40| Прегледни научни рад
Review paper
doi 10.7251/STP1813549K ISSN 2566-4484

SAVREMENI KONSTRUKTIVNI KONCEPTI VISOKIH ZGRADA

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Rezime:

Arhitektura visokih zgrada zavisi od niza faktora, koji uglavnom variraju od inicijalnih ideja, funkcionalnosti projektovanog prostora, percepcije i urbanističkog konteksta, kao i vrste nosive konstrukcije i tehnoloških mogućnosti neophodnih za realizaciju željenog koncepta. Kao jedan od faktora o kojima arhitektonsko rješenje ovisi je svakako nosiva konstrukcija, koja treba da ispuni četiri osnovna zahtjeva: statičku ravnotežu, stabilnost, čvrstoću i krutost. Prekretnica za ubrzani razvoj i izgradnju visokih objekata se desila u drugoj polovini XX vijeka, kada su jake ekonomije razvijenih zemalja poduprle tehnološki razvoj u sadejstvu sa razvojem novih generacija računara i programskih paketa, koji su zajedno doprinijeli razvoju efikasnijih konstruktivnih sistema visokih zgrada. Inovativni konstruktivni sistemi u obliku cijevastih konstrukcija, outrigera (vješaljki) i diagrida (dijagonalnih mreža) i megstruktura su doprinijeli projektovanju i izgradnji visokih konstrukcija kao neizbježnom novom stilu življenja.

Ključne riječi: Visoke zgrade, Konstruktivni sistem, Cjevaste konstrukcije, Vješaljke, Diagridi

MODERN STRUCTURAL CONCEPTS FOR HIGH-RISE BUILDINGS

Abstract:

Architecture of high-rise buildings depends on many factors, which greatly vary from initial concepts, functionality of designed spaces, its proportions to human perception and urban context, and structural support and technological capabilities to support desired concept. Thus, in any analysis of the factors that architecture depends on is its structural support, which has to fulfill four primary structural requirements: static equilibrium, stability, strength and rigidity of the structure. A turnover for fast development in construction of high-rises occurred in the second half of the 20th century; strong economy forced and supported technological developments, and even the new generation of computers and software helped in the development of more efficient structural systems. Innovative structural systems such as tubular forms, outriggers, diagrids and megastructures enabled design and construction of high–rise structures as common thing and inevitable part of new living style.

Keywords: High-rise buildings, Structural system, Tubular forms, Outriggers, Diagrids

1. INTRODUCTION

Race and desire in constructing tall and high exist since periods of early civilizations. The architectural heritage and remains from early civilizations, are undeniable evidences that constructing high and massive is not innovation and reflection of the contemporary society. Whether high–rise buildings function as commercial, residential or educational use of these forms of vertical architecture is becoming more and more popular.

Despite various contemporary requirements and technological developments of high–rise building's structural systems, history and beginnings of high–rises were less complicated and simple when compared to nowadays technology. During the period of the first–high rise building, widely in use and best known were massive load bearing masonry structures, rigid thick shear walls with small perimeter openings with low resistance to lateral forces which are crucial for structural design of high–rise buildings. Masonry structures were replaced with an iron and steel structures which created larger spans between columns, creating more open areas at the building's perimeter for the windows, and it also facilitated the construction. At that time, terms such as load–bearing systems, in shape of rigid steel frames and non–load bearing structural elements, such as separation walls, or fill–in brick non–load bearing walls between the columns at the perimeter of the buildings that were not glass surfaces, were introduced to structural design. [1]

