PIER LUIGI NERVI'S COLUMNS: FLOW OF LINES AND FORCES

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Editor's Note: Manuscript submitted 20 May 2013; revision submitted yy Month 2013; accepted xx Month 2013.This paper is open to written discussion, which should be submitted to the IASS Secretariat no later than March 2014.

ABSTRACT

The paper presents a detailed study of the columns in Pier Luigi Nervi's architecture. Geometrical analyses highlight the columns' complex formal gestures, such as the recurring use of ruled surfaces, as key in meeting the essential principles of structural architecture. The study links geometry articulations to functional, static, technological and economic considerations in six projects. Nervi's possible relationship with contemporary technological advancements is also reflected upon to enhance understanding of his design approach.

Keywords: *Nervi, columns, structural architecture, ruled geometry, parametric modeling, reinforced concrete*

1. INTRODUCTION

The union between art, science and craft was championed in Pier Luigi Nervi's prolific career. Indeed, his works must be read using what himself termed as the "vocabulary of architectural speech": materials, functional needs, statics, construction technology and economic efficiency [1].

This paper centres its attention on the columns in Nervi's buildings, exploring how the founding principles of structural architecture have been applied to these elements. The aim is to complement the available literature that celebrates Nervi's domes and thin-shell structures by investigating the solutions adopted for their supporting members.

The study analyses a number of representative projects whose column geometries are modeled through 3D parametric software. This process of geometrical analysis, underpinned by research of direct and indirect archive data, unravels distinctive features and supports structural design speculations. Investigation of project records and photographs also highlights the construction technologies adopted.

2. STRUCTURAL ARCHITECTURE

The relationship between art and science, aesthetic and engineering in architecture has been subject of debate for centuries. Nervi's view is clear from his writings and works: he deplored the art-engineering split and named himself as *Architect*, referring to the holistic notion of the term and breaking with the modern belief on specialism [2]. Huxtable further argues that Nervi re-established architecture as primarily a structural art, where buildings are an "incontrovertible fusion of science and art" [2].

Nervi distanced himself from the traditional aesthetic formalism and fully embraced the structural architecture movement [1]. This emerged with the development of theories of structural analysis, with the introduction of steel and concrete as new construction materials, and with the emergence of structures of ever increasing size [1]. The "three essential problems" – structural, constructional and architectural – found unique synthesis in the design and were addressed simultaneously [3]. Indeed this was direct expression of Nervi's experiences and duties as engineer, architect and builder.

Great emphasis was given to the rightness of buildings – *costruire correttamente* – to "build correctly", underlying Nervi's philosophy that encompassed functional, technical and economic essence of structural architectures [4]. These were "necessary and sufficient conditions" for aesthetic of results [4] in what Nervi considered the "mysterious connection between laws of physics and aesthetic sensibility" [3]. Such link was crafted by the designer in the initial intuitive phase defining structural architectures; the stage in which individual problems were addressed without formal preconceptions and resorting to static intuitions [1].

Nervi intuitions found seamless synthesis of engineering, architecture and building technology without keeping them "artificially separated" [3] in the project process. As consequence, the design flow distinguished from the contemporary one where aesthetic and function determine geometry and, only subsequently, structural analysis addresses static needs. Indeed the geometry was defined considering the static (as well as function and construction) from inception. Nervi's geometrical forms were the correct and appropriate solutions resulting from the individual problem as opposed to architectural formalism established by initial aesthetic concepts [5].

3. COLUMNS ANALYSIS

This study considers six representative projects (presented in §3.1 Table 1) and it unravels their columns' features while highlighting how Nervi simultaneously addressed structural architecture's essential traits. Firstly the architectural forms are explored, evaluating the columns' visual and geometrical features in §3.2 and classifying them in §3.3. Subsequently the structural characteristics are considered with analyses of the mechanical behaviour in §3.4. Finally, the construction technologies adopted to erect the columns are researched and illustrated in §3.5.

3.1 Case Studies

The case studies analyzed are listed in Table 1.

Table 1: *Project case studies analysed.*

<u>UNESCO Secretariat building – Paris 1952</u> Plans for the three headquarters buildings were prepared jointly by Breuer, Nervi and Zehrfuss. They were approved by an international panel of five architects: Costa, Gropius, Le Corbusier, Markelius and Rogers. It is the first of Nervi's projects to include complex geometry columns.
<u>New Norcia Cathedral – Perth 1958</u> The project for a large capacity cathedral building in rural Western Australia was advanced to detail design by Nervi and his architect son Antonio but not built. The hall is covered by a tripartite parabolic vault laid on an equilateral triangle 35m in length and supported by three columns.
<u>Palazzo dello Sport – Rome 1958-60</u> The multi-purpose arena was designed by Prof. Piacentini and Nervi for the 1960 Summer Olympics. The building, constructed by Ingg. Nervi & Bartoli, comprises a 100m diameter spherical dome supported by 48 radial columns.
<u>Corso Francia viaduct – Rome 1959</u> To facilitate access to Rome from the north, Corso Francia viaduct was built as part of the 1960 Summer Olympics infrastructures. Nervi followed the design and construction (Ingg. Nervi & Bartoli) for the 1km long dual carriageway viaduct which is supported on columns in its entire length.
<u>Railway Station – Savona 1959-61</u> Nervi won the Ministry of Public Works competition to design and construct the new railway station. The project was redacted jointly with his son Antonio. The station comprises of two buildings housing separate functions and supported on elaborate columns.
<u>Palazzo del Lavoro – Turin 1959-61</u> The vast hall was constructed for the Italia'61 Exhibition celebrating the Centenary of Italian Republic. Ingg. Nervi & Bartoli won the design and build competition proposing an innovative scheme to meet the tight programme. Sixteen structurally separate square roofed sections are supported on 25m-high concrete stem columns.

