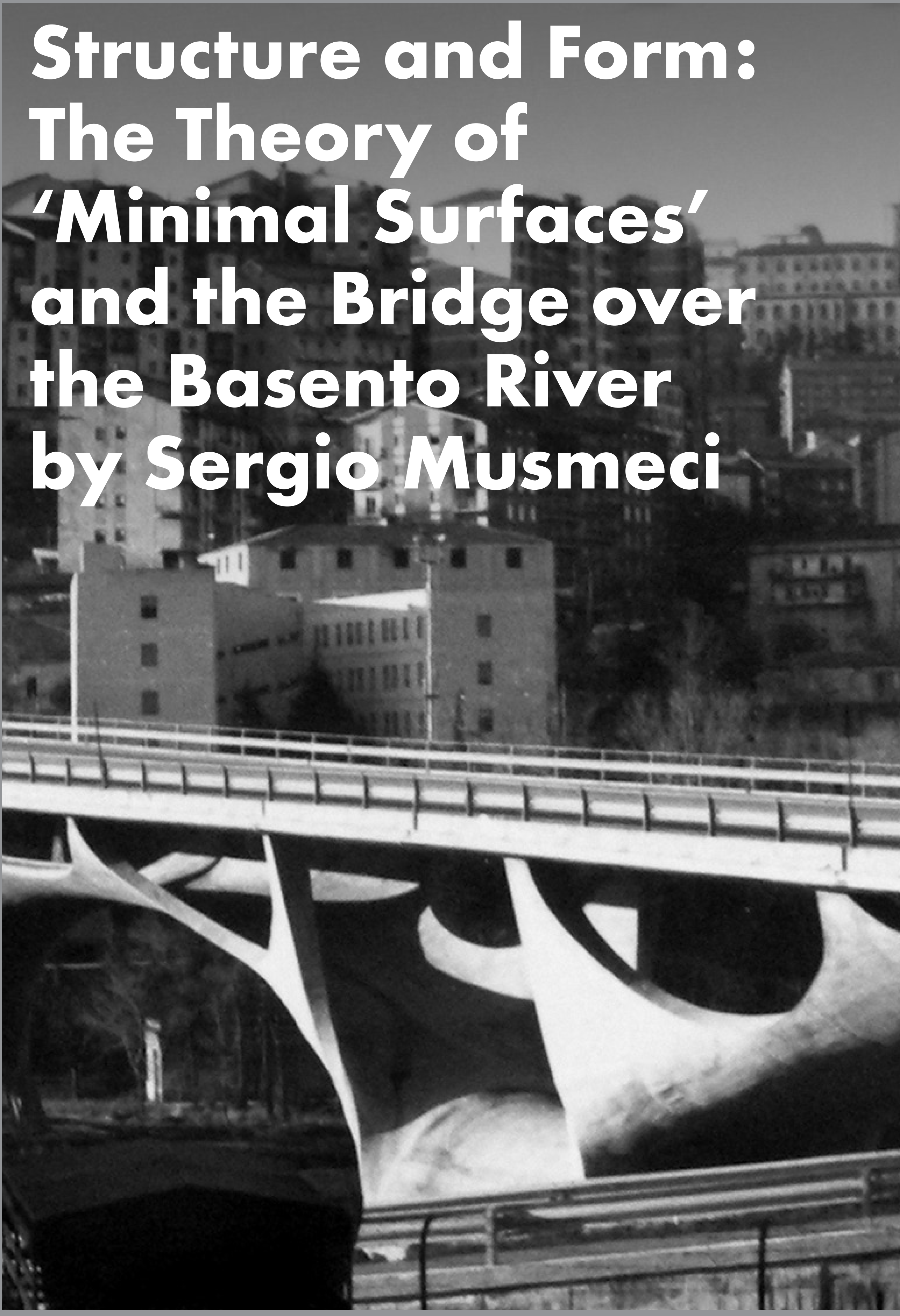
Structure and Form: The Theory of 'Minimal Surfaces' and the Bridge over the Basento River by Sergio Musmeci



SERGIO MUSMECI occupies a very important position in the history of late 20th century Italian engineering. Born in Rome in 1926, he initially graduated in civil engineering and later in aeronautical engineering. Following an apprenticeship with Pier Luigi Nervi, in whose office he worked from 1949 to 1951, and with Riccardo Morandi, he later opened his own engineering and architecture office together with his wife, the architect Zenaide Zanini. He taught at the University of Rome, initially as an assistant to the course in Rational Mechanics and Graphic Statics, and later as professor of Bridges and Large Structures.

