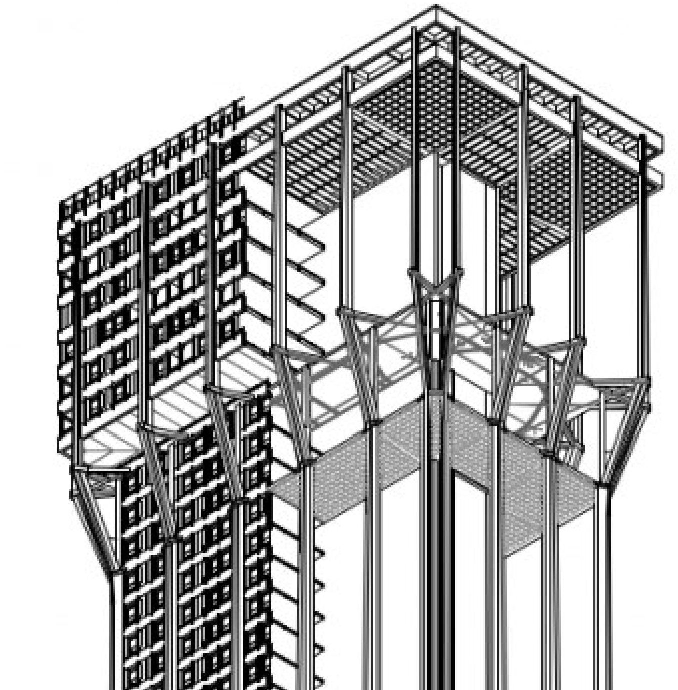
informes de la construcción

Volumen 72 | Nº 558 | abril - junio 2020 | Madrid (España) | ISSN-L: 0020-0883



CSIC

Instituto de Ciencias de la Construcción Eduardo Torroja

CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Informes de la Construcción
Vol. 72, 558, e342
abril-junio 2020
ISSN-L: 0020-0883
https://doi.org/10.3989/ic.71572

Italian style skyscrapers. High-rise construction in the fifties and sixties

Rascacielos a la italiana. Construcción de gran altura en los años cincuenta y sesenta

G. Capurso [(*)]

ABSTRACT

In the fifties and sixties, while Italian engineering was receiving important international awards, the theme of the tall building attracted the attention of the best architects. They made it a field of design experimentation, immediately sensing how the strategic use of the structure could revolutionize the already stereotyped image of the all-steel and glass towers proposed by the International Style. Gio Ponti, Luigi Moretti and the BBPR thus created formidable partnerships with Pier Luigi Nervi and Arturo Danusso, the most active engineers in the field of skyscraper design. The result was at least three masterpieces, among the works created in those years: the Velasca tower and the Pirelli skyscraper in Milan and the Stock Exchange tower in Montreal, which, at the time of its completion, also marked the record for the highest reinforced concrete building in the world.

Keywords: Italian Engineering, skyscrapers, structures, reinforced concrete, Pier Luigi Nervi, Arturo Danusso, Italian Style, International Style, Construction History, SIXXI research project.

RESUMEN

En los años cincuenta y sesenta del siglo XX, mientras la ingeniería italiana recibía importantes premios internacionales, el diseño de los edificios en altura atraía la atención de los mejores arquitectos. Estos entendieron inmediatamente lo mucho que el empleo estratégico de la estructura habría podido revolucionar la ya de por sí estereotipada imagen de la torre de acero y vidrio propuesta por el Estilo Internacional, y lo convirtieron en un campo de experimentación. De esta forma Gio Ponti, Luigi Moretti y la BBPR desarrollaron extraordinarias colaboraciones con Pier Luigi Nervi y Arturo Danusso, los ingenieros más activos en el campo del diseño de rascacielos. De entre los proyectos realizados en esos años, este proceso de colaboración dió como resultado a al menos tres obras maestras: la torre Velasca, el rascacielos Pirelli y la torre de la Bolsa de Valores de Montreal. Esta última, en el momento de su finalización, además significó el récord del edificio de hormigón armado más alto del mundo.

Palabras clave: *Ingeniería italiana, rascacielos, estructuras, hormirgón armado, Pier Luigi Nervi, Arturo Danusso, estilo italiano, Estilo internacional, historia de la construcción, SIXXI proyecto de investigación.*

(*) Università degli Studi di Roma "Tor Vergata" (Italy) - SIXXI Project, Senior Researcher.
Persona de contacto/*Corresponding author*: capurso@ing.uniroma2.it (G. Capurso).
ORCID: https://orcid.org/0000-0003-0149-0964 (G. Capurso).

Cómo citar este artículo/*Citation*: Capurso, G. (2020). Italian style skyscrapers. High-rise construction in the fifties and sixties. *Informes de la Construcción,* 72(558): e342. https://doi.org/10.3989/ic.71572.

Recibido/*Received*: 15/03/2019
Aceptado/*Accepted*: 05/08/2019
Publicado on-line/*Published on-line*: 09/06/2020

1. INTRODUCTION

In the fifties and sixties Italian structural engineering lived its golden age. Large roofs, dams and bridges, built first for the Reconstruction of the country, after the Second World War, and then in the years of the economic boom, represent the most typical and recognizable engineering products of this period (1). The best works were the result of a process of conception that attached great importance to formal research, but that was carried out by engineers independently or, in any case, in a hegemonic position compared to architects and other professional figures. In these works, it was the structural engineers who defined everything: the overall geometry, the proportions of the elements and the executive details were chosen mainly referring to the static solutions and the construction techniques identified as the most suitable for the specific site. In the same years, however, Italian engineers also participated in experiments conducted together with architects, with whom they shared a leading cultural role from the very years of the Reconstruction (2).

Tall building was, probably, the most significant theme of collaboration. So it deserved a special study during the research project "SIXXI - XX Century Structural Engineering: The Italian Contribution" (Erc Adv. Grant, awarded to Sergio Poretti and conducted by S. Poretti and Tullia Iori at the University of Rome "Tor Vergata", www.sixxi.eu), aiming to reconstruct the history of structural engineering in Italy in the twentieth century.

There are many reasons for this. First of all, precisely because the potential balance in the design activity between the role of the engineer and that of the architect gives the skyscraper, from the particular perspective of the history of engineering, a special position, due to a condition that is not found in other cases where the structure is challenging. In addition, the Italian tall buildings of the fifties and sixties are of particular interest because, despite the fact that in Italy, compared to other richer and more technologically advanced countries, experimentation on the subject started late, the works quickly reached levels of international importance.

Finally, it should be added that the distance between the architectural intonation of the Italian skyscrapers and the typical one of the Modern Movement was immediately recognised by contemporary critics and then confirmed by architectural history studies.

In this paper, the attention is focused on three Italian masterpieces, among the works built in these years: the Velasca tower (1950-57) and the Pirelli skyscraper (1954-60) in Milan and the Canadian tower of the Montreal Stock Exchange (1960-65), all characterized by peculiar Italian features, which are even more evident when compared with the contemporary American skyscrapers, the international de facto standard in those years. To build them, architects such as Gio Ponti, the BBPR group and Luigi Moretti formed partnerships with Pier Luigi Nervi, the most famous Italian engineer, and Arturo Danusso, who gave important scientific contributions to structural design (3).

