# Between Structural Theory and Construction Practice: The Role of Drawing in Pier Luigi Nervi's Ribbed Floor Slabs

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## Introduction

Among the many structural solutions that characterize the work of Pier Luigi Nervi (1891-1979), the leading Italian figure in twentieth-century structural engineering, the ribbed floor slabs arranged according to the isostatic lines of bending represent an emblematic outcome of his synthesis of structural logic, constructive efficiency, and expressive quality. In this solution more than in others, drawing plays a decisive role in translating the static principle into built architecture, acting as a critical instrument of selection: through drawing, among the multiple configurations referable to a single guiding principle, those capable of combining constructive correctness with expressive effectiveness are identified.

In the design of ribbed slabs, as in his broader activity as both designer and builder, Nervi makes an exceptionally conscious use of drawing and photography, going well beyond the conventional employment of these tools by structural engineers. This attention is fully consistent with his *modus operandi*, rooted in his dual role as conceiver and executor. On the one hand, two-dimensional hand drawing is crucial not only for the geometric and constructive control of structural and architectural solutions, but also for their communication to the client. In this regard, Nervi observes: "The graphic presentation of an architectural idea is a difficult and imperfect matter. Drawing is always a very unfaithful interpreter of architectural reality; only the designer is able

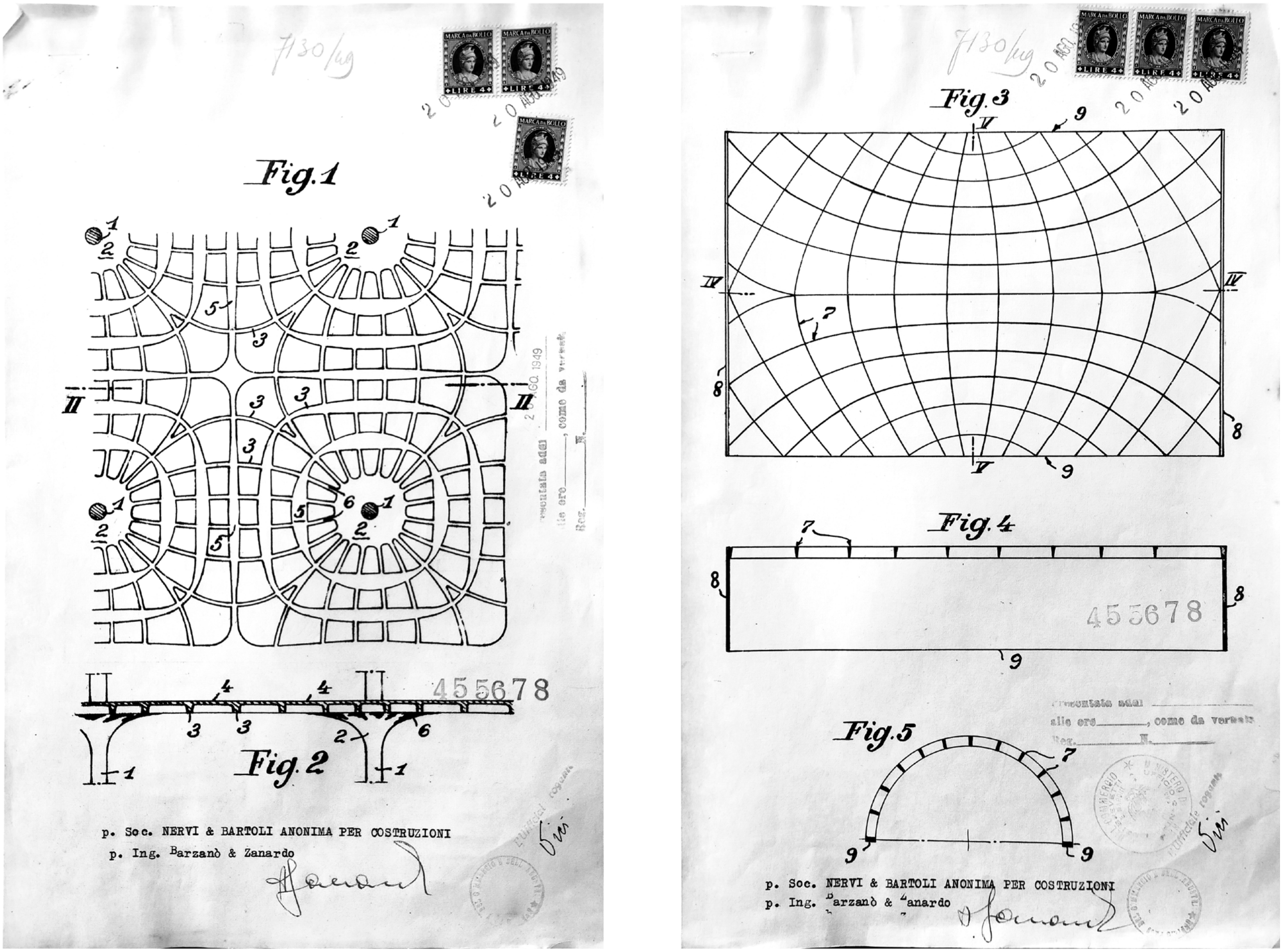
*This article was written upon invitation to frame the topic, not submitted to anonymous review, published under the editorial director's responsibility.*

to materialize it through mental procedures, comparisons, or references that are entirely personal and not communicable. […] One should therefore consider how difficult an architectural choice is, when to all the deficiencies of graphic representation are added the problem of scale […] and the concern arising from the moral and material importance that is always associated with a building" [Nervi 1945].
On the other hand, photography assumes a central role for its communicative impact and for Nervi's international recognition as a designer, functioning both as a tool for documenting the construction process and as a visual archive for future work. As with many of Nervi's innovations, the ribbed floor slabs based on isostatic lines of bending are accompanied by a corpus of drawings and photographs that extends beyond the design phase and the completed work, documenting the entire construction process and providing a graphic record rich in meaning.
To understand the emergence, at the end of the 1940s, of ribbed floor slabs laid out according to isostatic lines of bending within Nervi's design vocabulary, it is necessary to consider briefly the multiple factors that shaped their genesis: Nervi's design philosophy, the technical-scientific context, the contribution of engineer Aldo Arcangeli (1916-2000), and the constructive possibilities afforded by the historical period [Iori 2012; Halpern, Billington, Adriaenssens 2013; Neri 2014; Gargiani, Bologna 2016; Lembo 2026].
As early as 1945, in *Scienza o Arte del Costruire?*, reflecting on the relationship between architectural form and the potential of new materials, Nervi responds to the fear of a spiritual impoverishment brought about by technology in the following terms: "Approaching with modesty the mysterious laws of nature, striving to interpret them, and that 'commanding by obeying' which is the only way to place their majestic eternity at the service of our limited and contingent purposes, contains a profound poetry, capable of being translated into forms of high aesthetic and artistic expressiveness" [Nervi 1945].
From this perspective, structural form is never arbitrary, but derives from an understanding of static mechanisms and from their correct interpretation. This principle finds a more explicitly operative formulation in 1951: "I believe I can affirm that, for reinforced-concrete floor slabs with uniformly distributed loads, the standard solution has already been identified. It consists in the arrangement of the ribs along the isostatic lines of the principal moments: a layout proposed and theoretically studied by one of my collaborators, engineer Aldo Arcangeli, and made concretely feasible by a particular construction process of my own devising, which allows ribs of any shape to be executed without appreciable variations in cost. The isostatics are in fact the preferential lines of force flow within a solid, and concentrating the resistant material along them guarantees maximum structural efficiency. These lines depend solely on the system of acting forces, and our only possibility is to discover and exploit them, certainly not to modify them" [Nervi 1951].
Between the theoretical statement of 1945 and the applied formulation of 1951 lie the patents filed in 1949, from which the translation of the principle of isostatic lines into a construction system effectively begins.

