Michele Emmer
Marco Abate *Editors*

Imagine Math 8

Dreaming Venice

Springer

This volume is dedicated to
the Liberty of Ukrainian people.
—Rome, 27 February 2022

Massimiliano Botti, *PI MACHINE Architects*, Paris (February 2022)

Michele Emmer • Marco Abate
Editors

Imagine Math 8

Dreaming Venice

Springer

Editors
Michele Emmer
Sapienza University of Rome (retired)
Rome, Italy

IVSLA - Istituto Veneto di Scienze,
Lettereed Arti
Venice, Italy

Marco Abate
Department of Mathematics
University of Pisa
Pisa, Italy

ISBN 978-3-030-92689-2   ISBN 978-3-030-92690-8 (eBook)
https://doi.org/10.1007/978-3-030-92690-8

Cover illustration: M. Paladino, Senza titolo, codice MP P20041 (2020) tecnica mista su tela, 120,00 x 100 cm. Incorniciata misura 104 x 124 cm.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Sergio Musmeci and the Calculation of the Form

Tullia Iori

Sergio Musmeci was one of the four *heroes* of the twentieth-century Italian School of Engineering, along with Pier Luigi Nervi, Riccardo Morandi, and Silvano Zorzi. Musmeci was an eccentric and countercultural engineer, the most visionary of the four.

Today, Musmeci is most famous for being the designer of the Basento River Bridge in Potenza (1967–1975), probably the most beautiful bridge in the world.

The bridge is an equicompressed *nameless* form. Musmeci designed it in accordance with his theory: when an engineer designs, the form must be the only unknown. The shape that responds perfectly to given constraints and loads, according to Musmeci, can be calculated mathematically.

The bridge over the Basento is the last masterpiece of the Italian School of Engineering; it is the final moment of its glorious adventure [1], reaching its apex during the *economic miracle*. In those years, Morandi and Zorzi, together with all the best engineers, designed the *Highway of the Sun*; Nervi built his famous works for the Rome Olympics in 1960 and for the celebrations of the Unification of Italy in 1961 [2]. At that time, Musmeci was still too young.

His most productive years coincided with those of the crisis, which began slowly in 1963 and in the following years worsened without end. He designed many works, but few of his projects were built. Others remained on paper: *missed chances*, testifying to Musmeci's relentless design curiosity.

Musmeci died young, at only 55. At that moment, everyone felt to have lost a genius who could have given so much more to Italian engineering.

T. Iori (✉)
University of Rome Tor Vergata, Rome, Italy
e-mail: iori@uniroma2.it

M. Emmer, M. Abate (eds.), *Imagine Math 8*,
https://doi.org/10.1007/978-3-030-92690-8_16

1 The First Experiences

Musmeci was born in 1926 in Rome. In November 1948, he graduated in civil engineering from the University of Rome La Sapienza. He then enrolled in a master's program in aeronautical engineering to postpone his mandatory military service. At the time, this was a typical trick among very good students. In January 1953, he graduated from the master's program and then served in the Army Air Corps. During his military service, he married Zenaide Zanini, who later became his partner in the design studio.

In the meantime, he served his apprenticeship in the technical office of the company Nervi & Bartoli, owned by Pier Luigi Nervi. Thus, he became Nervi's favorite. In 1954, he founded a design studio together with Antonio, Nervi's eldest son, who graduated in architecture in 1950. That studio did not last long. Soon Antonio no longer had time for his friend Sergio because he had to help his father, who had begun to build the works for the 1960 Rome Olympics.

At the same time, Musmeci embarked on an academic career. In 1954, he began as voluntary assistant at the School of Architecture at the University of Rome La Sapienza (Architecture, not Engineering; Nervi also taught all his life at the School of Architecture). He later became a tenured assistant and was appointed to teach *Rational Mechanics* course. Beginning in 1969, he taught *Bridges and Large Structures* course, delivered to lucky students who were allowed to choose the course in their elective exam package [3].

Early in his design career, Musmeci was above all a beloved design accomplice. He was able to solve complex structural problems, helping the greatest Italian architects of his time. Just to mention the most famous ones, he collaborated with mutual satisfaction with Adalberto Libera, Eugenio Montuori and Leo Calini, Giuseppe Vaccaro, Francesco Palpacelli, and Carlo Mollino.

In some cases, those architects left Musmeci complete autonomy and entrusted him with part of the project, asking to design the form from scratch. In other cases, the project was already defined and the architect called for Musmeci's help to solve problems of stability.

The first fun exercises were two roofs, which were never built. In 1954, together with Vaccaro, Musmeci designed the roof of a rural market in Puglia, composing some parabolic vaults. Through a few analytical calculations, he demonstrated with satisfaction that his geometric composition was perfectly funicular to the loads. The architectural form, therefore, responded perfectly to the static functionality. Musmeci exercised his mathematical expertise in another project in 1955: the roof of the *Araldo* movie theater in Rome, which completed a block of houses designed by Carlo Ammannati. The plan of the cinema was almond-shaped; in the roof, Musmeci weaved a large number of polygonal arches. He established that the number of crossings between the arches should be minimal along the axis of symmetry; the *golden number* was used to establish the position of the pillars in the plan; the vertical height of the crossing points between the arches was the unknown; it was determined mathematically with a system of equations, introducing

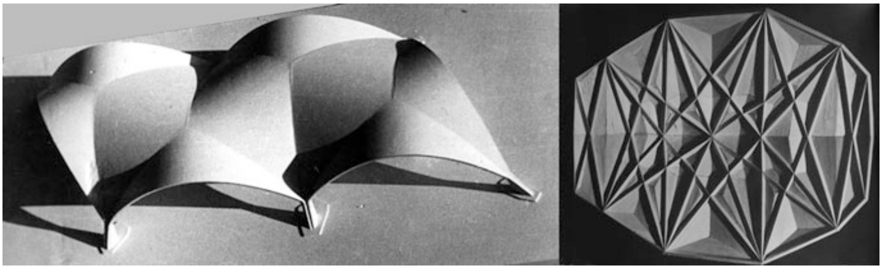

Fig. 1 (left) Rural Market in Tressanti, S. Musmeci, G. Vaccaro, 1954. Courtesy Private Archive G. Vaccaro, Roma (SIXXIdata); (right) The roof of the Araldo movie theater in Rome, S. Musmeci, C. Ammannati, 1955. Courtesy MAXXI Architecture Archive (SIXXIdata)

