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The Approach of Sergio Musmeci to Structural Folding

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Abstract

Thanks to the experimental nature of his work, Sergio Musmeci (1926-1981) holds an exceptional position within the Italian School of Engineering of the postwar period. Musmeci’s peculiar view on structural design is supported by the search for novel structural forms, which is initiated by his exploration on structural folding. In particular, during the 1950s, folded plates are applied by the engineer in place of the conventional beam and slab typology for the design of various roofs in reinforced concrete. In this paper, the approach of Musmeci to structural folding is discussed. The investigation is focused on the folded plate roof of Stabilimento Raffo in Pietrasanta, which is here regarded as a fundamental moment in the research of the engineer in the field of structural folding. The design method used by Musmeci for the development of the project is examined in details.

Keywords: Sergio Musmeci, folded plate structures, reinforced concrete, parametric design, postwar Italy

1. Introduction

The development of architecture and engineering in Italy after World War II originates from very specific conditions. While the rapid economic, technological and social changes trigger the prosperity of the building industry, resources are still limited. Under these constraints, structural engineering is strongly affected by the exploration of new typologies, particularly for reinforced concrete (Iori [7]). The search for structural efficiency leads to the production of various examples of innovative buildings. This is achieved with the introduction of new construction technologies, like prefabrication and prestressing, and a plurality of design approaches working according to the principle of resistance through form (Poretti [16]).

The employment of structural folding, like in the work of Sergio Musmeci, is a result of this process. One of the most peculiar properties of folded structures is their ability to resist the external applied load through their form. A folded system has a clear structural logic, which relies on the relationship between the flow of the forces within the system and its overall geometry. It is because of its inherent potential that structural folding has been investigated during the 1950s, especially in Italy.

The use of structural folding can be traced in the works of several engineers in postwar Italy. A very early example is represented by Pier Luigi Nervi’s Padiglione della Magliana in Roma (1945), which is built using ferrocemento elements with a corrugated shape. A decade later, the folded structure of Nervi’s Assembly Hall for the UNESCO Headquarters in Paris (1953-58, with Marcel Breuer and Bernard Zehruss), receives significant international attention (Nervi [14]). Structural folding is subsequently applied by other renowned Italian engineers for the design of churches: Riccardo Morandi in the Chiesa San Luca in via Gattamelata in Roma (1956, with Studio Passarelli) (Pedio [15]), Aldo Favini in the Chiesa Sacro Cuore in Ivrea, (1958, with Mario Oliveri and Marcello Nizzoli) (Barazzetta and Favini [2]) and Michele Pagano in the Chiesa Madre di San Pietro Apostolo in Satriano di Lucania (1956, with Giulio De Luca) (Gigliotti [4]).

In this context, one of most consistent explorations on the structural properties of folded plate systems is due to Sergio Musmeci. His work is encompassed within the theory of minimal structures based on his life-long research on structural design involving the optimum use of materials (Musmeci [11]). Folding represents an important topic of investigation for Musmeci, who has employed it on an extended series of projects, mostly developed at the end of the 1950s (Ingold and Rinke [6]). In fact, these projects bear witness to the evolution in the concept of structural folding within the design approach of Musmeci.

In the present paper, the analysis is specifically focused on the folded plate roof of Stabilimento Raffa in Pietrasanta (1956), which is regarded here as an exemplary project that reveals Musmeci's understanding of structural folding. The peculiar method used by the engineer for the design of the roof is discussed in details. In particular, the models employed for the definition of the geometry of the roof in plan and in elevation are presented.

2. Sergio Musmeci and his Research on Structural Folding

During his early career as a structural engineer, Musmeci applies structural folding in place of the conventional beam and slab structural typology for the design of several roofs in reinforced concrete. The series of folded plate roofs by Musmeci includes eight projects (Figure 1), which have been designed in a time span of twelve years (1954-1966). The evolution of the projects shows an increasing competence and desire for experimentation by the engineer. In this research on structural folding, three main phases can be distinguished.