## The 1949 patents

Patent no. 455678, entitled *Improvement in the construction of slabs, vaults, domes, wall-beams and load-bearing structures in general, of two or three dimensions, with the arrangement of resisting ribs along the isostatic lines of bending moments or normal stresses*, was filed on 23 July 1949 by the company Società Ing. Nervi & Bartoli in the name of engineer Aldo Arcangeli. At that time, Arcangeli collaborated closely with Pier Luigi Nervi both as an employee of the Nervi & Bartoli construction firm and as an assistant at the Faculty of Architecture of the University of Rome La Sapienza. The patent summarizes the theory of isostatic lines, identifies its possible fields of application, and emphasizes the economic advantages deriving from the concentration of resisting material along these lines [Arcangeli 1949] (fig. 1).
On the same day, 23 July 1949, Pier Luigi Nervi filed patent no. 455750, the third supplementary patent to the main patent no. 406296 of 15 April 1943, entitled *Improvement in the construction of reinforced-concrete slabs, plates and other cementitious structures*. This supplementary patent concerns a specific application of the construction method described in the main patent and in the two previous supplements, relating to the preparation of ferrocement formwork and moulds for casting slabs, columns, and reinforced-concrete structures, as an alternative to traditional timber formwork. As explicitly stated in the patent text, although the system is illustrated with reference to slabs with intersecting ribs, it is independent of the geometry of the ribs, which may be straight or curved and arranged in one or more directions according to structural requirements, without altering the conceptual or constructive substance of the method [Nervi 1949] (fig. 2).

*Fig. 1. Patent n. 455678, 23 July 1949, Società Nervi & Bartoli, inventor A. Arcangeli (Archivio Centrale dello Stato).*



In summary, while the patent filed in Arcangeli's name sets out the theoretical foundation of isostatic lines, identifies their possible applications, and highlights their economic advantages, Nervi's supplementary patent provides an effective construction method for their realization, making both the monolithic character of the finished structure and formal freedom practically achievable.

## Theoretical context

In order to clarify the scientific foundations of the proposed innovation, it is appropriate to briefly recall some principles of solid mechanics that constitute its theoretical premises.
In solid mechanics, the state of stress induced by mechanical actions within a body is described by the Cauchy stress tensor, which depends on the point considered and on the normal to the plane on which the stress acts. When referred to an intrinsic coordinate system, each plane orientation is associated with one normal component and two tangential components. The planes on which purely normal stresses act are known as principal planes; the mutually orthogonal normals defining them constitute the principal directions. The envelope of the principal directions at each point of the body defines three mutually orthogonal families of curves, known as isostatic lines. Along these lines, only axial stresses (tensile or compressive) act, attaining extremal values with respect to the normal stresses acting on the pencil of planes passing through the point.
When one dimension of the body is much smaller than the other two, the problem may be referred to the mid-surface (thin plates and shells), on which the isostatic lines reduce to two orthogonal families of curves. Similarly, for two-dimensional bodies subjected to bending –such as plates and shells in bending-dominated regimes– the previous concepts remain valid provided that normal and tangential stresses are replaced by bending and twisting moments. This leads to the definition of principal moments and their trajectories, or bending isostatic lines, along which pure bending acts in the absence of torsion. Their configuration depends on the geometry of the body, the loading conditions, and the nature and arrangement of the restraints.
The tracing of bending isostatic lines is governed by a first-order differential equation, expressed as a function of bending and twisting moments, which, within classical thin-plate theory, are derived from the integration of the biharmonic equation of the elastic surface. Exact solutions, however, are

