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Shape Finding or Form Finding?

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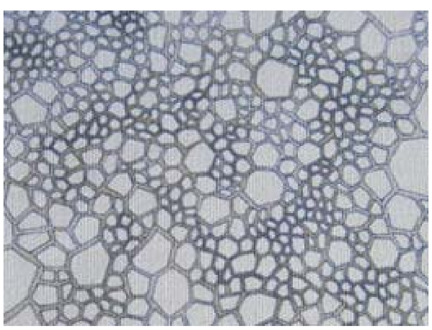
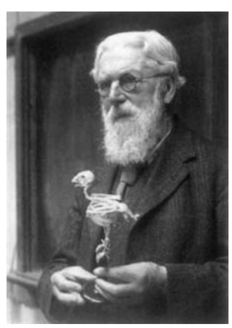
Abstract
This lecture will discuss the differences in the design process between a shape finding and a form finding approach. It will examine historical traditions of both approaches and look at these methods in today's design world. Examples of the work of FTL will be used as descriptive case studies to illustrate the different aspects of membrane envelopes including ETFE foil cushions, tensile membranes, and cable nets.

Keywords: *building membranes, acoustics, environmental, soap films, biomimetics, form-finding, shape finding, lighting, ETFE foil, PTFE glass, Frei Otto*

In the 18th century, naturalists started a movement which arose from a desire to understand the "universal laws of form" in order to explain observed forms of living organisms. Although it didn't have much traction at the time, during the early 20th century pioneers such as D'Arcy Wentworth Thompson expanded these notions to create a modern understanding that there are universal laws which arise from fundamental math and physics and that reflect the growth and form in biological systems. Thompson worked on the correlation between natural forms and mathematical models and showed similarities between such things as jellyfish forms and drops of liquid. His book, On Growth and Form became an important way finder in the study of nature and the instrumental in the later emergence of the field of biomimetics[1].





By understanding Thompson's correlation between natural systems, forms & structures and inherent definable rules, the appreciation of natural systems has become a growing field of interest. Patterns in nature follow simple mathematical formulas. Soap film studies have given us insights into minimal membrane structures, bee hives have given us a developed understanding in honeycomb structures which are now used in lightweight panel systems, and an understanding of photosynthesis has helped developed photovoltaics to become a major sustainable energy source. We have observed as swarms and schools of fish instruct us in the development of dynamic structures. In urban planning, we have even seen the study of non-planned settlements where cultural, social and external constraints allow settlements to develop incrementally as a result of actions and reactions as first documented in Bernard Rudofsky's, From Architecture without Architects[2] and later with the Institute of Lightweight Structures' publication, Non Planned Settlements [3].

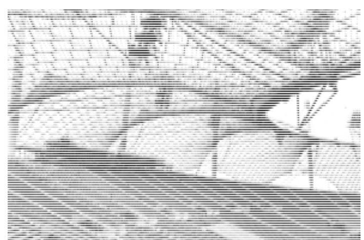
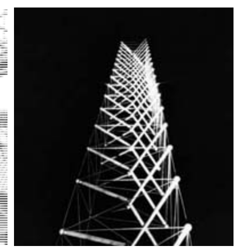
Traditionally in the architectural design process, there is an underlying belief that the design process is a rational linear one (which it isn't) and that the architect is somehow acting like God the creator (which he isn't). This traditional approach fosters more a shape finding design approach based on personal visualizations rather than a form finding one, where natural systems are based on processes and coordination arises out of interactions between components of these initially disordered systems.

In the Form-finding process, the designer looks at processes in nature to uncover ways in which to organize his or her building project. It is a study into the capability of discovering optimum form & dynamic adaptability. The beauty of the form does not have to be designed; rather it becomes an emergent property from the developed natural forms.