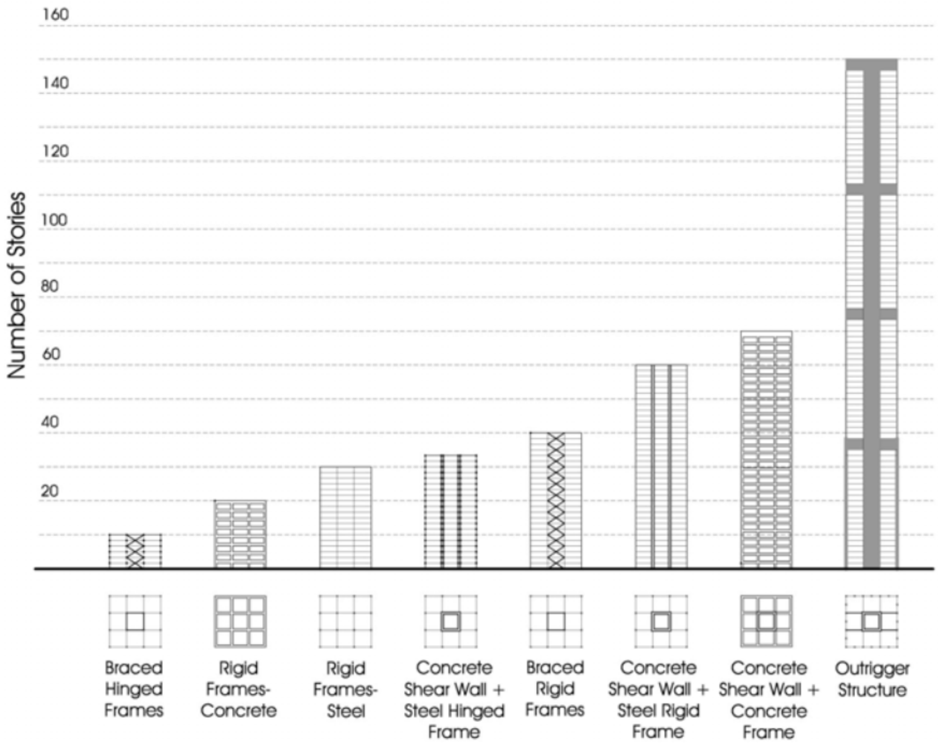

Figure 1. Classification of the Structures of High–Rise Buildings according to Mir M. Ali (interior structures) [2]

Non–load bearing elements and cladding materials were carrying nothing but self–weight and lateral wind load in their areas. Development in this range was more than sufficient for designers and investors to start racing for expansion in vertical dimensions. High rate in increase in height of the buildings was not equally accelerated with technological development of the structural systems and designs.

Notwithstanding fact that major requirements crucial for the structure are to meet equilibrium, stability, strength and rigidity, structures itself are nevertheless in architectural sense becoming an additional aesthetic value for a building supporting the concept. Structural diagrids, tubes, braces of the frame system, space trusses etc., commonly represent structural systems that bring an additional aesthetic value to high–rise buildings.

In 2007, Mir M. Ali developed new classification of structures for high-rise buildings guided by lateral load resisting capabilities. According to Mir M. Ali, each structure had a major structure which was capable to resists lateral actions (wind and seismic actions), and minor one which was not as dominant as major, but did have capacity to resist lateral actions. [2]

If the major structure was placed at the inner part of the building, while minor structural elements were positioned at the perimeter of the building, structure was classified as interior structure (Figure 1). If the major structure was positioned at the perimeter of the building and minor at the interior, structure was classified as exterior structure (Figure 2).

