

A STRUCTURAL INSIGHT FOR THE PRESERVATION OF MARINA CITY TOWERS IN CHICAGO

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Abstract

In relation to reinforced concrete high-rise buildings built in the Fifties and Sixties of the 20th Century in Chicago, it has acquired importance the re-analysis of their structural performance according to the provisions prescribed by new structural design codes, that have substantially changed both design actions and verification procedures. In this paper the case study offered by the two Marina City towers is analyzed. Marina City towers (1959 - 1967) designed by Bertrand Goldberg represent an important architectural landmark in the Chicago skyline. At the time of their completion, the Marina City towers were the tallest reinforced concrete apartment buildings in the world. Typically, this kind of high-rise buildings was designed for withstanding vertical and wind lateral loads only. Although the seismic hazard is classified as low in the area of Chicago, the design seismic forces could become more severe than wind actions for historical tall buildings, due to the limited ductility resources available in the structural elements, mainly in the shear walls. The aim of this work is the analysis of these towers from a structural point of view considering three different codes: the Chicago Building Code of the 1950s, the current Chicago Building Code and the ASCE7-10.

1. Introduction

Reinforced concrete high-rise buildings, built in the Fifties and Sixties of the 20th Century, are facing today the problem of safety verification in relation to the requirements of new structural design codes. The idea of this research stems from the consciousness that the provisions of the newest structural design codes have substantially changed both design actions and verification procedures, compared to building design criteria followed in the past. At the same time, during the last few years, the computational analysis of the structural capabilities of buildings to withstand seismic risk has acquired remarkable importance. Non-ductile reinforced

concrete structures, built in seismic areas before the introduction of modern design codes, represent an important fraction of the building stock worldwide and strongly condition its overall vulnerability. Reinforced concrete structures built without reference to a seismic design code, in areas that have subsequently been included in a seismic zone, may thus significantly increase the seismic risk of a country. The change in the codes and the introduction of new factors into the design process, at the end of the 20th Century, often resulted in a dramatic choice regarding many buildings, with the demolition as the prevalent option. In this paper a structural analysis of the two iconic Marina City towers erected in Chicago in the '60s, offered an interesting basis for the discussion of all this matter. Still nowadays, the Marina City towers (1959 - 1967) by Bertrand Goldberg represent an important architectural landmark, that needs to be preserved, in the Chicago skyline. Since their construction, they entirely expressed the intrinsic sculptural nature of concrete with their challenging height of 180 meters. Moreover, the two towers express the first attempt in the U.S. to explore a new structural layout composed by a rigid core in concrete with reinforced concrete columns all around. The architect, Bertrand Goldberg, decided that, unlike any project before it, Marina City had to be an experiment of allocating, in a unique structure, diverse programs into a "city within a city". This design choice is perfectly reflected in the architectural layout of the building as well as in its structural design. Typically, this kind of high-rise buildings were designed for the effect of vertical loads and wind lateral loads only. Through a Finite Element model of the structure, it has been possible to characterize the wind response of the building, comparing the:

- (1) the Chicago Building Code of the 1950s,
- (2) the Chicago Building Code as it is nowadays and
- (3) the ASCE7-10.

Moreover, even if the seismic hazard, in the Chicago area, is classified as low (as it appears from the 2014 Seismic Hazard Map of Illinois provided by USGS), a response spectrum analysis was conducted according to the ASCE7-10 load combination. Concluding, the effects of the wind action of the original project, the wind action now required and the seismic action have been considered and compared for a correct evaluation of the available safety margins of the structure.

2. The Marina City towers in Chicago

When completed in 1964, Marina City's apartment towers were the tallest concrete and residential structures in the world, with a peculiar curvilinear shape emphasized by semicircular concrete balconies. The architect, Bertrand Goldberg, described each tower as a "tremendous tree trunk". According to the architect, the curves of the balcony floors, flowing smoothly into vertical columns, represent a seamless transition between an integration of architectural and engineering decisions. Goldberg thought that rectilinear housing projects were depressing. He said: "*(I) wanted to get people out of boxes, which were psychological slums*", adding "*those long hallways with scores of doors opening anonymously are inhuman. Each person should retain his own relation to the core. It should be the relation of the branch to the tree, rather than that of cell to the honeycomb*".



Fig. 1 –Marina City photographic image and sketch by Bertrand Goldberg (courtesy of the Art Institute of Chicago).