3.2 Geometry

In terms of their geometrical articulation, Nervi's columns exploited the formal and constructive advantages of ruled surfaces − i.e. surfaces that are defined by the movement of a straight line in space. In addition, a number of these surfaces are specifically hyperbolic paraboloids [6], with the inherent benefit of being doubly ruled.

In relation to the role geometry played in the exploration and description of form, Nervi's use of hyperbolic paraboloids seemed to deploy the legacy of some of Antoni Gaudí's work, see Figure 1. In the Colònia Güell Crypt, for instance, the Spanish architect made extensive use of the hyperbolic paraboloids for the columns' geometry in order to find "the most efficacious structural minimalism" [7]. Made out of brick and stone, the columns' configuration in this building resulted from the employment of funicular models to study the transfer of loads in the structures − a performative use of ruled geometries which would be further investigated by Nervi.

Figure 1. *Portico of Colònia Güell Crypt, Antoni Gaudí, Barcelona, 1898-1915 [8]*

Although different in typologies, this research shows how Nervi's columns shared strategic design logic. Figure 2 presents illustrations of the geometrical articulations used in the six case study projects.

Taking Palazzo dello Sport in Figure 3 as reference, firstly the geometry of both base and capital profiles were set (two orthogonally-oriented rectangles). Secondly these shapes were divided into sub-segments or sub-curves (eight segments for each rectangle). Thirdly homologous points were defined along the resulting curves (each segment divided into a number of points). Finally, ruled surfaces were traced by connecting the homologous points through straight lines or, alternatively, by moving a straight line along continuous points (each pair of homologous base and capital segments defined directrices of a hyperbolic paraboloid).

The employed generative method, coupled with creative design variations, also implies that most of Nervi's columns were characterized by a combination of both ruled and planar surfaces, resulting in meaningful interplays between curved geometries and straight profiles. In fact, from a purely geometrical point of view, generating a form by directly connecting the base and top profiles would have resulted in complex surfaces – difficult to conceptualize, and surely to represent without the help of digital tools.

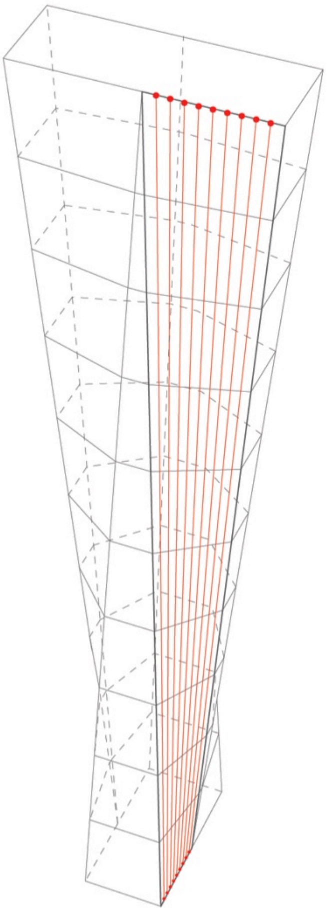


Figure 3. *Geometric construction of hyperbolic paraboloids in the Palazzo dello Sport's columns*

In addition, the logics of symmetry that characterized most of Nervi's columns also imply each column was often made up of a single ruled surface repeated four times and coupled with planar surfaces. This solution reduced the difficulties of building the ruled-geometry wooden formworks and required the use of straight planks only.

Nervi's design strategy of geometric manipulation could therefore be defined as *rational complexity*, turning the constraints related to the means of representation into design opportunities for enhancing both the structural and construction qualities of concrete-based hyperbolic paraboloids.