2. STATE OF THE ART AND METHODOLOGY

The magazines of the time documented the three masterpieces during their construction, while subsequent studies referred mainly to the field of the history of architecture. Within the SIXXI project, the aim was therefore to investigate these works, verifying the hypothesis of the existence of an Italian-style skyscraper, also in relation to the wider story of the Italian School of Engineering (1). The study described in this contribution was conducted with the tools typical of the history of construction. It was based not only on the existing bibliography, but also on the little explored archival documentation, relating to the executive development of the projects, to the events concerning the building contracts, to the construction and to the following interventions on the buildings. Particular attention was paid to the interactions between engineers and architects in the design and construction process, rediscovered through the examination of correspondence and original drawings found in the archives of designers, building firms and public authorities.

Moreover, the "reconstructive drawings" (4), special isometric axonometric views, seen from below, conceived to detach the skin of buildings in neuralgic points, revealing the stratification of all anatomical elements, were widely used as an operational tool for investigation. This tool, introduced by Sergio Poretti for the study of Italian construction of the twentieth century, proved to be excellent for analysing the data extrapolated from the original documents and obtaining a powerful 3D visual device, which allows to focus on the connection between the construction of the structure and architectural expression.

The specific features of what here it's called "the Italian Style skyscraper", are common to all three selected works. Nevertheless, each of these characters can be illustrated more effectively by referring mainly to one of the three skyscrapers, which embodies it most.

3. REINFORCED CONCRETE TOWERS

It is well known that twentieth century construction of architecture was closely connected, in Italy, to the reinforced concrete frame structure, almost always entirely cast in place, with a few significant exceptions. The application of the technology preferred by Italian engineers to tall buildings is the first clear sign of a departure from the international prototype.

In the United States, in fact, the metal skeleton was constantly used to build skyscrapers. The dry construction system is not affected by climatic conditions and, above all, allowing high construction rates, guarantees the immediate income of real estate, commercial or residential, reducing the payback period of the investment. For this reason, the structure was usually coherently set on a grid as regular and undifferentiated as possible, so as to obtain economies of scale in the production of carpentry and standardized assembly procedures. The use of reinforced concrete in tall Italian buildings was the result, therefore, of an evolution of construction techniques entirely within the country. Despite the success of the futuristic idea of a tensile skyscraper designed by Guido Fiorini and entirely made of steel, a glance at the real building sites, since the 1930s, reveals the spread of reinforced concrete for the construction of the first ten or twelve storey "skyscrapers". The frame construction made it possible to avoid the upwind elements, which are indispensable in the metal skeleton but often an obstacle to freedom in the distribution organization.

Before 1939, when Italian autarky prevented the use of reinforced concrete in public and private buildings, engineers and construction companies became familiar with this material even for tall buildings. Designers were studying increasingly efficient solutions to reduce the size of structures and meet the architectural program (5), while companies optimized the execution times. They were inevitably far from the rhythm of one floor a day, obtained thanks to the metalwork in the construction of the Empire State Building (6). Anyway, they got the record of one floor a week despite the limits imposed by the maturation and hardening of concrete.

After the end of the Second World War, when the theme re-emerged, aided by the Reconstruction and the growth of the cities, the same approach was still valid. This is demonstrated by the tall buildings built in Rome (7) and Milan, until the mid-sixties, when most of the opportunities for construction are found.

Among these building, the Velasca tower in Milan is certainly one of the most exemplary cases (Figure 1). When the "Società Generale Immobiliare", a real estate and construction company, commissioned BBPR architects to design it, they initially turned to the use of a steel skeleton, apparently more obvious for a 25-storey building. A careful technical-economic analysis revealed, however, that the metal framework would have cost 25% more than a reinforced concrete one (8). The persistent technological backwardness of the Italian building yard after the war, as well as the overall poor experience of Italian engineers, also weighed negatively on the option of steel construction, so much so that the relative feasibility study was entrusted to American consultants.

When the solution in reinforced concrete was finally chosen, on the other hand, it was easy for the technicians of the construction company and Arturo Danusso, called upon to collaborate with SGI, to dimension and calculate the structure. The engineers defined a scheme of external pillars, arranged on the façade every eight metres, connected by perimeter parapet beams and stiffened by a bracing core. When horizontal forces act on the core, made up of double-T walls, it behaves like a vertical shelf beam, embedded in the foundations.

The floor plan shows no respect for the grid logic, relying on the flexibility of the construction system of the floor framing, made of reinforced concrete and hollow clay blocks, in perfect continuity with traditional Italian construction methods (Figures 2 and 4). Even if the core walls were not aligned with the pillars, by appropriately arranging the blocks, hidden beams were easily created. They were solidarized to the

Figure 1. Velasca tower, Milan. General view.

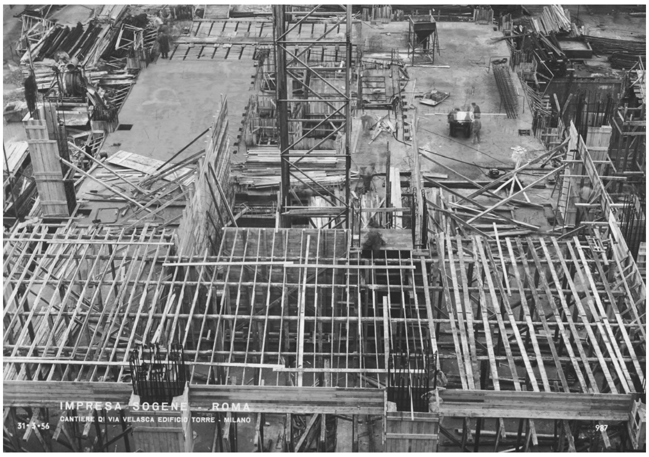


Figure 2. Velasca tower, Milan. Construction of a typical floor (Italian State Central Archive, SGI-Sogene Fonds, Rome).

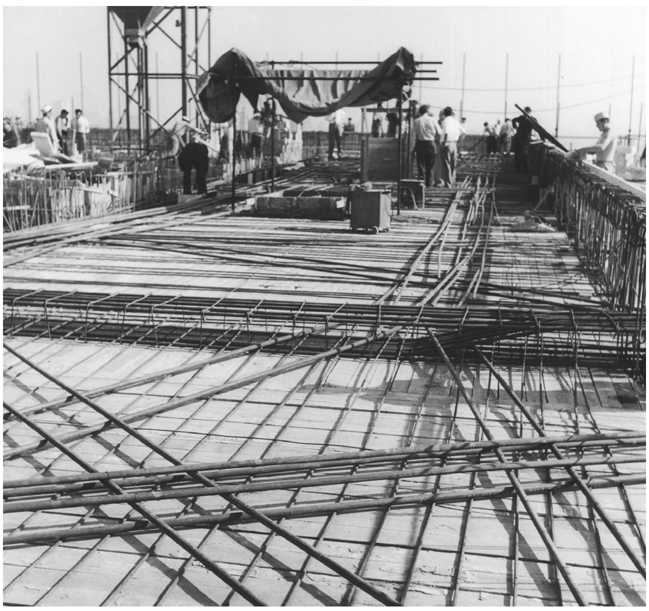


Figure 3. Velasca tower, Milan. Construction of the 18th floor (Italian State Central Archive, SGI-Sogene Fonds, Rome).

core and to the perimeter ring without the slightest concern for the orthogonality and divide the floors into quadrangular fields. The portions of the floors placed on the corners were made with crossed ribs, set on the parapet beams and on secondary ones, in order to resist the torsional actions that can be induced by the horizontal forces. The other parts of the floors were made, instead, with parallel beams, embedded in the central walls and in the parapet beams with different rigidity, calibrated by varying the arrangement of the clay blocks, specially designed.

