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Visionary Realism. Designing Sergio Musmeci's Bridge over The Niger River Today

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Abstract

The structures created by Sergio Musmeci (1926 - 1981) feature an "expressive language" combined with mathematically proven static efficiency. These "organic structures" are the result of a form-finding process in which the amount of material in the minimal surface form is reduced to counteract the potential energy of an external force system *[...] Rather than being motivated by whim or intuition, the search for the structural form is the result of a process concerned with the proper arrangement of matter in space to accomplish a specific structural task with the least amount of resources [...]* (Musmeci 1971 [1]). The concrete structure of the Niger Bridge, a double curved surface discretized into linear rods, is the project examined in this article. Despite the use of prefabricated concrete components, the structural design, and the complexity of construction management as well as high labor costs limited its feasibility, even if it makes sense in terms of spatial organization of materials. However, new digital developments in technical tools have opened up new possibilities for control over design and construction. This article questions the design method of the Ajaokuta Bridge and based on these considerations, analyzes its modeling using state-of-the-art computational design techniques. In particular, spatial exploration based on a system of prismatic and antiprismatic elements (nodes) is discussed as a recurring key role [2] [3]. Additionally, the research aims to apply Musmeci's form-finding methodology through an integrated digital workflow for construction-based strategies based on on-site 3D printing. In order to study the morphogenesis of three-dimensional structure creation in detail, graphics algorithms are established [4].

Keywords: Sergio Musmeci, historical design, computational design, conceptual design, structural morphogenesis, digital form-finding, Concrete 3d printing, additive manufacturing, fabrication optimization.

1. Introduction

Sergio Musmeci (1926 - 1981) created a novel concept of structural architecture based on a solid scientific basis and humanistic points of view. His goal was to develop a scientifically based architectural paradigm that addresses the debate about the technological age. Therefore, science acts as a stimulus for formal research, which in turn drives a renewal of aesthetic expression. A scientifically based design method can serve as a source of inspiration for creative knowledge. In fact, in several articles he challenges readers to look more closely at those brilliant mathematical concepts that make the interaction of science, technology and architecture a cultural enrichment: *[...] The comparison between architecture and scientific culture can and should be more direct since it takes place at the level of systems of ideas of universal scope, and it is natural to expect that this comparison will be of deeper meaning and perhaps, if developed coherently, can be as profitable as the parallel comparison between architecture and literature culture. In fact, there are many reasons to believe that architecture, due to its operational nature, can represent an ideal terrain for a fruitful encounter between the "two cultures", which today are so far apart that they often appear as expressions of two different civilizations [...]* (Musmeci 1979 [5]). Musmeci's education was an essential factor in the further development of his interest in the mathematical sciences and his extensive knowledge of structural mechanics. Musmeci completed his studies in 1948 with a degree in Civil Engineering and in 1953 with a degree in Civil Engineering for Aeronautical Engineering. In addition, during his early professional career he worked closely with several key figures in Italy's post-war reconstruction. In addition to Adalberto Libera (1903 - 1963), he worked for Pier Luigi Nervi (1891 - 1979) and Riccardo Morandi (1902 - 1989) [6]. All these experiences shape Musmeci's assessment of the architectural-structural project.

2. Musmeci’s creative process: the morphogenesis

A concept that arises from his theoretical approach to structural design is that the researcher who reveals the correct form is aware of the true nature of things. The formal expression of architecture, more specifically the morphogenesis of form, is the main topic of Musmeci's research. In fact, is science that drives the emergence of the structural geometry for an Equilibrated Applied Force System (S.E.F.A.) [7] through the use of appropriate stressed materials under limit state conditions. It is important to note that topology – essentially the proper arrangement of geometric relationships in space – is also what Musmeci defines as “material.” He wrote: *[...] The most important result of the design process of a structure is essentially a form which, while solving the technical problem, becomes the means of expression of the creative process that organizes the structural material in space [...]* (Musmeci 1979). As a concrete example, he used the formula y = log cos; a notable feature of this curve is that the angle between the central axis of the parabola and the horizontal line is directly proportional to the abscissa of the curve, or the distance from the vertical axis. Therefore, the maximum span of this arch is the distance that creates an angle of 90°.

Undoubtedly, the structural insights of Pier Luigi Nervi and Riccardo Morandi laid the foundation for Italy's *auctoritas et sapientia* in the 20th century, which ultimately represented the pinnacle of the Italian engineering school [8]; nevertheless, Musmeci argues that a complex structural form existed in the past, arising from brilliant intuition, and explained by a simple premise: the state of the tension is the unknown. The new paradigm is essentially reversed; The form is the true unknown factor, not the stressors (applied internal and external forces). A new paradigm, defined as form-finding, is explained in his manifesto “The form is the unknown, not the internal tensions” (Musmeci 1979). In particular, his structural physics experiments are based on models of soap films and membranes associated with a phenomenon observed in natural science (Nicoletti 1979 [9]). This all-encompassing method of architectural-structural design can be understood through an analogy to the principles of form development found in nature [9]. To finally validate the structural physics form-finding, extensive static tests were carried out on a methacrylate and micro-concrete model created in the ISMES laboratory (Experimental Institute for Models and Structures).