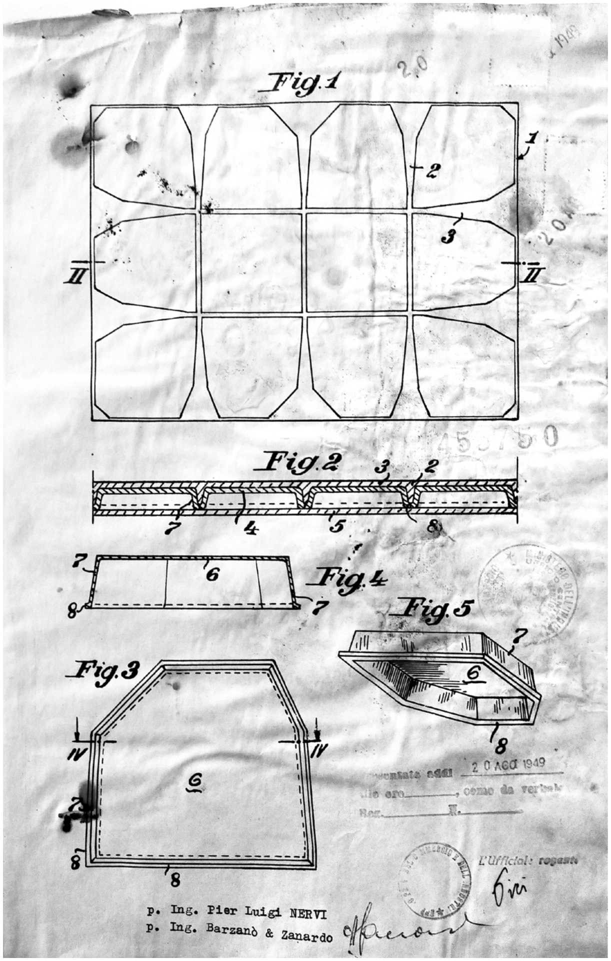
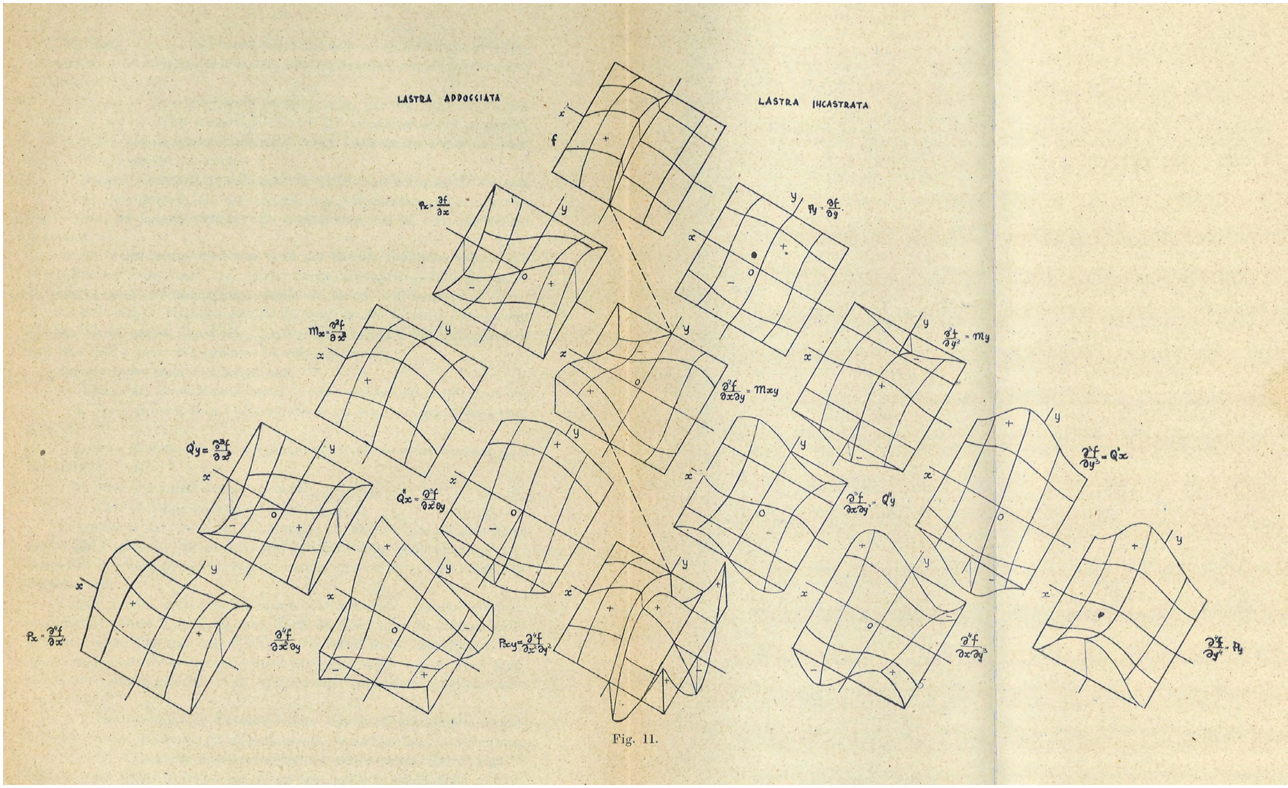



*Fig. 2. Patent n. 455750, 23 July 1949, Pier Luigi Nervi (Archivio Centrale dello Stato).*

*Fig. 3. Surfaces of the derivatives of function 'f', plate vertical displacement. (Kambo 1944, p. 34).*



limited to a small number of canonical cases. The principal methods available in the postwar period provided solutions only for simple configurations commonly encountered in practice [Belluzzi 1947], expressed in double trigonometric series (Navier), simple hyperbolic series (Lévy-Estanave), or through finite-difference methods (Nielsen, Marcus). These were complemented by attempts to reduce the analytical burden, such as Kambo's method of arbitrary solids [Kambo 1944], according to which bending isostatic lines may be derived from the surfaces of the third row in figure 3 and from the 'curvature circle' (Mohr's circle).
Arcangeli could therefore rely on a limited set of analytical solutions and on tabulated numerical results for selected canonical cases; his handwritten calculation notes reveal a familiarity with the solution expressed in simple hyperbolic series presented in Nadai's treatise [Nadai 1925] [1]. Figure 4 shows sketches by Aldo Arcangeli referring to the case of a plate simply supported along all edges and clamped at the four corners [Lembo 2026].
In response to the limitations of theoretical analysis –already highlighted in the early twentieth century by the groundbreaking design possibilities offered by reinforced concrete– many engineers systematically turned to experimental methods. This approach, which places Nervi alongside key figures of twentieth-century structural architecture [Chiorino 2010], took concrete form in his collaboration with the *Laboratorio Prove Modelli e Costruzioni*, founded by Arturo Danusso at the Politecnico di Milano.
In the seventh chapter of *Costruire correttamente* [1955], Nervi emphasizes the superiority of experimental methods for understanding the actual static behaviour of load-bearing systems, focusing in particular on strain-gauge and photoelastic techniques. The theoretical framework within which these methods operate is clarified by Enrico Volterra, who as early as 1930 introduced photoelasticity as a means of "seeing what manifests itself inside a structure subjected to external forces", likening it to the use of Roentgen rays in medicine [Volterra 1930]. It is plausible that Nervi's interest in these methods was also fostered by the applications carried out by Danusso together with his pupil Guido Oberti from the early 1930s onward [Danusso 1932], perceiving in them, as he himself writes, "the beauty and poetry of this transformation of states of stress into plays of light […]" [Nervi 1955]. Nervi's interest in photoelasticity, documented by images preserved in the Studio Nervi archives and published in *Costruire correttamente*, is to be understood within this context.

