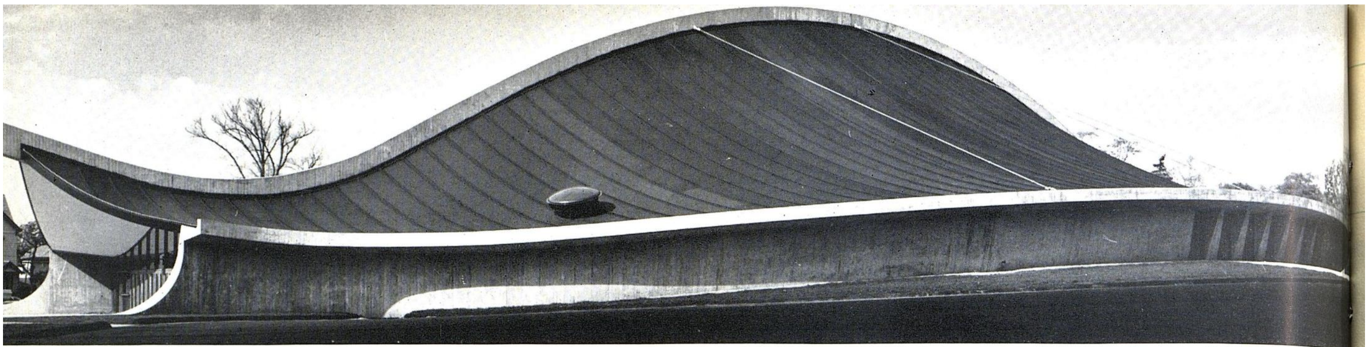
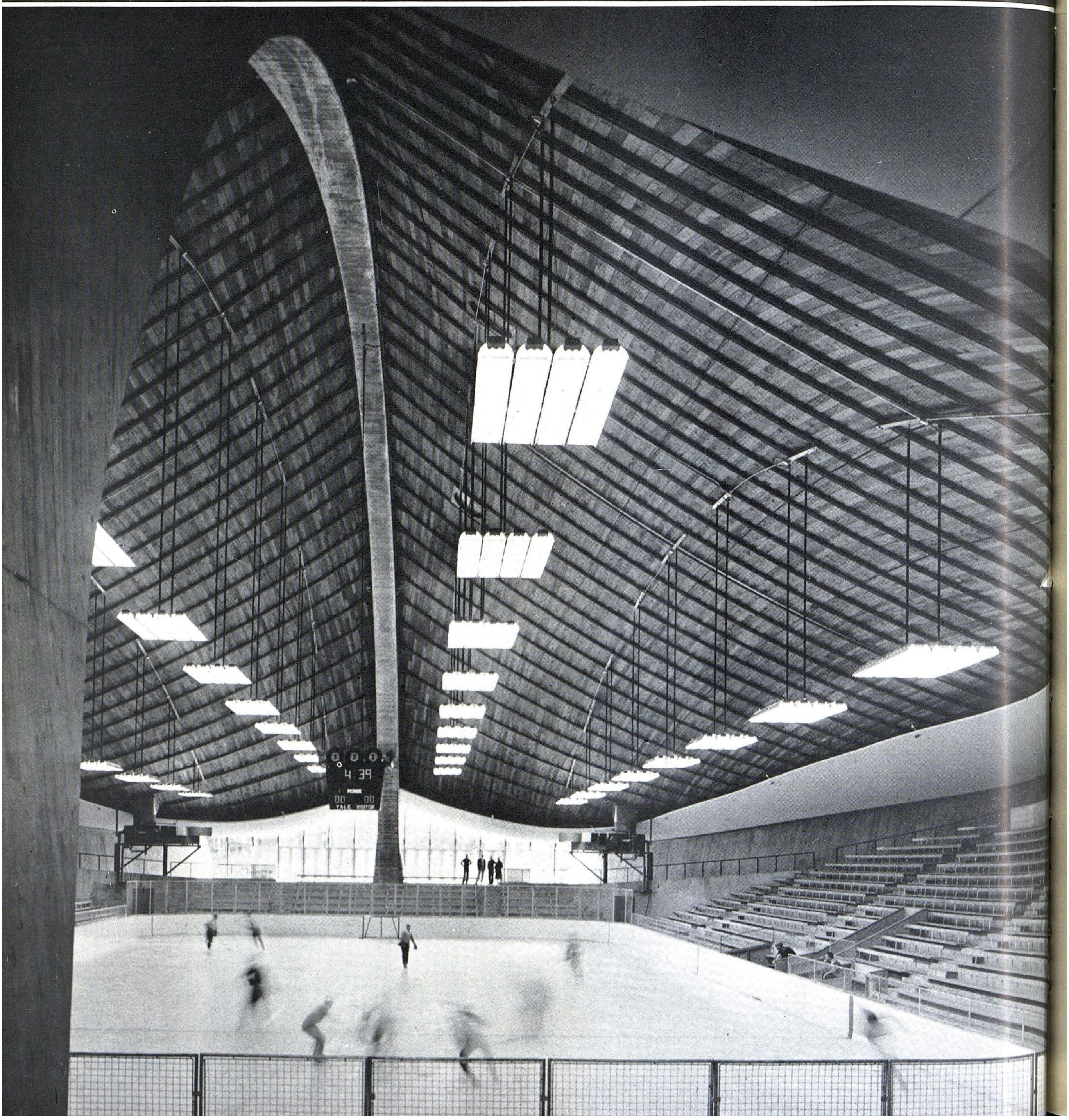




Robin Boyd

UNDER TENSION

Eero Saarinen's Yale Hockey Rink, 1, 2, opposite was one of a group of crucial buildings designed in the middle fifties, in which tensile construction passed from the status of an engineering novelty to that of architecture. In the article below, Robin Boyd, himself the designer and occupier of a suspended-roof house, considers the rise of tensile architecture in the light of a recent book by its outstanding visionary and philosopher, Frei Otto, *Zugbeanspruchte Konstruktionen*, published by Ullstein in Berlin.

World War II created a diversion which allowed modern architecture to escape from the box practically unnoticed. Before that, no matter how freely any walls might wander or curve, the final enclosing element—the roof—was essentially box-like: a flat lid. In the architectural Standing Orders of the war period, *Space, Time and Architecture*, Giedion could write, 'The dome of San Lorenzo presents the case of an architectural vision that goes to the very end of constructional resources. The situation today is just the reverse. There are available to us constructional possibilities which we have not been able to exploit to anything like their full extent' (p. 61). He referred to 'the unsolved vaulting problem of our period,' and advised, 'All that is needed are architects who know how to stir the imagination of the engineer' (p. 407). In no time after this the stirring began in earnest and Giedion must have felt at times like biting his tongue off. One by one the *avant-garde* looked up to the roof. Overhead, out of reach of the practical hands of time-and-motion experts, was exciting promise of an honourable escape from the functional discipline.

In short, what happened during the wartime pause in building was a transference of attention from walls to roof. Although the architects might not have realized it at the time, the significance of this change of emphasis was that it made necessary a *rapprochement* between the master designers: the architect and the engineer. Earlier twentieth-century essays in plastic form were tentative enough to be muddled through practically without consultants. Gaudi's and Mendelsohn's plasticity was as superficial as a thick sauce poured over conventional structure. Even the wanton walls of the common-room at the *Pavillon Suisse* were roofed by a thick flat slab, the computations for which would not baffle the most modest architectural office. But the idea of plastic structure in a roof curving threateningly overhead demanded much more than schoolboy mathematics and sent the architect, about 1950, back to the engineer, humble if not yet completely cap-in-hand.