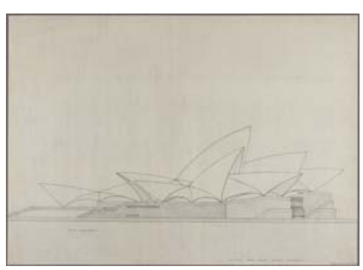
Structural optimization techniques for complex curved surfaces driven by new structural systems, digital fabrication techniques, interaction between tension structures and shaping elements and upgrading methodologies of "Form follows Force"[iv] structures with a permanent focus on life cycle thinking. As Frei Otto said, "the architect is more acting as a midwife than God the creator" using the form-finding process.

The work of Felix Candela in Mexico, Pier Luigi Nervi in Italy, Frei Otto in Germany and Bucky Fuller in the US serve as historical examples of this form finding approach to architecture which we can see below. Examples are Candela's High Life Textile factory in Coyoacun, Mexico City in 1955 consisting of concrete hyperbolic parabolas, Pier Luigi Nervi's Palazetto dello Sport in Rome for the 1960 Olympics using a curved ribbed thin shell concrete dome, Frei Otto's Olympic Stadium in Munich in 1972 using a steel cable net with acrylic panels and Bucky Fuller's tensegrity structure using discontinuous struts and cables.



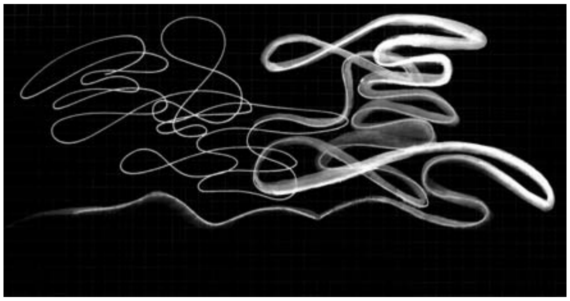



A clear example of the different two approaches (shape finding and form finding) is seen below in two images: the first is a soap film model of Frei Otto used for understanding the shape of a conoid form for a tensile structure which he used in his design of inverted umbrellas. The second is a drawing from John Utzon's initial design of the Sydney Opera House, where he generated the curved shapes by using a steel ruler in a bench vise. The soap film model shows a minimal surface where all the tension is equal across the entire surface. This minimal surface translates directly into a tensile structure with no fabric wrinkling and equal stresses throughout. The drawing of Utzon is an organic shape that looks efficient but actually is in bending and took massive amounts of engineering manipulations to realize these unique shapes into a built form. Ove Arup and his firm which engineered these concrete shells treated it as a problem solving exercise in a traditional architect/engineer relationship, although through their problem solving, Arup was able to develop the use of epoxy resins to bond thin joints of pre-cast concrete units[v].

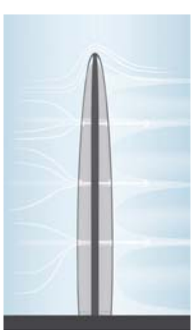
In this shape finding context, today we see the notion of shape finding using formal concepts and sometimes algorithms for shape analysis which are classified under various criteria, whether they examine boundaries or the whole area, they describe the original picture in terms of scalar measurements.

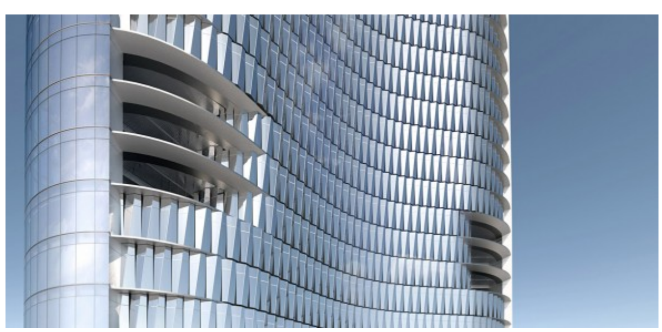
The work of Santiago Calatrava and Zaha Hadid are contemporary examples of the shape finding approach. Below is an example of a sketch by Hadid where she describes the concept her project, the Spiraling Tower in Barcelona as 'shooting in from outside the frame, the thread winds itself loosely into a semblance of a structure'. The sketch is then loosely translated into a series of building slabs which weave around a core like the thread in the sketch as seen below. It's a deliberate incremental design process which can yield visually dramatic forms, but contains limited embodied intelligence of physics and structural optimization as these elements are applied late in the design process.