When Pier Luigi Nervi and Arturo Danusso were commissioned, together with Gio Ponti, to design the Pirelli skyscraper the use of reinforced concrete for the construction of the structure did not seem to be open to question. The Velasca tower and other Milanese skyscrapers had by now demonstrated that, in Italy, reinforced concrete was the best choice for high-rise construction.

Instead, the choice of reinforced concrete for the Montreal Stock Exchange tower, following the involvement of Moretti and Nervi in the project, created many difficulties for Canadian builders, much more accustomed to metalwork. Due to the size of the pillars of the tower and the considerable local temperature ranges, the construction asked for extraordinary care. In summer, a special type of concrete, called “ice concrete”, was required, where water was replaced by crushed ice and cement was chosen from low heat ones. In winter, on the other hand, the surfaces of the castings had to be protected with insulating sheathing, to prevent low temperatures from negatively altering the mechanical characteristics of the structural members (9). Despite these foreseeable difficulties, the choice of the reinforced concrete solution prevailed, supported by an economic analysis conducted by the local architects and, above all, by the studies carried out by the project management group led by Paul Weidlinger, Mario Salvadori and Robert Panero. The latter, called upon to give his opinion about the matter, specified that the reinforced concrete solution, even though it was not the most commercial solution, was nevertheless the most suitable since it allowed the intervention to achieve greater media success. The tower set a world record for reinforced concrete skyscrapers, reaching a height of 190 metres, and the rental campaign for the building benefited from the considerable curiosity aroused by the original Italian product (Figure 13).

4. STRUCTURAL SHAPES FOR A NEW IMAGE

The peculiarity of Italian skyscrapers is not limited, however, only in the construction technology used for the construction of the skeleton. The use of the structure in the architectural language and the adoption of elegant structural solutions also contribute to characterize these works. Also these peculiarities become more evident looking at contemporary North American production.

In 1952, Skidmore, Owings and Merrill completed the Lever House, which influenced the other New York skyscrapers under construction, spreading the International Style language in tall buildings. These were mostly stereometric volumes, covered by an undifferentiated curtain wall, in which the structural frame, also indefinitely iterable, was reduced to the role of permanent scaffolding to support the metal facade, with which it shared only the ultra-industrial nature, but not the leading role in the language.

In the Velasca tower, on the contrary, the elevations have a masonry look and the structure plays a decisive role in

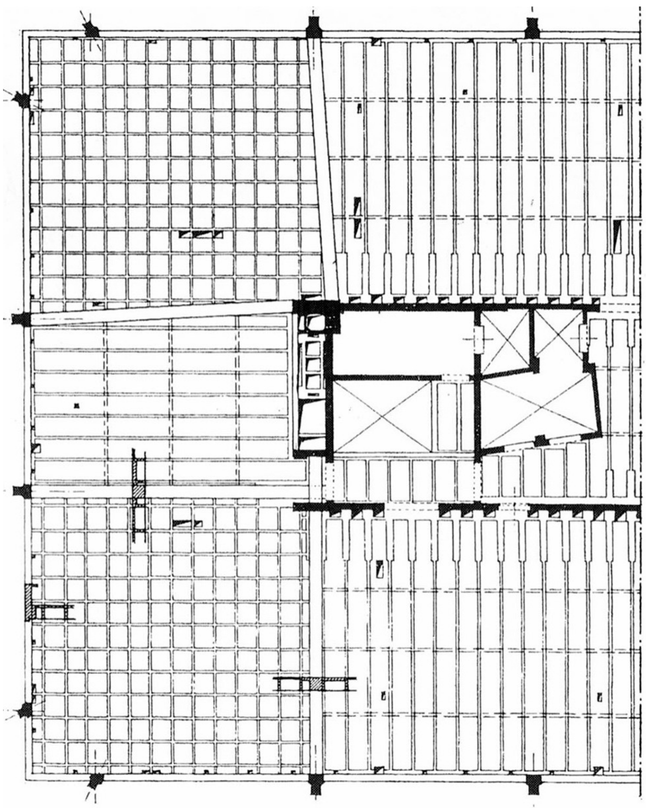


Figure 4. Velasca tower, Milan. Typical floor, upper volume. Structural layout.

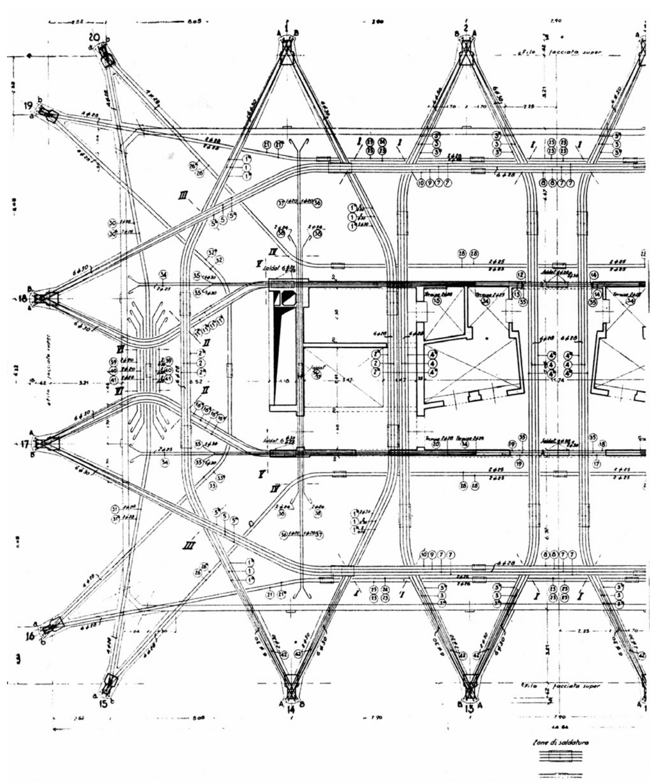


Figure 5. Velasca tower, Milan. 18th floor. Layout of the steel reinforcement bars.

defining the characteristic mushroom shape. The pillars, whose profile is tapered with the height, according to a uniform strength criterion, are exhibited on the wall, like vertical ribs; the columns are also doubled at the corners of the volume, specially chamfered to close the elevations; the high parapet beams, finally, preserve the solid image of the building even where the infill panels give way to the loggias of the houses.

In addition an ingenious play of weights and thrusts allows to obtain the characteristic shape of the volume, chosen by BBPR to insert the skyscraper in the panorama of Milan. The expansion of the upper block of the volume required an overhang of the floors of about three meters, for which the cantilever configuration was immediately discarded, as it was considered too expensive. Instead, it was decided to interrupt the pillars on the fifteenth floor and to use a series of inclined props to support the columns at the eighteenth floor (Figure 6). The entire construction can be kept in balance by setting up a system capable of absorbing the horizontal components of the stresses, which therefore involves two special floors. The fifteenth level one is compressed and was there-

