Pneumatic Form

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> pneu·mat·ic *adj*. 1. Of or pertaining to air or other gases....4. Filled with air, especially compressed air: *a pneumatic tire*....5. *Zoology*. Having air cavities, as the bones of certain birds....7. Of or pertaining to pneuma; spiritual.[1]

When Buckminster Fuller referred to his geodesic dome as a pneumatic structure he was offering not a description but an analogy. Unlike most pneumatic structures, a common tire for example, the domes did not depend on compressed air for their stability. However, like a tire, the geodesic dome was conceived to carry load by diffusing it across the surface of the form. As in true pneumatic structures, geodesic structures handle applied loads by an overall Poisson effect; an "inversion" of stresses that turns, for example, a compressive (gravity) load into a tensile "hoop" stress spread through the triangulated structural network.

1) PNEUMATIC MACRO-FORM

Truly air-supported""buildings" come in two varieties that are sometimes mixed. In their simplest form these structures are constituted of simple surfaces supported by an excess of internal pressure. This condition, which in itself is not unusual in buildings, requires constant maintenance when the integrity of the structure is at stake—the constant monitoring of airflow into as well as out of the building, including that lost by leakage, opening and closing of doors, etc. In order to be buoyant, the membrane surface needs to be light and strong. Until recently, this has meant that the membrane was also relatively primitive, and limited in its application to severe and changing climactic conditions. For these reasons air-supported structures have had rather limited application. They have, for the most part been used for primarily for special applications such as recreation facilities and transportable shelters. Recent innovations in the membrane material, including improvements in solar and insulating performance, has suggested their use for more demanding and permanent applications including, for example, in OMA's winning proposal for the Los Angeles County Museum of Art.

The second type of air-supported is closely allied to the first, but uses air-inflated ribs to provide some nominal degree of stability. Each of these ribs is, in itself, a sort of a box beam where the surface tension of the air pocket negates the danger of buckling, allowing for a true membrane stress condition in the beam shell. As so-called "air-beam" technology these structures have, like geodesic domes, have enjoyed the attentions of the US Military.[2] Light, demountable and quickly erected they are well suited to transport as well as short stays in severe climates. Their mobility is directly linked to their draconian sense of efficiency; in their own way each of these structural types comes as close as possible to LeRicolais's limiting maxim of "zero weight, infinite span." For similar reasons this type of structure has also found a lasting application in pool rafts and inflatable boats.

Although Philip Johnson once remarked that it is impossible to put a door in a dome, the really architectural "problem" with these forms is not either formal irresolution or the bad fit with societal norms. The problem has to do with the shape of the bubble; the round shape of the dome that is always the same, a singular form that eludes architectural language. The""problem" is visual and spatial monotony or, in a word, boredom. To overcome this sense of boredom we must try to see these structures for their directness rather than their efficiency. Efficiency is marked by measurement against an arbitrary standard; in the case of the engineer's efficiency, this is means material resources. Efficiency cannot generate of form, and it is only one measure for value. Directness, on the other hand, is related to a palpable transmission of forces. In air-supported structures this is obvious in the transparent relationship of form to the buoyant internal force, in their thinness and frailty, and their almost subjective "reaction" to the environment. This sort of immediacy can be seen as one of the principles behind pneumatic structures: it generates form.

2) PNEUMATIC MICRO-FORM

The third type of pneumatic structure stems from the use of foams. Foams contain air at the micro- or cellular level. Air may be introduced by either chemical foaming agents or through mechanical intermixing, forming either an open- or closed-cell foam fabric. In open-cell form, the air plays an intermediate rather than permanent role, filling-out the fluid matrix before it becomes rigid or sets. Foams have been made from a wide variety of materials, including organic compounds, plastics, metals, and ceramics.

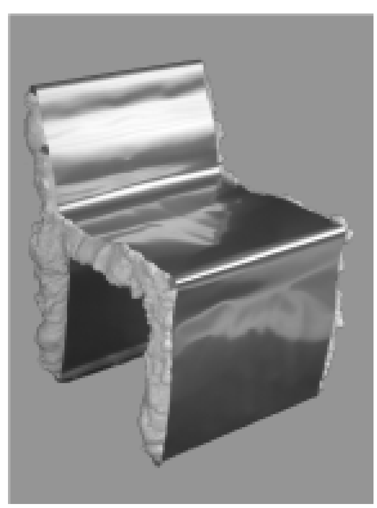
While there is a close relationship between foams and their parent materials, there are also significant differences. Because much of the volume is air, foams are relatively light and naturally good insulators. Although not as strong as the parent material, the filigree structure of the matrix makes them still strong, and also tough. They may be either stiff or pliable and carry load—true to Fuller's pneumatic analogy—by distributing it through a diffuse matrix, although not entirely through membrane stresses. Foams are not exotic to either the building industry or the field of product design. Common examples include insulating board, furniture cushions, and spray foam insulation.