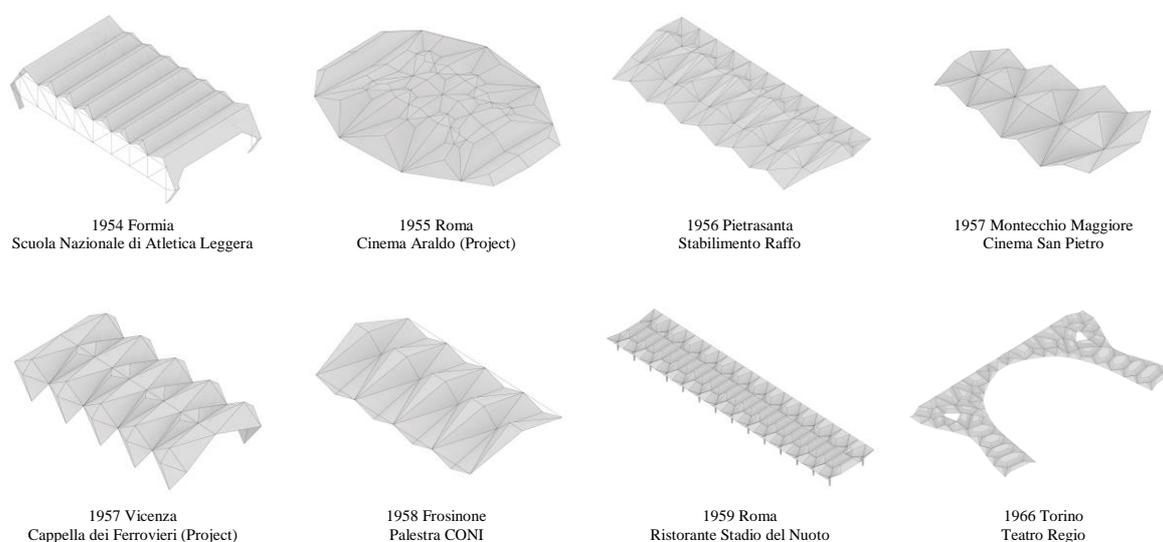


Figure 1: Chronology of the folded plate roofs designed by Sergio Musmeci.

The first phase includes the early design experiments by Musmeci on the structural properties of folding. The design of the roof of the gymnastic hall of Scuola di Atletica in Formia (1954, with Annibale Vitellozzi) is the first occasion in which the engineer employs a folded plate structure (Vaccaro [17]). In order to minimize the use of material on the roof slab and achieve the required static height, the engineer proposes a solution consisting on a typical accordion-like corrugated slab on a regular rectangular plan; the fold lines are parallel and oriented along the short side of the rectangle. One year later, while working on the project of Cinema Araldo in Roma (1955, with Carlo Ammannati), Musmeci designs a roof composed of a network of equally compressed polygonal arches spanning over a non-regular dodecagonal plan (Musmeci [9]). Folded plates are used here to fill the fields in-between the arches and not as the main elements of the load-bearing system of the roof. As a result, the segmented vault is based on a hierarchical structure made of main struts and secondary panels.

In the second phase, Musmeci introduces a design approach to relate the form of the folded structure to its static behaviour. The roofs of Stabilimento Raffa in Pietrasanta (1956, with Leo Calini and Eugenio Montuori) (Musmeci [10]) and of Cinema San Pietro in Montecchio Maggiore (1957, with Sergio Ortolani) (Morgan [8]) are designed in relation to the distribution of the bending moments within the structures. This leads to the definition of non-standard geometries, based on polygonal folded patterns. For the project of Cappella dei Ferrovieri in Vicenza (1957, with Sergio Ortolani and Antonio Cattaneo), Musmeci proposes a three-dimensional folded plate structure that is equivalent to a three-hinged frame. In this case, structural folding is not limited only to the roof, but it is applied to the entire load-bearing structure of the building.

In the third phase, which is associated to the roof of Palestra CONI in Frosinone (1958), the ceiling of Ristorante del Nuoto in Roma (1959) and the foyer ceiling of Teatro Regio in Torino (1966, with Carlo Mollino), Musmeci explores the possibility to work with hollowed folded geometries. This is usually achieved by incorporating the horizontal slab into the folded plate structure. These examples can be considered as hybrids between folded plate systems and spatial trusses, and directly influence the later work of the engineer on antiprismatic systems (Musmeci [13]).

3. The Design of the Roof of Stabilimento Raffa in Pietrasanta

The folded plate roof of the marble workshop Raffa in Pietrasanta (1956) is a self-supporting slab on a rectangular plan of around 1000m² with a uniform thickness of 10cm (Figure 2). The slab consists of a folded plate module that is repeated five times along the longitudinal axis of the roof. It is supported by two rows of six V-shaped pillars each with a maximum span of 12.40m. From a geometric point of view, the roof of Stabilimento Raffa achieves a higher level of complexity in comparison to the conventional solution adopted for the Scuola di Atletica a couple of years before. At the same time, the roof is entirely self-supporting, unlike the one previously designed for Cinema Araldo, which relies on an underlying network of load-bearing polygonal arches.



Figure 2: Stabilimento Raffa in Pietrasanta (1956), inner view – Source: Musmeci [10], p. 712.