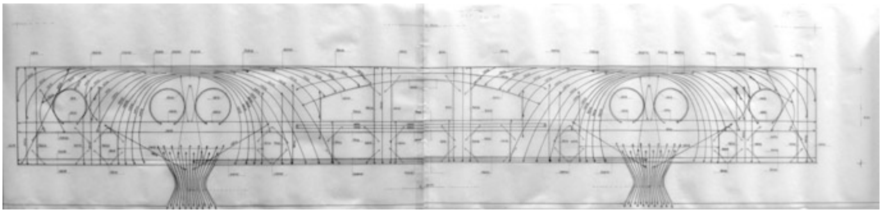

Fig. 2 Palazzo della Regione in Trento, 1956–1962, S. Musmeci, A. Libera. Courtesy MAXXI Architecture Archive (SIXXIdata)

the new condition that all the thrusts of the arches should be equal; maximum static efficiency had been achieved. The result of this apparently overly mathematical way of designing is incredibly beautiful: the roof resembles a *modern* Gothic vault (Fig. 1).

In the project for the *Palazzo della Regione* in Trento (1956–1962), on the other hand, Libera decided to span a large central beam against two enormous pillars, visible at the level of the square. That beam supported the cantilevered office floors, symmetrically on both sides.

Musmeci drew with maniacal care the voids and the solids of that beam and the reinforcement bars accordingly; however, in the end, the concrete casting concealed the beautiful web of rods. Disappointed, Musmeci understood that evidently the shape of the beam did not correspond to the natural flow of the internal forces; therefore, his careful design work had become invisible (Fig. 2).

Musmeci's most independent research began thanks to Annibale Vitellozzi, who in the mid-1950s was the consultant to the Italian National Olympic Committee (CONI). Since the 17th Olympics—to be held in 1960—were assigned to Rome, Vitellozzi had many works to do. He involved Musmeci in several projects; the most important was the roofing of the restaurant of the Swimming Stadium in the sports area called *Foro Italico* in Rome (1958). Musmeci designed a corrugated roof: he repeatedly folded the ceiling, obtaining resistance through the form. A folded sheet of paper resists much better than the same sheet left flat; the natural

Fig. 3 The roofing of the Restaurant for the Swimming Stadium, 1958, S. Musmeci, A. Vitellozzi. Courtesy Coni Archive (SIXXIdata)

pattern of internal forces guided Musmeci in establishing the shape. Thus, he varied the amplitude of the corrugation in tune with the variation of stresses: the greater the stress at a point, the greater the amplitude of the fold. He designed a didactic structure: even a non-expert user could understand the behavior of that structure; the stress of the members and the consequent static solution were clear to everyone (Fig. 3).

In the roof, the result of the calculations is no longer transferred to invisible quantities (the reinforcements inside the concrete casting) but to quantities evident in the form: "the degree of explicitness of the nature of the structure has definitely increased," commented Musmeci.

"Giving visible form to the bending moments": Musmeci did many tests to achieve this goal. In previous years, he experimented with his folding solution in smaller works: the roof of the *Raffo* industrial plant in Pietrasanta, Tuscany, designed with Calini and Montuori (1956); the roof of the *San Pietro* Cinema in Montecchio Maggiore, near Vicenza, designed with Sergio Ortolani (1957); and the roof of the gymnasium in Frosinone, together with Uga de Plaisant (1958). The walkways and the covering of the foyer of the *Regio* Theatre in Turin (1966), the last in order of time, designed for Carlo Mollino, are the most famous (Fig. 4).

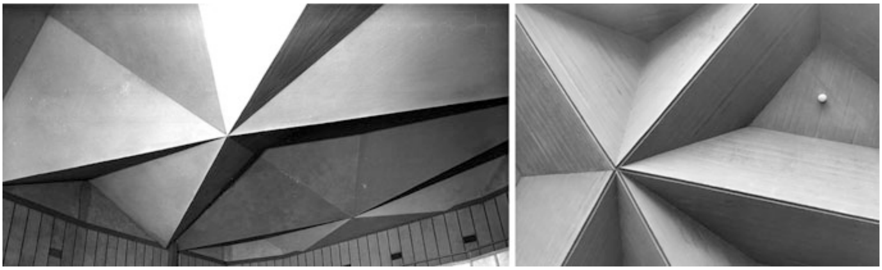

Fig. 4 (left) The roof of the San Pietro Cinema in Montecchio Maggiore, Vicenza, 1957, S. Musmeci, S. Ortolani (SIXXIdata); (right) The foyer of the Regio Theatre in Turin, 1966, S. Musmeci, C. Mollino. Photo Alessia Sisti (SIXXIdata)

2 Networks of Beams

At the end of the 1950s, Musmeci, boosted by these early successes, attempted the synthesis of form and structure by other means.

In the design of his folded surfaces, he noticed that the reinforcement was concentrated almost all along the edges; so he decided to simplify the structure, keeping only the edges, which were the only ones really useful. What remained was a network of beams.

Musmeci conceived many projects according to this criterion. In 1960, he designed with Calini and Montuori the roof of the Auditorium of the *Bhabha Atomic Research Centre*, in India. The roof is a shallow pyramid on a hexagonal plan; the six inclined pitches of the roof are generated by a triangular mesh of ribs (Fig. 5).

Musmeci told an anecdote about the project. He was able to estimate the behavior of that roof with a few calculations made by hand, introducing some simplifications. He submitted his report, not feeling that more complete and lengthy calculations needed to be added.

The Indian evaluating committee had never seen a structure so conceived. So they asked for a comprehensive calculation that took into account all the elements of the structure. Musmeci reluctantly set up the new calculation; he obtained a system of 122 equations, impossible to solve by hand. The commission then asked for a scale model; load testing on the model was very expensive. In the end, the scale model perfectly confirmed Musmeci's initial intuitions, based on his simplified calculations. This experience was very fruitful for the engineer: it proved to him the value of intuition in structural design.

In the same year, Musmeci designed the breathtaking roof of the *San Carlo* Church in the *Villaggio del Sole* district in Vicenza (1960–1962), whose general project had been elaborated by Ortolani.