The ring-shaped plan of Marina City apartments is a flower, a marigold. Not modular structures but elements evoking an organic growth using the repetitive forms of industry, but at the same time resulting in something unique. The circle doesn't

interest him just because it is a circle but because of the possibility to locate a focal point with certitude. At the heart of the flower is the efficient core containing all the utilities. And each petal of the flower equidistant from the core becomes a bay which contains an apartment, which combines with other bays to make a larger apartment. When he had the design completed, he saw that he could combine bays to make exciting desirable apartments of all sizes. Checking with engineers, he found out that the completed design had only 30% of the wind load that a building of rectilinear shape with the same dimension would produce. He found that he had a tall building with less than half the rate of deflection of the Empire State Building. He had the only high-rise building in this country with simplified window washing and exterior wall maintenance provided from the balconies. And in plan, he had a very high ratio of interior square footage to exterior wall surface which produces a tremendous saving of construction and upkeep. He had been asked about building “20-story garage” so that he decided to combine both apartments and parking lots in the tower design. Moreover, the idea to raise the apartments high above the downtown noise and dirt was extremely innovative at the time. Above seven or eight years earlier, he made a study of the “parking helix”. This is a form of ramp turning continuously at the same radius with parking space for automobiles provided on the ramp itself, rather than on a floor adjacent to the ramp. The most important thing about the garage operation was the length of time it takes a runner to get to a car. And here in Marina City, there is no car further than 50’ from mechanized vertical transportation for the car runner. There is a manlift at the central core which carries the carhop within a short walk to any automobile. And with the single depth parking, he had about the most efficient garage operation in the city. The last 40 floors are dedicated to residential purposes. From the circular central core, Marina City apartment plans radiate in the form of sixteen “petals”. An efficiency apartment occupies one petal, a one-bedroom unit occupies a petal and a half, while a two-bedroom unit occupies two and a half petals. Each petal’s radial geometry is subtle, with a gentle outward flare. The bathroom and the kitchen are close to the core and next to the entry, while living and sleeping quarters extend to the balcony. This reduced the utility distribution lines and placed darker areas inward, while opening living and sleeping quarters to the sun.

3. The structural layout

The towers structure is made up of a rigid frame and core. The rigid frame responds to lateral loads primarily through flexure of the beams and columns. This type of behavior results in large lateral drift for buildings of a certain height. However, introducing a core structure significantly increased the lateral resistance of the building as a result of the core and frame interaction. According to Goldberg: “*The shape of the core means that the buildings have only 30% of the wind resistance that they would otherwise have with the same dimension, but in rectilinear form*”. Each core is 180 m (588 ft) high and has an inside diameter of 9.7 m (32 ft). Its walls vary in thickness from 76.2 cm (30 in) at the base to 30.5 cm (12 in) at the top and take the main transverse load of the building. The core houses five elevators, two stairs, the utilities, the trash chute and all the vertical service facilities. The inner ring of rectangular columns has a diameter of 47 ft (14 m); an outer ring of diamond-shaped columns is on a diameter of 109 ft (33 m). Sixteen radial beams span from the interior core across the inner columns to the outer ones. Ramps or balconies extend 3 m (10 ft) beyond the exterior columns for a total outside diameter of 39 m (128 ft). The foundation system goes down to 33.5 m (110 ft) below the adjacent Chicago River through dump debris, soft Chicago clays, an abandoned railroad tunnel and boulders to rock. Structural engineers in the Goldberg office were Bertold E. Weinberg and Frank Kornacker. Frank Kornacker had been Mies van der Rohe’s structural engineer for all of his buildings, including the Seagram’s, had given up his own office and “joined” Bertrand Goldberg Associates full time. To them, Goldberg added Moran-Proctor Mueser_Rutledge, with Mueser and Rutledge working with them directly. Added to team were also, Professor Ralph Peck and Sidney Berman (Case Foundation Company was the general foundations contractor) for the foundation design. Engineering consultants were Severud, Elstad & Krueger, with Severud and Bandel as principals. Dr. Andrew Fejer was their adviser on aerodynamics. To this group came John Banker, Frank Randall, and R. H. Olson of Portland Cement Association, who gave them their seal of approval. The general contract was a joint venture between James McHugh Construction Co. and Brighton Construction Co., of Chicago. Commonwealth Edison and General Electric added their consulting staff to the mechanical engineering group. At construction time, Marina City was the most important concrete structure in the world, and the most important electrical installation in the world for living purposes.