The engineer's response was good. As a matter of fact while he was away working on his own he had developed, after some sad failures, a proficiency in two important new branches of structure. One of these was shell concrete, which had hardly been used in building apart from the parabolic vault of Maillart's Cement Hall in 1939. Its unexplored prospects seemed enormous, especially when one thought of possible applications of advanced solid geometry—and the engineer could help the architect here too, by actually suggesting shapes. The excitement that followed has already been discussed (in 'The Engineering of Excitement,' AR, November, 1958).

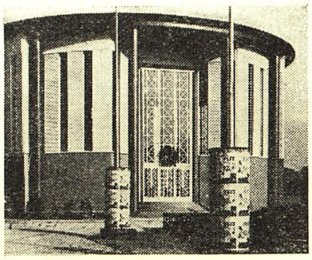
The second branch of engineering structure that had been practically ignored by architects was in some ways even more exciting. This was tension. The principle of tension structure was not new, of course. Its use goes back behind the grass rope spans across Tibetan gorges to some of the earliest human shelters slung between trees. Even in terms of modern engineering it was old. Steel suspension bridges were some of the proudest and most spectacular exhibits which the engineering profession produced at intervals over the century after Thomas Telford's Menai Strait bridge of 1826. Nor was tension a new principle in everyday building construction. For centuries it was well understood that the most conventional structures harboured tensile stresses, and that their strength could be greatly boosted by introducing metal at points so affected, preferably when no one was looking. Older than the chains that bind St. Peter's dome are numerous buildings that can now be called tension structures by virtue of their reliance on iron tie-rods and S-plates.

Every conventional structure nowadays has some members that act at least some of the time in tension, just as every one of the buildings which we now call tension structures have some compressive members. What distinguishes the latter type is not simply a higher proportion of tensile members, nor an architectural emphasis on these. The key is flexibility. A structure seems to qualify for the tension title if its main members are by nature limp, worthless in compression, and rely on tension to hold them rigid enough for the job in hand. Cables, rods and thin steel flats have been its usual media in recent years. Even on these terms, tension was not new in 1950. The idea of making suspended flexible cables an architectural theme was pioneered between the wars by Simon Breines and Joseph van der Kar in their entry for the Palace of the Soviets competition in 1932, and by Bernard Lafaille in a French Pavilion built at Zagreb in Yugoslavia in 1935. The latter gave a bold demonstration of the simplest kind of suspended roof. It was a cylindrical building covered by a shallow saucer of sheet steel resting on a single cartwheel of cables—the form probably used by the Romans for the *velarium* over the Colosseum.

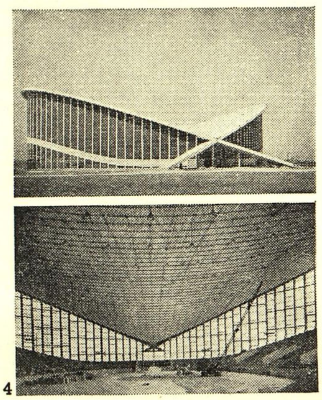
The Zagreb pavilion was a building of considerable temerity which was apparently protected by its comparatively modest diameter of 110 feet. It innocently ignored the problem which today preoccupies much suspension design. Fifteen years after it was built, when architects began to examine cables again as a means of climbing out of the box, the innocence was gone. The image of serene catenary curves was haunted now by a nightmare vision of Tacoma Narrows Bridge. The vision was of an elegant half-mile ribbon of hanging roadway fluttering in a medium wind, undulating, and finally racking itself to bits. The ugly tangle in the Tacoma water in 1940 was a terrible lesson not to underestimate the phenomenon of flutter.

The problem in building roofs was to find something more positive than the simple action of gravity to counter the upward pull of the suspension cables. This led to the idea of introducing more cables with a counter—downward—pull, thus developing a dynamic equilibrium irrespective of gravity. This might be marked as the subtle point of change between suspension and tension structure.

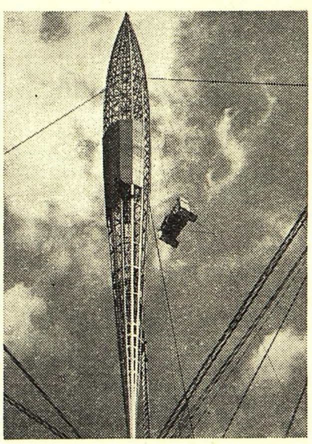
One of the first buildings to adopt the principle, and quite the first one to break into the architectural press, was Matthew Nowicki's livestock pavilion at Raleigh, North Carolina, in 1952. It deserved its fame, for it was essentially and eloquently a tensile concept, as single-minded as a student's project in cane and rubber bands. What was more, it worked. Its saddle of prestressed counteracting cables weathered two major hurricanes shortly after completion, and laid the spectre of Tacoma.



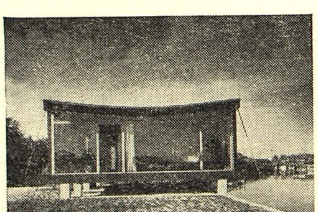
3, *exhibition pavilion, Zagreb, 1935. Lafaille's steel velarium concealed in a classical drum.*



4, *state fair pavilion, Raleigh, North Carolina, 1952, first of the modern suspended roofs; Nowicki and Severud.*



5, *Skylon, for the 1951 Festival, London, by Powell and Moya; an early popular success in tensile structures.*

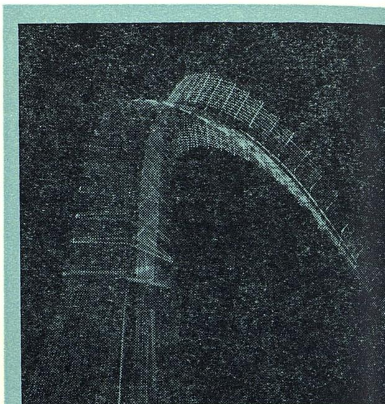


6, *house in Florida, by Rudolph and Twitchell, 1954; instrumental in launching both Paul Rudolph and small tension structures.*

Fred Severud, who supervised the pavilion after Nowicki's death, went on immediately to less fashionable success with a weighty concrete-composite saddle over a cafeteria at the Corning Glass Works, designed by Harrison and Abramovitz. Frei Otto, who visited Severud during the work at Raleigh, went home to Germany to build, and encourage the building of, several tension roof structures, and to celebrate the arrival of the new structural system in *Das Hangende Dach* (The Hung Roof) published in 1954. Otto stressed the problem of anchoring tension structures, explaining that the economies gained in the lightness of the span may be lost on the buttressing required to hold the ends, and he suggested tying the ends of tension cables to existing natural or artificial buttresses: for instance, roofing a valley by anchoring cables in the surrounding hills.

