PURE TENSION: INTUITION, ENGINEERING & FABRICATION

The Design, Development & Fabrication of the Pure Tension Pavilion

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Abstract. The "PURE Tension" Pavilion is a lightweight, rapidly deployable, tensioned membrane structure and portable charging station commissioned by Volvo Car Italia to showcase the new Volvo V60 Hybrid Electric Diesel car. Officially launched in Milan, Italy in October 2013, this experimental structure was developed through a process of rigorous research and development that investigated methods of associative modelling, dynamic mesh relaxation, geometric rationalization, solar incidence analysis, membrane panelling, and material performance. It is an experimental structure that, similar to a concept car, is a working prototype that speculates on the potential future of personal mobility and alternative energy sources for transportation while also exploring digital design methodologies and innovative structural solutions. This paper will illustrate the design, development and fabrication processes involved in realizing this structure.

Keywords. Form-finding; dynamic-mesh relaxation; geometric rationalization; patterning, digital fabrication.

1. Introduction
The Pure Tension Pavilion was the winning entry of Alvin Huang’s team at Synthesis Design + Architecture (SDA) in the international design competition organized by Volvo Car Italia and The Plan Magazine to design a porta-
ble structure to showcase the launch of the new Volvo V60 plug-in hybrid electric diesel car. The proposal was inspired by the characteristics of the Volvo V60, a modern, flexible and sustainable vehicle with 3 modes of operation: power (diesel), hybrid, and pure (electric). Inspired by these three modes, the pavilion's form was defined by a continuous perimeter ring that touched the ground at three points, and arced upwards with a trio of corresponding apices (Figure 1).

Conceived as an extension of the legacy of Frei Otto’s seminal lightweight tensioned membrane structures where Otto looked to precedents in Nature to describe principles of stable minimal energy surfaces that could inform and ultimately find the equilibrium between unique form and form-found material, enabling efficient and effective structural performance. The continuous form of the pavilion was developed with a parallel process of analogue form-finding (physical models) and digital form-finding (dynamic mesh-relaxation techniques) to explore the pure tension of the interior membrane skin against the external flexurally-active boundary frame. A carbon fibre perimeter ring was to be bent into shape by the tailoring of the skin which bound it. In response, the frame would push out while the skin pulled in, creating a form-force equilibrium that would result in a structure that was lightweight, cost-efficient, and easy to assemble and disassemble (Figure 2).
At the competition phase the uniquely sensual and continuous form was to consist of a tensioned HDPE Mesh skin with embedded PV panels and a perimeter carbon fibre rod. The effect of the structure’s organic form, perforated mesh, and PV transparent panels provided a striking graphic identity to Volvo’s V60 model which would encourage visual and spatial interaction while simultaneously enabling different configurations to accommodate a variety of activities including: vendors, demonstrations, car trade shows. The proposal added another level of innovation by utilizing the pavilion as a portable solar-powered charging station.

2. Form-finding and Intuition

The "architectural" form-finding process in this project was two-fold: digital models to explore architectural form, and analogue models as proof of concept to test form against material performance. In both cases, the process enabled the application of basic engineering principals and material properties to develop an intuitive design process which could be manipulated to iteratively generate, test, and refine design options. Rather than using these tools to develop a scientific method to form find, they were used to help develop a design intuition to help guide the discovery of form in concert with design intentions. An exploration of the application of spring systems in Kangaroo was conducted to develop an understanding of the relationships between low-poly mesh topologies and their respective relaxed meshes. This exercise resulted in a catalogue of low poly models (Figure 3) which could be relaxed to replicate known minimal surface types, thus providing a visual...
guide to reverse engineering known minimal surface conditions. As a result, an intuitive "feel" for low-poly minimal surface translations defined a technique for exploring how to anticipate, model, and manipulate new minimal surface topologies which could be adapted for different design intentions.

![Catalogue of low poly to minimal surface translations.](image)

The following work flow defined the process of digital form-finding and design development:

- low poly meshes were modelled in Rhino to define basic topology
- low poly meshes were refined with the Weaverbird plug-in for Grasshopper to define a smoother refined mesh
- an associative model with parametric variability of the perimeter frame was defined in Grasshopper
- the perimeter frame was defined as the anchor points of the refined mesh
- the refined mesh was dynamically relaxed against the perimeter frame with Kangaroo
- the geometric definition of the perimeter frame was adjusted to fine-tune the form-finding results against the aesthetic criteria of the design team and the technical criteria of the client.
These digital models were then iterated through a series of physical models, made from bent aluminium wire and nylon fabric (Figure 4). A process was developed to tailor the fabric against the frame by unrolling and approximating the relaxed mesh topology. This process, though not accurate, provided insight into material properties of tensioned skin vs. the bending-active frame. The purpose was not to represent the geometric properties of the digital model, but rather a proof of concept regarding material performance in the digital model. The iterative exchange between the parallel digital and analogue models enabled a refinement of the design technique and perhaps more importantly design intuition, in terms of achieving desired effects.