4. The Finite Element model

Through all the information gathered in the Goldberg's archive and Art Institute of Chicago archive, it has been possible to develop a mathematical model of the structure taking into account all the technical information of these two RC high-rise buildings, such as reinforcement details, the use of different materials at different floors and live loads in use at design time. It is interesting to note that the Marian City Towers were the first structure designed with lightweight concrete. For all vertical members – columns and walls – conventional aggregate was used to produce concrete in strengths of 34 MPa (5000 psi), 23 MPa (3750 psi) and 21 MPa (3000 psi), decreasing from bottom to top. For the horizontal members (slabs and beams), 21 and 23 MPa materials were used, made from lightweight aggregate. As all the ramps, as well as the balconies on the apartment floors, were going to be exposed to the ambient weather, a 6-bag mix with lightweight aggregate was used for greater durability. Use of lightweight concrete created a few problems. Some work days in winter were lost, when temperatures were very low but concreting could continue with regular aggregate concrete. Moreover, in constructing the ramps, it was noted that the square corners for the beams had a tendency to spall off when the forms were stripped. This problem in the apartment was not acceptable, as the beams were to receive paint only. Therefore, for the apartment floors, all the beams were given one bottom pass of normal aggregate concrete, about 2-3 in deep. The rest of the beam was filled with lightweight concrete. On the other hand, without the use of lightweight aggregate, the floor-to-floor height of 8 ft 6 in could not have been maintained, and the size of caissons, columns beams and slabs would have been considerably greater. Each half floor of the ramp required about 55 cu yd of regular weight concrete for the columns and 90 cu yd of lightweight concrete for beams and slabs. Basically, the same system of construction was used for the apartment floors as for the ramps. Form works, beam and slab reinforcing and concrete placing all were the same as for the ramps. The construction cycle called for a complete floor every other day.