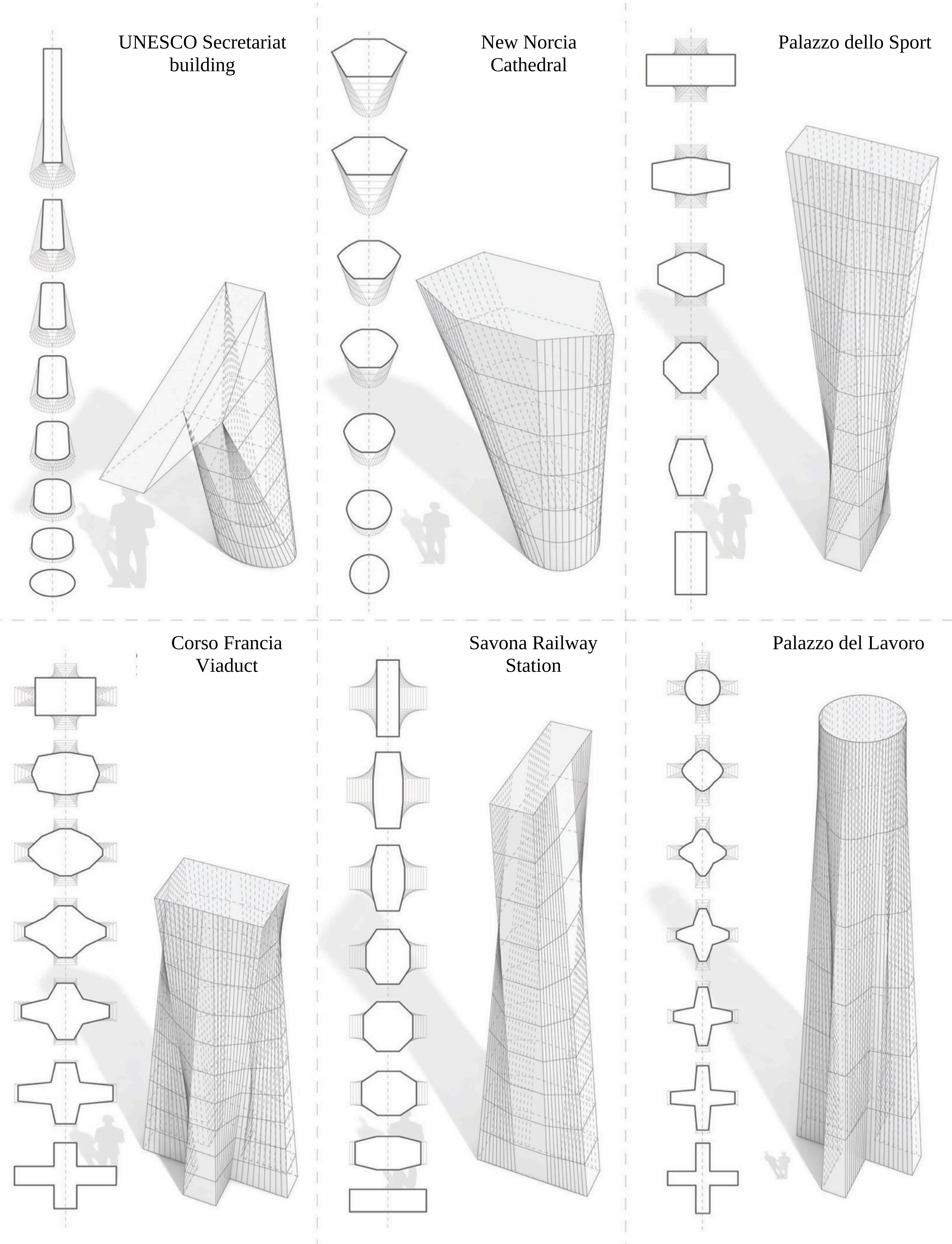


Figure 2. *Columns geometrical articulations in the six case-study projects*

3.3 Taxonomy

A proposed taxonomy of the column geometries is based on two features used by Nervi to define the volumes: variation of cross-sectional shape (WCSP) and revolution of the principal inertia directions (TWIST). Both are inspired by static considerations, refer to §3.5, and take full advantage of the concrete material's plasticity freeing these artefacts from the prismatic rigidity of vertical stone and masonry elements [9]. Figure 4 shows how Nervi selectively adopted WCSP and TWIST on individual projects.

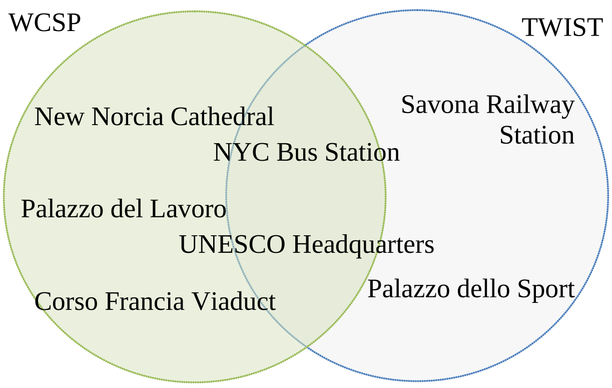


Figure 4. *Use of WCSP and TWIST in Nervi's projects*

With the use of WCSP Nervi "puts the material where it works best" [10] and splays volumes between two faces of regular shapes. This is a geometrical expedient proposed in many projects: cruciform to rectangular columns in Corso Francia viaduct; circular to hexagonal in New Norcia Cathedral; cruciform to circular in Palazzo del Lavoro.

TWIST consists in a progressive variation of principal inertia directions along the main axis of the column, resulting in base and capital oriented orthogonally to each other. Examples are the Palazzo dello Sport and Savona Railway Station buildings with their prismatic columns twisting as they rise. Mateovics suggests similarities between Nervi's TWIST and mannerist columns [11]. Indeed there is symbolic analogy amid the imposing pillars that frame the Vatican Audience Hall throne and altar baldachins; however, static and functional needs are herewith proposed as the sole and genuine drivers for the geometry.