![Figure 4. Physical models as proof of concept for tensile form-finding.](image)

### 3. Form-finding and Engineering

Early intuitive explorations in Kangaroo were then advanced through proper form-finding simulations, after which an elasticated analysis of the final form-found shape was considered; which accounted for the true material properties, both internal and external. The intent of this engineering analysis was to give a true performative engineering assessment of the structure in terms of strength, deflection, and actual installed pre-stress levels. To achieve the required installed aesthetic of the form requires all of these structure performative drivers to be hit accurately. This was facilitated by the speciality structure engineering team at Buro Happold Los Angeles (BH-LA). The mode of operation at BH-LA was to use bespoke digital plug-ins and processes within the Grasshopper plug-in to rationalize the form-found digital model produced by SDA, to a digital format acceptable for use by the ad-
vanced tensile structure engineering program NDN\textsuperscript{2}. The following key performative engineering drivers were set by BH LA to be met:

- **Internal Pre-stress Regime:** The structure can resolve imposed forces internally only through in-plane pre-stressing tensile forces. This requires two boundary limits to be met; the lower extreme where under no external load, the in-plane stress should be above zero to ensure non slack areas which could lead to “wrinkling of the fabric”, an undesirable aesthetic, and an upper extreme where the increase in-plane stress under an imposed load should be less than an allowable limit placed on the minimum breaking strength of the material. A suitable internal pre-stress regime has to be found that lies within these boundary limits.

- **External Boundary Stiffness:** The internal load path is resolved at the boundary by aluminium arch members. These members resist the loading through a combination of flexural and compression stiffness. The members must have enough material to ensure that the stiffness is suitably high to ensure the fabric does not go slack, and the required internal pre-stress regime load path can be met in practice.

- **Geometry:** The form-found shape developed requires a non-uniform internal pre-stress regime. It is not a minimal surface where an internal pre-stress regime is constant in all directions.

- **Fabrication:** The direction of the seams – the warp direction of the fabric lies in the direction of the seams – influences the geometry and the internal pre-stress regime. Warp stresses lie parallel to the warp direction, fill stresses are orthogonal. Seam lines have to be sufficiently spaced and aligned so that any excessive curvature can be accommodated by the single curvature of the unfolded fabric cutting pattern.

An atypical form-finding approach was adopted due to the extreme non-uniform internal stress regime of the fabric required to achieve the desired aesthetic. After rationalizing the geometry from a suitable layout of seam lines and fabric panels, the surface was immediately elasticated and allowed to relax (Figure 5). Large areas where the fabric is essentially slack became apparent. The typical form-finding approach is to form-find non elastically to equilibrium, that is, elastic stiffness of the material is not accounted for until a form-found equilibrium shape is found purely geometrically for user defined pre-stress values in different directions that do not change with the geometry during form-finding.
From the base line, a feed-back loop was established whereby the pre-stress regime found at the end of the form-found elasticated approach was used as the starting pre-stress values for subsequent form-found runs until the final elasticated pre-stress regime was within the upper and lower boundary limits set by the user, and the form-found geometry had not deviated excessively from the desired theoretical form-found shape.

4. Form-finding and Patterning

The pavilion's solar powered capabilities are made possible by the 252 lightweight flexible photovoltaic panels, embedded within its skin. The distribution panels is integrated in a graphic pattern of vinyl tiles along the mesh. This pattern is the result of Ecotect analysis to define areas of greatest solar incidence. As the pavilion would travel and specific site and sun orientations are not known, a compiled solar incidence analysis was conducted for 360 degrees of orientation over 8 hours a day and 365 days of the year on any given site in Italy (Figure 6). However, due to the multi-directional form of the pavilion the generated pattern placed solar panels pointing in multiple directions, and solar arrays are only as powerful as their weakest link. To resolve this a MPPT (Maximum Power Point Transmission) controller was utilized to sample the output of the cells, and selectively disable those that are not collecting enough energy, thereby ensuring that the pavilion is receiving as much charge as possible in any given orientation. The pavilion is able to generate about 450 watts of power on optimum sun conditions, which can recharge a fully depleted car battery in about 12 hours.
5. Form-finding and Fabrication

With the solar pattern informed by Ecotect Analysis, integrated with the NDN informed membrane panelling, the focus shifted from digital to physical. Major hurdles to be addressed were time and budget. To reduce costs, significant savings were made in the production of the perimeter frame through two considerations. First was the shift to an aluminium pipe systems with a swaged slip-fit assembly. The second was the rationalization of the freeform geometry into 5 rational arcs, thereby reducing the cost and time of the CNC pipe bending (Figure 7). Whereas the digital design of the skin was able to produce a fluent form, the precision of that form was enabled by a high level of handcraft applied to a highly empirical process of physical form-finding and adjustments. Digital geometries were physically recreated to identify seam locations, connection details, and the integration of the photovoltaic panels. The 3D mesh topologies were exploded into non-uniform quadrilaterals to allow for the digital mesh to become successfully unrolled into hundreds of "quilting" tiles that were then cut from the CNC fabric cutter. Tolerances were built into each tile so that sewing adjustments could be made on the 1:1 scale mock-up.

Following the erection of the perimeter frame, the tiles were sewn together and stretched onto the frame in two mirrored sections with zippered connections and spandex sleeves to wrap the frame. Areas of slack were identified and tailored to eliminate slack. The photovoltaic panels were produced in tandem with the production of the re-engineered mesh skin. The photo-
voltaic panels were attached to the skin via a substrate of a scaled-down series of "quilting" tiles cut from black vinyl. The photovoltaic panels were then wired together in parallel and it’s appendages fished through and concealed by fabric "conduits" along the perimeters of the "quilting" tiles.
6. Conclusion

The experimental nature of this project was dictated by parallel explorations into form, performance, and craft through months of design refinement, research, and engineering. Digital design technologies have been harnessed not only to create an iconic design piece, but also a vision for the future of transportation and an intuitive method for designing tensioned membrane structures.

Figure 9. The completed Pure Tension Pavilion.

Endnotes

2. NDN Membrane software by Martin Brown: martinbrownmanly@hotmail.com

References