*Fig. 4. Drawings of square plate flexural isostatic lines for different boundary conditions: top, simply supported sides; bottom, simply supported corners Archivio Arcangeli, Roma, Fascicolo A 237.*

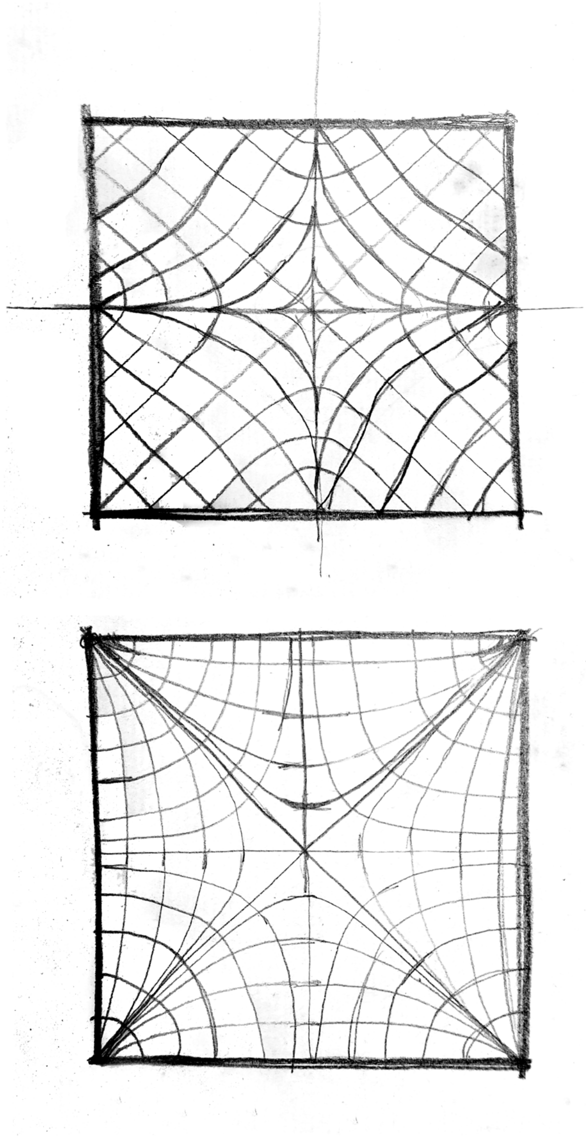
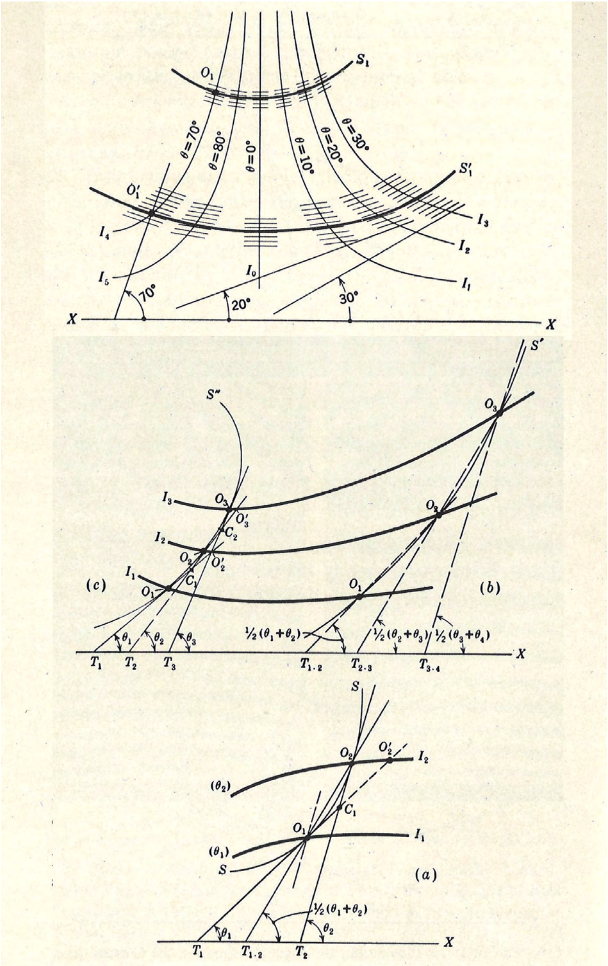
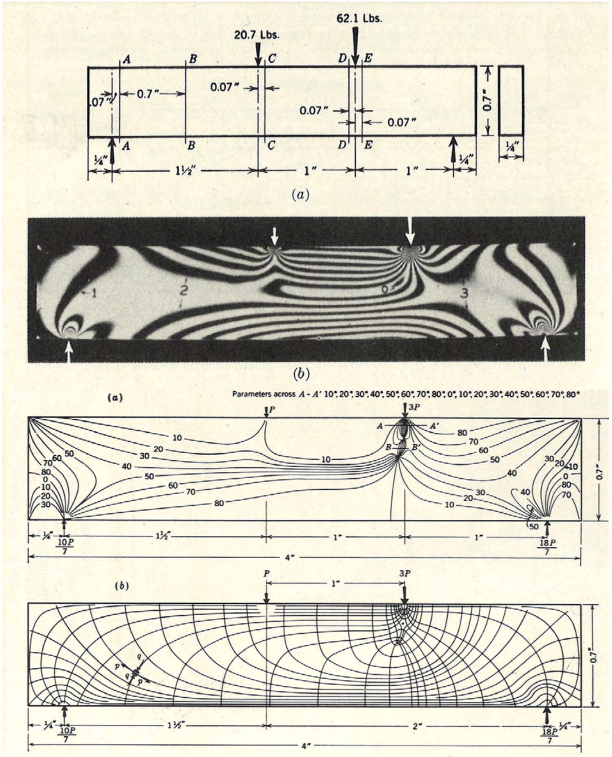


*Fig. 5. Alternative schematic methods for deriving isostatic lines from isoclines: Frocht M. 1941, pp. 199, 200.*

*Fig. 6. Experimental setup, photoelastic analysis, isoclines and isostatic lines: Frocht 1941, pp. 258, 259.*



The method allows for an immediate visual representation of the internal stress state of a body: the network of isoclines provides the orientation of the principal stresses, while that of the isochromatics conveys their relative intensity. From photographed isoclines, the layout of the isostatic lines can be reconstructed through graphic procedures (figs. 5, 6) [2]; the determination of the individual principal stresses, by contrast, requires integrative methods such as Mesnager's method or graphical integration based on Maxwell's formulas.
Within this framework, experimentation does not so much constitute a direct operational design tool [3] as a cognitive device capable of orienting the understanding of stress flows and of nourishing, on a graphical level, the construction of structural schemes consistent with the actual behaviour of structures.

