THE DIAGRID SYSTEM IN MODERN HIGH-RISE BUILDINGS

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ABSTRACT

In the architecture of high-rise buildings there are a multitude of architectural forms, such as twisted, tilted, tapered and free forms. The article describes the characteristics of the diagrid system and its applicability in the construction of tall buildings in relation to other modern construction systems: braced-tube and outrigger. The authors attempt to evaluate the effectiveness of this system for various geometric forms. The characteristics of buildings with very complex geometry and that use the diagrid system are presented.

I. INTRODUCTION

The design of tall buildings starts with the shaping of their spatial rigidity to gravity and horizontal forces (wind, seismic and para-seismic forces). As the height of a building increases, the importance of horizontal forces also increases in the process of selecting its load-bearing structure. The main problem here is the choice of a suitable construction solution that would meet the requirements for ultimate limit states (determined by the strength criterion) and serviceability limit state (determined by the stiffness criterion). The selected type of load-bearing structure of a high-rise building must have sufficient strength to transfer all loads and impacts and also have appropriate rigidity, which is determined by the admissible amount of inclination of the top of the building subjected to the lateral load. Contemporary high-rise buildings consist of one or several basic support structures: rigid frame, shear wall, core or tube. High-rise buildings with mixed constructions (shear-wall, braced-tube, tube-in-tube) are formed with the combination of several load-bearing structures. The application of particular types of load-bearing systems is determined by the height and geometric form of the building. Due to very complex geometric forms of tall buildings, it has recently been very popular to use the diagrid system for both steel and reinforced concrete. The stiffness of the bearing structure is a superior criterion in the shaping of a tall building, and its value lies in the size of permissible vertical deflection. Limitation of the vertical deflection of a high-rise building is not only aimed at preventing and minimizing the adverse P-delta effects on the structure of a building. The stiffness of a tall building can also be considered as an indirect indicator of its susceptibility to dynamic influences.

High spatial rigidity reduces the amount of acceleration associated with the horizontal displacements of a tall building and also increases the natural vibration frequency, which for low values can be dangerous for construction. Vortex induction is generated when a low-pressure area is formed on the leeward side of a building's structure. This causes the movement of the structure perpendicular to the direction of the wind. The structure can fall into resonance at critical wind speeds, which generates both high stresses and vertical deflection. The aim of this article is to present relationships between the development of modern architectural forms and the diagrid construction system. From a geometrical point of view, modern tall buildings can be categorized into the following groups: twisted, tilted, tapered and with free form.

II. CHARACTERISTICS OF DIAGRID CONSTRUCTION SYSTEM

Diagrid structures commonly use intersecting diagonal elements (Fig. 1) instead of conventional vertical columns. These elements are used as a structural support system that gives the building a recognizable character. Typically are two types of nodes in this system: the interior and corner. The interior nodes are planar and transfer the loads in two-dimensional space, whereas the corner nodes transfer the loads in three-dimensional space and thus form a more complicated arrangement. These nodes are joined to the other sections by welding or bolting (Fig. 2). A diagrid is a special form of spatial truss.

Fig. 1 Detail of the diagrid system

The difference between a conventional braced-tubestructure and the current diagrid structure is that thediagrid system has almost completely eliminated theuse of columns. This is possible because diagonal elements in the diagrid system can carry gravity loads as well as horizontal loads thanks to their triangular configuration.