The roof of Stabilimento Raffo has been conceived by Musmeci in line with his belief that in the process of structural design the form and not the inner stresses should be regarded as the unknown (Musmeci [12]). As pointed out by the engineer himself, it is not because of its dimensions or any construction principle adopted that the roof stands out from other contemporary examples of folded plate structures. On the contrary, the uniqueness of the design solution relies on the ability of the form to express its static behaviour in an explicit, nearly diagrammatic way. “The roof of Stabilimento Raffo had to be built quite quickly and above all with a low budget. It had to comply with nothing else but the static requirements, defined by the free spans that had to be realized. Therefore, it was a good occasion to make a kind of experiment [...]: to see to which extent a thin vault is able to express its statics through its own form” (Musmeci [10]). The aim of Musmeci is to reach a true integration between structure and architecture, where the form predominantly argues for its expressiveness through the statics; a form whose load-bearing behaviour is explicitly communicated to the observer (Brodini [3]). In fact, the roof has been designed in such a way that the form follows directly the inner forces. As such, the engineer proposes a specific design interpretation of the common principle of resistance through form and develops an explicit methodology how to apply it to structural design. Considering the relevance given by Musmeci to this project, which reflects his peculiar approach to structural design, Stabilimento Raffo in Pietrasanta marks a fundamental moment in his research in the topic of structural folding.

As already observed in relation to the development of other projects (Adriaenssens [1]), also in the case of Stabilimento Raffo the engineer makes use of diverse tools and models, both analytical and physical. Based on the analysis of the documents available at Archivio MAXXI Musmeci e Zanini in Roma, an overview on the methodology followed by Musmeci for the design of the roof of the marble workshop is presented in the following sections.

3.1 The Geometry of the Roof in Plan

Of particular interest is the topological study of the folded plate pattern of the roof of Stabilimento Raffo in plan, developed by Musmeci as a hand sketch (Figure 3). This drawing shows a series of design variations that share the same support conditions. By changing the position of the nodes as well as the number and connectivity of the folded edges, the engineer investigates diverse geometric configurations, which imply different structural behaviours for the distribution of the forces within the roof.

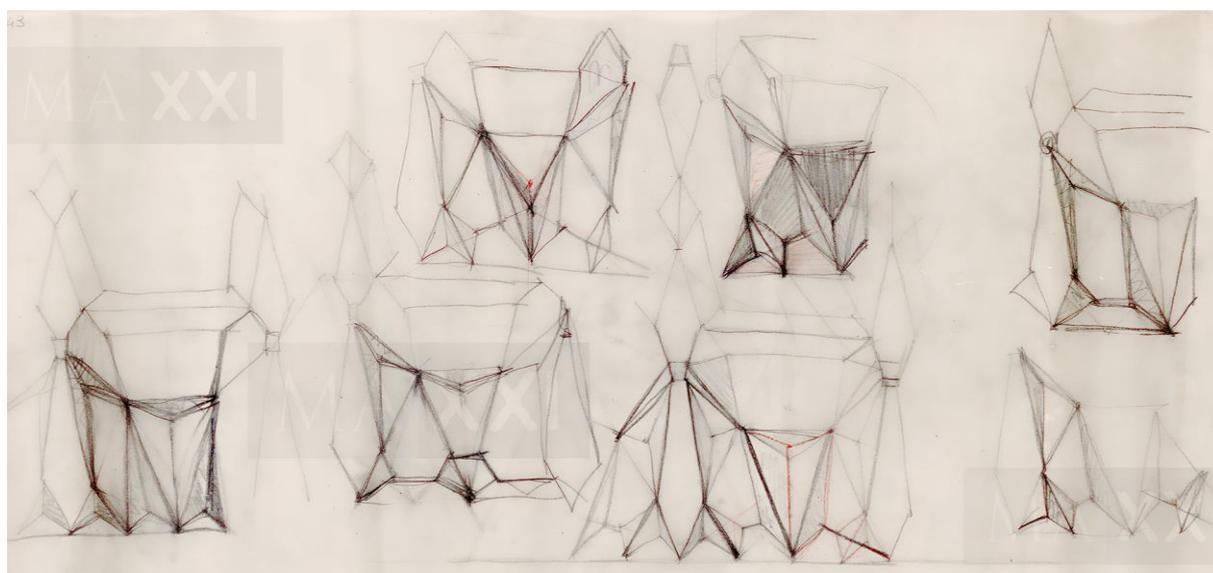


Figure 3: Stabilimento Raffo in Pietrasanta (1956), sketch of design variations of the roof plan by Musmeci
Source: Archivio MAXXI Musmeci e Zanini.

