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This article examines a difference of opinions that emerged during the 1950s regarding the use of models to generate structural form as the identifying characteristic of an architectural idea.

The architect's task: the use of models as structural expressionism

Matthew Mindrup

> *Eero was eating breakfast one morning and using the rind of his grapefruit to describe the terminal shell. He pushed down the center to mimic the depression that he desired and the grapefruit bulged. This was the seed for the bulges in the shell.*
> (Kevin Roche)

In the above cited quote, Kevin Roche, a principal associate at Eero Saarinen's architectural practice in 1957, recalls an early morning discussion about the design of the Trans World Airlines' (TWA) Flight Center. Roche's story about Saarinen reminds us that at the beginning of an architectural project, a solution may come from any variety of sources, not least of all from everyday objects. This was certainly the case for Saarinen, who found the seed for his design of the structural shells of the TWA Flight Center in the rind of a grapefruit. Despite its seeming novelty, Saarinen is not unique in his approach to the generation of architectural form with models; the Greek-French composer, architect and engineer Iannis Xenakis, who while working with Le Corbusier in 1957, used strings and thick wire to design the hyperbolic shell for their Philips Pavilion at the 1958 Brussels Expo. That a model will play a defining role in an architect's approach to structural design is also demonstrated by the 'spherical solution' that Jørn Utzon discovered while stacking models of his Sydney Opera House's shell roofs. These explorations with the expression of structure emerged at a time when a new generation of designers, including Eduardo Torroja, Pier Luigi Nervi and Felix Candela, had realised a handful of buildings using models to study and test structural form.

The beginnings of scientific model testing during the twentieth century are found in the interwar years, when reinforced concrete came into its own as a building material permitting the construction of varied shell and plate structures that challenged the limits of easy 'analysable' engineering calculations. From this group of engineers, the Spaniard, Eduardo Torroja is significant as the so-called 'father of modern scientifically-conducted structural modelling'[1] for having developed and used scale micro-concrete physical models to trial his reinforced concrete shells structures during the early 1930s.[2] Following Torroja, Nervi, who also made models of micro-concrete, developed a reputation for testing scale physical models of his concrete airplane hangars out of celluloid during the mid-1930s. Then, in 1951, Candela gained international recognition for his experiments with the use of the hyperbolic paraboloid (hypar) to model the forms of his thin-shell structures at full scale in Mexico.[3] Despite Utzon, Saarinen, and Xenakis's employment of models to test and refine their designs, when they began to explore the role that structure could play in the formation of the architectural idea, Nervi and Candela were quick to disparage their designs.


E. N. Rogers e P. L. Nervi

Architettura e strutturalismo

Questa volta cedo l'editoriale a Pier Luigi Nervi. L'argomento che egli tratta è dei più scottanti nel panorama architettonico internazionale e nessuno può parlarne con più competenza e riconosciuta autorità.
Ovunque si stanno svisando i termini di conquiste faticosamente raggiunte in sede teorica e comprovate da alcuni esempi realizzati. Il corretto costruire è sostituito da uno sfrenato strutturalismo, dove il mezzo tecnico si riduce a un mero gioco esibizionistico e perde ogni concretezza. E' giusto interpretare sempre più ampiamente i mezzi, ma il fine deve contenerli nel loro obbiettivo valore e non negarli, altrimenti lo sforzo per diventare più personali si riduce ad arbitrio o perfino a stramberia. Non è possibile dimenticare la realtà economica dei problemi tecnici. Ma agire economicamente non significa necessariamente costruire a poco prezzo bensì secondo una logica conseguenza tra causa ed effetto: anche quando la soluzione è costosa, bisogna che rappresenti la via più diretta per il raggiungimento di essa. Questo è, in fondo, un modo morale e sociale per impostare i problemi, perché anche nei casi eccezionali bisogna che, tendenzialmente, la soluzione rechi in sé una possibile quantificazione della qualità.
I lucidi scritti nella rubrica «Critica delle strutture», che «Casabella» si onora di pubblicare a firma di Nervi, hanno il preciso scopo di intavolare una discussione proficua sulle relazioni tra tecnica ed espressione, onde favorire la sintesi (ancora tanto lontana e troppo spesso sviata dai malintesi) tra questi due termini del fenomeno architettonico. La sintesi è, come più volte ho ripetuto — e qui ho detto con più rigore — nell'antico concetto di "téchne", dove il bello e l'utile si approssimano fino ad identificarsi nella perfetta soluzione. Solo mirando a questa, con l'uso di tutti i mezzi tecnici (con l'artigianato come con l'industria) che la nostra civiltà ci offre per esaltare i contenuti della società moderna, possiamo sperare di superare l'attuale grave condizione della produzione architettonica ai fini di un linguaggio comune: di un linguaggio che consenta le più audaci espressioni individuali in un discorso di vasta portata comune.

Ernesto N. Rogers

1 First page of article 'Architettura e strutturalismo', Casabella, 229 (July 1959), 4.

The debate, which transpired on the pages of *Casabella* in 1958 and 1959, criticised 'unbridled structuralism' as an approach to architectural design in lieu of 'correct construction'. In an article including a contribution by Ernesto Nathan Rogers, Nervi judged Saarinen's TWA Terminal and Utzon's Sydney Opera House as examples of 'constructive anti-functionalism', whose formal arbitrariness was in 'sharp contrast with the laws of constructive statics' *[1]*.[4] For Nervi, architecture should privilege the real needs of the programme in tandem with a stringent economic solution to the statics of the structural problem. A few months after Nervi and Rogers's articles, Félix Candela also published a letter in *Casabella* criticising architects (presumably Le Corbusier and Xenakis) who copied the Spanish engineer's designs but did not take advantage of the calculations that he offered for their invention.[5] If not mere formalism, what then were these designers hoping to achieve by their expression of structure?

Its more or less taken for granted that building designers never begin –or can ever begin – from the problems at hand without other influences or assistance. Everyday objects, modelling methods, rules of thumb, and solutions from the near or distant past, play an important role in the process of design. These experiences are fertile sources of inspiration that, by an intuitive insight the designer will draw upon in formulating new solutions. In their search for an architectural proposition, neither Utzon, Saarinen, nor Xenakis were ignorant to the rules of statics but sought to exploit precisely these sorts of imaginings in their use of models to generate an appropriate and efficient architectural proposition. This article examines how the use of models by designers exploring the role that structure plays as the identifying characteristic of the architectural idea during the 1950s provides a key insight into a difference of opinions that emerged between the economic and expressive generation of structural form in architecture. But even more, it aims to demonstrate the modern architect's real need for models to not only test an architectural idea in three dimensions but also to generate them.