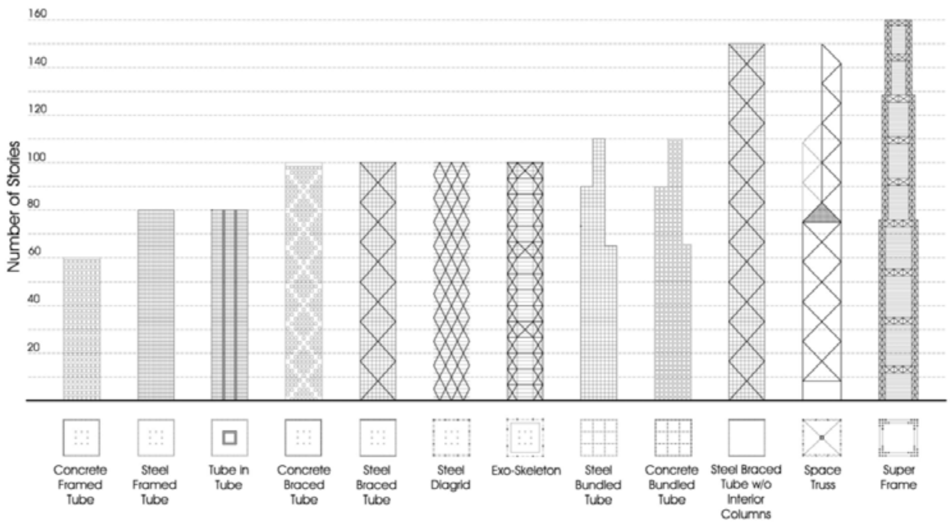

Figure 2. Classification of the Structures of High–Rise Buildings according to Mir M. Ali (exterior structures) [2]

2. TUBE SYSTEM

One of the most spread exterior structures of high–rise buildings is tube structure. Lateral actions in such structure are resisted with the structural element positioned at the perimeter of the building (Figure 3).

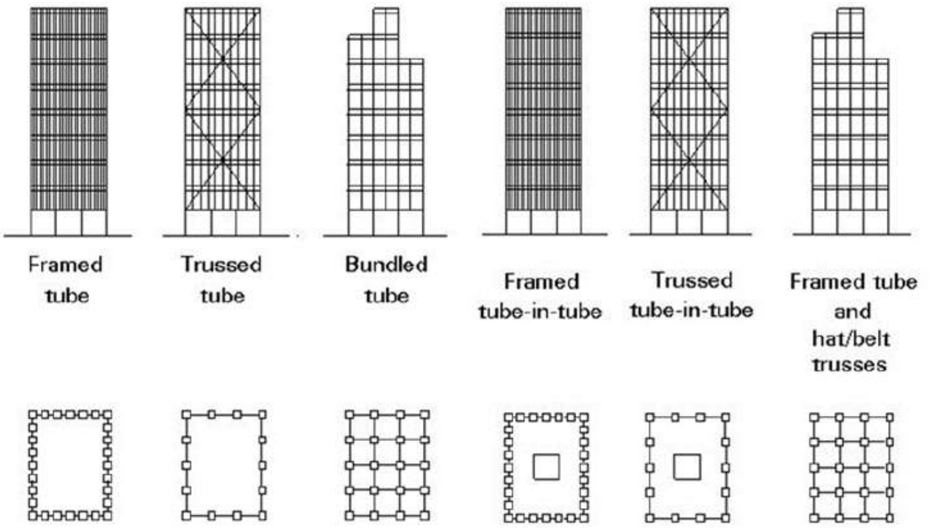

Figure 3. Variation of Tubular Structures [1]

As one of the greatest innovation in the sixties, tube structure was designed by F. Khan back in 1961. [3] It was delivered as an actual structure with De Witt Chestnut Apartment Building in Chicago. Construction was finished by 1963, with 43 storeys height, and in arrangement of framed tube (Figure 4).

