Wacław Zalewski: Shaping Structures

All designs and projects by Wacław Zalewski,
with collaborators as noted in exhibit text.

Edward Allen, Visiting Professor of Architecture and Building Technology
Exhibit Direction

David Foxe, M.Arch. Candidate
Design, Imaging, Text, and Coordination

Jeff Anderson, M.Arch. Candidate
Digital Project Reconstruction

With special thanks to:

Adèle Naudé Santos, Dean
School of Architecture and Planning

Yung Ho Chang, Head, Department of Architecture

Gary Van Zante, Curator of Architecture and Design, MIT Museum

Laura Knott, MIT Museum

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Force Diagrams for each project by **David Foxe** and **Edward Allen**

Additional video by **Paul Felopulos**

Physical models by **Edward Allen**


Wacław
Zalewski:
"...Geometry
is the mathematics
of structural imagination..."

Wacław Zalewski: Shaping Structures

Wacław Zalewski (VAHTS-wahff zah-LEFF-skee) was born in 1917. In 1935 he began his studies of structural engineering in Warsaw. Just before he was to receive his degree in 1939, German armies invaded and occupied Poland, making further academic work impossible. He joined the Polish underground army, as a result of which he was frequently forced into hiding for extended periods. These interludes provided ample time for him to reflect on his studies and read extensively about structural behavior. He soon looked beyond the narrowly mathematical curriculum he had been provided in engineering school to develop a strong interest in how the flow patterns of forces through structures might suggest more efficient structural forms.

In 1944, he took part in the ill-fated Warsaw Uprising against the Nazis. He escaped capture when this effort collapsed, but two members of his immediate family were killed in the punitive German bombing of Warsaw that followed. In 1947, he was able at last to take up work as a designer of structures. As his first projects were built, he developed another aspect of his philosophy of engineering: a strong concern for minimizing the difficulty and cost of construction. The dual goals of shaping structures according to their internal forces and designing efficient processes for their construction have been primary themes in Zalewski's work throughout his academic and professional careers.

In 1947, when academic records had been retrieved and reconstructed from the wreckage of the war, he received a master's degree in civil engineering from Gdansk Polytechnic Institute. After earning a doctorate in 1962 from the Warsaw Polytechnic, he accepted an invitation from the Universidad de los Andes in Merida, Venezuela, where he taught and worked as a structural designer for a period of three years. In 1966, he was invited to join the faculty of the MIT Department of Architecture, where he taught as a tenured professor until his retirement in 1988. He retained his connections in Venezuela for many years, however, and continued to design structures there during academic holidays and sabbaticals. He was awarded an honorary doctorate for his professional achievements by the Departments of Architecture and Civil Engineering of the Warsaw Polytechnic in 1998.

Zalewski's ongoing career as a designer of innovative structures is documented in this exhibition. He has been equally innovative in the classroom, where his teaching is characterized by its nurturing of imagination and creativity and its orientation toward finding good form for structures based on funicular forms and flow patterns of internal forces. He is coauthor with Edward Allen of an introductory textbook, *Shaping Structures* (Wiley, 1998), that is based on this approach.

In describing his design methods, he has stated that "The intellectual delights of...analytical procedures are very different from the sensuous pleasures of giving a structure its shape...Geometry is the mathematics of structural imagination." This exhibit is a celebration of his imaginative and richly diverse work and ideas.

This exhibition was organized for the Wolk Gallery at the MIT School of Architecture and Planning by:

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Nancy Dalrymple, Administrator
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Building Technology Group

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and many students for their insights, comments, and memories

1950s	1960s	1970s	1980s	1990s	2000s	**Years**
Poland	Venezuela	United States	South Korea			**Location**
Masonry	Unreinforced Concrete	Reinforced Concrete	Steel			**Primary Material**
Minimal Prefabrication	On-Site Prefabrication	Factory Prefabrication				**Prefabrication**
Structural principle specific to each project						**Structural Principle**

← This chart will provide an index to highlight the diversity of the various projects and buildings shown in the exhibit.

Inventive optimization in Wacław Zalewski's structures

introductory notes by David Foxe

Physical, visible form is both one of the strongest and the most deceptive aspects of Wacław Zalewski's incredibly varied body of work. For the past six decades of his professional practice as a civil engineer and a professor of structures, he has explored the shaping of structural form to solve specific problems of structural stability, conservation of material, and optimizing efficiency of construction processes. The work shown here gives an initial glance at some of the ways in which he has met these structural challenges. In pursuing such optimization and finding rational ways to bring these solutions to physical form, his work exhibits highly engaging uses of pattern, proportion, and light.

In his built projects and in his writings, Zalewski demonstrates a conscious acknowledgment of visual form and its influential nature, its power to captivate by providing a readily recognizable and memorable visual effect corresponding to abstract structural principles. Yet his work goes further in offering a perspective on how creating rational structure is not primarily a task of calculation or a mere result of unchanging rules, but rather a truly creative process that champions personal invention. He has often chosen to use ordinary projects and spans as vehicles for exploring mathematical and structural principles; he uses each project's particular requirements to investigate the underlying principle of optimization in shaping structures. Supermarkets can be places to experiment with funicular roof forms that eliminate the need for cable backstays, and industrial storage warehouses and factories can pioneer highly articulate and flexible prefabrication systems.

Zalewski's early works in Poland became widely known through his international publications and lectures from Paris to Berkeley, and were the foundation for his extensive projects in Venezuela, South Korea, Spain, and elsewhere. His method of structuring, a lifelong pursuit of demonstrating structural truth, is also particularly process-oriented. He has considered in great detail the sequencing and efficiencies of *building* – as an act, a verb – in each of these locations worldwide. This is highlighted in this exhibit by the preponderance of construction photographs and documentation which exist for these projects, and the relative scarcity of images of completed buildings.

His work is also the foundation for his inspirational teaching. In nearly four decades of teaching at MIT, Professor Zalewski's students and collaborators have benefited from both the basic and the advanced concepts in his work. His work with MIT students in the 1980s and early 1990s with deployable structures led him to be chosen to work as one of the designers of the Venezuelan pavilion at the 1992 Seville International Exposition, and his deployable truss for the pavilion hall and theatre was subsequently folded and taken back to South America so it could be redeployed for another use.

Zalewski's teaching and textbook collaborations with Edward Allen capture major portions of his ideas about how students should learn; he remains highly critical of both engineering and architectural education that all too often result in "passive attitudes toward research of rational forms...which constitute the essential task of studies and of construction projects." He has witnessed how problems relating to forces and construction processes can be the "Achilles' heel of architects" and has directed his teaching toward improving the ways in which students understand the inventive potential in shaping structures. At age 88, his wit and energy continue to inspire students with the fundamentals of geometric solutions to finding form. With the wisdom of a lifetime, his energetic pencil sketches, elegant mathematical simplifications, and demonstrations with objects as humble as umbrellas make for memorable teaching.

The architectural community has widened over time, and innovators who span architecture and engineering have gained increasing recognition for their structural art: Robert Maillart, Rafael Guastavino, Felix Candela, Eladio Dieste, and Santiago Calatrava are among these designers. Zalewski's work across the globe, in its many responses to local material and site constraints, shows his personal focus on inventive forms with diverse systems. Unlike the aforementioned designers, most of whom are known for their particular formal emphasis or their lifelong investigation of particular systems (unreinforced masonry in compression, in the case of Guastavino for example), Zalewski is far less easily categorized. His work can be understood on spectra rather than in pure categories, occupying one continuum spanning architecture and engineering, and another spanning theoretical mathematics and highly practical innovation. The buildings shown here, containing functions that range from the mundane to the celebratory, enclose spaces with structures that are truly architectural in that they show how a master's highly inventive work can elevate constructed tectonics. Zalewski has applied his optimization skills to shape structural solutions that are both rational and inspirational. In explaining the potential uses of the structural strategy employed at the Spodek hall in Katowice, the first project to the right, he describes this spirit of inventiveness:

> "The possibility for large...forms to be handled free from [ordinary] standing columns, vertical walls, and flat roofs, combined with the simultaneous task of finding a solution for functional and constructive problems, gives an occasion for creative invention. Such inventive possibilities, with both practical architectural tectonics and the artistic thought of antiquity, become the spiritual achievement of modern architects and engineers."

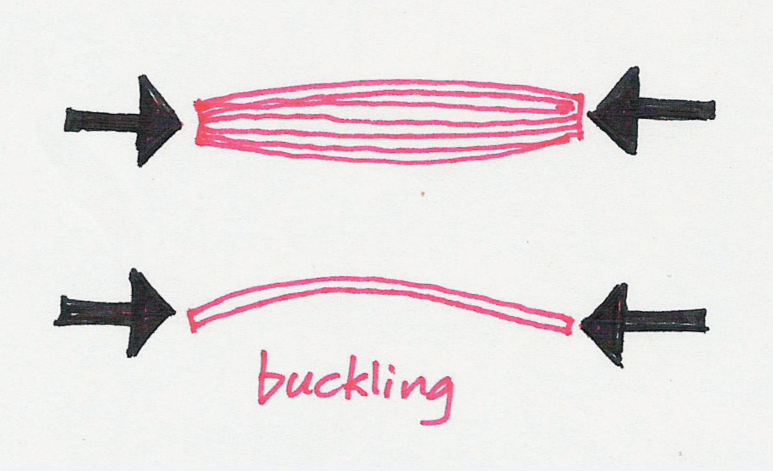
🡐 This view of the "Supersam" supermarket, under construction in Warsaw, Poland, shows the funicular roof system of tensile cables and compressive arches, with connecting members at various angles.

Structural Actions

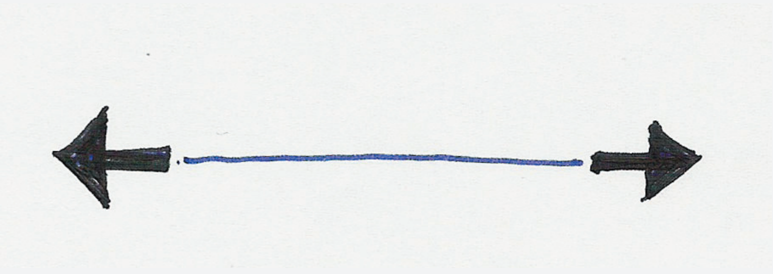
Any structural action, no matter how complex, can be reduced to just two types of forces, pushes and pulls.

A push is generally referred to as **compression**, and a pull as **tension**.

Compression can cause a slender member to buckle, so we will represent it with the color red to warn us of that potential problem.

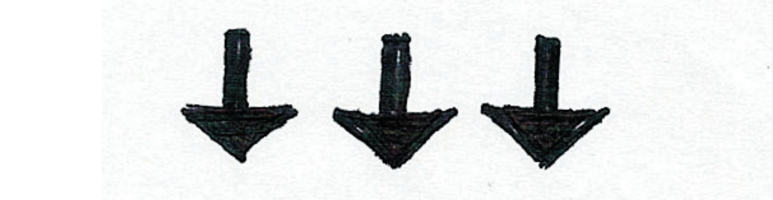


Members in **tension** cannot buckle; they only grow straighter as the pulling intensifies. We will represent tension with the color blue.

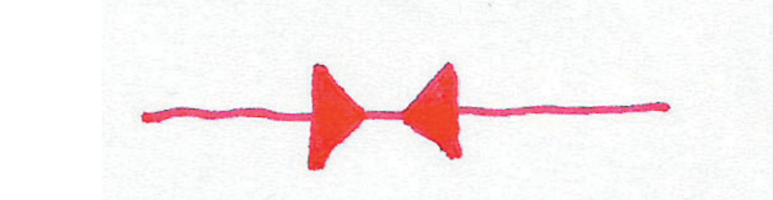


For each project in this exhibition, there is a simple diagram in the upper left hand corner that shows in red and blue how the structure utilizes pushes and pulls to support its load. In these diagrams:

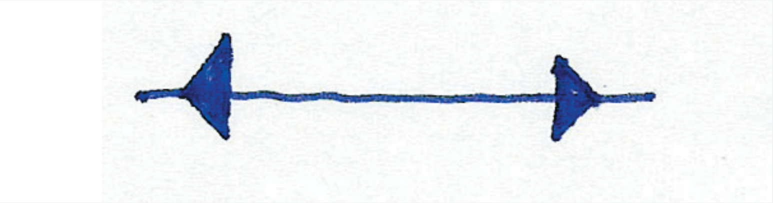
Black arrows indicate **external forces**.



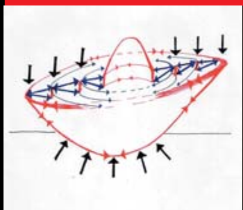
Red lines indicate pushes (**compression**).



Blue lines indicate pulls (**tension**).



Spodek

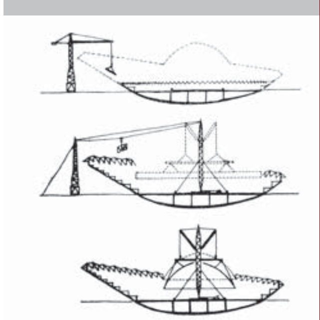


This multi-use hall in Katowice, Poland became nicknamed "Spodek," literally "saucer" in Polish, meaning "flying saucer" in popular usage. Its form developed in response to several factors: The bowl-like configuration of the seating area, which acts as an inverted dome, reduces the contact area between the structure and the ground. This would allow the entire building to settle as a single unit if the soil, which is honeycombed by old coal mining tunnels, should subside. The bowl exerts an outward push that is balanced by the inward pull of the roof cables at the perimeter. This balancing of pushes and pulls is a hallmark of many of Zalewski's structures.

The roof is the earliest known proposal for a cable structure based on the tensegrity principle, in which compression members are connected only to cables, and not to each other. A number of wire models of this structure were made to assess feasibility. After Zalewski's departure from Poland and prior to construction, the roof structure was changed to relatively conventional trusses.

The asymmetrical interior of the arena was designed to accommodate dozens of different interior configurations of both seating and event space to accommodate the wide variety of programmed uses. Since its opening the dramatically lit Spodek has hosted countless shows, sports events, and exhibitions, as well as concerts of popular music by international celebrities, including many American rock music groups. Collaborators on this project included architects Maciej Krasinski and Maciej Gintowt, as well as engineers Andrzej Żórawski, Aleksander Wlodarz, and Stanislaw Kuś.

↑ The half-constructed roof is viewed here from the interior of the building, looking up toward the center ring.



↑ This diagram of the proposed construction sequence was made prior to simplification of the roof structure.

↑ A scale model in wire was used for early load testing of the concept.

↓ Construction hoisting was done by a crane riding on a perimeter track.

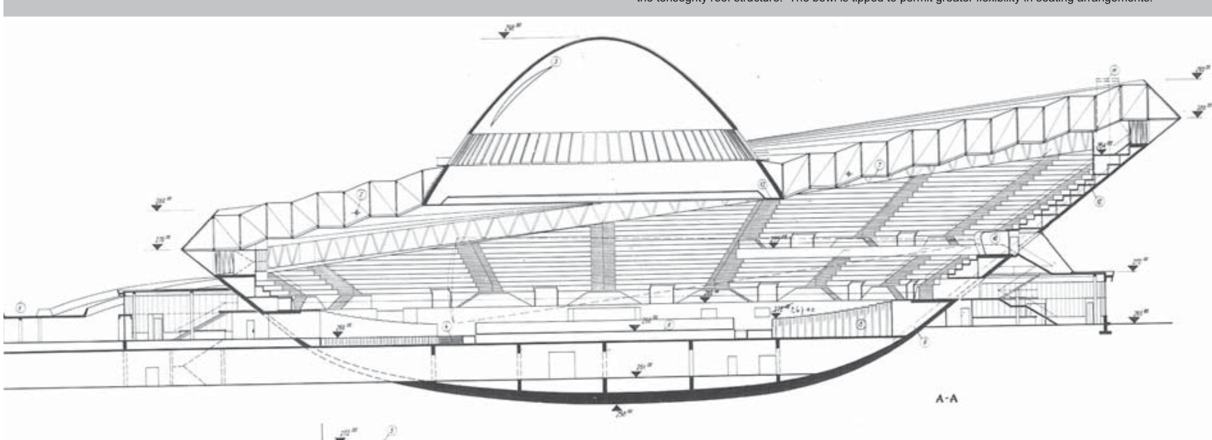
↓ These short columns are among those that balance the concrete bowl.

↓ This nighttime view was photographed shortly after the building's completion.

Years	1950s	**1960s**	**1970s**	1980s	1990s	2000s
Location	**Poland**	Venezuela	United States	South Korea		
Primary Material	Masonry	Unreinforced Concrete	Reinforced Concrete	**Steel**		
Prefabrication	**Minimal Prefabrication**	On-Site Prefabrication	Factory Prefabrication			
Structural Principle	**Discontinuous compression/tension cable roof on inverted dome**					

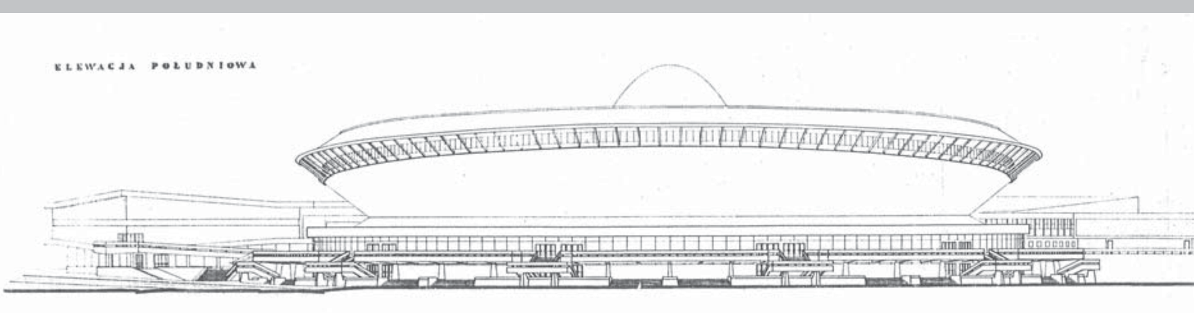
A view of the underside of the bowl (computational rendering).