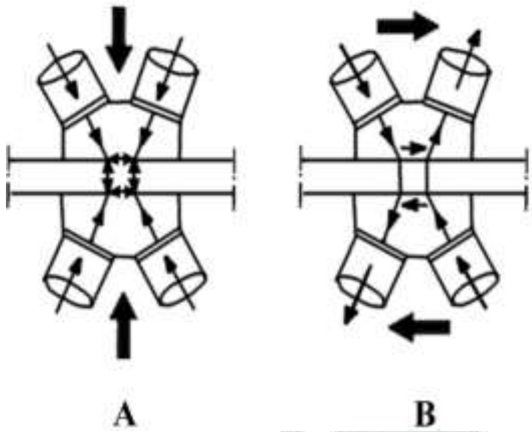

Fig. 2 The diagrid structural system node: A) under vertical

load,

B) under horizontal shear

The constructional function of the braced-tube structure and the diagrid structure is generally very similar, because both systems transfer lateral loads very efficiently through the axial action of structural components. However, bending stiffness in the braced tube system is obtained by vertical columns located on the periphery. In the diagrid system it is obtained by a diagonal grid, which also gives the shear stiffness. Both systems have advantages and disadvantages The diagrid system has greater stiffness and resistance to lateral forces. However, this type of construction is more complicated and costly than the braced tube system. On the other hand, the braced tube system has a greater shear lag effect than the diagrid system. In fact, the diagrid system is the evolution of a braced tube system with concentrations of mega diagonal elements. Moreover, by using a diagonal grid, structures require less structural material than a conventional structural system composed of orthogonal elements. The design efficiency of the diagrid system allows the number of internal columns to be limited and this is associated with the possibility of flexible interior design. In this system, the geometry of a single module plays an important role in both the internal distribution of axial forces and in global bending and shear stiffness. The diagonal grid module has

a trapezoid shape and its height is several floors. Depending on the number of stories, the modules are divided into small (2-4 stories), medium (6-8 stories) and large (over 8 stories). Modules and diagonal angles play a key role in the structural, architectural and aesthetic concept of the design of the building. Structures of this $K_{t} = 2N_{w}\frac{A_{d,w}E}{L_d}\cos^2\theta$ (2)

where: K_b - bending stiffness, K_t – shear stiffness, $A_{d,w}$ – the area of each diagonal on the front side, $A_{d,f}$ – the area of each diagonal on the lateral side, E – the modulus of elasticity of steel, θ – the angle of diagonal

type are made of steel, reinforced concrete or composite. Due to the form, they may be flat, crystalline or multi-curved. The steel construction expresses regular diagonals in the façade of a building, is easier and quicker to assemble and is highly compatible with the concept of a sustainable building. In the design of the diagrid construction, an important factor is to choose the right diagonal angle. If the diagonal angle deviates from the optimum value, the required amount of steel is substantially increased. Because the optimum angle of placement of the columns for maximum bending stiffness is 90^0 and diagonals achieve maximum shear stiffness at an angle of 35^0, the optimum angle for diagrid construction elements is therefore taken between the values of these angles. The arrangement of diagonal elements with larger angles in the corners of the building increases its bending stiffness. High-rise buildings with a high ratio (height/width) behave like bent beams. Therefore, when a building’s height rises, the optimum diagonal angle also increases. The stiffness of bending and shearing of the diagrid module (Fig. 3) can be represented in the form of equations (1) and (2) [8]:

$$K_b = (N_f + \delta)\frac{B^2 A_{d,F} E}{2L_d}\sin^2\theta \quad (1)$$

member, B - building width, L_d – the length of diagonal, N_w – the number of diagonals on each front side plane, N_f – the number of diagonals on each lateral side plane, δ – the contribution of front side diagonals for bending stiffness.

