

DOI: [10.38027/N12020ICCAUA316291](https://doi.org/10.38027/N12020ICCAUA316291)

Investigation of Diagrid Structures Over Gherkin Tower

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Abstract

21st. Century witnesses enormous technological development effecting Architecture also: New and improved building materials and construction techniques, highly innovative development of structural systems utilizing advanced computer software leads to significant novelties in built environment, worldwide. The 'Diagrid Structure', having a hyperboloid form, of which the first design and implementation was applied by V. Shukhov in, as early as, 1896. Both due to diagrid and to its doubly curved form, it proved to achieve greater lateral strength, rigidity and efficiency than rectangular frame system, decreasing the amount of the required material, besides offering the possibility of prefabrication and ease of assembly. Although the first diagrid structure was built in 1963- the IBM building in Pittsburgh- it did not utilize a doubly curved form. The system was not widely recognized until the Gherkin Tower designed by Sir N. Foster was completed in London, in 2003, displaying the twinning of architectural and structural design.

Keywords: Diagrid structural system; framed structural systems; steel; Gherkin Tower; tall buildings; contemporary architecture and structure; 30St Mary Axe.

1. Introduction

Due to the increase in world's population especially in the last two centuries from the past to the present day, the need for housing and other types of buildings emerged and has increased. Gradually as the a result of the growing urban spaces and changing intensive user requirements, need for number of buildings with wide spans increased and the space widths increased greatly. In the beginning, wooden stone and timber materials were used to cover the large-spans and the roofs were crossed with domes .Then, with the discovery of steel and the invention of new methods developments which are making to improve its mechanical properties steel harder and more durable, it steel has changed the history and become the basic material of structural science from past to present by giving direction to our civilization and way of life. Especially after the Industrial Revolution, the construction of high-rise buildings increased rapidly due to the increase in the population in the cities and the decline of the land to be built, and even high-rise buildings, and later, skyscrapers and tall-buildings became a symbols of power for the states. In this race of power, with the contribution of technology and materials science, the construction of ever-taller high structures became easier, and new structural designs were introduced, in which steel was used as the main material for large-span. The most striking of these structural systems is the diagrid structure system, which is widely used today.

This system, named with the defined as a combination of the words 'Grid' and 'Diagonal', allowed great sans wide openings to be covered without columns and reduced the number of structural elements. The advantage of "Diagrid systems" used in statically high structures over conventional orthogonal structures is that they can achieve great structural efficiency without vertical columns (Baytin, 2010). One of the main reasons for this efficiency is the use of a triangular frame instead of a rectangular frame because triangle is the most rigid geometric shape (Moon, Connor, Fernandez, 2007). Vladimir Shukhov, a Russian architect-engineer has innovated innovated both the diagrid structure and implementation of doubly-curved hyperboloid in structural systems, in 1896. 70 years later, in 1963, the first building with the system was constructed, the IBM building in Pittsburgh, USA. However, at the time of this building's construction, the diagrid system did not attract the attention of architects and engineers enough then. Only after the British architect Sir Norman Foster's use of diagrid structure in his designs beginning with the Gherkin Tower (2003) made in the following years provided the recognition of the diagrid structures the recognized tion of throughout the worldwide. In this study, the Gherkin Tower, as the first and most striking and impressive design ever realized with the diagrid system by the Norman Foster, who followed Shukhov's philosophy, is examined. In addition, the advantages of this structural system and its interaction with the architectural qualities of the building are discussed.

2. Historical Development of the Use of Triangle in Architecture

Geometry is defined as; "the branch of mathematics that deals with the deduction of properties, measurement, and relationships of points, lines, angles, and figures in space from their defining conditions by means of certain assumed

properties of space”(Webster’ Encyclopaedic Unabridged Dictionary of The English Language,1996). It is known that geometry’s place in our lives is quite wide, and it is used in many fields such as various form of arts, and engineering, and architecture. As the definition given above clearly indicates geometry is, inherently, coherent with space as architecture is, and every structure has a geometric form. For this reason, geometry and architecture are basically two different but interdependent and associated disciplines. Triangle, one of the basic geometric shapes frequently used in architecture; consists of three angles/three corners connected with lines to form a three-sided shape. The reason why triangle is widely used in architecture is its rigidity, and a building element in this shape has the capacity to carry large loads without deformation. Triangle has been the main form of structural elements, besides arch, when stone was the main structural material.