According to a chronology spanning the 1950s, 1960s and 1970s, the static strategies he examined can be summarized as folded surface, continuum surface and spatial frame [10]. They show how his thinking developed in relation to the technical problems that he occasionally encountered and which he skillfully solved. In order to specifically reduce local tensions, the first phase of the structural design begins with a concept that folds the surfaces in space and uses broken profiles for the roofs (first phase: folded surface). The classic examples of the rigidity of folding roofs from this early construction phase are the gymnasium of the Formia sports center in 1954, the well-known Raffo laboratory in Pietrasanta in 1956 [11] and the Araldo di Roma cinema in 1955. This approach allows validation of increasingly complex designs; The research brings with it the technical challenge of continuous surfaces with multiple curvatures. This path leads to the investigation of those thin vaults in which the shape corresponds exactly to the stress content (second phase: continuum surface), such as shells, membranes and tensile structures in general. Musmeci imagined a membrane subjected only to pressure loading, with its organic shape determined by the laws of nature (gravity): a form-finding. A prime example of this strategy is the roof of the General Markets in Rome (1958-1960), designed in collaboration with Vitellozzi, Castellazzi and Dall'Anese. Musmeci was able to demonstrably adopt this strategy with the construction of the Basento Bridge (1967-1976) in Potenza, southern Italy. In collaboration with Aldo Livadiotti and Zenaide Zanini, he designs and constructs a concrete structure similar to a membrane, taking advantage of the properties (physics) of the double curved surfaces.

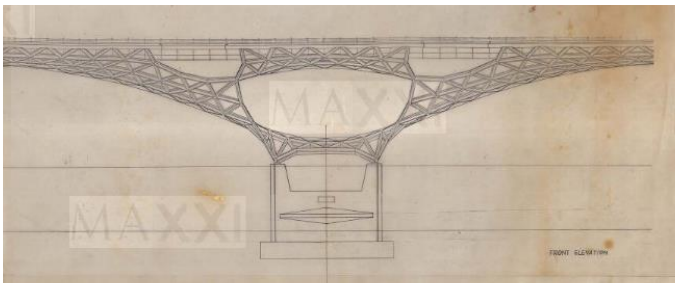


Figure 1: Niger bridge (1977) - Span Front Elevation - Centro Archivi MAXXI, Museo Nazionale delle arti del XXI secolo.

Finally, the discretized elements of rods and nodes that form an “abstract” space are the subject of his final research. These elements are framed in a strict geometric system, legible in plan, in which the polyhedral cells that make up the architectural structure are assembled. As a result, Musmeci focuses on a newly designed structural system consisting of regular and semi-regular polyhedra. In other words, interest arises in the space that is free of the static-expressive content that characterized the previous phases. (Third phase: discrete surface – spatial frame). An important example of this structural concept is the international competition for the Lao Bridge (1964) between Salerno and Reggio, which was part of the renowned “Autostrada del Sole” infrastructure project. In fact, Musmeci proposes a grid-shell construction made of prefabricated hollow elements injected on site with concrete to allow the construction of a large span of 150 meters. (Musmeci 1967). Another unique example of this discrete structural design technique is the Niger Bridge (1977) in Ajaokuta, Nigeria (Nicoletti 1999 [12]). A spatial structure - new shape typology-topology concept - which has evolved into a more detailed project, which has also been combined with the previous form-finding method (Fig.1). As in Moretti's parametric architecture [13], where his theory can be compared to James Dana's studies of the formal variation of crystals, in Musmeci's studies we see an analogy to those geometric laws that structure a crystal lattice: *[...] These bar systems are directly related to regular point systems according to which the atoms in a crystal are organized; The points correspond to the nodes at which the rods are connected [...].* (Musmeci, 1979 [14]). The geometric arrangement of the nodes defines the spatial order, and the elements define the structural topology. This study of “cellular” geometries vividly describes the guiding principles on which his design for large spatial roofs and bridge spans is based: *[...] What matters are the nodes and the bars that define them, the relationships between distances and angles, the ultimate manifestation of organizational laws that enable the reading of space. In this case, geometry plays a more direct role, since a bar is perceived not as a line of force, but as a geometric vector [...].*

3. The form of the spatial structures

Musmeci's research on spatial structure - truss - as a pure expression of geometry is initially based on the conformation of truss structures assembled into a frame of identical elements. These space frames work better than other structural systems because they are flexible and lightweight. These general considerations allow Musmeci to study this system, spatial, but with the aim of using an innovative material that can withstand the stresses under pressure better than steel. This creates a special concrete mix design with synthetic composite polymer for the compressed spatial structural system. On the other hand, his novel insight requires a new configuration design of the most complex parts of the truss structure: the nodes. Therefore, Sergio Musmeci published several articles on this topic. As can be seen from his drawings (Fig.2), Musmeci decided to remove the nodes that were usually intended as hinges and replace them with empty polyhedra, on the last section - faces - of which rods converge; they were firmly connected to each other using injection of concrete. The mesh system with polymer-based concrete manufactured by Italcementi allows to achieve a highly hyperstatic structure. Therefore, it is no longer the hinges that regulate the transfer of stress between the beams or rods, but the fixed connections that are considered the most suitable for creating structures with large spans. The most important feature of this design is that the

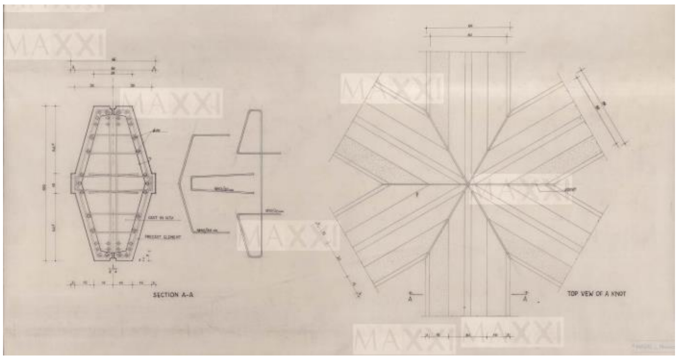


Figure 2: Niger bridge (1977) – Section of a Knot - Centro Archivi MAXXI, Museo Nazionale delle arti del XXI secolo.

