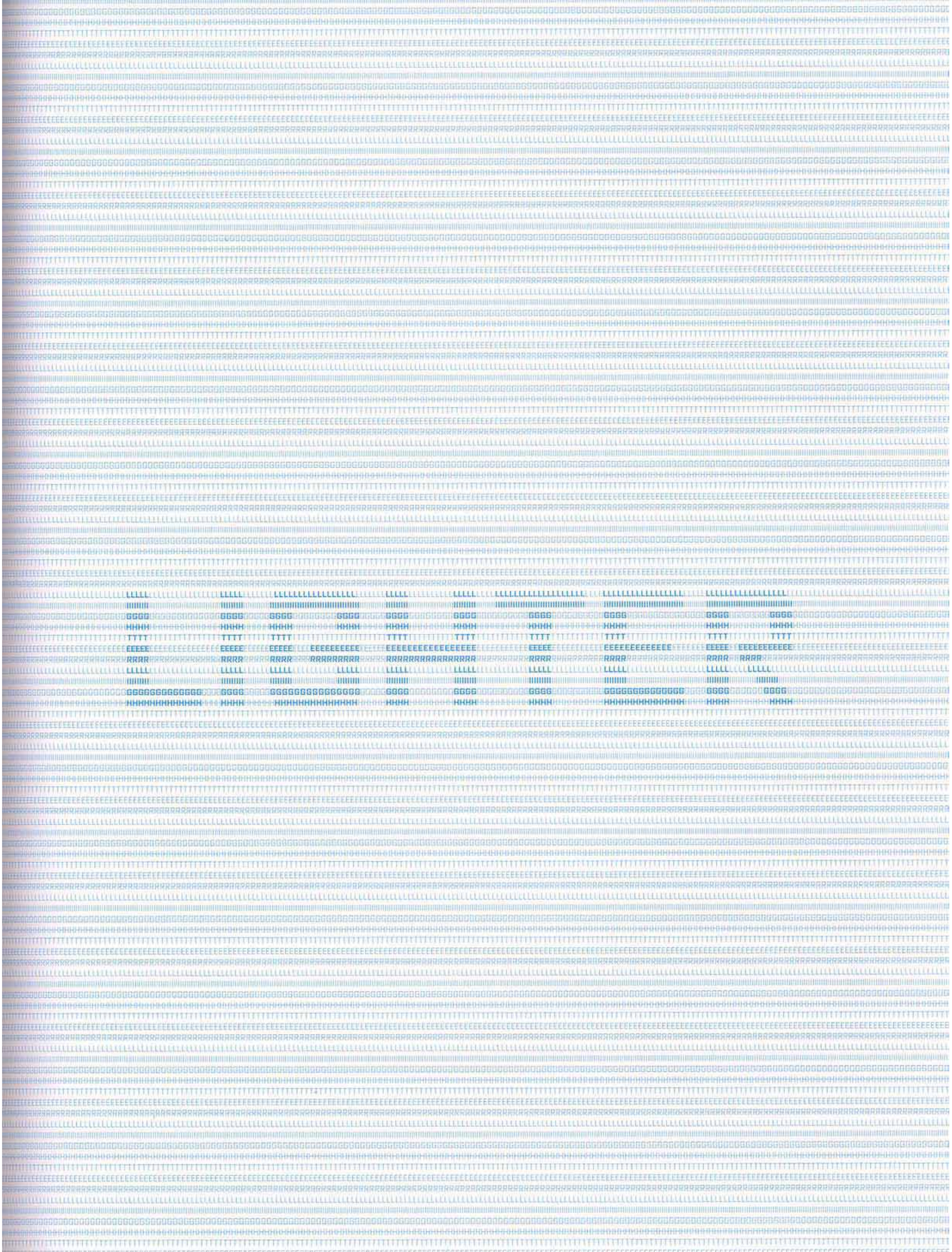
EXTREME TEXTILES

DESIGNING FOR HIGH PERFORMANCE

Matilda McQuaid



LIGHTER

fig. 1
Cladding detail of Swiss Re Headquarters
Foster and Partners, architects;
Ove Arup and Partners, engineers
England, 1997–2004

The mullion system is organized as continuous structural strands placed on bias, providing bracing for wind loads.

Philip Beesley and Sean Hanna

A TRANSFORMED ARCHITECTURE

A new generation of giant-scale textiles is at the core of a revolution in architecture. Soft textile foundations are fundamentally changing the way we think about our built environment. Textile-based building concepts range from flexible skeletons and meshwork skins to structures that move and respond to their occupants. These structures replace traditional views of solid, gravity-bound building with an interwoven, floating new world.

In a 1913 drawing published in *Scientific American* magazine, Harvey Wiley Corbett imagined a city that dissolves into a complex of layers: buildings, bridges, and roads rise up to the sky and stretch deep underground supported by airy lattices made of steel frames and meshworks (fig. 2). Just a few years after Corbett, the eminent American architect and engineer R. Buckminster Fuller began drawing his own early visions of an interconnected infrastructure built from an immersive web of lattices (fig. 3). Today, giant textiles are being used to realize these radiant structures.

Since the beginning of the Industrial Revolution, leading structural engineers have been fascinated with the potential of intermeshed, lightweight, flexible structures. These evolving structures have steadily increased the role of tension forces, replacing the dense masses of compression-based

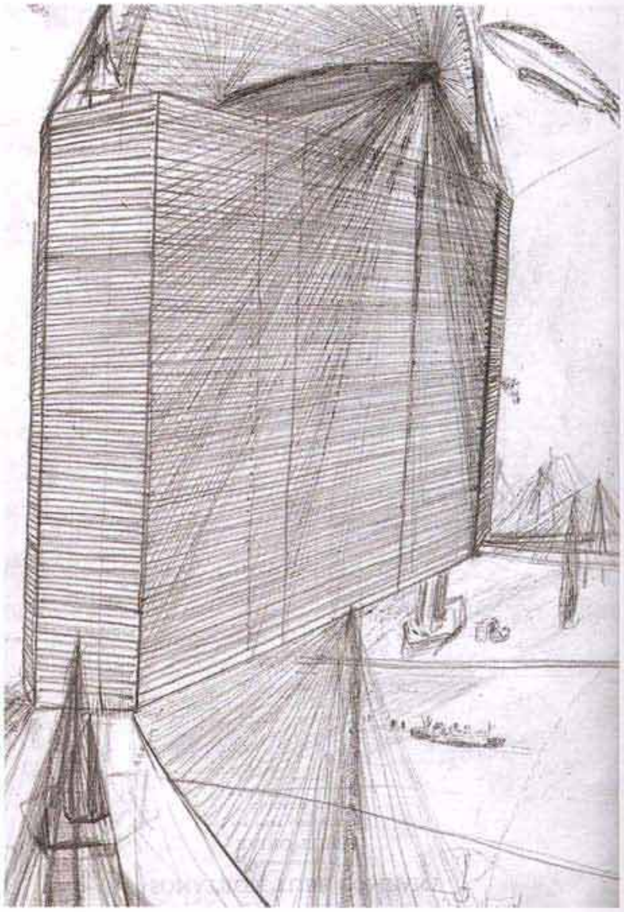


fig. 2 (left)
Harvey Wiley Corbett, 1913, in *Scientific American* magazine

Intermeshed skeletons support the multiple levels of Corbett's imaginary view of a city of the future.

fig. 3 (right)
Suspension bridge and office building, 1928
Sketch by R. Buckminster Fuller

Fuller attempted to integrate the structural systems of the Brooklyn Bridge and a Ferris Wheel in this visualization.

traditional buildings with open, more efficient systems. Some of these early experiments hid their slender interior structures. Alexandre-Gustave Eiffel's Statue of Liberty of 1886, for example, presides over New York Harbor as a presumably massive figure. Underneath the dress, however, is a light framework composed of continuous, supple bands of iron woven together into a basketwork that supports the sculptural drapery, made from thin overlapping tiles of bronze (figs. 4, 5).

While much of twentieth-century architecture continued to wear a mask of heavy cladding derived from ancient Roman and Greek construction, structural cores were being transformed into resilient skeletons that flex and respond to the dynamic loads of wind and earthquakes.[1] Instead of being built from the ground up, new building skins hung from above and became thinner and thinner. The development of the curtain wall, early in the century, was a turning point for architecture. In a break from previous construction methods, the enveloping jacket of a curtain-wall building is composed of a metal and glass cladding system formed from a continuous network of structural strands. The skin is able to support itself as a unified fabric, requiring only intermittent fastening to carry its weight (fig. 6).

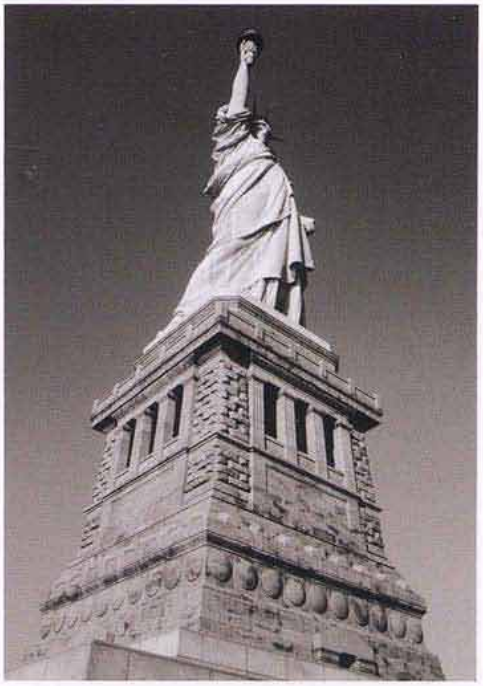


fig. 4 (right)
Liberty Enlightening the World
Frederic-Auguste Bartholdi and
Alexandre-Gustave Eiffel
U.S.A., 1886

fig. 5 (below)
Interior view of *Liberty*, showing forged meshwork supporting the folded profiles of the bronze drapery skin

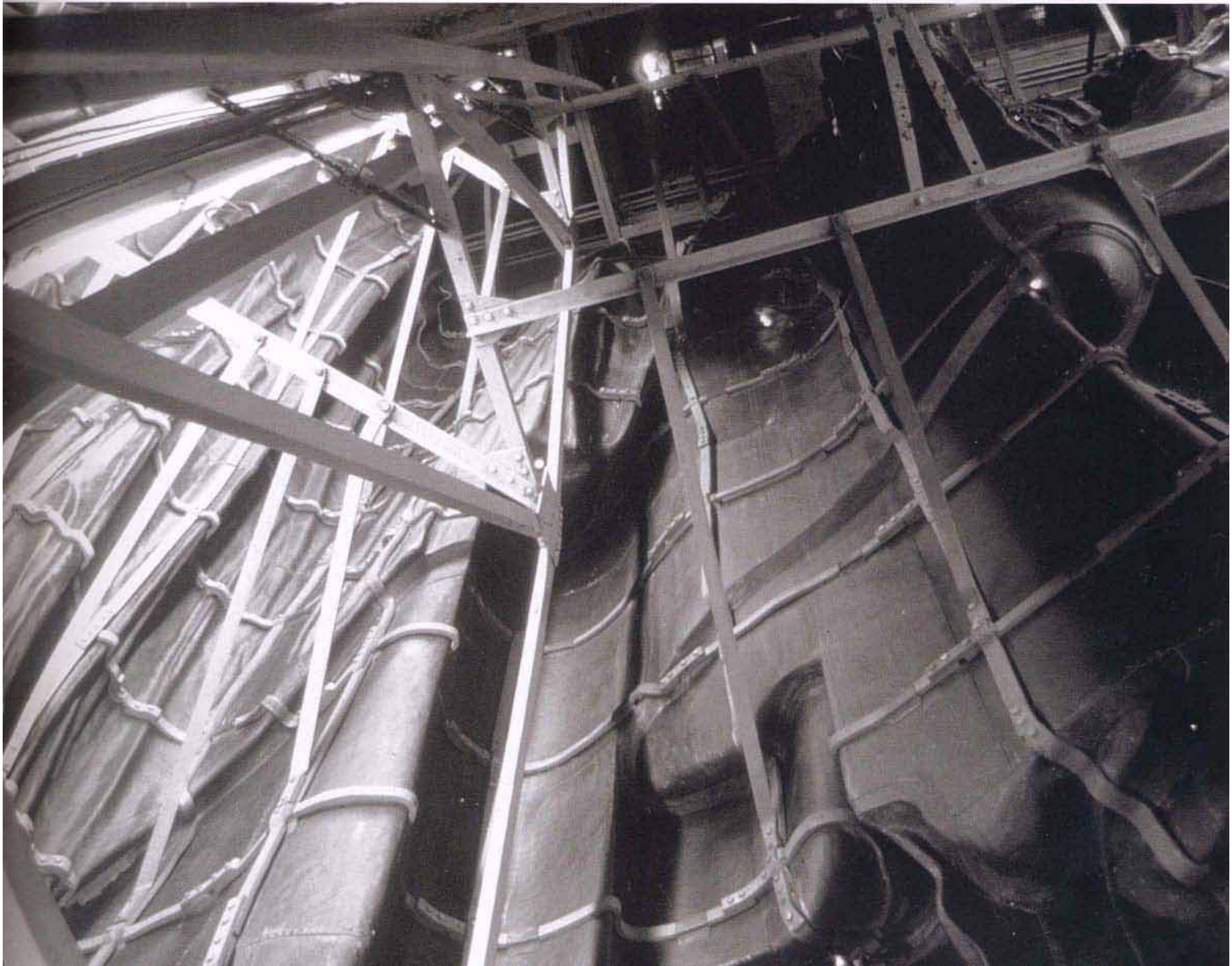


fig. 6
View of contemporary London, showing modern curtain-wall towers, with eighteenth- and nineteenth-century masonry buildings in foreground; Swiss Re Headquarters by Foster and Partners in distance

Recent projects continue the evolution of the curtain wall. Foster and Partners' tower for the Swiss Re Headquarters uses a unique structural skin made by placing members on a bias that dissolves the distinction between vertical and horizontal. The curved structural shell bulges gently in the middle and converges at the top, formed by an intersecting helical structure—essentially a skewed curtain wall. Similarly, the Seattle Public Library, designed by Rem Koolhaas's Office for Metropolitan Architecture, consists of a series of stacked, sloped floor plates, held in place by an angled, tight fishnet structure. The angled intersections of the exterior members and floor planes brace each other, keeping the structure stable (fig. 7). Pursuing even greater lightness, the face of Richard Rogers's Channel Four headquarters in London is composed of plates of glass assembled entirely without mullions, instead supported by a network of cables. This cable-net produces a hovering, agile presence that seems opposite to the classical paradigm of permanence (fig. 8).