By Rinaldo Capomolla

WITH his activities as a scholar and designer, Musmeci sought to bring a new impulse to Italian engineering in light of its rapid development immediately after the Second World War. He observed that the reconstruction and completion of the country's infrastructural network, given its vastness, was leading engineering to progressively repeat tired and simplified structural models; it was his belief that this trend could be inverted only by completely redefining the very objectives and methods of structural design.

Methods of calculation—Musmeci claimed—had made great strides, though they remained wholly inadequate for orienting engineering in the selection of the optimum form to be applied to a structure. "When we make basic design decisions—he stated—we are in the same conditions as a Renaissance architect: we possess intuition, experience and a sensitivity towards statics, though nothing places in a condition to choose…with awareness and responsibility". For Musmeci the form of a structure was not to be defined by the designer based on his personal experience, but was rather to be "deduced from a process of optimising its static regime".

These ideas placed Musmeci at the antipodes of Nervi's way of thinking, a master considered as the benchmark of Italian engineering at the time. Nervi believed that it was not possible to ask static calculations to provide more than they could give or, better still, the more space that was given to sophisticated mathematical calculations the more the architectural-engineering invention would suffer. For Musmeci, instead, only the calculation, if considered less a tool for verifying structural safety, and more as an instrument for selecting the 'optimum form', could broaden the inventive potentialities of engineering, offering a vaster repertoire of truly new, and thus unimaginable forms, though entirely rational.

< The bridge by **Sergio Musmeci** built in 1975 in Potenza.

The Theory of Minimal Surfaces

This optimum form was to have corresponded with objective, even if not absolute criteria, established *a priori* by the designer. Musmeci, in particular, held that the principal criteria of choice should be the "structural minimum": a criteria that would have allowed for the identification of the form of a structure capable of opposing external forces using the minimum volume of material. In any case, he believed that the designer had to be familiar with this "minimal structural form", even if he would be free to adopt it or not based on his personal evaluation of the real circumstances of construction.

However, the mathematical methods for identifying the form of minimum volume structures presented serious analytical difficulties. As a result Musmeci turned his attention to structures with minimum surfaces ("minimal surfaces"), whose form could by calculated with less difficulty and, above all, could be visualised using models realised with soap bubbles. In fact, these latter, once their edges have been defined, spread spontaneously along a minimal surface and assume a state of tension that is particularly favourable because it is isotropic and constant at each point.

From the forms of these equally tensioned surfaces of soap bubbles it is possible to immediately derive the forms of analogous equally compressed surfaces, because the positioning in space of the minimal surfaces neither depends upon nor presents any sign of tension—traction or compression as the case may be—nor of its value, but only the geometry of its edges. An equally compressed surface fully exploits the mechanical properties of a constituent material that can thus be used not only in its minimum extension, but also in very thin elements (and thus with minimum volume).

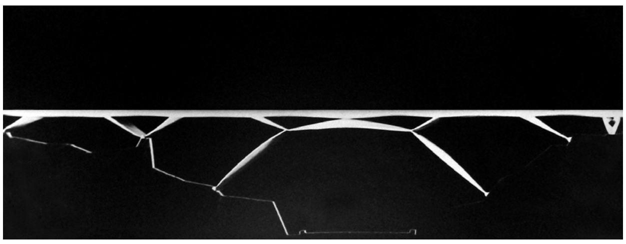
The difference between Musmeci's equally compressed shells and classical thin shells is evident: they are not only subject also to traction, but present a scarce adherence between the form, usually simple (cylinder, sphere, conoid, hypar, etc.), and the static regime: this is demonstrated by the strong perturbations in the tensions along the perimeter and their significant variability from point to point.