We also see in Calatrava's work a fascination with the bird as an inspiration on several of his projects. Projects such as the Walker Art Museum shown below take the visual forms of an open wing and translate it into a building brise-soleil with a wingspan of 217 feet that unfolds similar to a bird. During the day it shades the building and at night it folds back to cover the building. Here the feather is not analyzed, but rather abstracted as an icon and reinterpreted as a building element.


In contrast to this approach, the work of the firm Adrian Smith Gordon Gill Architects who are responsible for many of the world's tallest towers are required by their enormous scale to harness a form finding approach. The Wuhan Greenland Center in China schedule to be completed in 2016 is a 119 story tower of about 300,000 sq meters. The overall form is based on aerodynamic wind modeling, minimizing surface flow on the glass building skin. The tapered body and rounded corners with domed top reduce wind resistance and vortex action that builds up on super tall towers. This allows minimizing the structural material required. Apertures in the curtain wall assist in venting wind pressure against the tower as seen in the diagram below. They also house window washing systems and air intake and exhaust systems. It may well be that the scale of project requires a form finding approach rather than shape finding as super tall buildings become much more dependant on building physics requiring large teams to organize all the discordant information into a synthesized building design.

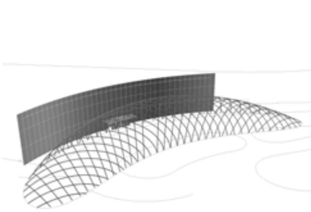
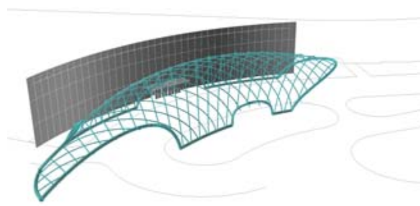
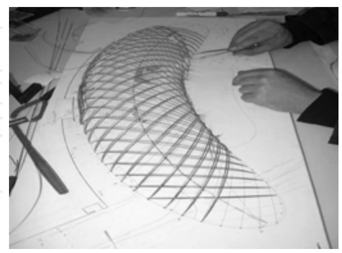




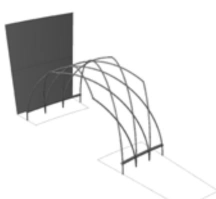
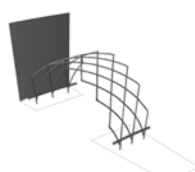
FTL's approach over the past 35 years has been one primarily in developing a form finding rather than shape finding approach in the development of innovative structural enclosures including grid shells, cable nets, tensile structures, and inflatables to achieve architectural spaces that inspire. I will discuss a few of our projects as case studies of permanent structures showing the exploration of the form finding process for three different technologies. This includes a new ETFE foil cushion casino entry building just outside of New York in Yonkers, a new campus center for Arizona State University's Scottsdale Campus using a tensile structure, and a cable net facility in Sun Valley Idaho. I will then show a couple portable projects some of which are designed using form finding and some designed with shape finding approach.

The design parameters for the Yonkers Casino Porte Cochere were to act as an entrance to casino, to provide rain protection for 30 cars, and to become a lighting element as icon for the casino. We worked in collaboration with Studio V Architects who were also responsible for a new addition to the casino and racetrack.

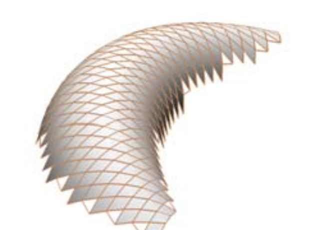
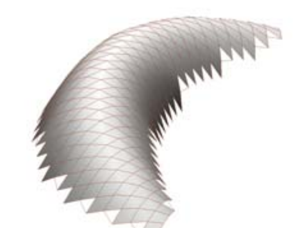
Using a partial toroid form as an initial surface to be carved away, we developed the form of a lattice shell which uses the same curvature throughout as shown below. We worked both in a digital modeling format and in a physical modeling approach, each showing different aspects and highlights.