Nervi also combined WCSP and TWIST features in some project columns, see Figure 4. As an example, the three wings of UNESCO administration building are supported by piloti columns splayed between longitudinal elliptical bases and transversal rectangular capitals.

3.4 Structural Engineering

As pervasive logic of Nervi's work, the true and appropriate design solution was guided by the singular structural problem [4] and the columns were not an exception to this principle. There was a close duality between form and physical behaviour: the geometry defined the structural model and vice versa. This duality was expressed both at global and local levels for the structure.

Globally, the columns geometries must be investigated as part of the whole architectural system as their forms contributed to the overall true project solution. Nervi was mindful that accurate understanding of structural behaviour led to increased economy of the design [3]. In his project inceptions, he employed intuitive and simplified methods to define the geometry so that fundamental design choices were addressed with static graphic and/or by reducing hyperstatic systems in simpler statically determined ones. Complex analytical calculations and scale model testing came into play only at a later stage and, by Nervi's own accounts, rarely brought significant variations to the projects [4].

In this context, it is likely that Nervi intuition led him to adopt geometries more apt to an immediate understanding of structural behaviour – for example three-pinned arches with their determined line of thrust as opposed to fixed arches [4]. Nervi most likely moulded the columns geometries with global structural models in mind and varied their section, hence the associated moment of inertia, and orientation to gauge better control of the flow of forces. A column with bending stiffness that differs substantially (say at least one order of magnitude) at its extremities could be assumed, in first approximation, as pinned at the less rigid end reducing static indeterminacy. Ideally columns could be reduced to simple struts and angled with the resultant thrust from the form-resistant structures sought-after in many projects.

Following these speculations, the two features introduced in §3.4 can be read as possible geometrical expedients for the variation of columns' stiffness. WCSP creates even (i.e.

positive-positive or negative-negative) variation of flexural rigidity in two transverse directions. Conversely, TWIST produces uneven (i.e positive-negative or negative-positive) change of bending stiffness along the length of the columns. Analyses of 3D column models demonstrate variations of moment of inertia in the projects considered, see Figures 5 and 6.

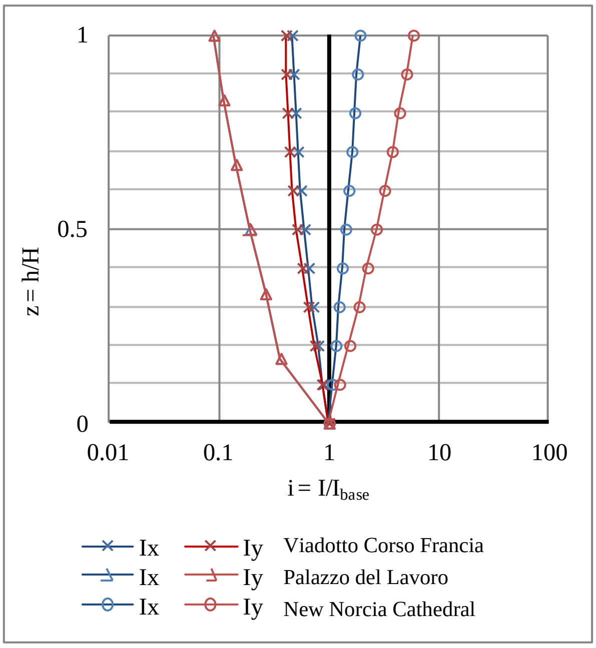


***Figure 5**. WCSP columns: variation of moment of inertia along height*

Figure 5 highlights even reductions or increments of moment of inertia with the height in WCSP columns. Their motives can be understood by analysing the elements' static functions within the global structure. Corso Francia viaduct and Palazzo del Lavoro columns (shown in Figure 7) are cantilever supports and their splayed geometries bring structural efficiency by varying capacity with the bending moment distribution. The racked piers of New Norcia Cathedral project increase inertia as they rise connecting to parabolic arches; their WCSP geometry directs the groined vault's thrust to the foundations with a gradual reduction of the cross section area.

Figure 6 shows bifurcating graphs highlighting uneven variations of moment of inertia in TWIST columns. Again their motivations are fully appreciated by analysing the elements in their structural context. The Savona Railway Station columns form two-pinned frames with both longitudinal and transverse beams [1]. Hinges can be assumed in two directions, at base and top respectively, as result of the geometry revolution. The columns in the Palazzo dello Sport are inclined to follow the resultant of the dome thrust, upper seat bank reactions and side gallery roof weight [1][2], refer to Figure 8. Their TWIST geometry transfers the thrust at the pillar below, while maintaining suitable cross section area. The UNESCO Secretariat building pilotis' geometry aligns with the portal beams at the top creating fixed moment connections, while the base is directed longitudinally originating semi-hinges and freeing the circulation along the building [4].