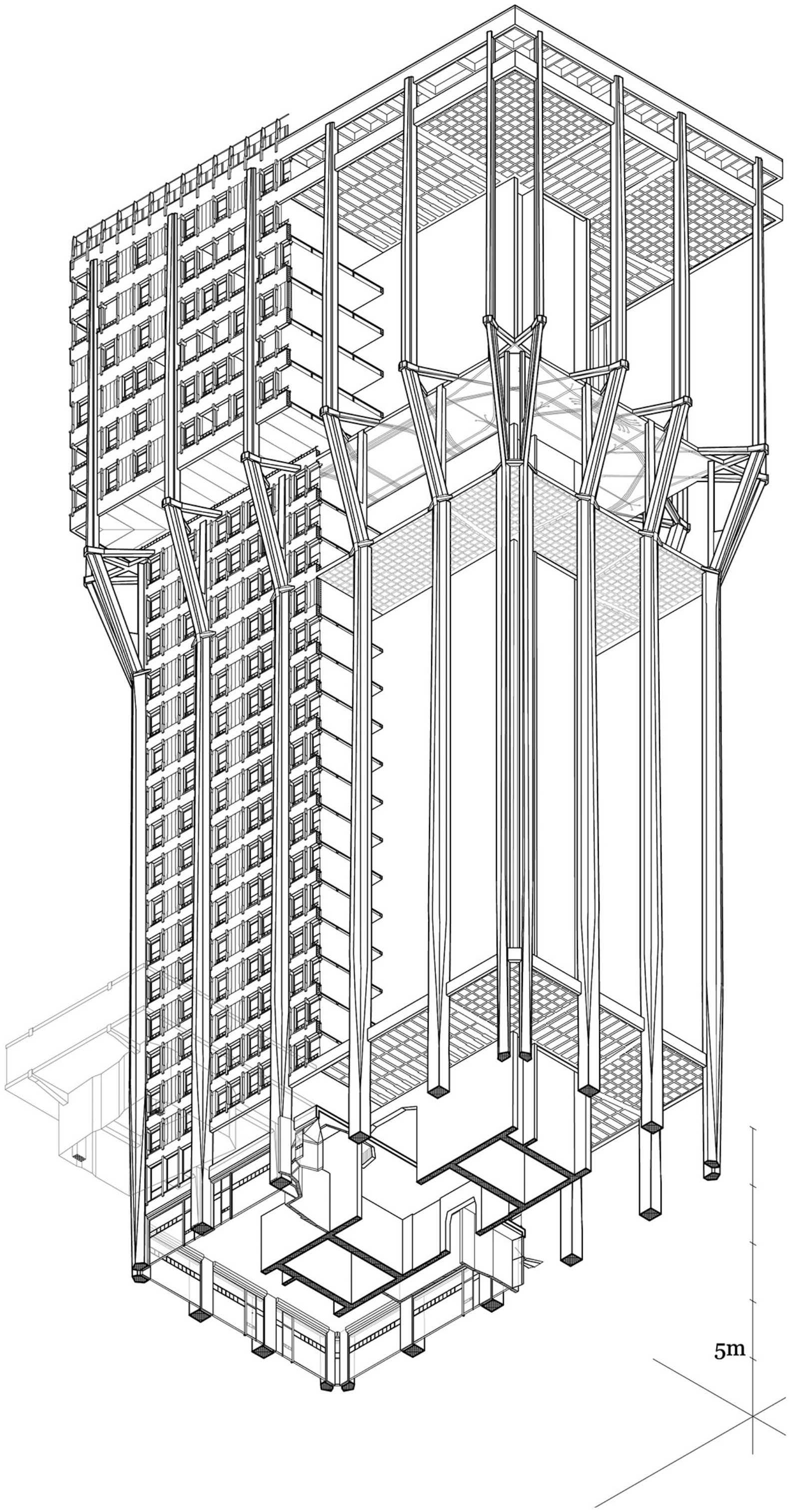


Figure 6. Velasca tower. Axonometric view (drawing by G. Capurso).

fore made with two slabs, each 10 cm thick, separated by a layer of lightened bricks so that the increase in inertia of the plate on the plane can prevent phenomena of buckling. The eighteenth floor slab, instead, is a 30 cm thick concrete slab, innervated by a web of thick reinforcement bars that hold the top of the struts two by two, so that the floor reacts as a whole like a membrane pulled along the edge.

The tension stresses, redistributed by the perimeter edge beam, thus assume values that are perfectly compatible with the conglomerate (Figures 3 and 5).

Although with different formal results, we find the same taste for the advanced engineering solution in the Pirelli skyscraper. Here, the lenticular shape designed by Ponti was arranged in a building 126 metres high, but only eighteen metres deep. The architect initially conceived a solution with pillars and frames, stiffened by reinforced concrete cores, similar to the projects for the Predio Italia skyscraper in Sao Paulo (1953) and the Lancia building in Turin (1954-57). But the Pirelli building was so challenging that Nervi and Danusso came to the conclusion that the scheme devised by Ponti, even though in line with building practice, was not adequate to solve the most difficult problem: the stability of the building body when the wind blows orthogonally to the façades.

Nervi preferred a "gravity" main resistance mechanism to the more common system, which he defined as "elastic". The gravity system, as in masonry buildings, or in certain dams, uses the stabilizing action of weight to counteract horizontal actions (10). The engineer had already used the same principle, in the 1930s, for his project of the "Monument to the National Flag", where he planned to construct a masonry tower, stabilized thanks to the compression induced on the structure by an internal, heavy mass, hanging like a pendulum at the top. In order to achieve the same goal in designing the skyscraper, Nervi made a tabula rasa of the small grid of pillars initially planned by the architects. The two triangular box cores, already arranged by the architectural project at the ends of the tower, are flanked by only two pairs of imposing intermediate pillars - gigantic shaped walls, more than seven metres long - placed at a great distance from each other (11).

The concentration of loads on a few massive vertical elements was used to make all the parts of the building to contribute to its overall stability. As a result of the reduction in the number of pillars, the floors must cover great spans: fourteen metres for the two lateral ones and twenty-four for the central one. The heavy weights supported are used to induce a beneficial and free pre-stressing in the intermediate walls, which effectively counteracts the tilting moment due to the wind. Coherently, since the lightening of the materials would have reduced the weights and therefore the stabilizing forces, the steel girders were discarded, and the reinforced concrete beams with variable section were preferred (Figure 9).

The scheme devised by Nervi had an innovative potential such as to induce Ponti to use it to characterise the architectural image of the skyscraper. The tapering of the pillars with their height – five centimetres per floor – is underlined by the design of the curtain wall, thanks to the use of special profiles and mirrors.

The geometry of the full concrete cores ends the elevations and marks the plan on the sides; the crowning canopy, supported by the ruled surface pillars placed on the terrace of the 31st floor and by a series of cantilevers with variable sections, emphasizes the slender shape of the building. It is therefore no coincidence that Ponti presented the skyscraper on the pages of Domus magazine (12) and other international journals using a series of slogans, among which the "structural invention" of the engineers stood out along with the "finished form", which is the core of the formal research of the architect after the war. The plan and section diagrams in the articles were used to show the direct relationship between form and structure of the building (Figures 7 and 8). At the same time, the schemes, elaborated to illustrate the project, show the contact established between engineering and the world of industrial design, thanks to which the colossal structure, reduced to a few essential elements, can effectively perform both its static and figurative role. Paradoxically, when the construction was completed, already Bruno Zevi unintentionally identified this relationship when, in a famous article, polemically defined the Pirelli building as a "bar cabinet enlarged to the scale of a skyscraper" (13). Furthermore, Ponti's presentations, with a lot of mentions of the collaboration with Nervi and Danusso, offer an opportunity to reflect on the relationship between the professional figures, for which it is appropriate to return briefly to the comparison with the United States.