Yet, as often happens, the roving eye of the progressive architect was not caught by these worthy attempts to conquer the structural and economic complexities so much as by one or two quite modest structures which ignored most of the engineering problems, but caught the spirit of tension with style. One of these was Powell and Moya's Skylon of 1951 for the Festival of Britain, the 'dangerous toy' whose suspended cigar demonstrated effectively the aptitude of tension for acrobatic balancing feats. Another about the same time was even smaller: Twitchell and Rudolph's tiny house of about 800 square feet on the edge of a Florida bayou, a glass box shaded by louvres and covered by a catenary bow that shot Paul Rudolph, in his early thirties, into the front rank of the rising generation of post-war architects. The span of the catenary was so small—less than 22 feet—and the effects of wind buffet and suction consequently so slight, that the structure could get away without stabilizing devices. The steel flats supporting the roof deck hung simply, almost limply, between wooden posts which were guyed back by steel rods to the ends of protruding floor beams. The beams, rods, threads, plates and nuts were all openly displayed. Because of the diminutive scale the structure had no engineering excitement. Moreover it did not carry resounding conviction from the logical or practical points of view, for there are easier ways to span 22 feet. The success of this nice little cabin was won entirely on architectural grounds. It was an early demonstration of the essence of tension structure in visual terms. It threw some light on a neglected branch of architectural aesthetics, in which complementary values to those of conventional compression structures might apply.

Every traditional ethnic division of architectural beauty one can bring to mind was based on some sort of empathy with earthbound solidity and stability. The modern movement's rebellion against such conservatism rather fizzled out after a bold start with pilotis and cantilevers. The attraction of those devices to artistic



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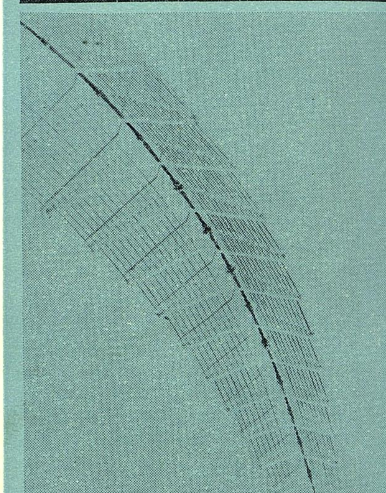

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The tensile and pneumatic inventiveness of Frei Otto

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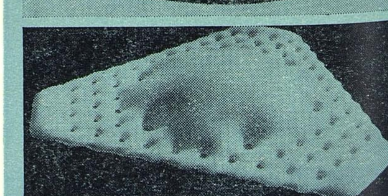

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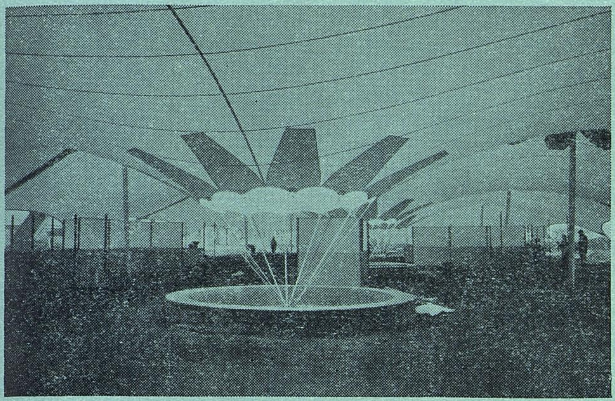
rebels of the early twentieth century was that they enabled mass to have practically no visible means of support. They borrowed the excitement of the magician's art of levitation, and the effect usually was a statement of defiance of the classical rules, even without the non-supporting caryatids of Highpoint. The architectural quality of tension structure is clearly different again. The means of support are likely to be as apparent in their own distinctive way as a row of classical columns. Tension is not the way of the magician, but of the trapeze artist, on the breathtaking high wires under the big top.

The rational enjoyment of architecture would be increased if one could subscribe unconditionally to Nervi's statement that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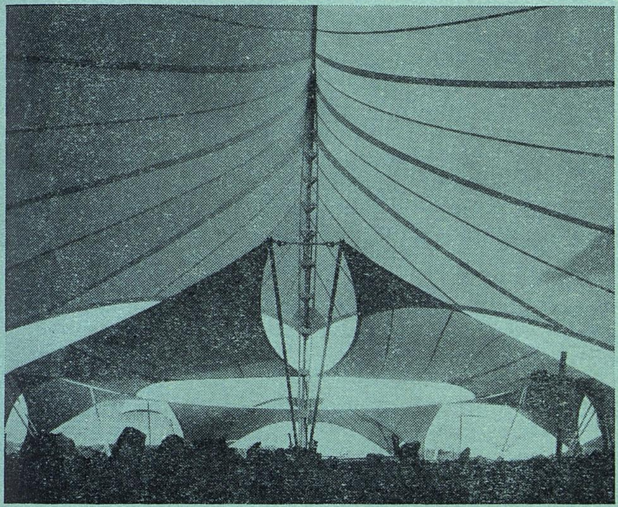
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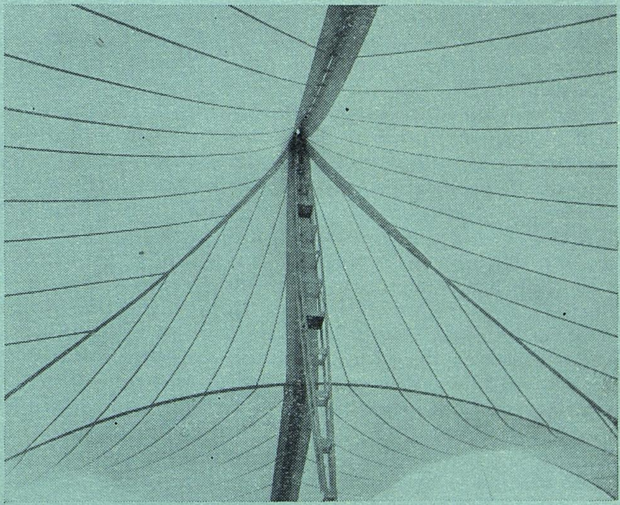
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7, 8, flexible jib of swan-neck crane project. 9, 10, two projects for pneumatic structures, the upper membranes restrained by internal guys to give a quilted form to the envelope.

11, 12, 13, 14, elements of support and restraint in typical tented structures developed by Frei Otto and his colleagues at the Entwicklungsstätte für den Leichtbau, Berlin. 12, the cafe at the Interbau exhibition, Berlin, 1957; the others are details from various tented structures at the Hamburg Garden Exhibition. 15, 16, tents by Frei Otto; at Interbau and Hamburg.


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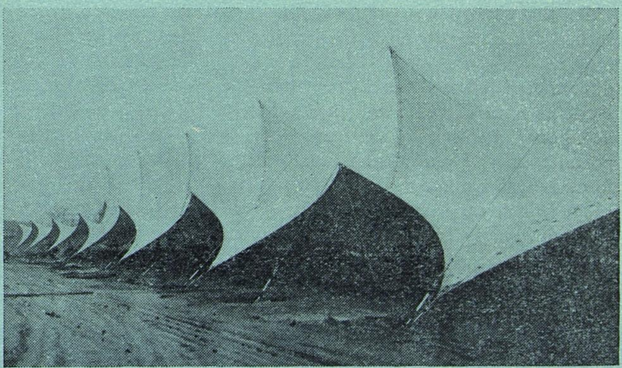
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'the intuition and sensitivity to statics which in a more or less confused form may be found in all people are satisfied by those structures which immediately reveal the play of forces and resistance. . . .' Unfortunately some admirable compressive structural systems are inherently secretive. Both sides of a concrete shell, for instance, can never be seen at the same time. Thus even the eye of the *cognoscente* has no means of judging how elegantly thin or clumsily thick the shell is and must rely on prior information or the unreliable evidence of the edges. But in tension structures, at least, the play of forces and resistance are instantly revealed under normal circumstances. Unless the structure is shamefully clothed, tension is inclined to explain itself in a most articulate way. The tensile member communicates its task and some impression of its load with clarity to the dullest child familiar with the behaviour of string or wire in his toys. Such thin members cannot conceivably be pushing; unquestionably they are pulling or being pulled. And the way such thin pieces drape themselves, or droop under weight, or bend suddenly at point loads—or if freed spring straight to the shortest cut between two points which want to separate—this behaviour makes up the language of tension.

