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[20] Construction was riddled with structural problems, and suffered frequent interruptions (R. Gutiérrez-Solana and H. de Diego, "El proceso constructivo de la iglesia parroquial de Santa Cecilia en Espinosa de los Monteros (Burgos)", in A. Graciani et al. (eds.), *Actas*, pp. 486-489).

[21] Vault deformation and the awkward springing design might cast some doubt on whether both arches were originally supposed to be concentric. However, presence of carved decoration in the half-octagon arch face indicates that it was, at the very least, intended to be visible.

[22] J. L. Gutiérrez Hurtado, *Sedano, Villa y Honor*. Burgos: Caja de Burgos, 1997, pp. 142-147. Transept vaults were finished in 1649, and the crossing was not begun until 1659. Construction of this relatively modest building, already "in a reasonably advanced state" in 1566, thus spanned over a century.

[23] This date, carved over its entrance, remains the main source so far for dating the building.

[24] A. López Mozo, "La cúpula de El Escorial: geometría, estereotomía y estabilidad", pp. 763-776 in S. Huerta et al. (eds.), *Actas del Sexto Congreso Nacional de Historia de la Construcción*, Madrid: Instituto Juan de Herrera, 2009, pp. 769-771.

[25] I. Rilova Pérez, *Olmillos de Sasamón. Villa, Iglesia y Fortaleza*, Burgos: Adeco Camino, 1997, p. 155.

[26] The Olmillos chancel had been vaulted by García de Arce in 1589. (Rilova, *Olmillos* (Note 20), p. 159). If the Villasidro church was indeed completed in 1603, vaulting would have been the last stage of construction, and thus slightly later than, or at least simultaneous to, the Olmillos apse, though precise dating remains difficult.

[27] M. Sobrino González, "Piedra labrada en la arquitectura burgalesa del Renacimiento", in E. J. Rodríguez Pajares (ed.), *El arte del Renacimiento en el territorio burgalés*. Burgos: Universidad Popular, 2008, pp. 55-56.

Pier Luigi Nervi vs Fazlur Khan: the developing of the outrigger system for skyscrapers

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Introduction

The structural development of tall buildings has been a continuously evolving process. There is a distinct structural history of tall buildings similar to the history of their architectural styles.[1] In this structural history it might be interesting to investigate how one of the most popular system used nowadays to build super tall skyscrapers, the outrigger structure, was designed for the first time. The paper focuses on how this particular structural system was first developed, trying to link the experience of two outstanding engineers who worked after the Second World War, the Italian Pierluigi Nervi (1891–1979) and the Bangledeshi-American Fazlur Rahman Khan (1929–1982).

In the outrigger structures, a lateral load-resisting system is extended from the conventional core to the building perimeter columns through the outriggers that connect them. This basic configuration often requires perimeter super columns or other structural components at the outrigger levels, and these elements of this system are sometimes integrated into the aesthetic of the building.

A very early example of outrigger structure is the Place Victoria Office Tower of 1965 in Montreal designed by Pier Luigi Nervi and Luigi Moretti (Fig.1). It was also used by Fazlur Khan in BHP House in Melbourne, completed in the 1972 and in the First Wisconsin Center of 1973 in Milwaukee. However, major applications of this structural system can be seen in the contemporary skyscrapers such as the Jin Mao Building in Shanghai and the Taipei 101 Tower in Taipei.

Skyscraper is a type of building where the structure has to efficiently match all the severe economical requirements needed. Indeed, a good structural scheme for a high-rise building has to employ the minimum amount of material in order to maximize the marketable space at each level and to contain the construction costs. The ability to form and shape a high-rise building is strongly influenced by the structural system. This influence becomes progressively more significant as the height of the building increases. Buildings up to 20 storeys can be shaped without undue influence of the structure. Between 20 and 40 storeys, one must begin to identify a specific structural system, its composition and its efficiency, and the flexibilities for shaping offered by the system. Structures that are 40-60 storeys tall will have more specific restrictions regarding asymmetry of profile and plan. Towers beyond 60 storeys are more decidedly affected by the structure. As every common structure, skyscrapers are subject to two main load categories: the gravitational loads (dead loads such as self weight of the structure, walls and cladding and live load such as people, furniture, vehicles) and lateral loads (wind, earthquakes). How these two main sets of loads affect the structural behavior of a skyscraper is extremely different than a low-rise structure. Indeed, the increase in structural material required for a tall building is largely due to the additional strengthening and stiffening necessary to resist lateral forces. In other words, the primary structural concern for a high-rise building is to develop sufficient lateral stiffness.