3) REIFIED PNEUMATICS: MACRO- AND MICRO-FORM

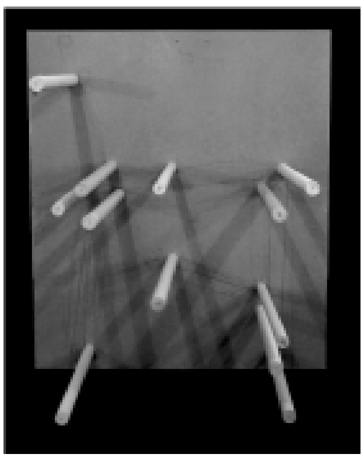
Foam-inflated structures combine the micro-pneumatics with macro-pneumatic to create large, lightweight, permanent structures. One such technology uses a resin-impregnated skin which, after inflation, hardens into a stiff and durable shell. One of the uses for such systems is in space, where large, lightweight structures need to be constructed with a minimum of effort from small transportable packages. Recently some researchers have looked at the feasibility of such structures for low-cost housing.[3]

Technically speaking, foam-inflated structures cure to become stress-skinned structures. Whatever the configuration, the primary stresses are carried in the relatively strong surface elements and the foam core manages secondary and connecting shear stresses of a web element. The shell enhances the strength and durability of the foam, while the foam supports the shell and, as in most pneumatic structures, prevents it from buckling. This allows the strength of the shell to be used nearer the limits of its capacity. In building construction, one common example of such an element is the so-called facade "sandwich panel" that combines waferboard faces with an insulating foam core. The resulting assembly is not only well suited to the needs of common wall and roof construction, in a finished state it is virtually indistinguishable from stud-infill construction.

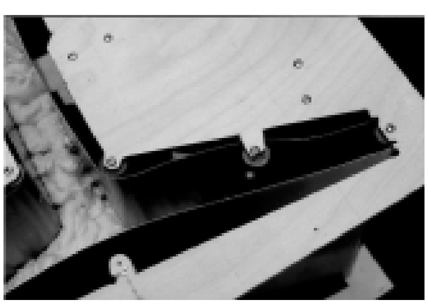
One of the motivations for the first project came from the desire to understand and modulate, rather than control, the nature of a foam-inflated form. The idea of foam-inflated furniture came from the observation that (a) a stress-skin structure could render a light and strong form and (b) that the expansive nature of the foam might be utilized to provide some of the complexity of form denied to traditional materials such as wood. Furniture is a good platform for testing ideas; it is as simple or as complex as any built object. Furniture, as Charles Eames said, is "architecture you can hold in your hand."[4]



A chair was chosen for the prototype. To begin to render it as a stress-skin object, the shape of the chair was considered to be an extruded shape. The simplest interpretation of this is was to use one of the orthographic views of the object. The simple, iconic, side-elevation was chosen because it, exclusively, renders all of the necessary elements. From this point of departure, the form was reduced to a system of control points and indexes governing the final form. Around these points the surface was drawn, considering that, when inflated, it would belly-out between these points.



Prototypes were made with a skin of 0.019" anodized aluminum flashing material. Since the skin is very thin, the foam in its cured state provides the stability, strength and toughness to the finished piece, which incorporate a center wood stay to facilitate the deposition of foam. The open ends of extrusion are to be capped with a polymer coating. The completed prototypes sit with the solidity of a heavy chair but weigh only about 6 pounds. They are made of inexpensive materials and, although they a handmade, they employ almost no handiwork.