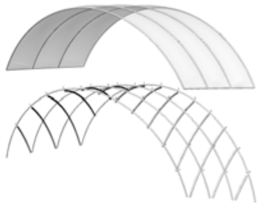
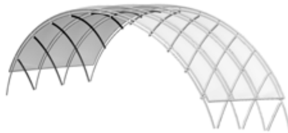
We then looked at different grid meshes, first one which showed the least amount of steel possible and then one more rectangular which the client preferred as shown below.

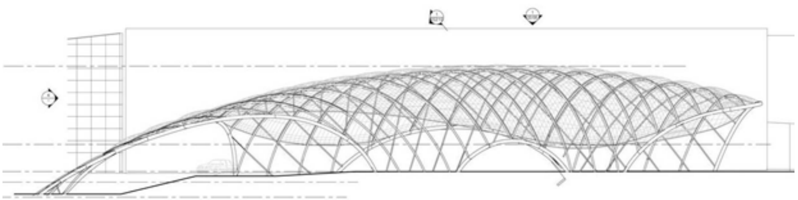
Next we examined the surface as both a pure toroid and as an inverted catenary hanging surface. Although the steel sizes were able to be reduced by 25%, the grid had become an element net made of straight components changing the design form considerably as shown below. We opted to stay with the rolled tubes, especially since they were all a single radius, saving rolling costs.

After locking in the shape, we began to look at the pillow cladding system which became much more efficient as a series of pneumatic strips rather than as defined diamond shapes, saving on inflation tubes, gasketing, etc.

From this point we were able to run analysis and size and detail all parts.



Next came the development of the lighting with the Architect and the lighting designer Susan Tillotson. The approach here was to illuminate the foil from above which was unique, but in order to do so, we had to have a solid frit on the ETFE foil material. However, we didn't want to loose the transparency of the material, so we opted for a solid silver frit on one side of the pillow which then fades to clear by the middle of each pillow. This provides both a reflective surface for the LED lighting and transparency underneath the structure vision through the structure. We made a mockup of the lighting at the fabricator's shop to better understand this effect as this is the first time an overhead lighting was used on ETFE foil pillows as shown below.


Steel was completely prefabricated off site and each piece was tested to fit in the shop before shipping to site which allowed for a clean and tight fit on site. Foil pillow extrusions were attached and the prefabricated foil cushions were installed and pressurized. LED lighting was then installed and tested for color range and connections.

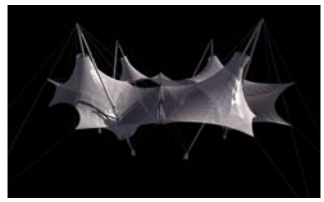

The final form of the structure reflects a manipulated geometry reflecting a synthesis of diverse arrays of competing systems each striving for an optimal form.

The second project is a tensile structure project which employs a very different set of geometries to create a central campus space at the new Scottsdale campus of Arizona State University outside of Phoenix, Arizona. Here with a very dry hot climate, shading and evaporative cooling is an important for the enjoyment of outdoor spaces which are useable almost the entire year.

We were approached by the renowned architectural firm, Pei Cobb Freed about a competition for a new campus in Scottsdale for ASU. The idea of a 'ramblas' similar to shaded streets in Barcelona was the architect's first idea. As the concepts developed, the covered space became a central court in the campus with both vehicular and pedestrian access.

We were intrigued by the notion of a shade system that was able to bring a sense of motion and life to the fairly low desert campus. Inspired by the rotational forms such as Matisse's 'La Dance', we worked with the notion of a 'rotational geometry' rather than a reflexive geometry so as to pervade the space with a sense of movement. We began to develop a shade structure that could cover the inside corners of the plaza by using a series of tensegrity trusses as shade extenders, since the fabric would not normally reach the inside corners. By deploying a series of tensile cone shapes both inverted and normal, we were able to create a considerable curvature to the form of the structure as shown below. Each field incorporated both cones in counterpoint with each other as seen below.