In the early 1960s, the Bangle-American engineer, Fazlur R. Khan, father of the modern skyscrapers structure, developed a method for assessing the differential between the material quantity associated with support of gravity loads only and the one required by actual load condition (gravity plus lateral loads). He named this differential with the expression "premium for height". Taller buildings could not compete economically with shorter buildings if engineers did not find a way to control, or most of all to reduce, this structural premium without increasing the size of structural components"[2]. Thus, in a skyscraper structure the main difficulty is to support the vertical load with a minimum increase of the structural element necessary to support the gravitational load. The research made by Khan in the early 1960s was oriented towards the shaping of tall buildings in order to make them act as pure cantilevers against lateral load. In the process he developed several new structural systems, most of them distinguishable by a full integration between structure and façade.

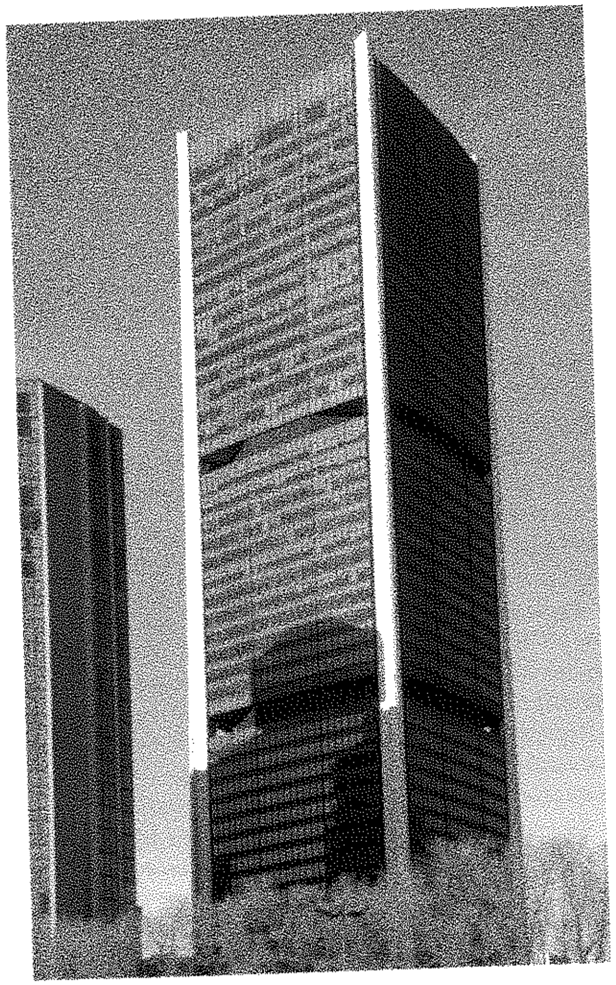

Fig. 1. Luigi Moretti, Pier Luigi Nervi, Stock Exchange Tower, Montreal, 1965. (Photo by the author)

Before that, the most predominant steel system of the 1950s and early 1960s was the plane frame system, which consisted of plane frames (rigidly connected columns and beams all in essentially one plane) arranged in two directions constituting a bay arrangement. The frame resists lateral loads primarily by the bending of member depths. Khan understood this frame behavior thoroughly, especially its inefficiency and limitations. As the bay dimensions increased or the structure grew taller,

disproportionately heavier members were required, which reduced the potential offered by this system for such applications. Khan considered this system to be the weakest and placed it at the beginning of a range of possible systems. At the other end of the range, he put a pure cantilever, which utilized the entire three-dimensional form, as the strongest.

In 1969, Fazlur Khan classified structural systems for tall buildings relating to their heights with considerations for efficiency in the form of "Heights for Structural Systems" diagrams [3]. This marked the beginning of a new era of skyscraper revolution in terms of multiple structural systems. Later, he upgraded these diagrams by way of modifications[4]. He developed these schemes for both steel and concrete. He introduced this chart in order to define a sequence of systems, each of them with particular limitations. This set the stage for the "system approach" in the design of tall buildings, whereby the selection of an appropriate system was a significant design event. He argued that the process of optimization of the structure rested with the appropriate system selection; member optimization was secondary. New systems were placed into the chart as they were developed. During that period, the structural emergence in high-rise architectural expression was primarily aiming at integrating façade and structure, almost into a single entity.