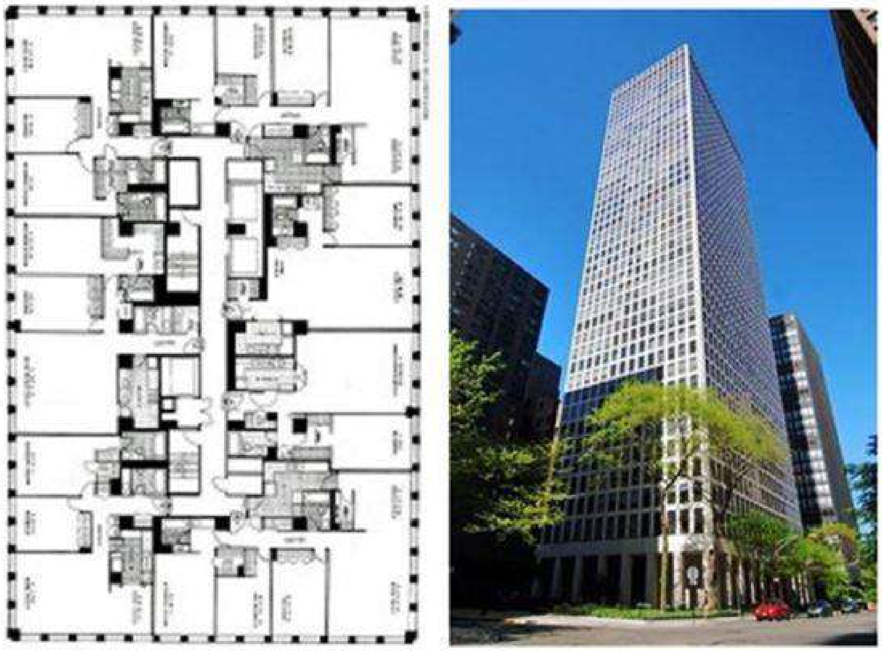

Figure 4. De Witt Chestnut Apartment Building in Chicago [4,5]

Frame tube structure was the first example of tubular approach for construction of in high–rise buildings. It is designed as hollow cantilever, fixed at the foundation to the ground, in order to resist lateral loads. It consists of closely arranged columns, while the span between central axes of columns' cross section is approximately between 1.5 to 4.5 meters and spandrel beams being rigidly connected. The depths of beams vary between 60 and 120 cm. Term framed tube structures is closely related to, shear lag effect, which means that within this type of structure corner columns experience the largest axial forces, which are not distributed linearly along the direction perpendicular or parallel to the wind.

Frame tube can be designed both out of, steel or concrete, with efficiency up to 80 storeys. For architectural functionality or aesthetics such system strongly leads the overall composition, dynamic and geometry of the elevation, while at the same time decreases costs for the additional curtain wall or fill in walls, but also reduces daily light penetration to the building.

A type of tube structure, braced tube, also called truss tube, was first used back in 1970 in Chicago, at John Hancock Centre (Figure 5).

Figure 5. John Hancock Centre, Representative Example of Braced Tube Structure [6]

Such structure developed as newly evolved frame tube. Instead of closely arranged columns, required structural stiffness was achieved by diagonal bracing. Braced tube overcame the problem of progressive inefficiency in over 60 storey high buildings which was the case with frame tube. With bracing, perimeter frames acted as stiffener and the braces overtook floors' gravity actions. Each joint of the diagonals and columns, in structure of braced tubes, eliminated effect of shear lag by being tubular in framework. Besides structural advantages of braced truss tubular structure, larger spans between columns that were provided by bracings, created larger areas for the openings glass areas increased the interior quality and at the same ratio, the glass areas increases themselves. Also, the braces which were left as visible by design, enhanced and gave a character to each elevation.

Bundled concept, unlike others structure's concepts gives variety of characteristic floor plans in areas, with greater lower storeys and those smaller at the upper storeys. There are different geometrical shapes in grid plan, such as: rectangular, triangular, hexagonal etc., which mould vertical volume of the high–rise tube. Bundled tube structures, efficiency is up to 110 storeys, with possibility of steel or concrete as main structural material. Even though such composition reduces shear lag and enables slenderer structural elements, the configuration of tubes may have created limitation in arrangement of the interior space.

Unlike other tubular structures, bundled tube system, made high–rise buildings structured with this system a vertical play of the various volumes, which differentiated it from the cubic shaped towers. In this variation of tube structural system, couple of tubes were interconnected and acted as one unit. Back in 1974, Sears Tower (Figure 6) was the first bundled structure, with 9 tubes at the base level, which created regular grid of 3 rows and 3 columns, while still following the principle of bundled structure; as the final storey was not cubic (Figure 7). Approach of the bundled structures, concept and the overall design of structure reduced the elements of the lower storeys, slandering lower structural elements, when compared to those that would be required for other type of structure.