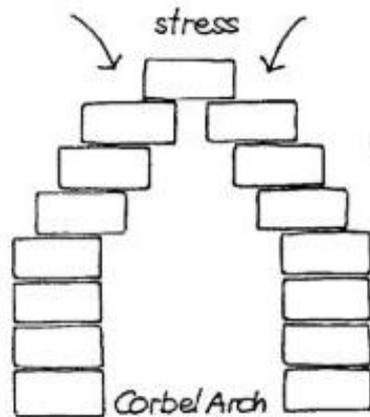


Figure 1.Corbel arch(Marr and Milner,1986).



Figure 2. Alabaster stone window- Madaba, Jordan (Jäger, Helmedag and Abu Jaber,2012)

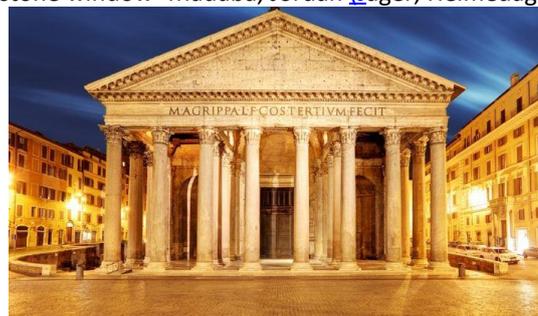


Figure 3. Pantheon, Rome-Italy (Taken by the author,2019).

Later, timber has become the structural material and has been widely used in frame structural system with diagonal bracings, and in constructing trusses of different kinds covering larger and larger spans, using triangle units.

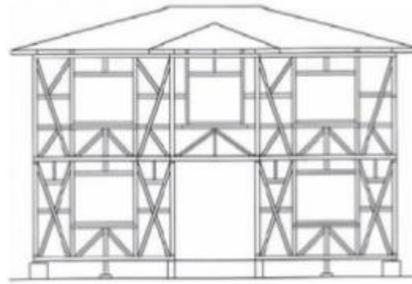


Figure 4. Traditional timber frame buildings (Aksoy and Ahunbay,2010).

Iron has been the next structural material to follow timber after the industrial revolution and began to be used in truss structures of first cast iron succeeded by wrought iron, in the 1800s, namely in bridge construction and large-span roofs. The famous Eiffel Tower is of cast iron metal trusswork.

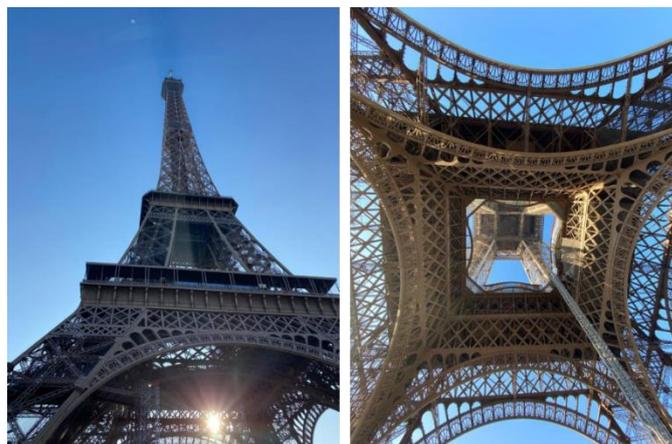


Figure 5. Eiffel Tower, Paris- France, constructed in 1889 with cast iron trusses(Taken by the author,2020).

Analysis of load transfer in truss structures was possible after Squire Whipple has set the relevant methods in 1847, but until the invention of steel rigidity of triangulated structures could not be made use of. Later, invention and improvement of steel and its properties first with the methods developed by Bessemer in 1856 and by Thomas in 1876, and, eventually, through more advanced technological developments, led to triangular tessellation in the structural elements, decreasing their weight in contrast to the huge increase in their structural capacity. Therefore, novel structural systems such as space truss, space frame system, and geodesic dome were innovated. The presence utilization of the triangle in architecture has always maintained its place.