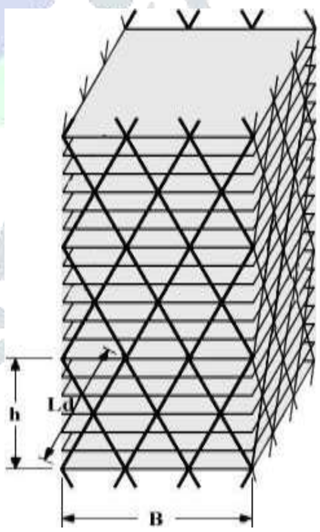

Fig. 3 Typical diagrid module

Buildings in this construction system are designed on a circle, ellipse, or other curved geometric form. Adoption of such forms is very beneficial for reasons of dynamic impacts. As the height of a building increases, the lateral strength becomes more important than the load-bearing system that carries gravity loads. Therefore, any modifications to the geometric form of tall buildings generally reduce the adverse effects of the wind, which is an additional reason for the greater creativity of architects. The diagrid system is perfectly matched in the modification of the classical geometrical form. In this system, the following forms are known: hyperboloidal, cylindrical, twisted, tilted and free. Due to such complicated geometric forms, the task of designers is even more complicated for optimal design. This task is possible to be solved using computer aided design and computerized visualization. Parametric structural models are generated using appropriate programs and can be exported to construction and energy analysis programs. Exemplary high-rise buildings using diagrid construction include the Doha Tower, Tornado Tower, Hearst Tower and Capital Gate. These buildings will be the subject of further analysis.

III. DIFFERENT GEOMETRIC FORMS OF HIGH-RISE BUILDINGS IN THE CONTEXT OF OPTIMAL CONSTRUCTION SYSTEMS

A. Twisted structures

The use of twisted forms for tall buildings has recently become an increasingly common architectural phenomenon in the world. The precursor of this type of construction is Santiago Calatrava, who designed the Turning Torso in Malmö (Sweden, Fig. 4)), the first twisted building in the world. When considering this geometrical form for optimum static work of a building, it is not advantageous compared to a straight rectangular body. For this geometrical form, diagrid, braced-tube and outrigger systems are used. For twisted tall buildings using the diagrid system, lateral stiffness decreases as the turn ratio increases. However, this system is much less sensitive to the turning ratio when compared to the braced-tube system. In the case of the outrigger system, the mechanism of the action determining the lateral strength of the building differs significantly from the two previous systems.

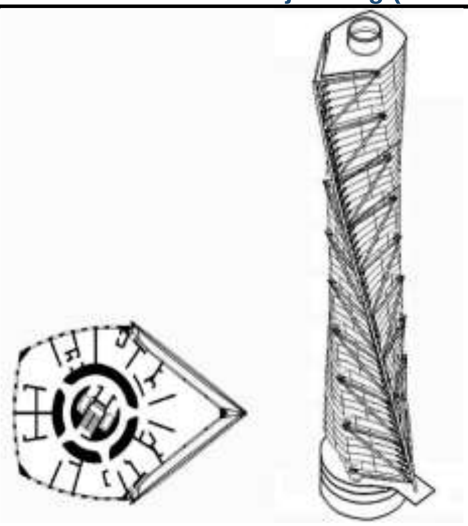

Fig. 4 The Turning Torso – Plan and cross-section

Lateral shear forces and the overturning moment in the diagrid and braced-tube systems are transmitted on the periphery. In an outrigger structural system with a braced core, the core carries lateral shear forces and part of the overturning moment. The perimeter mega columns connected to the rigidly braced core through outrigger trusses also have a significant share of bending stiffness in this system. As the outrigger structure is twisted, the perimeter mega columns wrap spirally around the building. The lateral stiffness of the outrigger system is substantially reduced as the twist ratio increases.

B. Tilted structures

Tilted tall buildings are designed to create a kind of dramatic architecture. An example of such a geometrical form is the Veer Towers in Las Vegas designed by Francisco Gonzalez-Pulido (Fig. 5). The static behavior of tall tilted buildings depends on the structural system and the tilt angle. Tilted buildings are subjected to a considerable initial horizontal deformation caused by non-centric gravitational loads. The induced gravitational horizontal displacements increase as the angle of inclination rises. Among the systems that can be used, the outrigger system produces the smallest gravitational horizontal deformation due to

