

## Draped Stone: A Synclastic Tensile Canopy

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Draped Stone is a research project that uses stone in tension through fiber-reinforcement, producing a hanging marble canopy. The research is in collaboration with stone fabricator Quarra Stone in Madison Wisconsin as part of a Research Fellowship. The project is still in development and is currently the subject of multiple grants to complete the pavilion. The project submission represents the work in progress to date—with all the research and development—for a fiber-reinforced stone and an automated workflow for 5-Axis machining marble and laminating fiberglass to machined marble surfaces.

The form of the canopy is derived from a hanging mesh simulation that produces a catenary draped surface. A traditional tensile structure is produced by stretched a surface between two boundary conditions with opposing curvature, resulting in an anticlastic surface. For this reason, tensile structures are

formally very limiting in that they must always maintain an anticlastic surface curvature for stability.

The designed hanging canopy utilizes the weight of the stone to put the fiber-reinforcement into tension, allowing for a synclastic tensile structure. Typically, synclastic surface typologies are not possible with conventional tensile structures. The primary precedents for the project include—Siza Vieira, Álvaro. Expo'98 Portuguese National Pavilion. 1998, Lisbon, Portugal. and Saarinen, Eero. Dulles International Airport. 1958, Dulles, Virginia, U.S. These two projects represent a rare structural system in which a catenary surface is produced utilizing the incredible spans of tensile structures while not prescribing to the geometric language and constraints of a tensile surface. In both projects, concrete is used as a sort of ballast to put the cables into tension, therefore stabilizing the single negatively



Figure 1. Granite Wall Construction Process. Photo by Author.



Figure 2. Granite Wall Construction Process. Photo by Author.



Figure 3. Granite Wall Completed Assembly. Photo by Author.