This section drawing shows both the bowl of the seating structure and the original, more complex version of the tensegrity roof structure. The bowl is tipped to permit greater flexibility in seating arrangements.

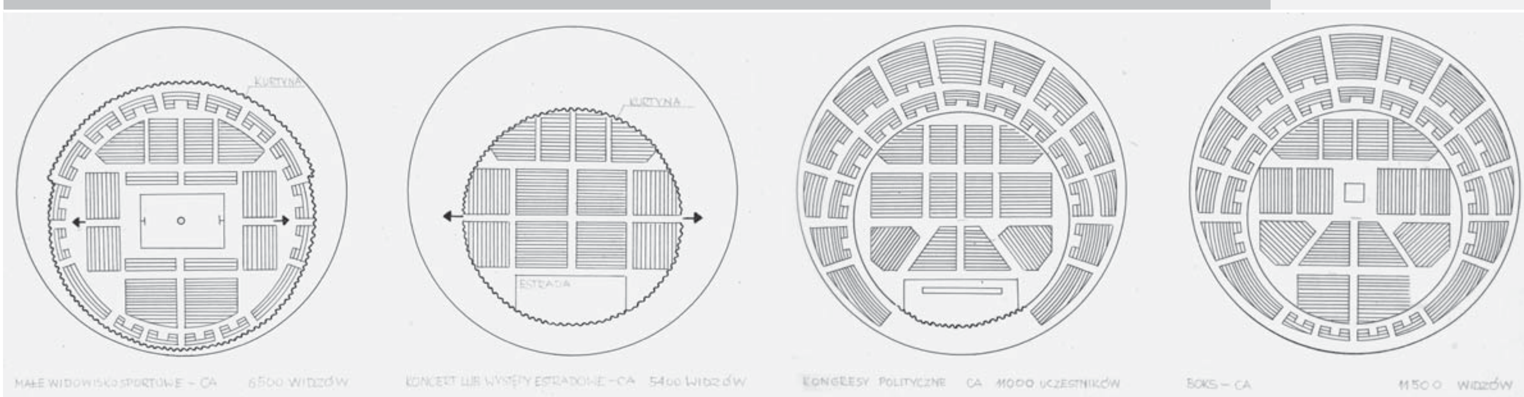


↑ This computational rendering shows Spodek before later additions were appended.

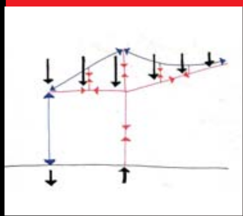
↓ An elevation drawing shows the taller end of the arena (as seen from the left in the above rendering).



↓ The tipped bowl configuration permits many different seating layouts for basketball, stage shows, and boxing, among other activities.

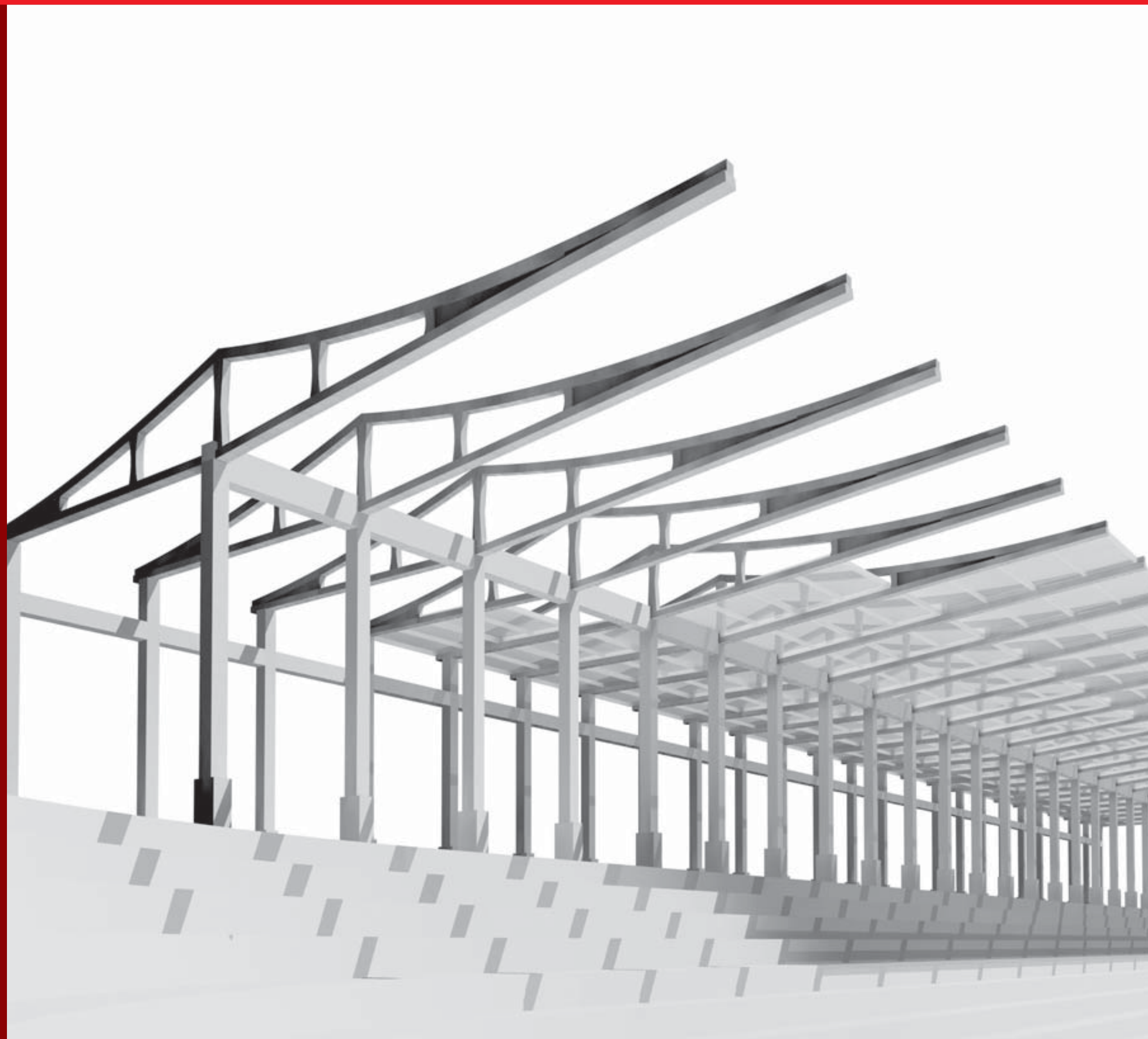


Torwar



Zalewski invented of a system of structurally efficient roof beams whose profiles are based on the funicular shape, that taken by a chain under the same conditions of supports and load. Beams of funicular shape do not need interior diagonals or a web. The beams he designed in collaboration with Stanislaw Kus were intended to be cast on site, using rising formwork, in stacks of six. The stacks were left to cure for several weeks before the beams were lifted and installed.

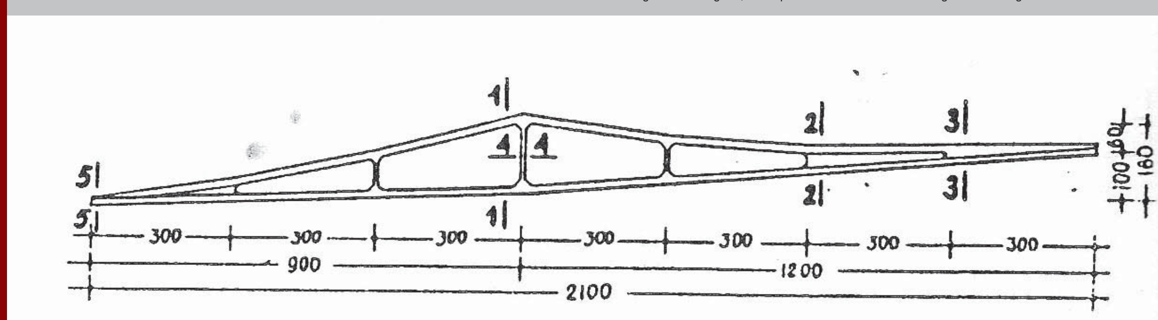
Torwar, the structure shown here, is a grandstand roof for a stadium for ice hockey and other uses built in Warsaw in 1960. It features an expressive cantilever of 12 meters (almost 40 feet). Tensile reinforcing cables along the tops of these long funicular beams were post-tensioned after being lifted into place. This type of beam? is one example from a family of analogously-shaped beams that were widely used in industrial construction in Poland. Although this may appear to the casual observer to be a Vierendeel truss design, it is fundamentally different. A Vierendeel truss is arbitrarily shaped and is made stable by bending action in its nodes. In contrast, this truss is funicularly shaped, which therefore results in an absence of bending.



↑ This computer rendering shows how the beams for a stadium roof are covered with precast concrete roof deck elements.

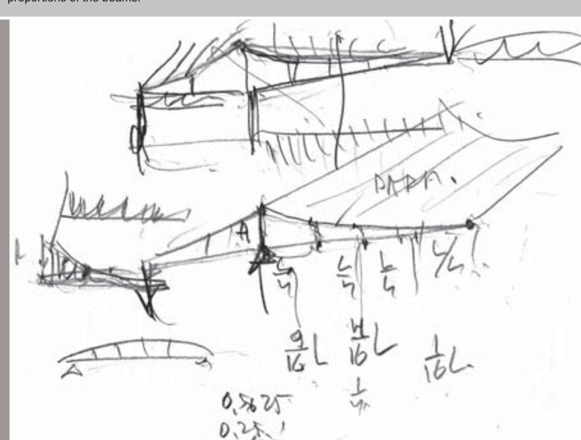
↑ The roof trusses for Torwar soar above the area where the seating was constructed.

↓ An elevation of a typical beam is dimensioned in centimeters. The shape of the element follows the shape of the bending moment diagram, which produces constant forces throughout the straight members.



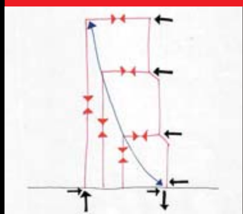
↓ Zalewski's sketches show the concepts and proportions of the beams.

→ Post-tensioning cables in the top chords carry tensile forces.



1950s	**1960s**	1970s	1980s	1990s	2000s	Years
Poland	Venezuela	United States	South Korea			Location
Masonry	Unreinforced Concrete	**Reinforced Concrete**	Steel			Primary Material
Minimal Prefabrication	**On-Site Prefabrication**	Factory Prefabrication				Prefabrication
Truss with no interior diagonals						Structural Principle

Funicular Skycraper



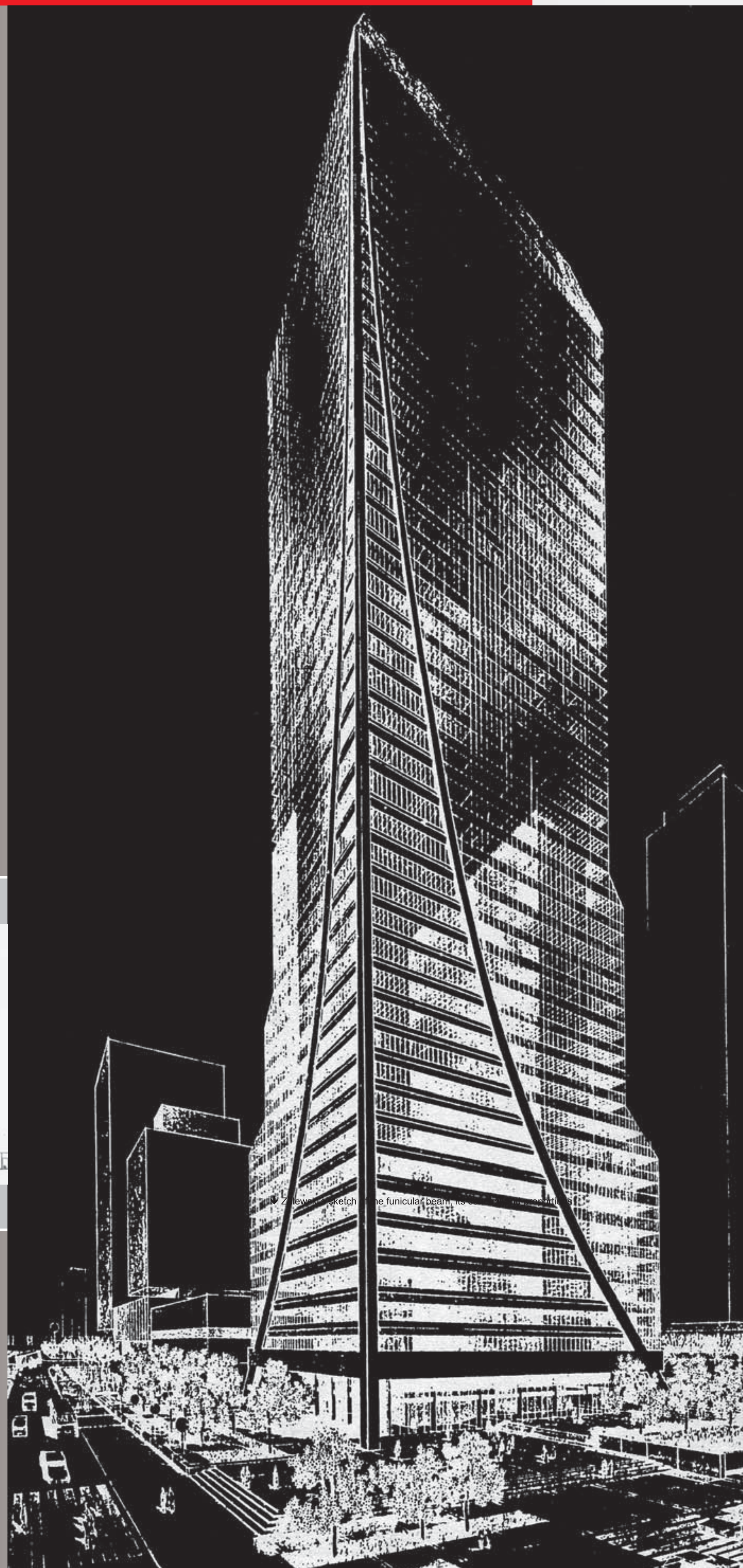
In these explorations, elements arranged along funicular lines act as both cables and arches to resist the lateral forces of wind and earthquake that predominate in tall buildings. In the same way that cable and arch bridges can span farther than truss bridges, funicular bracing is more appropriate for taller buildings than the wind-resisting trusses commonly used. The curves resemble those of the Eiffel Tower, which was designed on a similar principle. However, the full profile of the Eiffel shape would require a very broad building. The arrangement shown to the right uses just one side of the Eiffel shape on each facade. The arrangement below shifts the two sides of the Eiffel structure inward so that they overlap. Both arrangements permit a more slender tower.

Both examples are applied to buildings with very standard glass curtain walls. Either could become the basis for truly original skyscraper architecture. The symmetrical bracing scheme below was developed in collaboration with architect Manuel Sayago in Caracas, and the asymmetrical scheme to the right, with architect Jerzy Jakubowicz in Boston. The buildings' facades are enlivened by the gesture of the curved elements; the bracing emphasizes the relationship between the top of the tower and the foundation at ground level along the street.

➔ This rendering shows a single funicular brace on each building face.

↑ This structure would use even less material if the funicular braces ran to the ground.

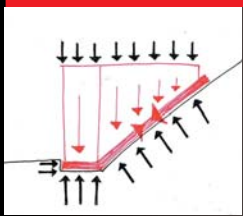
↑ Paired funicular braces create a graceful symmetry of curves.