Today, the substantial passing of pure stereometry in contemporary skyscrapers and the development of new and complex figurative solutions in terms of design, usually demand a hybrid approach combining different structural solutions, which can be adapted case by case to match better the requirements of the architectural form. Therefore, today the classification of structural solutions in relation to height presented by Khan, offering a clear diversification between different types of structure, cannot be integrated and updated. A quick and rough analysis shows that the recent high-rise structures have embodied more structural solutions previously associated to separate classifications: for example, the Spiral Tower in Nagoya, Japan (170 meters) has a structure consisting of an inner trusses tube with a triangular grid on the outside; the Swiss Re Tower of London (180 meters) by Sir Norman Foster is supported by a Rigid Frame steel inside and a triangular grid on the outside; the Al Sharq Tower in Dubai (367 meters) of Skidmore Owings & Merrill should have provided a structure composed of pre-stressed pipe system arranged in a Bundled Tube, braced by cables on the outside and concrete shear walls on the inside; the Shanghai World Financial Center (492 meters) has a Embedded Core, stabilized by four mega-columns and mega-diagonals on the outside, connected to the core with outrigger elements; the London Shard has at least three inner systems (Vierendeel Trusses, an "hat" truss and several outrigger elements) to increase the stiffness against lateral loads while producing the sharp outline.

Among all these hybrid systems in use, the outrigger structure has become one of the most popular solutions for super-tall buildings of more than one hundred storeys. Outrigger systems have been historically used by sailing ships to help resist the wind forces in their sails, making the tall and slender masts stable and strong. The core in a tall building is analogous to the mast of the ship, with outriggers acting as the spreaders and the exterior columns like the stays. As for the sailing ships, outriggers reduce the overturning moment in the core that would otherwise act as pure cantilever, and transfer the reduced moment to the outer columns through the outriggers connecting the core to the columns. These elements are configured as cantilevered structures that protrude from the core, made up of shear walls, towards the external structure. Outrigger components are generally allocated inside service floors among groups of regular floors in order to reduce the commercial loss of viable space. This system is able to stabilize the core in the horizontal direction, reducing greatly the bending moment at the bottom of the vertical shear walls, transferring a part to the elements in the facade that, depending on the motion of bending will be compressed or placed in tension. The structural principle can be detailed in several sub-systems, such as the Outrigger trusses, as in the Shanghai World Financial Center where four super columns at perimeter shape the profile of the building, or such as Outrigger shear walls in reinforced concrete as in the Burj

Khalifa in Dubai (828 meters), the currently world's tallest building (2013). Although loss of marketable surface occurs in the levels where the outrigger elements are inserted, the structure involves substantial benefits in the floor plan layouts and in the architectural vocabulary. Indeed, the use of this system releases the façade cladding from load bearing components (except the ones that have to be connected with the outriggers), so that the overlapping parts can have bulges, convexity, concavity, depression, and tapers. The visionary and expressive power of this structural scheme was brought to life for the first time by Pier Luigi Nervi in the Stock Exchange Tower (190 meters) in Montreal designed by Luigi Moretti.