One of the ideas followed by Musmeci for the definition of the general topology of the folded plate module was to activate in the roof an explicit load-bearing mechanism equivalent to a rigid truss where the folded edges represent the bars of the truss, loaded either in tension or compression. “In reinforced concrete the tensile stresses are channelled into the main reinforcement bars, and considering that these stresses tend to be confined to specific edges, it is natural to try to keep them as straight and continuous as possible. These edges are the ones that should connect geometrically the different parts of the structure, likewise a rigid truss. The intuition that along them tensile stresses run contributes to fix the form of the vault, moving away from any sense of arbitrariness. Compressive stresses have always been kept in large sections of the slab in order to facilitate their diffusion and, again, with the intention of expressing this characteristic structural behaviour in the form” (Musmeci [10]).

Among the various tools used by Musmeci, remarkable is the parametric model developed by the engineer to refine the geometry of the folded plate module, presumably in the mid-stage of the design process (Figure 4). Grounded on a series of geometric relationships expressed in an analytical form, the parametric model is analogous to the one set up by the engineer for the design of the roof of Cinema Araldo (Musmeci [9]). The model is based on a grid, whose nodes are located at the intersection of three main vertical gridlines parallel to the transversal axis of the roof, and four main horizontal gridlines parallel to the longitudinal axis. The main vertical gridlines are located at the transversal axes of the V-shaped pillars and their distances are represented by the constant i , which is set to 10.00m. Secondary vertical lines whose distances from the main gridlines are $i/2$ and $i/4$ are also present. Here various offset distances from the main and secondary vertical lines are defined with the variables x , y , z and t . In particular, the values $2y$ and $2x$ are used to describe the distances between the two branches of the V-shaped pillars, at the points where the roof is connected to the supports. The main horizontal gridlines consist of the two longitudinal axes of the V-shaped pillars and the projections on the ground of the two overhanging roof edges. The distance between the axes of the V-shaped pillars is described by the parameter b , which in this parametric model was set to vary between 12.55m and 12.72m. The two overhang lengths, which are asymmetric, are designated with the variables a and c respectively. An additional variable u is used to define the distance of two secondary horizontal lines offset from one of the pillar's axis and the variable v represents the distance of another secondary horizontal line that is offset from the other pillar's axis.

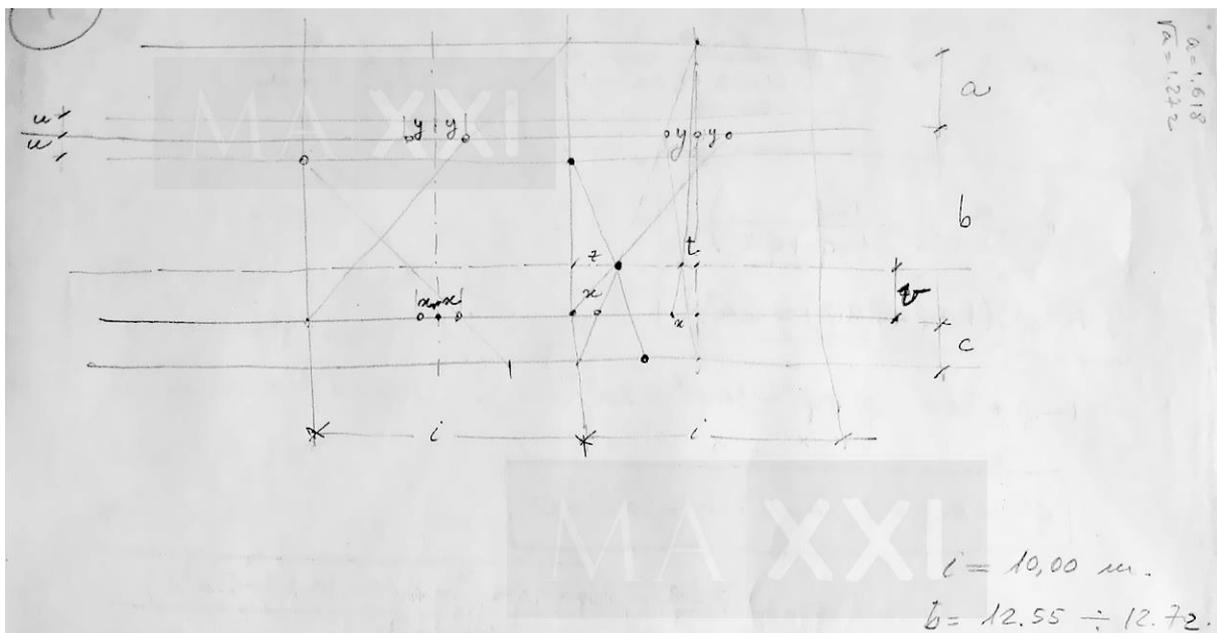


Figure 4: Stabilimento Raffa in Pietrasanta (1956), diagram representing the parameters used by Musmeci to describe the geometry of the folded plate module of the roof – Source: Archivio MAXXI Musmeci e Zanini.