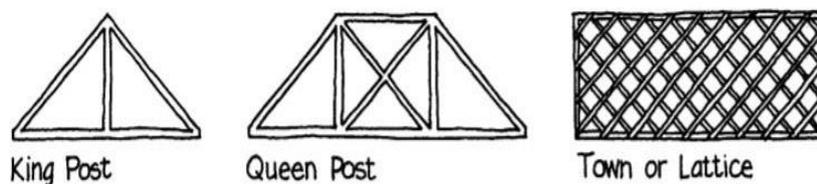


Figure 6. Types of trusses(Allen, 2005).

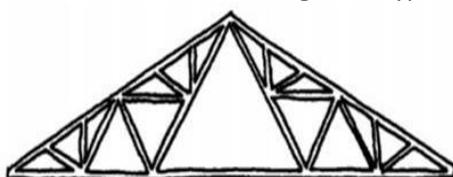


Figure 7. Types of trusses(Allen,2005).



Figure 8. Space frame system(Allen,2005).

As to the domes used as a shell covering system that passes covering large-spans, famous American architect Buckminster Fuller has formed the geodesic dome by dividing the sphere, which is a volumetric geometric element, into small triangular surfaces and successfully applied it in his designs.



Figure 9. Division of a sphere by triangles (Baytin,2010).

In the following process, triangulation systems in which more than one triangle was repeated to create a structure and support network/grid has been tried in various ways in the construction industry with the construction of Buckminster Fuller's geodesic dome (Figure. 10).

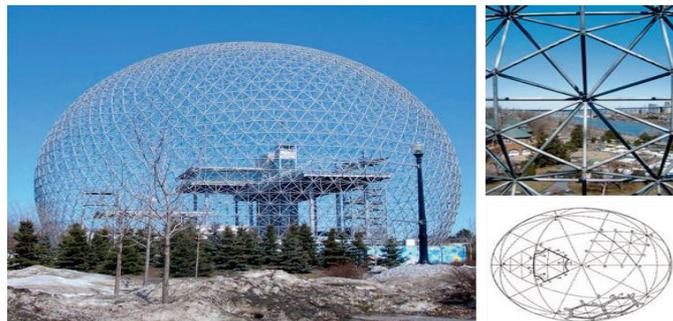


Figure 10. The USA Pavilion designed by Buckminster with a geodesic dome(Silver and McLean, 2013).

While triangulation systems are typically used for their natural structural properties, they display the prismatic patterns which demonstrate the aesthetical value of their architecture. In the meantime, famous architects and engineers such as Pier Luigi Nervi, Eduardo Torroja, Felix Candela, Eberhard Zeidler have applied the triangulation in ferrocement, consisting of first triangular, later diagrid units to cover large spans.

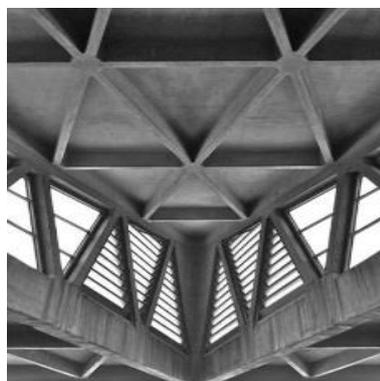


Figure 11. P. L. Nervi: George Washington Bridge Bus Terminal, New York,1963. (Baytin,2010)

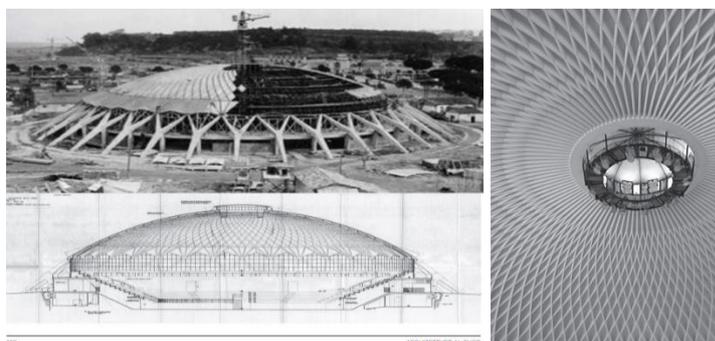


Figure 12. P. L. Nervi: The Palazzetto Dello Sport (Montuori,2018).