When completed, on May 1st, 1965, the Montreal Stock Exchange Tower with its 190 meters was the tallest reinforced concrete building in the world. But it is not only the type of structure which clearly distinguishes the work of Moretti and Nervi from the original model of the American steel frame skyscraper: there are far more significant differences. It is the architect himself who highlights the main differences in one of the reports compiled during the long designing process. Indeed, he does not even hesitate to indicate as sources of inspiration of the project a few flaws of the Seagram Building, universally regarded as the archetype of skyscraper perfection. For Moretti, however, the "shape of the prism without taper" and "uncatchable image of the structure and his behavior" are deficiencies which cannot be countered by the "glass walls beautifully sized"[5]. Indeed, in the main symbols of modernity for a high-rise building, which are the undifferentiated and indefinite stereometry and the texture of the curtain wall, Moretti sees the mechanical translation of the logic of industrial production. For him, that is a radical depersonalization of what is incompatible with the conception of architecture as an artistic creation of the individual: architecture must be unique and unrepeatable. It is not simply the preference for the reinforced concrete structure, then, that we are interested in investigating in this paper, but most of all how the particular structural conformation, tailored in the design process to strengthen the identity and originality of one building, has been developed from a customized engineering approach to a standard and popular structural scheme for high-rise building. The tower in Montreal is supported by a complex and innovative structural skeleton, the efficiency of which is entrusted to a static system called by Pier Luigi Nervi the "main-resistant"[6]. This system is three-dimensional, and allocated inside and outside of the squared floor plans of about forty meters per each side. In fact, a central core of two baffles of reinforced concrete crossing diagonally is connected by trusses (only in correspondence of three units) to the four pilasters arranged at the edges of the volume of the building. The structural intuition relies on the role of crutches on the corner posts, in order to stabilize the core cross against horizontal forces. As we said the main internal stress that the structure of a tower needs to reduce, in order to increase the efficiency of the structure without increasing the number of structural components, is the bending moment at the core base. Here the stiffness of the core is guaranteed by connecting the main core of the building with the four mega-columns at the building edges through four deep diagonal trusses (which Nervi had built in reinforced concrete to ensure a monolithic structural behavior). In detail, the angular pylons, almost free from bending stiffness due to their slenderness, behave like pendulums (either compressed or tensed), depending on the tower horizontal motion under vertical load, increasing effectively the bending inertia of the core and consequently reducing the moment at the base of the tower. Regarding the gravity loads they are carried out to the foundation through an ordinary concrete frame system which is made up by the four angular columns completed with two intermediate pillars on each side of the squared floor plan. Therefore it is possible to assume that the conformation and the static behavior of the entire structure are quite standard when supporting just the crossed ribs floor slabs. Although the structural solution was tailored on the tower in order to accomplish the will of the designer, not all the parts of the super structure collaborate with the image of the building. Indeed, the elevation of the tower shows only some components of the mega bracing system. This aspect is quite important in understanding the relationship between structure and architecture in this building. The balance between the structural elements exposed and the bracing components which are hidden and also the glazed cladding of the facades is quite sophisticated. The four corner pilasters, tapered and

conspicuously detached from the glazing skin with a deep shadow gap, are crucial to the building appearance. More precisely, in order to emphasize the image of the pillars, the other eight intermediate pillars are concealed behind the curtain wall. Consequently, to avoid separate deformation, the external portion of the structure exposed to the significant daily temperature changes of Montreal, are protected by a shell made by white concrete panels[7]. The outer shape of angular pylons visible is independently detached from the inner structural section of pillars. Significantly bigger in terms of dimensions, the external cladding for the pillars provides a cavity for the passage of conditioning pipes and increases the impression of the static effort as the will of the architect. According to Moretti "the centralization of the loads in just few elements of the structure" to give a "high sense of stillness" to the building[8]. Essentially with a similar figurative strategy, the three floors, where the rigid connections between the nucleus and angular pillars are allocated, must be perceived in negative, as net horizontal cuts in the volume of the tower, interrupting the continuity of external surface. Therefore in order to release these fractures from all the structural components designated in them, the large trusses are not visible and the perimeter anti-torsion device, initially resolved by exposed structural wall-beams, is eventually reduced to two small ring beams, protruding only slightly more than a meter from the slab soffit, carefully hidden by the curtain wall. In addition, to better understand the delicate balance between architectural image and structural inventions, the three "cuts " do not all have the same height: the amplitude is reduced from bottom to top in order to create a perspective effect. This device is strikingly in contrast with the effects caused by lateral load, which are higher on the beams at the highest level, as confirmed in the calculation report[9]. Therefore, although structural expression seems to be a focal point of the building, it is important to highlight that the structure is exposed not to show off its efficiency but to contribute to the image of the building in an unpredictable way. The great achievement of the system is not only the powerful effectiveness of the four giant columns at the corners but also the way it releases the glass façade from any bearing load components. Thus, meanwhile Fazlur Khan was researching the way to achieve the "pure cantilevered behavior" designing a system where a dense grid of structural components concretely embody (and almost blended) the façade, Nervi and Moretti were working in the opposite direction, designing few linear super-structure parts (exposed and recognizable) and a non-standard glass cladding free by the main structural constraints. The priority of the overall figurative perception of the architecture compared to the functional and structural requirements is confirmed in a series of tiny and invisible deformations impressed on the architectural components as optical corrections. Indeed, the most original optical correction for the skyscraper is certainly the one about the taper and the convexity of the prism. To achieve that, Moretti, not happy with the compromise achieved initially with the project management, which agreed to have the sets back of the facades in just three shots concentrated at the technical floors, finally obtained, in a crucial meeting in Montreal May 19, 1962[10], the gradual reduction of the floor slab from plan to plan. In fact, the cantilever portion of the floor (about 15 cm thick), which has a polygonal profile that roughly outlines the slight curvature of the facades, is set back to about half an inch on each floor of the building. As mentioned, these transfigurations are managed by Moretti and Nervi not to show the structure but to emphasize the completeness, uniqueness and the figurative nature of the object. This approach, in contrast to the iterative solutions of American skyscrapers, leads the design strategy being named as "the unique form"[11], which has its archetype in the Pirelli skyscraper in Milan designed a few years earlier by Gio Ponti, and not surprisingly, with Pier Luigi Nervi as structural engineer in charge. However, although this Italian interpretation of the high-rise building based on a substantial customization of the structure led to the Stock Exchange tower, the intuition of Nervi had an impact well beyond the success of that building. Indeed the structural scheme has been developed over the years and nowadays what we call "outrigger" system represents one of the most popular solutions for super-tall skyscrapers. However, before being used in super-tall buildings the first steps in the development during the late 1960s and early 1970s involved the standardization of the system in order to make it replicable and adjustable for buildings of about 40 storeys. Ironically, the depersonalization of the architectural product so disliked by