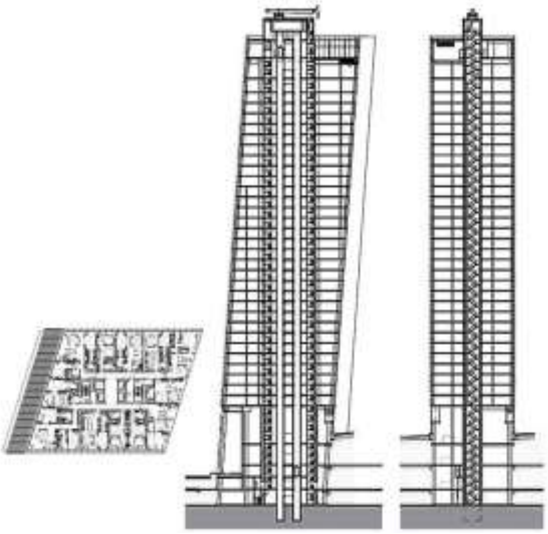

Fig. 5 The Veer Towers - Plan and cross-section

the triangularization of the major components of the structure. However, this system is exposed to dangerous impacts. As the tilt grows, high stresses are generated locally and there can be significant tensile forces.

C. Tapered structures

The geometric form of tapered buildings provides many favorable structural aspects for the design of very tall buildings. In addition, tapered high-rise buildings are more architecturally desirable due to the possibility of designing a mixed-use function. A model example of this type of building is the Shard in London, designed by Renzo Piano (Fig. 6). The most common characteristic of this form, due to its static and dynamic impact, is that the value of shear forces and overturning moments generated by lateral forces rises towards the base of the building. The value of lateral load, more than gravity, is critical when designing this type of structure. When analyzing the application of the diagrid, braced-tube, and outrigger systems, it can be stated that as the taper angle increases, their lateral stiffness increases. The effect of tapering on the reduction

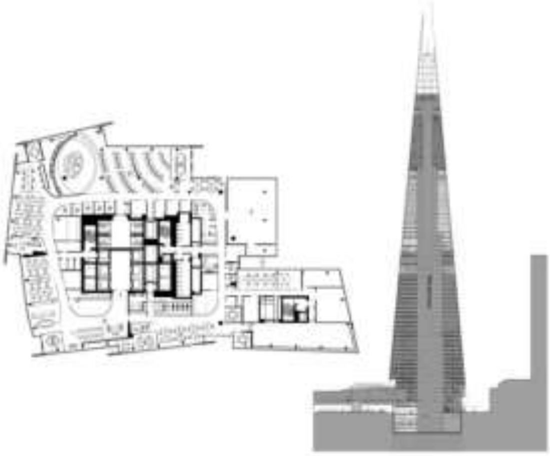

Fig. 6 The Shard Tower- Plan and cross-section

of lateral displacement is more significant as a building's height increases. When using an outrigger system, the rigidity of the lower level of the outrigger trusses that connect the mega columns and braced core is reduced because of their length.

D. Free form structures

In modern architecture, the number of tall buildings of free geometric form is increasing rapidly. Complex geometry is very often generated using sinusoidal curves with different amplitudes and frequencies. The most famous designers of this type of construction are Daniel Libeskind, Zaha Hadid, Frank Gehry, Norman Foster and Thom Mayne. A very interesting example of this type of building is Mode Gakuen Spiral Tower in Nagoya designed by Nikken Sekkei (Fig. 7). For these buildings, the most

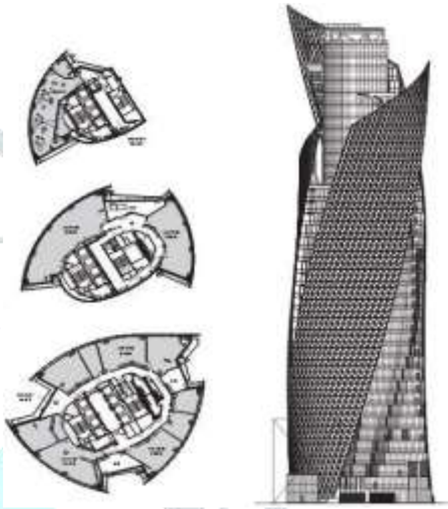

Fig. 7 The Mode Gakuen Spiral Tower - Plan and cross-section

common support system is the diagrid system. In this system, lateral displacements increase as the geometrical form deviates from the classical rectangular cuboid shape. As the degree of oscillation of the form increases, the diagonal angle deviates from the optimal value, which in turn reduces the lateral stiffness of the building.