The Shell Bridges

Prior to defining this theory, Musmeci already pursued a particular way of designing: instead of defining the form of the structure in all of its parts and then calculating the tensions, he established a property that the tensions would have to demonstrate and considered the form of the structure that this would have realised an unknown. One example of this approach is to be found in the bridge over the Astico River (1956) in the province of Vicenza [figure 1], whose highly articulated form was designed to obtain a harmonious insertion within the natural landscape and to best exploit the properties of concrete. The bridge is comprised of a deck integrally connected to a series of arches resting one atop the other. The deck, supported only a in few points, is necessarily very rigid in its resistance to bending, such that the arches can be reduced to thin slabs (between 35 and 45 cm in thickness), slightly curved in the transversal direction to keep them from twisting. When developing this solution Musmeci was inspired by Maillart's bridges, which he considered exemplary for their "perfect integration between static efficiency and formal expression". All the same, Musmeci soon focused his studies on double curving thin shells because, unlike the arches of Maillart, which are subject to compression only along their central axis, in shells the force of compression acts in two directions and makes the most efficient use of the properties of concrete.

The first application of the theory of minimal surfaces to the design of the bridge came with Musmeci's proposal for a structure spanning the Tiber River in Rome, near Tor di Quinto (1957) [figure 2]: a bridge whose road deck is supported on six double curving shells subject to uniform compression. After attempting to define their optimum form using mathematics, without obtaining satisfying results, he reverted to the use of a model made of soap film and later a model in rubber pulled by forces proportional to the constraining actions calculated.

Musmeci also used the same mathematical and experimental studies in the design of a bridge over the Lao River, in the province of Cosenza (1964) [figure 3]. Though he obtained a very different formal result: while in the bridge over the Tiber the supports and deck were statically integrated, though geometrically distinct, here the underside of the deck and the piers are fused to form a single, continuous and equally compressed surface. This project is also of interest for another reason, as it confronts one of the crucial problems of complex geometry: their construction. Musmeci transformed the curved surface into a grid of rectilinear concrete struts to be poured in steel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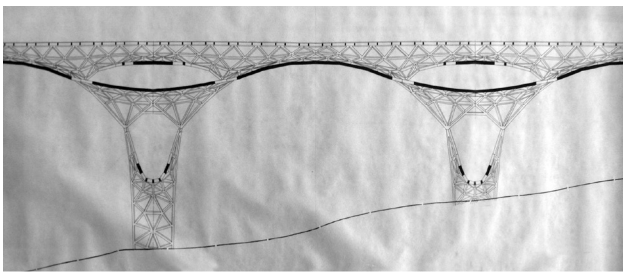
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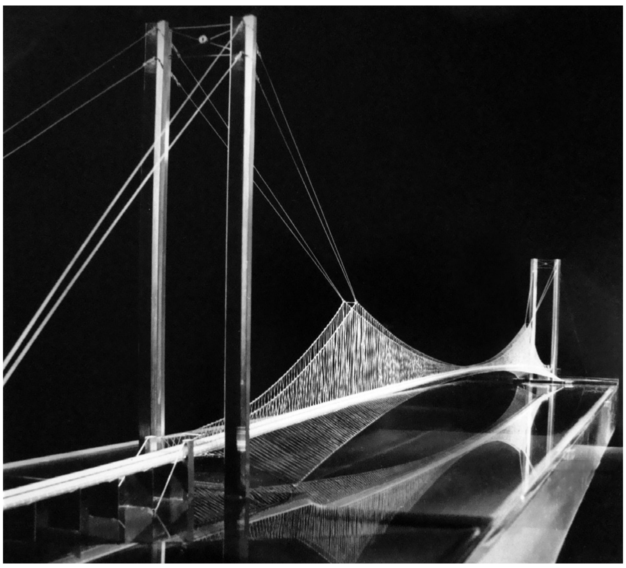
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Figure 1. Model of the bridge over the Astico River.

Figure 2. Model of the bridge over the Tiber River.

Figure 3. Longitudinal section of the bridge over the Lao River.

Figure 4. Model of the bridge over the Strait of Messina.

Figure 5. The bridge over the Basento River.

jackets. This idea was later proposed and perfected in the design of the lengthy bridge over the Niger River, in Nigeria (1977).

Of his other shell bridges, mention is made here only of that in Shiraz, Iran (1975–76), a long viaduct that remained on paper, its deck supported by an elegant undulating concrete ribbon, and the viaduct over the Via Appia Antica in Rome (1980–85), constructed using a limited number of drawings and a model realised only a few months prior to the engineer's death on March 5, 1981.