Moretti has turned the original structural scheme created for the Stock Exchange Tower into a paradigmatic solution that could be replicated for skyscrapers with identical architectural features.

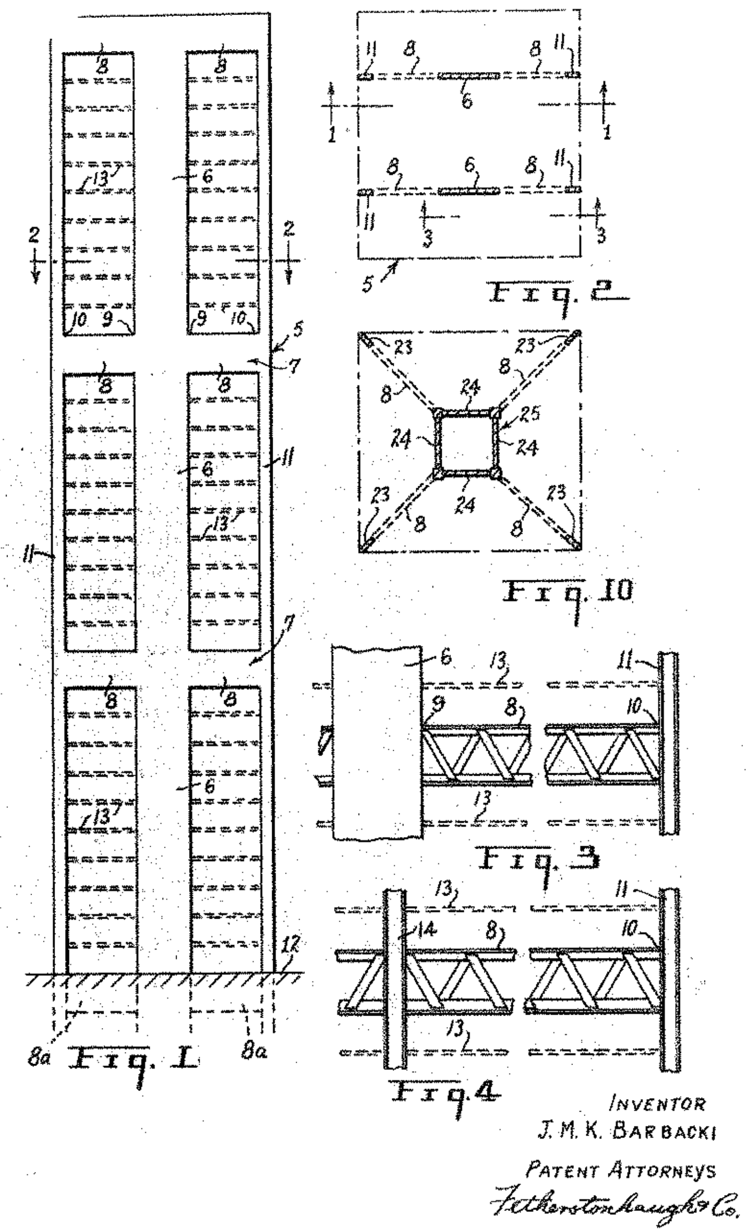

Fig. 2. Jacek M. K. Barbacki, Wind and Frame Earthquacke T-Frame system for building", drawing 1, patent n. 659142, CIPO. (Photo available on: cipo.gc.ca)