ANCIENT ROOTS

While many of these examples depend on highly advanced materials and technology, the principles have ancient roots using humble fabrics. Recent archaeological finds date the beginnings of permanent construction almost immediately after the last ice age, approximately seven thousand years ago, contemporary with the earliest evidence of woven textiles. As the nomadic existence of the Paleolithic age gave way to the first settlements, and transportable tentlike huts clad in animal skins were replaced by architecture designed to last for generations, the first building materials to emerge were

fig. 7 (top)
Seattle Public Library
Office for Metropolitan Architecture, architects; Front Inc., envelope consultants
U.S.A., 2004

External meshwork provides primary structural system, resisting wind and lateral forces

fig. 8 (bottom)
Channel Four Television Headquarters
Richard Rogers, architect
England, 1991–94

Interior view of front façade showing cable-stayed structural glass façade

not masonry, but woven. A meshwork of small, flexible branches formed the underlayer of cladding and served to brace the larger structural members, stiffening the then-circular house.

Thatch, which is the binding of straw or grass fibers together as a roofing material, and wattle, a lattice of flexible twigs and small branches woven horizontally through a series of vertical wooden stakes, were the standards for a building's exterior surface. The wattle provided excellent tensile strength, held fast by clay daub—the combination formed an efficient structure that made an integrated fabric.

The technologies emerging at the beginning of this new millennium return to these traditions and share many of the underlying principles.[2] Carbon-fiber and resin matrices are being fabricated to outperform the steel and concrete buildings of today. The basic concepts of ancient wattle-and-daub and thatch techniques still apply to these lightweight building systems.

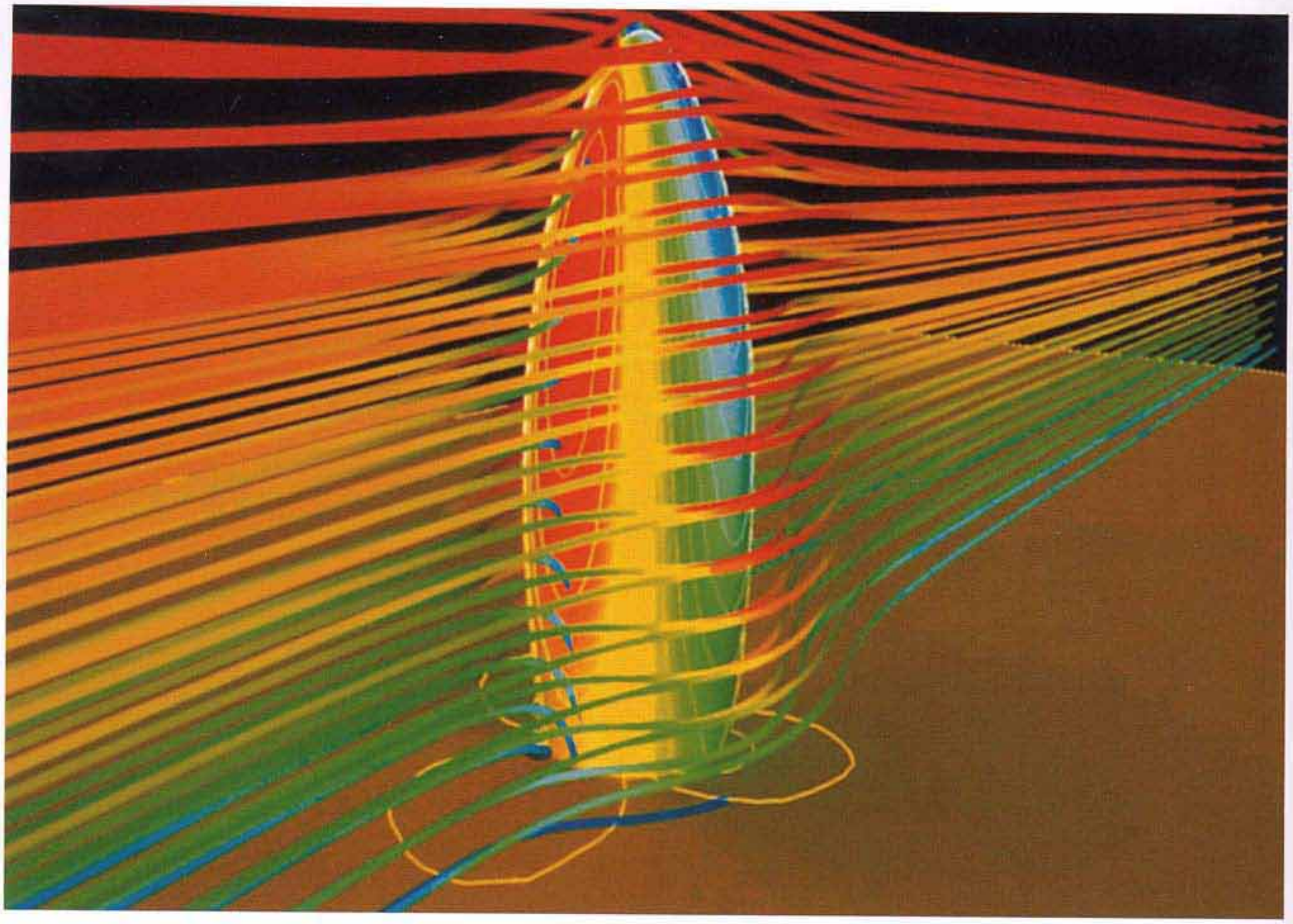


fig. 9
Swiss Re Headquarters
Foster and Partners, architects
England, 1997–2004

Illustration of wind loads on tower; structures that act in tension can handle these forces more effectively than compression-based masonry systems.

New fibers used in architecture include composites of glass and carbon that are stronger and more efficient than traditional steel and glass assemblies. These textiles require new methods of construction. This kind of building uses continuous chains of components and distributed structures that take advantage of a meshwork of woven elements. Because these materials are constantly evolving, specialists responsible for building systems are obliged to rethink fundamental systems of design and means of construction.

THE PROBLEM OF EFFICIENCY

A prime criterion for engineering is the concept of efficiency. Heavy materials naturally tend to take more energy to transport and form than lightweight materials, but for much of human history they seemed efficient because the only forces that they had to serve were the downward-directed forces of compression and gravity. It is a relatively simple matter to work with gravity using unskilled labor by piling one heavy block on top of another. However, traditional masonry buildings are quite vulnerable to shifting and buckling forces. Ancient history is marked by a succession of catastrophes in which entire cities were destroyed by earthquakes and floods. The challenge of building an effective structure dramatically increases when considering the lateral and upward-pulling pressures from wind and earthquakes, because these forces are much more complex than compression in the way they behave. These factors require tension, and masonry is extremely inefficient in handling tension (fig. 9).

On the other hand, tensile forces can easily be handled by thin, continuous strands of resilient material. To deal with complex back-and-forth waves of forces, a lattice of long strands applied in opposite directions can be used. Confronting the pull of upward-lifting wind and the twisting, buckling forces of gravity has required a change in engineering practice. The force of tension, which previously played only a minor role in architecture, has become just as significant as compression.

INTERCONNECTED SYSTEMS

Most traditional buildings engineered today use components of construction fabricated in a strict order. Primary elements support secondary, secondary supports tertiary, and so on. For example, a foundation and structural core in concrete might form the basis for a grid of steel columns between regular floor plates, and on these a skeletal grid of windows may be hung, with finishes added. The order of construction is roughly parallel to a steady decrease in size of each element, and in the hierarchy of support. Each must carry the combined load of every subsequent element that is later added to it. The first stages of construction therefore form the immovable, stable base that supports everything that is to come.[3]

In a textile, the process is quite different. Every fiber has an integral role in maintaining structure, each as important as its neighbor. The fibers are long, usually spanning the entire length or width of the textile. The structural properties are evenly distributed throughout the fabric, as each thread connects to the others. Instead of fixed, rigid connections based on compression, textile structures use tension. The binding of one fiber to the next is achieved through the tension exerted by the immediately adjacent fibers. Rather than relying on support from the previous, stronger member, the system is circular, holding itself in balance. The necessity of constructing components only after their supporting members are complete is removed, and a wide range of diverse elements can be built at the same time (fig. 10).

From 1947 to 1948, while working with artists at Black Mountain College in North Carolina, visionary Buckminster Fuller developed the concept of synergy, meaning the "behavior of whole systems unpredicated by the behavior of their parts taken separately."[4] During a career of pioneering work in engineering space-frame and tensegrity systems, Fuller explored complex interactions of structural elements that reinforce the whole. Using synergy, he described textiles as exemplary systems for architecture. A distribution of forces occurs as each thread joins a large number of similar threads. The whole collection can tolerate extensive damage, spreading this risk throughout many elements. If one thread snaps, the proximity of identical components, and their flexibility, allows the system to adapt dynamically to the new condition. However, the complexity and dynamic qualities of this behavior put it beyond the reach of standard nineteenth-century analysis methods and Fuller's time.

Another esteemed American scientist and engineer, John Argyris, invented Finite Element Analysis in the 1950s to study the attributes of complex systems and geometries. The method breaks down a continuous, dynamic structure into many simple, linked elements. Finite Element Analysis has become the standard method used today to design fabric structures. For example, a stretched membrane held in tension as a doubly curved surface can be simulated by a grid of individual, connected elements similar to the pattern of fibers in the fabric. Each of these components can be analyzed in relation to all elements to which it is connected to calculate the stresses, determine optimal curvature, plan the location of seams, and orient the warp and weft of the fabric (fig. 11).[5]

The textile examples that follow attempt to achieve tangible goals: lighter, stronger, more responsive, and more efficient. In pursuing these objectives, these projects present innovative ways of designing and looking at the world.

CARBON TOWER, PETER TESTA

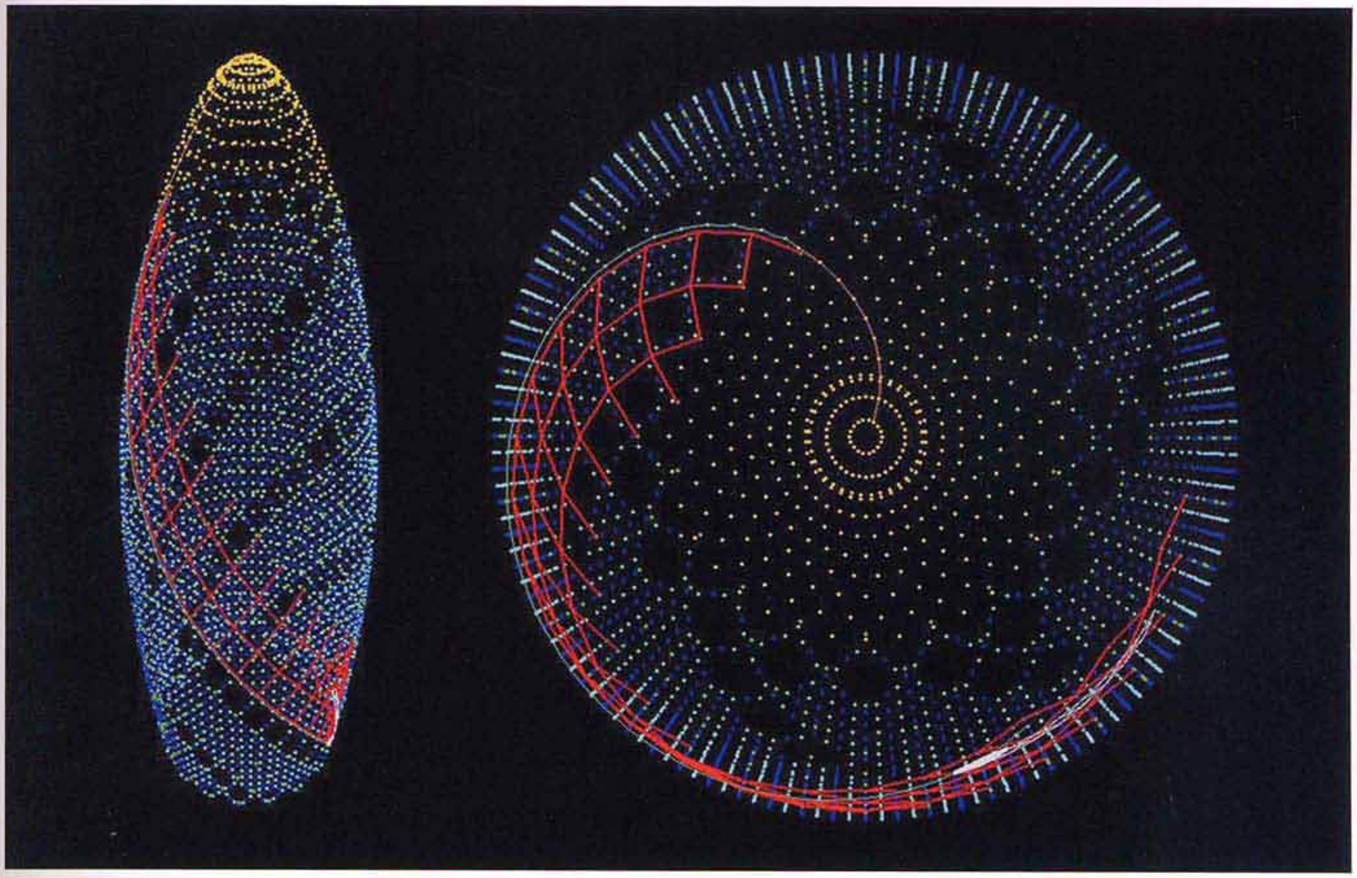
Perhaps no other project asserts Fuller's idea of synergy more than Peter Testa's Carbon Tower, an extraordinarily ambitious design based on advanced textile technology. The proposed tower is built of carbon fiber and composite materials. A prototype forty-story office building, the main structure is woven together, rather than assembled from a series of distinct parts. The building's shell consists of twenty-four helical bands thousands of feet long, winding in both directions around the cylindrical volume. Instead of relying on a rigid internal core and a series of columns for stability, these thin bands of carbon fiber, each a foot wide and an inch thick, run continuously from the bottom to the top of the building and take the entire vertical compressive load. The forty floor plates are tied in to the external structure, acting in tension. The floors keep the helix from collapsing while the helix, in turn, supports the floors. Both systems are interdependent; the helix, for example, would collapse in a scissor motion if the joints were not bonded together and the tension of the floors was removed (figs. 12–15).