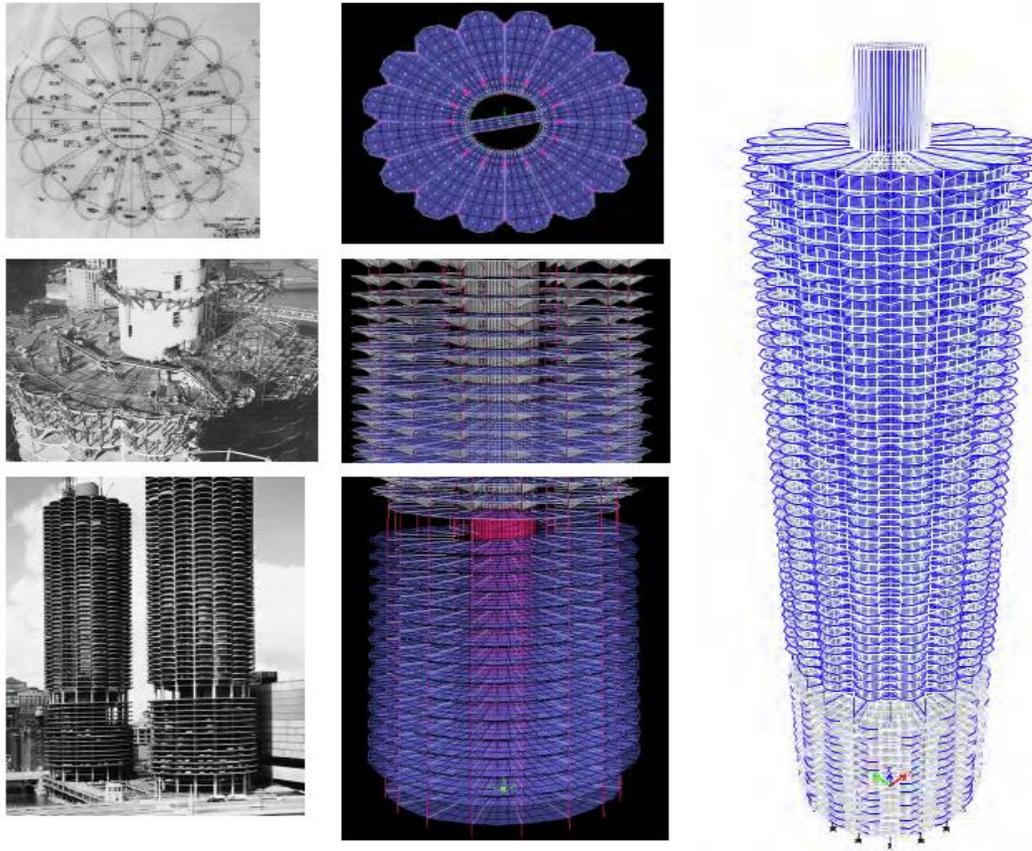


Fig. 2 – Finite Element model of one Marina City Tower

The finite element model developed in this study, built with the ETABS FE code, is composed of shell and beam elements. Beam element are used for columns and beams while shell elements for the core, the slabs and the parking ramp. On the basis of the information gathered in the archive, it was possible to assign to each element the proper material and a precise geometric definition (cross sections for beam elements and thickness for shell elements). The concrete core and the slabs were modeled using shell elements with varying thickness values. Fig. 2 shows some images of the mathematical model developed using the finite element method.

5. The structural analysis

The FE model was used to evaluate the structural performance of the building, in order to estimate which is today the most challenging design load combination, as prescribed by the Chicago Building Code and ASCE7-10. The results of modal analysis, in terms of periods and effective masses, are summarized in Table 1. The regular variation of period values and effective masses well reflects the building symmetric behavior.

Table 1 – Modal analysis of the Marina City tower

Mode	T [s]	Mx [%]	My [%]
1	5.685	5.2	59.64
2	5.635	59.78	5.23
3	4.007	0.00	0.00
4	1.579	0.21	13.79
5	1.576	13.66	0.23
6	1.086	0.00	0.00
7	0.798	0.02	6.12
8	0.795	6.06	0.02
9	0.671	0.00	0.00
10	0.515	0.013	1.01

Modal shapes for the first three natural modes are shown in Fig. 3.



Fig. 3 – Marina City modal shapes (1st, 2nd and 3rd mode).

The wind analysis for Marina City Towers was performed using three different codes:

- (1) the Chicago Building Code which was in force in the 1950s,
- (2) the Chicago Building Code in the present version
- (3) ASCE7-10.

The results show that the core is working as expected in terms of wind resistance as it takes 94% of the wind load while the columns just 6%. Moreover, the maximum deflection obtained is about 27 cm (10.636 in) with the most restrictive code (ASCE7-10). The wind analysis with the Chicago Building Code of the Fifties leads to a value of 22.4 cm (8.83 in) for the maximum displacement at the top floor. This result can be compared with the one corresponding to the Chicago Building Code as it is practiced today, 25.7 cm (10.1 in). Therefore, ASCE7-05 remains the most demanding Code for the structure.

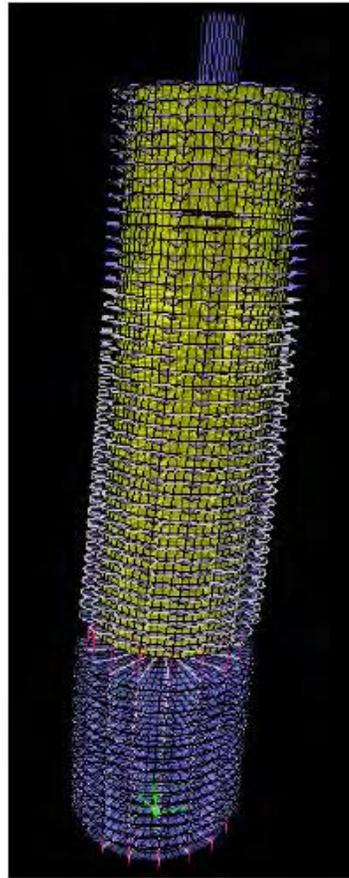
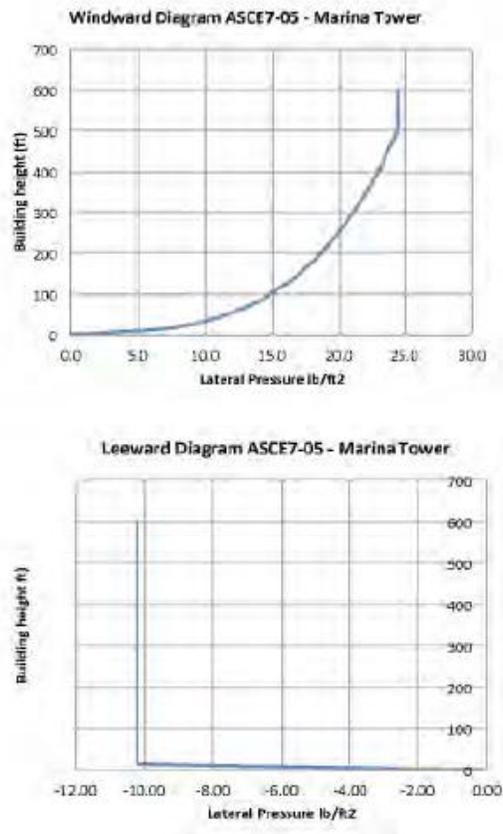