The triangle is one of the strongest shapes known by man. Therefore, it is observed that triangulation and triangular shapes have been used as the most common geometrical shape in the construction of buildings, bridges, towers and various structures in the early period and today. "In terms of influence on the concept, structure and detailing of diagrid structures, the invention and development of spaceframe and geodesic structures was important as an overlay to Shukhov's hyperbolic paraboloid towers. Geodesic domes, spaceframes and diagrids all derive their essential stability from triangulation. The detailing of geodesic domes and spaceframes has had an influence on the terminology, engineering and fabrication detailing for diagrids" (Boake, 2014).

3. Definition, History and Advantages of Diagrid Structure

3.1. What is Diagrid?

Diagrid is the abbreviated form of diagonal and grid words. In the Oxford dictionary, the word diagrid is defined as supporting and undercarriage framework systems formed by cross-cutting concrete or metal beams (Oxford Dictionary, 2010). The structural system formed by connecting the steel structurals, which are basically placed in a triangular geometric shape, via node points to each other, is a form of design developed for the construction of tall buildings and widely used today. By means of the diagrid systems, it can be used as roofing shell as well as creating large column-free spans. The system, which provides freedom in architectural designs and interior plans by creating large column-free spans, was originally used with triangulation methods in wooden buildings and wood was contributed to the development of the grid steel cage system as a structural idea.

3.2. The Origin of Diagrid

Although the use of diagrid systems became popular in the early 2000s, its history dates back to nearly 100 years. After the discovery of steel, ironstones were melted in coal mines in the beginning and the production of the steel was provided in this way. But with this method, both the production was limited and the cost was high. Only cast iron could be obtained in the high-temperature furnaces newly commenced production, the cost was even higher since it required a furnace again to turn it into steel. Henry Bessemer developed a method to transform the cast iron into steel by reducing the percentage of carbon in cast iron and succeeded producing qualified iron (Cuscoleca, 1954). In this way, lighter steel with higher tensile strength, higher tensile strength, and superior steel properties than cast or forged iron began to obtain and steel became the dominant structural material from the invention of the steel frame to the tall buildings of the 1800s. When technical developments allowed reinforced concrete and steel to be used together, iron cage structures were first used in bridge constructions in 1800s. Then, it was started to adapt to reach reinforced concrete structures to the top, to make them higher and to create large span roofs.

In 1847, American Engineer Squire Whipple has included some analytical methods to establish forces in steel cages in his book named as "A Work on Bridge-Building" on bridge structure. One of these analytical methods is that the natural hardness and strength of the buildings built using triangular shape in the structural elements was high which had been known by the Greeks since the 3rd century BC and Vitruvius had also mentioned. With this development, triangles has been started to be included in steel cages. In the later periods, the hyperboloid geometry curve was discovered by the Russian Constructivist Vladimir Shukhov and established a ground for today's diagonal structures. The 160-meter-high Shukhov Tower, built by Shukhov in Russia in 1896, was built with steel using the hyperboloid geometry curve and was the first example of the diagrid structure in the world (Figure.13). He also designed the Vyksa Metallurgical Factory in the town of Vyksa in Russia and the world's first double curved steel diagrid was used on its roof (Figure.14). Therefore, the first design and construction of the volumetric diagrid structural system belongs to the Russian genius Shukhov (Beckh, 2015).

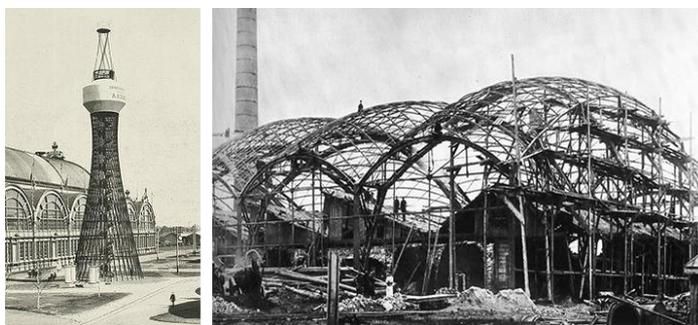


Figure 13. Shukhov Tower (Kinayoglu, Senyapılı, 2018)