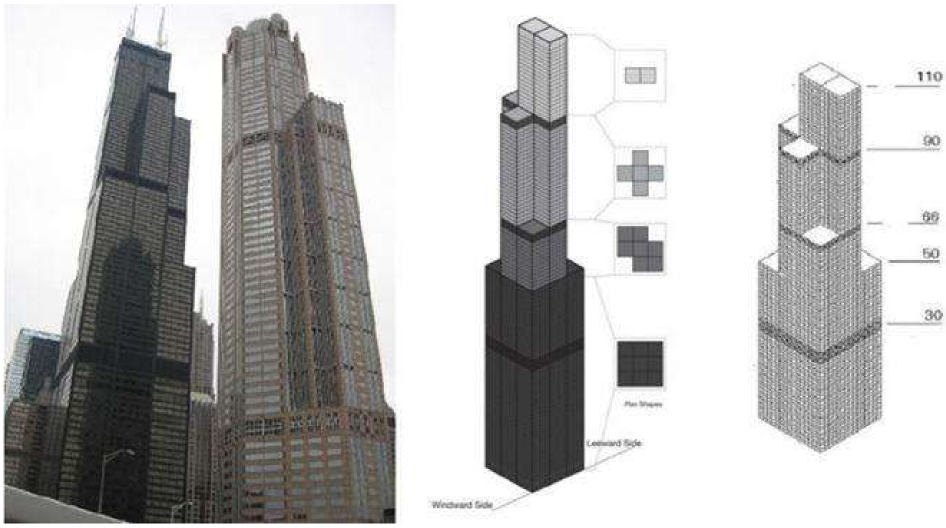

Figure 6. Figure 1. Sears Tower, Chicago (left),
Schemes of Modular Floor Configuration (mid and right) [7,8]

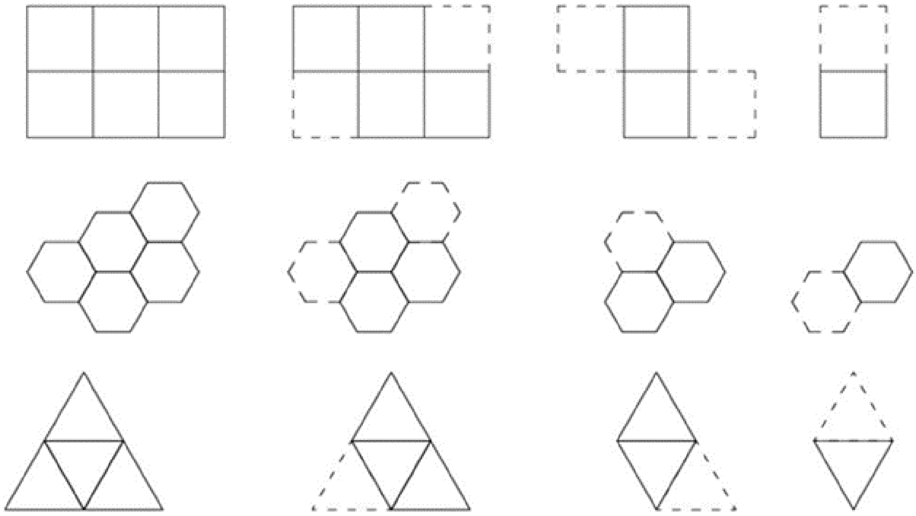

Figure 7. Different Plan Configuration for Bundled Tube Structures [1]

One of the safest tubular structures due to resistance to the impact loads, besides its high stiffness of structure in resisting lateral and gravity loads is tube in tube structure. It is usually composed of two tubes, one larger at perimeter and smaller inside perimeter of building, however it may be designed with more tubes within a tube if it is required due to higher safety and if such attempt and concept shows as efficient.