Fig. 4 – Windward and leeward pressures applied to the structure according to the code ASCE7-10. Right: Deformation of the structure due to the wind loads.

Table 1 – Shear force distribution in the internal and external RC columns around the core (the percentage is related to the total shear forces for the two wind load conditions).

Shear force distribution in the RC structure			
Chicago Building Code		ASCE7-10	
External columns [kN]	Internal columns [kN]	External columns [kN]	Internal columns [kN]
329	195	373	204
3.8%	2.27%	3.79%	2.23%
Core [kN]		Core [kN]	
8633		9007	
93.93%		93.98%	

An interesting aspect in this investigation about the design of Marina City Towers refers to the maximum allowable deflection; when the structure was designed, this was calculated by a very simple formula (the height of the building divided by 600) and amounted to about 28.2 cm (11.1 in). This result seems to be perfectly in line with the structural performance according to today’s standard of design. As to the seismic hazard, ASCE7-10 specifies the seismic load combination to be used in connection with the design response spectrum related to the specific site (Marina City towers: lat. 41.88 and long. -87.628).

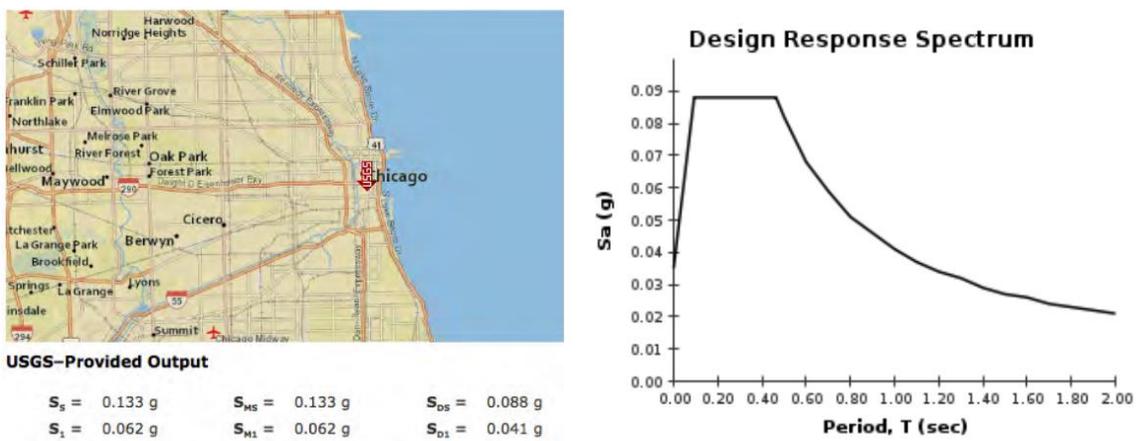


Fig. 5 – Chicago design response spectrum

Computations highlighted that the maximum displacement in X direction is about 12.5 cm (4.92 in) while in Y direction is 11.7 cm (4.6 in). Therefore, the resultant maximum displacement is 17.1 cm (6.72 in). The discontinuity in the displacement distribution at the 20th floor is mainly due to the different structural layout of the first 20 stories of the building, which have been designed as a concrete spiral ramp with parking lots. Instead, the 60 floors above the parking ramp, having residential purposes, are made of horizontal slabs supported by RC concrete beams. This explains the reason why the first 20 spiral shaped floors increase the stiffness of the building and effectively contribute to resist horizontal loads (wind and earthquake). Moreover, the resultant shear force due to the earthquake load combination at the tower base is lower than the one obtained through the wind load combination analysis by about 33%. The shear force distribution remains qualitatively the same as in the previous case, confirming the proper structural design of the RC circular core acting as the main bracing system. As to the dynamic behavior of the tower, the first vibration period is 5.68 s, which corresponds to a response acceleration in the Chicago design response spectrum (Fig. 5) of about 0,007 g, equal to 1/5 of the peak ground acceleration estimated in Chicago.