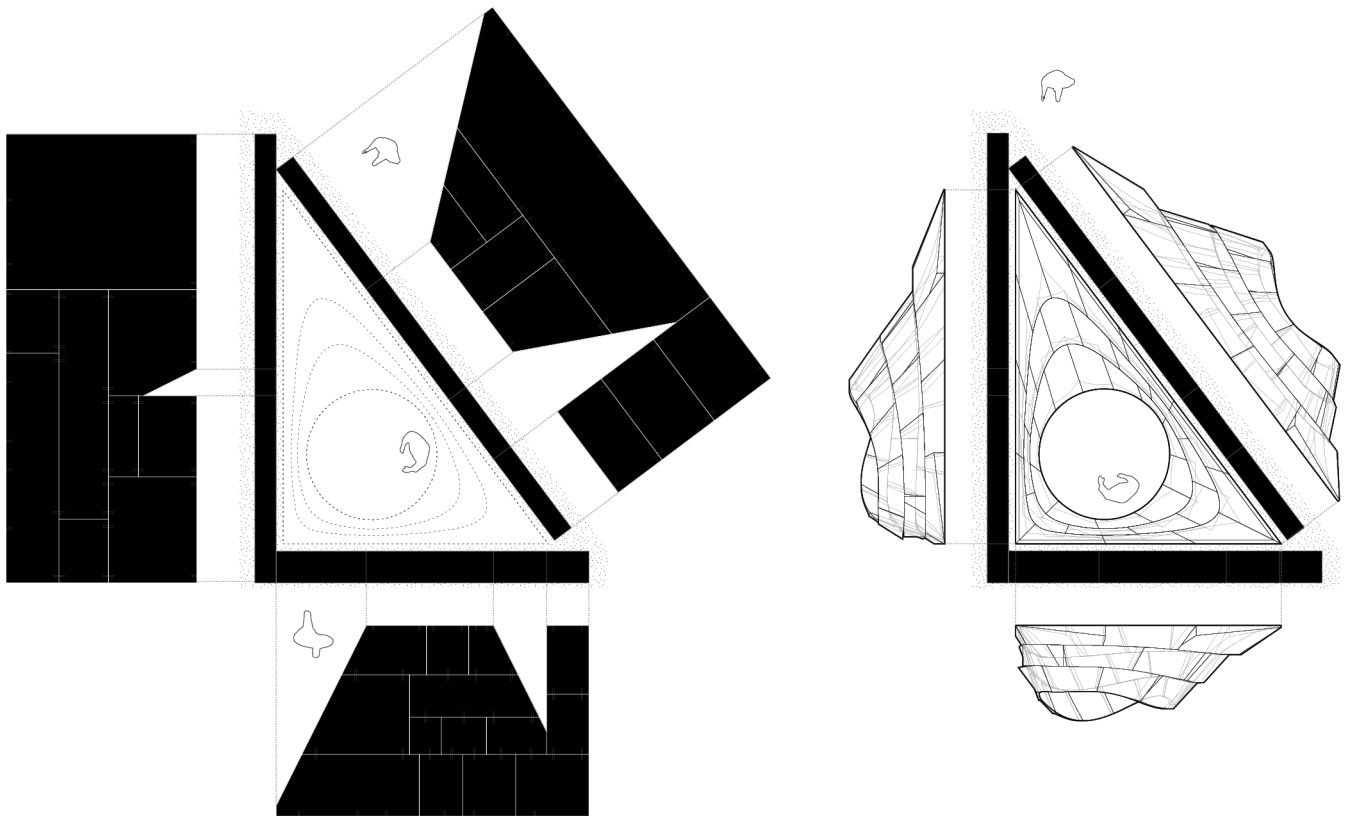


Figure 4. Granite Wall With Unfolded Elevations and Marble Canopy With Unfolded Elevations. Drawings by Author.

curved surface typology. Draped Stone builds on the structural logic of the Expo '98 and the Dulles airport by introducing a synclastic doubly curved geometry and by internalizing the tensile structure. Rather than steel cables with a concrete ballast, the project utilizes a sandwich panel of marble and fiberglass, where the fiberglass is continuous and used to transfer the tensile loads and the marble is used for its weight to put the fiberglass into tension and to stabilize the otherwise unstable surface typology.

Kangaroo 3D was used to simulate the catenary surface and to discretize the surface into bands made up of flat face units. To manufacture the units using the 5-Axis CNC one of the faces of the surface had to remain flat on the bed of the machine. For this reason, the canopy was designed with a smooth continuous interior surface and a rougher exterior surface made up of the various flat faces of the units. The flat face simulations allowed for the optimization of the material thickness and the manufacturing process. After many tests and iterations, the simulated mesh was discretized into 3 closed bands, resulting in 36 discrete units. For the canopy to be constructed without the need for scaffolding or falsework, each band needed to close in on itself, positioning the blocks in the correct location.

Each of the units is conceived of as a sandwich panel. The fiberglass reinforcement is in the middle of two doubly curved, machined, marble blanks. The machined surface is extracted

from the hanging mesh simulation and represents the pure catenary surface in the middle of the canopy. Each of the units is connected with small steel tabs through the middle layer of fiberglass, keeping the tension at the center of the blocks, never on the face of the marble. Pull tests were used to develop the connection detail between the units. The steel tabs are made of 1/8" steel plate and is located between the two layers of fiberglass mat.

The process for constructing the sandwich panels consists of first preparing the machined stone surface, then laminating each face independently. A three-way fiberglass mat was used as the reinforcement. The fiberglass mat takes the place of a more involved built-up fiberglass isotropic assembly of 5-13 layers of plain-weave fiberglass. The entire assembly is vacuum bagged at -29 In.HG to compress the assembly and remove access resin. The two halves were laminated separately in order to produce small pockets for the steel connecting tabs. Finally, Part A and B are then epoxied together.

The development of the lamination workflow evolved over many tests and iterations. The iterations consisted of varying amounts of fiberglass, different types of laminating epoxies, and different stones. The sample magazines were then load tested using a 3 point test to analyse the role the fiberglass reinforcement played in strengthening the stone.