In the production of the Chicago School, where scholars unanimously acknowledged the beginning of the history of the tall modern building, the balance between the role of engineers and that of architects was certified by the co-ownership of the design companies, as in the case of Burnham & Root or Adler & Sullivan. However, this original condition did not

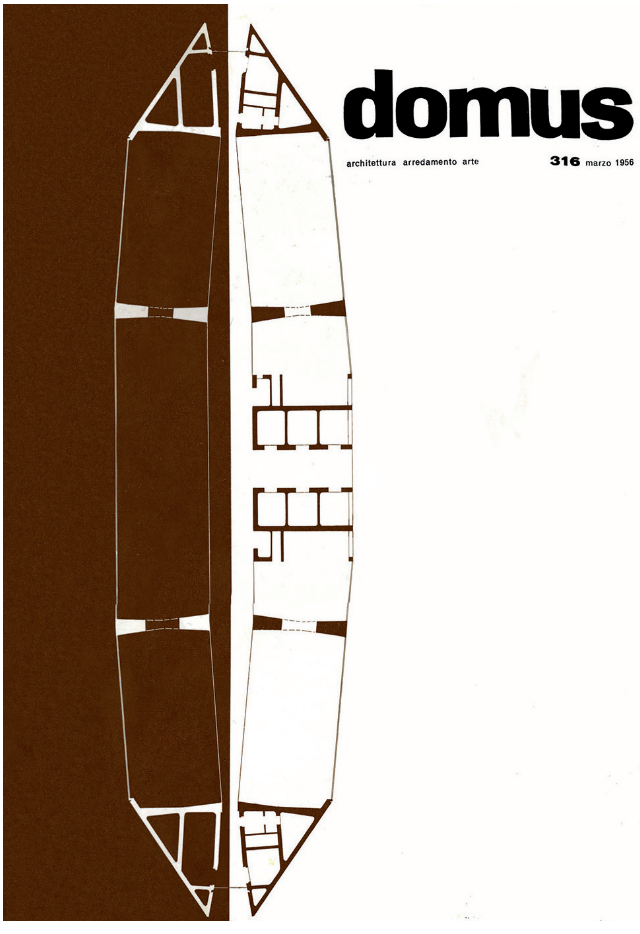


Figure 7. Pirelli skyscraper, Milan. "Domus", 316, 1956. Cover page.

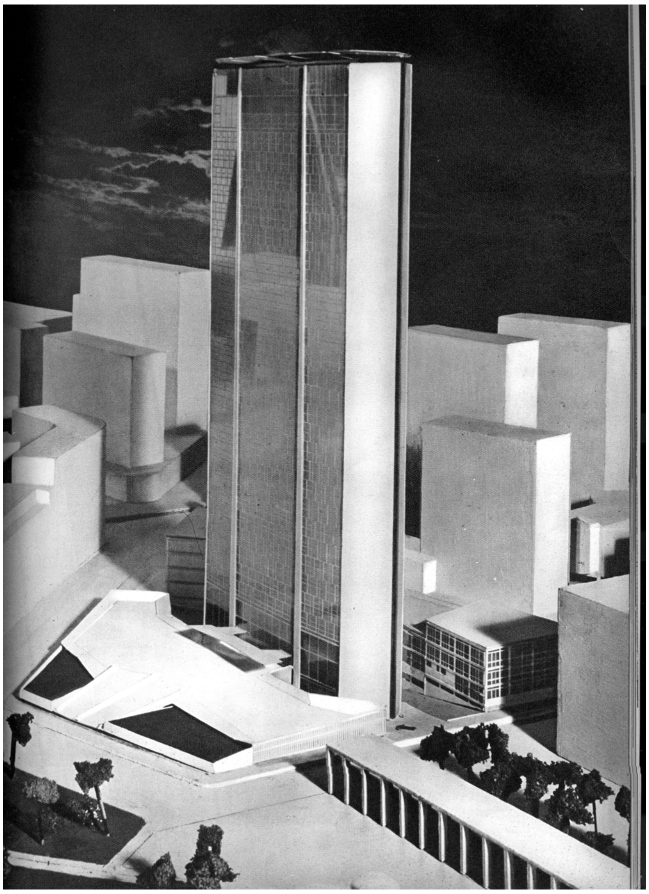


Figure 8. Pirelli skyscraper, Milan. "Domus" 316, 1956. Model of the project.

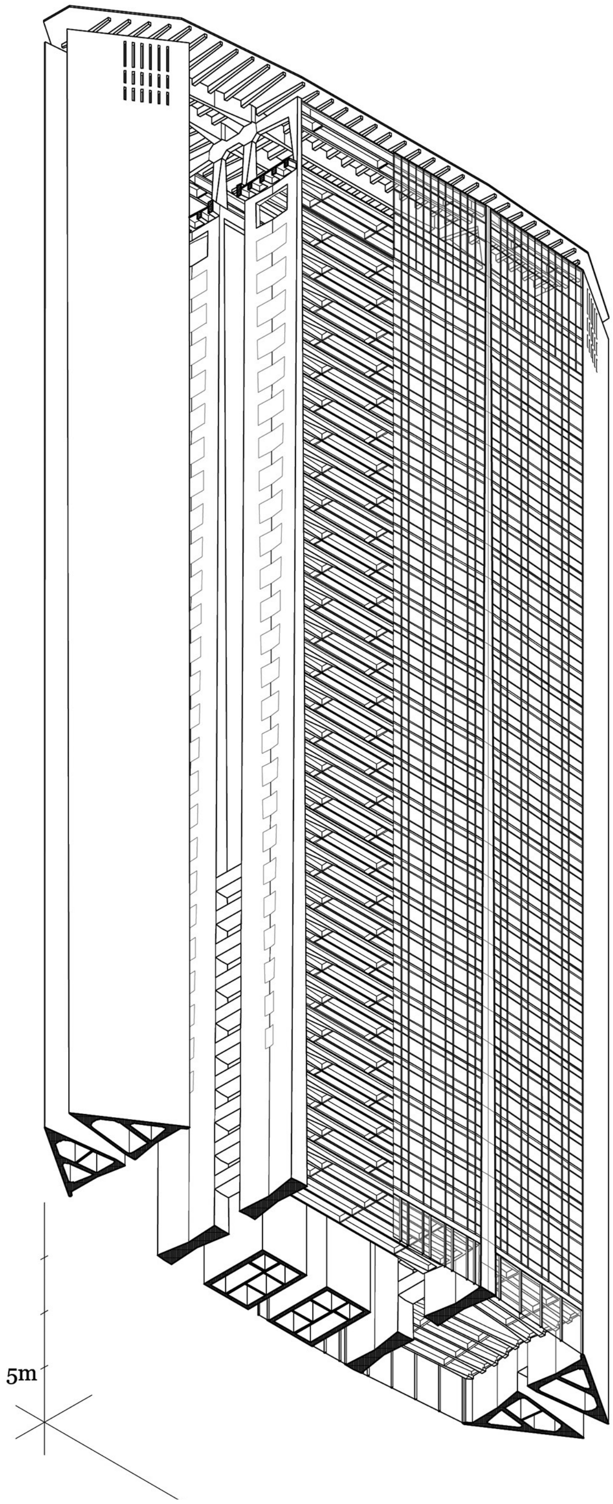


Figure 9. Pirelli skyscraper, Milan. Axonometric view (drawing by G. Capurso).

survive the growing specialisation of skills. After the Second World War, the architect was given the role of coordinator of the design team, where we find the structural engineer together with the plant engineer, the environmental engineer, the expert in estimates and building regulations, as Mario Salvadori effectively described the genesis of the American skyscrapers in the second half of the twentieth century (14).