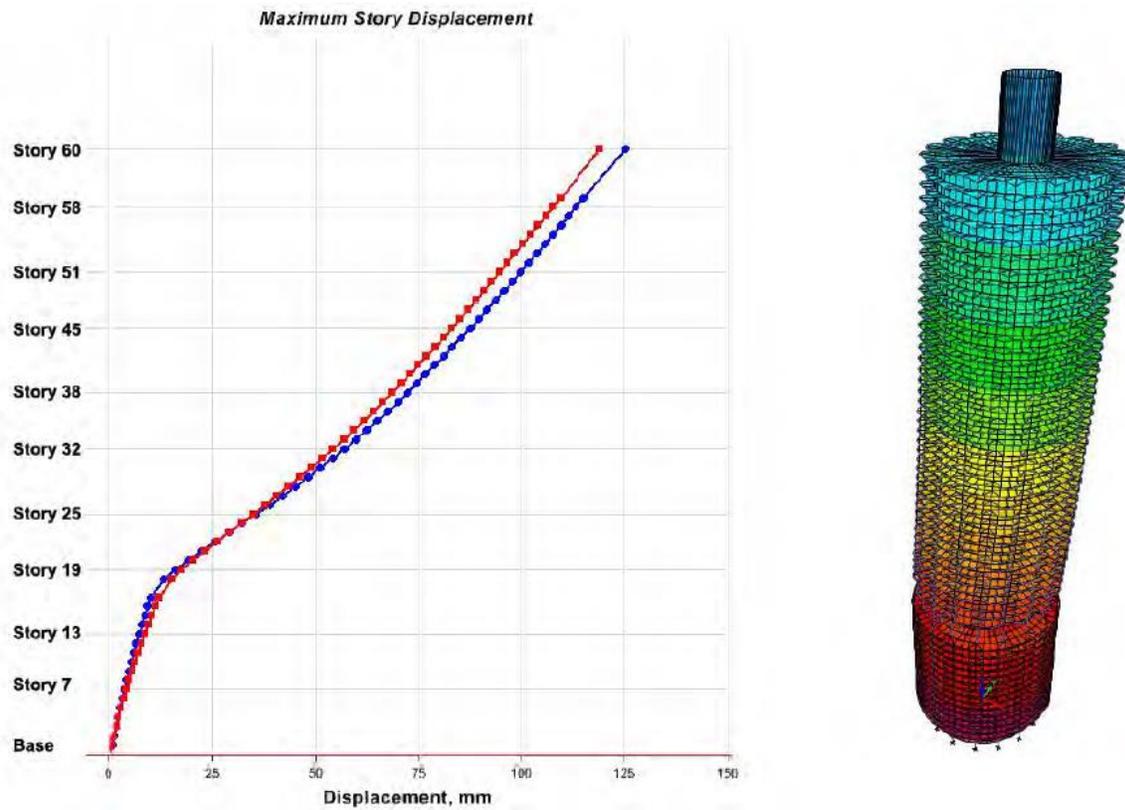


Fig. 6 – Left: Marina City tower displacements in X direction (in red) and Y direction (blue) with the seismic load combination (ASCE7-10). Right: Resultant displacements with the seismic load combination (ASCE7-10)

4. Conclusions

Reliable computational models are needed to perform the safety evaluation of existing structures according to new code requirements and action definition. The availability of the original design documentation of Marina City towers at the Art Institute of Chicago allowed a precise numerical simulation of the building response to both wind and seismic actions. Through the implemented FE model of the entire building, a response spectrum modal analysis with has been performed. A major result offered by this analysis is given by the total shear force at the base of the building. A total value of 6628 kN has been obtained, smaller than the design wind action in the same direction. The seismic load, therefore, comes out to be less challenging for the structure than the wind load. In general, the research highlighted that in Chicago wind actions remains the main issue for tall buildings. An interesting outcome from this investigation on the design of Marina City Towers has to do with maximum building deflection; the value of 28.2 cm (11.1 in) which was estimated at design time by a very simple formula well matches the values coming from a sophisticated FE element model of the structure. In conclusion, notwithstanding today's standards for design which require the consideration of seismic loads, old-style hand calculations and the structural choices made by Bertrand Goldberg back in the Sixties seem to comply with the results provided by detailed computer models.