Figure 14. Vyksa Metallurgical Plant (In Structures Congress, 2005)

The form of the tower is based on non-Euclidean hyperbolic geometry. In addition to the designs of a great variety of light-weight hyperboloid towers and roof systems, Shukhov had also developed mathematical computing to calculate these systems. Famous engineer and architect Shukhov is also famous for the unique designs of many civil

buildings, bridges and hyperboloid towers (In Structures Congress, 2005). In this context, the invention and development of space lattice and geodetic domes and Shukhov's implementation of hyperbolic, parabolic geometry towers by designing have a great importance in terms of their effects on the creation, detailing and construction of diagrid structures. The first building example built with the diagrid system is the IBM building located in Pittsburgh, USA, completed in 1963, its the architectural design belongs to Curtis and Davis (Figure. 15).



Figure 15. IBM Building (Mele, Torenó, Brandonisio, and De Luca, 2014).

Famous British architect Norman Foster, who derived from the system developed by Shukhov, has also used the diagrid structure in 2000s in many of his buildings such as Bow Encana and Gherkin Tower and in the British Museum renovation project. The leading examples of the design and construction of the system by Foster are the Hearst Tower and the Gherkin Tower. In this article, besides the advantages of Gherkin Tower and its structure, which is one of the most successful and striking examples of the diagrid structure, the interaction of the diagrid structure used in the building with the architectural design has been examined as well.

3. 3. Why Should We Choose Diagrid?

Recently; the use of diagonal (the word diagrid is derived from this) for structural strength/resistance efficiency and aesthetic appearance has created a new interest for architectural and structural designers. Diagrid systems can also be considered as an improved version of the braced tube system. The main difference between traditional braced tube frame systems and diagrid structures is that almost all columns are removed, given space and design freedom in architectural plans. At the same time, conventional structure systems carry only horizontal loads, while diagonal elements in the diagrid system have the opportunity to resist gravity loads as well as horizontal loads due to their triangular arrangements. Compared to traditional non-diagonal framed tubular systems; structures with diagrid structure are much more effective in reducing shear deformation. Since the diagrid systems carry the cutting/shear through the axial movement of the diagonal elements, the traditional frame tubular systems can carry by bending the vertical columns (Balci, 2013).

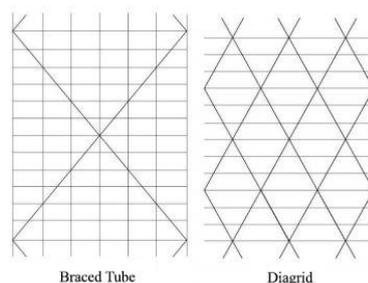


Figure 16. Braced tube vs. Diagrid structure (Moon, Connor, and Fernandez, 2007).

Diagrid structure; the vertical cantilever is modelled as a beam/girder and is divided into longitudinal modules according to the repeated diagrid pattern. The diameters and angles of the steel modules used vary according to the number of floors and the condition of the floor. The diagonal elements of the diagrid structure, which are the node, intersection points, and horizontal support rings of the diagrid connection to the floor are shown in the figure (Moon, Connor, and Fernandez, 2007).

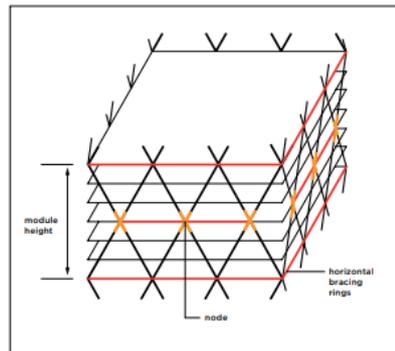


Figure 17. Typical diagrid module(Moon,2011).

3.4. What is Node?

Node is the designated connection points for the connection of typically triangular modules, one of the diagrid elements. Nodes can be designed differently according to the width, angle and functions of the diagrid elements.