Pragmatically, instead, American engineers took on the role of guarantors of the validity of the structural calculation and, above all, of the financial investment, with the consequent complete separation of the professional fields. In short, they were no longer designers, but consultants. Even in the case of the best projects the approach is not very different. In the case of the Seagram building, for instance, the renowned engineering company in charge of the structural project - Severud Associates - was forced to develop the structural solution on a module that did not comply with the conventional measures of the building products and that was established by the architects.

And, above all, the engineers rigorously avoided altering the image, which Mies van der Rohe entirely entrusted to the perfect proportions of the volume and metal facade, as well as to the elegance of the materials. The attitude of the Americans was nonchalant and detached, incompatible with the approach of the part of the Italian School of Engineering led by Danusso and Nervi, promoters of a renewed unity between the competences of the architect, engineer and builder.

It is a position connected to the belief that the project is the result of a process of synthesis, which requires the involvement of the engineer from the conception of the work and not in the mere subsequent validation.

In Montreal, the comparison with the international model became even more direct. Nervi and Moretti replaced the experts Skidmore, Owings & Merrill in the coordination of a group of Canadian technicians, who had planned, for the same area, a rectangular tower, supported by an ordinary metal frame skeleton, packaged in perfect International Style (Figure 12). When Nervi had to face the problem of building

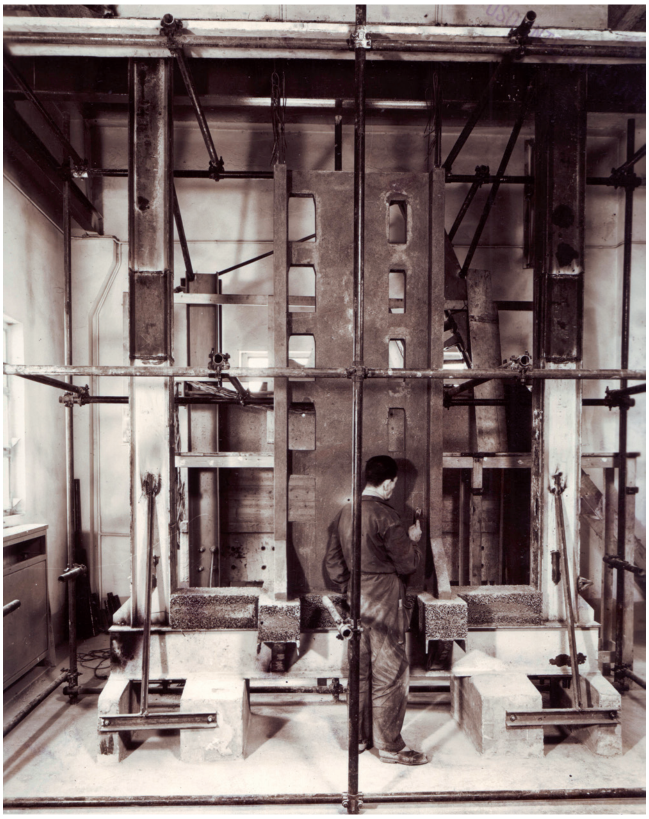


Figure 10. Velasca tower, Milan. Model at Ismes, central core (ISMES Historical Archive, Bergamo).

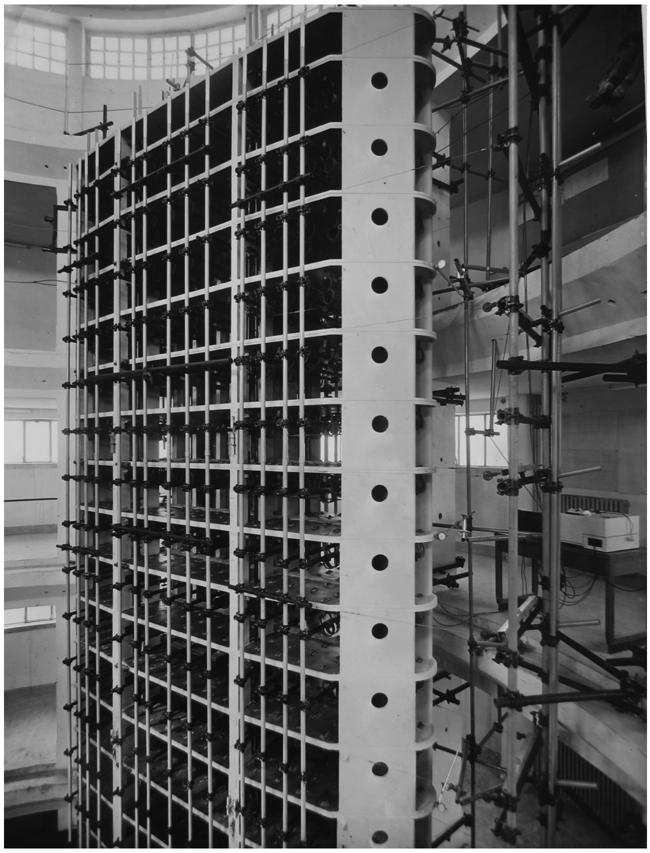


Figure 11. Pirelli Skyscraper, Milan. Structural model at Ismes (ISMES Historical Archive, Bergamo).

there the tallest reinforced concrete skyscraper in the world, in a city where there was already strict anti-seismic regulation, he set aside again the traditional structural schemes and organized the skeleton into two distinct devices. The "main resistant system" and a secondary system. The first ensured the overall stability of the building and consisted of two reinforced concrete walls, arranged in an X configuration to form the central nucleus and connected by reticular beams to the four pillars at the top of the floor plan, about 40 metres wide. The other, consisting of eight smaller pillars, only helped to support the set of slabs (Figure 15). The main system solution was futuristic and anticipated the "outrigger" systems adopted by Fazlur Khan, from the late Sixties, to design some of its most important skyscrapers (15).

In this configuration the perimeter pillars, involved in the stabilization against horizontal actions, are particularly efficient thanks to the high distance from the vertical axis of the building. They behave like pendulums, alternatively stretched or compressed, and the considerable stabilizing moment they provide is guaranteed by the maximum lever arm, resulting from the geometry of the building, equal to the diagonal length of the floor.

Compared to the "framed tube" systems, already tested in those years, the scheme is more advantageous because the vertical structures occupy only a few isolated points of the facade, thus leaving a high degree of freedom in the organization of plans and elevations.

As the framework's sizing progressed, the two Italian designers became more and more aware that the project also led to a rethinking on the theme of structural expression in tall buildings: for both, by that time, the model of the American skyscraper was no longer satisfactory. However, the approaches adopted by the engineer and architect did not converge on this occasion. Nervi, faithful to his poetics, would have expressed the structural system making it coincide with the image, without alterations, confident that the rational skeleton was sufficient to ensure an intrinsic formal quality to the building.

This conviction had guided the engineer throughout the design process, inducing him to formulate a series of "full-structure" proposals. In the first versions, in fact, the skyscraper was made with an external tube made up of perforated partitions, in which the glass surfaces, set backwards, had just the role of completing the interstices. Then the walls were replaced by an exoskeleton, made with twelve continuous pillars, marking the facades, stiffened by connecting beams.

But in this project Moretti prevailed, and he also guided Nervi towards "more inventive games of structures". He worked independently on the architectural language and in fact used a series of optical corrections on the skeleton and on the entire volume to completely modify their image (Figure 14).

Some of them can be ascribed to the strategy of "finished form", already seen in the skyscrapers built in Italy, such as the progressive receding of the floors, a few centimeters per floor, in order to taper the volume.