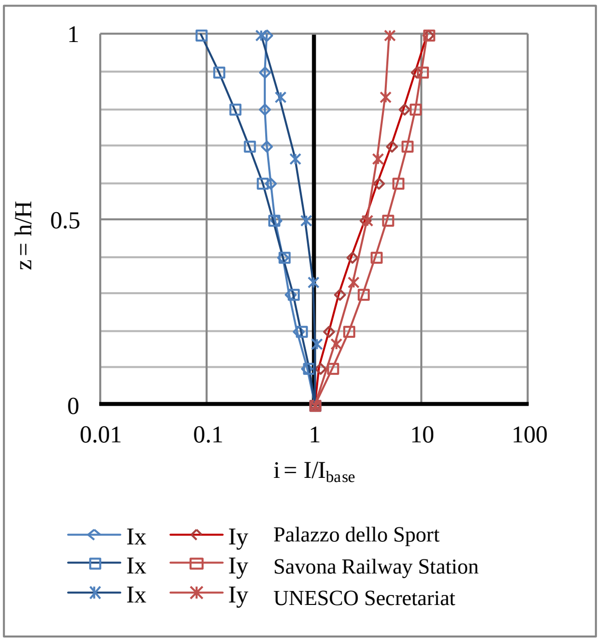
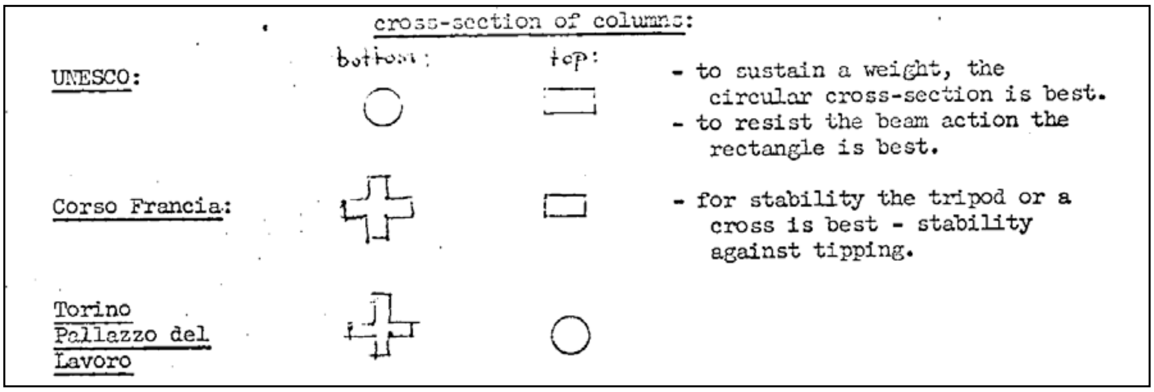


***Figure 6.** TWIST columns: variation of moment of inertia along height*

Local duality between columns' form and physical behaviour was expressed through the use of different shapes to suit the varying forces. This is recorded with great precision in Einaudi's lecture notes [10] as shown in Figure 9. Changes in cross-section are expression of "architectural liberty", and "static considerations" inspired design as opposed to limiting it [10]. The forms adopted were truthful expressions of the three basic static actions [4] and knowledge of mechanic of elastic systems is evident in the consideration of section shapes: circular is best for compression forces; rectangular for bending and shear; cruciform for stability against bending in different directions. It is therefore evident how local duality between form and structure stimulated the creation of splayed column geometries.

Figure 7. *Palazzo del Lavoro stem columns [1]*

Figure 8. *Palazzo dello Sport raking columns [1]*



cross-section of columns:

	bottom:	top:	
UNESCO:			- to sustain a weight, the circular cross-section is best. - to resist the beam action the rectangle is best.
Corso Francia:			- for stability the tripod or a cross is best - stability against tipping.
Torino Pallazzo del Lavoro			

Figure 9. *Extract from Einaudi's Lecture Notes where different column cross sections are examined [10]*

3.5 Construction

The complex column forms required by the "continuous and varied flow of stress" [9] posed challenges to the available technology: only effective and correct solutions could achieve cost efficiency and ease of construction. Desideri stresses the importance of considering Nervi *the master builder* (owner of Ingg. Nervi & Bartoli) ahead of *the designer* [12]. His construction proceeds were directly related to the rightness of projects and led to the adoption of appropriate structural forms, to research of suitable concrete finite surfaces that avoided additional treatments and coatings, and to essential optimisation of project material requirements.

The ratio between material and labour prices – unbalanced towards the former conversely from nowadays – is key in reading Nervi's geometrical creativity that enabled reduction of costs [12]. Form articulations were expression of construction pragmatism (as opposed to aesthetic formalism) and gave Nervi the opportunity to demonstrate his abilities as both designer and builder. In this context, he researched and refined construction procedures to free his work from the rigidity of wooden forms – from an architecture of wooden planks [9] to a true structural one.

Geometry was a strategic factor for erecting the complex shapes carefully sketched by Nervi. The formworks' wooden planks followed the straight generatrix lines of the ruled surfaces employed in each column, see Figure 10, with the great advantage of requiring straight elements only. The planks often needed to be shaped to accommodate the variation of width at the various levels, as shown in the drawing in Figure 11. Where scale allowed, the planks connected homologous points at the extremities; otherwise, they were split into regular segments according to specific horizontal sections.