A few short essays or statements were made in this language in the early nineteen-fifties. It was the season for tension. Students laboured over projects in matchsticks and cotton. Progressive designers strung almost anything from the ceiling: bookshelves, tables, shop counters. Three separate continuous catenary systems were used for a house near Melbourne by Kevin Borland with engineer Bill Irwin in 1952. They were made by draping reinforcing mesh over convenient supports and spreading a thin layer of concrete on top. With spans of modest scale and methods of guying back at the ends literally down to earth, the tension structure proved to be a manageable and remarkably economical challenger to any of the cheapest conventional cottage constructions.

By this time it was apparent that two rather different practical applications of tension were emerging. One was two-dimensional, as used most directly in the Rudolph house. In this the tension system acted only in a series of vertical planes, or portal frames. Usually each of these was formed by a catenary slung between two props which on the outside were guyed back diagonally to some kind of ground anchor.

These portal frames were then connected laterally by conventional rigid ties. This system promised immediate economical, utilitarian results within the capacity of ordinary building practice and applicable to ordinary buildings, multi-roomed and rectilinear. In the second application, as seen in the Raleigh livestock pavilion, the tension system was three-dimensional, finding equilibrium between counteracting pulls from all directions. Usually the tension members were flexible cables and the cradle to which they were anchored took a fine exciting shape in solid geometry. This system promised to be the more glamorous sister, applicable mainly to the enclosure of big public spaces whose functional shape was more or less indeterminate.

In 1956 in Melbourne Bill Irwin was engaged on a major structure of each kind. In the first category, he completed an Olympic swimming stadium with architects Borland, Peter McIntyre and John and Phyllis Murphy, and with the architects Yuncken Freeman he began the three-dimensional Sidney Myer Music Bowl. The pool building was exemplary 2-D tension design. The compressive props were sloped at about 35 degrees and were the principal functional members of the concept, for they also carried the spectator seating, facing the central pools. The back guys dropped vertically. The roof between the props was not made of flexible cables, for too much vibration would have carried through to the seating. Instead the wide space was spanned at each structural bay with a light diamond-shaped truss, which was stiff enough to resist objectionable vibration. Tightening of the vertical guys post-tensioned the horizontal trusses.

The music bowl shelter was an equally good example of 3-D tension. It lay within a fold of parkland that offered ground anchorage on three sides to a tension roof whose purpose was to shelter an orchestra stage and a few thousand people in favoured seats. Only two compression members were required. They finished as cigar-shaped props to hold a mouth open on one side to a larger audience on the lawns behind those seated. The cables were strung in counteracting tension, as at Raleigh. The main, longitudinal, members swept up from the ground at the rear of the stage to a massive cable strung over the props and forming a lip to the mouth. Lateral cables were pulled over the top and tied down each side. The shape was not precisely predetermined.

Cable lengths were adjusted to mould the form to the architect's taste and the engineer's two guiding rules: to maintain a double curve at all points and something close to a right angle at all cable crossings. Finally the upper cables were tightened, pulling down on the draped longitudinal cables and prestressing the system. The covering of aluminium-faced plywood panels was tailored to the cable grid. The heaviest live load that ever strikes the structure in practice puts the system, not into greater tension but into compression, since the long, draped lower cables suffer an additional tensile load which is only a fraction of the relieving or compressive force enjoyed by the upper cables.

About 1957 both the freshly proved kinds of tension structure were applied in many buildings throughout the world. Two-dimensional systems were adopted by some airports for no reason but economy. At Kansas City, for instance, acres of column-free housing for aircraft were created by hanging corrugated concrete roofs of enormous size like wings from either side of an unimaginatively utilitarian workshop block. Also in 1957, Hugh Stubbins promoted the simple cross-cabled saddle to its first monumental task, in the Congress Hall of Berlin. Somehow it did not seem ideally cast for the role, and the inherent delicacy in the light roof was finally lost in concrete compromises with the massive structure below.

In the year 1958 developments came faster. Eero Saarinen completed his famous Yale hockey-rink, with its central humped spine and symmetrical saddles, a characteristic piece of his Expressionist sculpture in extension of an engineering concept. Saarinen managed to retain the lightness of the cable web, and almost made the tensile and compressive elements jell into an architectural whole, although three stabilizing guy wires to the top of the spine on each side stood out rather rudely, refusing to accept the architect's discipline.

Also in 1958 another celebrated architect tried his hand with tension: Edward D. Stone built the US Pavilion at the Brussels Fair. He introduced a sub-category of three-dimensional tension structure. This type embraces all the different attempts in the last five years to rethink and perfect the earliest and simplest form of tension roof: the wheel over the pill-box. In the past the wheel was simply a cartwheel made with flexible, radial cables. This soft cartwheel was draped, Dali-style, over open space.

It trusted to gravity to hold it down and to luck to keep it from excessive vibration. About 1957 some rather crude if successful efforts were made to prestress it. For instance the soft cartwheel over a circular stadium at Montevideo, designed and built by L. A. Mondino, L. I. Viera and A. S. Miller, was loaded with thousands of bricks during construction. While thus extended, the precast slabs that lay on the cables were grouted; then the bricks were removed. The main advance at Brussels was that stability came from a geometrical cable system capable of being prestressed.

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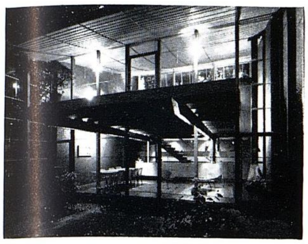

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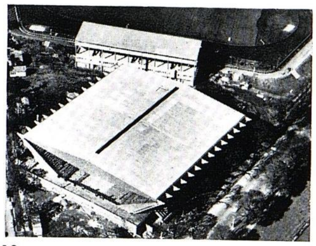

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UNDER TENSION

17, *house near Melbourne by Kevin Borland; engineer, Bill Irwin.*
18, *Robin Boyd's own house, Melbourne (see also AR, November 1960).*
19, *Olympic Stadium, Melbourne, by Borland, McIntyre, Murphy and Murphy, with Bill Irwin as engineer.*
20, *the great triumph of Bill Irwin and the Melbourne School—the Sidney Meyer Music Bowl, Yuncken and Freeman, architects.*
21, *roofs of Bavinger House, Norman, Oklahoma, by Bruce Goff.*

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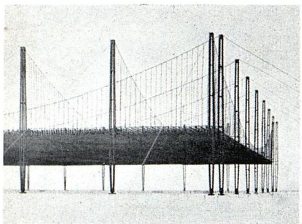
UNDER TENSION



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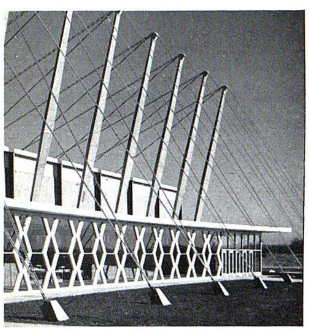
22, projected exhibition-hall structure, Chicago, by Alfred Caldwell.
23, 24, Central Washington College gymnasium, by Ralph Burkhard; engineers, Anderson, Birkeland and Anderson.
25, pneumatic pavilion for the US Atomic Energy travelling exhibition; architect, Victor Lundy; engineers, Walter Bird and Fred Severud. This was the largest of a series of major structures in which Bird, and his Bird-Air system, have been involved (see also illus. 31).