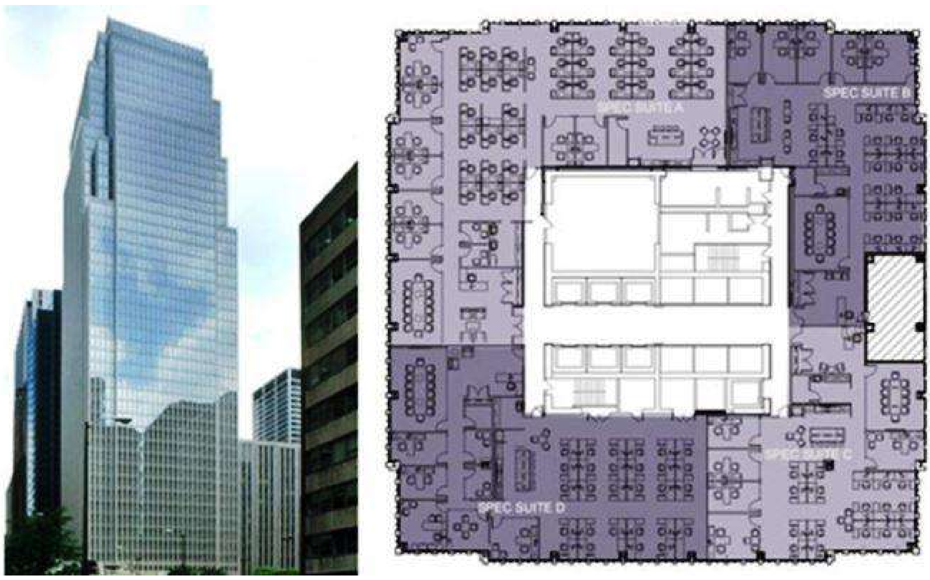

Figure 8. West Madison Street 181, (left), Characteristic Floor Plan (right) [9,10]

An example of tube in tube structure is 181 West Madison Street in Chicago, which has 52 storeys (Figure 8). Such structure effectively resists lateral actions with both tubes due to its system that inner core (inner tube) and outer tube with slabs, which makes both core and cube able to resist lateral actions.

As far as the structural material is concerned, both exterior and interior tubes can be designed as concrete or steel cores or frame tubes. In terms of height, tube in tube system is efficient up to 80 storey high buildings.

However, such structures excludes a high demand for numerous columns in interior design, inner core if not used with specific purpose as elevators, stairs, mechanic installations core, can develop limitation in arrangement of interior space.

3. OUTRIGGER SYSTEM

Outrigger structures are generally a unity of the core, outriggers, belt trusses and mega columns. Shear cores are mostly designed at the axial center of the floor plan; however it is not impossible for it to be located at either one side of the building. Commonly in a form of concrete cores or rarely in a form of steel trusses, shear cores do act as vertical cantilevered beam fixed at the foundation. Outriggers, might be in a form of steel trusses or concrete walls, and depending on the design the outriggers are approximately 1 to 2 storeys deep.

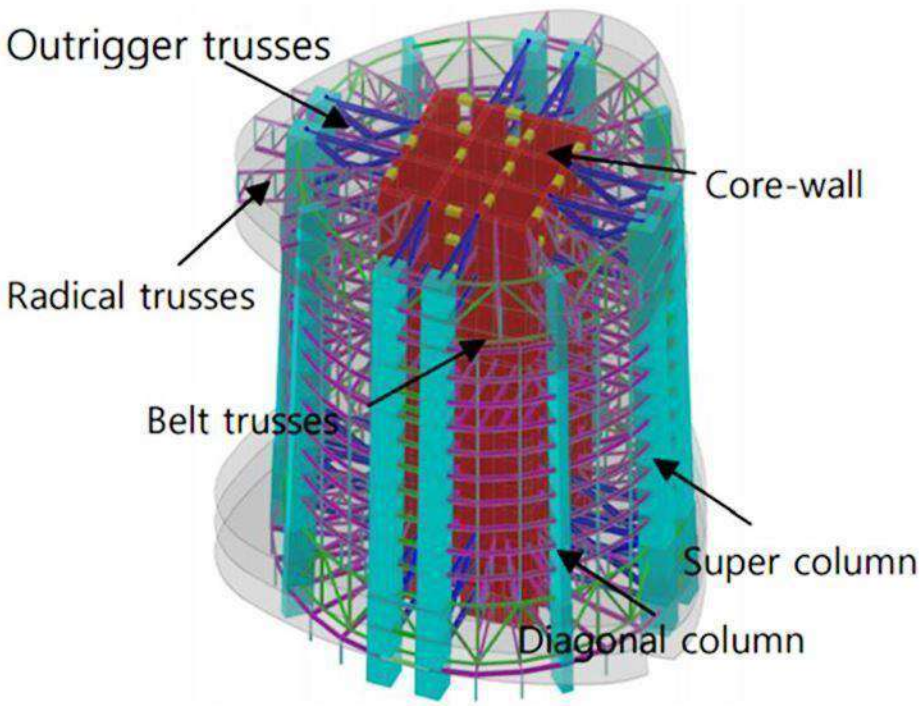

Figure 9. Shanghai's Tower Structural System [11]