At first glance, the preference given to exclusively compressed structures may cause some confusion regarding Musmeci's use of tensile structures in some of his projects. However, this is clarified by the fact that these elements realise a perfect correspondence between form and the static regime. Of the tensile structures he designed, the most daring is without a doubt the bridge over the Strait of Messina [figure 4]: a long–span suspended bridge (3,000 m) that was awarded ex aequo the ideas competition held in 1969. Musmeci looked with great interest at tensile structures not only because they are complex systems of cables that, working in synergy, perform their static duties with the maximum efficiency, but also because they are a structural and formal prototype that, by analogy, may suggest the form to be given to compressed shells in concrete: an idea that Musmeci would exploit in the design of his most famous bridge spanning the Basento River, in Potenza (1967–1975).

The Bridge over the Basento River

This is the only bridge based on the theory of minimal surfaces that Musmeci managed to build. It is not the concentration of an extravagant idea or an extemporaneous creative gesture, but an original reflection on the foundations, the practice and the aims of structural design. This condition makes it one of the most representative fruits of Italian structural research after the Second World War.

The bridge is composed of four continuous reinforced concrete arches, one every 69.20 m, comprised of double curving shells supporting the deck, also in reinforced concrete [figure 5].

The arches are similar to those of the bridge over the Lao River, in turn the development of an idea that was previously formulated in the design of the roof of the *Palazzo del Lavoro* in Turin (1959).

The development of the project is particularly interesting, as it reveals how Musmeci, placing his trust in his own personal talent as an engineer and working without collaborators, did not hesitate to launch himself into an adventure of design and construction filled with unknowns, and employing procedures of static verification that would now be considered inadequate.

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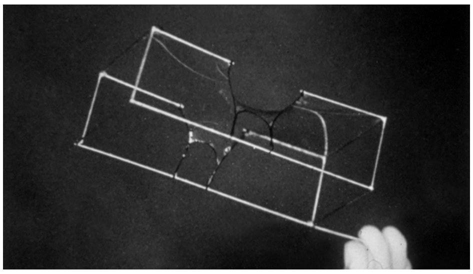

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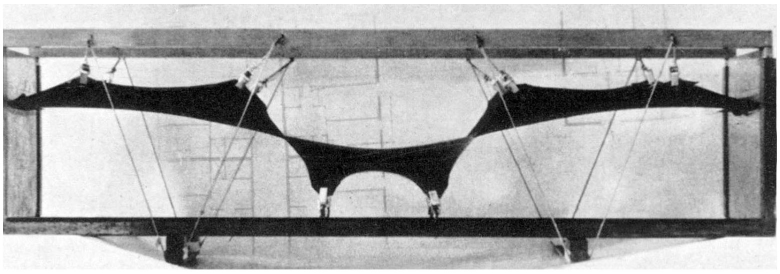

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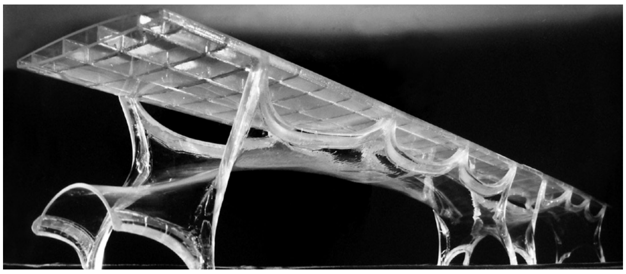

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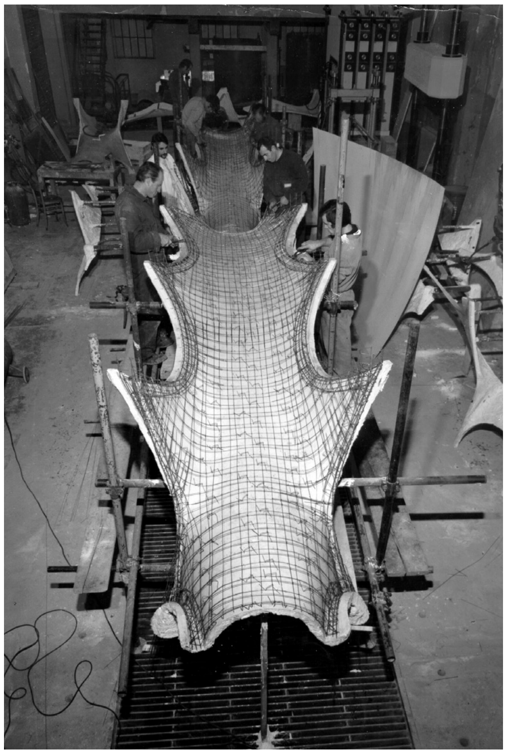
Figures 6, 7, 8, 9. Models in soap film, rubber, perspex and concrete.