## The application context

The proposal of ribbed slabs arranged according to bending isostatic lines is embedded within the broader development of reinforced concrete slabs, which began as early as the late nineteenth century. From the Monier slab (1869) to the Hennebique systems with primary and secondary ribs (1898), and further to the mushroom-type slabs developed by Turner (1907) and Maillart (1908), the evolution of reinforced concrete slabs was accompanied by an intense production of patents aimed at transforming pioneering experiments into consolidated construction practices. Although structurally effective, these early solutions soon revealed limitations related to self-weight, material consumption, and acoustic performance.
Research initially focused on reducing slab thickness through the densification of secondary ribs, and subsequently on replacing concrete in the tensile zones with lighter materials, such as hollow clay units. Systems with lightweight infill elements placed below the neutral axis, between parallel or orthogonally intersecting ribs, thus became widespread, progressively supplanting reinforced concrete slabs with exposed ribs. Among the double-joist systems, those developed by Bollinger (1902) and Danusso (1911) are particularly noteworthy.
It is within this context that Nervi's professional career began. In 1913, he joined the Società Anonima per Costruzioni Cementizie of Professor Attilio Muggia (1861-1936), holder of the Hennebique patent concession for Emilia-Romagna and the Marche. Technical innovation immediately became a defining feature of his work. The constructional refinement described in the 1949 supplementary patent represents the outcome of a long trajectory of experimentation [Greco 2008]. Within this framework, structural drawing assumes the role of a control instrument for an advanced construction process, in which prefabrication makes it possible to achieve levels of technical complexity and formal refinement that would have been difficult to attain through cast-in-place concrete and traditional timber formwork. The 1949 supplementary patent, for example, describes a system of ferrocement formwork arranged on a lowering and sliding scaffold, allowing for formwork removal and progressive reuse of the moulds in the construction of large-span slabs composed of repetitive bays, thereby optimizing construction time, costs, and execution quality.

*Fig. 7. Plan and section of the Lanificio Gatti basement floor: Lembo 2026, p. 138.*

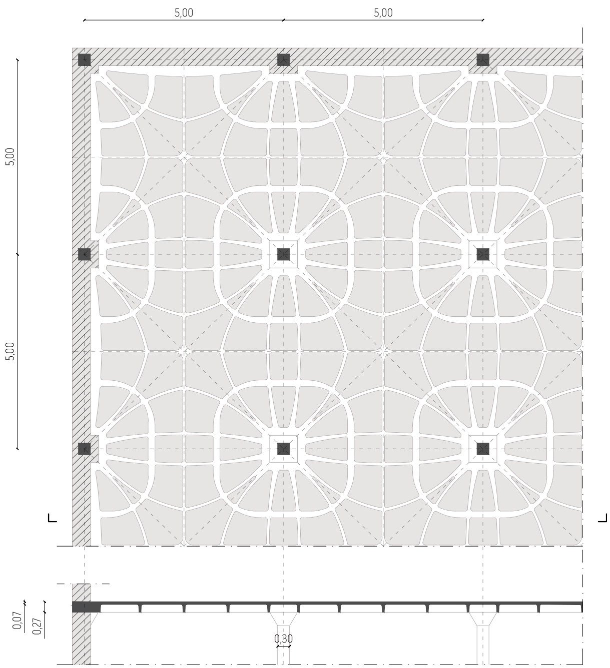
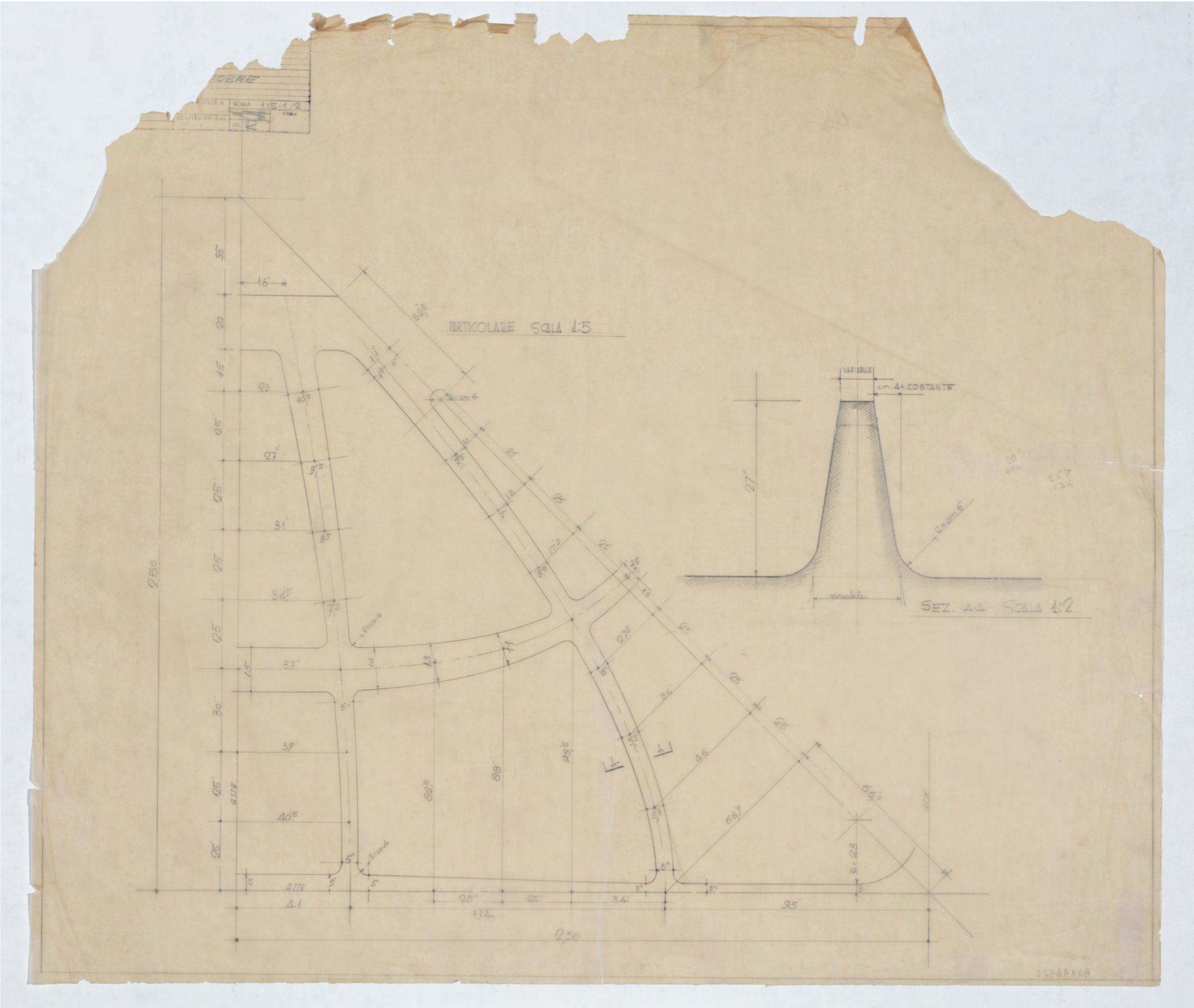


*Fig. 8. Tracking of the axes and thicknesses of the ribs of the Lanificio Gatti basement floor (Parma, CSAC).*



## Projects and built works

From the very first applications of the solutions patented in 1949, it became evident that a strict adherence to the isostatic bending lines was impossible. In the transition from a continuous plate to a ribbed floor composed of a slab and ribs, the geometry of the original plate is necessarily altered, and with it the arrangement of the isostatic lines. In addition, the boundary conditions may vary between the construction phases and the final configuration. Consequently, as noted by Mario Desideri, regardless of the accuracy with which these trajectories are determined, the slabs are always ribbed slabs 'inspired' by the isostatic bending lines rather than an exact transposition of them [Castelli, Del Monaco 2011]. This awareness does not hinder the adoption of this solution, initially proposed as a variant of the traditional orthogonal rectilinear grid and progressively established as an independent choice, eventually requested by clients.