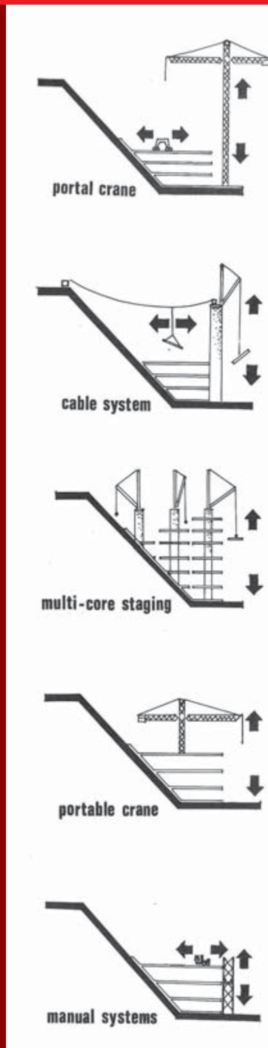
↓ Zalewski's sketch of the funicular beam, its [illegible] and proportions

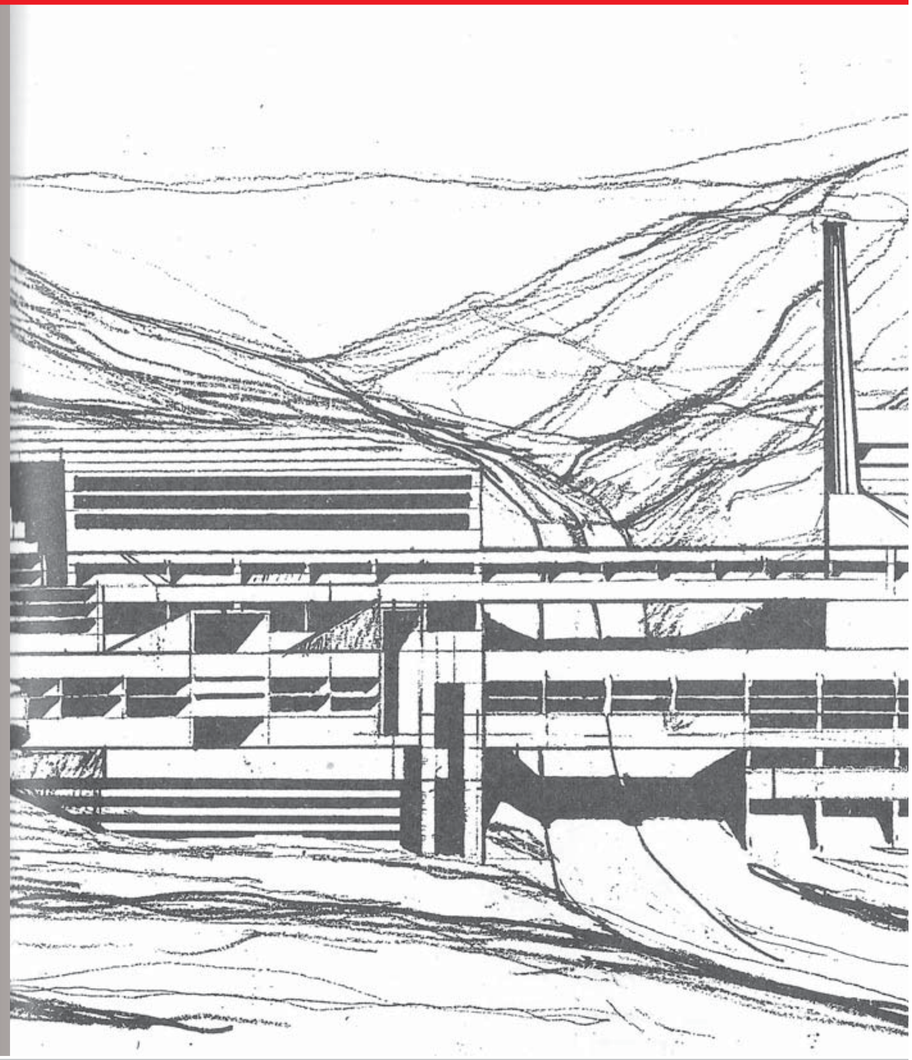
Years	1950s	1960s	1970s	1980s	1990s	2000s
Location	Poland	Venezuela	United States	South Korea		
Primary Material	Masonry	Unreinforced Concrete	Reinforced Concrete	Steel		
Prefabrication	Minimal Prefabrication	On-Site Prefabrication	Factory Prefabrication			
Structural Principle	Funicular arches and cables					

Buildings on Slopes



This unbuilt research exploration was conducted at MIT during the spring of 1969 and published soon after by the MIT Press. Zalewski was aided in this project by research assistants W. Robert Kirby and Reinhard K. Goethert, and the drawings were produced by student collaborators. Based on the premise that the growth of many dense urban areas is restricted by precipitous valley walls, the drawings demonstrate simple strategies to build on steep areas with challenging soil conditions. Applications were proposed for places such as Los Angeles, Rio de Janeiro, Caracas, Hong Kong, and Honolulu. The most developed example, the one shown here, explored the possibilities in Pittsburgh, Pennsylvania. The overall strategy is to concentrate the major foundation elements (driven piles, caissons, or a foundation mat, depending on soil conditions) in a small, flat area at the foot of the slope. From this is constructed a strong slab, a concrete carpet that reaches up the slope as far as the highest portion of the site. This slab, which works primarily in axial compression, carries inclined components of loads to the foundation at the foot of the slope. The forces in the slab compress and thus stabilize the soil beneath it. This strategy avoids having to construct independent foundations of questionable stability under the difficult working conditions and uncertain soils presented by steep terrain. The design is for an underlying, innovative construction process rather than a single final form. The amalgamation of structures such as these at the urban periphery holds potential for expanding many of the world's densely populated cities at reasonable cost.

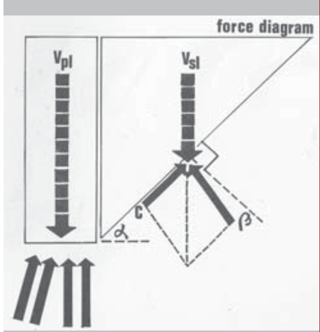




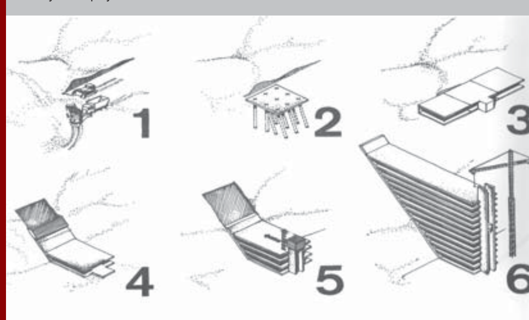
↑ Any of several construction methodologies may be employed.

↓ The same underlying principles may be applied to other shapes.

↑ Roads and pedestrian ways ascend the slope between structures.

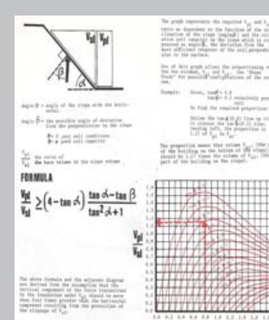


↑ Loads on the inclined slab are supported by compression of the slab and the earth beneath.



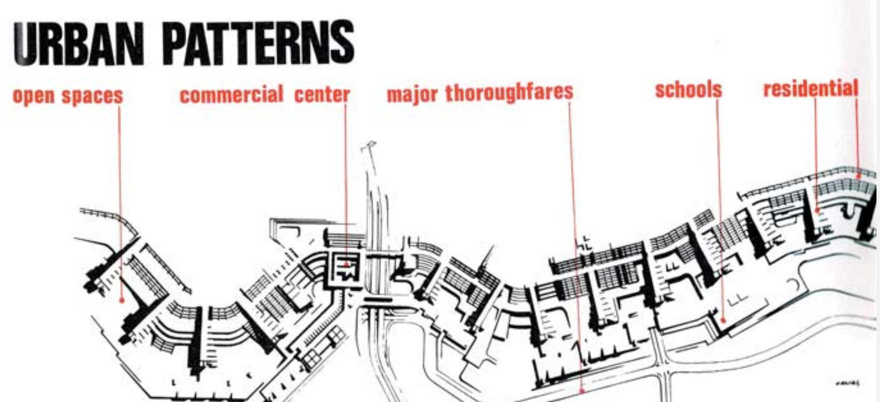
↑ (1) The base is prepared and (2) piles are driven to support (3) the first level; (4) The compression slab is slip-formed up the slope; the (5) utility core and (6) floor plates proceed.

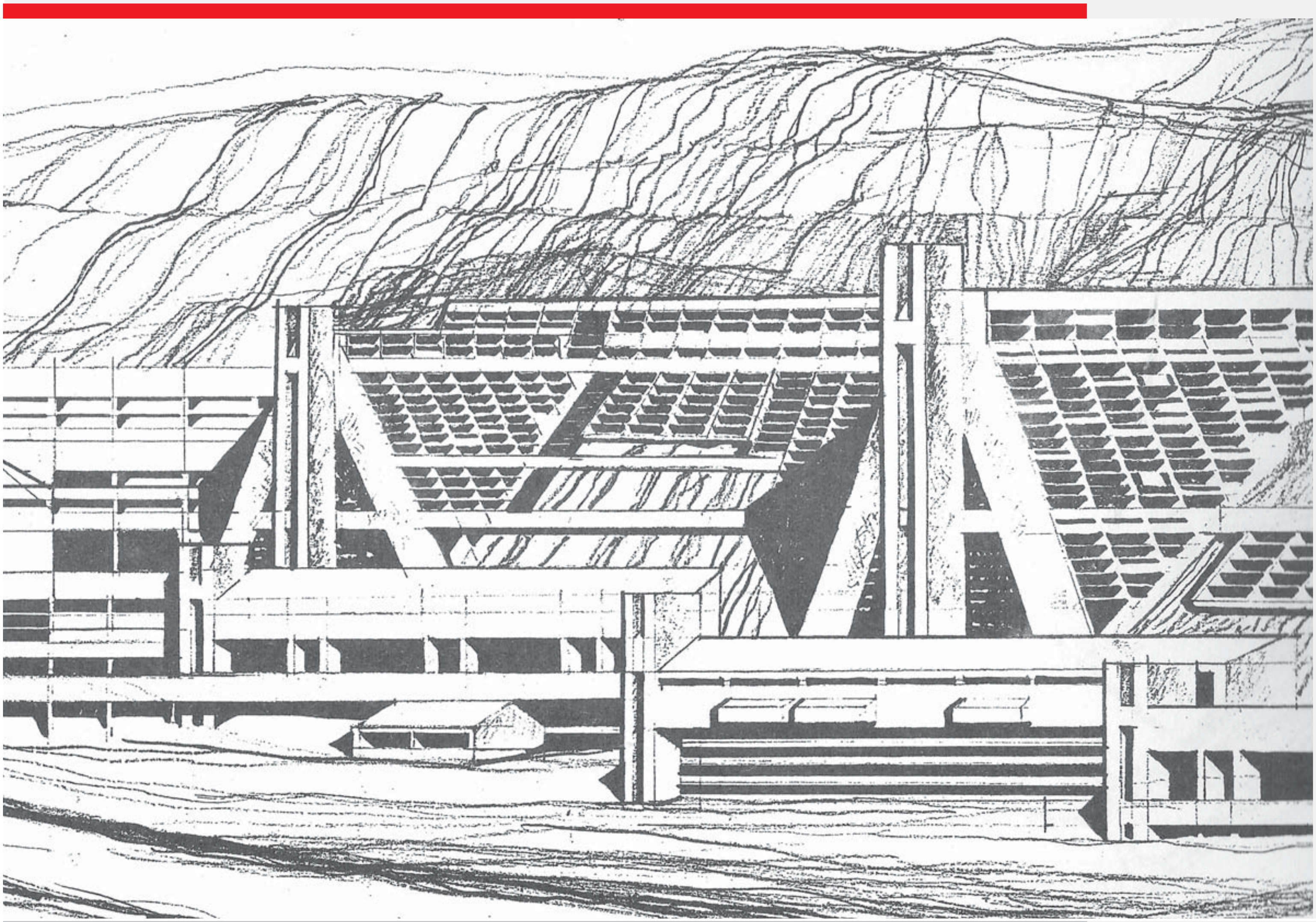
↓ A prototypical plan for a large-scale development on formerly unbuildable slopes.



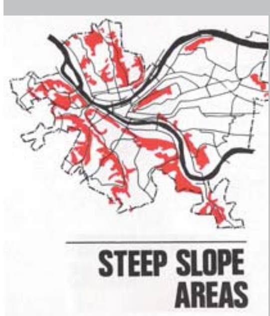
↑ Structural strategies vary, depending on local soil conditions.

Years	1950s	1960s	1970s	1980s	1990s	2000s
Location	Poland	Venezuela	United States	South Korea		
Primary Material	Masonry	Unreinforced Concrete	Reinforced Concrete	Steel		
Prefabrication	Minimal Prefabrication	On-Site Prefabrication	Factory Prefabrication			
Structural Principle	Inclined compression strut					

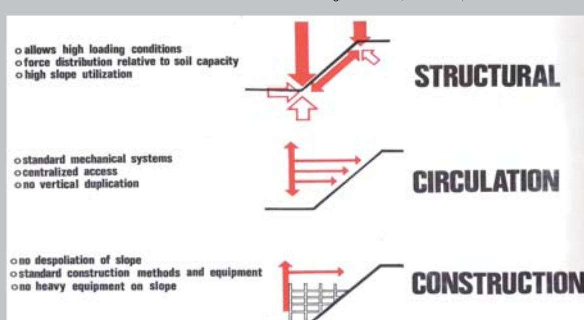




↓ The proposed system has advantages pertaining to structure, circulation, and construction.

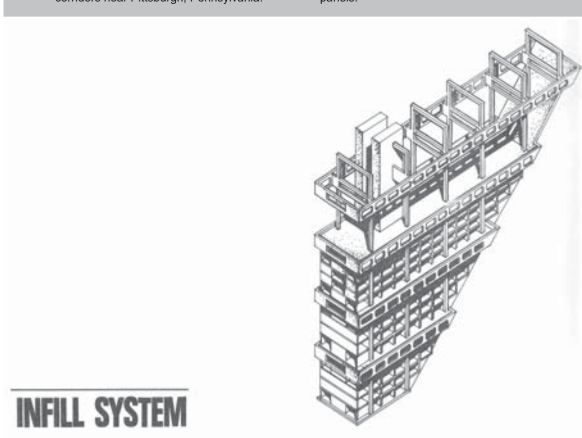


↑ Red areas show steep slopes in river corridors near Pittsburgh, Pennsylvania.

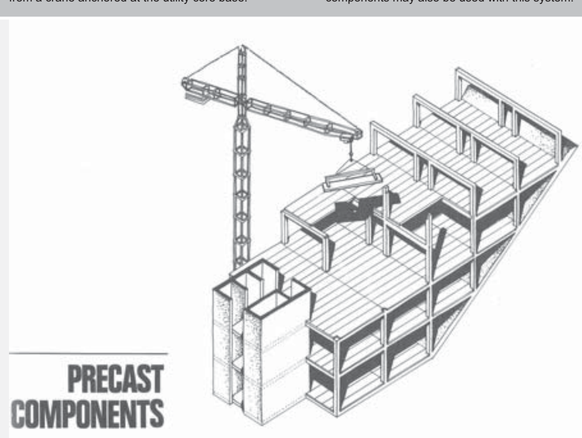


↑ This sketch perspective shows how box-type components may also be used with this system.

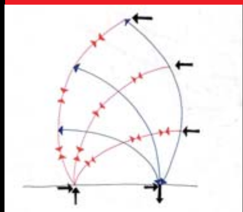
↓ The frame may be infilled with precast concrete panels.



↓ Structural components are hoisted into place from a crane anchored at the utility core base.

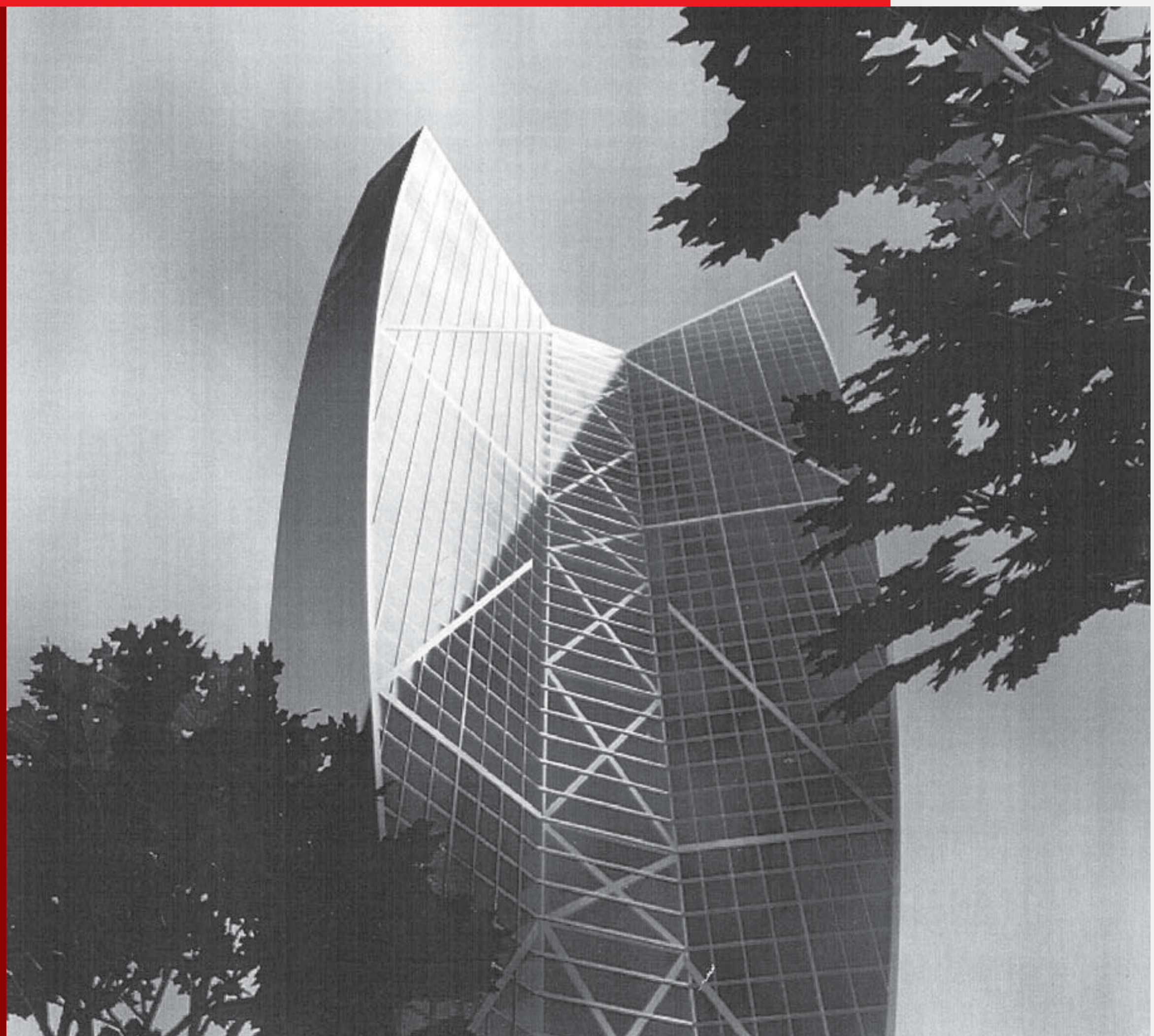


Michell Structures

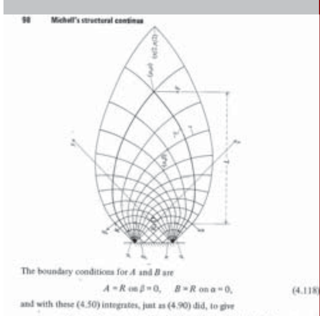


These unbuilt studies are directed toward finding optimal forms for structural bracing in tall buildings. As structures increase in height beyond 200 feet (60 m), accommodation of wind forces requires more structural material than is required by gravity forces, and the design of more efficient lateral bracing systems becomes increasingly important. In these theoretical investigations, Zalewski drew upon research completed a century ago by the Australian mathematician Michell. Michell developed shapes that require the absolute minimum of material for a given applied force. The flame-like shape of an ideal cantilever truss, shown below, would use less material than any other shape for a wind truss in a tall building, and would have the advantage of placing a building with very large total floor area on a compact base, thus minimizing foundation costs as well. But without architectural interventions, the floors would become very large in extent, too large to be daylit and with too much windowless space, especially for apartment buildings.