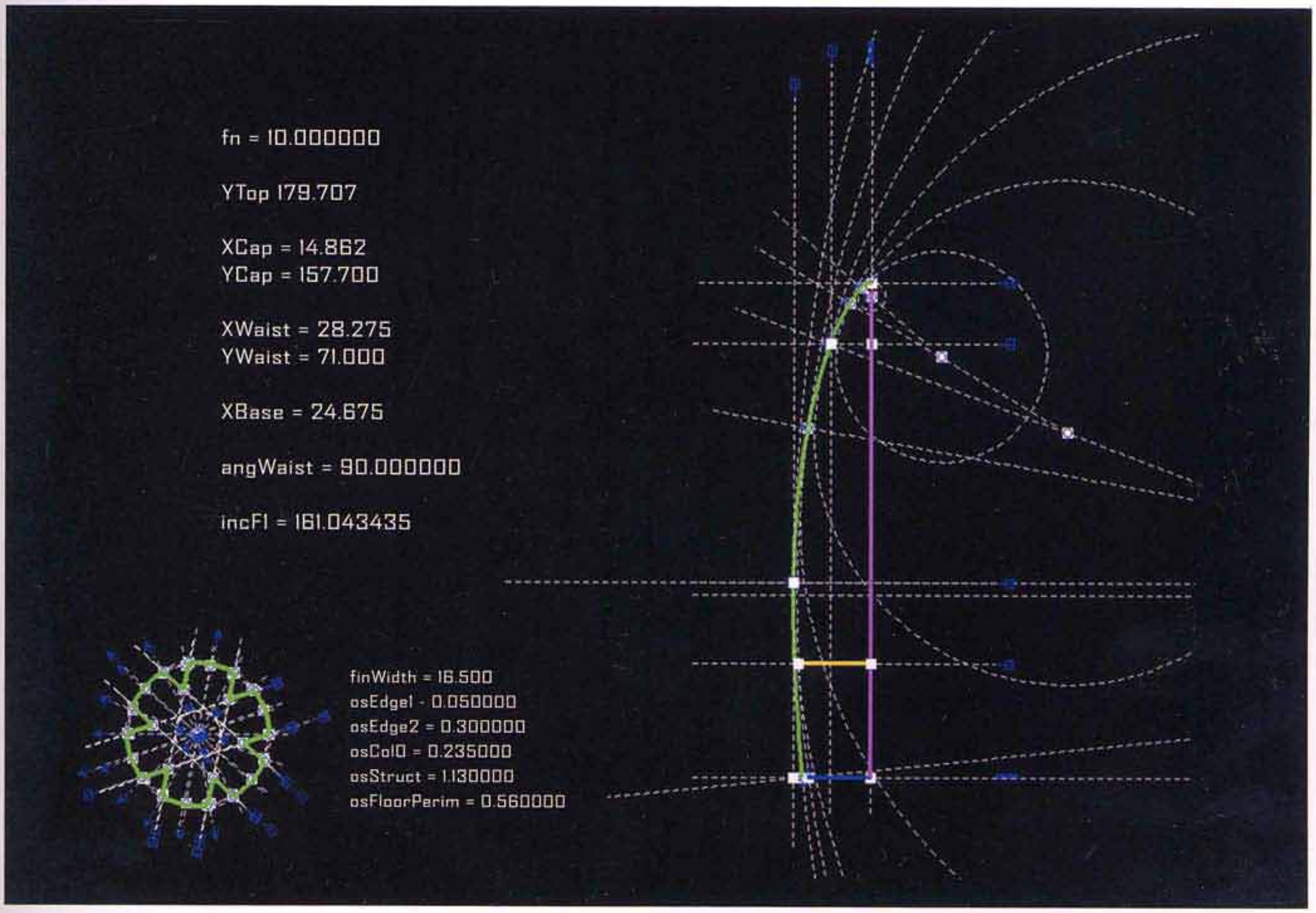
The goal of Testa's project is to achieve an unparalleled synergy of elements, where multiple systems in the building—structural members, airflow, and circulation of people—act together. The Carbon Tower offers a strategy to eliminate joints and abrupt changes in material. This approach requires a break from the tradition of reductionism, and an almost complete abandonment of the principles of hierarchies in building systems. Massive calculation is required to model the complex interactions between elements and the environment. In the most recent generation of computing, this simulation and analysis have become possible. Connections between structural elements are crucial to the design, and the transformation between the floor and helix

figs. 10, 11 (facing page)
Swiss Re Headquarters, tower envelope
Foster and Partners, architects
England, 1997–2004

Layout system of structural elements showing fabric system of interconnected spirals and circular matrices of elements (top)

Analysis of arching structural fibers within tower; example of Finite Element Analysis software by Bentley Systems (bottom)





fn = 10.000000

YTop 179.707

XCap = 14.862
YCap = 157.700

XWaist = 28.275
YWaist = 71.000

XBase = 24.675

angWaist = 90.000000

incFl = 161.043435

finWidth = 16.500
osEdge1 = 0.050000
osEdge2 = 0.300000
osCol0 = 0.235000
osStruct = 1.130000
osFloorPerim = 0.560000

fig. 12
Carbon Tower, exterior
Testa Architecture and Design
Peter Testa and Devyn Weiser, principal architects; Ian Ferguson and Hans-Michael Foeldeak, project designers; Markus Schulte, principal structural engineer; Mahadev Raman, principal mechanical engineer; Ove Arup, New York, engineers; Simon Greenwold, Weaver software designer
U.S.A., 2004
Double-helix woven structure of twenty-four twisted strands of pultruded and braided carbon fiber, stabilized by continuous braided tendons within floor plates, two external filament-wound ramps providing lateral brace, exterior of a ventilating tensile membrane

features gradual movement of one component into the next. The same cables that form the helix also provide the basic structural framework for the floors.

A new construction method is used for making these cables from impregnated carbon fibers. Pultrusion is a method for producing continuous extrusions of composite materials. Carbon-fiber composite is formed by passing raw strands of material through a resin-impregnation bath and then through a die to shape it into the appropriate cross section. The resin cures while the material is passing through the die, and the final product emerges immediately. This technique is used to make a range of stiff rods or flexible fibers that can be twisted, braided, or bundled into cables. The equipment for the fabrication process is portable, and allows many of the materials to be made directly on site.

When the main structural members of the perimeter helix are pultruded, the fibers cross at the point of a floor plate. Some of the carbon strands are diverted from the main vertical member and are grouped to form cables that run to the opposite side of the helix, tying the external structure together. A floor structure is then woven into and layered onto this surface network of cables. The building is literally woven and braided together.

All fibers in the structure are continuous as they travel up and around the helix, spanning the full height of the building. The bands comprising the helix are constructed by two robotic devices working in tandem: a pultruder on each of the twenty-four vertically spiraling members, closely followed by

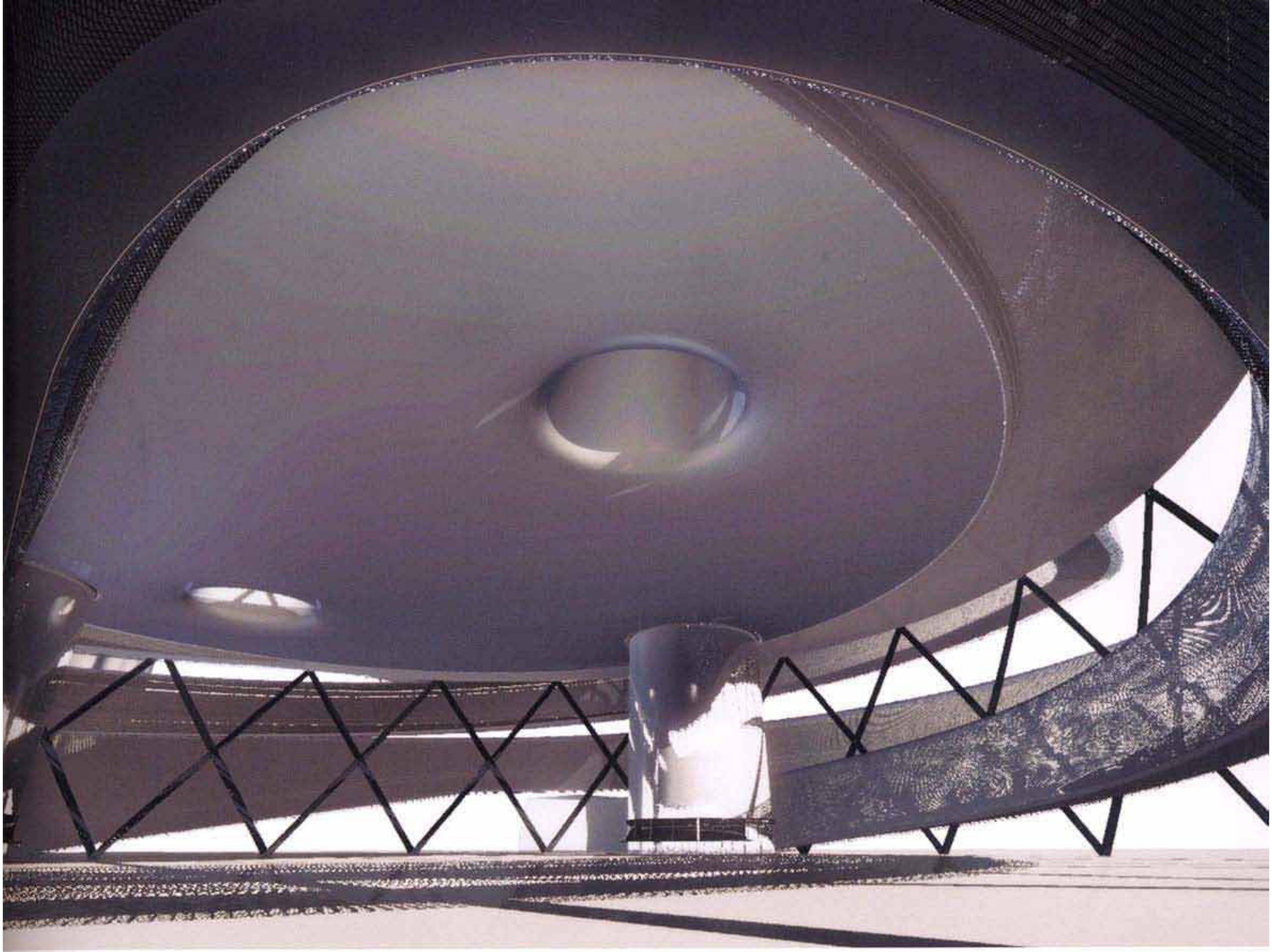


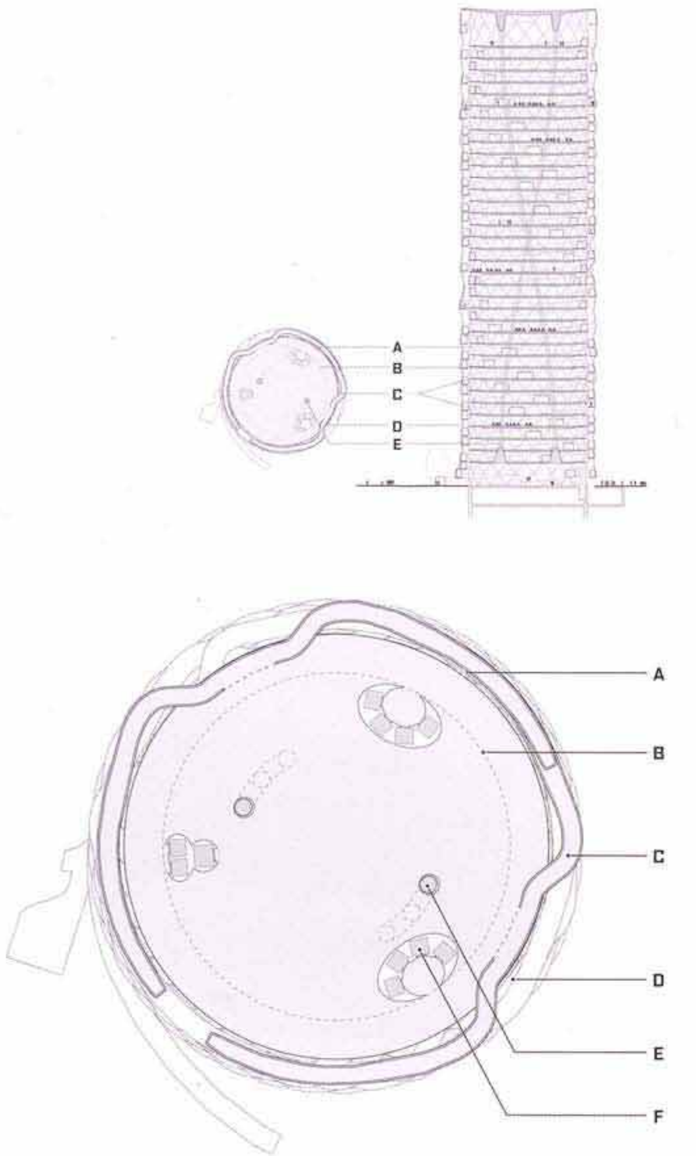
fig. 13
Carbon Tower
Testa Architecture and Design
U.S.A., 2004

Interior of lobby, with the "virtual duct" that runs the full height of the tower

a series of braiders that shape the same fibers into floors. The robots weave simultaneously, moving up the steadily rising building floor by floor.

