the structure. This cast embeds a fiberglass wire mesh. As a last step of our pipeline, we found a clustering method for the wire mesh, dividing it into flat patches having specific shapes and cuts so that these patches can be laid on the target doubly-curved surface without significant distortions or wrinkles. As an additional fabrication constraint for the patches, we impose to fit into commercial sheets of material. Simultaneously, the ducts can be grouted so that the cables can be effectively coupled with concrete and prevent steel corrosion.

Bounding box size	15.0 x 13.0 x 5.0 m
Total surface area	141 mq
Projected surface area	110 mq
Faces num.	269
Target tile edge lenght	1.00 m
Average tile edge lenght	0.70 m
Shell thickness	0.06 m
Average tile weight	67 kg
Total weight of the tiles	18 tons
Candidate cables num.	44
Selected cables num.	32
Total cables lenght	404 m
Cable diameter	0.008 m
Vertical load	2.96 kN/m^2
Total vertical load	418 kN
Concrete type	C25/30
Steel type	S275

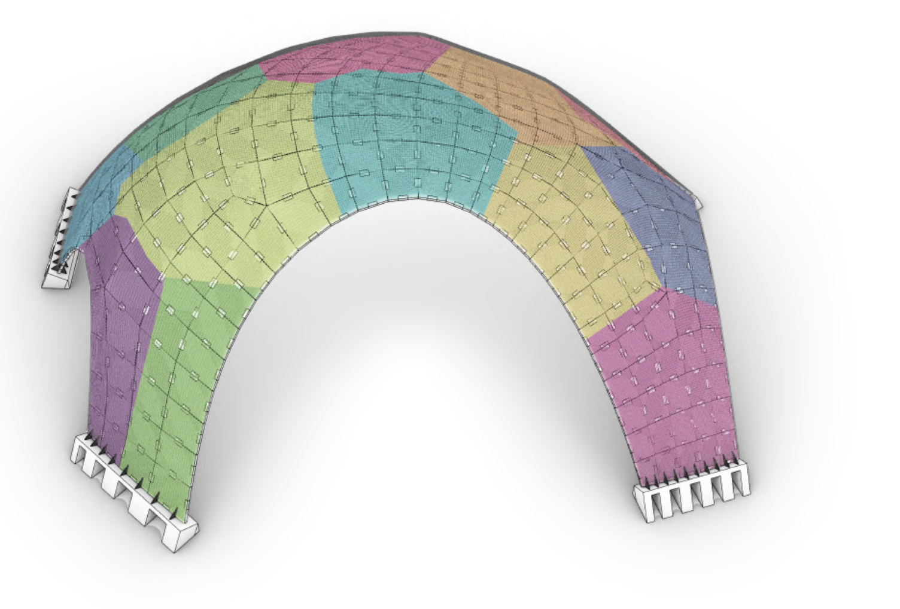
ASSEMBLY OF SUPPORTS



TEMPORARY SUPPORTS



MINIMUM DISTORTION CLUSTERING



FIBERGLASS PATCHES LAYING AND CASTING