References to the golden ratio φ , which had been already used by Musmeci in the analytical model of Cinema Araldo (Musmeci [9]), can be detected in the model. The value of the ratio and its root are noted by the engineer on the side of the document and they are used to define the upper extreme of the domain of the parameter b , being $i\sqrt{\varphi} \cong 10.00\text{m} \sqrt{1.618} = 12.72\text{m}$.

Grounded on this set-up, each edge of the folded plate module of the roof is represented by a segment that connects two nodes of the grid. Based on the constant i , its divisors $i/2$ and $i/4$, the eight variables x, y, z, t, u, v, a and c and the parameter b , a series of relationships on the slopes of the segments have been established by Musmeci in an analytical form. This has led to the definition of a system of eight independent equations in eight variables and one parameter (Figure 5). By conveniently reworking the equations, the variables x, y, z, t can be expressed as functions of u, v, a, b, c and i ; by allowing the parameter b to vary within its domain, the space of the solutions of the system can be explored.

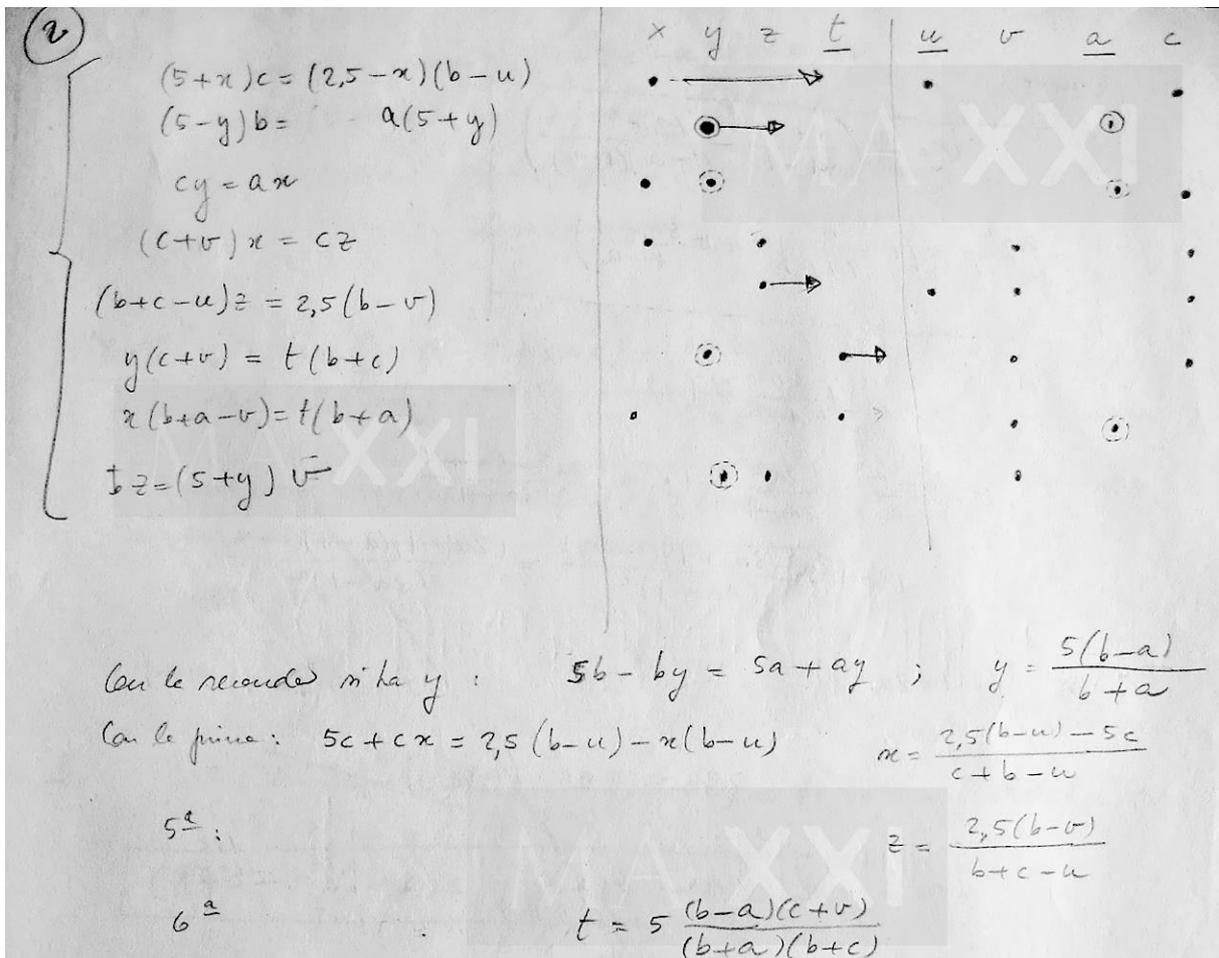


Figure 5: Stabilimento Raffo in Pietrasanta (1956), system of equation used by Musmeci to describe the geometry of the roof – Source: Archivio MAXXI Musmeci e Zanini.

3.2 The Geometry of the Roof in Space

The diagram of the distribution of the bending moments on the transversal section of the roof (Figure 6) has been used as a guideline to arrange the folded edges in elevation (Musmeci [10]), with the aim to achieve a uniform distribution of the bending stresses within the structure. In the diagram, the transversal section of the roof is represented as a continuous beam on two pin-jointed supports with asymmetric