Anyway, these corrections were not enough for the architect who, also against the opinion of Nervi, obtained other changes. In order to further enhance the image of the tower, the height of the trusses was reduced from the bottom to the top, contradicting the real trend of the efforts. The most important change, however, was to hide the eight pillars of the secondary structural system behind the convex curtain wall, with expensive structural measures aimed at not penalizing the commercial surface of the offices. The four corner pillars, on the other hand, are artificially enlarged thanks to a shell made of white cement panels, completely independent of the structural shape.

The abstract geometries that were typical of the International Style are, therefore, definitively outdated. In the eyes of the observer, who is led to believe that only the four pillars of the main resistant system support the entire building, the entasis that characterizes the cladding materializes their "evident suffering", as Moretti said. Transgressing Nervi's rational aesthetic, a first baroque inflection provocatively appeared in twentieth-century engineering.

5. CALCULATIONS AND MODELS

The creative and "artistic" conception of the project activity, typical of Italian designers, also has an operative aspect, nested in the methods used by Italian professionals for structural design and verification. A comparison with the American model can help, also in this case, to highlight the originality of the approach of Italian engineering to tall building design. The engineers who designed the skyscrapers in Chicago first, and then in New York, had numerous analytical tools for calculating the structures. Some verification methodologies were developed between the end of the 19th century and the first decades of the 20th century. Force and displacement methods presented high computational complexities for multi-storey buildings. The tests of behaviour under the action of the wind were already carried out in the 1920s with simplified methods, such as that of the equivalent cantilever.

Since 1932, however, when Hardy Cross published his "moment distribution method", calculation techniques based on iterative procedures quickly spread in America for the verification of skyscrapers, soon assuming a predominant position (16). These tools allowed the complete separation between the role of the designer and that of the engineer who dealt with calculations.

The latter, in fact, is no longer required specific engineering skills, but only to apply correctly and quickly the resolution method. The methods above, at least initially, required the simplicity of the structures to be analysed, which had to be described by means of flat systems of rods and nodes, and taking into account only the elastic behaviour of the materials.

Danusso, who widely influenced the Italian School of Engineering, on the other hand, was oriented as early as the 1930s to investigate the elasto-plastic phase of reinforced concrete. He aimed to go beyond analytical calculation as the only tool for dimensioning structures. The innovation was identified in the use of model experiences, which after the World War II will be conducted at the ISMES laboratory in Bergamo. The model tests allowed to avoid the typical simplifications of the purely mathematical approach and to consider all the interactions between the parts of the skeleton.

They also offered precious indications on the real structural behaviour, in particular when dealing with reinforced concrete.

The main structural elements of the Velasca tower were tested at ISMES, between January and July 1956. A series of tests was conducted on three 1:2 scale prototypes of the pillars in order to choose the best composition and distribution of the reinforcement bars. A five-storey, 1:8 scale portion of the core was also tested to verify its actual deformability and breaking point (Figure 10). Finally, shortly before the construction of the structure of the upper volume, a 1:5 scale model repro-

Figure 12. Place Victoria, Montreal. First project by Skidmore, Owings & Merrill (Italian State Central Archive, SGI- Sogene Fonds, Rome).

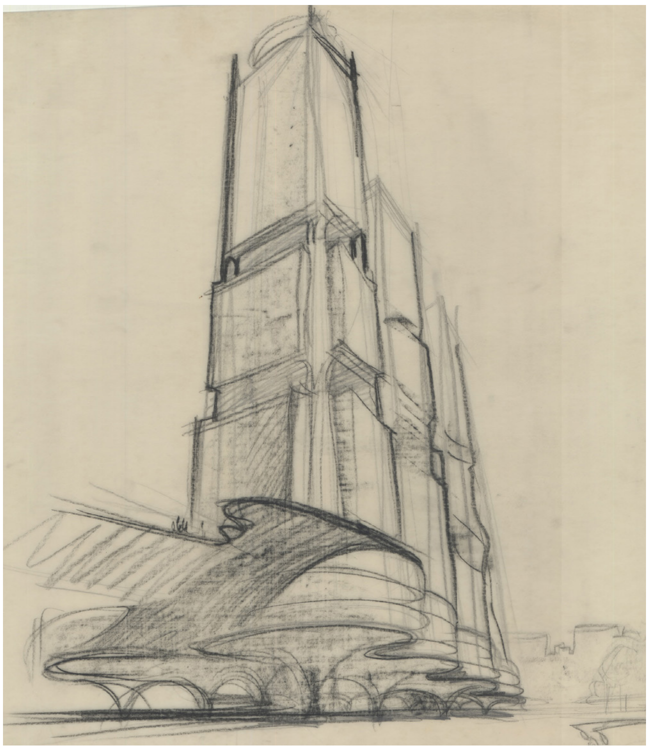


Figure 13. Place Victoria, Montreal. Sketch drawing by L. Moretti (Italian State Central Archive, L. Moretti Fonds, Rome).

ducing five spans of the floor, made with small pumice blocks instead of brick ones, was verified at breakage.

But it is in the case of the Pirelli skyscraper that the experimentation became spectacular. In addition to a reproduction of the typical floor, on a scale of 1-5, a large model was, in fact, developed on a geometric scale of 1-15, ten meters high, which enabled to examine the structure in its entirety. The main purpose of the experiment, in this case, was to obtain assurances precisely on the predictions of the "gravity behaviour" of the structure (17).

The analytical verification would, in fact, have been too complex, also because of the indeterminacy of the static scheme of the floors, variable one by one. The deformations detected in the model structures provided encouraging responses during the tests, carried out from the end of 1955 to November 1956 (Figure 11). The miniature construction, in pumice mortar and cement, was then subjected to dynamic actions, allowing engineers to evaluate some properties of the skyscraper structure that were even more difficult to evaluate with numerical methods, such as the periods of oscillation due to wind forces. The activities at ISMES also suggested improvements to the structure and corrections were made to the model to submit it to a second series of tests. The building site itself was then involved in the experimental spirit of the project and became an appendix to the laboratory, so that further modifications were decided during works.

The designers, worried about the extent of the elastic deflection of the floors, had in fact established that the horizontal structures had to be pre-stressed, to redistribute the moments of the central span on the two sides. Such a solution had to be applied to the higher floors: here, in fact, the progressive reduction of the section of the central wall implied a consequent weakening of moment connections at the ends of the floors. The simply supported configuration of the top floors risked inducing excessive deformations in the middle of the large span. However, when load tests were carried out on the first floors built on site, the measuring instruments revealed deformation values considerably lower than those theoretically foreseeable. Therefore, the idea of pre-stressing was abandoned. The story confirmed the benefits induced by the mutual collaboration between the various parts of the structure, which inevitably had escaped even experimentation on the model.

Figure 14. Stock Exchange tower, Montreal. Frontal view (Italian State Central Archive, SGI-Sogene Fonds, Rome).