Over approximately thirty years, from the late 1940s to the late 1970s, Pier Luigi Nervi and the Nervi Studio designed and built numerous ribbed floor slabs that, in various ways, can be traced back to the isostatic bending lines. These structures refer to slabs of very different sizes, shapes, boundary conditions, and loadings, for which the ideal isostatic configurations assume highly variable geometries. Beyond the designer's formal intentions, the exact identification of such lines was limited both by the theoretical knowledge and computational tools available and by practical construction constraints. The proposed solutions, whether realized or remaining at the design stage, can therefore be interpreted as compromises between theoretically infinite geometries and construction constraints, resulting in a wide repertoire of variations on a theme, reflected in the variety of drawings required for their definition and execution. A measure of the 'distance' between the ideal isostatic lines and the ribs as actually built can be effectively assessed through the magnitude of torsional moments [Lembo, Bologna, Romeo 2024].

Once the configuration of the ribs was determined, the design of reinforcement for bending and shear was carried out by considering each rib as straight, with a span equal to the curve's development and semi-fixed end restraints, neglecting torsional effects, which were counteracted by the intersecting ribs. Loads, calculated according to influence areas, were conservatively assumed to be concentrated at the intersection points.

*Fig. 9. Reinforcement of the side panels of the floor of the Lanificio Gatti (Parma, CSAC).*

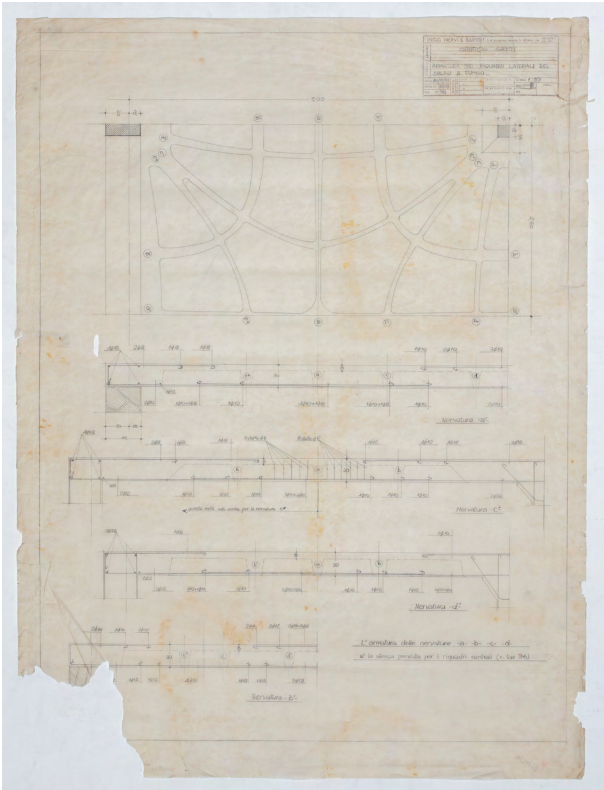


*Fig. 10. Close-up photograph of the ribs of the ceiling of the Lanificio Gatti (photo @ Matteo Cirenei).*