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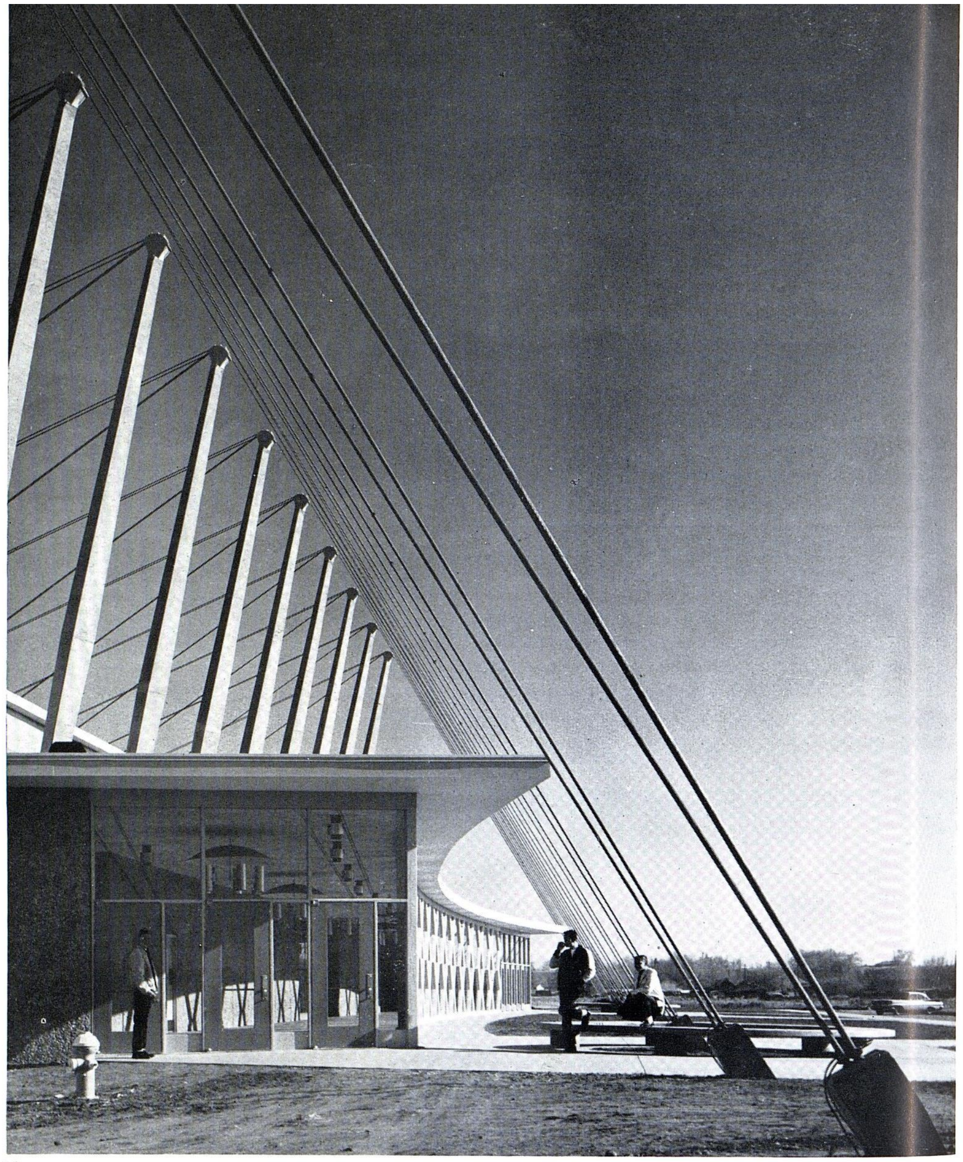

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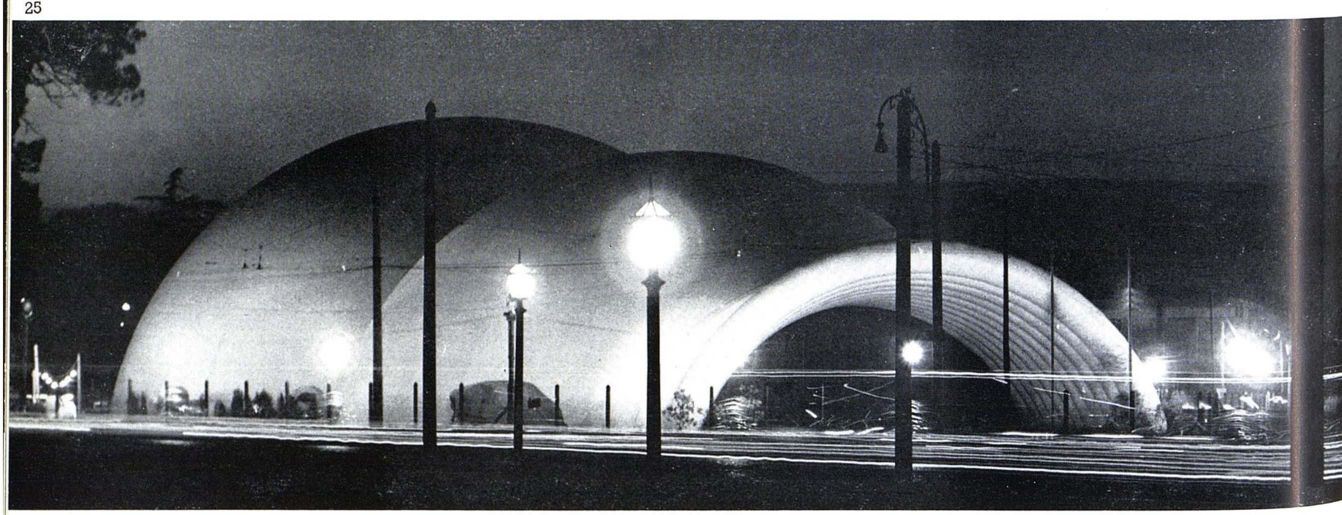


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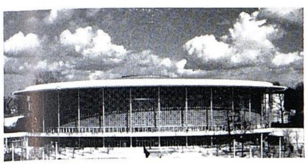
26, *Congress Hall, Berlin, by Hugh Stubbins and Associates.*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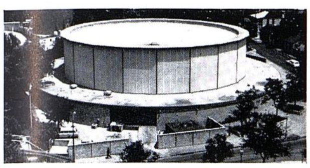
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27, *Utica Memorial Auditorium, by Gehron and Seltzer, employing Lev Zetlin's system of unequal pretensioning.*