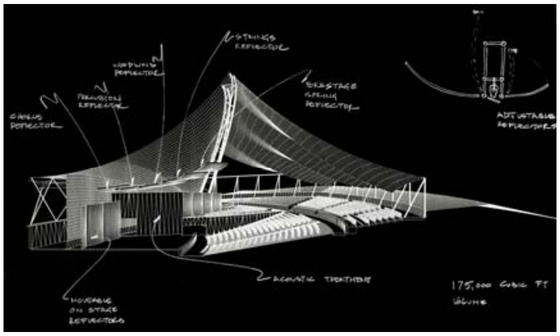


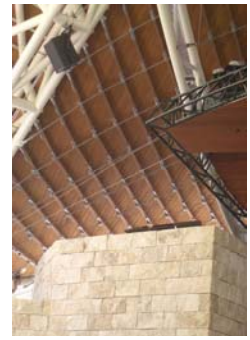



Again both physical modeling and digital modeling were used simultaneously to understand the form, curvature and loading. Using a series of A-frames which straddle the vehicular roads and serve as portals to the central space, they became the compressive support elements for the entire structure. The corner trusses are supported and stabilized by cables which attach to the plinths on the plaza.



Besides the membrane providing about 80% shade, in the evening the lighting of the membrane is done with both LED lighting in a blue color on the A-frames and white HID lighting on the fabric surfaces.
The third project in the Sun Valley Idaho, we were given a site in the Rocky Mountains which was a large open site surrounded by a crown of mountains and asked to create to a open air classical music amphitheater. We wanted a sense of openness surrounding the facility to preserve the mountain views yet simultaneously preserve a sense of enclosure of the performance space. Using a series of stone walls as the site organizing elements, we created a seasonal facility that had a small footprint in the winter covering the stage house and support facilities and a larger footprint in the summer when the facility was in use. Here the form finding process came out of a series of acoustical elements, including the required volume of the interior space and the shape of the ceiling and roof structure which could project and blend sound. The hypar or saddle surface has a unique quality of being able to reflect and blend sounds of percussion, strings and woodwinds. For material choices we used a wood shell for acoustics which we supported by a steel cable net and be able to resist the high snow loading of winter (2oo lbs per sq ft). Over the audience, we developed a tensile fabric membrane as the seasonal cover, with all the steelwork remaining intact during the winter. The end result was a building form which imitated a musical instrument and received great reviews from both the orchestra and musical critics.



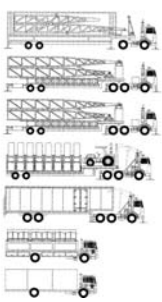


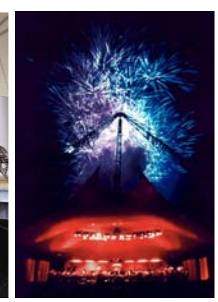
In portable structures, the notion of form finding takes on a new reality due to the requirement that the structure is required to fold up and move. This moving process eliminates many options that are possible with permanent buildings and sets a heightened level of constraints. The American designer, Charles Eames once described this approach that he observed in the circus setup…

"Everything in the circus is pushing beyond the limit….within this apparent freewheeling license, we find a discipline that is almost unbelievable. There is a strict hierarchy of events and an elimination of choice under stress, so that one event can automatically follow another. The layout of the circus under canvas is more like the plan of the acropolis than anything else; it is a beautiful organic arrangement….there is a quality of beauty which comes from the appropriateness of a given situation…The concept of appropriateness, this "how–it-should-be-ness" has equal value in the circus, in the making of a work of art, and in science."[vi]

This concept of appropriateness in design is in essence a reflection of the self form finding design process. It demonstrates "the elimination of choice under stress" as Eames calls it.