Modelling new structural forms

Building designers have been using scale models to study and design architecture for over two millennia.[6] With the exception of a few examples from the eighteenth century, their use as a tool to test and improve the structural behaviour of architectural propositions came into practice predominantly during the early twentieth century in connection with advancements in the use of reinforced concrete. Before this time, relatively little was published on the construction and computational methods of building with reinforced concrete, a heterogeneous material whose behaviour could not be likened to steel or masonry. During the second half of the nineteenth century there was extensive testing with full-sized models of reinforced concrete beams, columns, slabs, and arches to determine their behaviour, compressive strength, and modulus of elasticity.[7] However, the analysis of more complex structures like those for thin shells curved in one or two dimensions required significantly more consideration of bending, the tension and compression in the plan of the shell, and the effects of strengthening needed at the points of support and stiffening of the unsupported edges.[8] To limit the amount of equations required to calculate these forces, early designs were predominately symmetrical and reduced scale models of entire edifices were enlisted as a method of verifying and improving upon designs.[9]

In Italy, the experimentation with structural form using scale models dates back to the 1920s, but systematic research only began in 1930, when Arturo Danusso[10] founded the Laboratorio Prove Modelli e


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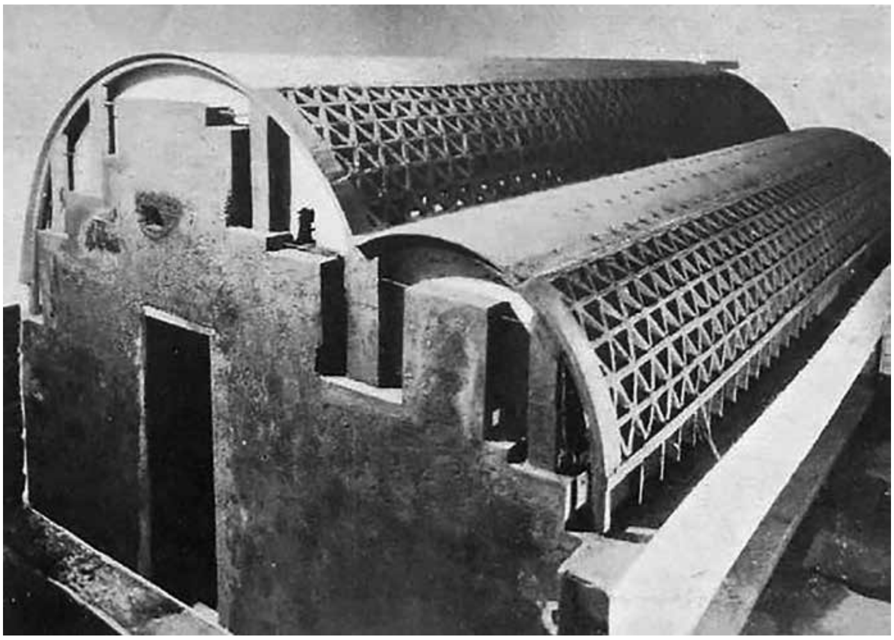
2 Pier Luigi Nervi, celluloid reduced scale model (1:37) of Orvieto Hangar, 1935.



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3 Eduaro Torroja, micro-concrete model shell roof of Fronton Recoletos, 1934.

4 Félix Candela with Jorge González Reyna, created the ruled surface formwork for the Pabellón de Rayos Cósmicos (Cosmic Ray Pavilion), National Autonomous University of Mexico, 1951.

4

Costruzioni (Laboratory for Testing Models and Construction) at the Reale Politecnico di Milano.[11] Nervi's relationship with the experimentation and testing of structural form using models grew out of his contacts and friendship with Danusso and his pupil Guido Oberti. The first collaboration between Nervi and the Laboratorio began in 1935 with the tests carried out using 1:37 scale celluloid models of the hangars that Nervi was about to build in Orvieto (1935–8) and then in Orbetello and Torre del Lago (1939–42) *[2]*.[12] The main reason for the use of celluloid to model the hangers was determined not by the large dimensions of the proposed vault, 110 x 36 metres in plan, but because the unusual slenderness of the crossed ribs that formed it were difficult to model in micro-concrete. A celluloid model by contrast permitted experiments known as photoelastic testing – a method of test to confirm the stress/strain of a structure by using a material like celluloid that will generate a colourful fringe pattern when loaded with weights – to simulate the effects of gravity and wind loads at full-scale. After an interruption of activity during the war, the collaboration between Nervi and Oberti resumed on some of the most prestigious building projects of the age including the reinforced concrete frame of the 135-metre-tall Pirelli Tower in Milan, designed by Gio Ponti. This time, working with Oberti, Nervi tested a micro-concrete model of pumice-stone and cement at a scale 1:15 (nine metres tall) and resting on a layer of rubber to simulate the deformity of the soil. It permitted the engineers to test the structure beyond service conditions up to failure.

Simultaneous to Nervi's experiments in Italy, Torroja was conducting his own tests with models at the lnstituto Técnico de la Construcción y del Cementa in Spain for his shell-roofs of the Algeciras Market Hall (1933) and the Frontón Recoletos (1935). To develop an initial understanding of the behaviour of the El Frontón Recoletos roof, Torroja created a simple card model attached to timber end-pieces representing the concrete transverse walls of this beam at either end. Simple testing on the model gave Torroja an insight into how well the intersecting barrel vaults behaved as a longitudinal beam spanning between the end-walls. Satisfied with the efficacy of the form, Torroja constructed a large 1:10 scale model in micro-concrete, using sand as the aggregate and steel wires like that for the Algeciras Market Hall (1933) *[3]*. The aim of these tests for the market hall's dome was to load a model to failure so that the elastic deflections could be studied under different loading conditions and his theoretical calculations corroborated. The model for the Market Hall, however, collapsed earlier than expected requiring Torroja to reconsider the number of ties specified for it and thus improving the design.

Known for his hyperbolic thin reinforced concrete shell structures, Candela is certainly included in this survey of designers challenging the possibilities of reinforced concrete structure during the mid-twentieth century. A Spaniard by birth, Candela emigrated to Mexico during the Spanish civil war where he developed a career as a builder whose work earned him the reputation as a 'creator of extraordinary forms'.[13] Since 1951, Candela focused on the principles of statics and geometry demonstrated by Fernand Aimond and Eduardo

Torroja,[14] seeking to improve the functioning of shells, vaults, plate structures, and domes. It was on the Mexico City university campus that Candela created his first example of a hyperbolic paraboloid in reinforced concrete for the saddle roof of Pabellón de Rayos Cósmicos designed by Jorge González Reyna *[4]*. To familiarise himself with the vagaries of the doubly-curved surfaces, Candela employed stick models but gave special preference to the actual construction claiming, '[a]ll my models are life-size'.[15]

In his book *Scienza o Arte del costruire?* (*Is Building an Art or Science?*) from 1945, Nervi sought to address the question posed by the structural possibilities of reinforced concrete and verified in scale model.[16] In answer to the question raised by his book's title, Nervi claimed that '[t]he conception of a structural system is a creative action only partly based on scientific data' and emphasised the priority of the intuitive conception of structural architecture, arguing that static sensitivity as well as aesthetics are a personal aptitude.[17] His vision was echoed by Torroja who declared in *Razón y Ser de los Tipos Estructurales* (*Philosophy of Structures*) that, 'the birth of a structural complex, the result of a creative process, the fusion of art and science, talent and research, imagination and sensibility, goes beyond the realm of pure logic to cross the arcane frontiers of inspiration'.[18] For these individuals, the structural imagination thus transcended the possibilities of analytically rigorous verification and became a principal justification for their keen interest in experimental research using mechanical-scale models. Their emphasis on the expression of structure resonated with a handful of modern architects who began to emulate the work of these designers in southern Europe and Mexico in shaping architectural form.