Two central strands can be seen winding vertically through the middle of the building. These are air-distribution ducts, or "virtual ducts," which consist primarily of voids in the floor plates. A fabric-based duct system, which varies in weave density and strand thickness, hangs from the top of the building through these voids. The alterations in the weave are based on air pressure, such that the weave opens up as the building gets higher. The movement of air is handled by a dynamic and responsive system that allows the enclosure to contract and expand seasonally as ventilation conditions change. The floors through which the vertical voids pass are also hollow, allowing air to be drawn from the outside of the building, effectively integrating air flow with the structure. Standard ductwork as a separate, applied system is eliminated, increasing the floor-to-ceiling height and bringing more daylight into the building, offering reduction in energy consumption.

An external ramp system that follows the perimeter of the building performs several functions. By connecting to the structure at the floor plates, the ramp stiffens the entire building. It is shallow relative to the primary helix, and the



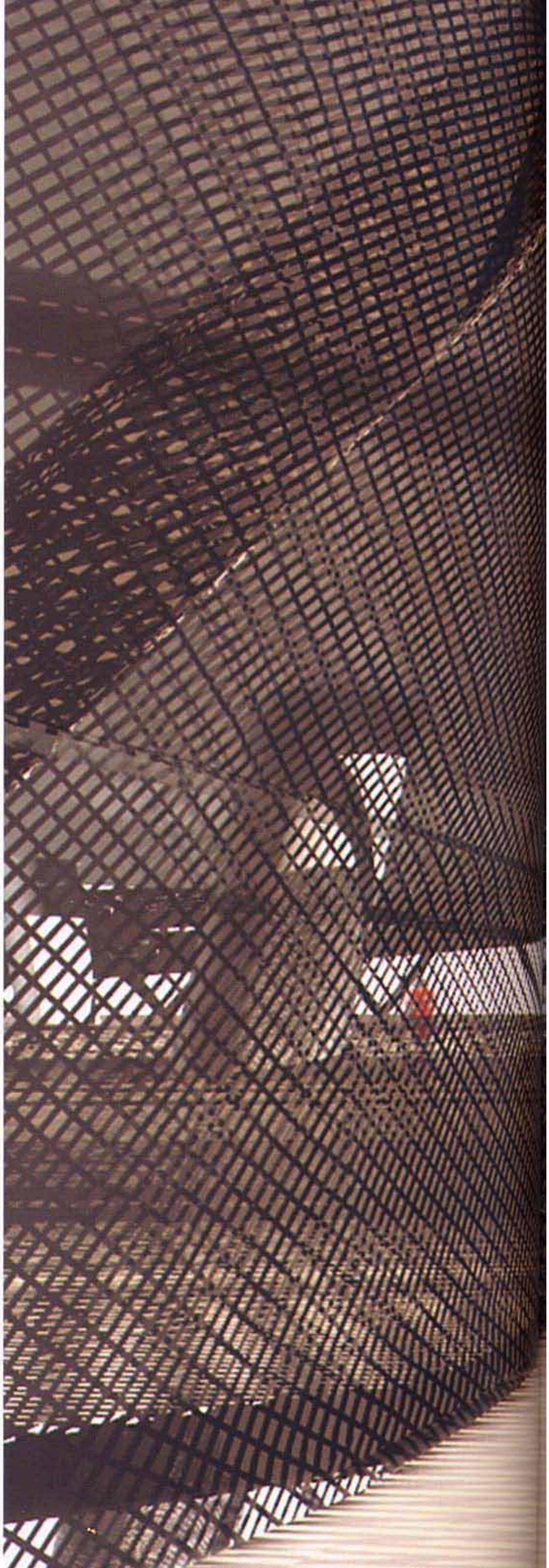
A Carbon Fiber Double-Helix Primary Structure
B Tensile Composite Floor Plates
C Filament-Wound Carbon Fiber Ramps
D Transparent Thin Film Enclosure
E Woven Ventilation Ducts
F Elevators

fig. 14 (right)
Carbon Tower
Testa Architecture and Design
U.S.A., 2004

Interior, showing filament wound ramp

fig. 15 (above)
Carbon Tower
Testa Architecture and Design
U.S.A., 2004

Section and typical floor plan



resulting increase in length allows it to create a substantial torque around the structure. The ramp is designed to contract with cables along its length to form active lateral bracing, which can be adjusted in relation to high winds, allowing the building to react to extreme weather.

Many of the structural problems of the Carbon Tower stretch the boundaries of standard design software. Testa developed a program titled Weaver to assist visualization of the structure. The program allows interactive play with geometry, mocking up woven patterns quickly by adjusting parameters of existing options. Because of the demanding nature of the new materials and the synergy between them, testing and analysis for this project lie outside established engineering practice. The practical limit on what can be designed is therefore based on what can be physically tested. No substantial precedents have been found for the use of composites in an architectural project of this magnitude and complexity.

The Carbon Tower suggests a number of future benefits for the construction industry. Carbon fiber offers many advantages over traditional materials. It is strong and light, and manufacturing carbon fiber and resin requires half the energy of steel. In the construction of a large building project, much of the cost of materials lies in the expense of transportation to the site, and here, too, there is a substantial saving; many components in the Carbon Tower, including the core elements, are manufactured on-site, and others are very light components that are easily transported. The advanced materials have the potential to last longer and require less maintenance than many standard materials currently in use.

LEONA DRIVE RESIDENCE, MICHAEL MALTZAN

Exploiting the extraordinary visual qualities of carbon fiber, California architect Michael Maltzan has developed a design for a lightweight house made of a shimmering meshwork of translucent walls. The house, organized in three overlapping rectangular volumes, floats on a plateau overlooking the basin of Los Angeles. The public and private spaces pass over each other using long cantilevered structures. The stiff, light material, consisting of a woven carbon-fiber textile in a resin matrix, is ideal for supporting the loads of the long cantilevers (fig. 16).

Visually stunning, Maltzan has used a technique termed "ghost fiber" that binds aluminum powder to the carbon fibers, producing a reflection that dramatically decreases the apparent opacity of the gridded construction matrix. The overlapping layers of each space produce interference patterns that result from phase-relationships of the intersecting geometries of the fiber reinforcement. Wide spacing of the matrix fibers creates a distinct moiré effect, transforming the minimal, rigid geometry into a dynamic, open work.

A host of technical challenges accompany this project, raising provocative questions about the building industry. Carbon fiber is not an unusual material for transport vessels, but it is virtually unknown in the North American

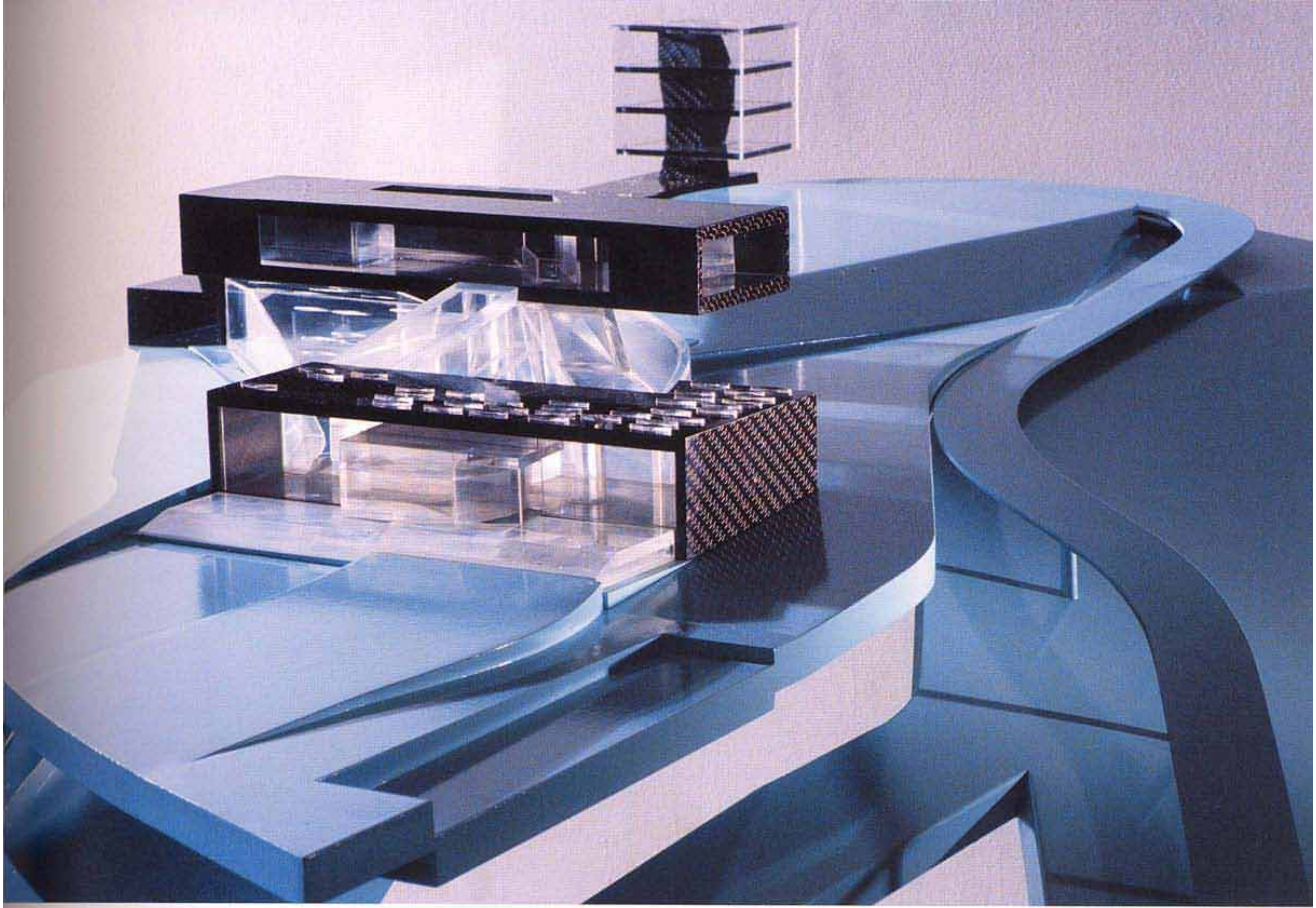


fig. 16
Leona Drive Residence, Beverly Hills, California, model (southeast aerial view)
Michael Maltzan Architecture, architects; Michael Maltzan, Tom Goffigon, Tim Williams, Yong Kim, Gabriel Lopez, Bill Mowat, John Murphy, Nadine Quirmback, Ivy Yung, project team; Ove Arup, Los Angeles, structural and MEP (mechanical, electrical, and plumbing) engineers
U.S.A., designed 2002, completion date 2006
Carbon fiber, acrylic and epoxy resin, painted medium density fiberboard base
335.3 x 81.3 x 45.7 cm (11 ft. x 32 in. x 18 in.)

construction industry, where housing construction is normally managed with a catalog of predetermined parts. Intensive testing of each component has been required for the project. The thickness of the panels has generally been determined by structural performance tests, and a sandwich system is currently being developed to integrate the different needs of interior partitions and exterior areas requiring insulation and weather seals. The resin binding matrix has received special scrutiny because the longevity of the entire structure is restricted by the way the resin ages. Cleaning, resistance to scratching, and protection from the California sun have been particular issues requiring refinement of the resin formulation.