An example of this design process as it relates to portable buildings is a project that we designed a few years back. We were asked to develop a portable opera and music pavilion for the Metropolitan Opera and NY Philharmonic that could travel to all the parks in NYC for over 20 events per year. The result was the Carlos Moseley Pavilion which was a completely mobile; six custom semi-trailers carry the entire facility to any open performance site. Designed to be set up in six hours with minimal impact on the fragile park locations, this traveling music pavilion had no precedents. The trailers included a self-contained foundations for the pavilion and operable booms required for deployment of the facility. The Pavilion's pyramidal open truss structure incorporated a translucent fabric shell, a 40' x 78' folding stage, computerized lighting system, video projection screen and a distributed sound system employing twenty-four wireless remote speaker towers.



The basic design approach to the project was to allow the engineering of the mechanism dictate the forms and geometry of the structure. In order not to create arbitrary architectural compositions, it was desirable that the steelwork be permitted to express its essential character. This approach also held true for the fabric membrane in that it took its shape from the reflective acoustic requirements and the need to provide cover for the stage. The architectural poetry was to be found in the proportions and the relations of these elements to each other. In so doing, the design became a mixture of architecture, industrial design and engineering thereby raising the question: when is a structure a machine and when is it a building?

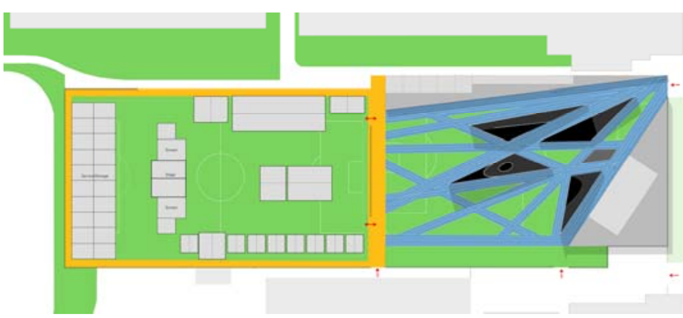
Seven semi-trucks carry the entire facility to any open site. One trailer is for the stage and rear truss, two trailers are for the structural trusses, one truck for the fabric and lighting, one trailer for sound towers, one truck for electrical distribution and one truck for props. The center trailer contains folding beams which open to provide a 40' x 78' structure for the stage. On the same trailer, hydraulic pistons unfold hinged panels which serve as the stage surface. In its final position, the stage rests upon the two front corner trailers and the two rear corner cabs, and the entire assembly is joined together to form one continuous rigid structure.

The two hinged structural trusses on the front corner trailers are unfolded to their full 86' length and are attached to the rear truss. As the rear truss unfolds itself utilizing the hydraulic hinge, it also raises the two front masts into their final position. The hinge at the rear mast is then mechanically secured, and the resulting tripod structure has its apex 70' above the ground.



The translucent fabric acoustical shell is then unfolded on the stage and corner connection points are fastened to the four corner tractors before the membrane is raised to its pre-stress position by means of a winch. The overhead lighting truss is assembled on the stage below the fabric and is lifted with hoists into position. A forklift with special balloon tires designed for minimal impact on the turf places each of the twenty-four speaker towers around the site. On-stage reflector panels are installed, lighting and sound are checked, and stage props are positioned. Six hours after the trucks have arrived on site, musicians are ready for rehearsal in the facility. After the performance, the whole facility is struck and loaded back onto the trucks, to be driven away to another site where the whole process will be repeated for the next performance.

A project where we developed a portable facility using a shape finding approach was the NIKE Pavilion we designed for the 2012 Olympic Trials in the US. The client wanted to show a sense of speed with iconic shard like elements which evoked movement frozen in place. Working with local architects in Portland, we developed the design to accommodate the form of these slipping shards (see below).