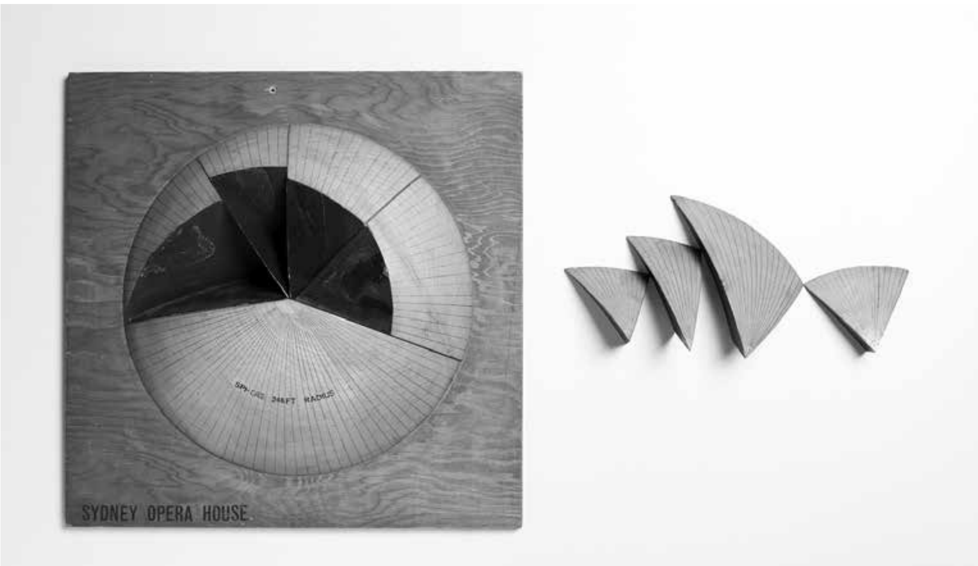
Expression takes command

It was not long after Nervi, Torroja, or Candela's projects were celebrated in the pages of magazines and newspaper articles that others began to take inspiration from their emphasis upon structural form in their own work. Remarkably, three of the most familiar projects exemplifying this approach to architectural design, Utzon's Sydney Opera House, Saarinen's TWA Terminal, and Xenakis's Philips Pavilion (in collaboration with Le Corbusier) were all designed between 1956 and 1957. These projects utilised structural form as a medium and defining characteristic of the architectural idea.

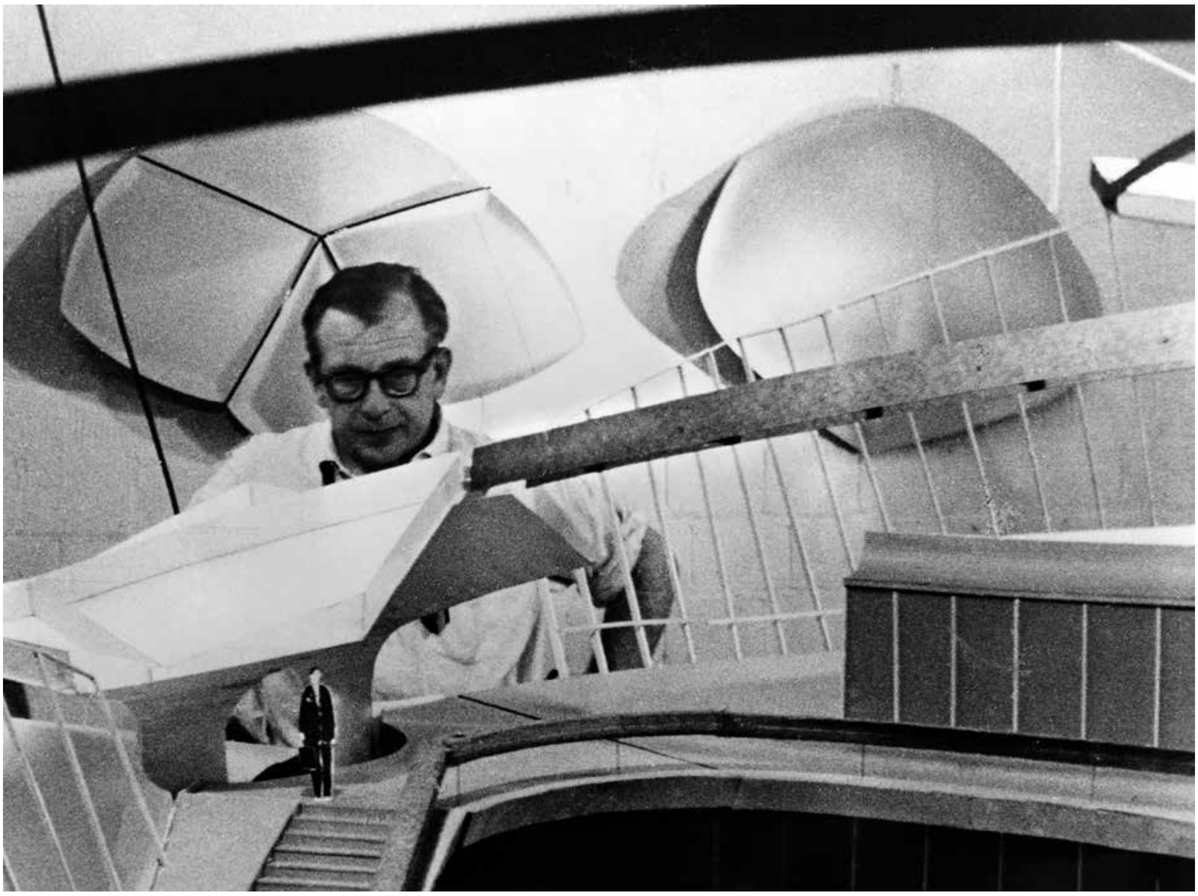
Utzon won the commission for the Sydney Opera House after the competition closed in December of 1956 and the twelve drawings Utzon submitted illustrating his design was one of more than 223 entries. Saarinen, who was one of the four jury members had missed the beginning of the ten days set aside for judging in January of the following year. A widely told and unverified story is that when Saarinen arrived in Sydney, he was underwhelmed by the entrants his colleagues had already shortlisted and pulled Utzon's design out of a pile of rejected schemes, exclaiming that it was easily the winning design. Contrary to the popular clean, ornament-free volumes of the international style, Utzon's design was a sculptural set of interlocking, open-air, vaulted thin shells without walls or supports, which his preliminary sketches compared to clouds, the roof of a Chinese pagoda or two overlapping curved forms hovering over a large platform. As Utzon explained:

> *During the process of developing the architectonic structure of the Opera House, there was a constant endeavour to achieve simple, clear, constructive forms of expression in which everything, including the manner of building, supported my demand for totality, from the least detail to the great final form.*[19]

Thin-shell structures were popular among architects and engineers of the 1940s and 1950s, but Utzon's proposal was largely diagrammatic and he had not consulted an engineer before submitting his design.[20] To build the shells, Utzon and the engineers at Arup & Partners quickly came to the conclusion that it was not possible to construct the original proposed shells since their very shape introduced high bending moments and instead chose to create



5 Jørn Utzon, model illustrating the origin of the roof geometry of the Sydney Opera House (the so-called spherical solution), 1961. © Joern Utzon/ Copydan Tekst and Node/Writing. Copyright Agency, 2020.