Working with the architect W. Zablocki, several ways of resolving this problem were developed. The solution shown here is a Y-shaped plan that opens up the deep interior of the building to natural light and air. The Michell "flame" configuration is applied to the geometry of the lateral bracing elements, which are expressed in the facade geometry. Zalewski's hand-drawn comparison at the lower right shows that the last two alternative bracing schemes for tall buildings, both Michell-based, use substantially less material than conventional systems.



↑ This architectural rendering of a building of approximately 50 stories uses a simplified pattern of Michell bracing. The overall building form is a Y-shape with three wings on a central core; Zalewski notes this could also be further braced with enclosed elevated walkways between wings.



98 Michell's structural continua

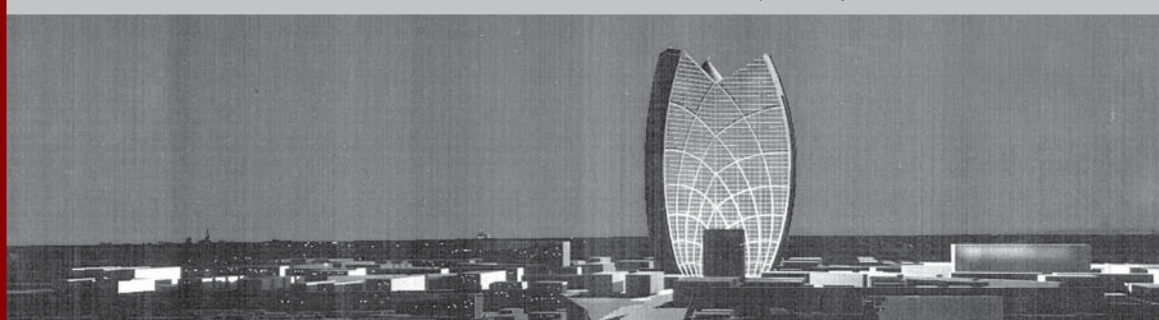
The boundary conditions for A and B are

$$A = R \text{ on } \beta = 0, \quad B = R \text{ on } \alpha = 0, \qquad (4.118)$$

and with these (4.50) integrates, just as (4.90) did, to give

$$A(\alpha, \beta) = B(\beta, \alpha) = R\{I_0\{2\sqrt{(\alpha\beta)}\} + \sqrt{(\beta/\alpha)}\, I_1\{2\sqrt{(\alpha\beta)}\}\}. \qquad (4.119)$$

↑ Mathematical field of low-weight solutions to end-loaded cantilevers (W.S.Hemp, "Optimum Structures")

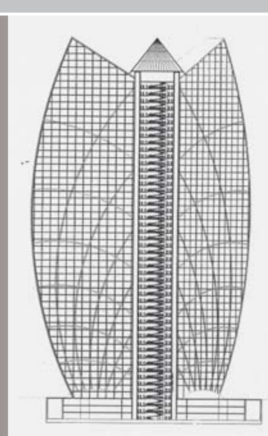


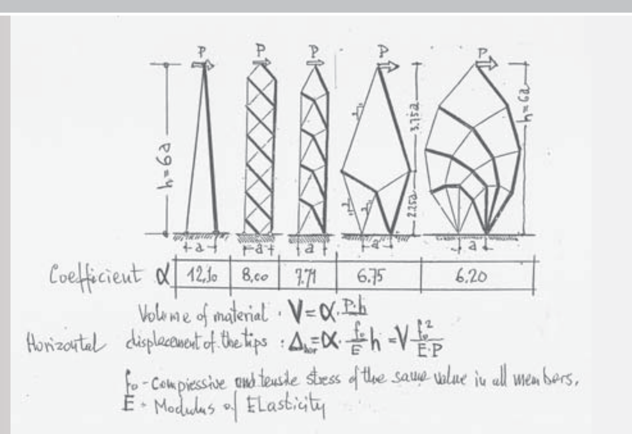
↑ This version uses a more literal pattern of Michell bracing

↓ This section drawing illustrates the core and floors of the building shown immediately above.

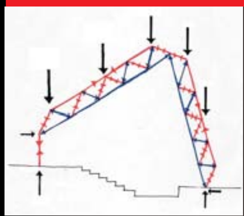
↓ In this handmade sketch, Zalewski compares the relative amounts of material in five different bracing schemes. The last two, both Michell configurations, are by far the most efficient.

Years	1950s	1960s	1970s	1980s	1990s	2000s
Location	Poland	Venezuela	United States	South Korea		
Primary Material	Masonry	Unreinforced Concrete	Reinforced Concrete	Steel		
Prefabrication	Minimal Prefabrication	On-Site Prefabrication	Factory Prefabrication			
Structural Principle	Trusses of optimal shape					



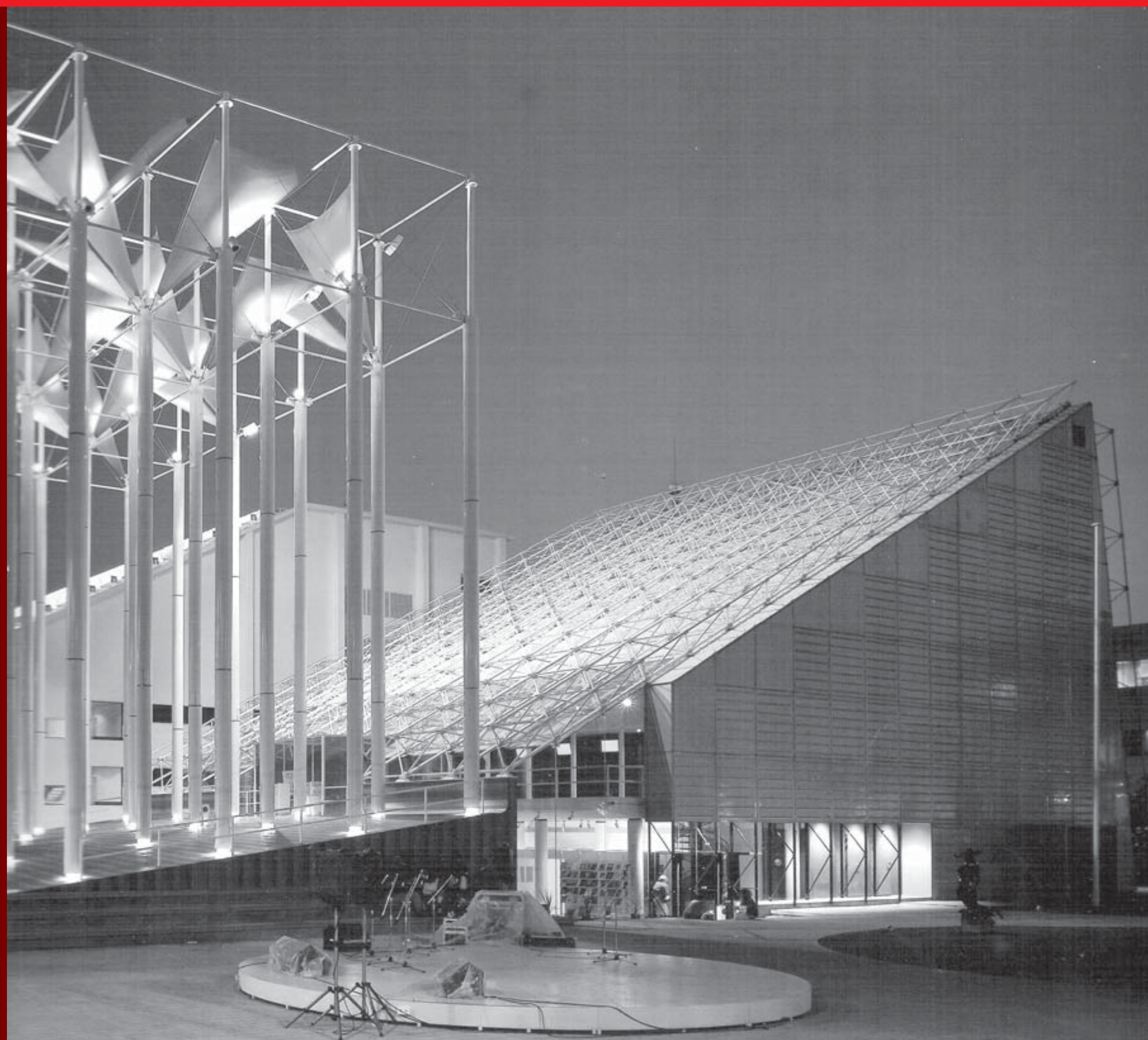


Seville Pavilion

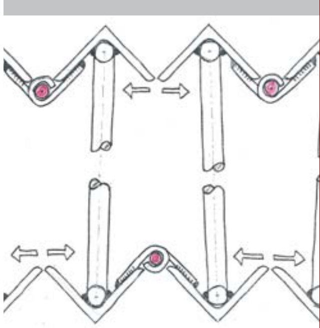


There existed a compelling reason to design a deployable structure for the Venezuelan National Pavilion at the 1992 International Exposition in Seville, Spain: The exhibition was deliberately temporary. If the structure were deployable (able to fold and unfold), it could be made in Venezuela, where costs were lower, transported in its folded form, and unfolded quickly in Seville. At the conclusion of the exposition, it could be taken down promptly, refolded, transported, and unfolded again on other sites.

Zalewski was selected to design the frame of this structure because of his work on deployable structures at MIT and his ongoing participation in the design community of Venezuela. Collaborators on this project included architects Henrique and Carlos Hernandez, the latter of whom also collaborated as structural engineer, with supporting work by IDEC (Instituto de Desarrollo Experimental de la Construccion). There were many collaborators who designed special artistic elements.

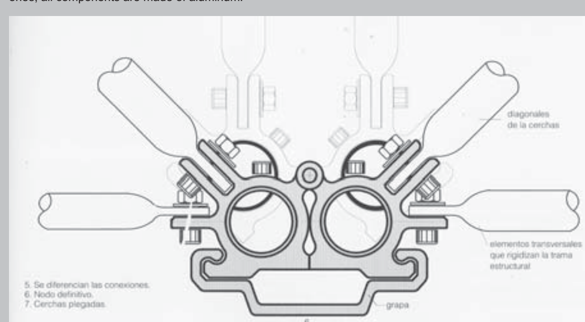


↑ A view of the completed pavilion shows the deployed roof trusses.



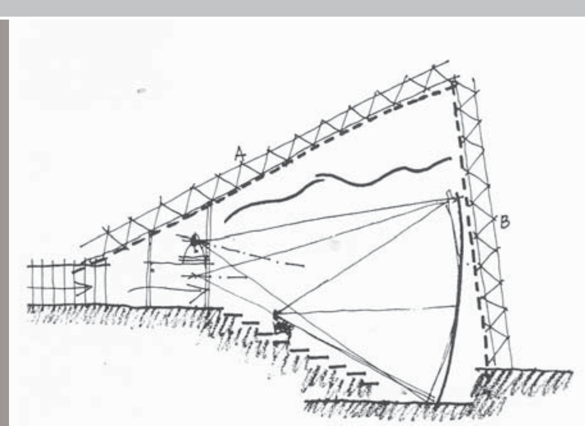
↑ An early concept sketch shows the mechanical principle of the roof.

↓ In this connection detail, the folded position is shown with light lines, and the unfolded position with heavy ones; all components are made of aluminum.



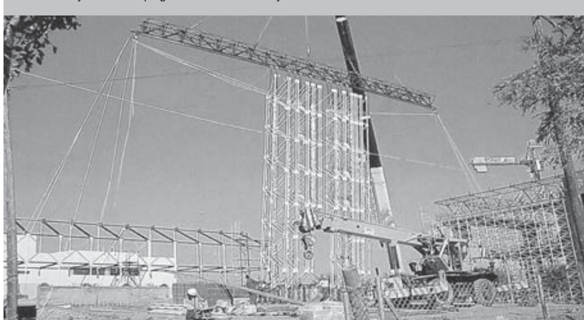
↑ The trusses were lifted in their folded position.

↓ A section sketch shows how the trusses relate to the auditorium space inside.



Years	1950s	1960s	1970s	1980s	**1990s**	2000s
Location	Poland	**Venezuela**	United States	South Korea		
Primary Material	Masonry	Unreinforced Concrete	Reinforced Concrete	**Aluminum**		
Prefabrication	Minimal Prefabrication	On-Site Prefabrication	**Factory Prefabrication**			
Structural Principle	**Deployable truss**					

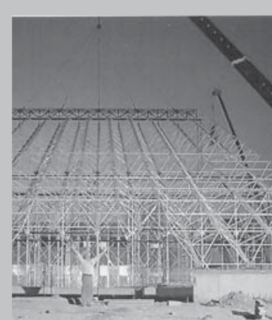
↑ This interior view shows the auditorium lobby and the sloping trusses over the entry.



↓ The trusses lie side by side when the roof is in its folded position.

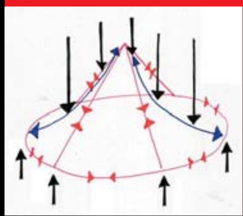
↑ The roof is unfolded with the aid of an auxiliary beam.

↑ The unfolded truss is tilted into place.



↑ The fully deployed roof is anchored to the foundations.

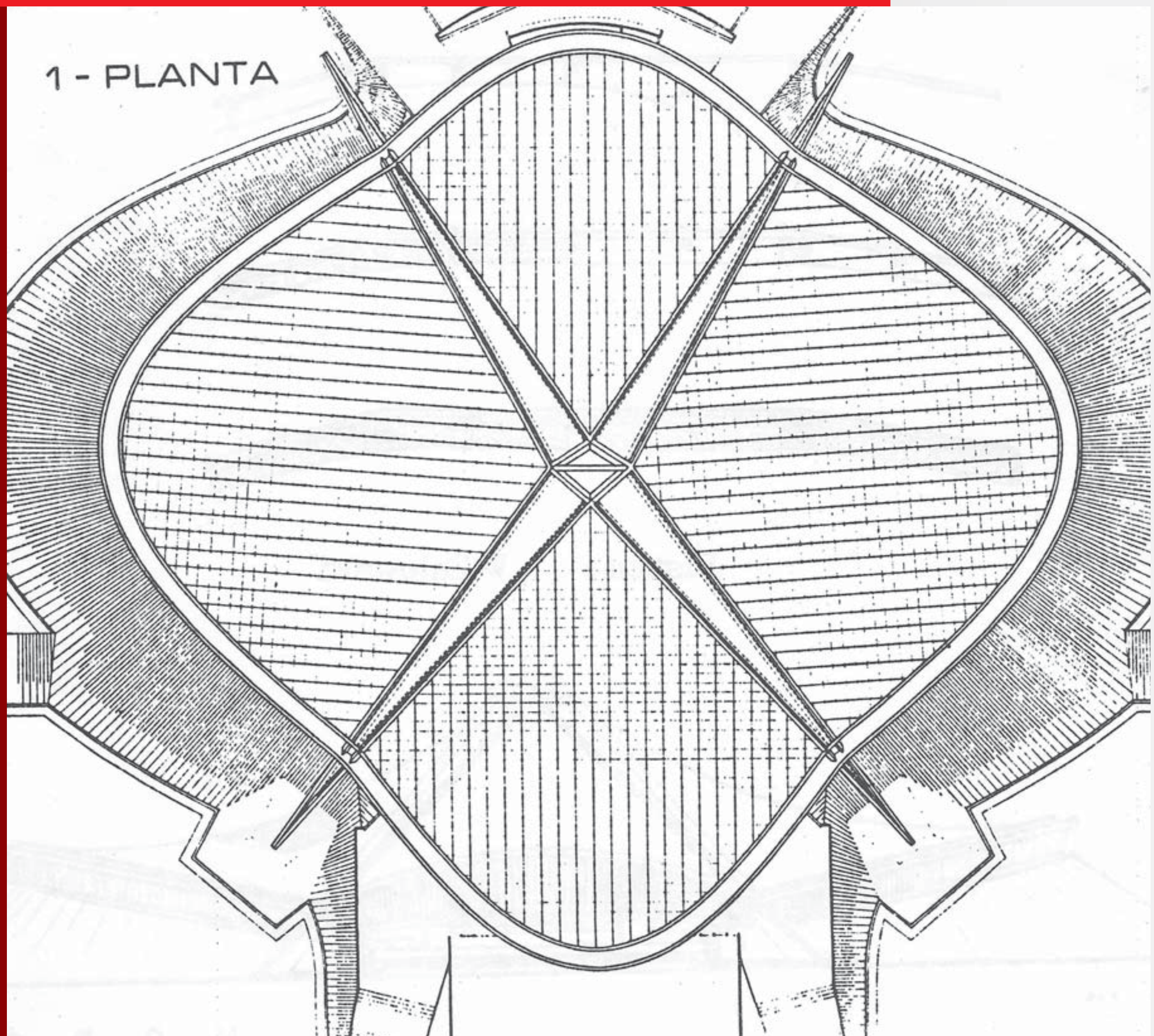
Venezuelan Arena



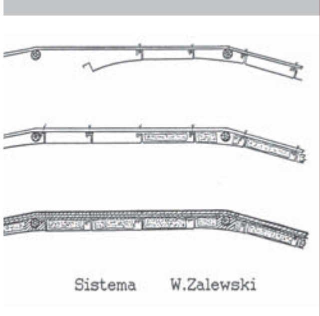
After moving from Poland to Venezuela in 1962, Zalewski worked for the Venezuelan Department of Public Works. In this capacity he designed a number of civic structures, including several dramatic enclosures for athletic facilities. These sport arenas enclose column-free spaces over 80 meters (260 feet) wide.