Depending on the position of the core, outriggers may extend from both sides if the core is centrally positioned or from one side if the core is placed on one side of the building. The role of the outriggers is to reduce moment in the structure's core by acting as the stiff headers that transfer the moment from the core, to the mega columns generally located at the perimeter of the building by stimulating a tension–compression couple in mega columns. Belt trusses connect the mega columns at the perimeter of the building, reducing the elongations in tensile zone and shortening in compression zone of mega columns, while also being capable to resist a shear load, which can cause bending (Figure 9).

Even though, the columns and belt trusses are capable of taking over lateral actions, the design of major structure is interior core and outrigger, which classifies this structure as interior structure. (Figure 10)

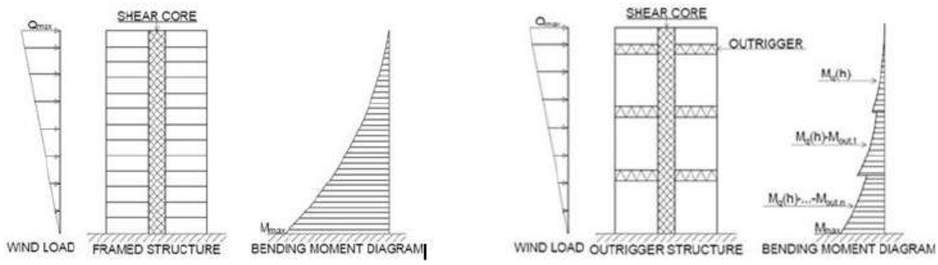

Figure 10. Bending Moment Diagram under Applied Wind Load on Shear Core and Frame Structure (left) and Bending Moment Diagram under Applied Wind Load on Outrigged Structure (right) [1]

Outrigger structures are lately becoming very popular in super high-rise buildings, where outriggers trusses or walls advance shear wall/core system in resisting lateral actions in a form of redistribution of shear forces. With outriggers in buildings higher than 70 storey, bending caused by overturning is highly resistant.

Besides valued advantages, in terms of additional stiffness, stability, higher resistance of the structure to crucial lateral loads, high performance and efficiency in use of the materials and design, the main disadvantage is perceived in occupied rentable space reserved for outriggers.

If consider that 1 or 2 storeys are required per one outrigger, it becomes obvious that the greater height leads to the percentage of occupied stories respectively increasing as well. However if well planned and designed, outrigged stories can be used as mechanical floors; such approach excludes "waste" of space. Considering structural material, this structure might be designed as steel structure or concrete, or in most cases as composite structure. Due to the high fire resistance requirements, cores are mostly designed in concrete, which adds to the safety for occupants of the building in the case of emergency. However, lightness of structural steel makes steel preferable in comparison to heavy concrete for outriggers and belt trusses, such structure and relation between materials and structural elements, is showed as efficient when constructing 150 storeys high buildings.

4. DIAGRID SYSTEM

Diagrid is an exterior structural system used in high–rise buildings, which is even though entirely exposed at the elevation, both in architectural and structural fields of science and art, defined as extremely aesthetic.

Figure 11. Hearst Headquarters Centre in New York (left), and 30 St. Mary Ave in London (right) [12,13]

Unlike, diagrid braced tubular structure, which may be seen as a forerunner of diagrids, it is mostly degraded by expertise and critics. Entirely braced John Hancock Centre in Chicago (Figure 5), was one of the pioneers in braced tube structures; despite the improved structural efficiency, new aesthetic style, innovation, structure exposed through all four elevations was not welcomed.