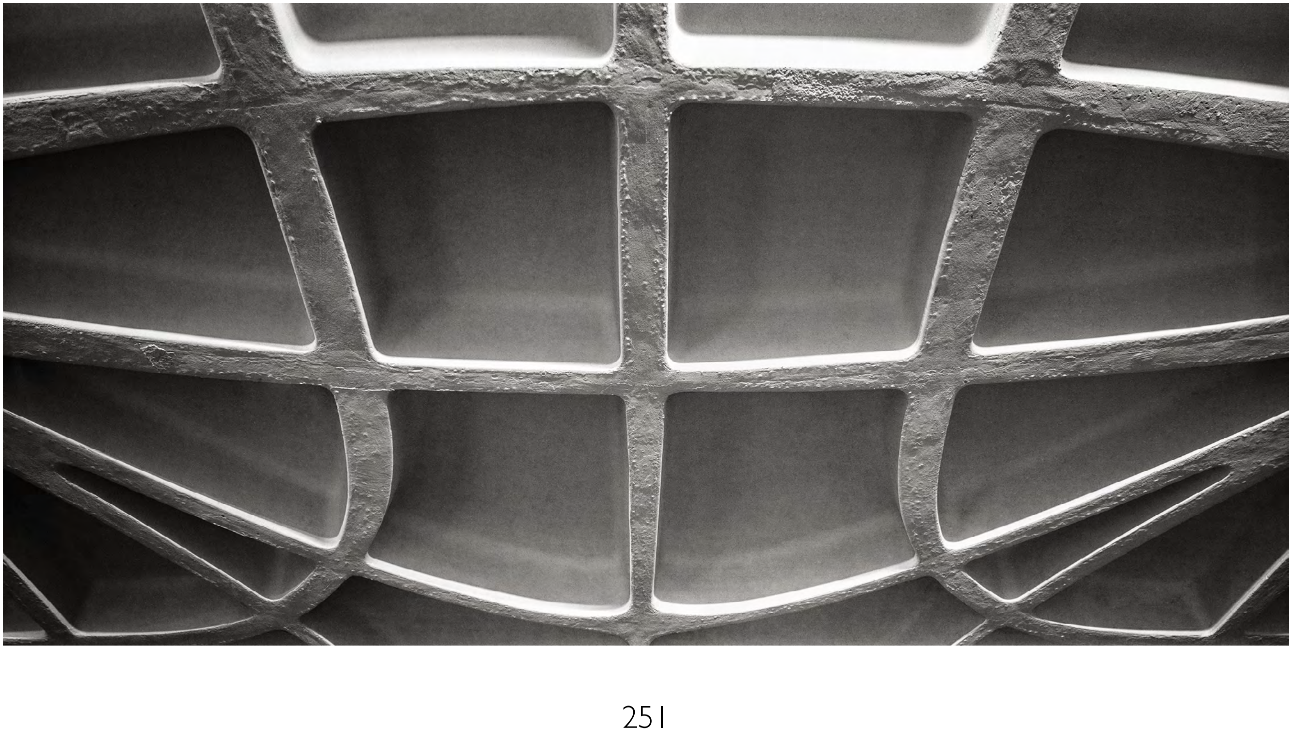
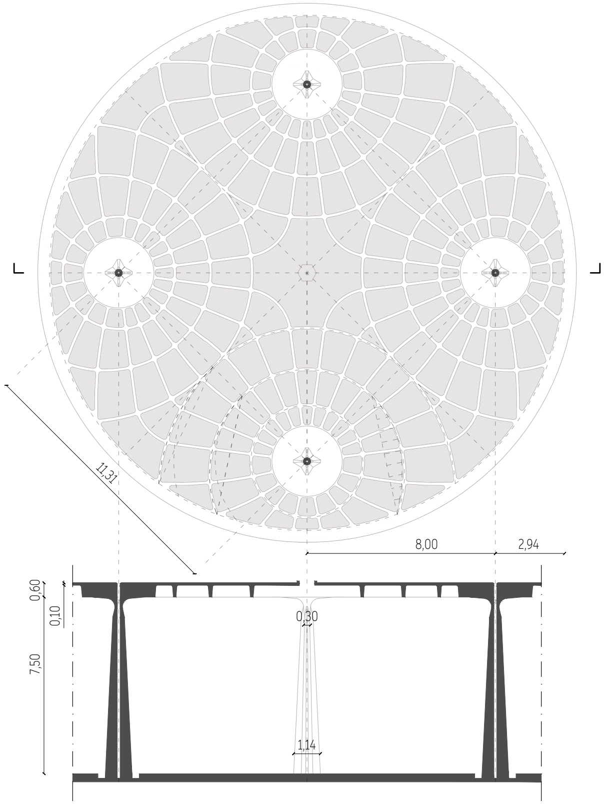
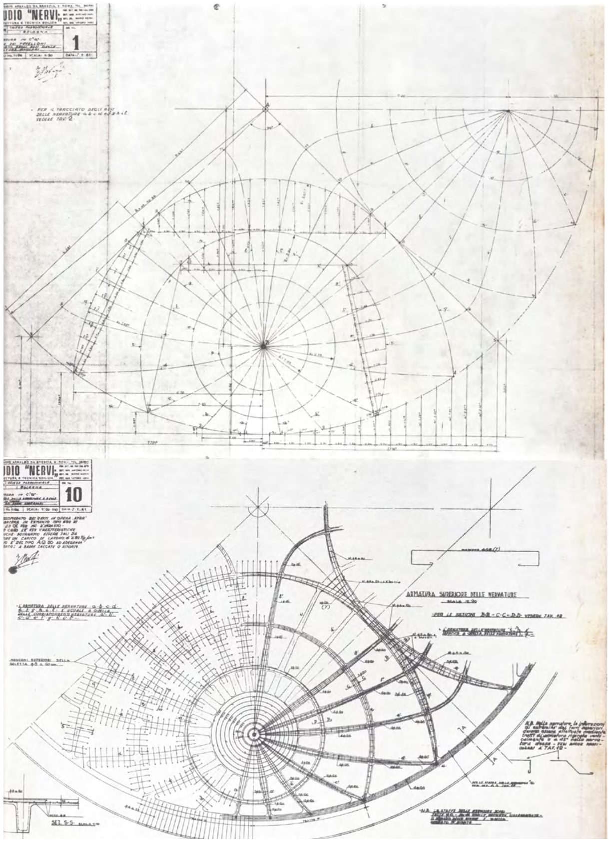


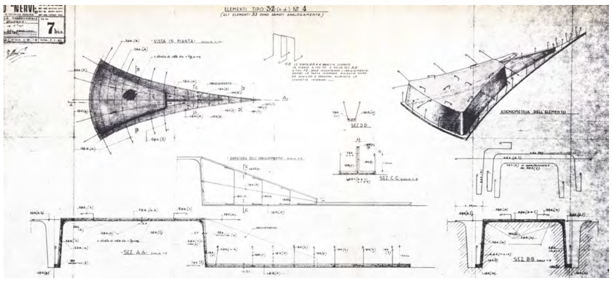
Fig. 11. Plan and section of the roof of the church Cuore Immacolato di Maria in Borgo Panigale: Lembo 2026, p. 155.

Fig. 12. Tracking of the axes and reinforcement of the ribs of the roof of the church Cuore Immacolato di Maria in Borgo Panigale: Nervi 1961.

Fig. 13. Roof of the church Cuore Immacolato di Maria in Borgo Panigale: ferrocement 'tavelloni' (type 32): Nervi, Vaccaro 1961.