28, 29, *US Pavilion, Brussels exhibition, by Edward D. Stone.*

30, *Villita Assembly building, San Antonio, O'Neill Ford and Associates.*


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31, *Tent theatre, Boston, by Carl Koch and Margaret Ross; engineers, Walter Bird and Paul Weidlinger.*

32, *Schaeffer Centre Exhibit project, by Eggers and Higgins with Walter Dorwin Teague.*


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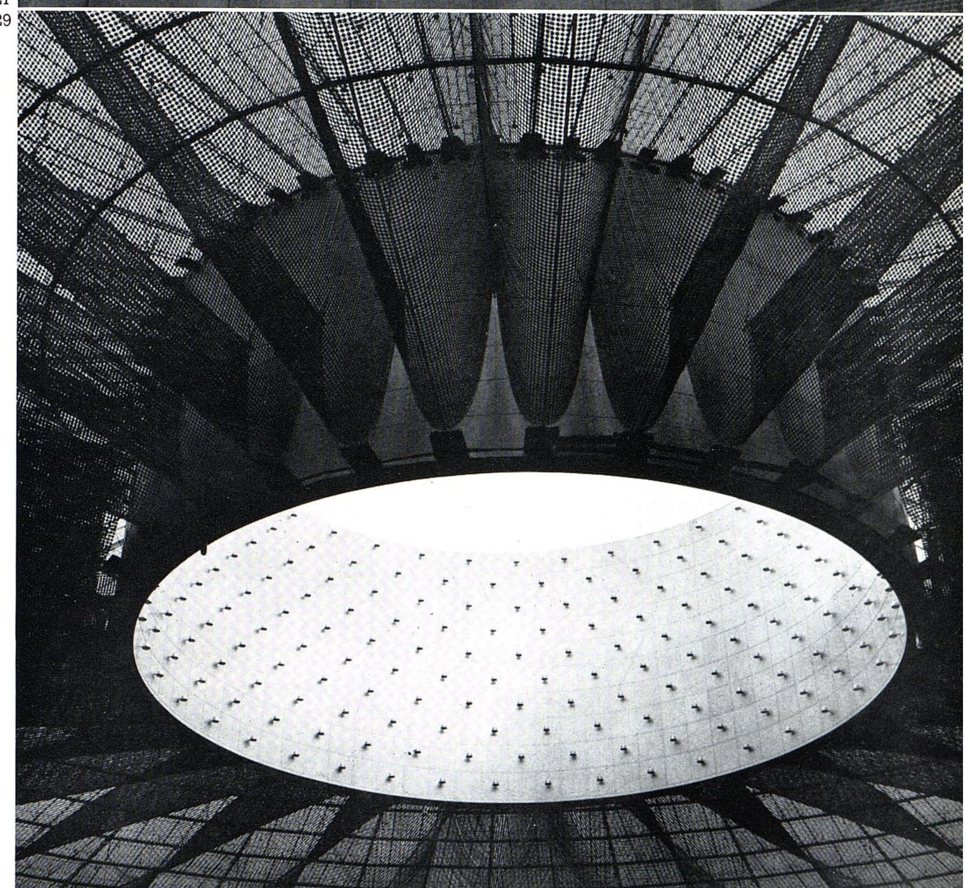

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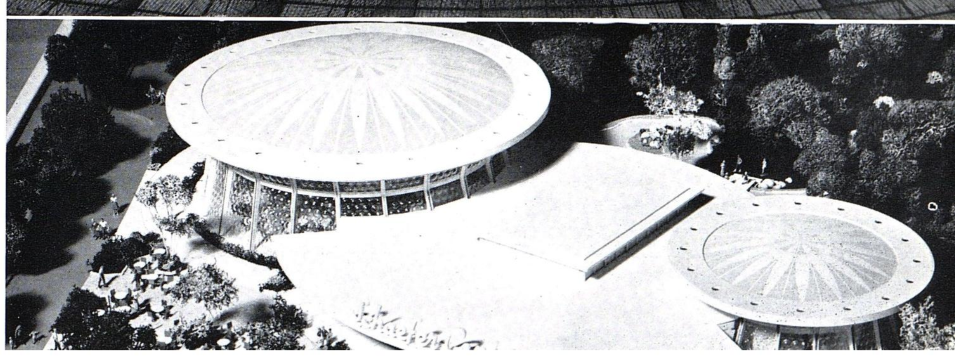