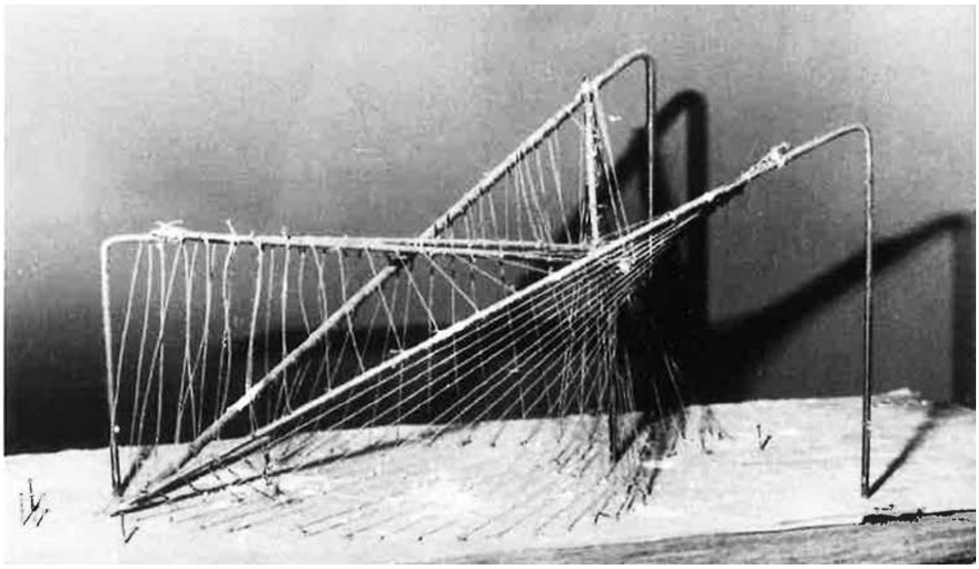


6 Eero Saarinen standing in front of two-scale fiberglass concept models (hanging on the wall) of the TWA Terminal at Kennedy Airport, New York, c. 1958.

their surfaces by employing precast, post-tensioned segmental arch ribs. Their shapes, however, needed to be expressed mathematically, and Utzon spent four years working with parabolic geometries to accommodate the structural forces acting on them. However, because the design of each ribbed shell was unique, it lacked a defining geometry that would make it possible for the builders to reuse formwork and thereby reduce the building's costs. Then, in 1961, while stacking pieces of a large model of the opera house in his office, Utzon noticed their similarities and observed that the shells could be derived from the surface of a sphere; he went on to produce a wooden model to demonstrate the efficacy of the so-called 'spherical solution' for determining the building's form and its exterior tiles using repetitive geometry *[5]*.[21]

Shortly after returning from judging the competition of the Sydney Opera House, Saarinen resumed work on the commission for the TWA Terminal. At this time, Saarinen was also moving away from employing the rectangular shapes of international style architecture in his *oeuvre* and was exploring the expressive forms made possible with the use of reinforced concrete in his designs for the Kresge Auditorium (1955) on the Massachusetts Institute of Technology's (MIT) campus. Similar to Utzon, Saarinen aspired to employ a thin-shell, concrete roof for this project and also used the curvature of a sphere. The engineering challenge Saarinen faced with this decision was exceedingly difficult, and he was inevitably forced to use deep-curved arch beams as a way to compensate for the bending stress. Saarinen himself admitted, 'In retrospect, one has to criticize this building […] we learned that one cannot depend on geometry for the sake of geometry.'[22] For the TWA Terminal, Saarinen was requested to design a building that the airline's president, Ralph Dawson explained, 'expresses the drama and excitement of travel, not a static, enclosed space, but a place of movement and transition'.[23] From the beginning, Saarinen sought to improve passenger flow, and sent people from his office to other terminals with stopwatches, looking at traffic counts and bottlenecks. In terms of structure, to avoid the challenges he encountered at MIT, Saarinen initially opted for a more structurally logical form – a single, large undulating elliptical paraboloid concrete shell structure that was more ambitious but intuitively reasonable. Saarinen also chose to work with Boyd Anderson, a consulting engineer for Ammann & Whitney, because he had been 'very patient, and gentle with his guidance'[24] and was willing to discuss options for how to 'express the drama and wonder of air travel'[25] through a building form made of reinforced concrete. As the project developed, however, Saarinen began to stray from structural logic arguing that the 'structural and rational cannot always take precedent when another form proves more beautiful. This is dangerous but I believe true.'[26] After dozens of clay and fiberglass study scale models, the shell roof was separated into four individual vaults supported on four Y-shaped columns that were shaped to dramatise the upward curving sweep of the vaults connected by continuous skylights – all to increase the sense of airiness and lightness. Springing from the columns, the vaults are stabilised with continuous, curving, and cantilevered beams along their edges that connected back to a central keystone in the middle – presumably where Saarinen's finger depressed the grapefruit *[6]*. In its final design, the forms of the interior appear sculpted as if from clay to accommodate the movements of forces and people through the terminal, while the structural continuity and logic of the original large shell idea was refined by Saarinen's intention to create a sense of lightness and uplift.

Simultaneous to these events in Australia and the United States, Le Corbusier and Xenakis were also pursuing the construction of a thin-shell structure for the 1958 World Expo in Brussels, Belgium. Le Corbusier was approached by a building committee in the winter of 1956 to design a pavilion for the Philips company at the Expo. The architect was almost seventy years old and initially paid little attention to the project as he was preoccupied with the governmental centre for the new capital of Chandigarh in the Indian state of Punjab. One aspect, however, apparently piqued his interest, the creation of a structure for the first electronic poem in which '(e)verything will happen inside: sound, light, colour, rhythm. Perhaps, a scaffolding will be the pavilion's