The splayed pilotis of the UNESCO Secretariat were cast in wooden formwork supported by timber sub-structures. The project specification placed great emphasis on the quality of workmanship and prevented the use of plywood or metal forms: the architectural intent requested wood patterns and irregularities to be fully expressed [13]. Nervi was part of the design team and not responsible for construction but, nevertheless, provided detailed drawings of the formwork planks' layout, width and jointing to ensure aesthetic quality of the fair finished surfaces [4].

Palazzo del Lavoro columns were cast in steel frame-work lined with narrow timber boards clearly legible in the finishes [14]. The temporary formwork was divided in three lifts, each assembled from four parts. The casting of each lift was carried out in two phases (see original sequence drawing in Figure 12) dividing the columns in six sections expressed through horizontal joints [1]. A single formwork structure was used for all 16 columns with a complete casting cycle taking ten days, thus ensuring speed of construction to meet the overall tight project schedule [1] [9].

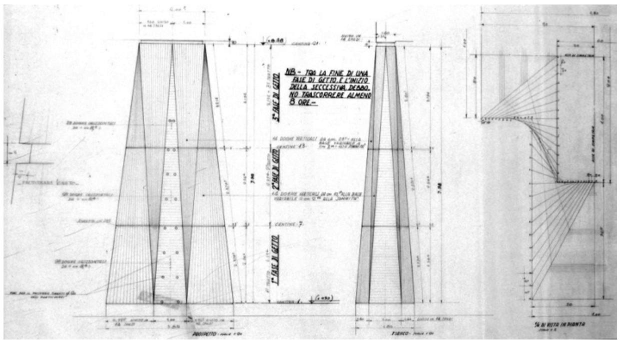


Figure 11. *Column formwork design drawing [15]*

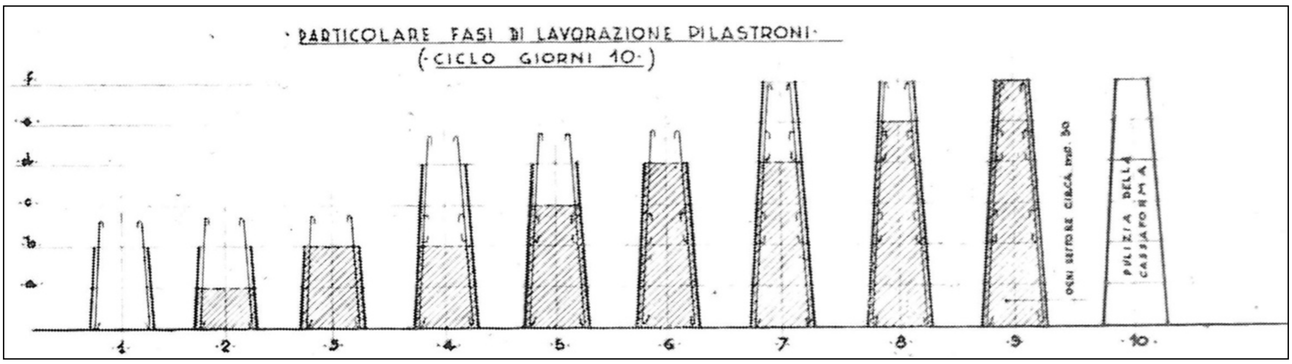


Figure 12. *Palazzo del Lavoro – construction sequence of columns [1]*

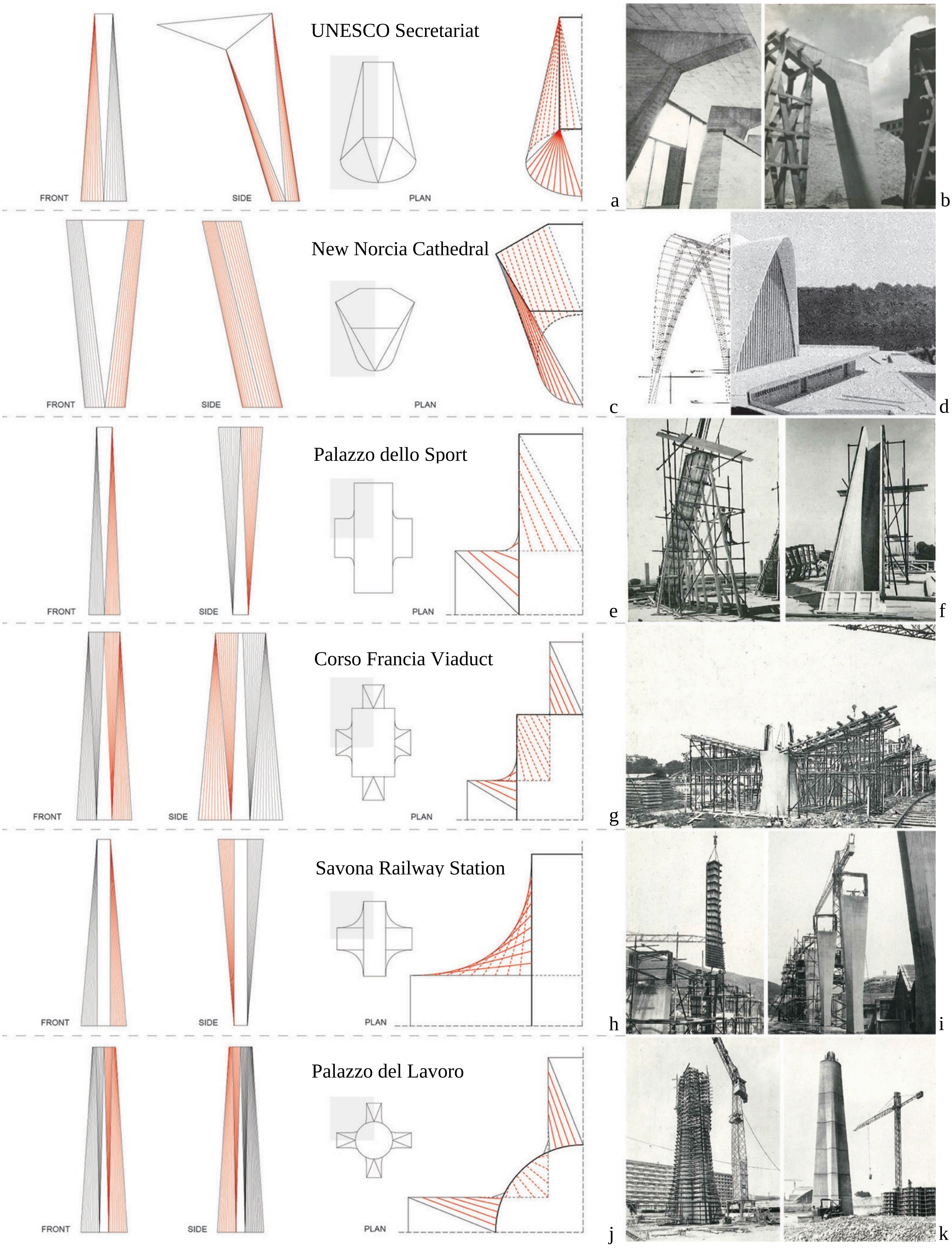


Figure 10. *Geometrical studies of column formwork, and site photos of the six case-study projects [1] [2] [16]*