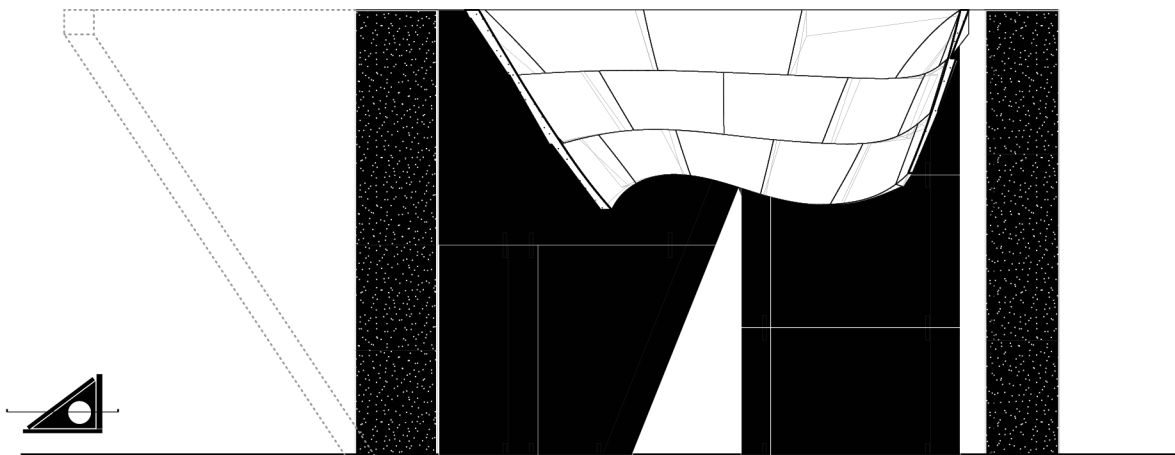
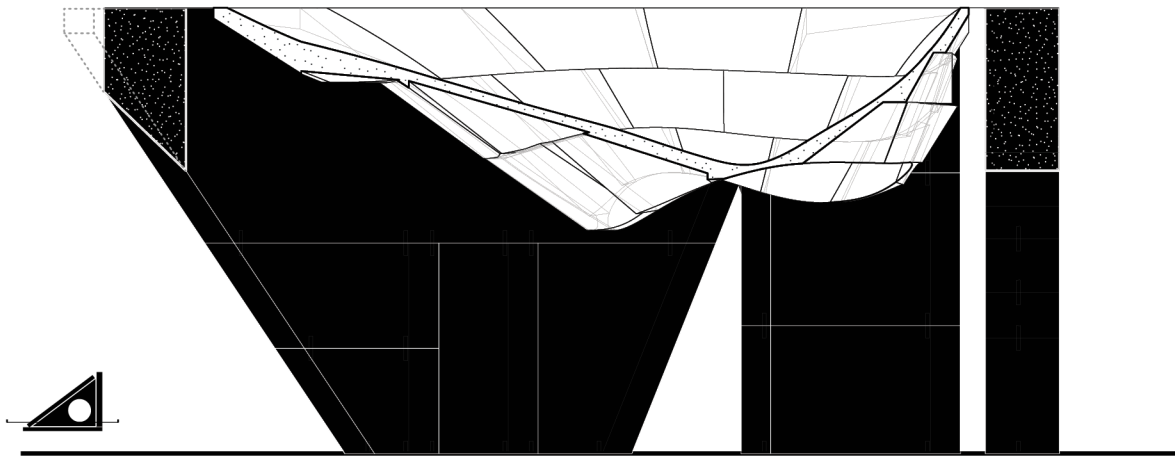
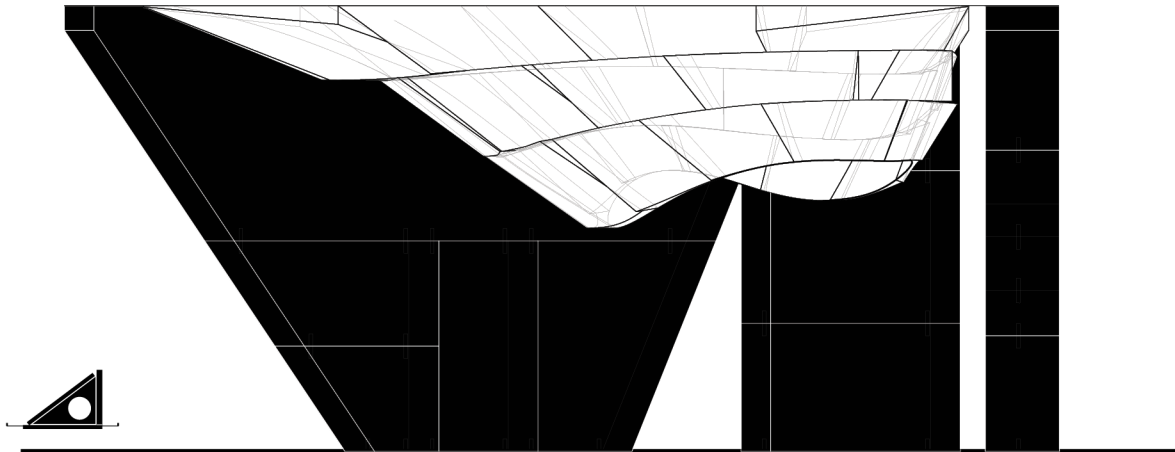


Figure 5. Marble Tensile Canopy in Granite Wall. Drawings by Author.