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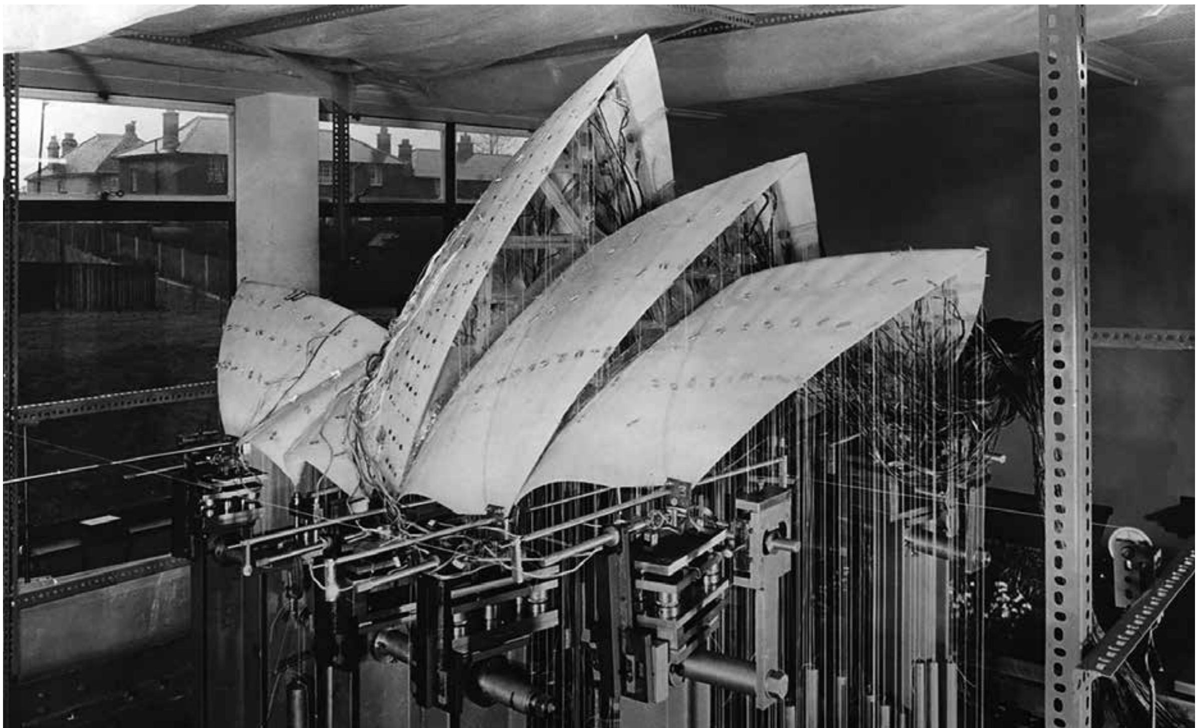
7 Iannis Xenakis, preliminary model of the Philips Pavilion (co-designed with Le Corbusier), 1958. © Foundation Le Corbusier/ADAGP. Copyright Agency, 2020.

8 Perspex Model of Sydney Opera House roof undergoing stress distribution testing at Southampton University, c. 1960. © Joern Utzon/Copydan Tekst and Node/ Writing. Copyright Agency, 2020.



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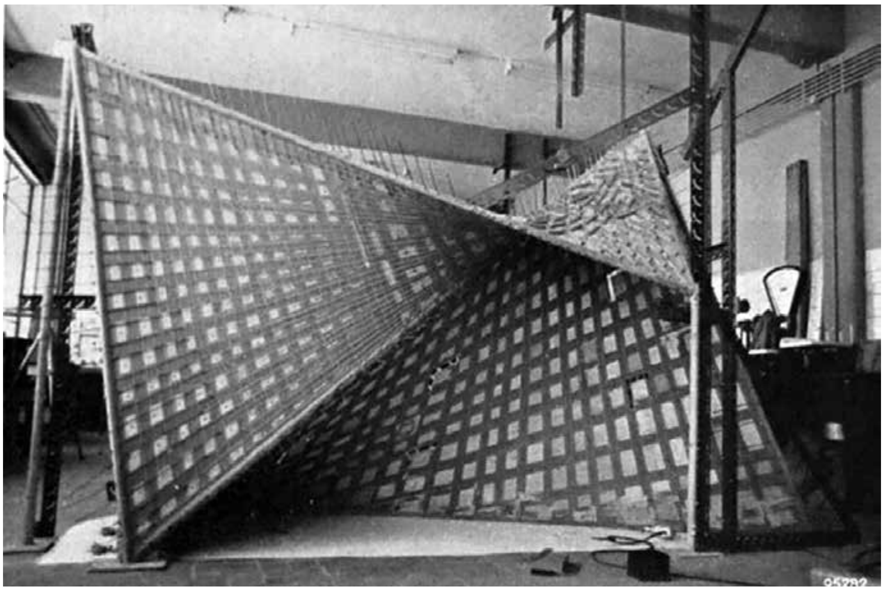

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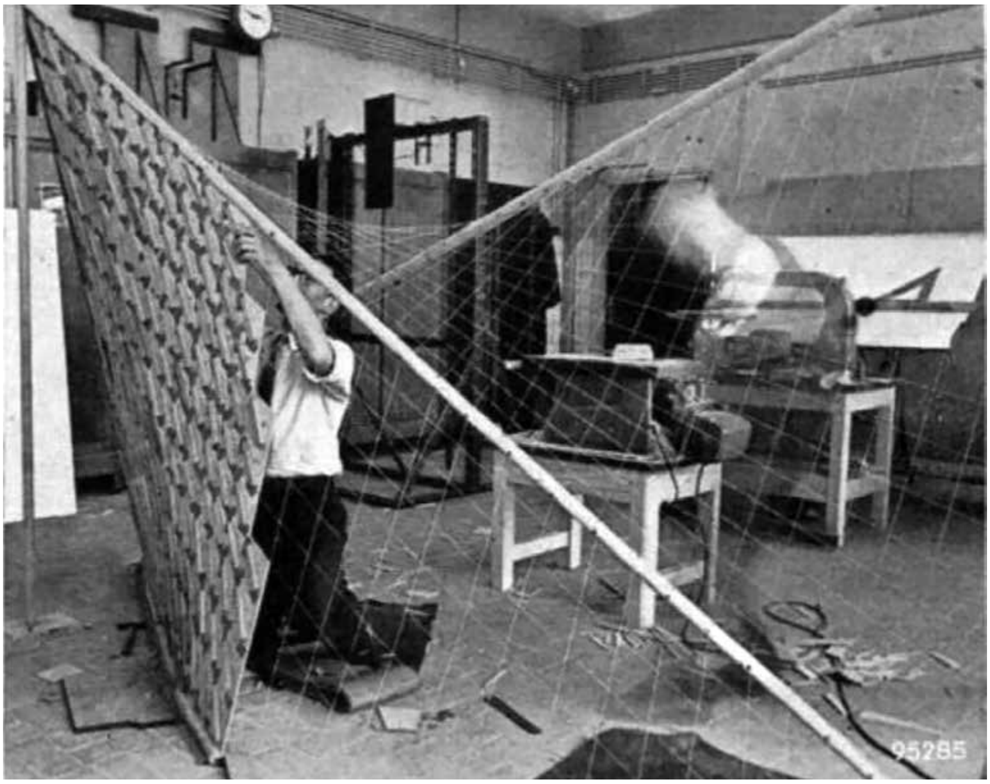

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9 The 1:10 scale model of the Philips Pavilion for investigating the system of construction planned by Messrs Strabed (Stevin laboratory, Technische Hogeschool, Delft), c. 1958. © Foundation Le Corbusier/ADAGP. Copyright Agency, 2020.