However, a decade later, newly named form of diagrid, gained full attention. Dating back to 1980's Sir Norman Foster, proposed diagrid solution for the Humana Headquarters composition. Even though diagrid was not a best solution for Sir Norman Foster, Hearst Headquarters Centre in New York and 30 St. Mary Ave in London received praise and become monuments of Sir Norman Foster, and were closely related to diagrid structures (Figure 11).

In diagrid structures, the whole structure depends on diagonal members. Due to stored shear by axial forces in diagonal members diagrid structures reduces and minimize shear deformation. Diagonal members of diagrid were also capable of carrying gravity actions, and its triangulated configuration of diagonals could resist for lateral actions. As structure, diagrid did not seek for shear rigidity cores, because diagrid had high bending and shear rigidity at the perimeter's diagonals (Figure 12).

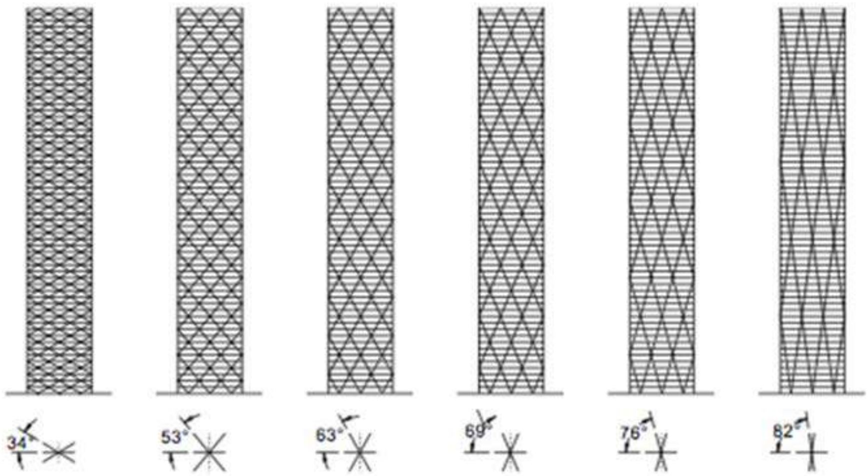

Figure 12. Variations of Diagrid Geometry [14]

Diagrid structures are commonly steel structures, with very complicated joints of the diagonals, however they are efficient in up to 100 storeys buildings, and represent regular geometry in diagrids. Lately diagrids are designed and constructed out of concrete, as main structural material, which is far different from steel diagrid, with more irregular and organic shape, which lead to the new futuristic architectural aesthetics. Concrete diagrid structures, require expensive formwork and the construction. An example of such design is reflected in O–14 Building in Dubai (Figure 13).

Figure 13. Concrete Diagrid, O-14 Building Dubai (left)
and Construction of Diagrid (right) [15,16]

5. CONCLUSION

High–rise buildings are inevitable part of contemporary living style, and at the same time represent futuristic direction of structural and architectural development. For present societies where there is a constant increase in population number and ratios between constructed land and natural environment, high–rise buildings present new environmentally friendly and sustainable way of living, as they occupy practically small areas of the ground and expand vertically. High–rise building are becoming taller and taller, thus there is a necessity for very careful and detailed design of each structure in order to provide safe, comfortable, stable and resistant structure, and to be trustworthy for potential users and inhabitants of high–rise living. High–rise structures themselves deal with the critical load combinations, where at this specific case of high–rise structures, lateral loads (wind and seismic actions) are crucial in structural design. With these enormous heights, wind acting increases and may cause a noticeable building movement and sway. However, high–rise structures can be of high–quality and detailed architectural, structural and mechanical design with carefully monitored construction process and efficient with the choice of the best suitable, resistant and safe structural material. There are similar and approximately the same structural systems and designs all around the world, which are efficient up to the certain heights, with correspondence to the use of the specific structural materials and ability to resist the critical loads combination in specific environment.

Common types of structures in high–rise buildings are as follows: frame system, shear wall system, outrigger system, tube system, diagrid system, space truss system, exo–skeleton system, super frame and hybrid systems. These structural systems are basics but combined or modified can support any architectural concept and form, while resisting the critical load combinations.

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