shape of each rod is created on the condition that each node does not contain any elements that are not related to the overall geometric shape. Better expressed, the composed structure depends on the polyhedral node - the section shape - or, as called in the magazine Parametro, the «poliedro di nodo». Therefore, Musmeci studied the geometric properties of the five regular polyhedra - tetrahedron, cube, octahedron, dodecahedron, icosahedrons - and two semi-regular polyhedra - triangular bipyramid, rhombic dodecahedron - on the one hand as a potential structural bar section, on the other hand as a node (2d-3d). The Platonic solids - regular polyhedra - must have at least three faces at a vertex and these can be regular triangles, squares, or regular pentagons. If a regular polyhedron with triangular faces can be formed by collecting 3 around a vertex (tetrahedron), or 4 (octahedron), or finally 5 (icosahedron), then with 6 you get a plane instead that cannot be enclosed in a volume. In this case we get geometric structures defined as anti-polyhedra.

3.1. The key role of the geometry: Anti-polyhedra

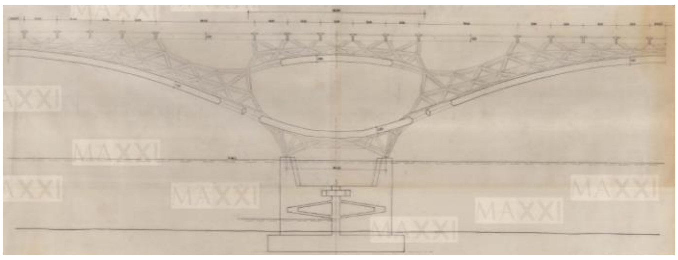
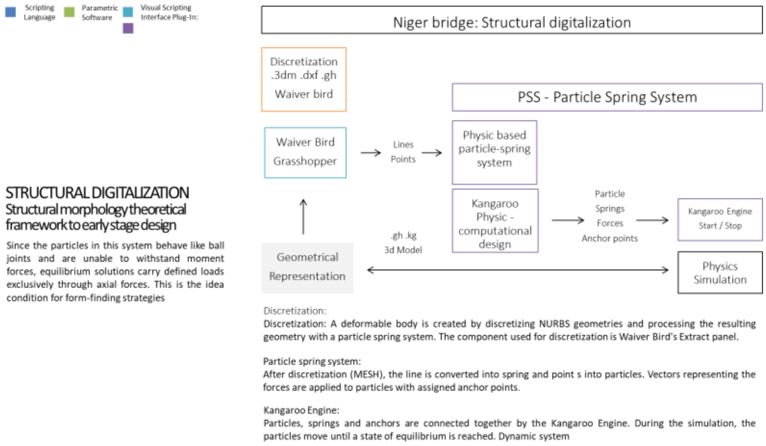


Figure 3: Niger bridge (1977) - Span Section - Centro Archivi MAXXI, Museo Nazionale delle arti del XXI secolo.

Considering the fact that a sphere has a constant positive curvature, an anti-spherical surface has a constant negative curvature: surfaces of this type are defined as “minimum surfaces” because they represent the minimum area for each possible assigned contour. The shapes of such anti-spherical surfaces are infinite and depend on the contour. So, if the anti-polyhedral nodes are always at a greater distance from each other than a certain point (e.g. saddle point), we can get a system of rods arranged according to a saddle surface, i.e. according to a hyperbolic paraboloid: a "minimum mesh.". These nodal grids are of great structural interest as they allow the transfer of forces from one part of the contour to the other with the regime of a rods characterized by uniform stresses. An example of this is the network topology of the Niger Bridge, where the rods are arranged on a minimal surface and identical normal stresses occur in all elements (Fig.3). Specifically, in this case the discrete and continuous structures are combined, and thus differential equations replace the number sequences for analysis. Based on these considerations as well as geometric properties and physical principles, Musmeci investigates the semi-regular polyhedral, as they are more suitable. In fact, the triangular bipyramid, and rhombic dodecahedron have equivalent rods. We can construct it starting from a flat grid of equilateral triangles (Musmeci, 1979 [15]). The rhombic dodecahedron with diagonals 1: $\sqrt{2}$ is a convex polyhedron with 12 congruent rhombic faces, 24 edges and 14 vertices of two types. The rod system is arranged according to the edges of octahedra and tetrahedra, which together completely fill the space in the ratio of one octahedron to two tetrahedra. The rhombic dodecahedron can actually be stacked to fill a space, similar to how hexagons fill a plane to tessellate complex surfaces. We can imagine this polyhedron as a Voronoi tessellation of the face-centered cubic lattice in a space-filling form. Finally, four unique orthogonal projections centered on a face, an edge (hexagon – Niger bridge shell- membrane), and the two types of vertices (triple and quadruple) extend along the symmetrical axes of the rhombic dodecahedron. The process is digitally reproduced, and a framework is created as shown in (Fig. 4).



STRUCTURAL DIGITALIZATION
Structural morphology theoretical framework to early stage design

Since the particles in this system behave like ball joints and are unable to withstand moment forces, equilibrium solutions carry defined loads exclusively through axial forces. This is the idea condition for form-finding strategies

Discretization:
Discretization: A deformable body is created by discretizing NURBS geometries and processing the resulting geometry with a particle spring system. The component used for discretization is Waiver Bird's Extract panel.

Particle spring system:
After discretization (MESH), the line is converted into spring and point s into particles. Vectors representing the forces are applied to particles with assigned anchor points.