The roof of the church is a kind of inverted funnel. On the outside it appears perfectly smooth; on the inside, however, three different families of logarithmic spirals, crystallized in the concrete, move toward the center, rising like a whirlwind. The spirals embrace the community of worshippers, favoring the participation of

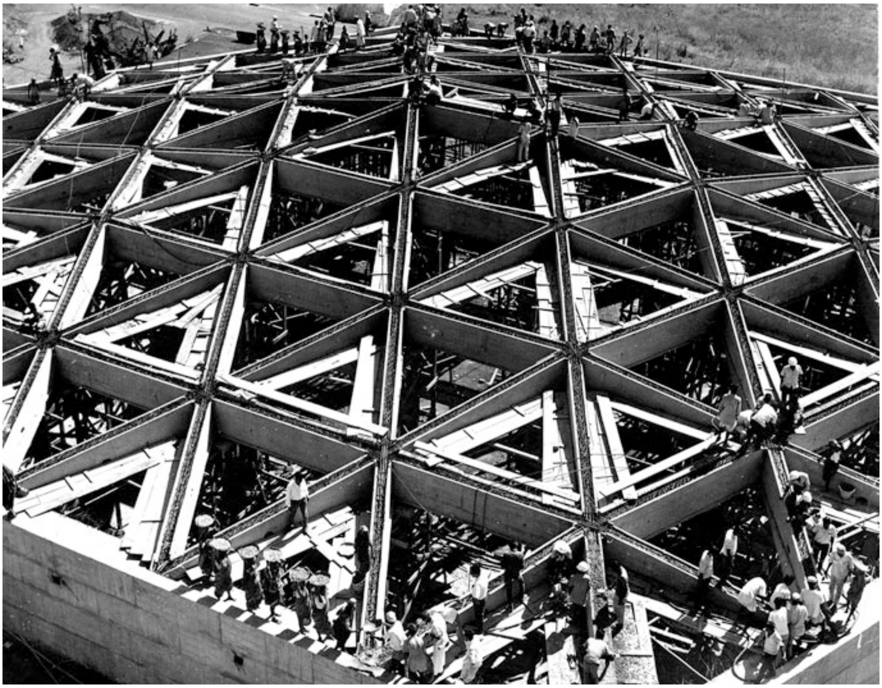

Fig. 5 The roofing of the Auditorium of the Bhabha Atomic Research Centre, India, 1960, S. Musmeci, L. Calini, E. Montuori. Courtesy MAXXI Architecture Archive, Montuori Archive (SIXXIdata)

the assembly around the altar; the center of the spirals, at the top, coincides in plan with the position of the altar. The shape of the structure is adapted to the liturgical requirement.

At each point three spirals intersect, with angles whose tangents are equal to 4, −1, 1/4. The mesh of the spirals is triangular. Pure mathematics: and the effect is spectacular. The stress on the spiral ribs changes gradually from the center to the edge: at the center, the behavior is that of a membrane; then it transforms and gradually bending takes over; on the edges, the ribs behave like cantilever beams. These variations in behavior are reflected in the gradual increase in the thickness of the ribs: small in the center and much larger on the perimeter. The construction site was quite complicated, creating very stormy relations between the designers and the construction company (Figs. 6 and 7).

The Marian Temple overlooking Trieste (1963–1967), designed together with Antonio Guacci, also belongs to the *triangle phase*. In the church, the usual elements of architecture—the pillars, the beams, the roof—disappeared. The exterior facades, the roof slabs, and the interior walls have been transformed into ribs, whose triangular meshes are closed by panels. The striking texture is entirely in reinforced concrete. For verifications to the stress of the *bora* wind, a model is tested at *Ismes*, the Experimental Institute for Materials and Structures of Bergamo (Fig. 8).

Fig. 6 The roofing of the San Carlo Church, Villaggio del Sole, Vicenza, S. Musmeci, S. Ortolani, 1960–1962. Photo Sergio Poretti (SIXXIdata)

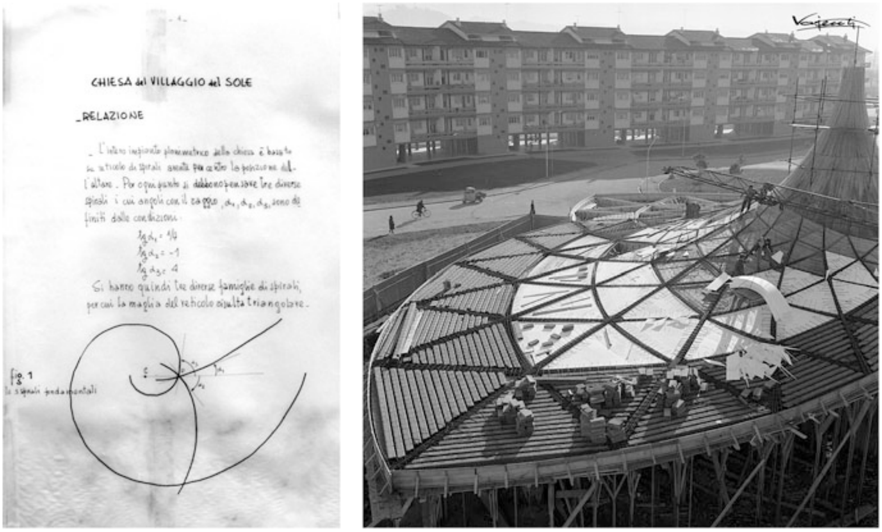

Fig. 7 The roofing of the San Carlo Church, Villaggio del Sole, Vicenza, S. Musmeci, S. Ortolani, 1960–1962: (left) Calculation report, 1960. Courtesy MAXXI Architecture Archive; (right) The construction site, 1961, Vajenti Photo (SIXXIdata)