While a high level of experimentation characterizes the Leona Drive residence, the project carries the immediate reality of serving a family's daily life. This imperative has heightened the importance of practical solutions for maintenance and weather seals, while at the same time it has encouraged a highly personal approach to the sensual effects of the building material. Perhaps this suggests a working method for the next century: the combination of increasingly sophisticated materials created by a highly technological and remote industry and advanced structural applications will be balanced by a careful, hands-on approach. In his house, Maltzan is physically and intimately involved in the craft of building.

fig. 17
AirBeams by Vertigo™ inflatable support beam
Developed for U.S. Army Natick Soldier Center, U.S. Army Project Engineer Jean Hampel, designed by David Cronk (Vertigo™ Inc.), manufactured by Vertigo™ Inc.
U.S.A., designed 2001, manufactured 2004
Seamlessly braided Vectran™ fiber
Length: 36.6 x span: 25 m (120 x 82 ft.)

RIGIDIZABLE STRUCTURES

Inflatable and rigidizable beam structures offer an architecture that can readily change its shape. The technologies in development at ILC Dover and Vertigo™ are intended for building in extreme conditions in space and on Earth. Designs range from low-gravity habitats on the Moon or Mars to deployable structures such as emergency shelters and army tents. Military and space astronautics are the first users of this technology; however, the potential performance and commercial applications of this adaptable system mean it will soon enter every neighborhood shopping center.

The AirBeam™ is a close relative of forms that are common today (fig. 17). Floating pool toys and air mattresses are small-scale cousins of inflatable architecture used for tennis domes, fairground buildings, and other temporary structures. Standard inflatables are usually made from coated textiles. A flexible polymer matrix covers the structure creating an airtight seal. Air is pumped into the form, acting as a compressive element within the tensile surface enclosure. This pressure must be sustained over time to maintain rigidity. While these inflatables offer an easily transportable and assembled architecture, they are prone to failure by puncture or power loss. Rigidizable structures are erected in the same way, but the high-performance matrix material in the surface becomes rigid and supports the structure without internal air pressure, removing the need for a constant power source. It suggests a new kind of semi-permanent structure that can be readily reused.

A typical rigidizable assembly from ILC Dover uses fiberglass fabric coated with epoxy resin and sealed with a polymer film to prevent the inactivated surface from being sticky to the touch. This initially flexible epoxy matrix becomes rigid and holds the fibers in place. It is the efficient combination of the flexible fabric and the rigid matrix that gives the structure its overall strength. Both are required in unison to hold the form — the matrix and textile act in compression, and the textile in tension. The stiffness and load-carrying capacities for a rigidizable beam are magnitudes higher than a similarly-sized inflatable beam.

A number of different methods can be used to make the structure rigid. Some of these result in a permanent shape, while others can be repeatedly deployed and retracted. The epoxy-coated fiberglass, used in cases of natural or artificial light exposure, forms a permanent, stable structure and can be made into specialized shapes, such as inflatable wings for aircraft. For forms intended to be repacked and transported, an alternative is based on a thermoplastic matrix made of "shape-memory" polymers that are imprinted with a memory of their fully-deployed shape. These polymers can change their states from soft to hard with heat (fig. 18).

Other methods differ in activation techniques. Some are set by a chemical reaction that generates foam inside the inflatable structure, while others are stiffened by a reaction with the chemical-laden gas used to inflate them. A variation of this structure uses thermosetting composites containing

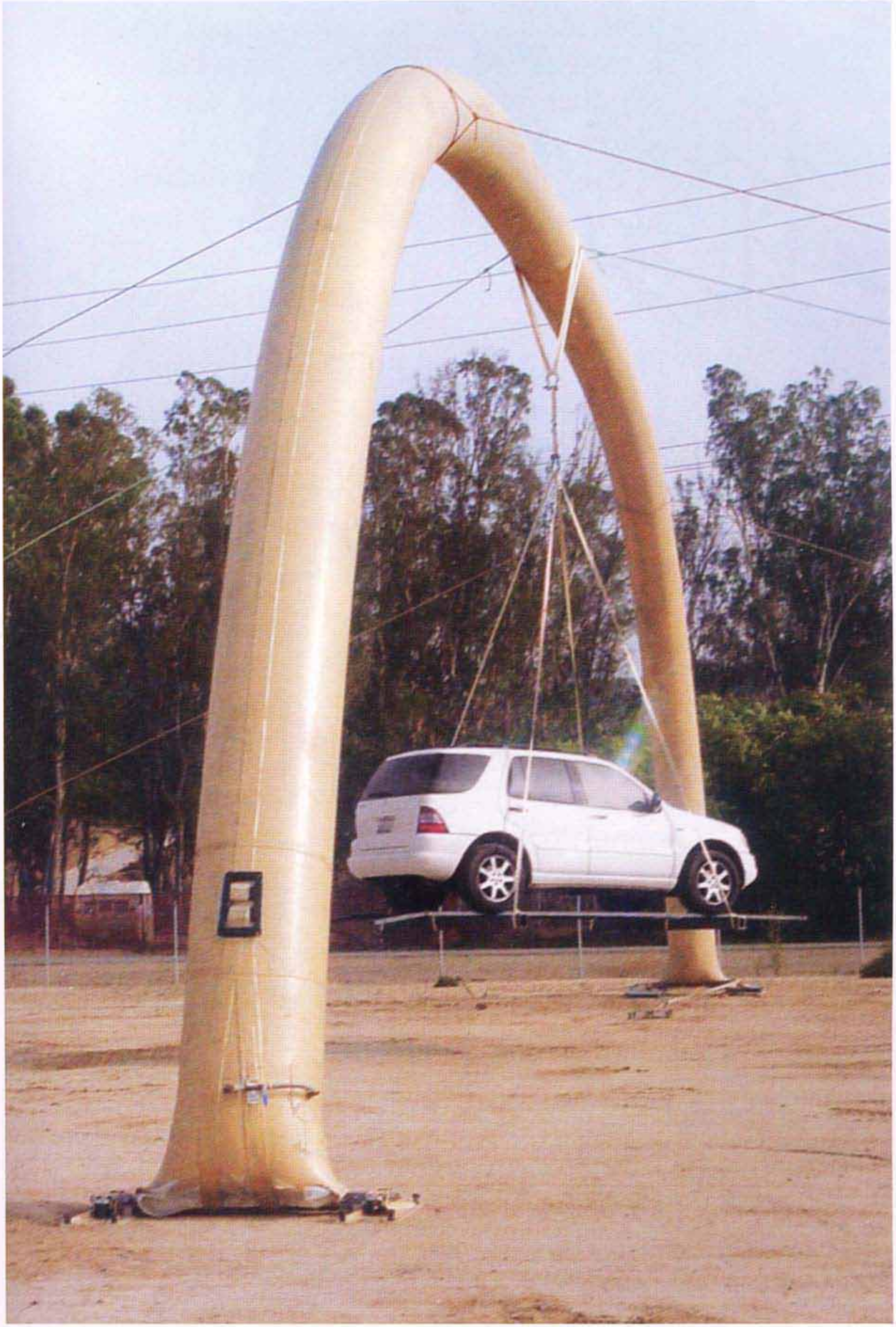


fig. 18
Examples of lightweight collapsible carbon/epoxy boom structures for space applications
Developed by ILC Dover Inc. and NASA
U.S.A., 1998–2001
Glass and carbon-fiber filaments; UV or shape-memory epoxy; Mylar® layers on both sides for gas retention; self-deploy when heated to a prescribed temperature

fig. 19
Carbon Isogrid rigidizable boom, deployed and packed
Developed by ILC Dover Inc. and NASA
U.S.A., 2001
Carbon filament wound structure with shape-memory epoxy; Kapton™ layers on both sides for gas retention; self-deploys when heated to a prescribed temperature

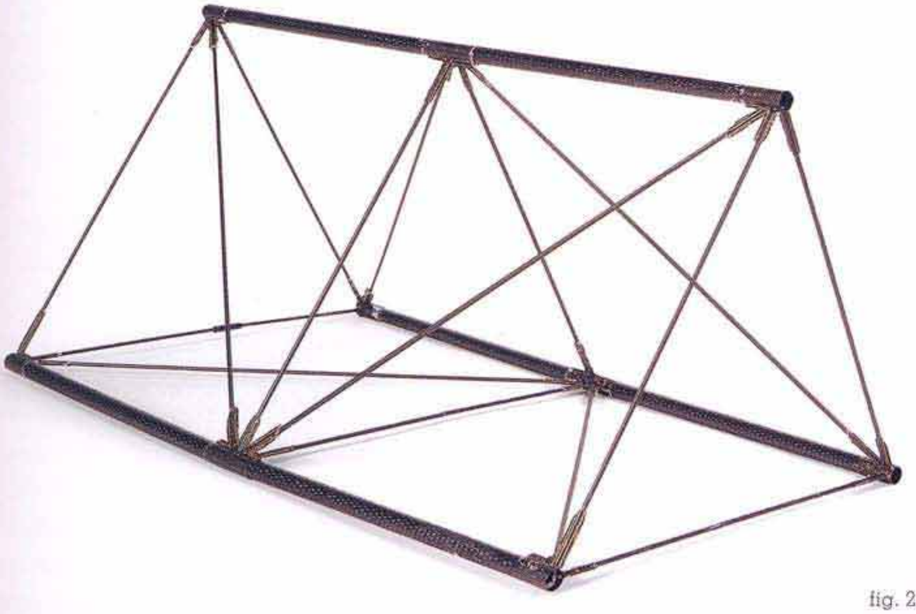


fig. 20
Space solar power rigidizable truss
Manufactured by ILC Dover Inc.
U.S.A., 2002
Carbon, epoxy

fig. 21
Wire gabions reinforce a slope in Tuscany, Italy

graphite that stiffens when subjected to a combined heat and pressure. In this case, a series of heaters is placed over the form while it inflates and sets. As an example, Isogrid booms, which are a class of structures, implement textile weave variations based on a low-density filament-wound construction (fig. 19). In contrast to the tight, regular pattern of woven reinforcement, these booms can be manufactured from loosely interlaced fiber bundles that resemble giant pieces of yarn.

Unlike inflatable structures, the strength of rigidizable beams can be readily analyzed, making them reliable as critical members of large assemblies. Standard inflatables derive their stability from a complex interaction of the exterior tensile membrane and the compressed, fluid air. While the interactions of the materials in the rigidizable structure are complex, their dynamic behavior can be analyzed quite simply by treating the components as traditional column, beam, and strut elements carrying tension and compression forces.

There are strong possibilities for these elements in buildings of the future. The range of scales for this technology is wide, from miniature rigidizable members measuring less than one-eighth of an inch in diameter to a nine-hundred-foot-long truss with triangular faces of ten to fifteen feet, intended for use in space (fig. 20). In a full-gravity environment there is a practical limit on vertical size, because thick walls are required to support the compounded loads that accumulate toward the base of large structures. Horizontally oriented components, however, can be arrayed along the ground indefinitely.