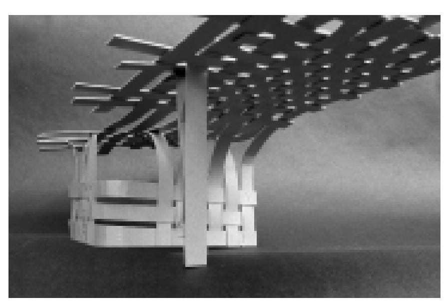


4) EXTENDING PNEUMATIC ANALOGIES

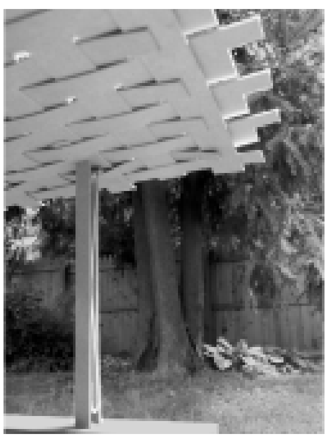
With few exceptions, Fuller's domes were never dependent on compressed air for their formation or their stability.[5] However, during the baroque phase of dome-making, Fuller translated the geodesic concept into assemblages of plastic shells and bent plywood. These systems, which in comparison to the refined space-truss assemblies of the early domes must have been considered bastard systems, actually come closer to being analogous pneumatic structures. There are a number of reasons for this. First, loads in these structures are carried by surface elements whose strength is more a matter of their configuration than their inherent materials properties. In other words the surfaces, which are shaped to form the dome, truly act as membrane or shell elements. Second, the configuration tends to "shake-out" the load based a combination of in-plane stress and flexural displacement. This is especially true of the plywood domes, where surface elements, bent into position, are already under stress.

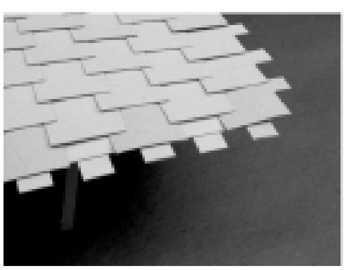
The second project, for a small pavilion, is closely allied to this work. The concept was to create a "strong surface" similar to that of the plywood dome, but without the hemispherical form. The idea was to create the surface from woven plywood elements, adapting the configuration to provide the cover and enclosure. Woven forms are, as Frank Gehry's recognized in his confrontation with the "peach basket," are inherently strong and flexible. They are also unusually adaptable. Baskets, for example, routinely incorporate both flat sections and curved 3-dimensional forms without any contradiction or breakdown in technique.

The first studies for using a woven structure looked at exploiting the continuity of elements inherent in a basket structure, "turning it over" and opening it up to create wall and roof elements.

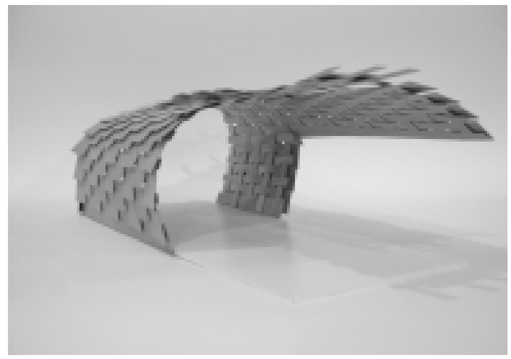


The next studies attempted to overcome one of the obvious inadequacies of architectural basket-making: the open lattice structure. This was achieved by conceptually separating the nature of the boundary into constituent functions. Roofs and walls may need to protect against moisture, water, and air infiltration, but for many purposes, only the blocking of air and the shedding of water need to be treated directly at the outer surface. This is, of course, the principle at the heart of the rain screen facade. Typically considered in the context of large buildings, these systems utilize, behind the outer layer, an internal membrane and structural support. However, in the case of this pavilion there seemed to be no need for the internal membrane and this simplification allowed for the rethinking of the relationship between structure and surface.





The system that was designed was a synthesis of a basket weave and a shingled surface—at once, both structure and surface. Its complexity suggested, at least initially, returning to a more generic level of investigation. Isolating the flat surface, the system was tested using structurally using finite element analysis. The initial model, using beam elements for the plywood strands, showed too-large deformations. However, later models including plate elements and pre-stress loads indicate better results. Actual deformations can be expected to be even smaller owing to member interaction. The assurance as to the viability of the system has prompted continued experimentation with the forms, in which the warped and bent geometry are allowed to arise from within the material itself.



While these systems may not yet be architecture, they do say something about architecture. Gottfried Semper's theory of architecture[6] proposed that the supporting structure, or frame, and the roof be taken as one unit; that the infill wall elements, including the signifying potential of their ornaments, derive from the legacy of textiles. In Semper's scheme, woven elements were used to fill in the spaces in the frame; these elements along with the roof provided enclosure and protection from the weather.