Corso Francia viaduct columns were cast in-situ in formwork made of light steel work lined with two layers of fir boards, the inner one was designed with care to leave wood marks on fair concrete surfaces [17]. Ingg. Nervi & Bartoli cast 120 columns of variable height for the 3km viaduct using three formwork sets only [17]. These were adapted to variable elevations by progressively shortening them from the bottom partially compromising the cruciform base shape in the shorter columns (as shown in Figure 13) but, nevertheless, achieving economy of construction [1] [17].

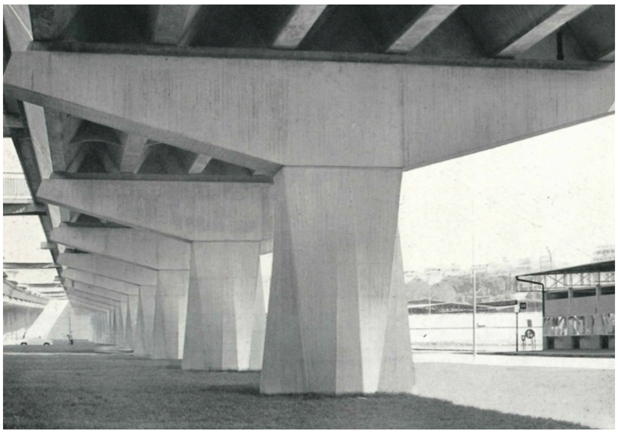


Figure. 13. *View of a short column without exact cruciform base shape [1]*

A natural progression of Nervi's research was the exploration of ferrocement formwork for splayed columns so as to remove limitations given by timber geometry and scarcity, and to allow smooth surface finishes [9]. In the Palazzo dello Sport Nervi considered the use of ferrocement for the inclined columns of the main gallery [1]. Figure 14 shows the construction proposal: the 48 columns were to be cast-in three reusable formwork sets made of bolted steel "T" sections lined with ferrocement. The shape of column in the sketch, a WCSP element with circular base and rectangular top, differs from the final design. In fact, the actual TWIST columns constructed (ref. §3.3) were cast in steelwork lined with timber boards. Ferrocement was eventually used in the same project for precasting the slender peripheral columns supporting the upper gallery [18].