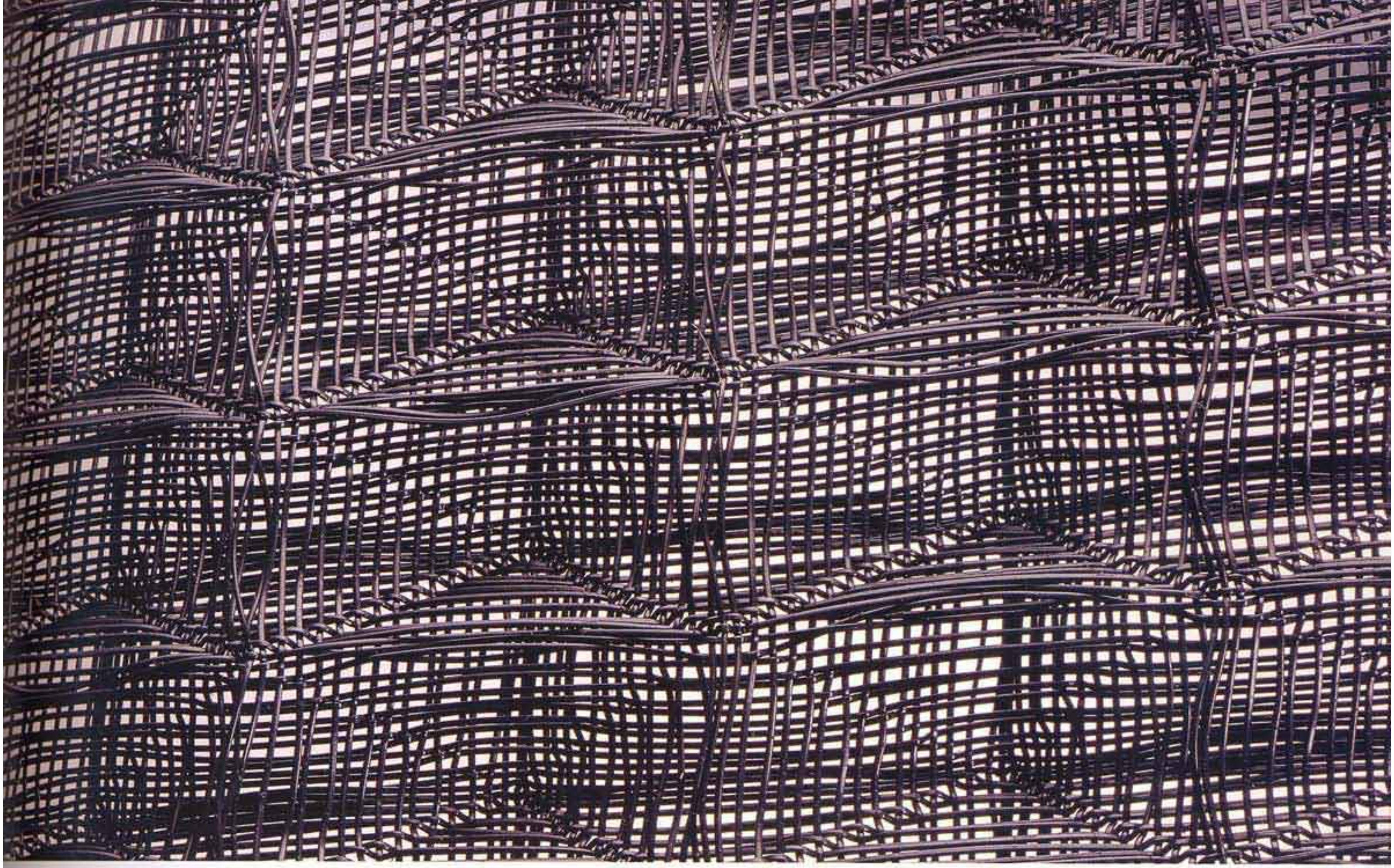


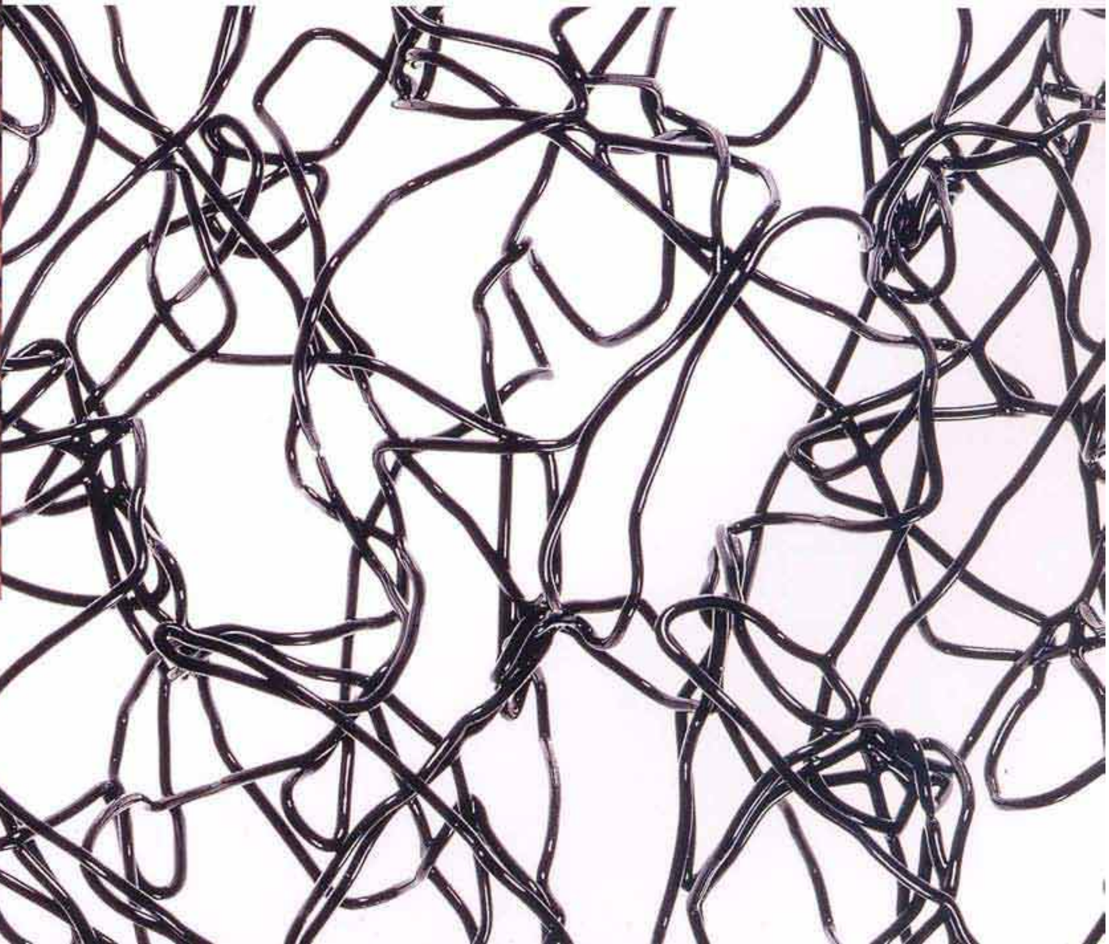
fig. 22
Pyramat® turf reinforcement mat
Manufactured by Synthetic Industries Corporation, Performance Fabrics Division/Geosolutions
U.S.A., 2004
Waffle weave (interlocked structure of uniform voids and projections) of UV radiation stabilized polypropylene monofilament yarns

FLOATING CITIES

The ground that buildings stand on has been transformed. It is now common practice for civil engineers to include geotextiles—heavy-duty fabrics used for earthworks—in large-scale landscape construction. Filtering and drainage layers, reinforcing cable nets, beds of earth anchors, and arrays of wire gabions run beneath new cities (fig. 21).

Geotextiles are landscape-engineering technologies that are literally woven into the earth. Applied as a fabric to the surface, they can be integrated into the soil or root systems of vegetation, preserving existing fragile landforms and creating entirely new landscapes. Erosion protection is one very common use for the technology, providing a soft armor, as opposed to the hard erosion control of rock or concrete. New plantings and their embedded textiles grow together to form a single, integrated structure. The scale of these functional support systems is often enormous. Pyramat®, produced by Synthetic Industries, is used to prevent soil erosion and consists of a fabric woven of monofilament yarns formulated to resist breakdown under harsh sunlight (fig. 22). Pyramat's structure interlocks and combines with the existing ground. This three-dimensional geotextile has pyramid-like projections that capture and contain soil, holding it fast while water flows. The textile allows vegetation to take root in a now-stabilized soil. Enkamat®, made by Colbond, is another product that provides protection of embankments or slopes, both wet and dry (figs. 23–25). It is primarily used adjacent to roads and railways, and is seeded and filled with soil. The resulting textile-and-

figs. 23–25
Enkamat® turf reinforcement mat
Manufactured by Colbond Inc.
U.S.A., designed 1965, manufactured 2004
Three-dimensional matrix of entangled,
fused Nylon 6 filaments



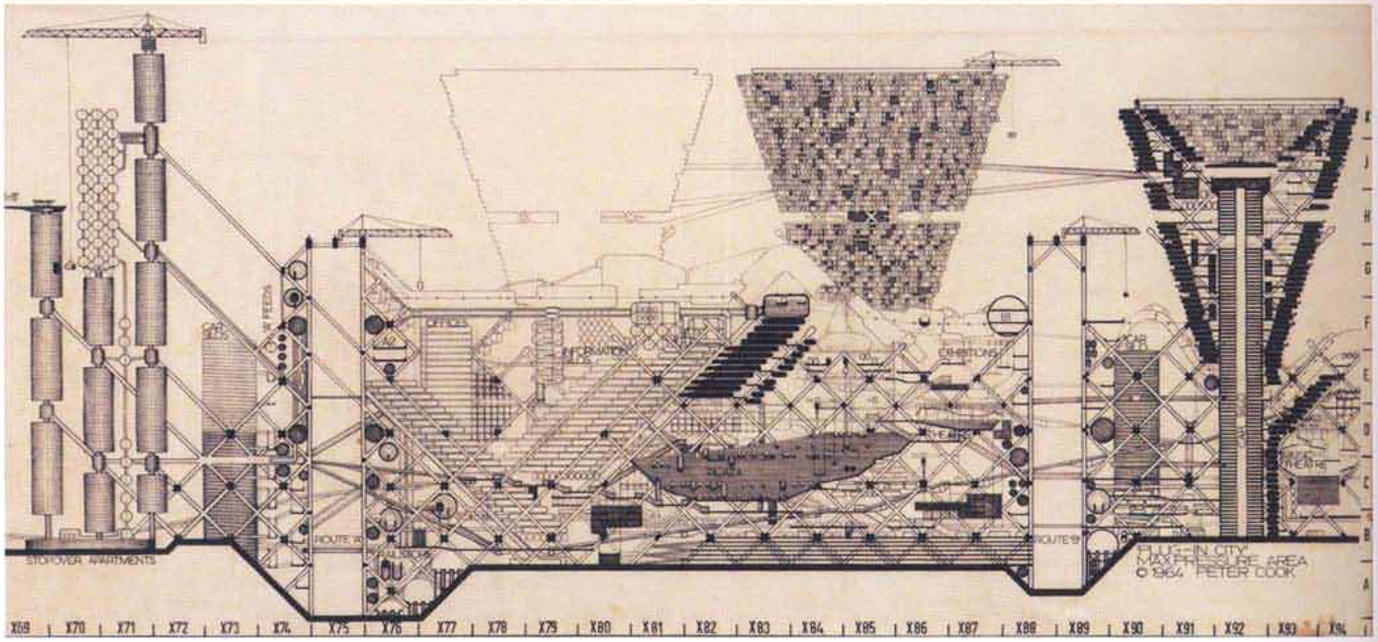


fig. 26
Plug-in City, visualization of the city of the future
Peter Cook, Archigram, 1964

earth combination is permeable by water and roots, and allows the growth of vegetation.

Repotex, manufactured by Huck, is a mat used for plant cultivation and repositioning in new environments, usually water and soft mud. The woven fibers form a base in which plant roots grow in the textile matrix, and the whole can float on top of the water's surface. Because the roots are held only to the textile, the entire living surface can be moved, forming islands of floating plants. The material itself is a coarse fabric structure made of either decomposable or non-decomposable materials, depending on the desired use. It can also be used to hold water and allow growth on flat and angled roofs. Purification of surface water can be accomplished by positioning plants on the surface. The plant textile can remove organic compounds from runoff from sewage farms and filter inorganic nutrients in intense agricultural areas.

NOMADIC HUTS, OLD AND NEW

The nomadic huts of the Mesolithic age consisted of only a surface skin, stitched together of animal hides, transported from site to site. In the 1960s, speculative projects like Archigram's Plug-in City explored the possibility of rapid change in new architecture of the future for a society dedicated to speed and novelty (fig. 26). The recent development of disposable shops—filling retail vacancies in major cities for a month or two of intense promotional activity, and then disappearing—indicates that the fantastical proposals of two or three decades past are now a reality. A flexible structure using the technology demonstrated here by ILC Dover offers a means of reaching this vision while avoiding the waste of single-use temporary structures. Similarly,

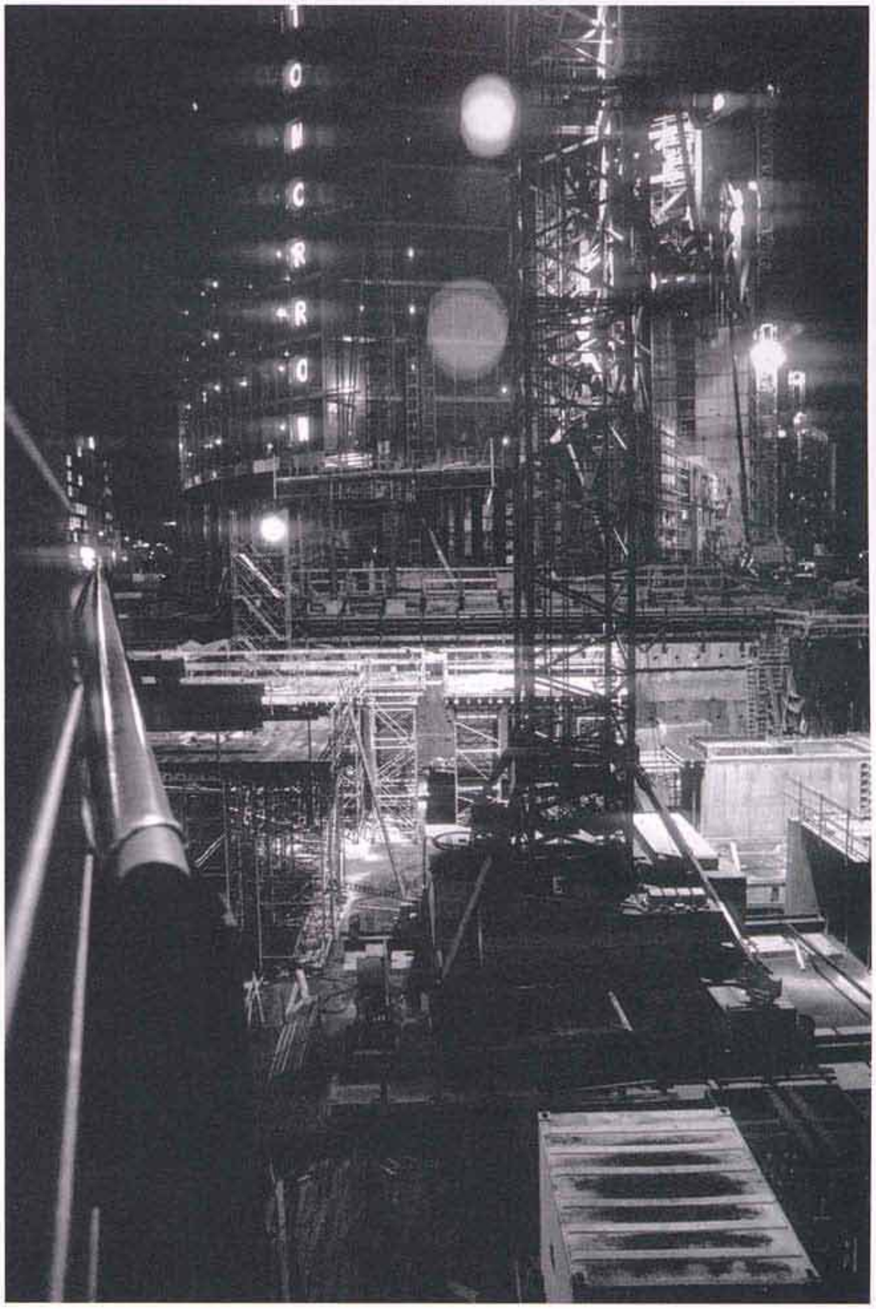


fig. 27
In a 2002 view of Potsdamer Platz in the heart of Berlin, new towers stand on a hollow ground plane that covers a vast underground web of submerged expressways, subways, and utility corridors. The horizon is at the mid-point of this image.

with the implement of structural textiles, Buckminster Fuller's vision is coming true. Landscapes constructed from geotextiles and cities built from lightweight flexible skeletons are at the core of this new world.