overhangs. The position of the supports and the length of the overhangs are related to the previously described parametric model of the roof in plan.

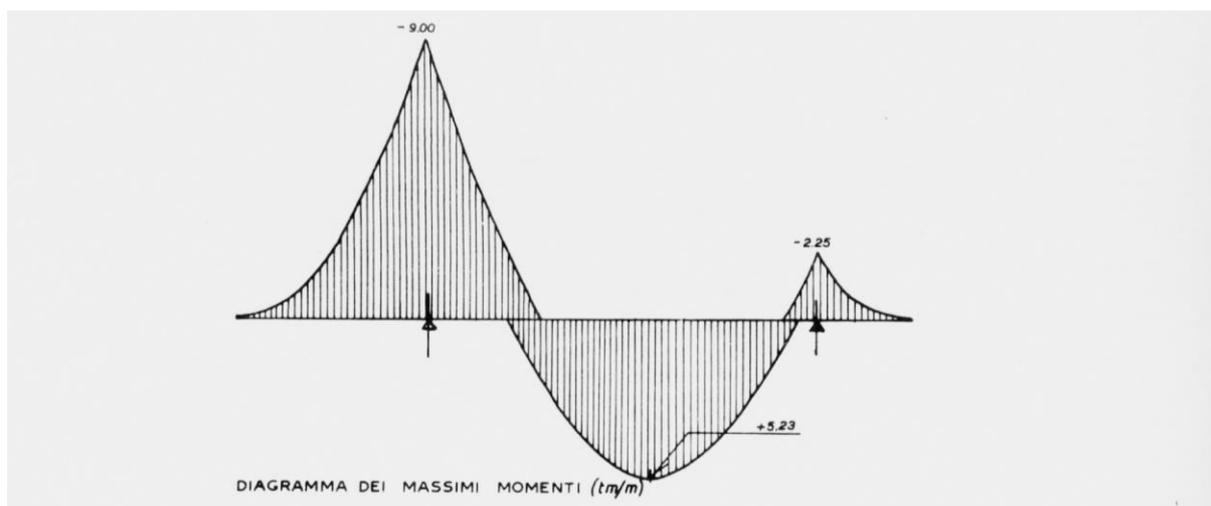


Figure 6: Stabilimento Raffa in Pietrasanta (1956), Diagram of the maximum bending moments on the transversal section of the roof – Source: Musmeci [10], p. 710.

The diagram shows the envelope of the bending moments generated by a series of uniformly distributed vertical loads; in particular, three extrema can be identified, at the supports and nearby the mid-span. Giving a design interpretation to the principle of resistance through form, the engineer has adjusted the elevation of the nodes of the folded plate module in relation to the variation of the bending moments (Figure 7). That is, the distance between the portion of the folded plates under tension and the one under compression due to bending has been adapted by Musmeci to relate to the magnitude of the bending moments along the transversal axis of the roof. The cross-section of the folded plate module is higher at the supports and nearby the mid-span. As a result, the distribution of bending stresses within the folded plate structure is kept uniform, allowing the engineer to overall minimize the cross-section of the folded plates and to adopt a slab with the same thickness all over the roof. In fact, this approach could be regarded as an early example of form-finding based on mathematical models (Ingold and Rinke [5]).