Kangaroo Engine:
Particles, springs and anchors are connected together by the Kangaroo Engine. During the simulation, the particles move until a state of equilibrium is reached. Dynamic system

Figure 4: Digital framework - computer-aided design process - shell - membrane form-finding - digital workflow.

4. The Niger bridge (Ajaokuta - 1977): Structural digitalization

The digitization shows how the bridge can be schematized into geometric vectors that provide a system that makes the three-dimensional space of the structural spans legible. In fact, a form-finding process is virtually reproduced to achieve the same geometry that makes up the double curvature membrane - compressed - and then discretized for a mesh. To validate the design of the Niger Bridge, Musmeci combined several laboratory approaches: physical, numerical, and analytical approaches, divided into three main phases that play a key geometric role in this digitalization: the computer-aided design of the bridge deck, the shaping the shell-membrane (soup film method) and surface tessellation with rods (hexagon static analysis). The 24 span, 3000 m long Niger Bridge is an equally compressed system based on a system of prefabricated concrete rods with constant negative envelope curvatures. More than six rods always converge at a junction. The dimensions and proportions for the deck design were first determined by reconstructing the cross-section from the original drawing. This has an extension of 32 m and a height of 1.2 m (reinforced concrete box) and is symmetrically divided into three equal parts of 4 meters each with a central part of 8 meters (Fig. 5). The deck is completed by a bike lane below the center section. The weight of the deck exerts a vertical load on 16 support points of the shell membrane (Fig. 6). The longitudinal section examined precisely frames a span of 120 m (60 m symmetrical). The shell design is based on the geometric identification of its arrival points under the deck beams (+60.80 m) and in relation to its support points (+40 m) above the foundation pylon in height (+22 m) (Fig. 7). It should

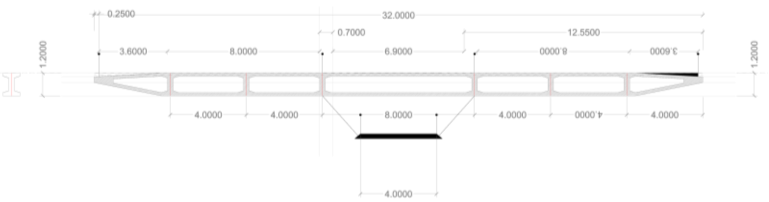


Figure 5: Digitization of the Niger Bridge deck

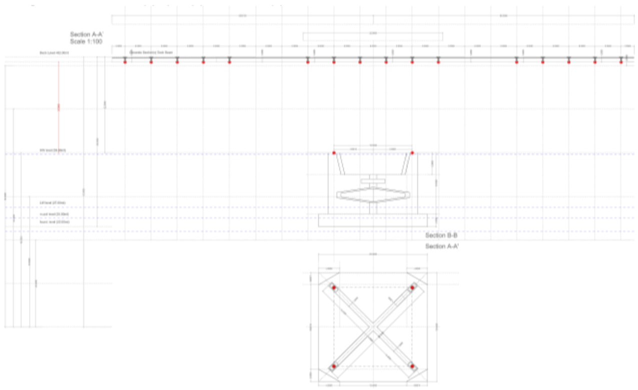


Figure 6: Digitization of the Niger Bridge span - computer-aided design - 16 support points of the shell membrane connections.

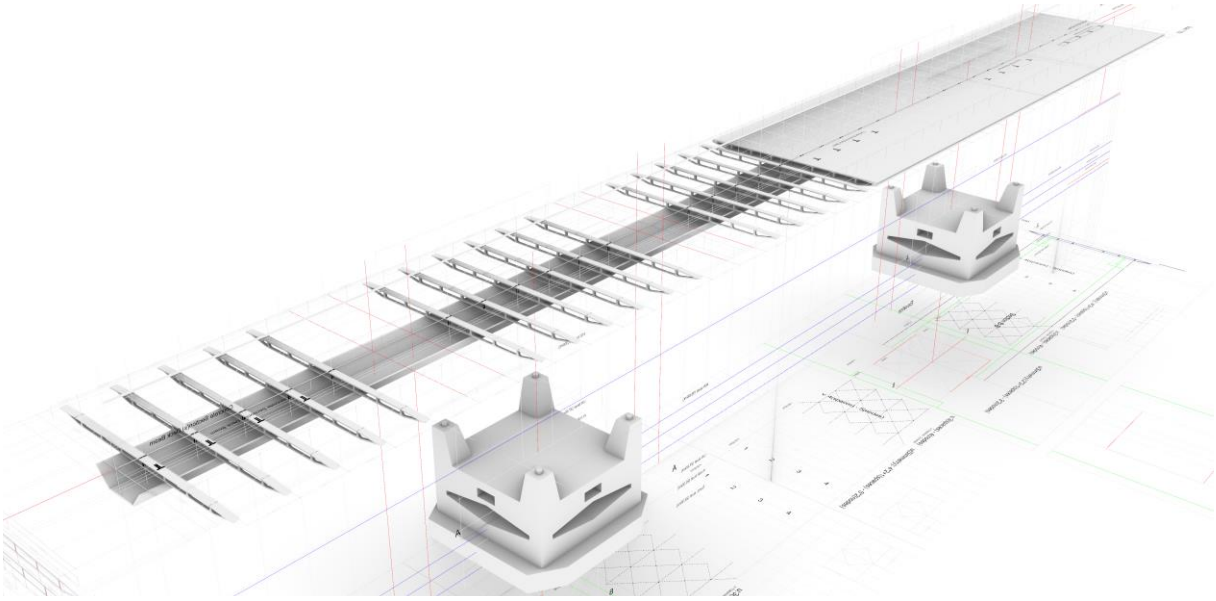


Figure 7: Digitization of the Niger Bridge spans - computer-aided design – foundations and ground levels