IV. EXAMPLES OF TALL BUILDINGS WITH DIAGRID SYSTEM

The Doha Tower is a reinforced concrete building with a diameter of 45 m circular floor plan and cylindrical cross-section (Fig. 8), designed by Jean Nouvel. The basic vertical load of the building is carried by the diagrid system in the form of diagonal circular columns with a diameter of 1.7 m that form a structural frame located on the perimeter of the circular floor plan. These frames take more than 75% of the horizontal wind load. The diagonal reinforced concrete columns with an eight-story module taper slightly upwards and withstand the basic loads along with the central core and the tensioned ring on each floor. The spatial form of the building is based on a circular floor plan connected by a diagonal grid of reinforced concrete pillars located on the perimeter of the building and on a slightly non-central rectangular core with elevators. The support structure of the reinforced concrete diagrid system provides an open space for the free planning of office areas.

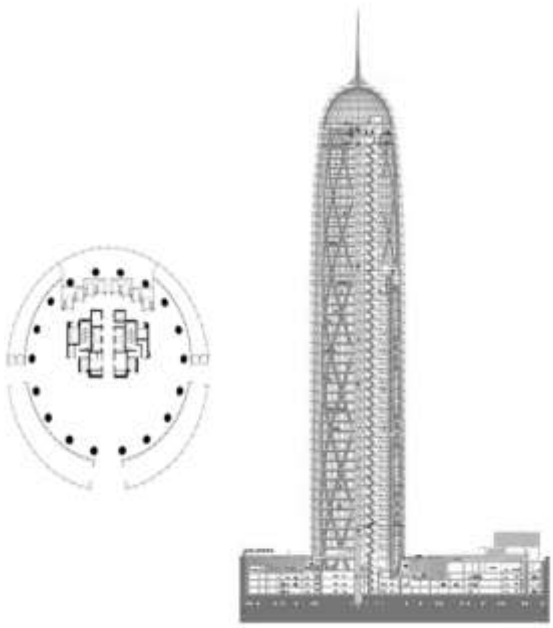

Fig. 8 The Doha Tower – Plan and cross-section

E. The Tornado Tower (Doha, Qatar)

The Tornado Tower is a steel-reinforced concrete building with a hyperboloid shape, designed by CICO Consulting Architects & Engineers (Fig. 9). Its supporting structure consists of a central reinforced concrete core with a diameter of 23.8 m and a peripheral steel diagrid system. This system increases the stiffness of the peripheral walls against lateral forces.
The reinforced concrete core of the building is connected to the diagrid construction with radial steel beams that are topped with a composite slab floor. These beams are subjected to considerable tensile forces resulting from the shape of the building. Floor slabs were designed as diaphragms tighten a steel diagonal structure with a reinforced concrete core by tensile forces.

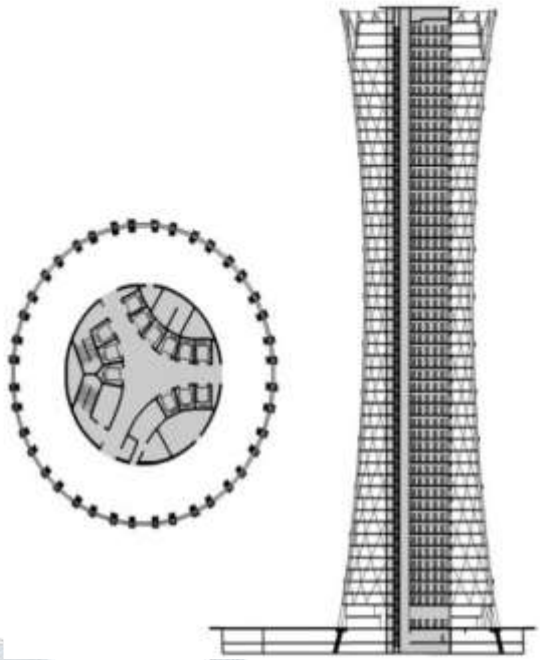

Fig. 9 The Tornado Tower – Plan and cross-section

F. The Capital Gate Tower (Abu Dhabi, UAE) Capital Gate Tower is a steel-reinforced concrete building with an original geometric form, designed by RMJM (Robert Matthew Johnson Marshal), Fig. 10. The form is meant to represent a swirling spiral of sand, while the curved canopy that runs over the adjoining grandstand creates a wave-like effect reflecting the building's proximity to water and the city's sea-faring heritage.