The example shown here, at Barcelona, Venezuela, designed in collaboration with Adolfo Peña, is spanned by steel cables that stretch from a quadripod – four large reinforced concrete compression struts – to curved perimeter edges, also of reinforced concrete. The parallel loadbearing cables are stiffened by secondary cables of opposite curvature that wrap over them and exert a downward pull.

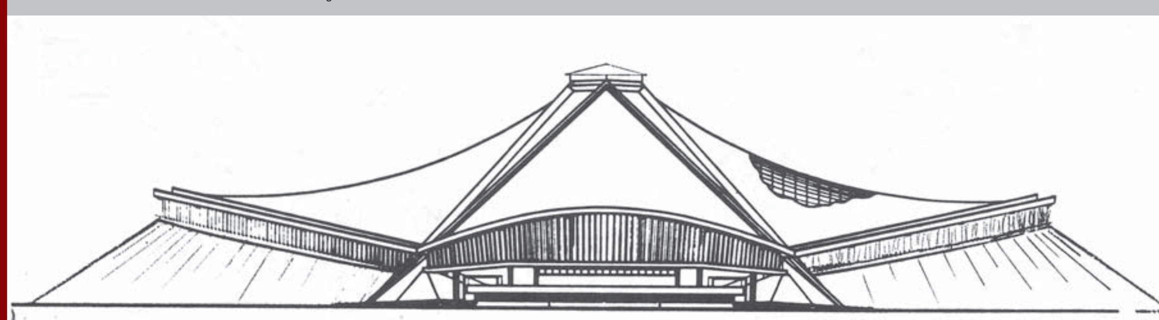
The arena is naturally ventilated by convection currents that enter at low perimeter openings and exit at a large roof cap vent at the apex of the quadripod. The roof deck was created by first attaching simple sheet metal pans to the secondary cables, then placing insulating foam panels in the pans before installing steel reinforcing fabric and pouring concrete over the entire roof.



↑ The roof plan shows the "X" of four compression struts, the curved perimeter edges, and the parallel loadbearing cables.



↑ Successive roof deck sections show the installation sequence of metal pans, foam insulation, and concrete fill.

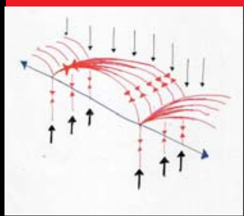


↑ An elevation drawing shows the curvature of the main cables and the secondary cables that wrap over them.

↓ The completed hall, over 80m wide, has a finished ceiling formed by the metal pans.

Years	1950s	**1960s**	1970s	1980s	1990s	2000s
Location	Poland	**Venezuela**	United States	South Korea		
Primary Material	Masonry	**Unreinforced Concrete**	**Reinforced Concrete**	**Steel**		
Prefabrication	**Minimal Prefabrication**	On-Site Prefabrication	Factory Prefabrication			
Structural Principle	**Cables suspended from concrete struts**					

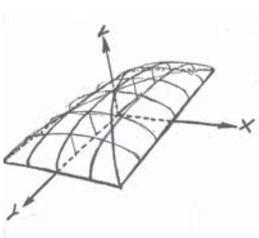
Shell Roofs for Factories



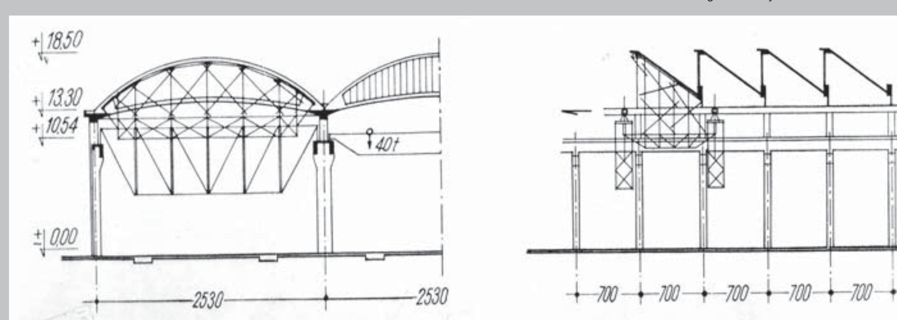
This diverse series of buildings, of which only a sampling is presented here, explored the repetitive use of thin concrete shells as roofs for industrial buildings. Once the overhead crane rails were constructed on the beams spanning between the columns, they became tracks that allowed a single, wheeled module of formwork to be used to form one shell. This was then lowered, moved down the rails, raised, and used anew for the next shell.

The shells' funicular forms allowed them to act largely in compression, which minimized the volume of concrete used for the vaults and gave an overall feeling of lightness to the roof. Large clerestory windows are featured in all the variant designs. They admit generous quantities of north light to provide even, diffuse illumination within.

↑ All the shells feature generous daylighting by means of large clerestory windows.



↑ A diagram of a double-curved surface, a portion of which was used as a roof shell.



↑ The extreme depth of the trusses used to support the formwork kept member forces very low and allowed the use of small, economical sections for the members.

↓ An exterior urban view of the shells whose interior is shown above.

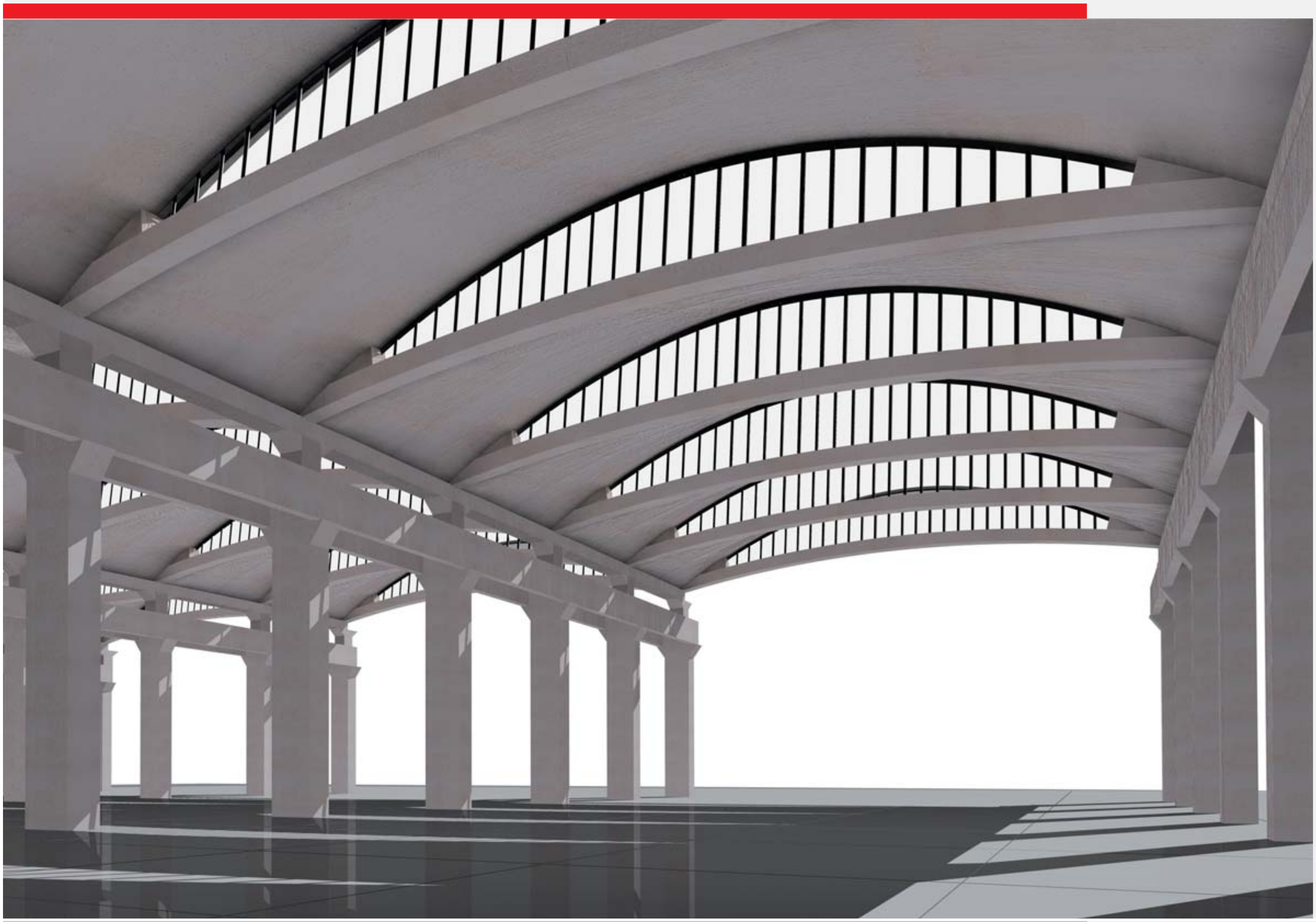
Years: 1950s | 1960s | 1970s | 1980s | 1990s | 2000s

Location: Poland | Venezuela | United States | South Korea

Primary Material: Masonry | Unreinforced Concrete | Reinforced Concrete | Steel

Prefabrication: Minimal Prefabrication | On-Site Prefabrication | Factory Prefabrication

Structural Principle: Funicularly shaped thin shells

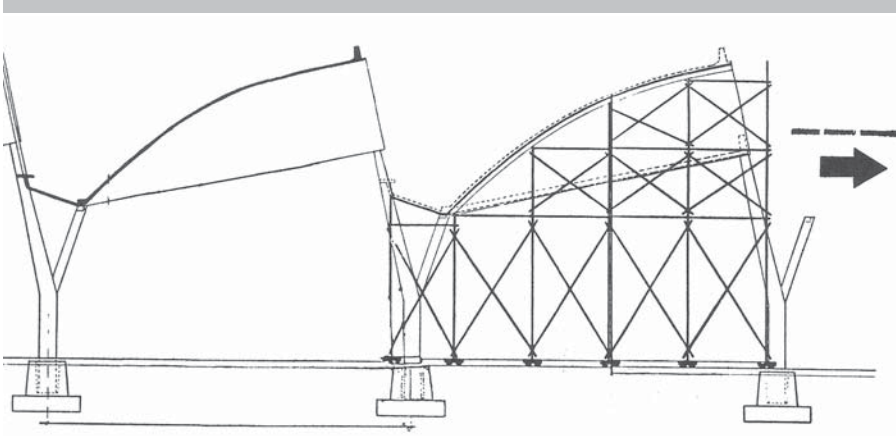


↑ This computational rendering shows the effect of the repeated clerestory windows.

↓ The north-facing crescents of glass make up a compelling rhythm.

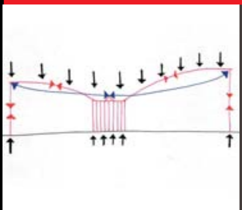
↓ The clerestory windows are framed with thin steel mullions.

↓ This sectional diagram, for the variant with Y-shaped columns, shows the relationship of the final poured concrete shells (left) shown with their actual poured thickness, to the temporary formwork and bracing (right) which can be reused in the construction of successive shells.



↓ The Y-shaped columns are a prominent feature of the interior space of the factory.

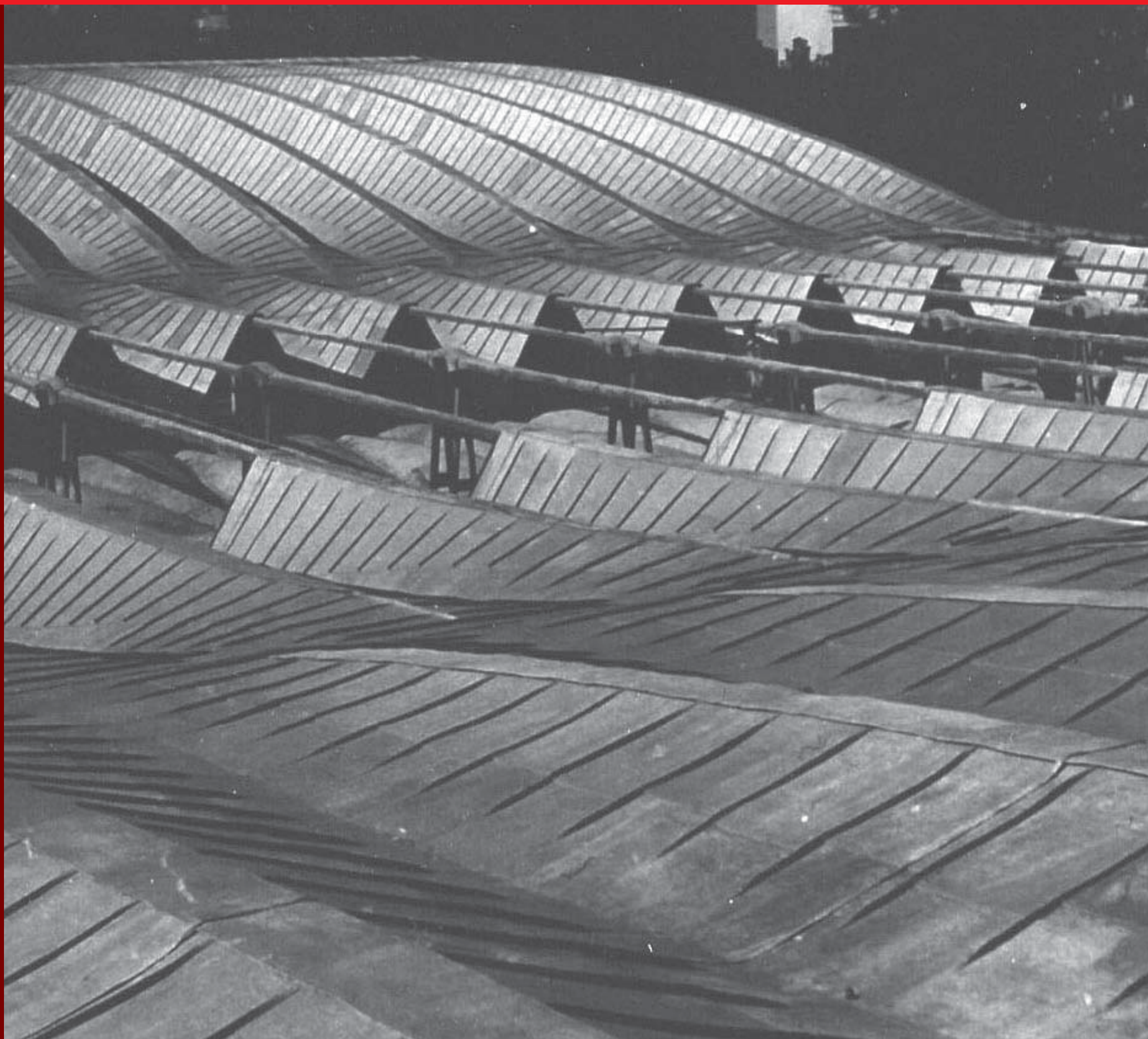
Super Sam



The Super Sam building in central Warsaw houses two supermarket self-service food areas (“sam” means “self” in Polish) that flank storage and preparation areas in the center. The problem addressed in the structural solution for this prominent urban site was to create a “signature” roof that would also express the tripartite configuration of interior spaces.

A hanging roof was favored from the start of the design process. However, this design would ordinarily require sloping cable backstays that would consume valuable land area and, because of their outdoor, ground level exposure and small cross-section, could be particularly vulnerable to catastrophic damage caused by vehicular collisions or vandalism. Through progressive design iterations, a solution was developed that eliminates backstays by alternating cables and arches of similar curvature. The outward component of arch thrust exactly balances the inward component of cable pull at each end, leaving only the vertical components of these forces to be supported by columns. The steel angle components of the roof were fabricated in pieces 3 meters (10 feet) wide so that they could be transported through the city streets.