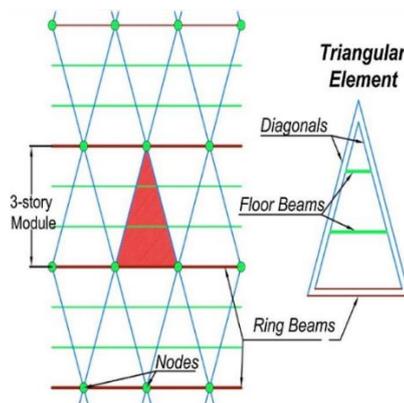


Figure 18. 3-story diagrid module and a triangular element sample(Asadi and Adali,2017)

Figure 19. Gherkin Tower node sample(Boake,2016).

3. 5. Module and Module Selection Criteria in Diagrid Structure

The design of the modules comes first among the items to be decided by the designers and engineers while planning the diagrid structure. The design of the modules used in the diagrid structure is decided according to the criteria such as the suitability of the gap angle, topographic conditions of the ground, its strength, height of the structure, load calculations/load designs, etc. How many floors there will be between node numbers of each modules, the angle and dimensions of the structural tubes vary according to various criteria. For example; there will be a module node on the 2-6-8-10-14-16th floor. The angle of the diagonals allows natural and direct load flow through the structure and down to the foundation of the building.

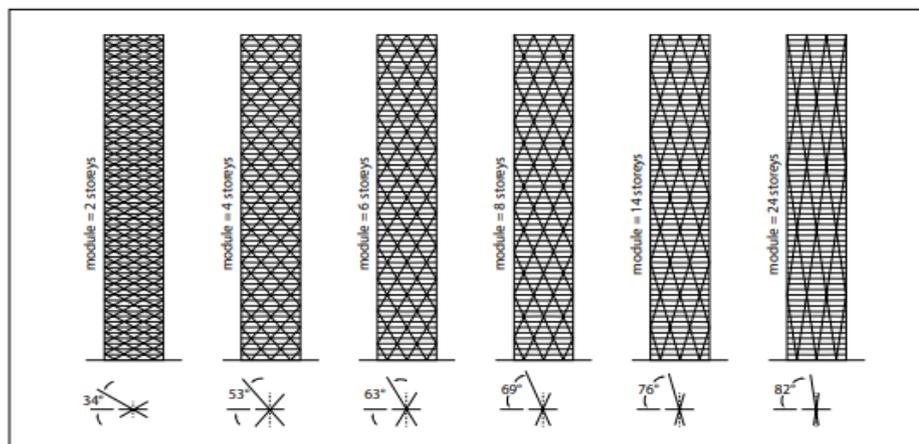


Figure 20. Module design with different diagonal lengths and angles that vary depending on the floor-design status of a 60-story building (Boake, 2014).

The following matters affect the design of the diagrid system and selection of the module.

- Geometry of the building
- Occurrence of eccentric loading
- Structural efficiency
- Floor-to-floor heights
- Requirements for fenestration pattern and window sizes
- Selection of AESS or concealed steel structure

There are additional criteria that impact the module size for tower type buildings:

- Height/width and proportion of the building
- Core design (ability or not to assist with lateral load resistance)
- Wind and seismic loads (Boake, 2014).

In other words, the module on a construction refers to the distance between connection nodes, the number of floors where one of them passes vertically from end to end. The size and angular arrangement of the modules directly affect the building's structural design, element sizing and node design, and therefore its architectural design.

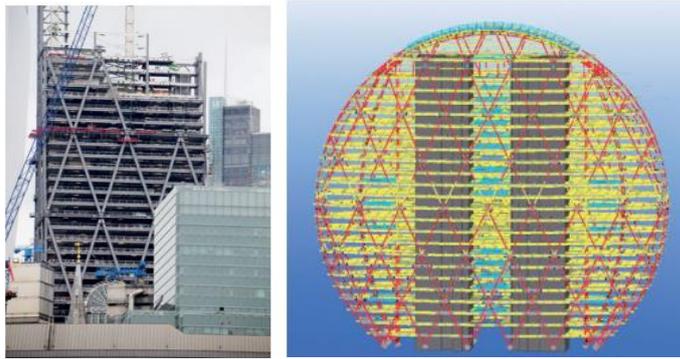


Figure 21. The 14-story module used in The Leadenhall Building in London, England and the 8-story module used in the Aldar Headquarters, Abu Dhabi building (Boake,2014).