Capital Gate's base structure is a vertical concrete core surrounded by a steel diagrid that determines the external form of the tower. Steel beams span between the two, and support metal deck and concrete composite floor slabs. The atrium is formed above the base with an internal steel diagrid attached to the core. Steel girders span directly between the external and internal diagrids. The post-tensioned core was designed with vertical cables on one side that are tensioned to counteract the lean on the other side. The Capital Gate's wind bracing is designed as a separate system. On the ground floor, a massive concrete ring beam transfers the thrust of the diagrid into the foundations.

Fig. 10 The Capital Gate Tower – Plan and cross-section

G. The Hearst Tower (New York, USA)

The Hearst Tower was designed by Foster & Partners on the site of an existing Art Deco façade (Fig. 11). The tower sits on a six-story cast stone base, which was designed by Joseph Urban in 1928. The main architectural characteristic of this building is its relatively simple geometry and regular square plan. The existing supporting steel columns and spandrel beams provide vertical support for the façades. An additional grid of vertical and horizontal framing elements was designed behind the façades. The building employs a hybrid structure of concrete and steel [11]. The new tower has a constructional steel diagrid system that forms the network of a triangulated truss system. The diagrid members are typically wide flange rolled steel sections. The building has a centrally located core that serves as a communication area and plays an important role in the transmission of gravitational forces. The live load and wind load are transferred through the diagrid system to the mega columns and mega diagonals.

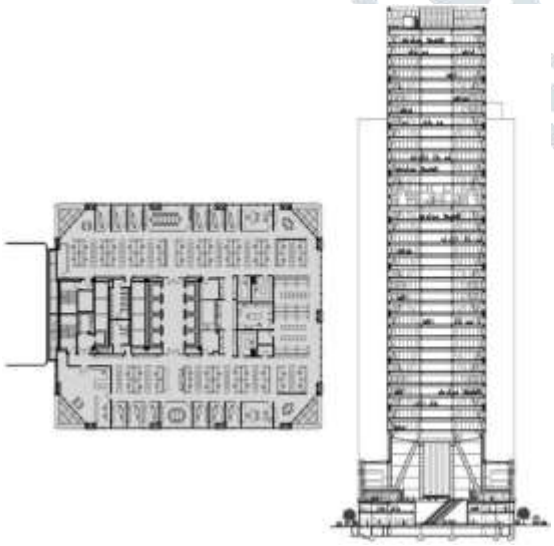

Fig. 11 The Hearst Tower – Plan and cross-section

I. The Swiss Re (London, England)

The Swiss Re is a steel building, designed by Foster & Partners on a circular plan with cylindrical section (Fig. 12). The tower diameter varies with height, the maximum diameter is at level 17. The building widens in profile as it rises and tapers towards its apex. This profile reduces wind deflections compared with a rectilinear tower of similar size. The steel framed structure includes the central core and a perimeter diagrid structure, with circumferential ties in the external wall, linked by main beams. The floors are of the composite metal deck and concrete construction.

The local geometry of the diagrid connection varies at each floor level, due to the differing floor diameters. In the Swiss Re building, all horizontal forces are carried by perimeter hoops at each node level, which also provides equilibrium for any asymmetric or horizontal loading conditions. The combination of these geometrical actions results in compression in the hoops at the top of the building and very significant tension forces at the middle and lower levels.