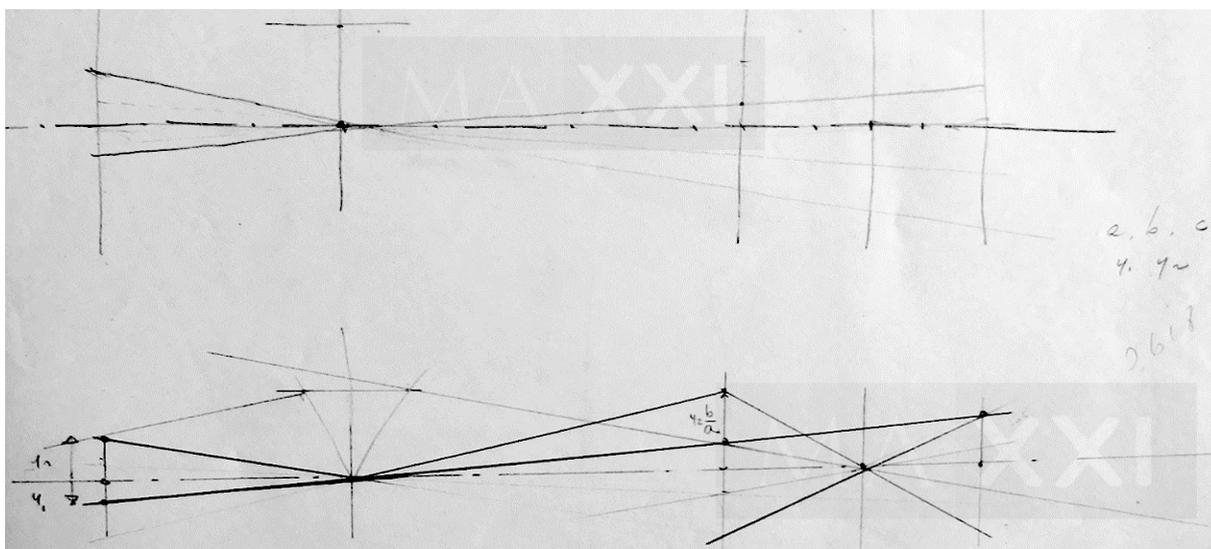


Figure 7: Stabilimento Raffa in Pietrasanta (1956), construction of the transversal section of the roof
Source: Archivio MAXXI Musmeci e Zanini.

Grounded on the geometry of the folded plate module of the roof in plan and the one in elevation developed through the parametric model, the geometry of the roof in three-dimensions can be derived (Figure 8). To visualize and control the complex geometry of the roof in space and to test its global structural behaviour, Musmeci made use of physical models (Figure 9).