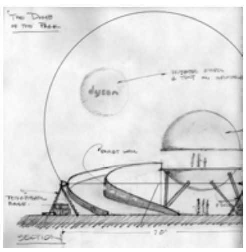


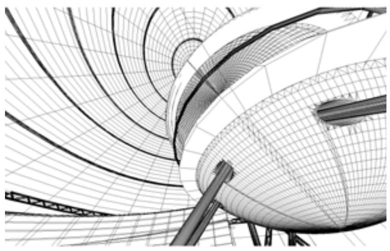
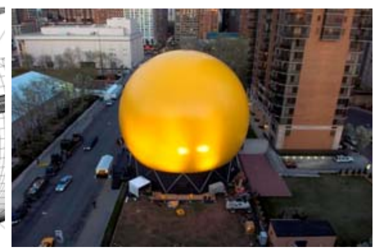

The site was the University of Oregon running track which had an artificial turf field, so we had develop a ballasted foundation system using plywood flooring to cover the field. The fabric was designed as a quick install lace system using flat panels with a very high translucency fabric giving about 60% translucency inside the pavilions. The fabric was not optimized for fabric stresses or developed for minimal surfaces, as the look of the shards was the primary design element. Here a shape finding approach was used which produced a unique geometry different than if we had used a form finding approach to the design process.




In contrast to this project, we completed a project for the Dyson vacuum cleaner where we were able to use a form finding approach instead of shape finding. The Dyson Company wanted to showcase their new vacuum cleaner product the DC-15 with an event launch. This product uses a revolutionary ball instead of wheels to drive the vacuum cleaner which allows for much sharper turns in the vacuuming process.

FTL in collaboration with Event Quest, developed a ball concept as an air supported inflatable structure held down by a steel tetrahedral ring. The tetrahedral frame created an eight foot double wall service zone which housed electrical distribution, air handling equipment and fabric sacks filled with water from NYC fire hydrants were used as ballast.




Entry into the structure began with a lightweight lattice portico which joined onto the tetrahedral frame and opened into a large 85 foot diameter dome shaped space where the exhibit began. The exhibit continued along a curved ramp which ascended a full floor until one reached a spherical geode which contained a small cinema. The cinema showed a 360 degree film about the new product.

Using pneumatic technology, the entire structure was assembled on site at Lincoln Center in three days. The event and subsequent exhibition continued for four days and the structure and exhibit was dismantled in two days. By using double skin fabric walls on the first floor, a clean exterior and interior space was maintained. Generally in portable buildings, the exterior space is filled with the services such as temporary power and HVAC. The water ballast allowed the installation to occur without a single permanent attachment to Grade.

Here the pneumatic force inherent in a vacuum cleaner became the form generator, a pure sphere using inflatable single skin technology. The interior space was experienced by a gentle ramp which sloped up to the theatre pod inside the sphere. The exhibit of Dyson vacuums was a pneumatic experience.

Form-finding in Architecture looks at processes in nature to discover a more correct way in which to organize building. It is a study into the capability of discovering optimum form, dynamic adaptability, and exposes a set of unique relationships not normally relevant to architecture. The beauty of the form does not have to be designed, rather it is an emergent property of natural systems. However, the wonder lies not only in the aesthetics, but also in the manner in which forms come into being seemingly without a plan, at a multitude of scales, and in a vast array of materials. Pattern in nature opens a vast array of potentialities for the study into new methods of architectural design. When possible, we use this form finding approach, but as shown good design can often be driven by a more shape finding approach.

"The lesson in the airplane is not primarily in the forms it has created...the lesson of the airplane lies in the logic which governed the enunciation of the problem and which led to its successful realization." Le Corbusier [vii]

References

[1] Biomimetics was coined by the American inventor Otto Schmidt and first used in 1974 as the imitation of the models and systems of nature for the purpose of solving complex human problems
[2] Rudofsky, Bernard; Architecture Without Architects, Museum of Modern Art 1964
[3] Schaur, Eda; Non-Planned Settlements, IL 39, Institute for Lightweight Structures 1991.
[4] "Form follows force" is based on the notion of the form of a building is an optimization of the forces acting on the structure
[5] Jones, Peter; Ove Arup, Masterbuilder of the 20th Century 2006
[6] Quote from 100 Quotes by Charles Eames 2007
[7] Le Corbusier, Vers Une Architecture, Lesson 2, 1923