One of the qualities of Semper's theory of architecture is the fluid and transformable treatment of the elements that are, nevertheless, considered to be fundamental constituents to architectural form. The wall surfaces covered with ornament such as mosaic and relief can be seen as the coalescence of the desire for a durability and meaning in one architectural surface. The project for a woven structure can be seen as an extension of this attitude, transforming the categories of both structure and infill wall—along with their ornaments. Following the example of textiles, the woven structure takes a linear element and transforms it through repetitive interweaving into a space-defining surface. The process of aggregation brings out one of the hidden characteristics of the material—not only its mechanical properties such as strength, but the qualities of its origin, cultural valuation and, of course, the impact of its form. A parallel argument could be made for the application of stress-skin, foam-inflated principles to a small chair.

An interest in pneumatic structures fills virtually the entire first volume of Frei Otto's treatise *Tension Structures*[7] and functions as the groundwork for the more applicable, and adaptable, discussion of cable and non-pressurized membrane structures in the second volume. Otto seems to think through material and material phenomena towards particular forms in application. This, along with his boundless interest in his topic, prevents these volumes from being simple studies in engineering. Still, interaction with material phenomena should not stop at the level of a structural investigation, but extend to all levels of perception and significance evident in the results. The small projects presented in this paper attempt to walk a line from technical innovation to life experience: this takes them out of the realm of material science and places them in the realm of architecture. As "experiments" they are atypical and do not offer complete solutions to the problems of building. Current technologies provide the means to build on an unprecedented scale, under all sorts of conditions, and to meet almost any variety of needs. The exploration of alternative techniques cannot and will not compete with such methods. It will have limited results. Where such experiments will lead, no one can tell. What we do know is that as more and more architects incorporate project-driven material research into their work, the field will, for the immediate future, continue to expand.[8]

NOTES

[1] *The American Heritage Dictionary of the English Language*, New College ed., s.v. "pneumatic."

[2] See for example, *Timothy Anderl,* "Researchers Make Shelters Lighter By 'Blowing Them Up'" (ASC-01-2178). *In* "Breaking News", *Air Force Research Laboratory (AFRL) Materials and Manufacturing Directorate, Airbase Technologies Division (MLQ). http://www.ml.afrl.af.mil/news/mlq-0004.html* (No date; perhaps circa 2001.)

[3] Van Dessel, S., Chini, A., R., and Messac, A., "Feasibility of Rigidified Inflatable Structures for Housing,""*ASCE Journal of Architectural Engineering*, Vol. 9, No.1, 2003, 1-10.

[4] Charles Eames, interviewed by Digby Diehl in "Q&A Charles Eames,""*Los Angeles Times WEST Magazine*, 1972, 16. Reprinted in Digby Diehl, Supertalk (New York: Doubleday, 1974). Cited in Beatriz Colomina, "A Name, Then a Chair, Then a House,""*Harvard Design Magazine*, Fall 2001, 35. Prof. Colomina cites the many architects of the 20th-century for whom the design of a chair was a significant aspect of their career.

[5] Exceptions include the Manhattan dome project, a tensile-stressed lattice dome, and the surface panels used in the so-called "pillow domes." Fuller also used in a least one case a pneumatic scaffolding to erect a dome. Most of these are cited in Frei Otto,"*Tension Structure, Vol. 1*, pages 11, 87, 115, 166 (see note 7 for full citation).

[6] Gottfried Semper, *The four elements of architecture and other writings*, trans. Harry Francis Mallgrave and Wolfgang Herrmann (Cambridge [England] ; New York: Cambridge University Press, 1989).See also Rosemarie Haag Bletter, "On Martin Fröhlich's Gottfried Semper,""*Oppositions 4*, 1974, 146-153.

[7] Otto, Frei, ed., D. Ben-Yaakov and T. Pelz, trans. *Tensile Structures*. Cambridge: MIT Press, 1973. First published in English translation, MIT Press, Vol. 1, 1967, Vol. 2, 1969. First published as *Zugbeanspruchte Konstructionen*, Frankfurt: Ullstein Verlag, Vol. 1, 1962, Vol. 2, 1966.

[8] See for example, Toshiko Mori, ed. *Immaterial¿Ultramaterial: Architecture, Design, and Materials.* (New York: Harvard Design School and George Braziller, 2002).

All images by author.