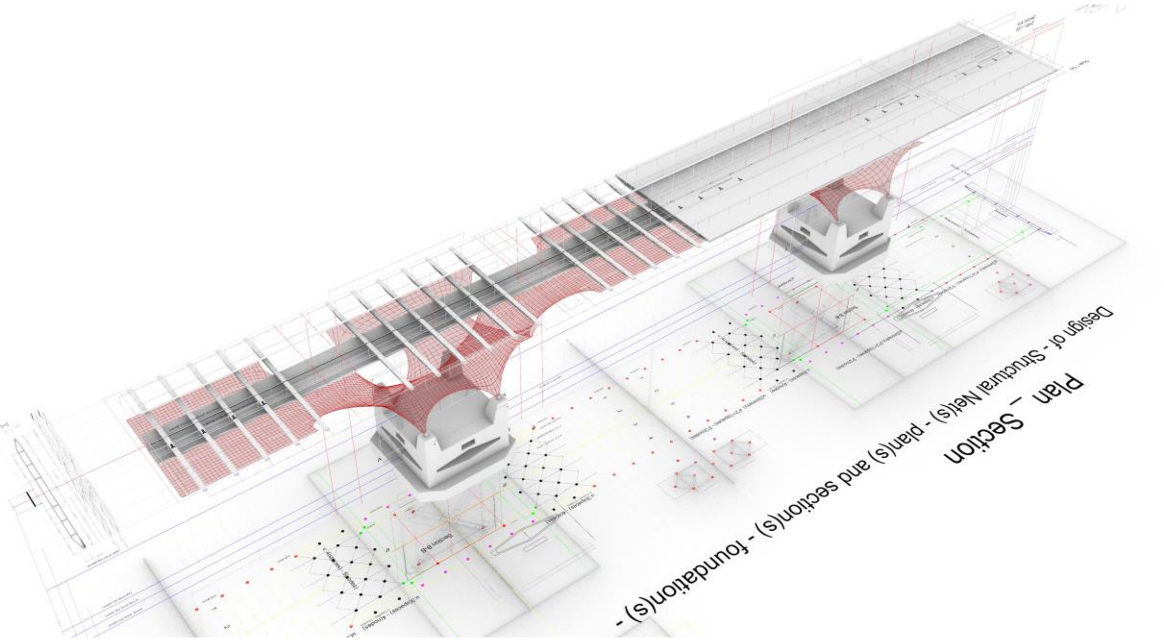


Figure 8: Digitization of the Niger Bridge shell - computer-aided design – foundations and ground levels - form-finding structurally integrated – minimum mesh

be considered that the digital processing of the PSS method – particle spring system - [16] (with constant rods length, non-deformable), assuming that the reference network is subjected to the vertical loads at the node, almost reproduces the membrane effect of a (minimal) surface in space (Fig. 8). The hypotheses are statically discussed in detail in the next paragraph. To study the static behavior of the structure in a preliminary design phase, it is assumed that the system, whether continuous or discrete, consists of linear elements (networks) arranged in space by varying only their node position to achieve a state to determine the pure compression. Once the system is represented, the structural shape - which is the unknown - is discretized using a hexagonal tessellation, and/or a basic system of equal triangles (square). This results in a system limited to rods subjected only to normal loading and forming part of the minimum surface. The digital modeling of Musmeci's project is founded on a meticulous geometric reconstruction of the design, using data from the graphic tables.

4.1. The key role of the of the hyperbolic paraboloid: Soap film method

A parallel exists between the soap film's behavior and that of the bridge shell. The assumption that all stresses have been reduced to a uniform, basic state of tension in all directions for the surface or soap film's shape. A (typical) model for finding the minimum surface area is to solve the multivariable mathematical function using the Laplace operator: soap film $z = z\ (x,\ y)$; $z = x^2 - y^2$; solved with $\Delta_2 Z=0$; $div(\nabla z)\ = q/N = 0$. Therefore, Musmeci is believed to have researched the ability of a soap film to produce the ideal shape that represents the three-dimensional morphology of the Niger Bridge shell. Specifically, the film defines an area based on certain boundary conditions, i.e. based on its complete border. It is therefore tied to a metal wireframe (Fig. 9), (representing the continuous perimeter beam and the attachment to the deck through the struts), which reduces its energy to a minimum: the "ideal" morphology to aim for. This shape, assuming negative curvature (zero mean), is arranged to form a surface whose area is the smallest possible among all surfaces within this boundary. This is because the surface tension of the soap film tends to reduce its expansion. Well, this is a physical-

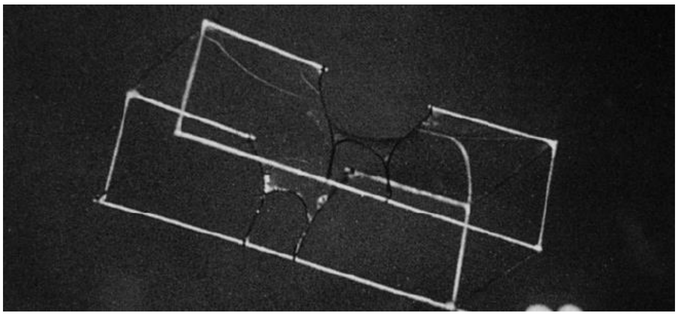


Figure 9: Soap Film Model – Finding the minimum surface area in the metal wireframe.