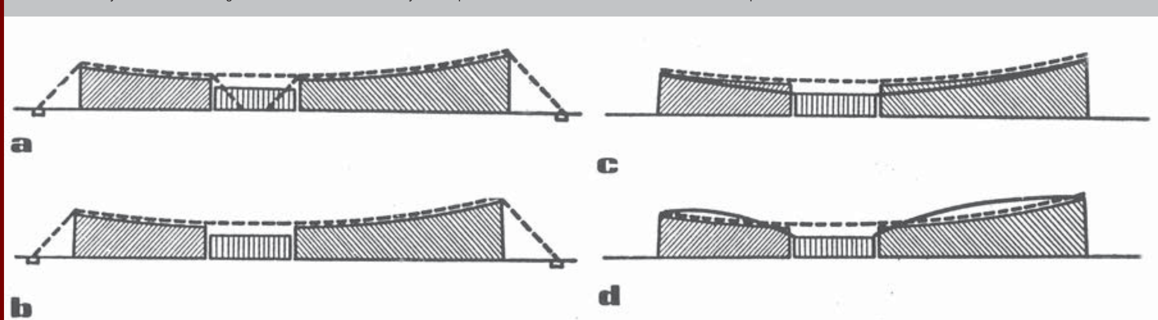
The alternation of cables and arches produces a pleasingly rich, pleated form for the roof. Inside the market, the roof structure is covered with wood slats that visually reinforce the pleated geometry. Collaborators on the project were architect Maciej Krasinski and engineers Andrzej Żórawski, Aleksander Wlodarz, and Stanislaw Ku .



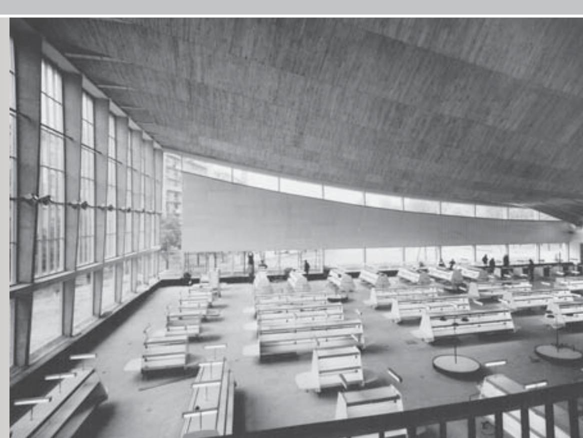
↑ The completed roof displays the forms of the arches and cables as a “fifth facade.”

↑ An aerial construction view shows the site within central Warsaw.

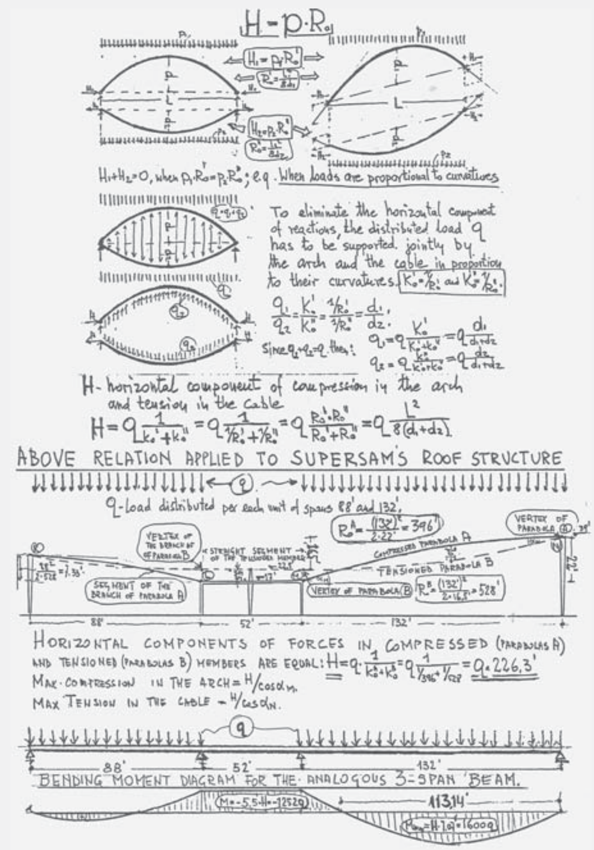
↓ How the structural concept developed: a. Separate cable roofs for the two sections would require four sets of backstays. b. A single cable span eliminates interior backstays. c. Struts alternating with cables eliminates all backstays. d. Replacement of struts with arches balances horizontal components of force.



↓ A wood slat ceiling reveals the form of the roof inside the market.



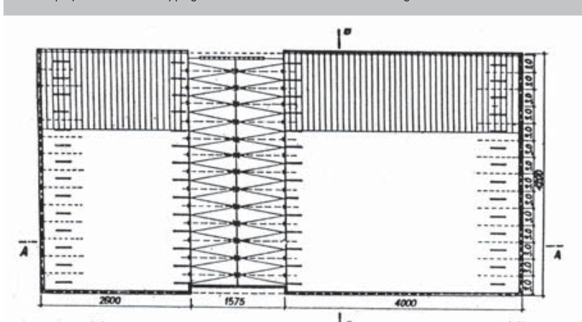
Years	1950s	**1960s**	1970s	1980s	1990s	2000s
Location	**Poland**	Venezuela	United States	South Korea		
Primary Material	**Masonry**	Unreinforced Concrete	Reinforced Concrete	**Steel**		
Prefabrication	Minimal Prefabrication	On-Site Prefabrication	**Factory Prefabrication**			
Structural Principle	**Mirror image arches and cables**					

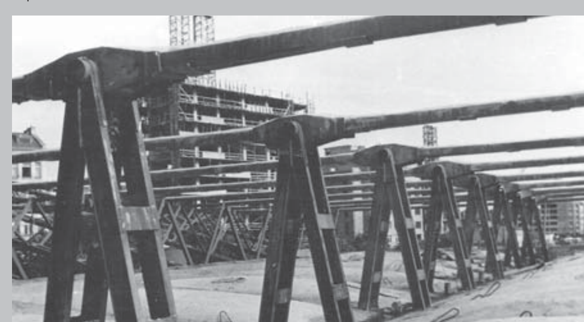


↓ The dimensions of the roof are shown in centimeters on this plan, which also shows the unequal proportions of the shopping areas on either side of the central storage zone.

↑ This construction view shows the alternation of cables and arches.

↑ Zalewski created these notes on the design of Super Sam for his MIT classes.



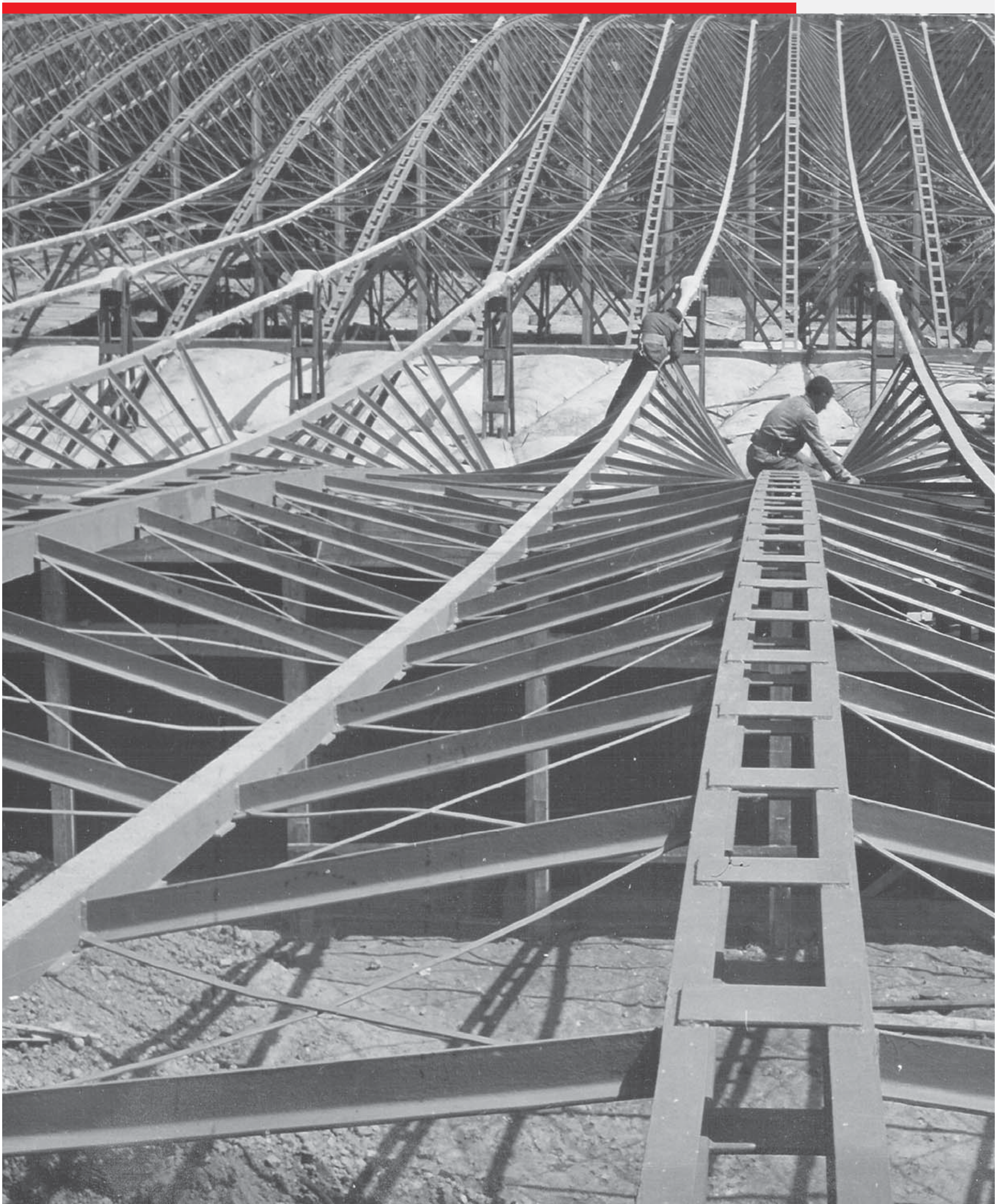


↓ The roof terminates with a cable rather than an arch at each side for a more unified appearance.

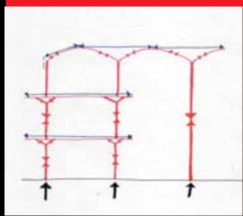
↑ The columns taper toward the bottom, allowing them to flex with small roof movements.

↑ Steel bipods resist differences in cable tensions caused by asymmetrical wind or snow loads.

→ To protect them from weather, cables were grouted into channels created by paired steel angles.



School in Valencia



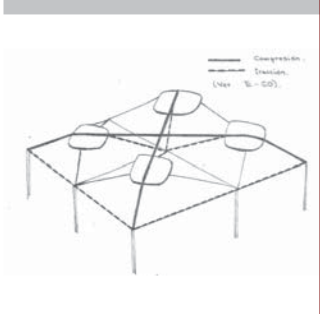
This building for a Jesuit Lyceum (high school) in Valencia, Venezuela, was designed in collaboration with architects Iñaki Zubizarreta and Felipe Montemayor and engineer Josè Adolfo Peña. It includes the further development of precast concrete capitals for the floors, and precast concrete roof vaults. This combined strategy capitalized on the need for the floor spans to have flat-topped slabs while the roofs had sloping surfaces to shed water.

Taking advantage of the light floor loading for schools, Zalewski designed a slender cruciform column capital that lies within the thickness of the floor structure. The capital and floor slabs are designed on a two-meter grid with eight meters (26 ft.) between columns. The columns are square with chamfered corners.

Roof vaults are precast in four identical segments per bay. The oculus at the top of each vault is sheltered with a cap that permits free airflow but excludes rain. The school, which has no windows, is naturally ventilated by convection currents that rise through the vaults and out each oculus. At the perimeter of the roof, saddle-shaped vaults provide scuppers at their low points to drain water from the integral gutters between the lines of vaults.

↑ At the entrance, the multilevel nature of the building is revealed, together with the vaulted roof.

↑ Each vault is made up of four identical precast segments.



↑ This explanatory diagram shows tensile and compressive forces in the roof vaults.

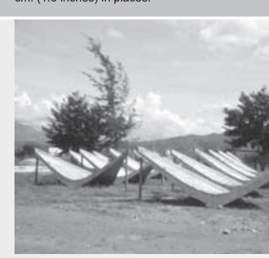
↑ A canopy shelters each oculus but allows free convective airflow.

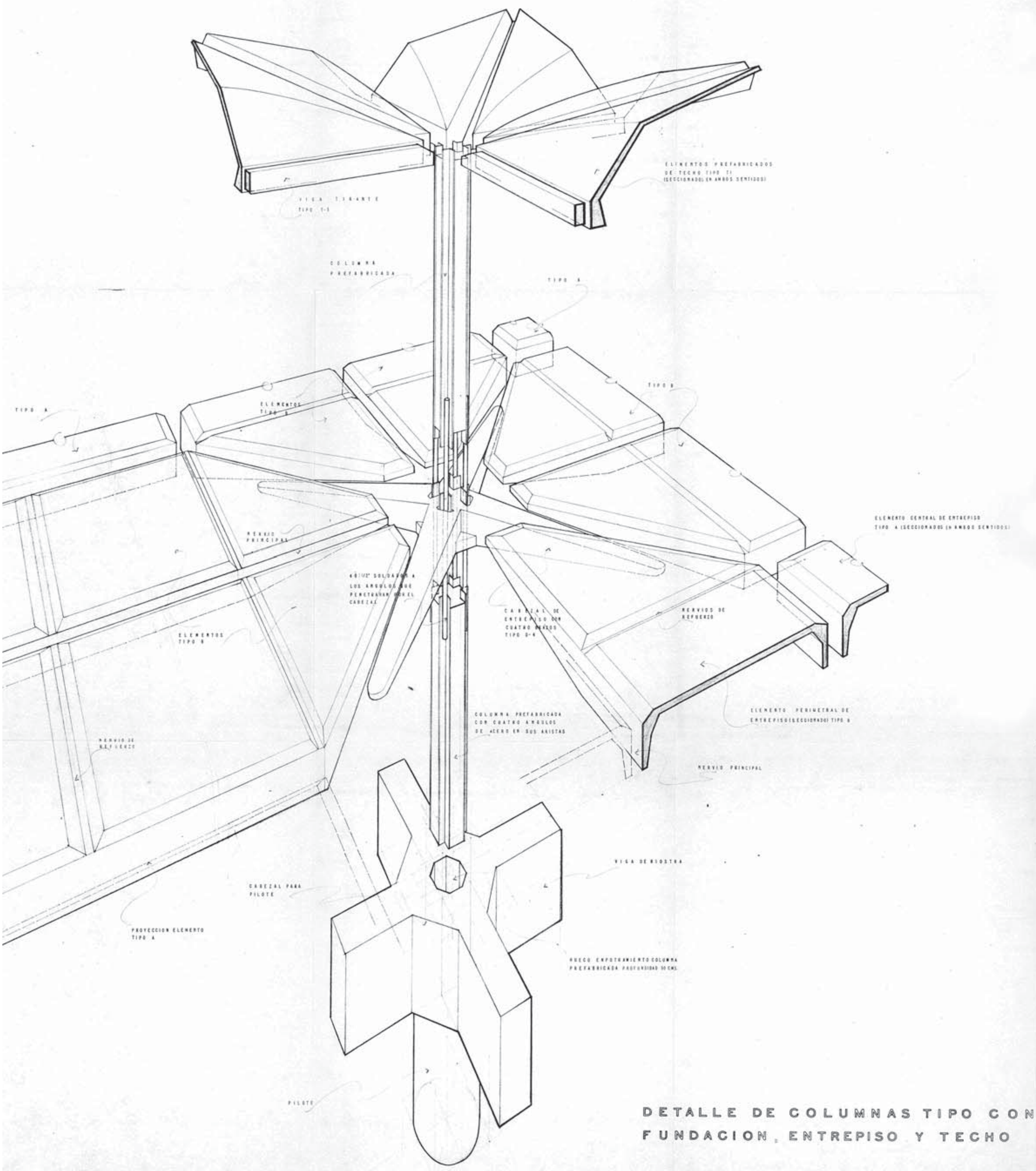
↓ A view of the central courtyard features the scalloped edges of the roof.