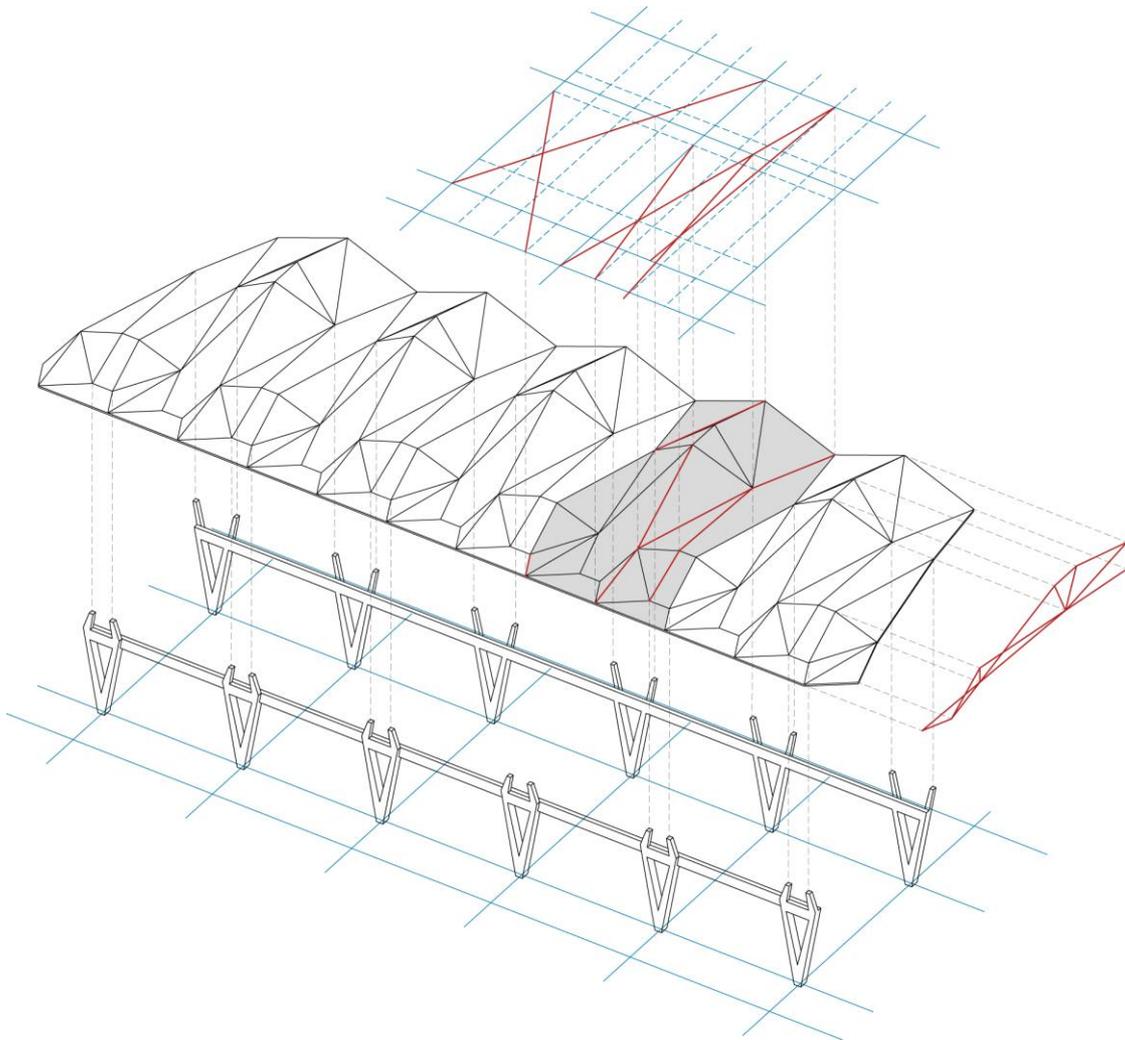


Figure 8: Stabilimento Raffa in Pietrasanta (1956), axonometric diagram of the roof constructed from the parametric models of the roof in plan and elevation.

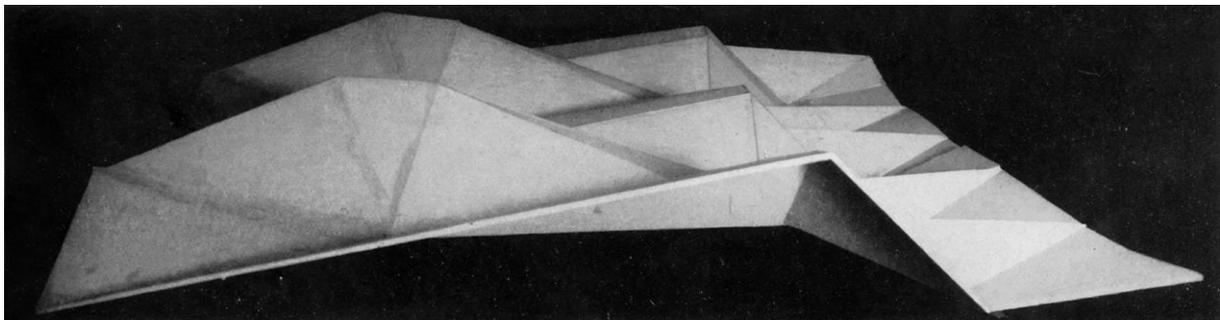


Figure 9: Stabilimento Raffa in Pietrasanta (1956), physical model of the roof – Source: Musmeci [10], p. 711.

The structure of Cappella dei Ferrovieri is based on a folded plate module, which works as a three-hinged frame and is repeated five times along the longitudinal axis of the building to generate an overall corrugated surface. The geometry of the folded plate module evidently reflects the distribution of the bending moments along the section of the frame. In fact, the distance between the portion of the folded plates under tension and the one under compression due to bending reaches its highest value at the frame corners and it is reduced to the minimum at the mid-span and at the supports.

These three projects are representatives of an exceptional approach on structural folding, which distinguishes Musmeci among the other engineers of his time. This is especially evident in relation to the resulting geometries of the folded plate modules emerging out of structural considerations.

5. Conclusions

Following the concept that in the process of structural design the form is the unknown and not the inner stresses, Sergio Musmeci investigates the properties of structural folding in a series of eight projects during his early career. Among these, particularly relevant is the roof of Stabilimento Raffo in Pietrasanta, where the engineer for the first time tries to attain a precise relationship between the form of the structure and its static behaviour. The analysis of the tools used by Musmeci to define the geometry of the roof clarifies his methodology, which is based on a parametric design process. At the same time, it outlines his specific approach to structural folding, which directly influences the subsequent folded plates projects as well as his lifelong research for new structural forms.

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