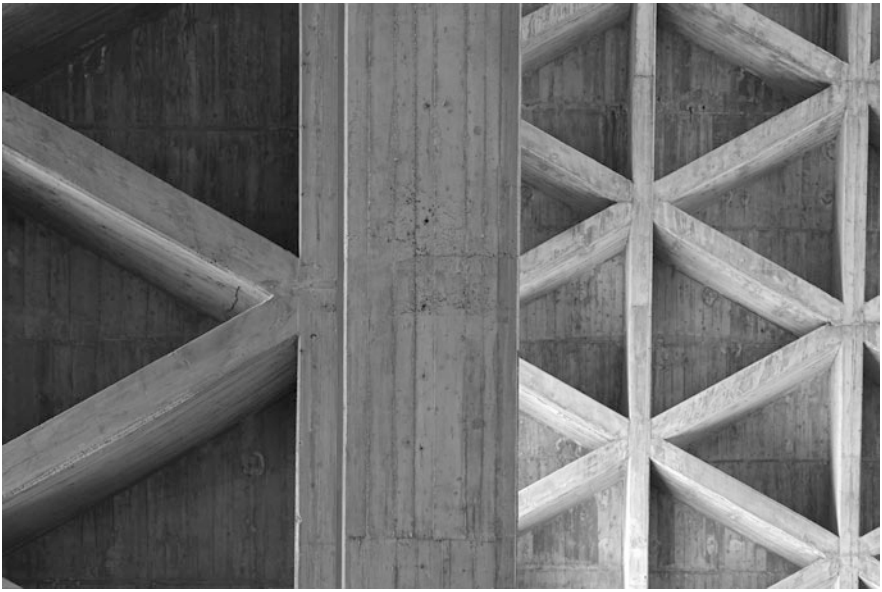

Fig. 8 The roofing of the Marian Temple, Trieste, 1963–1967, S. Musmeci, A. Guacci. Photo Sergio Poretti (SIXXIdata)

Musmeci returned to studying spatial networks of rods even in the last part of his life. But at this stage, the composition of triangles was very difficult to compute. In 1956, Turner, Clough, Martin, and Topp published the famous paper on the finite element method. Between 1954 and 1957, John Argiris systematized tensor notation and applied it to the mechanics of structures. Olgierd Zienkiewicz's textbook did not appear until 1967. To easily compute his reticular textures, Musmeci should have used finite element meshes. He was, however, ahead of the research that later became the future of automatic computation of structures.

3 Equicompressed Minimal Surfaces

Musmeci continued to work on beam networks for a long time. In 1964, he participated in the competition of ideas for the bridge over the Lao River for the Salerno-Reggio Calabria Highway. His project did not win but was later awarded by Inarch, the Italian Institute of Architecture.

The general shape of the bridge is a double-curved surface, uniformly compressed. The shape was suggested by a soap film model, which materialized the uniformly compressed members. Perfectly flexible wires, subjected to simple normal stress, located the edges of the membrane. The soap film placed tension on the wires determining their geometry. The resulting surface was uniformly stretched.

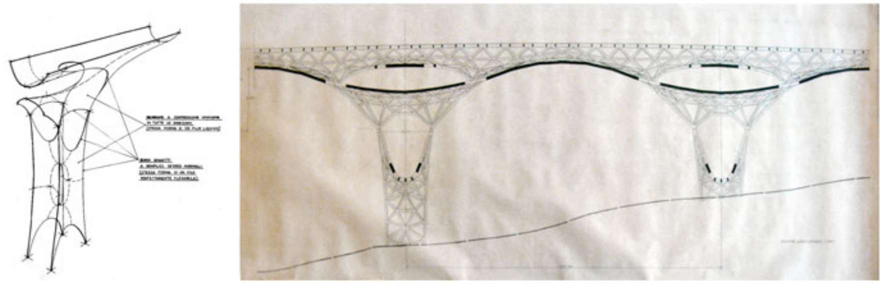

Fig. 9 Bridge over the Lao River for the Salerno-Reggio Calabria Highway, 1964, S. Musmeci: (left) the soap film; (right) the triangular mesh. Courtesy MAXXI Architecture Archive (SIXXI-data)

Musmeci showed that the surface described the minimum area compatible with the fixed contour, achieving the condition of maximum material economy (Fig. 9).

Soap bubbles are *minimal surfaces*: the bubble finds the state of minimum energy and assumes the shape that minimizes its area. In architecture, minimum area means, with the same thickness, minimum volume and therefore minimum weight and minimum consumption of material [4].

In the project submitted to the competition, a spatial reticular structure approximated the shape identified thanks to the soap bubble. Musmeci designed a network of linear elements, with constant section, uniformly compressed, in a triangular mesh.

In that project, Musmeci investigated the minimal surfaces with wisdom, because he had already elaborated several projects with this technique. Musmeci's research, in fact, had changed again, remaining on the frontier between mathematics, geometry, and theory of structures.

After the folded slabs and the networks of discontinuous beams, he returned to continuous surfaces, where the loads flowed more naturally and softly.

The genesis of that new experimentation can be traced back to the project for the bridge over the Astico river in Chiuppano, near Vicenza, whose tender was closed in August 1956. Musmeci designed the bridge following a rudimentary process of optimization; the two-dimensional curve of the arch was schematized with ropes loaded by uniformly distributed weights obtaining a uniformly compressed shape. Then in 1958 Musmeci drew his first *minimal* surface, on the occasion of the competition for the bridge over the Tiber at *Tor di Quinto* district in Rome, together with his colleague Ugo Luccichenti (Fig. 10).

In the calculation report attached to the drawings for the competition, Musmeci wrote: "Once shape and external forces are assigned, the equations of equilibrium allow to calculate the stresses in the membrane. But those equations can also be used to determine the shape once certain conditions are imposed on the stresses." In this particular case, Musmeci imposed the condition that the stress regime be hydrostatic.

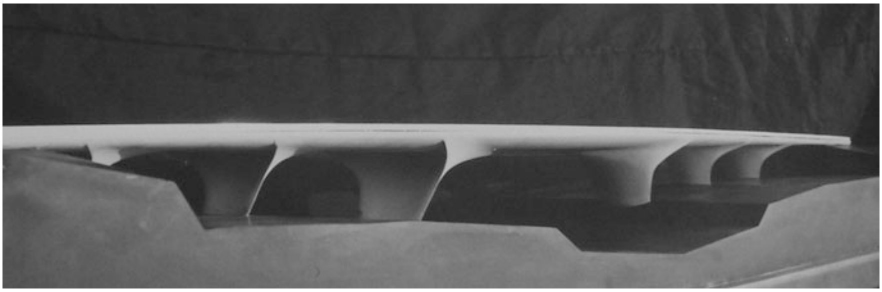

Fig. 10 Bridge over the Tiber at Tor di Quinto district in Rome, 1958, S. Musmeci, U. Luccichenti. Courtesy MAXXI Architecture Archive (SIXXIdata)