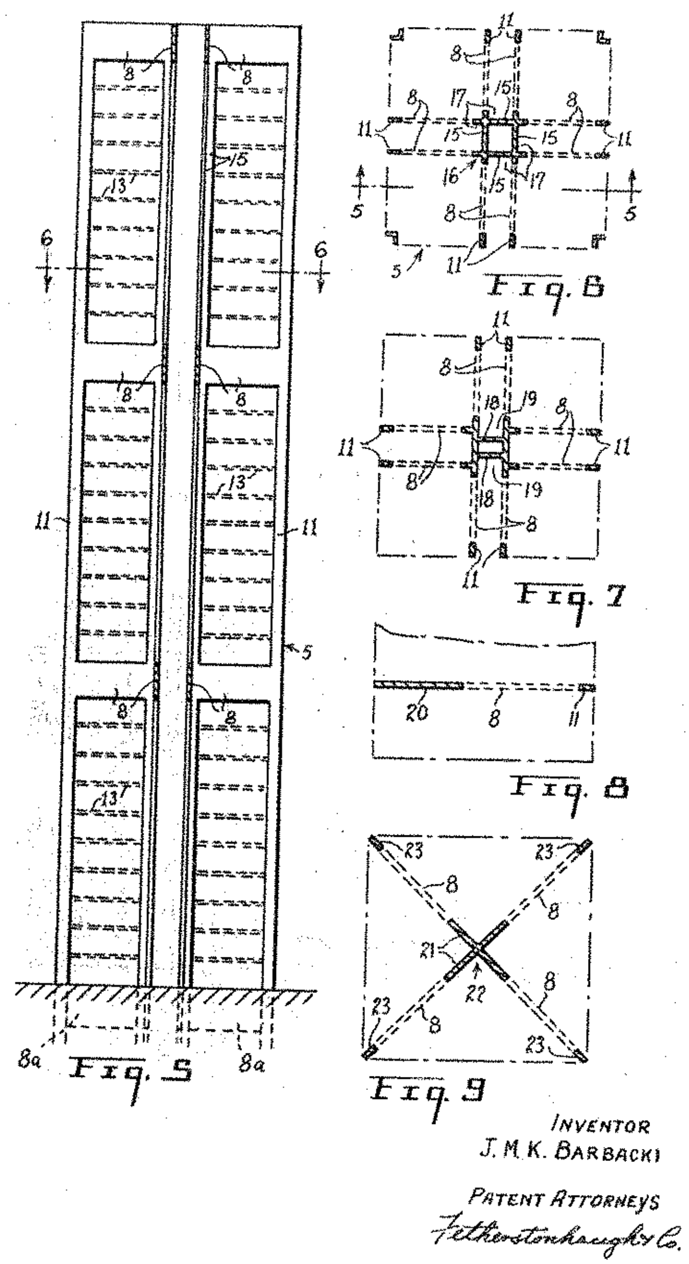

Fig. 3. Jacek M. K. Barbacki, Wind and Frame Earthquacke T-Frame system for building", drawing 2, patent n. 659142, CIPO. (Photo available on: cipo.gc.ca)