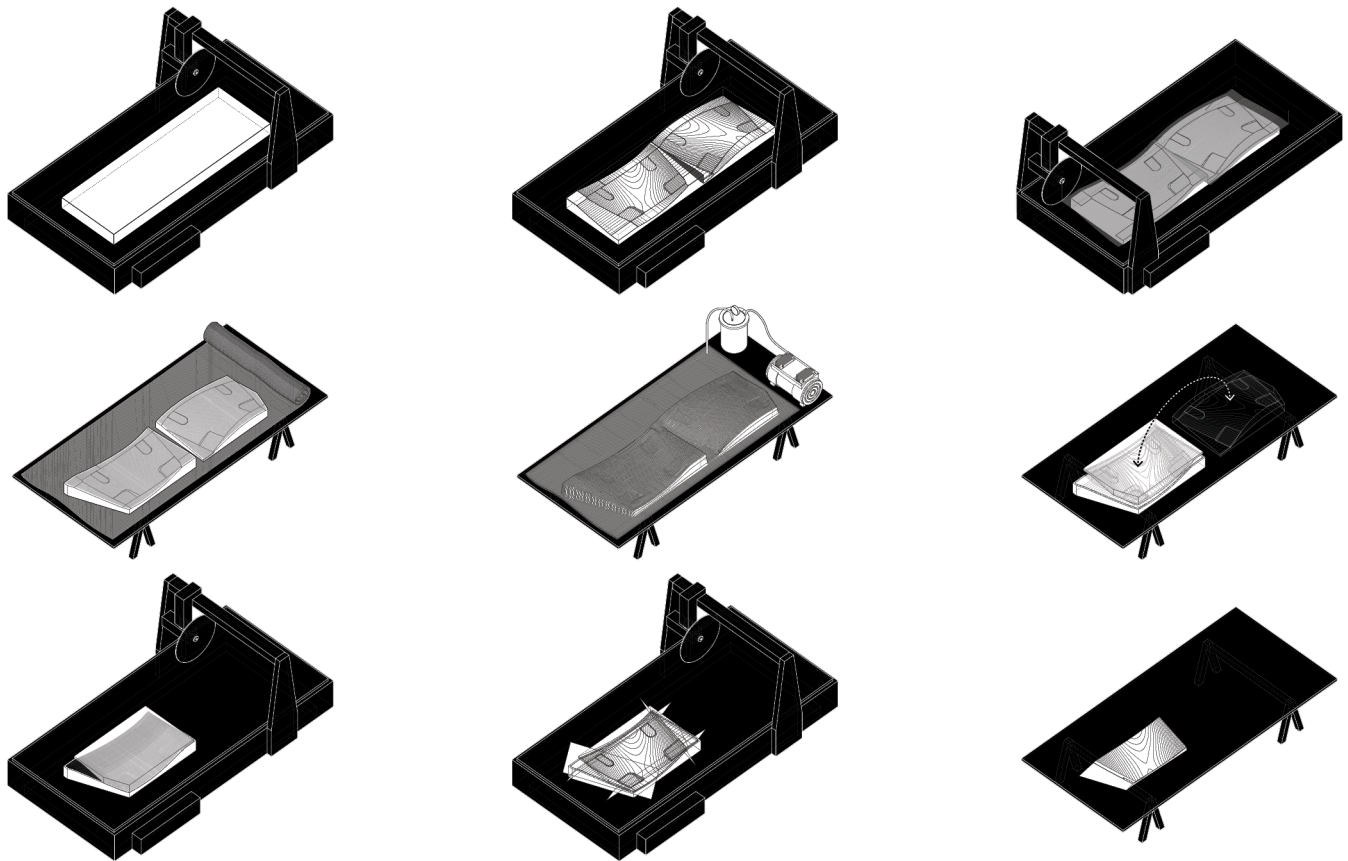


Figure 6. Marble Canopy Machining Process. Drawing by Author.