10 Plywood model of the Philips pavilion in the course of construction, c. 1958. © Foundation Le Corbusier/ADAGP. Copyright Agency, 2020.

only exterior aspect.'[27] Given the quantity of work in his Paris studio at the time, Le Corbusier relied on the assistance of Xenakis who joined the office in 1951 and had, despite his lack of architectural training, impressed the master with his intelligence and skill working on a handful of projects including the Unité d'Habitation of Nantes-Rezé.[28] Although Le Corbusier did not establish the precise form of the walls and roof in the early meetings, he fixed the shape of the building's footprint as that of a 'stomach' with a narrow entrance and exit 'spout' on either side to shelter it from external light and sound. The stomach was intended to be a large central space where a six-to-seven-hundred-person audience could sit or lay down and experience an eight-minute piece of electronic music by composer Edgard Varèse, synchronised to various effects of light, changing colours and black-and-white photographs projected onto curved enclosing walls. In his first studies, Xenakis 'went through several unfruitful attempts based for the most part on Le Corbusier's design, which [he] was trying to respect as much as possible'.[29] Possibly recalling the graph of the musical composition that he composed a few years previous – a glissandi for strings he called Metastasis and which resembled of ruled surface of a hyperbolic paraboloid – Xenakis began to work with string and stiff wire to model the walls and roof as a seamless superstructure of ruled surfaces *[7]*. With this model, a form began to emerge, a mixture of conoids and hyperbolic paraboloids, that was less a result of logic but '[i]ntuition's arbitrariness', one whose curves would enhance the experience of being surrounded by sound, theatre, and light.[30] At this time, engineers were consulted, who proposed changing all conoids to hyperbolic paraboloids – to more easily define the curvatures and simplify the calculations – and to use a similar structural form as the model in which strings became a heavy metal skeleton and the vertical bent wire became prestressed reinforced concrete stanchions. Once Xenakis found an acceptable form working with the model, he drafted it in orthographic projection.

Similar to the structures of Nervi and Torroja, the Sydney Opera House and Philips Pavilion were also tested in model. Despite having no engineering consultation upon submission, the search for a solution to Utzon's winning design was driven by a close creative partnership between the architect and Arup engineers, who developed as many as twelve different versions for the concrete roof between 1957 and 1963. These various roof forms were subject to a series of model tests including stress distribution tests conducted on a large Perspex model of the roof at the Structural Laboratory in Southampton University, as well as a series of tests on models in wind tunnels at the National Physical Laboratory in Teddington and Southampton University *[8]*.[31] For Xenakis's Philips Pavilion the first question was whether his structure of such intricate shape, in which the boundary conditions are not fulfilled and give rise to much more complex states of stress can indeed be realised as a shell structure of reinforced concrete. To confirm the build-ability of the shell, a plaster model on a wire-gauze framework was created at a scale of a 1:25 scale model at the Netherlands Institute TNO for Building Materials and Building Constructions *[9]*.[32] However, because the pavilion was not intended to be constructed as a monolithic structure, but as an assembly of precast slabs which, after all the surfaces had been built up, were to be pressed together by pre-stressing high-tensile steel wires on the inside surface only, a second model of three-ply saddle-shaped plywood slabs was built at a scale of 1:10 in the Stevin Laboratory of the Department of Civil Engineering at the Delft Technische Hogeschool *[10]*.[33] Despite these verifications, Nervi, Candela and a handful of other engineers were quick to differentiate their work from those produced by these individuals.

Correct construction

In this period of structural and formal exhibitionism, the dispute that emerged in the pages of *Casabella* during 1959 centred on the use of models as a tool for verifying what Ernesto Nathan Rogers claimed to be 'correct construction' versus 'unbridled structuralism, where the technical medium is reduced to a mere exhibitionist game and loses all concreteness'.[34] The projects that provoked the debate were undoubtedly Saarinen's TWA Terminal and Utzon's Sydney Opera House. The criticism, which was levied above all by Nervi and Candela, concerned the arbitrariness of Utzon, Saarinen, and certainly also Xenakis's structural forms.

Throughout 1959, Nervi published three articles in *Casabella* that explored the relationship between structural technique and expression in architecture. In the first publication, Nervi argued for an approach to structural design as the economic, visible materialisation of the system of forces and reactions in the material used. The second article, however, sought to polarise the work of *l'Ingegnere edile* (the construction engineer) or his specialisation as an engineer-architect, and on the other, the *Architetto* (architect) the graduate of the *Ecole des Beaux Arts* who 'is the decorator of facades or interior'. The evolution of architecture during the twentieth century had for Nervi, found that aesthetic expressiveness and the functional as well as constructive substance of a building, are inseparable elements. It was in the final issue that Nervi included an image of the models for Utzon and Saarinen's projects and judged them as:

> *examples of the most outspoken static and constructive anti-functionalism, a consequence of the arbitrariness of forms in sharp contrast with the laws of constructive statics. You can easily imagine the acrobatics of calculation, of technique, and the squandering of materials that will be necessary, even if you succeed without substantial formal changes, to make them stand up.*[35]

In Nervi's opinion, the aim of architecture is static stability in an absolute sense, and its economic-constructive possibility in a more relative sense. Contrary to the perceived separation between the functions of construction engineer, and those with the title of architect, Nervi saw architecture as the 'art and technique of building'.[36] For Nervi, the contemporary separation between these two factors is related to the limits of training any one individual with the knowledge and skill of both engineer and architect. Their incompleteness is an insurmountable difficulty and the reason for specialisation arguing that the architect's work increasingly becomes a work of 'collaboration which must be in place at the beginning of the architectural ideation to avoid both formalistic excess and the inexpressive purely technical solutions'.[37] In what would seem to be a direct reference to Utzon and Saarinen, Nervi reasons that formalistic excess is the consequence of 'layman, and even architects and critics, who are not fully acquainted with the limits and the possibilities of statics, think that with more thorough calculations of stability and the massive use of steel and reinforced concrete, there are no limits to bold constructions'.[38] In Nervi's opinion, technical accuracy is not merely a fundamental requirement for a large structure, rather, as he claimed, 'an indispensable premise of architectural beauty'.[39]

A few months after Nervi and Rogers's editorial articles criticising Utzon and Saarinen's projects, Félix Candela published a letter in *Casabella* that similarly took aim at those architects who rely on the Spanish engineer's skills but do not take advantage of the techniques, albeit equations, which he offers for their invention. Candela's letter echoed many of the concerns he penned the previous year for the August issue of *Architectural Record* about the use of entirely free forms in architecture. As Candela argued, 'I believe architects should consider them a little more soberly, if only to spare themselves much distress and disappointment. Free surfaces defy simple analysis.'[40] Unlike Nervi and Rogers, Candela does not mention Corbusier's and Xenakis's Philips Pavilion directly, but he was certainly familiar with the project that was still on display at the 1958 Expo when his article was published. In what reads like a direct reference to the design development of the Philips Pavilion, Candela warns against the use of scale models to test the efficacy of one's designs:

> *because the problem is never to discover the internal stresses in a structure (which are normally very low) but to find the forces at the edges* [...] *Moreover, the material used in models is always different from the real thing, and at the same time the size and disposition of the edge members have a fundamental influence on the distribution of internal stresses; so we enter a vicious circle.*[41]

Instead, Candela promoted the use of calculations for doubly-curved or compound surfaces to stabilise these structures, preferring above all the hyperbolic paraboloid since '[t]his is its real justification and a far more valid one than the beauty of its form'.[42]

These accusations raise the question whether the architects they criticise are simply naïve or as ignorant of statics as Nervi and Candella make them out to be. To their credit, the structures that Saarinen designed employed less repetition than some of Nervi's larger projects while Xenakis's use of the hyperbolic paraboloid was more adventurous than Candela's predominately symmetrical works. Although Utzon didn't know exactly how he would build the vaults of the Opera House when he submitted his competition entry, he wasn't completely unappreciative of structure having begun his career working with his father at the naval shipyard designing boats and often remarked upon his appreciation for the structural forms of nature claiming, 'if it grows naturally, the architecture will look after itself'.[43] By contrast Saarinen, who already had encountered problems resolving the structure for his design of the St Louis Monument and the MIT Kresge Auditorium knowingly challenged convention at the beginning of the design process. Yet, even working with an engineer, as mentioned previously he decided to break with his preliminary approach to the TWA shell roof and pursue a more complex four-part vault design. Of the three, Xenakis was an engineer by training, well aware of the principles and application of the hyperbolic paraboloid in practice. If the designer's aim was not primarily to create an optimal, easily calculated, and analysable structural form, what then were these architects aspiring to do?

The architect's task

Among the new materials available to a building designer during the first half of the twentieth century, reinforced concrete had a significant influence on the size and shape of structures. In the hands of a structural engineer, the propriety of the forms this material should take were guided by two fundamental rules: an economy of form and the resolution of the static requirements. This approach to structural form clearly resonated with Louis Sullivan's famous 'form ever follows function' that was echoed by the American modernist architect and industrial designer, Walter Downing Teague's call from 1940 for a building whose 'stresses and strains [are] evident to the eye'.[44] However, for building designers like Utzon, Saarinen, and Xenakis, the resolution of the structural form was dependent not only upon the economy of material and statics but also upon how well it contributed to the resolution of the architectural idea.

In 1957, the British architectural historian, John Summerson, published an essay about the different aims of engineers and architects during this period of time entitled, 'The Case for a Theory of "Modern" Architecture'.[45] Similar to Nervi's 'construction engineer', Summerson identified that an engineer is the heir to rationalism and an economy of means in construction, whose responsibility concerns only one component of the entire project, the 'whole sectional trace of a large building'.[46] By contrast, Summerson reasoned that the crucible of the architect's creative endeavour was not limited to the decoration of facades but to the programme, which he defined as 'a description of the spatial dimensions, spatial relationships and other physical conditions required for the convenient performance of specific functions'.[47] Within this programme, architectural relationships bound by the movements of human users over specific periods of time are being suggested – whether it is the movements of people through an airport terminal, the viewing of an opera or simply their repeated movements in a circulation system. Nervi was also concerned with the propriety of a simple and economic structural form for a particular program but believed it was the engineer's task to suggest these and 'the aesthetic sensitivity of the designer, who understands their intrinsic beauty and validity, welcomes the suggestion and models it, emphasises it, proportions it, in a personal manner which constitutes the artistic element in architecture'.[48] In the works from Utzon, Saarinen, and Xenakis, however, the structure is not a servant of the architectural programme but a medium for forming the visual and spatial experiences of specific activities at a particular site.

What set the works of Utzon, Saarinen, and Xenakis apart from many of their peers is that they were not ascribing to a particular style in their design of architecture. In the December of 1956 issue of the *Architectural Review*, James Stirling noted this change of attitude in Le Corbusier's work around the time he began the Philips Pavilion project with Xenakis. The article entitled, 'Ronchamp: Le Corbusier's Chapel and the Crisis of Rationalism' was principally critical of the great master's design for his chapel, Notre Dame du Haut in Ronchamp, France and its failure to utilise modern technological advancements in lieu of an 'entirely visual appeal' that was completely removed from contemporary thinking about modern architecture, specifically the international style that Le Corbusier's *Towards and Architecture* inspired.[49] In the case of Saarinen, throughout his career he was criticised for his explorations with different styles, from the classically inspired plan of the Morse and Stiles Colleges at Yale, to the emulation of Mies van der Rohe's international style modernism in his General Motors Technical Center (1956) project in Warren, Michigan. However, by 1958, Saarinen sought to align himself with Le Corbusier's new approach, arguing that:

> *modern architecture is in danger of falling into a mold too quickly – too rigid a mold. What once was a great hope for a great new period of architecture has somehow become an automatic application of the same formula over and over again everywhere. I feel, therefore, a certain responsibility to examine problems with the specific enthusiasm of bringing out of the particular problem the particular solution.*[50]

At an early stage of his career Utzon also remarked about employing a similar approach in his own architectural pursuits. In 1948 during his travels throughout Europe, Utzon reflected on the making of architecture whose aims he compared to the seed of a plant or tree, which he argued '[o]n account of differing conditions, similar seeds turn into widely differing organisms'.[51] This notion of architectural design as an evolutionary process resonated with Nervi's approach to structure he believed could attain a teleological 'final truth' he called beauty – an ideal combination of material, method of construction and purpose.[52] The problem with this teleological approach to architecture is that, unlike a car or airplane in which successive improvements and economic pressures influence the perfection of form and not 'the designer's tastes or aesthetic aspirations', a building is, as Gilbert Simondon would argue in *L'individu et sa genése physico-biologique*, an individual.[53] The transferral or transduction of a building concept through a material medium will experience the same challenges as the growth of a seed crystal, which will always produce an individual snowflake because of the different, winds, temperatures, and moisture levels it encounters on its path to the ground.[54] Further as demonstrated by the Sydney Opera House competition, there were 223 different submissions for the same programme and site implying that there is not a best or correct solution but one that is deemed appropriate to the expression of the program that resonates with the client or community in a meaningful way.