Pier Luigi Nervi developed the scheme for the Stock Exchange Tower collaborating with two Canadian engineering firm, Greenspoon, Freedlander & Dunne and D'Allemagne & Barbacki. The structural system was patented in Canada by Jacek M.K. Barbacki[12] in 1963 under the title "Wind and Frame Earthquake T-Frame system for buildings". In order to understand how the system was modified and consequently applied to other buildings over the following years it is necessary to analyze carefully the Canadian patent (Fig.2-3). The documents submitted for the patent showed a structural system made by components extrapolated from the Stock Exchange Tower, combined with different and more flexible and adjustable solutions. The patent proposal consists of a description where the main advantages of the system are highlighted and two pages of drawings showing how the same structural components can be assembled for different functional solutions. According to the description, the fundamental parts of the scheme are the vertical shear walls, the outer columns and the "horizontal frame" (the outrigger elements).[13] In addition, going beyond the Montreal experience, the report stressed that the T-Frame system "may be of any well known type of construction such as structural steel, reinforced concrete or other structural material or any combination of these types. For instance, the shear walls may be of reinforced concrete construction and the horizontal frames may be of steel, either solid beam or open truss construction."[14]. The drawings are two sections, six floor plans and two detailed enlarged vertical sections showing the connection between inner and outer structures. The floor plans describe six different ways of arranging the vertical shear walls, according to different architectural core layouts. In fact, "it is to be understood that the number of shear walls to be incorporated within the building will depend upon the size and shape of the building. For instance, in a building that is square in plan, only one shear wall may normally be required, whereas, in a building with a long face in plan, two or more shear walls may be installed" as it is shown in the figure number 2 of the drawings (Fig.2). In detail, the first two floor plans display shear walls parallel to the edges of the building. The figure number 8 (Fig.3) describes how to modify the system allocating the vertical walls at one side of the building with the horizontal frame spanning the floor to a column at the opposite exterior wall. The figure number 9 (Fig. 3) displays the original Stock Exchange Tower solution with the shear walls in form of a cross and with the horizontal components disposed diagonally towards columns at the corners of the building. Among the others, the most interesting shown layout is the one with the outrigger elements parallel to the side of the building. Indeed, there is no indication about how this system could be integrated in the building elevation especially because the outer main structure should be allocated in the middle portion of the façades. It is a significant change from the Nervi and Moretti approach who had put the outer super structure at the corners in order to combine structural improvement and architectural expression. Indeed, it should be noted how the system conceived in order to increase the formal independency of the façade from bearing load parts in Montreal, has been developed in the patent with options alluding to differing architectural outcomes. However, it is clear that any other external column allocation except the one with the columns at the corner would be weaker in terms of bending and torsional inertia[15]. From this assumption we can understand the development that Khan brought to this system, starting from the layout with the parallel outrigger ribs. Indeed, although the structural system was patented in Canada in the 1963, apparently Khan did not mention it in the chart of 1968 with the name of "outrigger" system. It is clear that Nervi and Barbacki came up with that system to improve the lateral stiffness of a framing "regular" building structure, while Khan's approach has always been oriented towards the "pure cantilever" behavior working on the stiffness of the building envelope. In fact, according to his research path, he developed his own version of outrigger system for two buildings around 44 storeys each, integrating the efficiency provided by linking inner shear walls with external structural components with the experienced tube structure. That system became the belt truss structure, employed for the BHP House in Melbourne (Fig.4), completed in the 1972, and for the First Wisconsin Center in Milwaukee (Fig.5), completed in 1974. The belt-truss is a structural component invented by Khan to reinforce the external wall structure at the specific levels where the outrigger elements are provided. The main aim was to improve the way in which the wind load was transferred to the foundations of the building.

Acting as a rigid belt around the building the orientation in plan of the outriggers was no longer an issue. The loss of bending and torsional inertia occurs from pointing the horizontal ribs to a central field of the facades and has been balanced with the belt-truss which is able to absorb the vertical load all along the exterior walls of the building and transfer it to the core at the outrigger levels. In more detail, "Khan suggested that at least two levels of horizontal outrigger trusses were needed to engage the perimeter wall: one around mid-height and one at the building top. Equally important, he suspected, was the stiffening of the exterior frame at these same levels to increase their participation in the interaction system. Without the stiffening, only a few columns of the frames would be directly engaged by the trusses, leaving the potential restraining influence of the exterior frames largely untapped: while the few engaged columns would work to anchor the core, the large majority of columns, further removed from outrigger connection points, would not"[16]. His idea, therefore, was to force the full width of each frame to participate in resisting the bending of the core structure by introducing storey-high "belt" trusses in the perimeter at each outrigger truss level. The two buildings structurally designed by Khan with the belt-truss system have development path extremely different.[17] However, when comparing the architectural expression of both it is easy to understand how the result led to a similar identical appearance.