Because the marble was reinforced, the canopy was constructed entirely from scrap marble found at Quarra. Many marble blocks which otherwise could not be used because of fracture lines and other natural deficiencies, could now be reinforced with fiberglass and used in a structural capacity. The reinforced hanging canopy, which reads as precise, delicate, and thin, made from white marble and digitally produced, is held up by a dark grey granite wall, which is massive and rough, exposing the texture derived from the quarrying process.

The potentials for a fiber-reinforced stone, operating in tension is great. Typically, stone is used in smaller blocks that tie back to steel hat channels as a façade material. Stone, as a brittle material, has a thickness to span ratio that limits the way it is typically used. For stone to span further, it also must increase in thickness, limiting the possible application for the stone, due to the increased weight. New techniques for laminating stone to plastic or aluminum backers, has allowed for a more predictable and stable material, though still limited in size and reliant on a steel substructure for support. Projecting forward, the capacity to tension stone between floors offers several advantages to the existing systems. Firstly, the stone remains visible on both sides of the unit, rather than treated as a backer. This is particularly valuable for instances where the stone is used as a screen in front of a curtain wall system.

Secondly, being fiber-reinforced means the stone cladding would not require an elaborate steel substructure. Finally, the capacity to use stone in tension allows for a thinner stone surface and therefore a reduction in the material consumption.

Team—David Costanza, Alex Marshall, Rachel Henry

#### ENDNOTES

1. Siza Vieira, Álvaro. Expo'98 Portuguese National Pavilion. 1998, Lisbon, Portugal.
2. Saarinen, Eero. Dulles International Airport. 1958, Dulles, Virginia, U.S.
3. Faircloth, Billie. *Plastics now : on architecture's relationship to a continuously emerging material*. London New York: Routledge, Taylor & Francis Group, 2015. Print.
4. Bell, Michael, and Craig Buckley. *Permanent change : plastics in architecture and engineering*. New York, New York: Princeton Architectural Press, 2014. Print.
5. Campbell, F. C. *Manufacturing processes for advanced composites*. New York: Elsevier, 2004. Print.



Figure 7. Marble 5-Axis Diamond Blade Machining. Photo by Author.

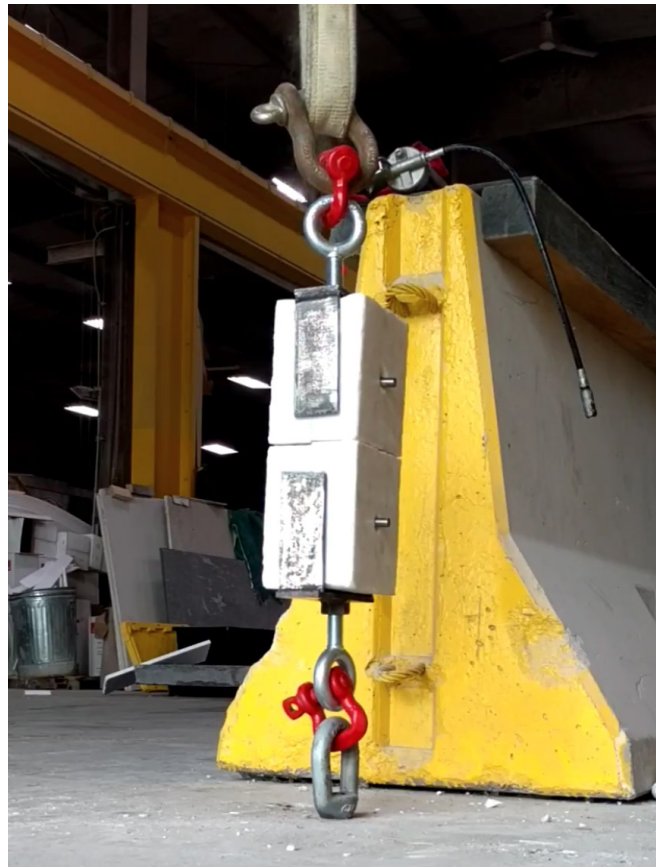


Figure 8. Marble Connection Pull Test. Photo by Author.



Figure 9. Marble Canopy Fiberglass Lamination and Vacuum Bagging . Photo by Author.