A surge of possibilities accompanies this technology. These possibilities affect scales from molecular engineering to artificial landscapes that support entire cities (fig. 27). Peter Testa's explorations into self-assembling structures and lightweight fiber-producing robots offer tangible ways for the structures of the future to grow themselves. The Carbon Tower is an advanced illustration of the generation of buildings that will soon make up our surroundings. The dramatically expanded three-dimensional web that Corbett imagined is very nearly here.

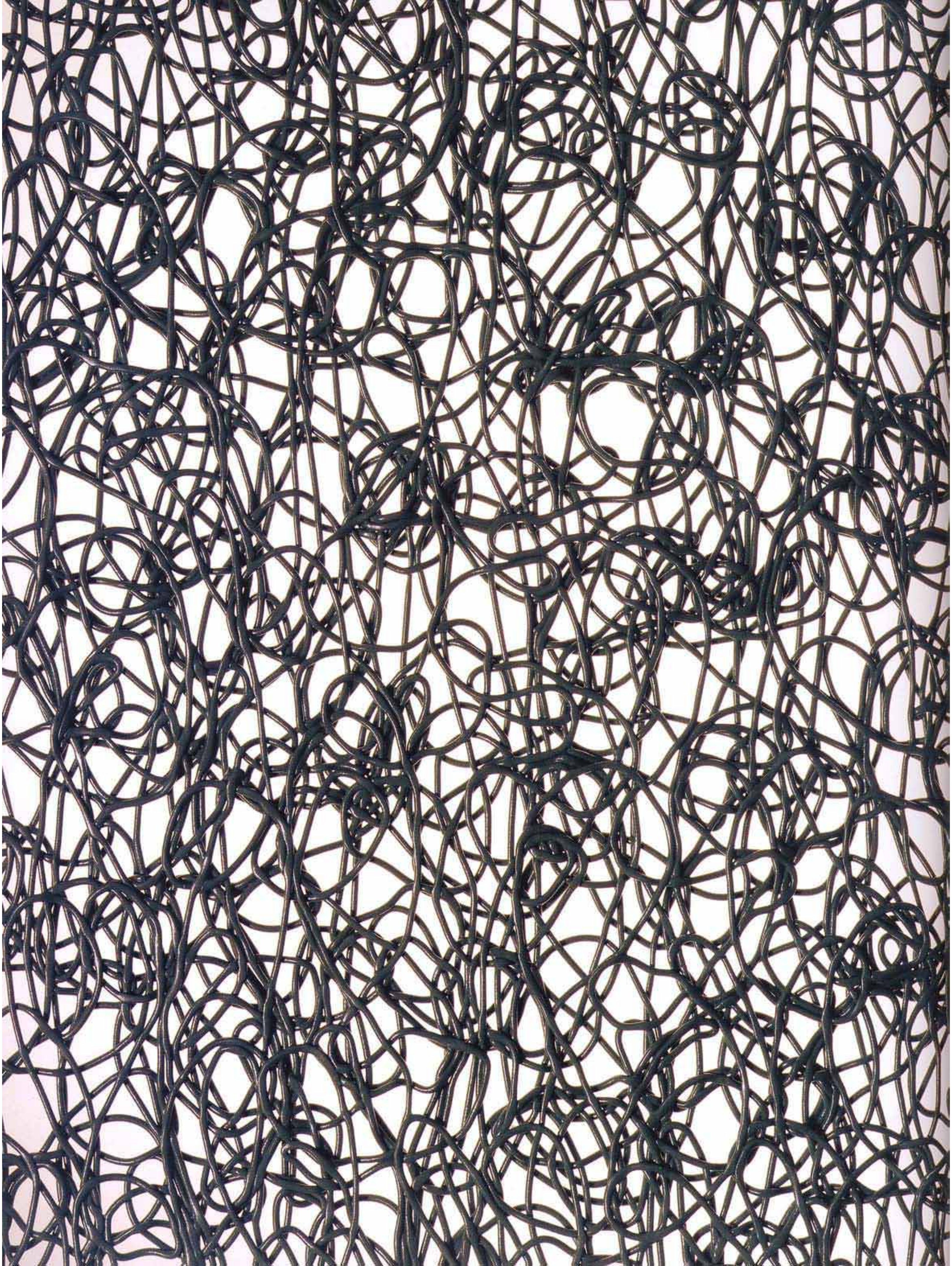
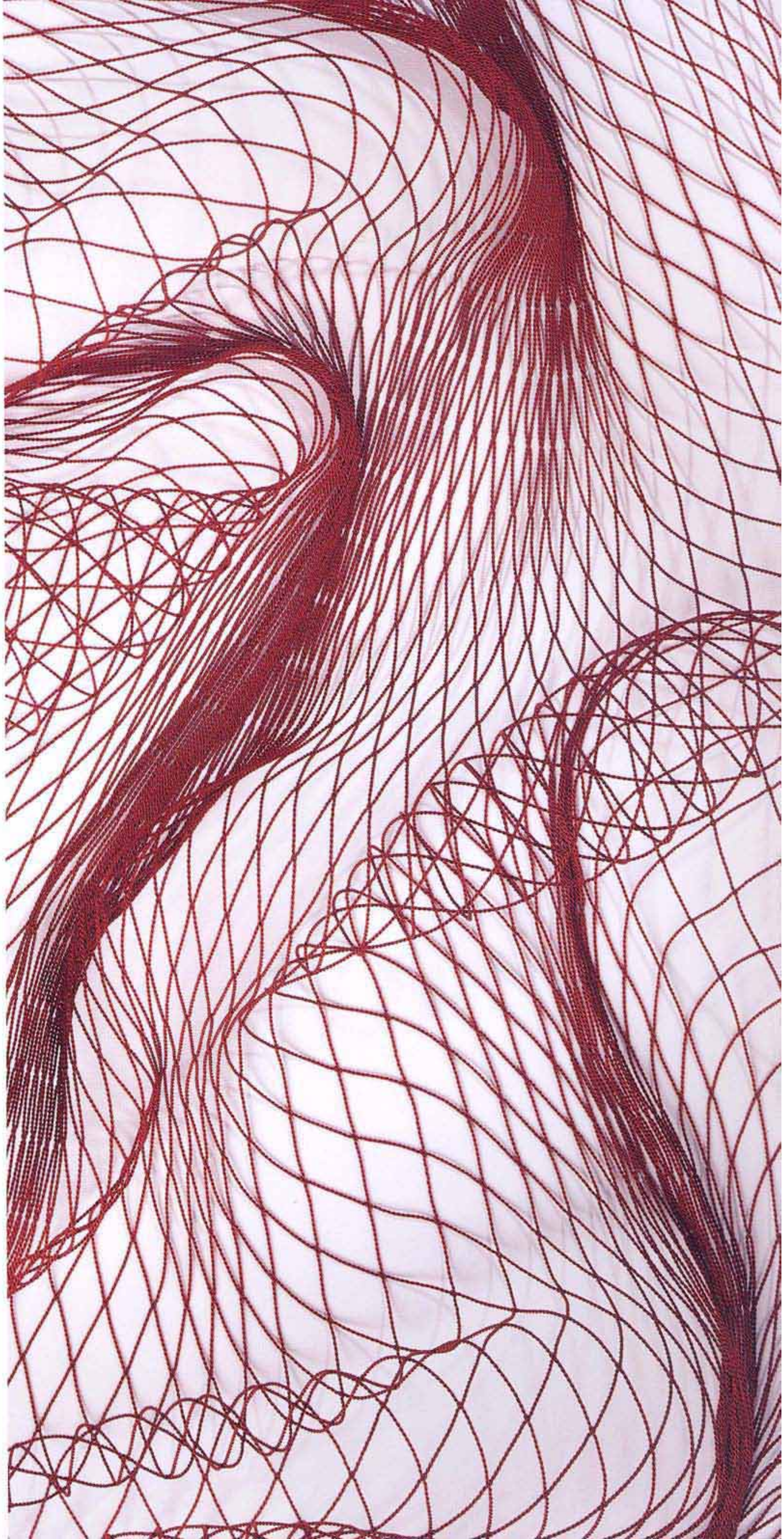


fig. 28 (facing page)
PEC-Mat® turf reinforcement mat
Designed by Thomas P. Duffy, manufactured by Greenstreak Inc.
U.S.A., designed 1986, manufactured 2004
Thermally welded PVC monofilament

fig. 29 (right)
Encircling fishing net
Manufactured by Toray Industries Inc.
Japan, designed 1996, manufactured 2003
Machine-made knotless netting of interconnected twisted polyester threads, heat treatment finish
4 cm (1 9/16 in.) compacted; expands to 226 cm (7 ft. 5 in.)
Cooper-Hewitt, National Design Museum, Gift of Toray Industries Inc., 2003-22-1



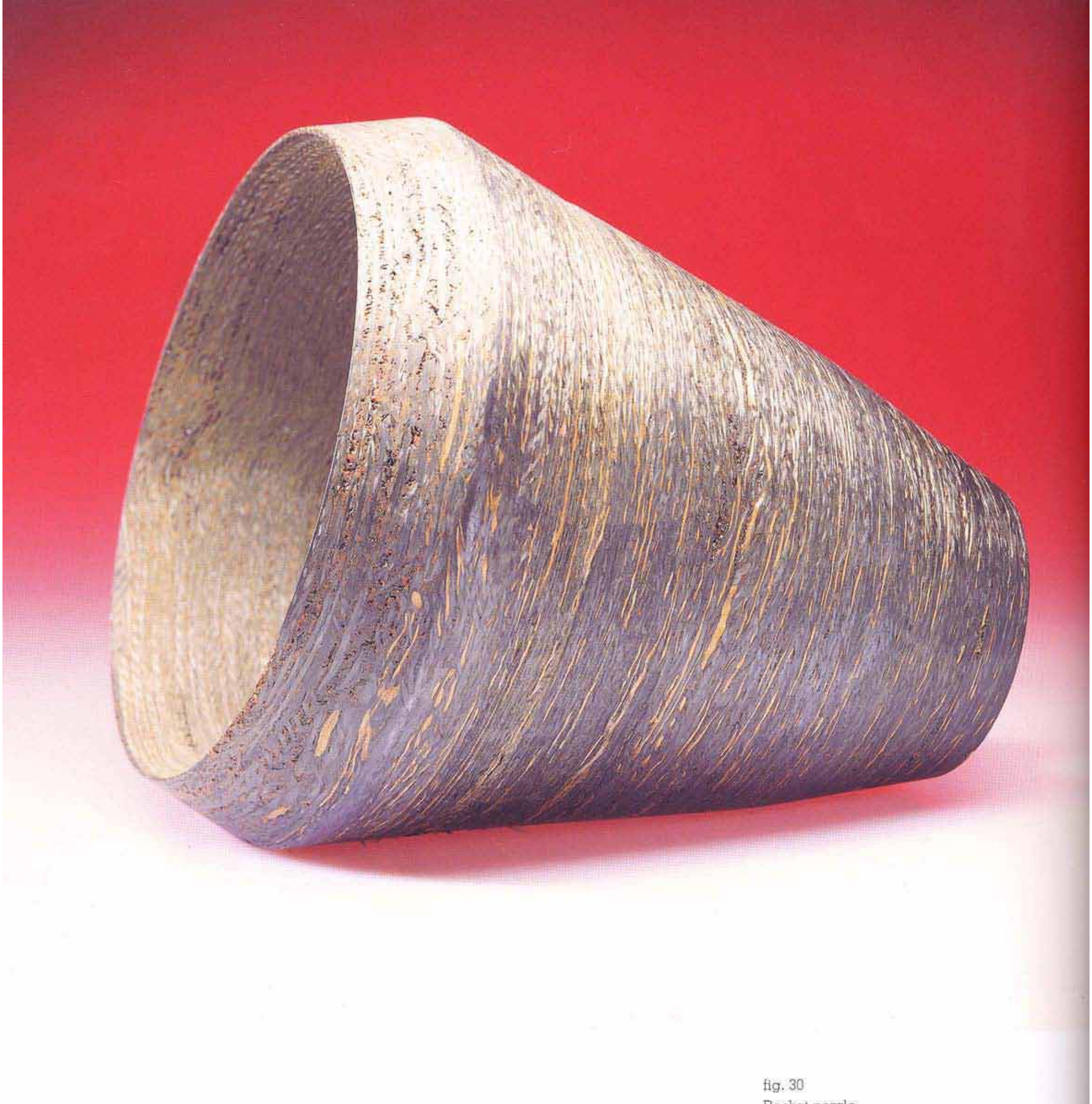


fig. 30
Rocket nozzle
Designed by Thiokol®, textile designed and manufactured by Foster-Miller Inc.
U.S.A., 1998
Braided carbon fiber, epoxy matrix
Length: 25.4 cm (10 in.); diameter at wide end: 22.9 cm (9 in.)