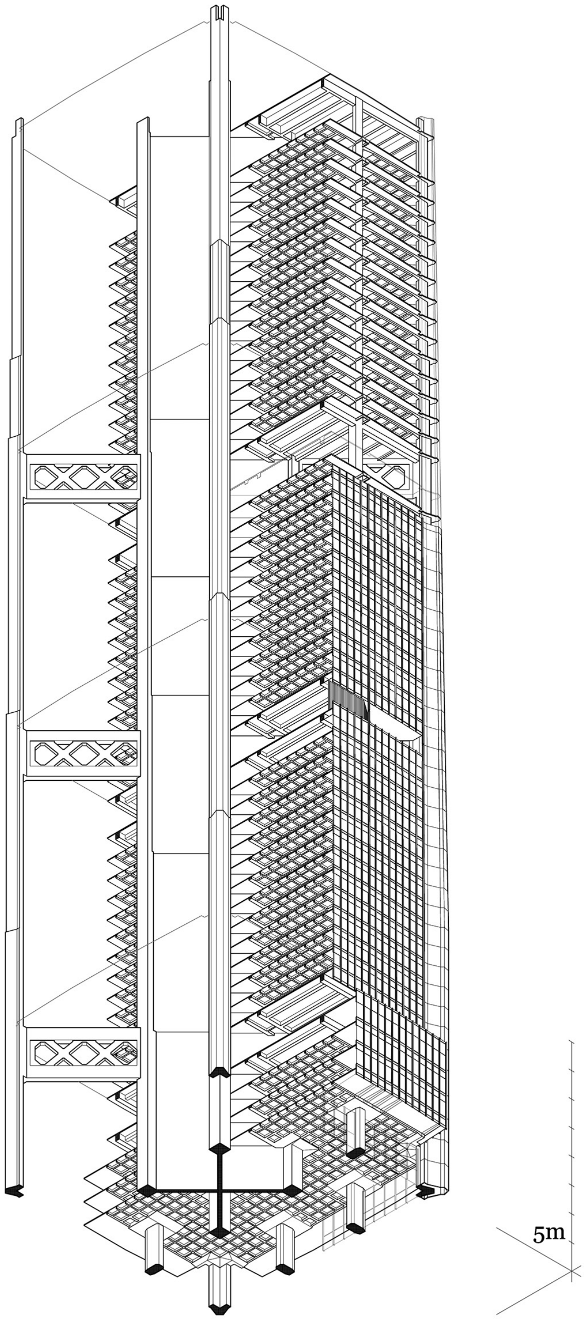


Figure 15. Stock Exchange tower, Montreal. Axonometric view (drawing by G. Capurso).

Following the success achieved in Italy with the Pirelli project, Nervi was able to confirm the use of structural models for verifying tall buildings, even in other countries. For the Montreal Stock Exchange Tower, the concept of the main resistant system was preliminarily validated through the application of simple calculations based on the four moment equation.

Considering that it was impossible to grasp the complexity of the structural system with numerical methods, Nervi required, however, the performance of tests on models. First, a wind tunnel study was carried out at the Polytechnic University of Turin, on a small wooden maquette of the entire complex. This study provided some basic data for the analyses then carried out at ISMES, where a celluloid model was made, on a scale of 1: 52.8, to verify the structural response, both to the wind and to the earthquake. To examine two different construction solutions of the typical ribbed slab, further tests were finally carried out in Canada, also requested by Nervi, on a model in scale 1: 1 of half of the floor.

6. CONCLUSION

Through the history of the construction of the three masterpieces specifically analysed in this article, it was possible to recognize the most representative aspects of the identity of what we have called "Italian Style" skyscraper.

The first element is the use of construction techniques, with a high level of craftsmanship, typical of the Italian post-war building yard. The reference technique to create the load-bearing skeleton is cast in place reinforced concrete, so that the realization of each component of the skeleton can be modified punctually, without worrying about obtaining standard or homogeneous solutions throughout the building. This is a factor so deeply rooted in the way Italian designers operate that even in a skyscraper built abroad, under different site conditions, they do not intend to give up the freedoms granted by artisan construction.

Then, the use of original structural schemes, developed to satisfy refined architectural programs. This element is further characterized by the preference for the finished form of the buildings, in plan, elevation and section, clearly distinguishable from that accredited by the international model. A general affinity between the way structures are conceived and industrial design, which remains an underlying trend, can be traced back to the same area: it can be expressed in the form of the entire building, as in the case of Pirelli, or it can have an impact on the design of individual structural "pieces", such as the pillars of the Velasca or those of the Montreal tower.

Finally, among the less evident aspects, because nested in the operational procedures of the design, we should mention the important role played in Italy by the use of physical models in the sizing and verification of the structural work, while American engineers preferred simplified tools based on numerical and iterative methods.

ACKNOWLEDGMENTS

This article is the outcome of a survey conducted in the framework of the research project Erc Adv. Grant "SIXXI -XX Century Structural Engineering: the Italian contribution", awarded to S. Poretti and conducted by S. Poretti and T. Iori at the University of Rome "Tor Vergata". (www.sixxi.eu).

REFERENCES

(1) Iori, T. & Poretti, S. (2016). Storia dell'ingegneria strutturale italiana. Ascesa e declino. *Rassegna di architettura e urbanistica,* 148: 8-52.
(2) Poretti, S. (2013). *Italian Modernisms: Italian Architecture & Construction in the Twentieth Century*. Roma: Gangemi.
(3) Iori, T. & Poretti, S. (2017). Fotoromanzo SIXXI. 7. Il grattacielo all'Italiana. In T. Iori & S. Poretti (Eds.). *SIXXI 4. Storia dell'ingegneria strutturale in Italia* (pp. 116-128). Roma: Gangemi.
(4) Giannetti, I. & Capurso, G. (2018). Architecture and structure in the Italian school of engineering. redrawing and 3d printing for Construction History. In *Proceedings of the International Conference on Construction Research – AEC, Madrid* (pp. 317-324). Madrid: Dayton.
(5) Goldstein Bolocan, A. (1935). Le prime realizzazioni milanesi di edifici a grattacielo. *L'Industria Italiana del Cement*o, 5: 146-158.
(6) Willis, C. (2004). *Empire State Building. 21 mesi per costruire il grattacielo più alto del mond*o. Milano: Electa.
(7) Mornati, S. (2009). La sperimentazione a Roma sul tema del grattacielo. In P.G. Bardelli, A. Cottone, F. Nuti, S. Poretti & A. Sanna (Eds.). *La Costruzione dell'architettura. Temi e opere del dopoguerra italiano* (pp. 187-194). Roma: Gangemi.
(8) Golinelli, G. (1958). Torre Velasca in Milano. *L'Industria Italiana del Cemento,* 1: 3-8.
(9) Poretti, S. & Capurso, G. (2010). Trasfigurazioni di strutture. In B. Reichlin & L. Tedeschi (Eds.). *Luigi Moretti. Razionalismo e trasgressività tra barocco e informale* (pp. 374-385). Milano: Electa.
(10) Nervi, P.L. (1960). L'ossatura. *Edilizia Moderna*, 71: 35-42.
(11) Poretti, S. (2007). Struttura e architettura nel modernismo italiano. *Rassegna di architettura e urbanistica,* 121/122: 9-32.
(12) Ponti, G. (1956). "Espressione" dell'edificio Pirelli in costruzione a Milano. *Domus,* 316: 1-16.
(13) Zevi, B. (1959). Londra chiama – telegraficamente Roma risponde. *L'architettura. Cronache e storia,* 50: 512-513.
(14) Salvadori, M. (1990). *Perché gli edifici stanno in piedi*. Milano: Bompiani.
(15) Ali, M.M. (2001). *Art of the skyscraper. The genius of Fazlur Khan*. New York: Rizzoli.
(16) Kurrer, K.E. (2008). *The History of the theory of Structures: From arch Analysis to computational Mechanics*. Berlin: Ernst & Sohn.
(17) Danusso, A. (1958). Esperienza e teoria nella tecnica del costruttore. In *Nuova sede Pirelli in Milano* (pp.51-54). Milano: Arti grafiche milanesi.

* * *