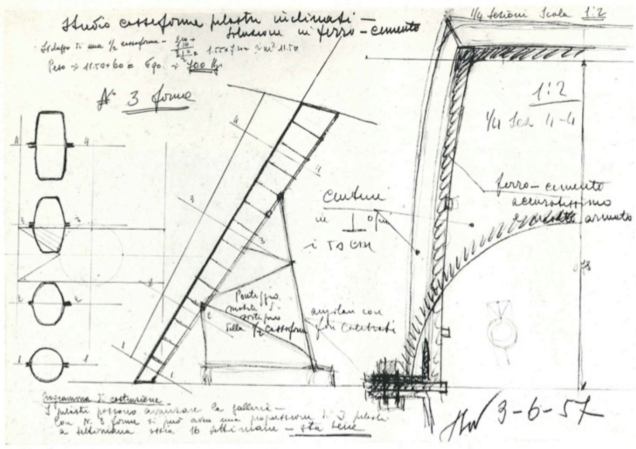


Figure 14. *Sketch study of ferrocement formwork for Palazzo dello Sport columns [1]*

4. NERVI TODAY

Analysis of the columns in Nervi's buildings highlighted a strategic approach: geometry was pivotal in comprehensively pursuing project aesthetic, static and construction technology. Nervi's success and international recognition proven his structural architectures as "creative highpoint in 20th Century design" [2]. It is of interest to reflect on Nervi's potential relationship with the contemporary technological means and constraints in his design approach. This section centers again on the column forms, and it speculates on how (and if) they would differ if designed and constructed by Nervi nowadays addressing the three recurring geometrical, structural and constructional themes.

In terms of the formal approach to geometric articulations, there is no doubt that the flexibility offered by contemporary digital tools in exploring tectonic shapes would have enhanced Nervi's design repertoire. Speculating on Nervi's deployment of parametric instruments, one could image the rational methodology with which the engineer would have manipulated the geometric parameters of forms in the digital space. Probably, he would have been one of the masters of what Panagiotis Michalatos defines as "simplexity" – a term in system science which describes the emergence of simplicity out of intricate and complex sets of rules [19]. Instead of post-rationalizing seemingly complex surfaces – as it often happens today – Nervi would have combined the formal opportunities of the digital with his structural intuitions from the very beginning of the design process, resulting in tectonic morphologies rational a priori rather than a posteriori.

Structurally, the second part of the Century has seen the refinement of theory of structures and, most importantly, the development of computer-aided design. Such new possibilities would without any doubts be used during the design process in Nervi's studio and exploited to enhance understanding of structural behaviour so as to increase project economy. Yet structural architecture found their defining moment during the initial project intuitive phase that set strategic decisions (see §2). It is likely that this essential trait would be vital even at present time and that Nervi's static sensibility would still be inclined towards elemental static schemes. All the structural expedients highlighted in §3.4 were driven by research of form efficiency, a principle that modern analysis techniques can only strengthen.

Construction technological progress has seen relatively little advancement (excluding limited exceptions) since Nervi's time; the building industry rested almost immutated if compared with others, e.g., automotive. This is especially true considering Nervi's work as he was at the forefront of his time's innovations. However, the economic context of the countries in which he operated has changed substantially, above all the ratio between material and labour prices is toppled unbalancing towards the latter.

The previous sections showed how Nervi sought reduction of material cost with column forms while exploring suitable construction solutions. Desideri claims that such research of material economy would not be exploited by Nervi nowadays because the cost associated with formworks complexity [12]. Conversely, Allwood et al. argue for the renewed need of "material efficiency" within the construction industry prompting to reverse the substitution of energy-intensive materials for labours [20]. It is hard to imagine Nervi abandoning the research of geometry purely on the basis of economic considerations as his rightness of construction encompassed much more, not least the link between aesthetic sensibility and static forms [3] [4]. On the contrary, it is likely that the research of economic efficiency would have simply addressed the different *boundary conditions* and explored diverse forms and construction technologies. In this last regard, the use of precasting, little exploited by Nervi for erection of columns, could offer new possibilities in light of the current processes and plants.

5. CONCLUSIONS

This paper shows how the dichotomy of complex geometry and structural efficiency finds great expression in Pier Luigi Nervi's columns. His work researched economies of construction and material investigations.

The study analysed the columns of six projects exploring and reflecting on how structural architecture principles were applied to these elements. Nervi resolved simultaneously geometrical, structural and constructional problems with the use of complex yet rational forms. The following points were found significant:

- All columns share a strategic design logic that exploited the formal advantages of ruled surfaces (frequently hyperbolic paraboloids) in combination with simpler planar surfaces.
- The volumes were defined with the selective use of two geometrical expedients: variation of cross-sectional shape and revolution of the principal inertia directions.
- Nervi's static intuitions led to close duality between column forms and structural behaviour at both global and local levels.
- Column designs were ultimately expression of construction pragmatism, articulated through constant refinement of formwork technology and research of finished surfaces. The ruled geometries provided forming advantages and required the use of only straight planks for moulds assembly.

The elegance of the complexity given by the smooth shapes finds formal rigour in Nervi's columns, in which curves had deep meanings that went beyond the mere creation of appealing architectural artefacts, as it is often the case in contemporary avant-garde. In this constant quest for aesthetic and efficiency, "form must be the necessary result, and not the initial basis, of structure" [5], a principle still valid in contemporary architecture, perhaps now more than ever.

PHOTO CREDITS

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Figure 10 (Photo a): Reproduced from *Pier Luigi Nervi*, by A. L. Huxtable, George Braziller, 1976.

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