This prototype rocket nozzle exit cone is constructed from an advanced carbon-fiber braid. It is designed to replace significantly heavier metal exit cones and increase rocket payload.

fig. 31
Pi-braid
Designed and manufactured by
Foster-Miller Inc.
U.S.A., 2001
Three-dimensional braid of carbon fiber

This prototype three-dimensional pi-braid is designed to form strong yet lightweight joints between composite panels on aircraft fuselages.

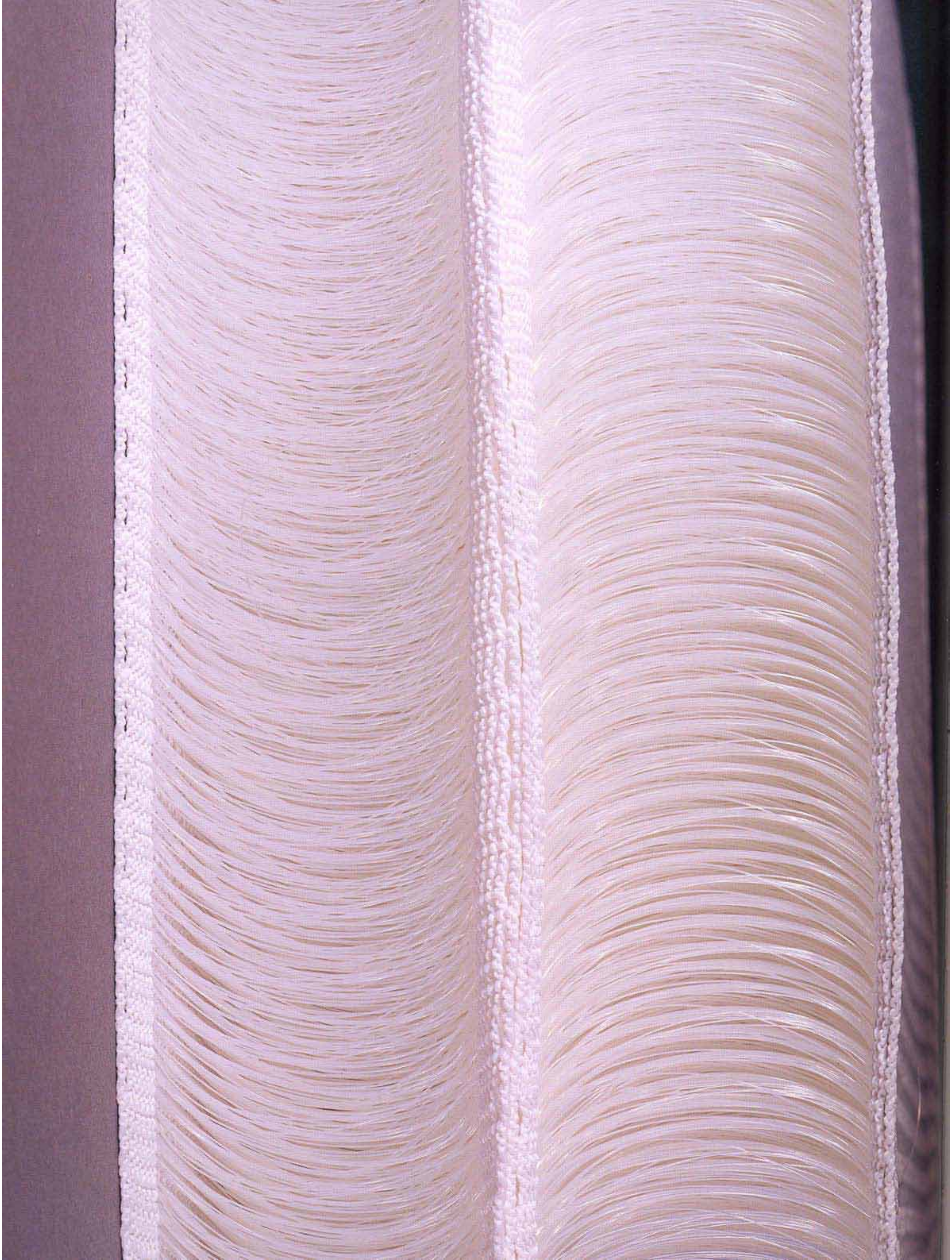


fig. 32 (facing page)
Spacer fabric
Designed by Stefan Jung,
manufactured by Karl Mayer
Textilmaschinenfabrik Obertshausen
Germany, designed 2002,
manufactured 2005
Warp-knit polyester and
polyester monofilament

Spacer fabric can be used in a number of applications, including filtration and insoles for shoes, and as a substitute for foam in automobile-seat padding and upholstery.

fig. 33 (right above)
Pedestrian bridge for hiking trail
in Maui, Hawaii, 80' span
Designed by E. T. Techtonics, Inc.,
fabricated by Structural Fiberglass Inc.,
composite components manufactured
by Creative Pultrusions, Inc.
U.S.A., 1995
Pultruded fiberglass rovings and
non-woven mat, polyester resin
Courtesy of E. T. Techtonics, Inc.

Lightweight fiberglass components can be easily hand-carried to remote locations and assembled on-site. Fiberglass also resists rust, rot, salt corrosion, and termites, making it ideal for wilderness use.

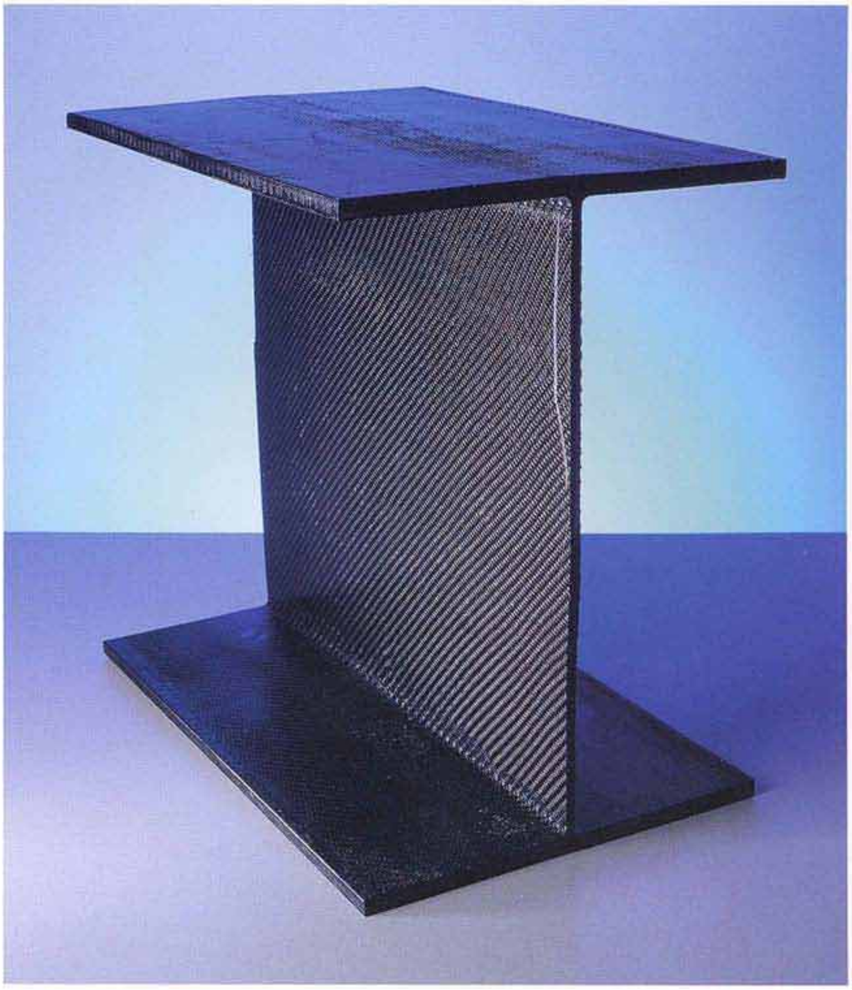
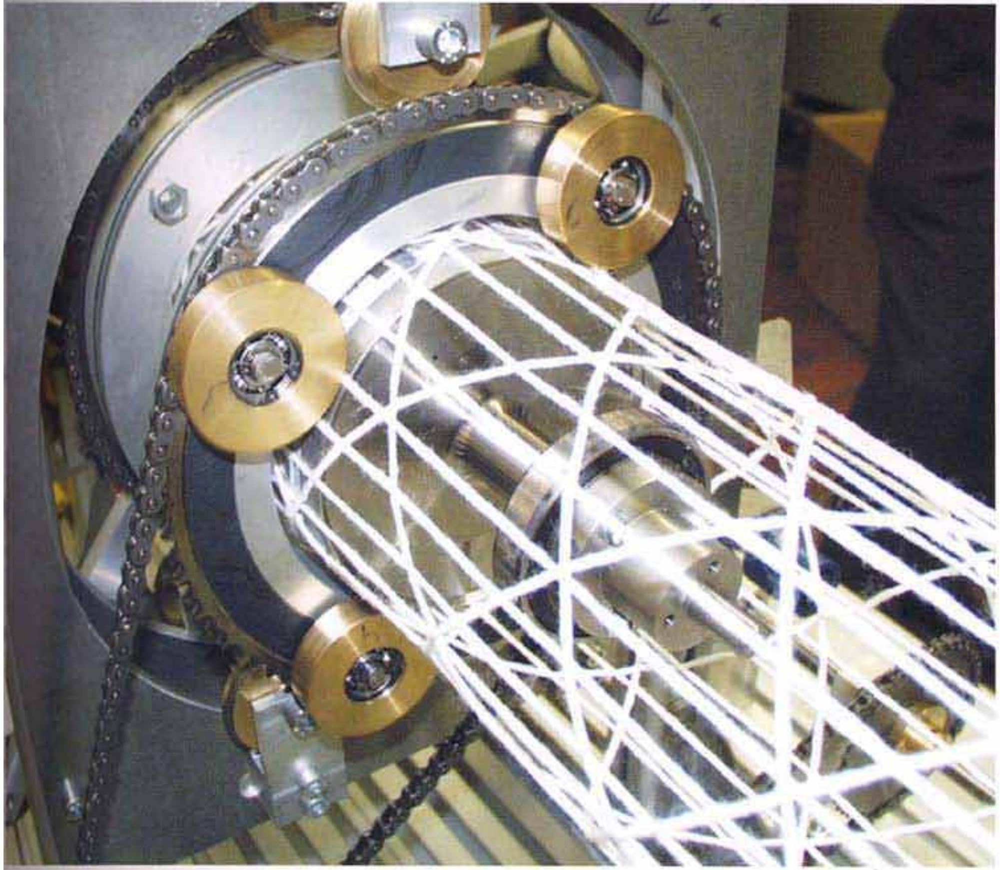


fig. 34 (right below)
I-beam
Designed by Thomas Campbell, textile
designed and manufactured by Foster-
Miller Inc., manufactured by ACME
Fiberglass, sponsored by the National
Cooperative Highway Research Program
under the Innovations Deserving
Exploratory Analysis (IDEA) program
U.S.A., 1997
Carbon fiber composite
Courtesy of Foster-Miller Inc.

The composite I-beam was designed to extend an existing bridge by attaching a cantilevered pedestrian walkway as a retrofit, where traditional steel and concrete construction would be too heavy.



figs. 35–37
Ultrasonically welded tubular fabric
Designed by Prof. Dr. Thomas Gries, Dr. P. Stockmann, A. Roye, Prof. Dr. D. Eifler, Dr. G. Wagner, and S. Kruger; engineering partner Pfaff Industriemaschinen AG
Germany, designed 2001,
manufactured 2005
Seamless circular non-crimp ultrasonic welded tube of stretched yarns of 90% AR (alkali-resistant) glass and 10% PP (polypropylene) fibers
Diameter: 12 cm (4¾ in.)

Winner of the Techtextil 2003 Innovation Prize, this ultrasonically welded tubular fabric is one example of a textile being used to enhance the safety and structural performance of building materials. Designed as a reinforcement textile for concrete, the multi-axial, multi-ply tubular fabric would give normally brittle concrete increased strength, energy absorption, and two-way bending ability. As a replacement for steel reinforcements, it drastically reduces weight, and can be fabricated on site. The plastic portion of the yarn is joined by softening the thermoplastic components at the intersections with an ultrasonic welding wheel.

EXTREME TEXTILES
DESIGNING FOR HIGH PERFORMANCE

Stronger, faster, lighter, safer, smarter—these are the textiles of tomorrow. From the carbon-fiber composite bicycle frame to the cardiac constraint sock and the Mars *Pathfinder* lander airbag, material innovations surround us. Our landscape, our buildings, our vehicles, our clothes, and our bodies all benefit from these highly engineered performance textiles.

Accompanying a major exhibition organized by the Smithsonian Institution's Cooper-Hewitt, National Design Museum, *Extreme Textiles: Designing for High Performance* surveys the stunning variety of technical textiles and examines how their intrinsic beauty and extraordinary flexibility are revolutionizing contemporary design. *Extreme Textiles* features examples of fully realized projects and products from architecture, apparel, medicine, transportation, sports, aerospace, and the environment and highlights the remarkable collaboration between science and industry. Vibrant illustrations and essays by some of today's most influential designers and scientists trace the developments made in textiles over the past century and suggest what is to come. As these new materials continue to provide inspiration and new possibilities for design, textiles will increasingly become the foundation for the world around us.

Smithsonian
Cooper-Hewitt, National Design Museum

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