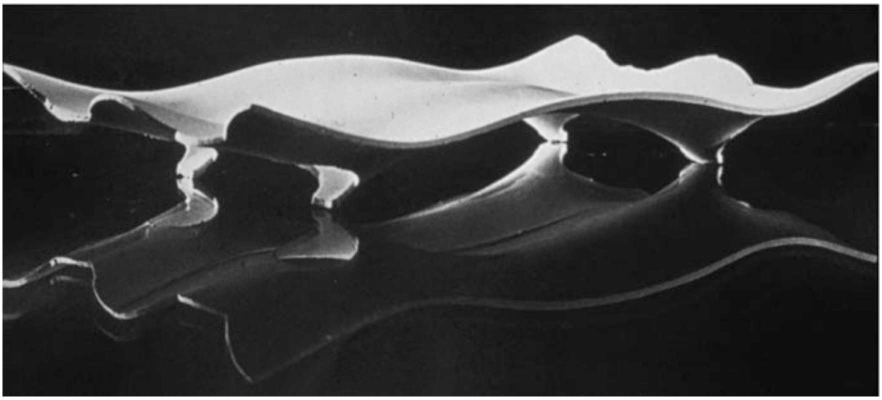

Fig. 11 The New General Market in Rome, project, S. Musmeci. Courtesy MAXXI Architecture Archive (SIXXIdata)

In the calculation reports of all his works, whether actually built or never built, Musmeci never addressed the specific static problem. Normally an engineer's goal is to solve a structure, simplifying so as to quickly apply to the data of the single project, in a given site, with certain specific dimensions. On the contrary, Musmeci always looked for a general mathematical equation, the closed-form solution, in order to be able to apply it in a thousand other occasions, simply by varying the parameters appropriately. In most cases, however, he never used his beautiful closed-form equation again.

When the project for the bridge over the Tiber was ready, none of his colleagues had understood Musmeci's hypotheses and calculations. The last night before the deadline for the submission, Luccichenti, who was a very witty man, improvised a poem to the bridge designed by his friend. He wrote in rhymes that he would never cross the bridge: "Who says it won't fall? You don't fool me. I don't move from the mouth."

Musmeci also created minimal surfaces for the competition project for the New General Market in Rome on Via Prenestina (1957) (Fig. 11) and for the competition for the monument to the *Mille*, in Marsala (1960). Both equicompressed and unreleased surfaces, however, remained only drawings [5].

But that was the road that gave Musmeci international fame.

4 Equi-Stressed Surfaces

In Musmeci's research, there was also room for two prototypes and a project based on equi-stressed surfaces, which certainly felt the influence of contemporary international experimentation.

These works are also related to the initial projects by Musmeci, in which he sought geometric forms uniformly stressed by compression. In these, on the contrary, the prevailing tension is traction.

In 1964–1965, Musmeci designed the chapel of the Pontifical Sanctuary of Pompeii, now called *La Vela*: two conical surfaces and a hypar were juxtaposed to create a soaring roof, whose highest point again coincides with the plan position of the altar (the chapel has some formal analogies with the chapel of St. Vincent de Paul in Coyoacán, Mexico City, designed by Felix Candela in 1959) [6] (Fig. 12).

The *Sant'Alberto* Church at Sarteano (1969–1972) near Siena is more interesting from the point of view of the original formal conception. Musmeci intervened on a project already approved, drawn up by the architect Giancarlo Petrangeli.

The roof is wrapped in a helix around a vertical cylindrical element, which acts as a bell tower. A system of radial cables is anchored, on one side, at different heights to

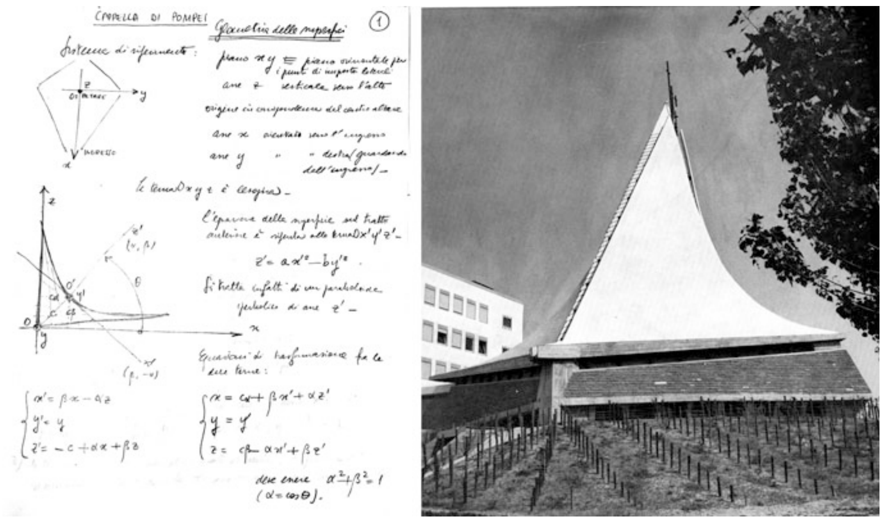

Fig. 12 The chapel La Vela in the Pontifical Sanctuary of Pompeii, 1964–1965, S. Musmeci. Courtesy MAXXI Architecture Archive (SIXXIdata)

Fig. 13 The Sant'Alberto Church at Sarteano, Siena, 1969–1972, S. Musmeci, G. Petrangeli: (left) Inside view; (right) The plan. Courtesy MAXXI Architecture Archive (SIXXIdata)

the cylinder and, on the other side, to the perimeter walls, which follow an irregular geometry. Each cable has a different length and different anchorage height, but the geometry of the cables is identical. From a static point of view, the roof behaves like a suspended shell of reinforced concrete, prestressed by the load-bearing cables. Musmeci was maybe indirectly inspired by some Eero Saarinen's works (David S. Ingalls Rink, 1953–1958; Dulles Airport in Washington, 1958–1962) (Fig. 13).