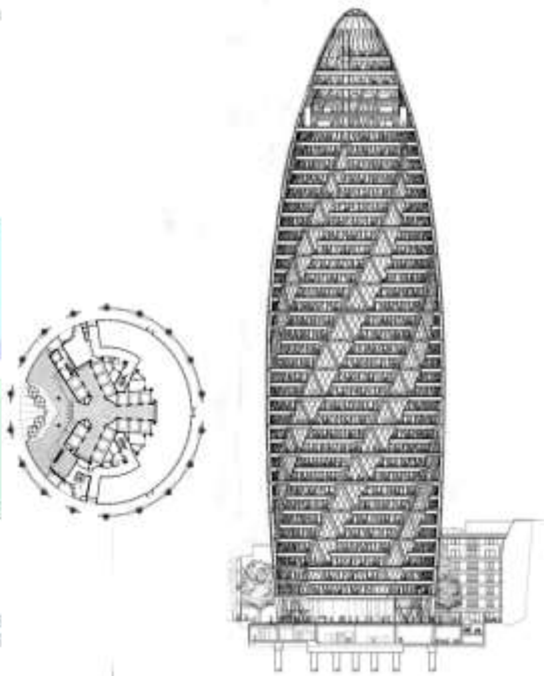

Fig. 12 The Swiss Re – Plan and cross-section

J. The Bow Tower (Calgary, Canada)

The Bow is a steel building planned by Foster and Partners on a bow-molded arrangement that gives the tower its name

(Fig. 13). The structure was molded by examination of the breeze. By transforming the arched façade into the overarching wind, the primary stacking is limited. The construction is the half breed diagrid border framework, in which the pinnacle is propped by three separate appearances. In diagrid structure, each located area binds together six stories.. Where the building

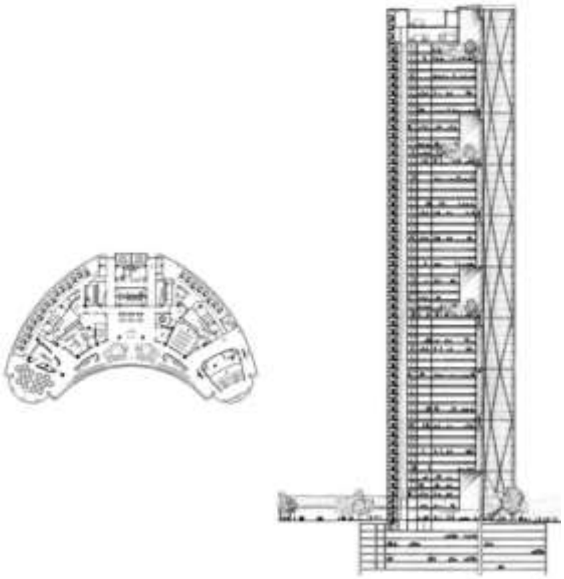

Fig. 13 The Bow Tower – Plan and cross-section

curves inwards, the façade is pulled forward to create a series of atria that run the full height of the tower. On the curved sides of the perimeter are the primary truss diagrid tube frames. The main core is a braced tubular frame that couples primary diagrid frames. These braced faces connect through the core with a series of secondary braced frames that lock structure between elevators and stairs. The structural system reduced both the overall weight of the steel and number and size of columns required.

II. CONCLUSION

The point of the article was to introduce the common relations of the improvement of current design structures and development frameworks of high structures with unique assessment of the diagrid framework. Complex shapes and prerequisites coming about because of the tallness of structures cause an increment in the heap of constructional components. Upgraded static and dynamic impacts should be reflected in an appropriately chosen development framework. Toward the finish of the nineteenth century, the proficiency of corner to corner supported components that neutralize parallel powers was considered when planning the primary elevated structures. The utilization of the diagrid development framework isn't new, yet there is presently an observable expansion in interest and use of this framework in the plan of tall structures with huge ranges, particularly in complex math. Diagrid structures don't need a center with a high shear solidness since shear powers can be conveyed by the corner to corner components situated on the border of the design. Border diagrids convey even and gravity stacks and are utilized to help the edges of piece floors.

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