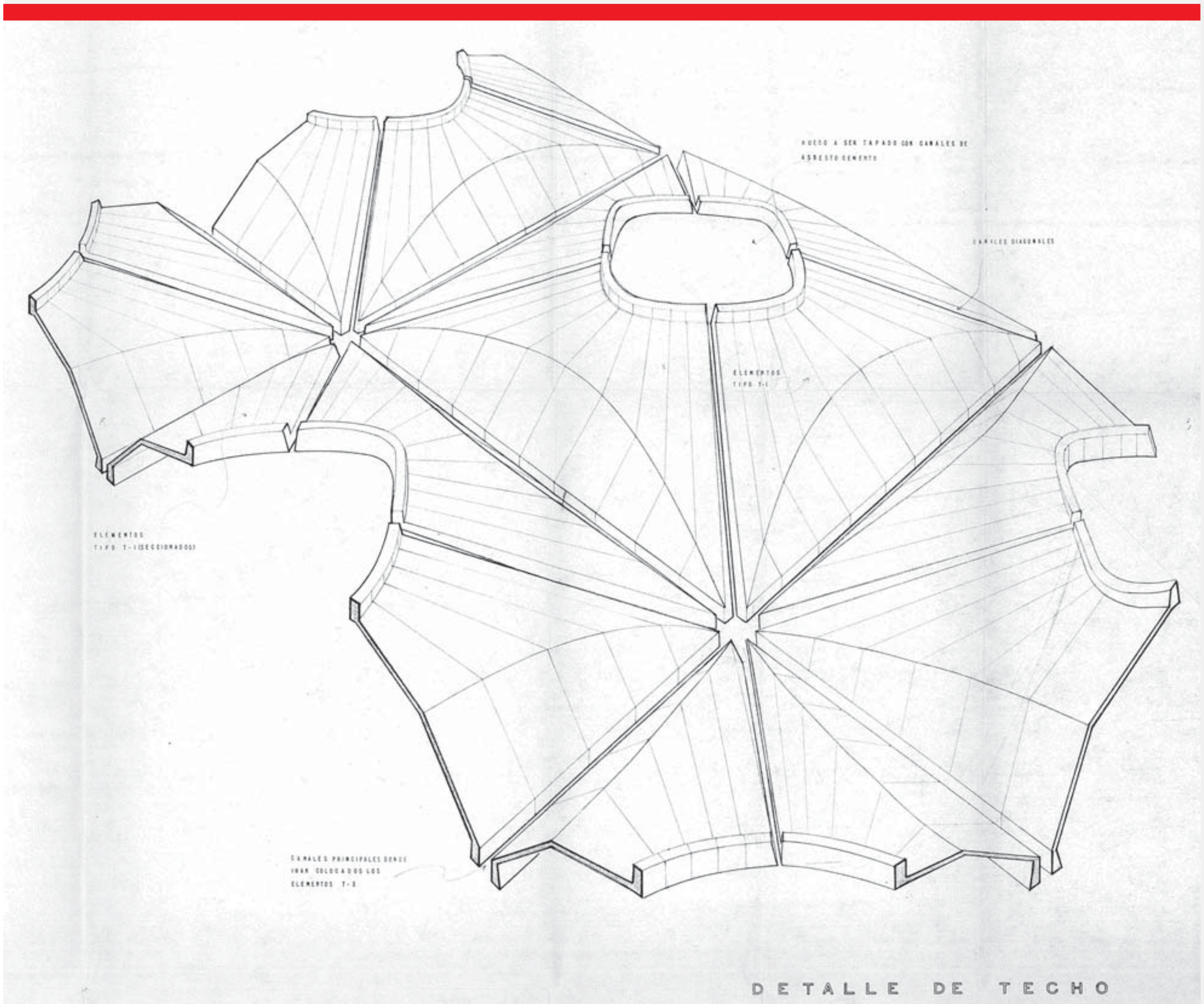
↑ The floor capitals appear delicate.

↓ The precast roof vault elements are as thin as 4 cm. (1.6 inches) in places.

Years	1950s	**1960s**	1970s	1980s	1990s	2000s
Location	Poland	**Venezuela**	United States	South Korea		
Primary Material	Masonry	**Unreinforced Concrete**	**Reinforced Concrete**	Steel		
Prefabrication	Minimal Prefabrication	**On-Site Prefabrication**	Factory Prefabrication			
Structural Principle	**Two-way floor slabs; Vaulted roofs in compression**					




ELEMENTOS PREFABRICADOS DE TECHO TIPO T1 (SECCIONADO) EN AMBOS SENTIDOS
VIGA TIRANTE TIPO T-1
COLUMNA PREFABRICADA
TIPO A
TIPO B
ELEMENTOS TIPO B
ELEMENTO CENTRAL DE ENTREPISO TIPO A (SECCIONADOS) EN AMBOS SENTIDOS
NERVIOS DE REFUERZO
ELEMENTO PERIMETRAL DE ENTREPISO (SECCIONADO) TIPO B
COLUMNA PREFABRICADA CON CUATRO ANGULOS DE ACERO EN SUS ARISTAS
NERVIO PRINCIPAL
VIGA DE RIOSTRA
CABEZAL PARA PILOTE
PROYECCION ELEMENTO TIPO A
PILOTE
DETALLE DE COLUMNAS TIPO CON
FUNDACION, ENTREPISO Y TECHO



← This exploded perspective by the architect shows how components connect, from roof to foundation.

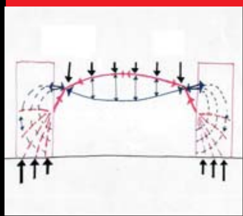
↓ The forms of the shells are echoed by the hills beyond.

↑ The mode of assembly of the roof shells is shown in this reproduction from the blueprints.

↓ The formwork for the roof vault segments includes pipes through which water is pumped to separate the concrete from the form. These produce a ribbed pattern on the interior of the shells.

↑ This photograph of the uppermost floor was taken before the canopy was installed.

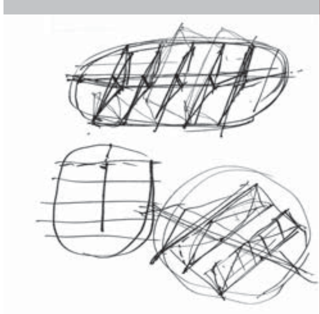
Keum Jung Sports Park



Awarded by the metropolitan government of Pusan, South Korea through a national competition, this project, the Keum Jung Sports Park and Stadium, was designed by Kyu Sung Woo Architects Inc. of Cambridge, Massachusetts, with Zalewski as structural consultant for the main roof. The building was constructed as one of three major sport venues built for the 2002 Asian Games. The site continues to serve as an athletic facility, community center, and park for the surrounding Keum Jung area. In particular, this 4000-seat gymnasium functions as both a sports venue and as a hall for gatherings and performances.

The structural solution for the roof is a three-dimensional truss that is similar in profile to a lenticular truss of funicular profile, tapering towards brackets that connect to masonry supports at the edge of the roof. What appears to be a main girder truss on the long axis of the building does not continue to any vertical supports, but rather is a device for connecting the shorter trusses that carry the load to the walls. This shaping of the structure, combined with the central and perimeter skylights, allows natural light to filter through the center and at the edge of the roof, creating a dramatic illusion of levitation.

→ This view of the gymnasium demonstrates the levitating effect of the perimeter skylights.



↑ Zalewski's early sketches show exploration of several alternative roof structure schemes.

Years: 1950s | 1960s | 1970s | 1980s | 1990s | **2000s**

Location: Poland | Venezuela | United States | **South Korea**

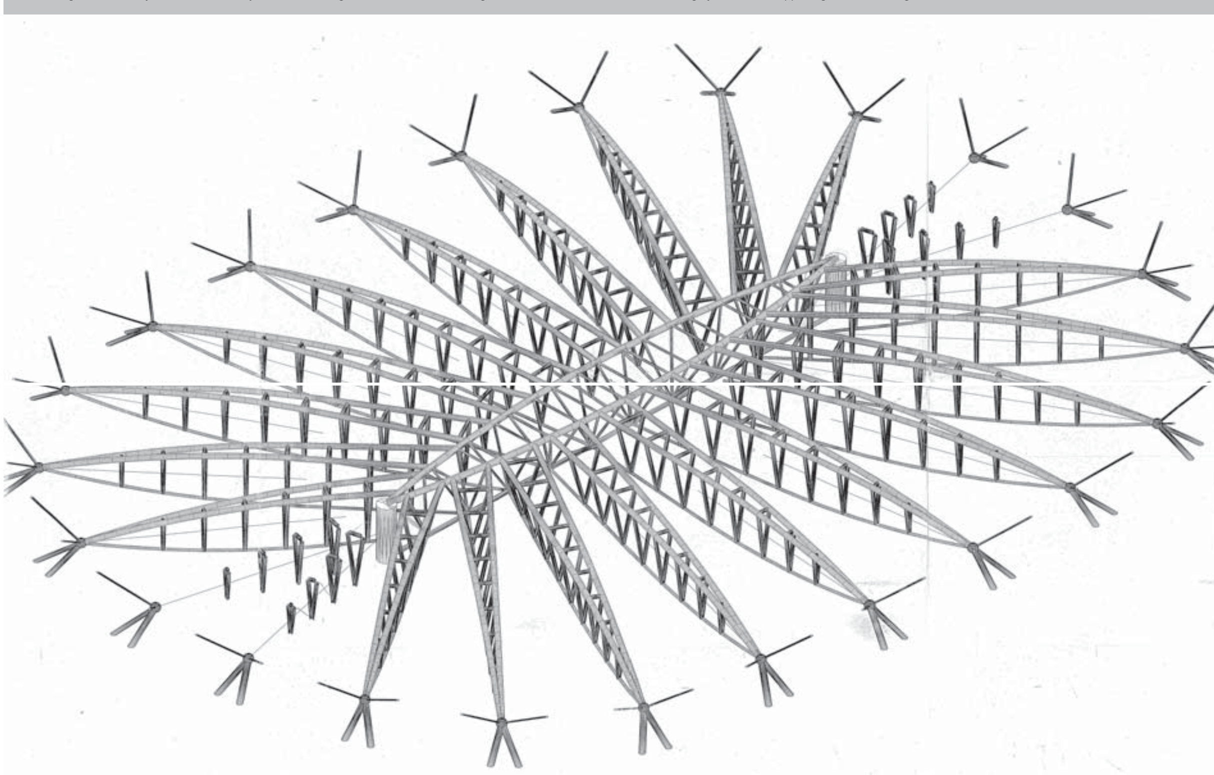
Primary Material: **Masonry** | Unreinforced Concrete | **Reinforced Concrete** | **Steel**

Prefabrication: Minimal Prefabrication | On-Site Prefabrication | **Factory Prefabrication**

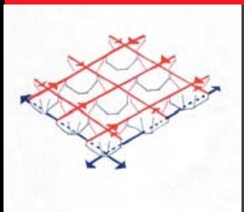
Structural Principle: **Steel pipe delta trusses**

↑ The large inclined tubes carry the weight of the roof to the walls; two smaller tubes brace each large tube laterally. The tubes midway between the large tubes are for roof drainage.

↓ This axonometric drawing shows the form of the roof structure. The entire structure forms a lenticular shape, which is highly efficient in supporting uniform loading conditions.



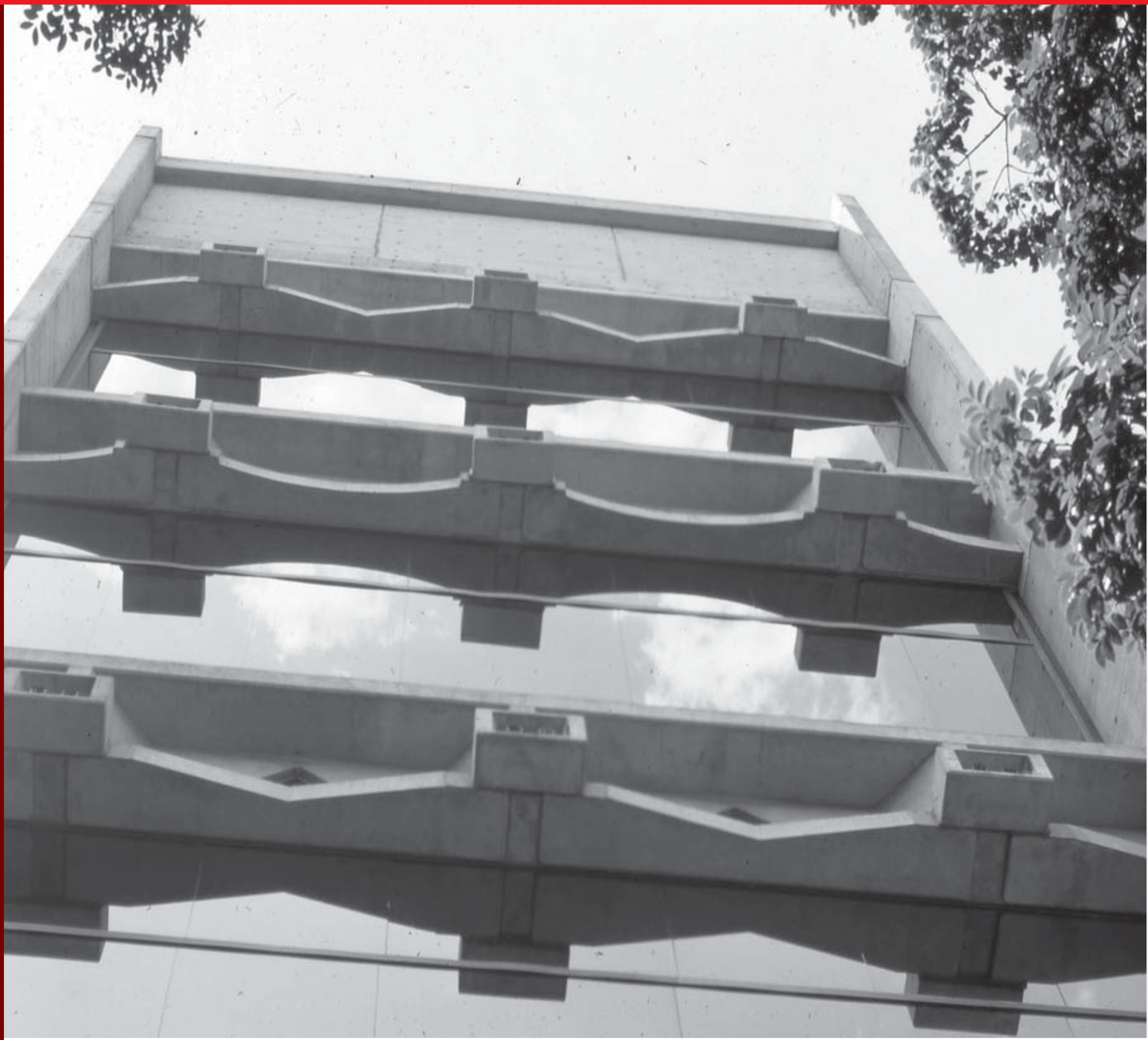
Caracas Art Museum



While working and teaching in Venezuela, Zalewski's work attracted the attention of Carlos Raul Villanueva, one of the country's most renowned architects. Three decades earlier, Villanueva had designed the original art museum in a classical style. Now he was designing extensions to the museum, including this wing for modern art and sculpture. He asked Zalewski to develop an innovative, sculptural floor system for this five-story building, one that could be exposed to view.

The primary challenge was to provide 450 square meters of floor space on each level with the capacity to support heavy sculptures weighing several tons, while not distracting from the sculptures or creating a strong directionality. Zalewski's solution satisfied these requirements and also enabled the floor system to be exposed without a false ceiling. Visitors from the building and design trades throughout Venezuela flocked to the project during its construction in the late 1960s and early 1970s, noting its efficiency, elegance, and the way its post-tensioning system made the assembled kit of parts able to act as a monolithic structure. Here Zalewski's early explorations of precast capitals for industrial uses informed this architectural work which was completed and opened in 1973.

The structure is made up of three components: a precast concrete slab element on top, a star-shaped concrete element in the middle, and an open rectangular plate of concrete on the bottom. These were assembled on temporary supports and grouted together. Then prestressing cables were laid and tensioned and a topping was poured. The system acts as a space frame and presents a pleasing, coffered appearance as seen from below.



↑ In this view looking upward along the facade, exposed concrete boxes mark the anchorages of the prestressing cables. The indentations of the slabs' edges express the manner in which compressive forces radiate from the anchorages.

↓ Steel formwork was used repeatedly to form all the elements of the system.

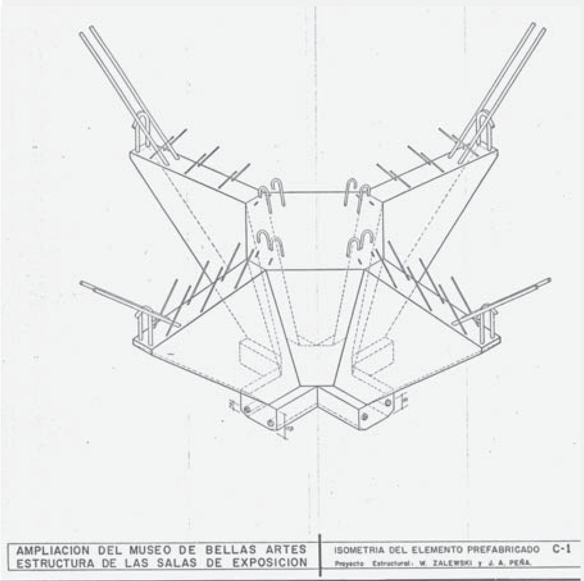
↓ Workers install a floor panel.

↑ A model (ca.1967) of the main addition (left) and the rest of the museum wings.

↑ Workers assemble reinforcing for the structural elements.

↓ This interior view of an upper-level gallery shows the coffered ceiling and narrow slit windows offering views out above the surrounding foliage.