Then, on May 28, 1969, the Azienda Nazionale Autonoma delle Strade and the Italian State Railways announced a *Competition of ideas for a stable connection between Sicily and the Continent*. Connecting Messina to Reggio Calabria was an old dream, the dream of every engineer. About 150 competitors from all over the world took part in the competition, but only 85 presented solutions respecting the rules of the call. Of those, more than half proposed the solution of a bridge, suspended or cable-stayed, with one or more spans; the others preferred the tunnel or various solutions, including dams, floating islands, and some crazy geometry. On November 25, 1970, the Judging Committee, composed of foreign and Italian experts, awarded 6 first prizes and 6 second prizes ex aequo to the best solutions for each proposed type. Greatest attention was inevitably paid to the most daring project: the suspension bridge that with a single gigantic span crosses in a single hop the three kilometers of water of the Strait. The winner for this solution was Musmeci himself; Nervi was only second (Fig. 14).

The structure proposed by Musmeci was a tensile structure, like those designed in those years by Frei Otto (Fig. 15) [7]. Musmeci's project was a mixture of a suspension bridge and a cable-stayed bridge. According to Musmeci, founding piers in the Strait was impossible. So he designed a suspension bridge with a span of 2 kilometers, which in turn was cable-stayed to 600 meters high and 3 kilometers apart antennas.

Then he invented another trick: in addition to the main suspension cable, he placed a second cable, in the opposite position, under the bridge. That cable looks like an arch but is made of steel strands. A spider web of well-stretched strands connected the main suspension cable and that second one, called *stabilizing* cable according to the typical terminology of tensile structures. The spider web wraps and tightens the two decks, the one for the cars and the one for the train, which travel at

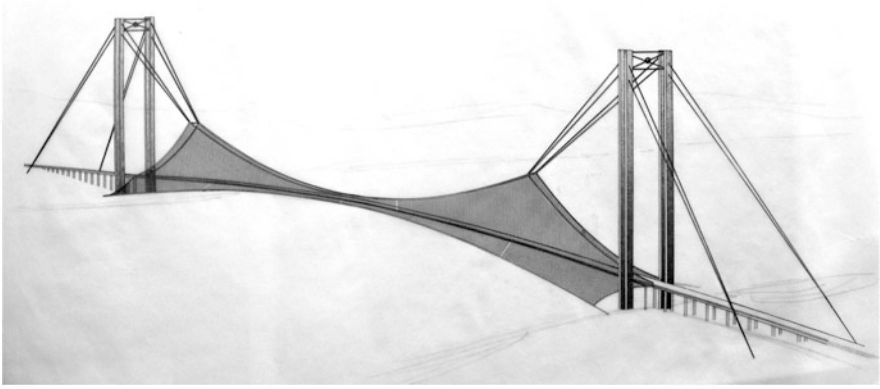

Fig. 14 Suspension/Cable-stayed Bridge over the Messina Strait, 1969, S. Musmeci. Courtesy MAXXI Architecture Archive (SIXXIdata)

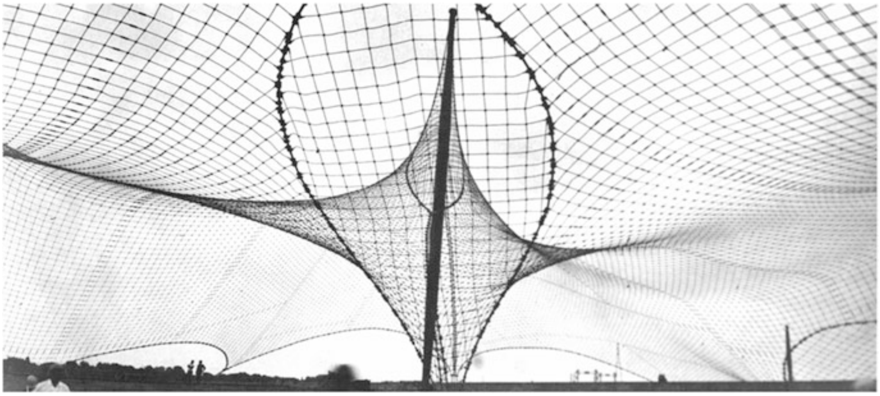

Fig. 15 Frei Otto, German Pavilion, Montreal, 1967, a detail (SIXXIdata)

different heights. The decks are aerodynamic: they are fusiform like the wings of an airplane, so the wind slips better and the bridge sways less.

That adventure was a story without a happy ending.

5 The Nameless Shape Bridge

Meanwhile, in 1967, Aldo Livadiotti involved Musmeci in the project for a bridge at the gates of Potenza. The bridge had to cross the Basento River and connect the city with the state road *Basentana*. The client was the Consortium for the industrial nucleus of Potenza, chaired by Gino Viggiani. In fact, the bridge was meant to encourage the industrial development of the area. The *Cassa per il Mezzogiorno*, which was responsible for promoting the South of Italy through various types of economic investments, financed the work [8].

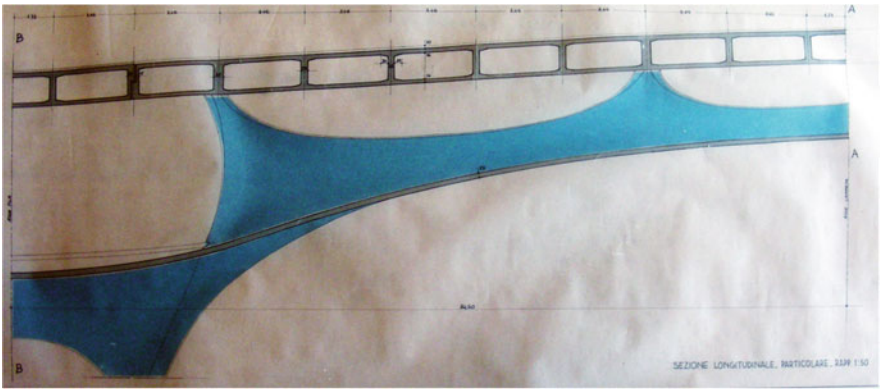

Fig. 16 Bridge over the Basento river in Potenza, 1967–1975, S. Musmeci: partial cross section. Courtesy MAXXI Architecture Archive (SIXXIdata)