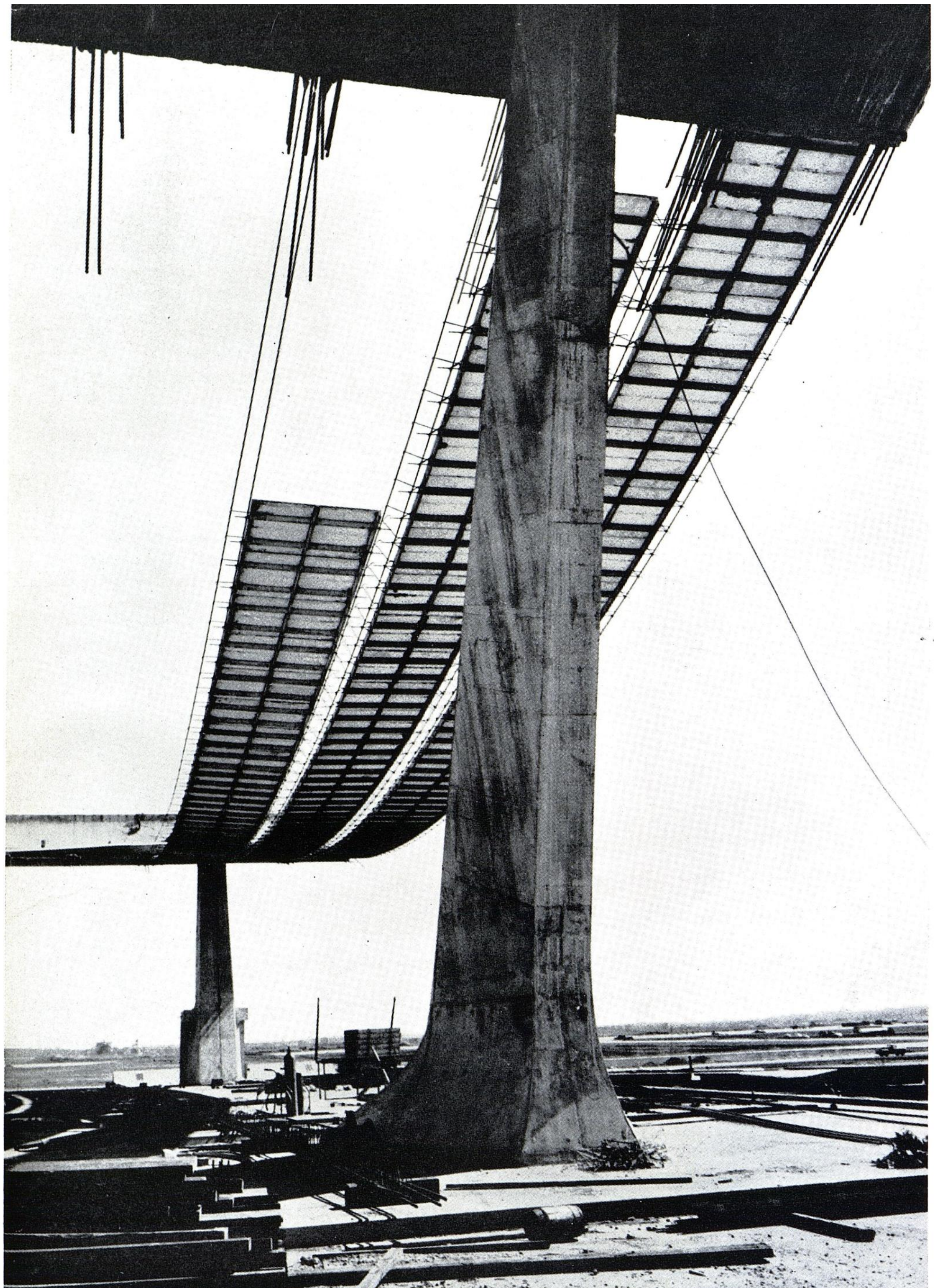

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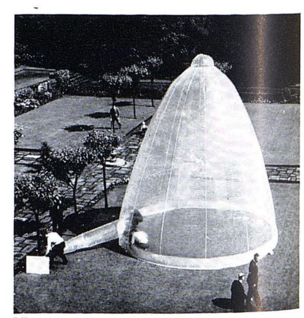
UNDER TENSION

33, 34, two-dimensional suspended roof of Washington (Dulles) airport terminal, by Eero Saarinen and Associates, the most elaborately monumental use of a plain hangende Dach *to be made so far in any part of the world.*

35, transparent plastic pneumatic dome of parabolic section; experimental project by Arthur Quarmby and students at Bradford Regional College of Art.



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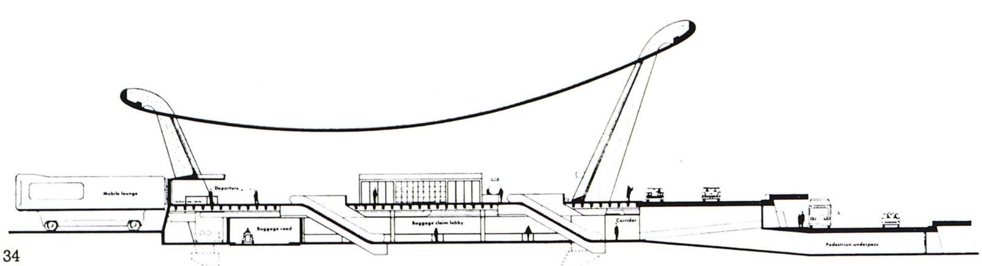

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The 330-foot span of the pavilion was roofed with a double system of spokes, radiating from the top and bottom of a central cylindrical tension hub to an outer compression ring. It was a rigid, triangulated system, as in a bicycle wheel, which naturally was the name immediately given to this kind of roof. An incidental improvement was that the top of the roof was now conical instead of concave. Rainwater now drained to the outside wall where it could be disposed of simply. This eliminated the old embarrassment of having to convey the water that collected in the centre out to the perimeter by means of hanging pipes.

About the same time, engineer Lev Zetlin, working on the Municipal Auditorium for Utica in New York State with architects Gehron and Seltzer, invented a subtle improvement. He tied two systems of unequally prestressed cables together by rigid vertical spreaders. The natural frequency of each set of cables being different, they will be out of phase in any wind-induced vibration and one set will always damp out any vibratory tendencies of the other. Zetlin, patenting the system, remarked that it could be suitable for spans of any distance between about 200 and 1,800 feet.

Other new theories came to light in 1958. Led by Robert Le Ricolais at the University of Pennsylvania's school of architecture, students all over the world began exploring the field of tension and minimal surfaces, as demonstrated fascinatingly by the activities of soap films on twists of wire. Le Ricolais was not impressed by the wheel form, whether cart or bicycle, even over circular plans. He believed that triangular grid systems of cables without central tension rings were more promising.

Paul Chelazzi made one of the few proposals for the adaptation of tension principles to multi-storey building. He demonstrated a variation on an old device, which he called the 'Suspenarch.' This is a sort of coathanger for office floors. He proposed that it would sit on the top of the lift or service towers, erected first, and would drop tension cables to carry a stack of ten or so floors below. The 'Suspenarch' has a rigid top member bent in an arch and a cable connecting the ends, which sags the same distance as the arch rises. Arch and cable are connected at any suitable number of points along their length, and tension rods drop from the points of connection. The introduction of a light load-spreader like this, to substitute for a skyhook at the top of a building, improves the economical chances of tension in multi-storey work. Chelazzi became enthusiastic enough to envisage the idea developed in convenient stages up to a 300-storey tower, as innocent of architectural considerations as most visionary towers, including Frank Lloyd Wright's, have been innocent on the structural side.

But the man to leave all others behind in visionary projection of the tension idea was still Frei Otto. He pressed on from his studies of mechanically stressed membranes to the logical next step: pneumatically stressed membranes. His researches took two paths. One had been pioneered in Britain during the first World War by F. W. Lanchester, who realized that the increase in normal air pressure required to hold a big balloon inflated was slight enough not to cause discomfort to an occupant. During the second war this idea had been revived and in the nineteen-fifties balloon shelters served many practical purposes in a semi-experimental way. Blown-up plastic membranes were made as silos, sun-traps over pools, and shelters for conventional building operations in severe weather. The balloon shelter also had strong attraction for American travelling-exhibition designers, because it was the first structure since the teepee that could be rolled up and taken with you. In the US Atomic Energy exhibition which opened at Rio de Janeiro in November, 1960, a balloon consciously became architecture for perhaps the first time. Like a great, obese, waisted white slug it sprawled on the grass, the clever prophetic creation of architect Victor Lundy, with construction by Walter Bird, assisted by Fred Severud.

The other path of pneumatic structure pursued by Frei Otto was the way of the air-cushion. In this system the designer leaves the occupant normally pressurized but creates a rigid shelter over him by maintaining pressure between the double skins of a flexible covering. In its simplest, earliest form it was no more than a giant elevated circular air-cushion, supported all round, a technical advance along the same lines as the first dished tensile roof. This kind was elegantly demonstrated in an outdoor theatre built in 1959 for the Boston Arts Centre, again by Walter Bird, this time with architects Carl Koch and Margaret Ross, and engineer Paul Weidlinger. In more advanced applications the construction is divided up into some system of comparatively small and manageable pneumatic cushions.

Frei Otto took both these ideas and after much laboratory work with bewitching bubbles, cushions and balloons he published in August, 1962, the first comprehensive report on pneumatic structures, *Zugbeanspruchte Konstruktionen* (Tensile Structures). Although this book was labelled only Volume One, Otto blew up the two pneumatic ideas seemingly close to bursting point, producing a breathtaking collection of schemes for super-bubbles containing harbours, reservoirs or cities. He also examined balloons stiffened by concrete and a variation in the form of 'Sail Shells,' which may be catalogued about halfway between shells and balloons. He studied further the all-important details of ground anchors and he gave over the centre section of his book to a most thorough mathematical study of membranes under load by Rudolph Trostel. But the main interest in his profusely illustrated work still centred on the visual implications of pneumatic shapes, the bulbous curves that are familiar enough now in and around swimming pools expanded to vast proportions. In the course of his experiments he produced, with diverse practical demonstrations or applications in mind, multiple balloons with various strange effects. The most common was some fairly orderly geometrical variation on the buttoned cushion or rubber air-bed themes, but the more advanced suggested other images from modern life: perhaps an inner tube straining through a worn tyre, or an eiderdown after a sleepless night. The associations were invariably non-architectural. Frei Otto's book heralded a medium of building that has no apparent reference to any style known previously outside science-fiction, nor to any canons of taste or judgment, nor to any recognizable aesthetic experience.