1950s	1960s	1970s	1980s	1990s	2000s	**Years**
Poland	Venezuela	United States	South Korea			**Location**
Masonry	Unreinforced Concrete	Reinforced Concrete	Steel			**Primary Material**
Minimal Prefabrication	On-Site Prefabrication	Factory Prefabrication				**Prefabrication**
Prestressed concrete space frame						**Structural Principle**

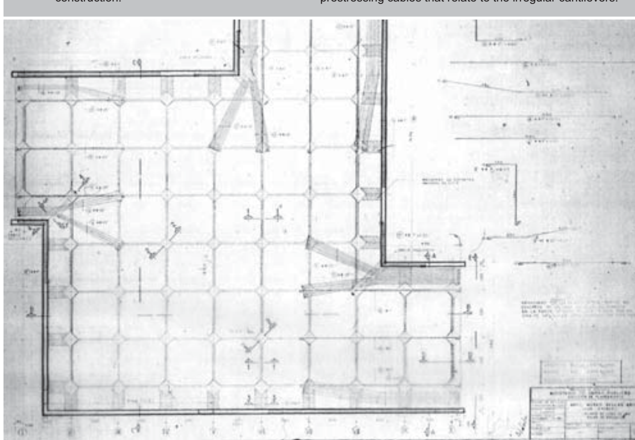


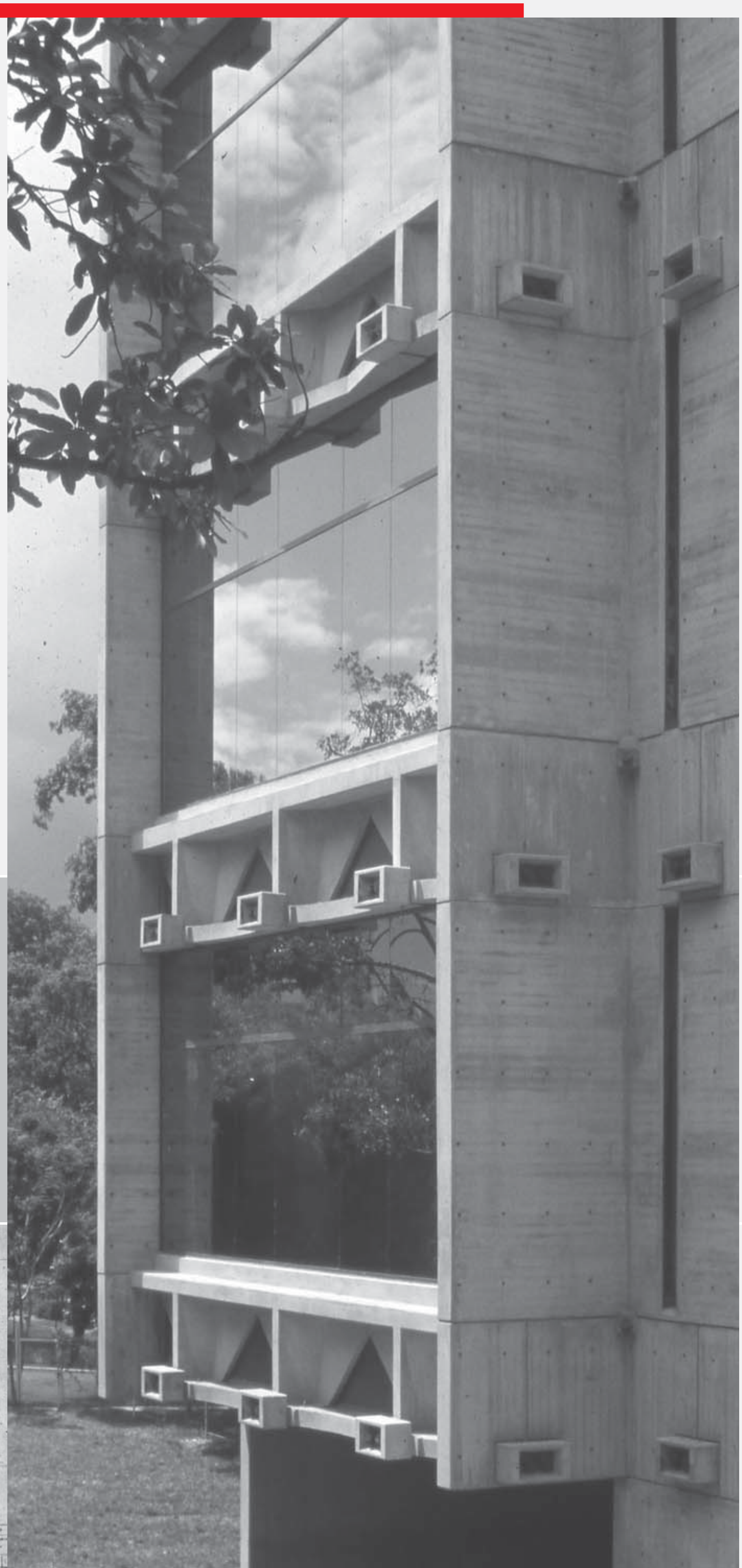
↑ Zalewski's proposal for details of the reinforced precast concrete capitals.

→ The cable anchorages are strong visual elements in the facade of the building.

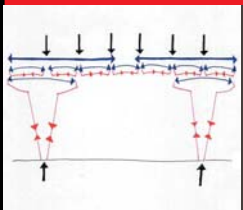
↑ A component being hoisted during construction.

↓ This plan shows the layout of the floor panels and the prestressing cables that relate to the irregular cantilevers.



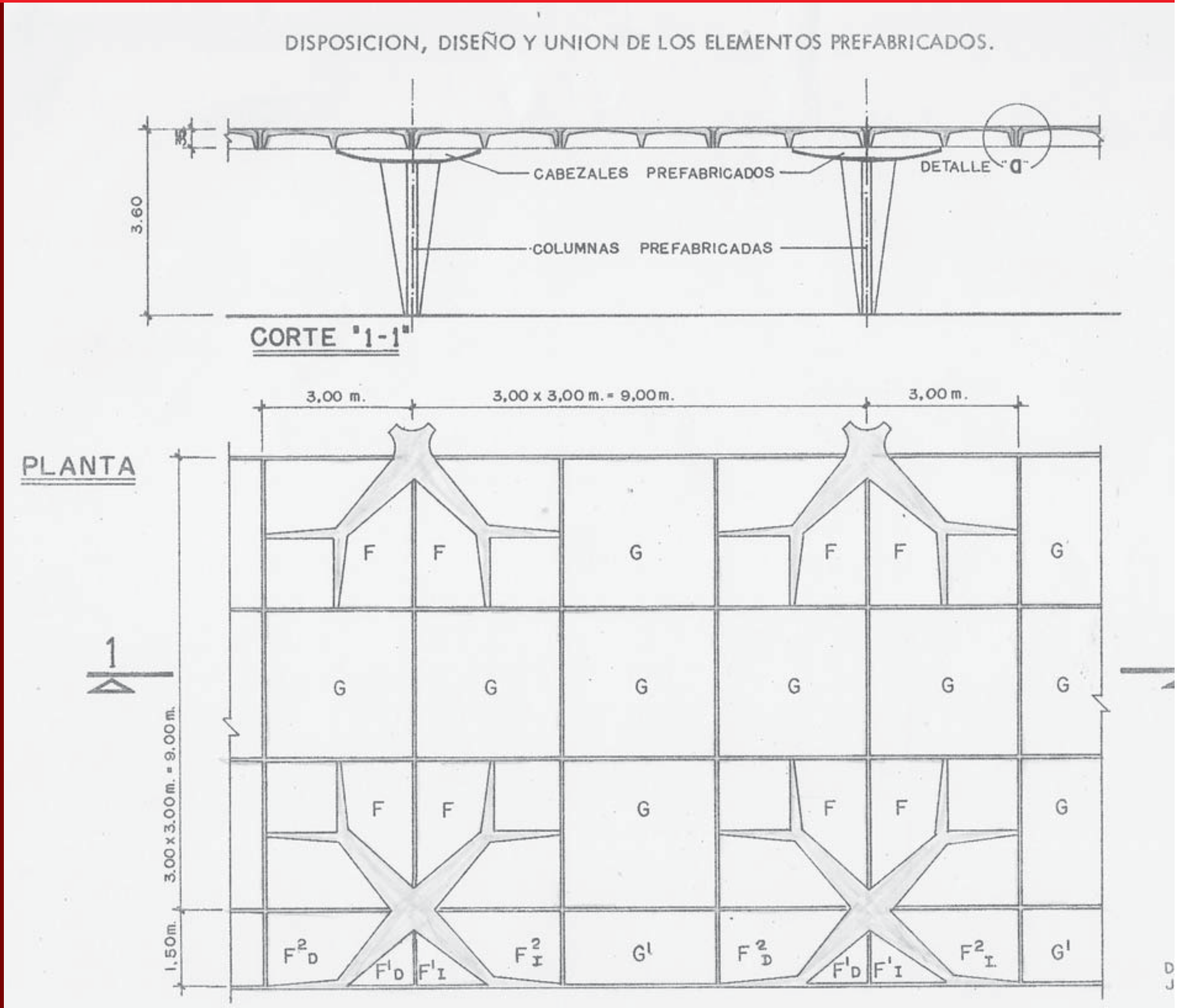


University Building in Merida

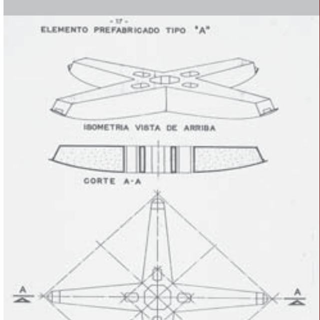


This building was constructed at the campus of the university (Universidad de Los Andes) in Merida, Venezuela where Zalewski taught from 1962- 1963. The building was designed in collaboration with architect José Adolfo Peña, and housed the Department of Forestry Engineering. It constitutes another step in Zalewski's long development of precast concrete column capitals. In this case, the architectural concept required a slab with a rectilinear grid of beams to facilitate a modular system of partition panels. The capitals, which lie entirely beneath the slabs, have long arms that reach out to become part of the grid at their extremities. The cruciform columns are shaped to accept wall panels on their indented faces.

This system was far lighter and spanned wider bays than the earlier capital designs, because the institution's academic spaces had floor loadings far lower than those in the industrial factories and warehouses in Poland. Capitals in the lower columns within multistory spaces are shorn of their arms where they are not carrying floor loads. This truncation articulates the versatility of the system and its potential for enclosing multistory spaces with the same limited number of discrete floor, column, and capital elements.



↑ The section and plan drawings for a typical bay demonstrate how the three components–slabs, capitals, and columns–work together to create a floor structure.



↑ Isonometric, section, and partial plan views show the prefabricated capital with curved arms.

↑ The upper lobby shows effects of reflected and diffused light on the underside of the coffered slab.

↓ A detailed section through a typical capital reveals its reinforcing pattern.

↑ The lower lobby features truncated columns that support full columns for the floor above.

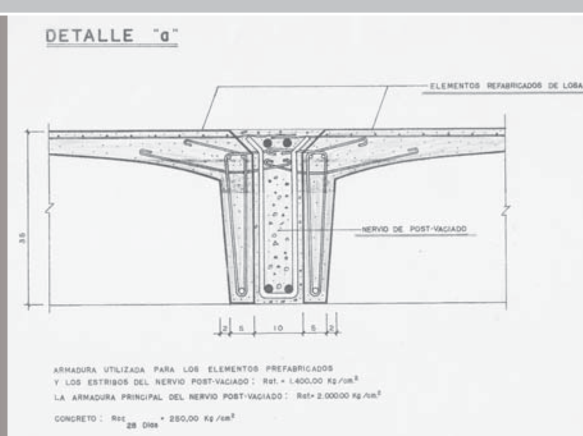
Years: 1950s | **1960s** | 1970s | 1980s | 1990s | 2000s

Location: Poland | **Venezuela** | United States | South Korea

Primary Material: Masonry | **Unreinforced Concrete** | **Reinforced Concrete** | Steel

Prefabrication: Minimal Prefabrication | **On-Site Prefabrication** | Factory Prefabrication

Structural Principle: **Two-way post-tensioned concrete slabs**

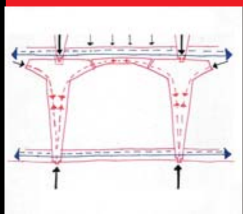


↑ This construction view shows the two-story columns that are without arms on the lower level.

↑ With the upper story columns in place, the next level is ready to be formed and concreted.

↓ Reusable steel forms produced precisely detailed capitals.

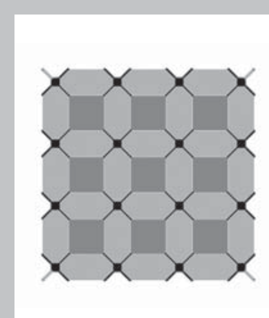
Capital System



This system for efficient construction of concrete buildings consists of four discrete types of elements, all of them precast on the building site: a tapered column; two floor slab components, one hexagonal and one square; and the "capital" component, which serves to transfer loads from the floor to the columns. The arms of the capital decrease the effective length of each of the spans in this two-way system and facilitate intentional omission of individual floor components to create circulation shafts, atria, and other multistory spaces. After all the precast elements are in place, post-tensioning cables are laid on top of the floor surface. These run in both the principal directions of the building and in parallel pairs, one cable on either side of the bases of the columns. Then a concrete topping is poured over the cables and precast pieces to create the finished floor. After this topping has cured, the post-tensioning cables are stressed, causing the finished building to behave as a monolithic whole.

This system might be envisioned as a modern reinterpretation, in precast concrete, of stone cross-vaulting techniques pioneered by ancient and medieval masons. The profile of the assembled arms and slabs is a funicular arch, and the horizontal component of the arch thrust is resisted by the post-tensioned cables. A number of variants of this system were produced in a process of development that sought to make the profile of the structure express more elegantly the arch-like structural behavior, and to simplify the formwork and details. Most of the built examples in Poland were for industrial storage, but the system was also extended to far more expressive applications including office and apartment towers and other buildings for human occupation. Buildings of many types continued to be constructed with this system even after Zalewski left Poland. This general type of system also became a precedent he drew upon and revised for other applications in Venezuela including those in this exhibit from Caracas, Merida, and Valencia.

↑ The columns were prepared for upper floors.
↓ Typical partial plan.

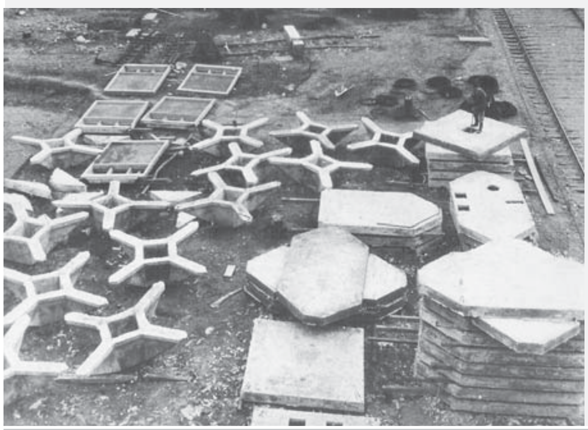


↑ Each floorplate component had internal reinforcing bars.

↑ Omitting hexagonal panels allows for multistory utility shafts.

↓ The construction process required allowances for tolerances and assembly; the post-tensioning cables under the final pour of the concrete slab for the finished floor made the system monolithic and filled tolerance gaps.

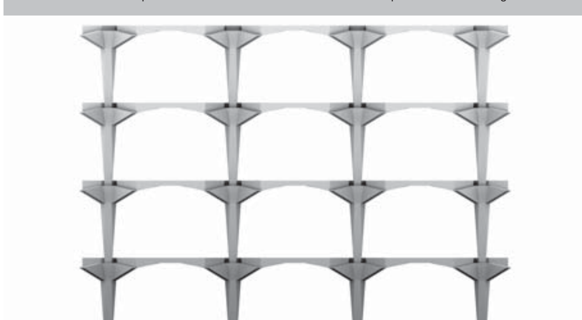
Years	1950s	1960s	1970s	1980s	1990s	2000s
Location	Poland	Venezuela	United States	South Korea		
Primary Material	Masonry	Unreinforced Concrete	Reinforced Concrete	Steel		
Prefabrication	Minimal Prefabrication	On-Site Prefabrication	Factory Prefabrication			
Structural Principle	Two-way floor slabs and vaults					



🡡 Square and hexagonal floor panels, and cruciform capitals were cast on site.

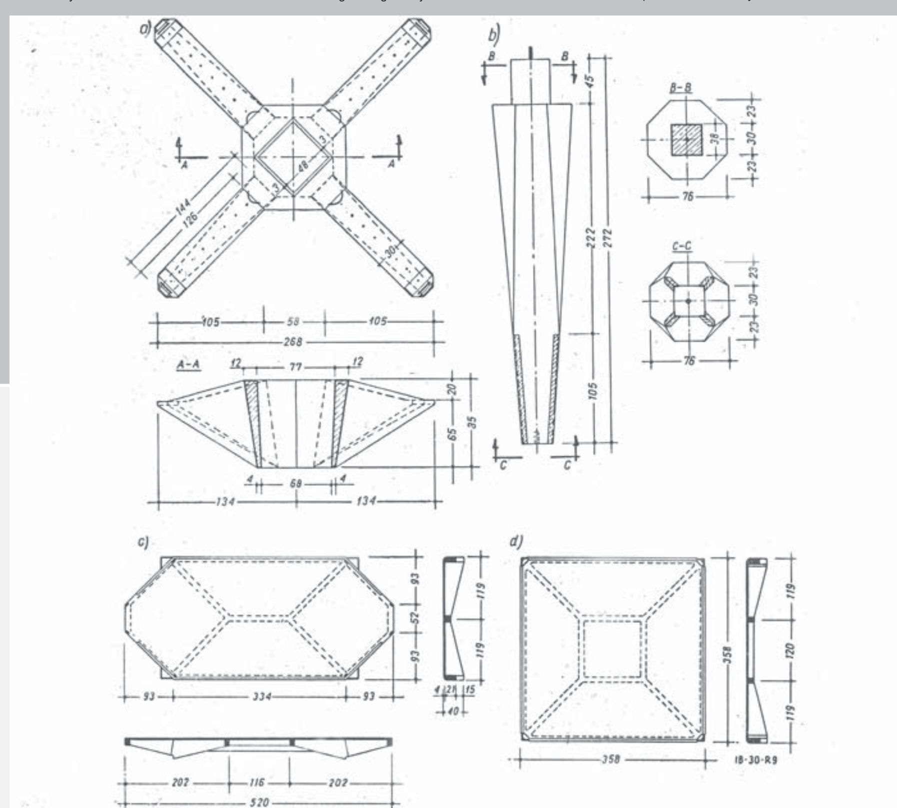
🡡 This construction view shows potential panel enclosure systems.

🡣 Elevation showing exposed concrete capitals and floor components at facade edge



→ This computational rendering shows the spatial potential of multistory voids.

🡣 Construction drawings were published in engineering trade journals.



🡣 Precast elements were guided down onto columns within the constrained site context.