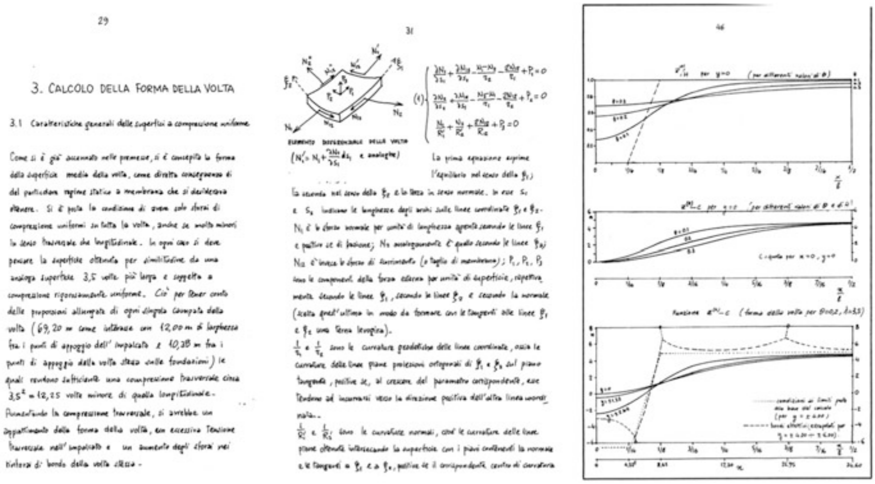

Fig. 17 Bridge over the Basento river in Potenza, 1967–1975, S. Musmeci: Calculating the form of the shell. Courtesy MAXXI Architecture Archive (SIXXIdata)

Musmeci radically changed the very simple first project by Livadiotti and created a *nameless form*. The project was based on this theory: Knowing the constraints and loads, then the unknown is the form.

The designer must *calculate* the shape of the bridge. How do you calculate a shape? Musmeci introduced an additional condition: the shape must be minimal, that is, as light as possible; more, the material must be equally stressed; that is, it must be equicompressed.

The shape of the structure was deduced from its static regime. Musmeci developed a mathematical theory for this, with relative closed formulas (Figs. 16 and 17).

In the technical report dated January 30, 1968, attached to the preliminary design, Musmeci made explicit reference to the methods used by Frei Otto to calculate the tensile structure that covered the German pavilion at the Montreal Expo 67.

The bridge is composed of four *lowered arches* with spacing of about 70 meters and free span of about 60 meters. A double-curved shell generates the arches; in each arch, the shell bends upward, creating four pairs of apophyses. Toward the foundation, the shell bends creating four supports, which behave as virtual hinges (or elastic joints). The deck consists of a hollow beam of lenticular shape. The shell and the deck are made of reinforced concrete; the deck is transversally prestressed at the apophyses. The shell is not isotropically stressed: longitudinal equicompression reaches values 12 times higher than transversal equicompression.

On July 26, 1968, the Cassa per il Mezzogiorno approved the project, but Musmeci was asked, in addition to more complete analytical calculations, to verify the shape on scale models.

The first model was a simple soap film, stretched between iron wires and cotton threads. In November 1968, Musmeci created a model with a stretched rubber membrane; under inverted loads, it ensured an equicompressed shape. The rubber model was accurately measured and became the basis for building another model, at a scale of 1:100, out of transparent acrylic material (*perspex*) (Fig. 18).

In April 1969, that perspex model was subjected to loads in the laboratory of the Faculty of Engineering in Rome, under the direction of Musmeci himself, measuring the deformations with electrical strain gauges. The result was that the stress values in the shell were about half of those indicated by the analytical calculation.

Then, a much larger model, in microbeton, on a scale of 1:10, limited to two spans of the bridge, was commissioned to Ismes in Bergamo.

In February 1970, the Ismes technicians carried out the first test, but it was not positive: the model required important modifications in the drawing of the shell, in particular on the central part of the arch, to increase the two curvatures; in July, they tested the second correct model. Thanks to the results obtained, Musmeci further improved the project and made important variations to the model: for example, he interrupted the continuity of the deck by inserting Gerber joints and beams. He also

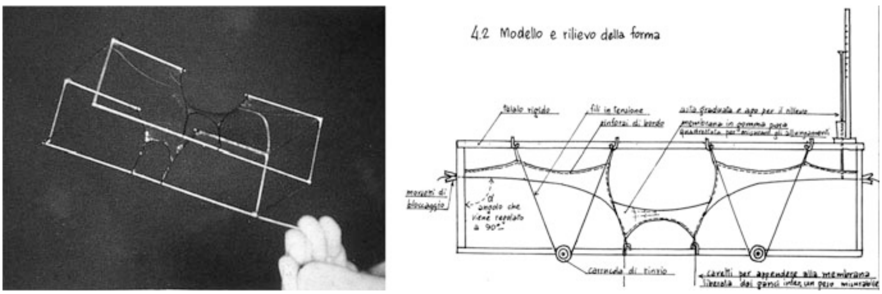

Fig. 18 Bridge over the Basento river in Potenza, 1967–1975, S. Musmeci: Soap film model and rubber model. Courtesy MAXXI Architecture Archive (SIXXIdata)

Fig. 19 Bridge over the Basento river in Potenza, 1967–1975, S. Musmeci: Microbeton model, 1:10, 1970–1971. Courtesy ISMES Archive (SIXXIdata)

Fig. 20 Bridge over the Basento river in Potenza, 1967–1975, S. Musmeci: the complex construction site. Courtesy Edilstrade Archive (SIXXIdata)

thickened all the edges of the shell. Between March 29 and 31, 1971, the new revised model was brought to failure; the test was interrupted because the foundation block broke before the shell. The many tests cost a total of 24 million liras (Fig. 19).

The final form is difficult to draw as well as to describe in words. In order to follow the dream of the *perfect form*, Musmeci eliminated all conditioning: above all, he disregarded construction problems.

On July 1, 1970, the Edilstrade Company of Forlì, directed by Gilberto Flamigni, won the private bidding for the construction of the work. Thirty companies were invited to bid, including Condotte and Salini, which were much more experienced but would probably have modified the project, simplifying it. Musmeci was appointed director of works and the construction site began in September. Mr. Buattini, an elderly worker expert in the construction of wooden boats, was called to design the complex formwork, based on a plaster model provided by *Ismes*. The formwork, supported on tubular scaffolding, changed for each span, with no possibility of reuse. Musmeci thanked Buattini warmly in many articles (Fig. 20).