mathematical modeling that, through an abstraction process, becomes the reference for the final definition of the bridge shape. After creating the physical model of the shell, Musmeci utilizes mathematical methods to express the surface analytically, specifically by writing the Laplace equation. This equation allows us to determine the divergence of the gradient, providing insight into the curvatures of the surface. The constant ratio q/N expresses the dead weight per unit area q and the applied normal force per unit length N. The scalar equation (to be determined) z = z (x, y) resulting from the interpretation of the Laplace equation corresponds to the height of the deck, i.e. the surface of the shell. It is therefore assumed for the soap film that the relationship between weight q and tension N is negligible and therefore q / N = 0; $div(\nabla z)$ =0. In contrast, for surface representing the cement shell (discretized), the ratio between q / N is assumed to be equal to K, non-negligible $div(\nabla z)$ =q/N=K

4.2. The key role of the of the hexagon: Static analysis

When determining the stresses between the rods of a spatial system in the elastic field, a significant number of hyperstatic unknowns arise that make qualitative assessment impossible; FEM methods must be used to perform a reliable calculation. Despite this, we can analyze the equations as a function of the geometric system's basic logical structure and by making some initial assumptions about it.

First of all, assume that the rods are identical in length, shape, and cross-section. This leads us to a system of equations that repeats precisely and contains only integer coefficients; its values, its ratios, and the structure of the rules according to which they appear in systems of hyperstatic equations are further aspects of the spatial organization that the system proposes. The system is evaluated qualitatively.

Second, we assume the nodes are hinged and that the external force is only node-shaped applied. This means that a network of rods must be created in which the force vector acts vertically exclusively on the node - so that all rods are only subject to normal stress. Therefore, in a three-dimensional system - a rhombic dodecahedron system - or in a hexagonal plane system, we can approach static analysis in a simplified way. A single triangle with three rods is an isostatic structure, a component of the plane system. It also seems obvious that this simple structure would remain isostatic even if a node and therefore two rods were added, creating two new unknowns and two new equilibrium equations (those of the new node). A first degree of hyperstatic occurs when the plane is closed in a hexagon by adding a rod instead of a node. Therefore, the degree of internal hyperstaticity is indicated by the number of hexagons with the six radial bars that can be identified in the structure-surface. Consequentially, every degree of hyper-staticity consists in a constraint affecting the hexagon with identical stresses in the 6 perimeter rods and identical, but of opposite sign, in the 6 radial rods. These stresses represent a constraint because they balance each other out and can therefore represent the difference between two distributions of stress in the structure, both in equilibrium with external forces. So, the solution to the hyperstatic problem is to find the set of these types of interactions that must be added to any balanced initial distribution to obtain the one that satisfies not only equilibrium but also congruence of the elastic deformations.

The normal stress in a rod is: $N = N_0 + n_1X_1 + n_2X_2 + \ldots + n_kX_k$, where N_0 is the stress in the initial balanced output distribution and the others are the corrections that need to be added to obtain a balanced and elastically congruent structure. Every correction term is proportionate to one of the K hyperstatic unknowns X_i and the coefficients n_i represent the coaction stresses corresponding to the unit values for the X_i. Thus, n_i is equal to zero in all the rods except those that pertain to the hexagon, where it is equal to 1 in the radial ones and -1 in the perimeter ones. Since every rod is the same, we can say also that their deformability is equal to 1 and therefore the deformation work in the structure is expressed by:

$$\mathrm{L} = \frac{1}{2} \sum_{s}. \mathrm{N}^2 \tag{1}$$

(1/EA for rods with constant section with 1=length, E=elastic modulus, A=section area), and $\sum_{s}.$ is extended to all structural members). The values of X_i that solve the problems are those that must minimize L and satisfy the equations:

$$\sum_{s}. \mathrm{N}_{\mathrm{nj}} = 0 \tag{2}$$

$$\sum_{j}(X_j \sum_{ninj}) = -\sum_{s} \mathrm{N}_0\ \mathrm{nj} \tag{3}$$

This a system of K equations in the K unknowns X_i with a symmetric coefficient matrix.

$$\sum_{s}.\, ni\; nj_{.} \tag{4}$$

this coefficient is the sum of 12 terms equal to 1 and its values is 12 if i=j

The equations can be easily written by determining if the hexagons overlap, touch each other, or have no connection. In the latter case, the two co-actions have no common auctions, so the sum of ni and nj is zero; on the other hand, if they have a common side, the sum is 1. In the case that they partially penetrate each other, as in the case of the "shell-membrane" structure of the Niger Bridge, they have 5 common rods, 4 of which ni and nj have unit values of opposite signs, while in the last one the value is 1, so the sum is -3.

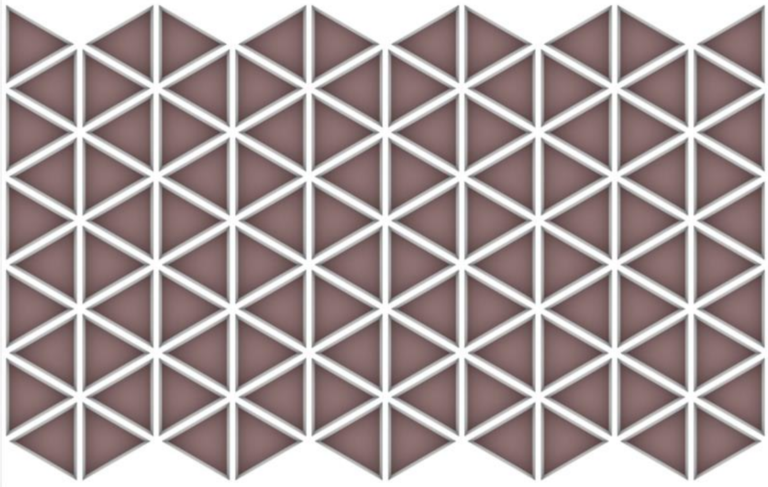


Figure 10: Digitization of the shell hexagon – structurally manufactured form-finding – minimum mesh size.