Thus architecture has come to acknowledge tension as a major structural principle with unexplored applications and untold potentialities. Certainly it should be added to shell concrete and space frames in the top drawer of fine things for special occasions. But apparently, unlike the other two, it has more mundane value as well. It offers ample scope for visual inventiveness to maintain the interest of creative architects, and it holds out vague but tempting promises of economies to workaday builders. After 1958 nothing could hold back the steady growth of the tension principle wherever big spans were called for. A giant hangar at Idlewild Airport was built in 1959 at a cost claimed to be 60 per cent less than a conventional structure. In the same year, the first wholly supported cable structure on the west coast of the USA, a gymnasium at Central Washington College by architect Ralph H. Burkhard and engineers Anderson, Birkeland and Anderson, won a local AIA Award of Merit. In buildings such as these, tension structure was visibly growing more assured. The Tacoma traumas were past. Tension began to belong in the workaday building industry.

But even now tension is very young and carrying a load of youthful problems. It is inclined to concentrate on rather exhibitionist achievements and neglect its opportunities and duties in simpler fields such as housing. No significant development has followed its early successes in small buildings. Lacking co-ordinated research, its techniques are often quite crude: for example, the use of loads of bricks for prestressing even the smart-looking Villita Assembly Building in Texas. Then the novelty of some of the shapes is inclined to defeat them after a first successful showing. The most experienced architects, who should be coaxing the tension movement forward and helping to perfect its language, often will avoid using the striking shape again simply because it has been done before. Again, while schemes like Chelazzi's and Otto's send the mind racing ahead to all sorts of exciting possibilities, in practice tension is thwarted in many kinds of buildings by the requirements of fireproofing. The bulk of the thinnest fire protection tends to cheat the method of its main advantages in spinning silk-thin webs. More basically, from the engineer's viewpoint, the field of tension still has large unchartered areas. The behaviour of tensed materials is still by no means fully understood, even under laboratory conditions, not to mention the hazards of freak conditions in the field. The more enticing 3-D shapes usually cannot be analysed by conventional or any other known mathematical methods and the engineer sometimes must return to the spirit of the Middle Ages, feeling his way far out beyond the numbers. The architect of course is used to this sort of adventure, but nevertheless he would be happier to feel a confident engineer striding surely beside him in the dark. And even if the engineer was entirely confident in tension design the architect would still have plenty to do on his own account to reach understanding of the character of this reversal of familiar stresses.

The *rapprochement* between architect and engineer after World War II was welcomed immoderately by some idealists who believed that it heralded the end of the art-science split and the reappearance of a single master-designer: architect and engineer rolled into one, to the great benefit of building. But this worthy wishful thinking is hardly more logical than an argument that all other consultants—ventilating, acoustical, plumbing and so on—also should be rolled into the paragon. On the contrary, the extra complexities introduced by all the new structural methods are more likely to increase the number of separate building specialists. And if the architect is to justify his own position as the top specialist, the specialist designer and controller, he must do his homework. To be able to design successfully in tension he should understand at least the laboratory behaviour of tension, if only to know when to call the engineer. And no less urgently he should understand the visual qualities of tension character, which is a sort of negative version of compression character.

As already noted, the involuntary character of any correctly designed tension member is not pushing, but obviously pulling. A major part of the conscious area of architectural design in tension must come from the visible degree of the pull as shown most clearly by the curves of the cables or membranes, especially when a curve changes in mid-length under a change of load. The first aesthetic rule of the genre is that structural tension need not be transmitted into emotional tension. Structural tension's mood, conveyed primarily by the visible pull of the members, ranges from the exceedingly highly strung down to a relaxed droop. In the selection of tension for any job, the quality of the visible pull is worth at least as much consideration as the economics and the flutter.

Writing under tension, in a house with a tension roof built in 1958, I can suggest that there may be numerous reasons for adopting it not connected with economics or big spans. In the case of this house the tension was symbolic. Here was a family plan based on convictions of anti-togetherness: parents' and children's blocks were planned to be separated by a court for mutual privacy. Yet it was still intended to be one shared home, and a tension roof covering both blocks and spanning the central court to carry sunshades, seemed to symbolize this in a suitably naïve way. Today the cables almost literally hold the family together.

In tension design the candid exposure of the structure is more than merely a moral or artistic nicety; it is practically obligatory to the peace of mind of those sheltered. While an exposed tensile member is likely to communicate its task with remarkable eloquence compared with most stolid compressive members, concealed tensile structure is likely to produce forms which seem alarmingly defiant of natural laws, at least to eyes accustomed to compressive behaviour. The need for some sort of false ceiling may do the damage, as in the case of the neat bandbox of the Villita Assembly Building, where an almost continuous ring of tidy acoustic panels slung under the drooping cables at a contrary angle give a misleading suggestion of some insecure dome-like compressive structure.

For the same reason the frank exposure of tensile details is important to visual understanding. The joint between any two things in compression needs no explanation or celebration. The eye understands that the two things—suppose they are bricks—are being held together by the force. Now, it is often quite practical to treat joints between two things in tension with no more visual fuss than a joint between bricks. Perhaps they can be held together by a secret weld, or the joint may be hidden behind some sheathing. But the empathetic eye is undoubtedly made uneasy by such concealment. It knows the two things want to separate and is not really satisfied until it sees a firm grasp by one tensile member upon another, or upon something solid. Any direct and unselfconscious expression of this quality automatically produces the most eloquent explanation of the balance of forces. And the effect is so different from anything known in compression structure that it promises the emergence, if treated well, of a new detail style, architecture's first prehensile style.

More fundamentally, and much more importantly, the idea of tension seems now to be feeling its way to a formal expression, and this expression threatens the most cherished principles of form as known in this civilization. The predictable shapes of cabled membranes were an exciting novelty in the fifties, but even the hyperbolic-paraboloids were capable of conforming to known concepts of grace and beauty. Now some of the shapes proposed in the more advanced reaches of the tension movement overturn practically all accepted values. Far more organic than the state ever approached by the most poetic compressive structure, the pressurized building is made in the image of a blood vessel, in man's image, though not, it must be admitted, in the image of the nicest looking man one has ever seen. Perhaps only because they are so young and inexperienced the balloons often tend to look so old and fat. An unemotional constructivist approach to this kind of structure will frequently lead not to dullness but to a gross visual clumsiness which, seen through our conditioned eyes, can hardly be called anything but ugly. Yet in this kind of ugliness there may be one of the first really new keys to an escape from the historical vision that has been offered since the eradication of ornament. If that seems to be overstating the case, at least this can be said:

The salvation of architecture from its present backslide into irrelevant romanticism lies, most of us will admit, in the artistic understanding and development of all practical new ventures in building science. And tension now promises the most revolutionary means of broadening the genuine expressive range of the medium that has turned up since the romantic tail began wagging the modern architectural dog.