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He initially constructed rudimentary models in soap film [figure 6]; this was followed by the realisation of a model of two semi-arches using a sheet of rubber, pulled by forces applied at the points where the real structure would be subjected to forces of compression from the deck and foundations [figure 7]. The model, in a state of tension very similar to that of the soap film, consented him to measure the geometry of the surfaces and to summarily evaluate the state of tension of the membrane.

In 1967, based on these tests and a calculation of the arches, schematically compared to a planar system of rectilinear and curvilinear beams connected by hinges, he prepared the general design.

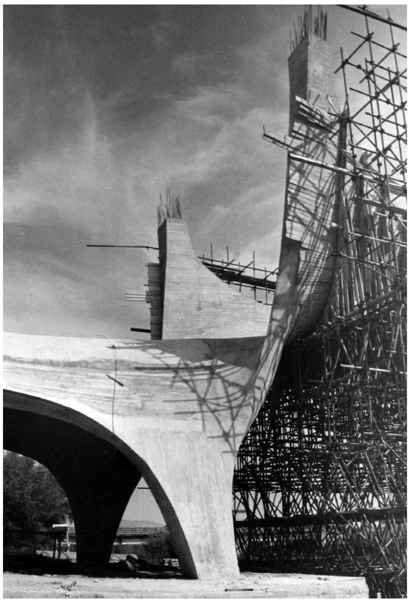
In order to have more precise indications regarding the static behaviour of the bridge Musmeci commissioned a 1.4-meter-long perspex model, which he used to measure deformations under various loading conditions [figure 8].

In the meantime, he managed to approximately determine the geometry of the surface of the bridge, utilising a procedure for the calculation of the form of soap films developed by Rudolf Trostel and published in the first issue of *Zugbeanspruchte Konstruktionen* by Frei Otto (1962).

Based on these tests and calculations, during the early months of 1969 Musmeci completed the working drawings, which presented a few differences in terms of details with respect to the general design, in particular an increase in the curvatures and thicknesses of the vaults: the original thickness, of only 30 cm, was conserved in correspondence with a narrow band along the longitudinal axis, while its grows progressively towards the free edges. This change means that the behaviour of the vaults moves away from the theoretical model of the shell under uniform compression and towards that of a succession of four arches.

When the contractor began construction of the bridge at the end of 1970, he immediately became aware of having underestimated the difficulties related to its realisation: he initially claimed that the project was unbuildable, requesting substantial modifications and threatening to break the contract, however, after obtaining a significant increase to the project budget, he changed his mind. The Italian Ministry of Public Works was also sceptical about the feasibility of the design and requested further test, this time using a concrete model. A model of two bays was realised, some 14 m in length; it was a perfect reproduction of the bridge to be built, right down to the reinforcing bars [figure 9]. While revealing the need for further adjustments, the tests, completed in March of 1971, eliminated any doubts.

Construction began the same year, and straightaway



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revealed all of its complexities: it was very complicated to construct formwork capable of following the vast variations to the curvatures of the surfaces; it was difficult to shape the reinforcing bars in skewed curves; finally, it was anything but simple to pour the concrete, above all in the sections with steep inclines [figure 10].

The bridge was inspected and tested on May 22, 1975 and the job site was finally closed.

The built work [figures 11–14] imposes itself with the abstract lightness of a membrane stretched between the foundations and the deck and, simultaneously and ambiguously, with the hyperbolic realism of a massive body comprised of compressed arches that twist and bend to support the weight of the deck and transfer it to the foundations. However, more than the adherence of the result to its theoretical premises, the greatest value of this bridge—recognised by Musmeci himself after its completion—is to be found in the successful metamorphosis of a vague initial idea into a concrete and vigorous "architectural event".

Figure 10. The bridge under construction

Figures 11, 12, 13, 14. Images of the bridge today: partial views; view of the pedestrian passage between the vaults and the deck; view of one of the bases of the bridge.

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The author wants to give special thanks to the MAXXI *Architettura Centro Archivi* in Rome for its gentle concession to publish photographs and drawings from the Sergio Musmeci and Zenaide Zanini archives.