Thus, the coefficients of the system of equations along the diagonal equal twelve, whereas the coefficients of the other systems can only be three or one. In other words, based on established hypotheses and assumed consideration, the hyperstatic unknowns can be identified by counting the complete hexagons present in the structure (Fig.10). Automated additive, subtractive and formative production processes could reinterpret the prefabricated construction state of the elements, based on the hypothesis' explained. 3D printing technologies have the potential to facilitate the production of highly customized building components through automated and cost-effective on-site processes, all within digital manufacturing tools. Nowadays, indirect concrete 3D printing appears to be one of the most interesting techniques due to its immediate applicability. The creation of special formwork for concrete components combines the application expertise of widely used building materials, such as polymer concrete, with technical optimization potential. In addition, with regard to Sergio Musmeci's project, this positive methodology finally seems able to offer tangible solutions to the designer's vision. One can imagine the use of indirect 3D printing of concrete to produce the rods and nodes of the structure as a scenario that needs to be investigated and confirmed in later studies. In particular, stay-in-place formwork can be produced by combining robotic arm 3D printing technology with robotic arms. The production of these components is completed with the introduction of the reinforcement and the subsequent concreting. Bars, which were originally characterized by the same length, can now be distinguished by optimizing their topology [17]. The nodes, which are a symbol of the complexity of the construction due to the many crossing rods, can also be optimized. (Fig.11).

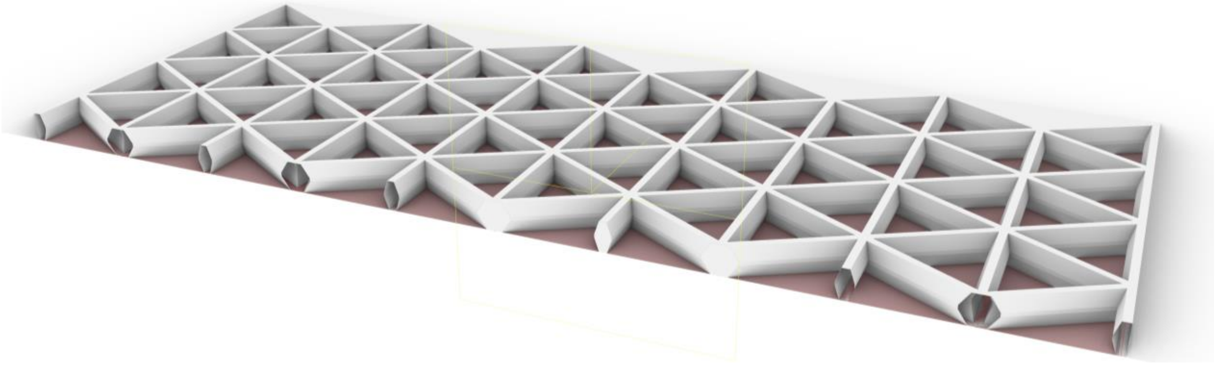


Figure 11: Digitization of the shell hexagon section – structurally manufactured form-finding – minimum mesh size. Digitization of the Niger Bridge topology – computational design

5. Conclusion: A visionary Realism

Sergio Musmeci's development of a cogent theory of architectural expressiveness is not out of place in modern formal research, which uses genetic algorithms to implement ideas and forms related to architecture, such as structural morphogenesis. In this sense, we rediscover in Musmeci an anticipation of the theory that, together with mathematical calculations of hardware capacity, supports computational morphogenesis in digital design, i.e. modeling techniques for form-finding.

However, the Roman engineer understands structural form as a spatial configuration that descends directly from that theoretical system that makes "universal invariants", such as symmetrical geometries and dissonances properties its compositional rule; a design approach that can ultimately be assigned to a classic cultural horizon. In fact, he proposes a duality within which the spatial imagination can discover previously unimaginable expressions in the relationship between geometric and physical properties; therefore, state the following: *[…] It is a kind of synthesis between the geometric space of the Greeks and the physical space of Galileo and Newton. The unity achieved should be expressed in forms that represent and tangibly express this synthesis. Only then can it be said that we work in a modern space in which the forces and static balances are so linked to the space itself that they coincide with it and contain inseparable connotations of its fundamental properties […].* (Musmeci, 1979).