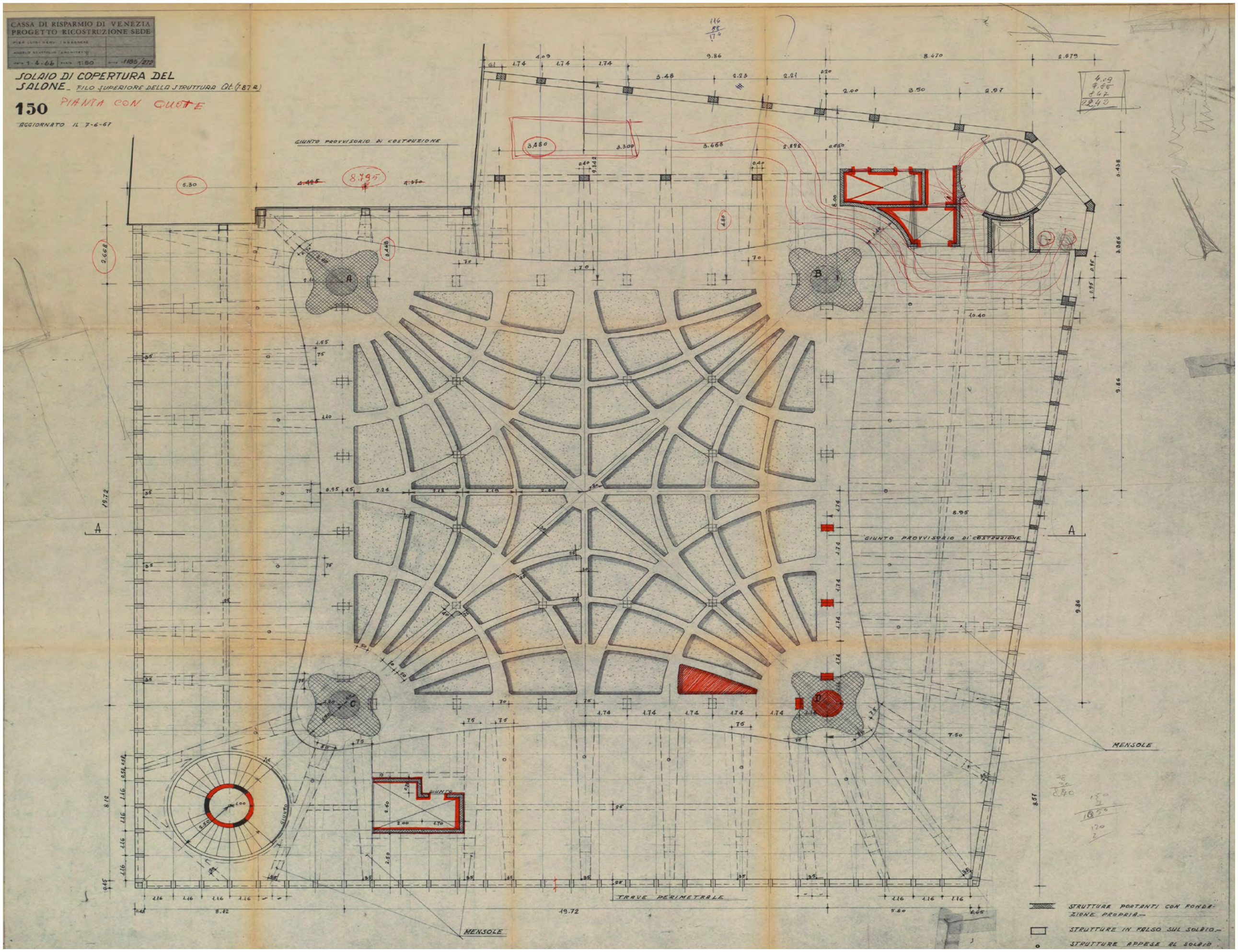





The first applications using ferrocement formwork date to the early 1950s: the Manifattura Tabacchi in Rome (1951), with a central square bay and a lateral rectangular one, and the unbuilt variant of the slab on a rectangular grid at the Magazzino ballette of the Manifattura Tabacchi in Bologna. The same period also saw the Lanificio Gatti (1951-1953), designed with Carlo Cestelli Guidi (1906-1995), featuring the basement slab based on a 5 × 5 m square grid, repeated over 6 × 15 bays (fig. 7).
The design of the ferrocement formwork, together with the corresponding template shown in figure 8, refers to the minimum module, which, due to double symmetry, reduces to an isosceles triangle equal to one-eighth of the square. The formworks corresponding to a bay framed by four columns are mounted on mobile scaffolding, following a technique previously tested for the slab at the Magazzino ballette. The plan layout of the ribs is partly derived from the square slab with central restraints and partly from the slab supported at its four corners, while the variable cross-section follows the distribution of the internal forces [Lembo 2026]. As shown in figure 9, the ribs are reinforced for positive bending moments at midspan and negative moments near the alignments between the columns, where starter bars ensure continuity between adjacent spans (fig. 10). These initial experiences were followed by the trapezoidal canopy at the north entrance of the UNESCO Secretariat (1952-1958), executed with timber formwork.
Among the numerous subsequent works, the circular roof supported by four columns at the Church of the Cuore Immacolato di Maria in Borgo Panigale (1957-1962), designed in collaboration with Giuseppe Vaccaro (1896-1970) (fig. 11), stands out for its geometry. For this roof, with a radius of 11 m, 59 negative mould were produced on the ground using masonry blocks finished externally with plaster (fig. 12); these moulds, corresponding to a single quadrant of the roof, were then used to cast the ferrocement '*tavelloni*' (fig. 13), whose execution quality defines the intrados of the roof (fig. 14).

*Fig. 14 Photograph of the underside of the roof of the church Cuore Immacolato di Maria in Borgo Panigale (photo @ Matteo Cirenei).*

*Fig. 15. Roof covering the hall of the Cassa di Risparmio di Venezia (Parma, CSAC).*



Other significant works followed in the 1960s: the perimeter slab composed of trapezoidal panels at the Palazzo dello Sport in Rome (1958-1960), the square-grid slab of the first mezzanine of the Palazzo del Lavoro in Turin (1959-1961), and the slab of the headquarters of the Cassa di Risparmio in Venice (1963-1972) (fig. 15). For the latter, of particular structural relevance due to its size and loading, an experimental investigation was carried out at ISMES (Istituto Sperimentale Modelli e Strutture - Experimental Institute for Models and Structures) in Bergamo on a 1:25 scale model, confirming the conservative approach adopted in the manual calculations.
Alongside these works, a series of projects followed in which the ribs, while maintaining a curvilinear layout, progressively lose reference to the flexural isostatic lines and the genuine role of 'deep decoration' [Rappaport 2006]. This occurs both geometrically, with the orthogonality between the two families of curves being violated (projects for the Cultural Center in Tripoli, the Sports Center in Kuwait, the MLC Center tower in Sydney, and the branch of the Bank of Italy in Cosenza), and structurally, when boundary conditions are disregarded or when the slab is reduced to a mere ceiling, as in the case of the Aula delle Udienze Pontificie in the Vatican (1963-1971).

## Conclusions

Ribbed slabs based on flexural isostatic lines demonstrate how drawing can translate theoretical principles into buildable and expressive solutions. The geometry of the ribs emerges from the interplay between scientific rigor and a visual reading of force flows, which informs the form. Although the ideal trajectories are never followed rigidly, drawing makes static intuitions operative and allows complex solutions to be controlled. In Nervi's work, structural form is thus shaped through a cognitive process in which theory, vision, and construction converge, establishing drawing as a central instrument of design.

### Notes

[1] It is interesting to note that Arcangeli's notes, alongside the analytical series solution for determining the bending and torsional moments of the square slab in the mid-span, there is an indication for the approximate calculation of negative moments for mushroom-shaped floors in the area adjacent to the pillars, which considers a circular plate with a radius equal to 1/5 of the side loaded with the distributed load and an upward reaction at the centre: Nadai 1925.

[2] To determine isostatic lines, graphical procedures based on isoclines are used, which are equivalent to the graphical solution of differential equations starting from the values of the derivatives.

[3] Nervi used the photoelastic method in 1965 for the Motta Grill project in Limena to deduce the stress state in the large wall beams characterised by 13 octagonal openings of varying sizes: Neri 2014.

### Author

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