After the consolidation of the concrete castings, when the wooden formworks were lowered, the shell made very dangerous movements. At that time, Edilstrade consolidated the foundations with inclined steel micropiles, 14 centimeters in diameter, in order to absorb the thrust. The engineer Arrigo Carè, a great designer of bridges, was entrusted with the testing; on May 22, 1975, load tests were carried out on the span above the railway; on September 25, 1981, at the end of all contracted works, Carè issued the test certificate. In 1989, Edilstrade was still waiting for the last payments.

In the transition from design to construction, the form was not distorted, as could be expected (especially after the many recommendations of the *Ismes*). On the contrary, the form became even more mysterious. Today, looking at it, on the one hand the shell seems very light, like a fabric hanging from the deck, descending to the ground; on the other, it looks like a wrinkled rhinoceros, or an extinct pachyderm. The fabric petrified in the concrete appears powerful and robust. The indelible traces left by the wooden formwork on the shell reveal the fatigue and difficulty of construction. In this contradiction, beauty lives on; the bridge is a unique sculpture, visited every year by hundreds of engineering and architecture students from all over the world (Fig. 21).

Fig. 21 Bridge over the Basento river in Potenza, 1967–1975, S. Musmeci: The indelible traces left by the wooden formwork on the shell. Courtesy MAXXI Architecture Archive (SIXXIdata)

The visitor can walk inside the bridge, over the shell, under the deck: this is a very rare case. Children ride bicycles or skateboard. It is forbidden: but if you don't try it, you can't feel the bridge.

The bridge over the Basento River, the highest point of the Italian School of Engineering, coincides with the definitive decline of that School. It is its swan song: when the bridge was completed, the Italian School of Engineering had already lost its way, disappearing along with Pasolini's *fireflies* [9].

That work by Musmeci is visionary; it anticipates by decades the engineering of *form finding* and the parametric engineering of this millennium. Musmeci anticipated our time. Today engineering, like architecture, has lost its strictly functional role; it must rather astonish and it must attract attention, with new and complex forms. In this millennium, pop structures have taken over. Bridges can be repeated identically anywhere, in Buenos Aires, in Dublin, or in Cosenza, like the ones designed by Santiago Calatrava. They are both repeatable and stunning, like the *Pop Art* masterpieces.

The previous generation engineers were faithful to the strict principles of maximum economy, assimilated directly from Gothic construction sites. Today's designers follow new principles, much closer to the astonishing and limitless cost of Baroque construction. Musmeci was the transitional element in this process of transformation. With his exceptional mathematical ability and his pursuit of optimized but uneconomical forms, he symbolizes the transition to the baroque engineering, dedicated to wonder, of the new millennium [10].

After the bridge in Potenza, Musmeci continued to search for minimal forms. But Italy no longer had much to offer him. By the end of the 1970s, the economic crisis, which had begun in the mid-1960s, became very harsh.

On March 5, 1981, Musmeci died, taking with him many good structural ideas and his personal vision of the future of engineering. Musmeci had a dream. He saw the birth of the computer, but he could use the machine only once for small verification calculations. He understood that the computer was the future. He wrote in a manuscript: "When the computer becomes powerful enough and when we really understand how to use it, it will help us not only to verify structures, but to design them." Musmeci dreamed of the powerful computers of today's times, which make it possible to correct form, to optimize structures. Today, computers help when we have to take really important decisions, at the design stage and not just verification step. Perhaps, Musmeci lived too far in advance: if he were reborn today, the Italian School of Structural Engineering would be reborn with him [11].

Acknowledgments The author thanks the European Research Council for financing the SIXXI research project—ERC Advanced Grant 2011 (PI: Sergio Poretti, Tullia Iori).

Thanks also to the MAXXI Architecture Archives and to Carla Zhara Buda for supporting the consultation of the materials of the Sergio Musmeci Archive.

Thanks to Stefano Pinci for helping to consult Coni Archive, Gianluca Ortolani for opening Sergio Ortolani's Private Archive, and Gilberto Flamigni for sharing his Private Archive.

This paper is dedicated to Sergio Poretti (1944–2017).

References

1. Iori, T., Poretti, S.: The rise and decline of Italian School of Engineering. Construction History: J. Const. Hist. Soc. **2**(33), 85–107 (2018)
2. Iori, T.: The language of structures. In: Emmer, M., Abate, M. (eds.) Imagine math 7 - between culture and mathematics, pp. 213–229. Springer International Publishing, Berlin (2020). https://doi.org/10.1007/978-3-030-42653-8
3. Iori, T., Poretti, S.: SIXXI Fotoromanzo. 9. Capolavori postumi. In: Iori, T., Poretti, S. (eds.) SIXXI 5. Storia dell'ingegneria strutturale in Italia, pp. 115–157. Gangemi, Roma (2020)
4. Emmer, M.: Bolle di Sapone: Arte e Matematica, Bollati Boringhieri, Torino (Premio letterario Viareggio saggistica 2010) (2009)
5. Guccione, M., Iori, T.: Roman Structures. Montuori, Musmeci, Nervi, Exhibition held in MAXXI- The National Museum of 21st Century Arts, 17 April–5 October (2014)
6. Sisti, A.: Struttura e Forma nella Sperimentazione di Sergio Musmeci, Phd Dissertation, University of Rome Tor Vergata, tutor: T. Iori. (2020)
7. Otto, F.: Zugbeanspruchte Konstruktionen: Gestalt, Struktur, und Berechnung von Bauten aus Seilen, Netzen und Membranen, Ullstein Verlag, Frankfurt, vol. 1, 1962; vol. 2, 1966; English translation: tensile structures. Design, structure, and calculation of buildings of cables, nets, and membranes. The MIT Press, Cambridge and London, vol. 1, 1967; vol. 2, 1969
8. Guccione, M. (ed.): Il ponte e la città. Sergio Musmeci a Potenza. Gangemi editore, Roma (2003)
9. Pasolini, P.P.: Il vuoto del potere. Corriere della Sera. February 1st. (1975)
10. Iori, T., Poretti, S.: Pop structures per il nuovo millennio. Rassegna di architettura e urbanistica. **137–138**, 9–28 (2012)
11. Iori, T.: Sergio Musmeci. Radio Broadcasting Wikiradio, RAI Radio 3, May 28th. https://www.raiplayradio.it/audio/2019/05/WIKIRADIO%2D%2D-Sergio-Musmeci-950c342b-7165-4efe-8608-9438940c1b81.html (2019)