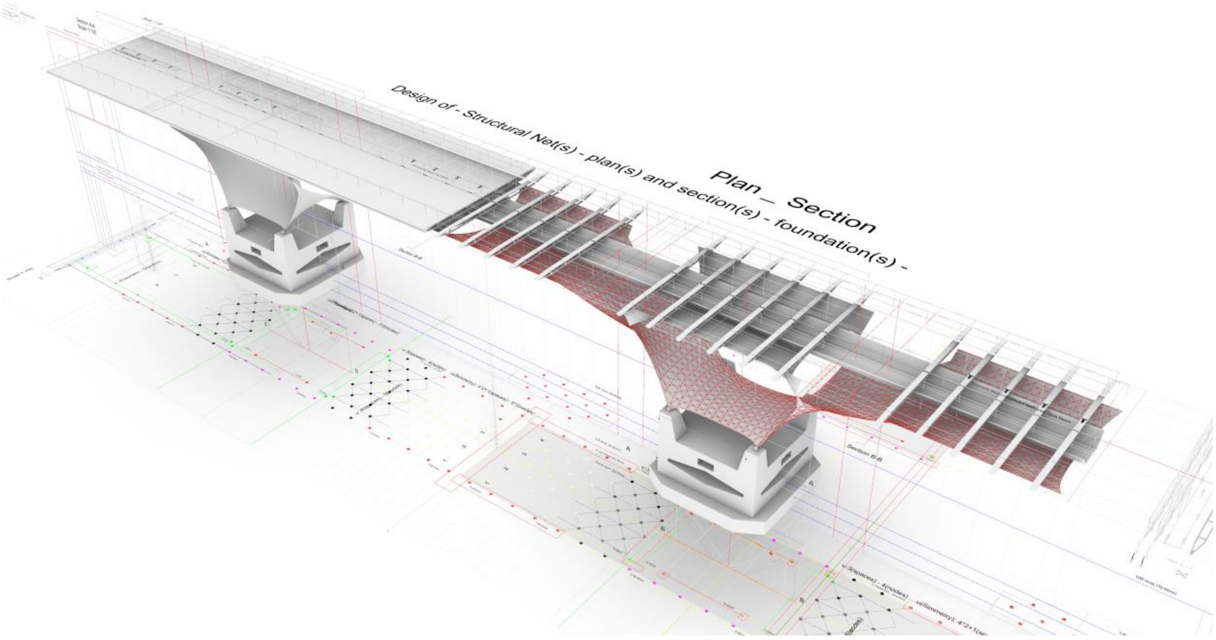


Figure 12: Digitization of the shell of the Niger Bridge (square network based on triangular - hexagonal form-finding) - computer-aided design - foundations and floor levels - structurally integrated form-finding - minimum network width.

At the same time, digital technology enables the effective design of complex morphologies that required major professional challenges. Furthermore, spatial complexity is now controlled by the computational process itself, with the "Know-how" always anticipated by the theory being the "Know-why". This allows us to rediscover a part of this draft that was temporarily put aside due to representation difficulties (Fig.12). From another point of view, large-format concrete 3D printing could enable the renovation of Musmeci's works, as labor costs are higher than material costs. In fact, the advantages of these manufacturing technologies lie in their high production accuracy and predictable running times. A tool that can be used directly on-site in production and, more importantly, significantly reduces manual effort. This latter advantage may lead to a rethinking of Sergio Musmeci's organic structural design for practical design and affordable construction. In other words, 3D printing technology could materialize Musmeci's structural morphology studies, as it better meets financial requirements and provides a reason to experiment with new organic structures.

References

[1] S. Musmeci, *La statica e le strutture*, Cremonese, Roma 1971

[2] S. Adriaenssens, P. Block, D. Veenendaal and C. Williams (eds.), *Shell Structures for Architecture: Form Finding and Optimization*, Routledge, 2014.

[3] S. Musmeci, “La genesi della forma nelle strutture spaziali”, *Parametro mensile internazionale di architettura & urbanistica*, no. 80, pp. 13-47, 1979.

[4] R. Naboni and G. Paparella, *“Circular concrete construction through additive FDM formwork”,* Proceedings of the 25th International Conference on Computer-Aided Architectural Design Research in Asia, CAADRIA 2020. pp. 233-242.

[5] S. Musmeci, “Architettura e pensiero scientifico”, *Parametro mensile internazionale di architettura & urbanistica*, no. 80, p. 35, 1979.

[6] Iori T., La storia italiana del cemento, in Iori T., Marzo Magno A. (eds.), *150 anni di storia del cemento in Italia*. Gangemi, 2011, 18-21.

[7] S. Musmeci, *La statica e le strutture*, Cremonese, Roma 1971, pp. 3-21

[8] Iori T. and Poretti S., Il linguaggio delle strutture, in Iori T., Poretti S. (eds.), *SIXXI 2. Storia dell’ingegneria strutturale in Italia*, Gangemi, 2015, 15-18.

[9] T. D’Arcy, *On Growth and Form*, Cambridge University Press., 1917

[10] D’Acunto P. and Ingold L., Structural Folding as a Source of Research for Sergio Musmeci, *IASS 2017. Interfaces: architecture.engineering.science*, Hamburg, Germany Annette Bögle, Manfred Grohmann (eds.), 2017.

[11] D’Acunto P. and Ingold L., The Approach of Sergio Musmeci to Structural Folding, *IASS 2016. Spatial Structures in the 21st Century*, Kawaguchi K., Ohsaki M., Takeuchi T. (eds.), 2016.

[12] M. Nicoletti, “Sergio Musmeci: organicità di forme e forze nello spazio”, *Universale di Architettura collana di Bruno Zevi*, no. 54, pp. 58-59, 1999.

[13] L. Moretti, “Ricerca matematica in architettura e urbanistica”, *Moebius Unità della cultura: architettura urbanistica arte, 1971*

[14] S. Musmeci, “La genesi della forma nelle strutture spaziali”, *Parametro mensile internazionale di architettura & urbanistica*, no. 80, p. 18, 1979.

[15] S. Musmeci, “La genesi della forma nelle strutture spaziali”, *Parametro mensile internazionale di architettura & urbanistica*, no. 80, p. 24, 1979.

[16] A. Kilian, J. Ochsendorf, *Particle Spring Systems for Structural Form-Finding,* Journal of the International Association for Shell and Spatial Structures, 2005

[17] R. Naboni and G. Paparella, *“Circular concrete construction through additive FDM formwork”,* Proceedings of the 25th International Conference on Computer-Aided Architectural Design Research in Asia, CAADRIA 2020. pp. 233-242.