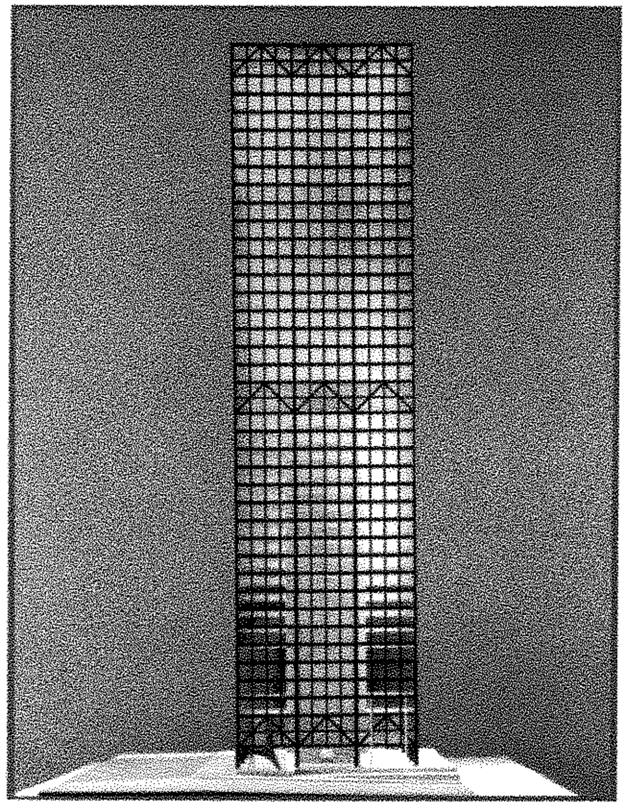

Fig. 4. Yuncken Freeman Architects with Fazlur Khan and Hal Iyengar (Engineers, S.O.M.), 140 William Street (formerly BHP House), Melbourne, 1972, model of the tower. (Picture by Wolfgang Sievers, available on:<http://nla.gov.au/nla.pic-vn4902728>)

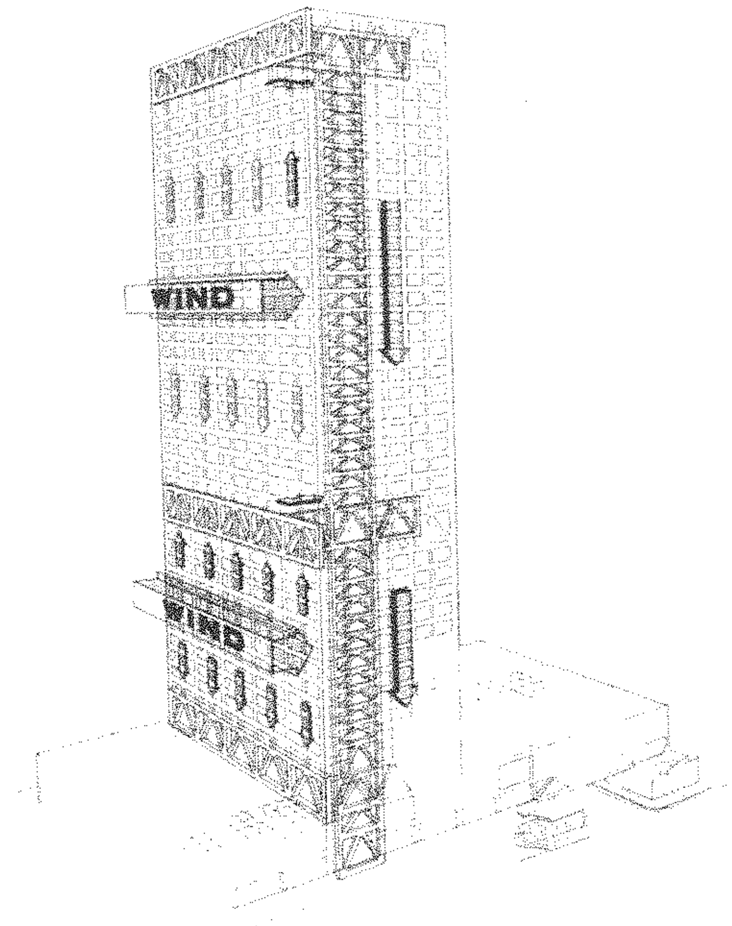

Fig. 5. Bruce Graham, James DeStefano (architects, S.O.M.), Fazlur Khan (Structural engineer, S.O.M.), First Wisconsin Center, Milwaukee, 1973, structural diagram. (Courtesy: James DeStefano)

Conclusion

Starting from the first experimentation, the system modified and developed by Khan is more replicable and adjustable for buildings with a boxy silhouette. According to Hal Iyengar, one of the engineers associated with Fazlur Khan on many projects, "the systems must be applicable over a broad cross section of structures and not just to particular solutions to particular buildings. The systems must be architecturally relevant, providing a basis and often a vocabulary for visual expression". [18] In these words is possible to recognize the outline of the American approach: it is the structural system that has to provide the architectural language of the building rather than being shaped as a non-standard support for the figurative artistic expression, as it was in the Montreal.

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