While a building concept may not be copied from place to place without difficulty, its principles or composition can certainly inform new designs. If the examples of Saarinenss grapefruit, Utzon's clouds, or even Xenakis's glissandi are any indication, an architect's memories, experiences, and encounters with the designs of their peers are also a primary source for invention. The American art historian George Kubler makes a similar observation in his challenge to a taxonomical approach for the study of a history of things, including architecture that considers forms the product of a single author, time, and place.[55] As Kubler reasons, the language of electrodynamics is a more appropriate approach to thinking about the transmission of forms in art and architecture since they act as signals which trigger other individuals to repeat them. Kubler does not deny the value of 'true inventions' but contends that invention without replication 'would approach chaos', whereas an 'infinity of replicas without variation would approach formlessness'.[56] Clearly Saarinen, Utzon, and Xenakis thought about the transmission of architectural forms and ideas along similar lines as Kubler. While the original meaning and intent of an everyday object or architectural form(s) has its own applications, by applying them to a new use or context, they go through evolutions with no relation to their original or intended uses. Rather as Utzon remarked about the study of existing architecture in design, we must let 'ourselves be spontaneously influenced by it and appreciating the ways in which solutions and details were dependent on the time at which they were created'.[57] The physical model is unique in this regard by embodying the same (but not all) structural properties within it. Pushing on the grapefruit rind is a perfect example. It facilitates creative thought in a more totalising way than a drawing can only approximate. This is why structural expressionism turns to models, partly because it facilitates the testing of structural designs, but even more because it inspires the imagination to discover new designs in the test results.

Conclusion

Architects and engineers use models, precedents, and found objects to see, for that is their real purpose, to permit their user to not only study or test a proposed or existing design but to also imagine it. The 1940s and 1950s were a remarkable period of time in which engineers and architects employed reinforced concrete as a medium for shaping their structures as efficient and economic expressions of forces, movements, and human activities. Inspired by the clarity of form and function in the work of Torroja, Nervi, and Candela, a handful of designers sought to emulate their approach in the formation of architecture as an expression of structure. This introduced new questions about the methods with which structural form was conceived. To Nervi and Candela, the structures which some designers created to emulate this new approach appeared arbitrary and indeed, required 'brilliant feats of calculus, technique, and the waste of materials'.[58] For the Utzon, Saarinen, and Xenakis, however, their designs were not arbitrary but intuitive, viable approaches to the use of structure in a way that satisfies the aspirations of an individual client or enriches the programmatic activities of its users. When new materials, methods of construction, or ideas about its formation arise, these examples demonstrate the real need for models to not merely demonstrate the possible but to manifest the imaginable.

Notes

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3. Arguably it was the article, 'The Work of Felix Candela', that brought Candela's shell designs to the attention of architects. 'The Work of Felix Candela', *Progressive Architecture*, 7 (July 1955), 106.
4. Pier Luigi Nervi, 'Architettura e strutturalismo [Architecture and Structuralism]', *Casabella*, 229 (1959), 4–5.
5. Felix Candela, 'Strutture e Strutturalismo: Una lettera di Felix Candela [Structures and Structuralism: A Letter from Felix Candela]', *Casabella*, 232 (1959), 48–9.
6. See, for example, chapter 3, 'Descriptive Tools', in Matthew Mindrup, *The Architectural Model: Histories of the Miniature and the Prototype, the Exemplar and the Muse* (Cambridge, MA: MIT Press, 2019).
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13. See K. Frampton, *Studies in Tectonic Culture: The Poetics of Construction in Nineteenth and Twentieth Century Architecture* (Cambridge, MA and London: MIT Press, 1995).
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15. *The New Mexico Quarterly*, 27–8 (1957), 192.10.
16. Pier Luigi Nervi, *Scienza o arte del costruire? Caratteristiche e possibilità del cemento armato* [*Is Building a Science or Art? Characteristics and Possibilities of Reinforced Concrete*] (Roma: Edizioni della Bussola, stampa 1945).
17. 'L'ideazione di un sistema resistente è atto creativo che solo in parte, si basa su dati scientifici [The design of a resistant system is a creative act that is only partially based on scientific data].' Pier Luigi Nervi, *Scienza o arte del costruire?: Caratteristiche e possibilita del cemento armato* [*Is Building a Science or Art?: Characteristics and Possibilities of Reinforced Concrete*] (Roma: Edizioni della Bussola, stampa 1945), p. 51. Unless otherwise noted, all translations by author.
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21. Yuzo Mikami, Utzon's Sphere: Sydney Opera House: How It Was Designed and Built (Tokyo: Shokokuska, 2001), p. 65.
22. Eero Saarinen, 'General Statement about the sculptural, curved/ shapes that we have been involved with, beginning with St. Louis, the water tower and dome at General Motors, MIT, Yale, TWA, and now the Washington International Airport', undated and unpublished transcript from dictation, c. 1558–9, in Eeva-Liisa Pelkonen; Donald Albrecht, *Eero Saarinen: Shaping the Future* (New Haven: Yale University Press, 2006), pp. 343–4 (p. 344).
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30. Ibid., p. 32.
31. Yuzo Mikami and Osamu Murai, *Utzon's Sphere: Sydney Opera House – How It Was Designed and Built* (Tokyo: Shokokusha Tokyo, 2001), p. 59.
32. A. L. Bouma and F. J. Ligtenberg, 'Model Tests for Proving the Construction of the Pavilion', *Philips Technical Review*, 20 (1958/9), p. 18
33. Ibid., p. 23.
34. '[...] frenato strutturalismo, dove il mezzo tecnico si riduce a un mero gioco esibizionistico e perde ogni concretezza [... unbridled structuralism, where the technical means is reduced to a mere exhibitionist game and loses all concreteness].' Pier Luigi Nervi, 'Critica delle strutture [Critique of the structures]', in *Casabella*, 223 (January 1959), 55.
35. '[...] sempi del più schietto anti-funzionalismo statico e costruttivo, conseguenza della arbitrarietà delle forme in netto contrasto con le leggi della statica costruttiva. Si possono facilmente immagi-nare le acrobazie di calcolo, di tecnica, e lo sperpero di materiali che saranno necessari, se pure ci si riuscirà senza sostanziali modiche anche formali, per farli stare in piedi.' Pier Luigi Nervi, 'Architettura e strutturalismo', *Casabella*, 229 (July 1959), 5.
36. '[...] sia stata la constatazione che espressività estetica e sostanza funzionale e costruttiva di un edificio, sono elementi inscindibili [... was the observation that aesthetic expressiveness and functional and constructive substance of a building are inseparable elements].' Pier Luigi Nervi, 'Rapporti tra ingegneria e architettura [Relations between Engineering and Architecture]', *Casabella*, 225 (1959), 50.
37. 'Collaborazione che, quando il tema costruttivo è notevole, deve essere in atto all'inizio dell'ideazione architettonica per evitare sia gli accessi formalistici, sia le inespressive soluzioni puramente tecniche.' Ibid.
38. Nervi, 'Architettura e strutturalismo', p. 5.

39. '[...] una indispensabile premessa della bellezza architettonica'. Ibid.
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53. Gilbert Simondon, *L'individu et sa genése physico-biologique: L'Individuation á la limiére des notions de forme et d'information* [*The Individual and His Physico-Biological Genesis: Individualization at the Limit of Notions of Form and Information*] (1964; repr. Grenoble: Jérome Millon, 1995), pp. 81–5.
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56. Ibid.
57. Utzon, 'The Innermost Being of Architecture', in Weston, *Utzon*, pp. 10–11.
58. Nervi, 'Architettura e strutturalismo', p. 5.

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