3.6. Structural Performance

The structural performance criteria of the diagrid system are different for each structure. Tall buildings are exposed to much more wind, pressure, seismic events and lateral loads than low-rise buildings. For this reason, the diagrid modules used for high rise are designed to act as a vertical cantilever and to be very durable. The diagrid system applied for a tall building resists the moment forces at the base and the cutting forces towards the top. There are modules in the system, which are one of the main elements that enable the transportation and transmission of loads. Angularly designed modules are designed to be four floors and larger floors according to certain design criteria. These angular modules intersect with multiple cross sections and nodes with connection points. With the nodes used at these intersections, the module's being too long to be supported and solid/one piece is prevented, it provides restriction and prevents buckling. In this way, the steel grid connected to each other displays a more robust and rigid behaviour.

In the face of medium and large earthquake shocks, a typical seismic force resistance system provides adequate ductility and energy propagation properties. At the same time, they were more resistant due to their triangular arrangement (Boake,2014).

3.7. Load Transfer in Diagrid Structure

The loads on floors in diagrid structured structures and the weight of the floor are transferred to the modules to which they are connected. Each of the modules ensures the loads reach the foundation by transferring it to another module it is connected with node. The thickness of the modules used and the distance between the start of both edges change the design of the node points. These steel modules are matched and screwed together by nodes. It is known that these plates are processed with tight tolerances to achieve a uniform load transfer. On the ground, the modules connected to the foundation with anchoring system successfully transfer their loads to the foundation.

3.8. Advantages of Diagrid Structure

Diagrids are structural systems that emerged as a choice of contemporary architecture and there are various functional and economic advantages underlying the system;

- Thanks to the system, higher structures/buildings can be built.
- Large-spans can be easily formed and used as roof cover.

- The steel used in the system is more resistant to both drawing and pressure and also gravity.
- Due to the triangular arrangement of the structure elements, it allows building more solid structures.
- Structural performance is high.
- It is prefabricated and combined. So, they are built faster.
- Recycling is possible due to material properties of steel.
- It provides the opportunity to create more curvilinear and angular surfaces, facades.
- It allows regular and irregular architectural forms.
- It provides the advantage of free design and wide space in the interior in storey plans.
- Since there are no columns in the interior, daylight can be benefitted the a lot.
- Since there are no columns inside and outside, clear, clear and unique storey plans can be created. Thus, space is saved by providing a large and spacious area, and the space usage increases in the interior.
- The visible part of the structure stands out in the facade design and gives the building an aesthetic appearance.
- Due to the triangular form of the supporting frame/undercarriage, it provides arise of aesthetic and impressive facades.
- High structures are exposed to more winding loads; these systems are more successful against wind and under wind loads than traditional systems.
- The combination of gravity and lateral load-bearing systems potentially provides greater efficiency.
- In addition, it does not require lateral load-carrying assistance and is extra resistant for lateral loads.
- It makes possible to reduce the amount of steel used by approximately 20%.
- The fire protection strategy is strong (Baytin, 2010).

4. History of the Gherkin Tower



Figure 22. Gherkin Tower and its surroundings

Gherkin Tower, also known as 30 St Mary Axe, is a skyscraper located in the financial district of London City, near the famous Liverpool Street and Leadenhall Market. The important commercial building of London, Baltic Exchange, is destroyed by the bomb dropped by the IRA (Irish Republican Army) forces in 1992. Later, the area was sold to Trafalgar House in 1995 and the 88-storey Millennium Tower project, the first design in 1996, was withdrawn shortly after it was submitted for approval. Then, Swiss Re, the Swiss reinsurance company, has purchased the area and has the famous British architect Norman Foster design the building to build one of London's most ambitious/challenging commercial buildings (Russel, 2004). At the same time, the historical building around it was restored. The Gherkin Tower, which is built in a central and easy access area, was designed by Foster + Partners and the engineering company Arup. Foster wanted the building to be striking and remarkable, stand out amongst the 100-year-old buildings in the vicinity and in a contrasting harmony with them. The philosophy of the design was to create an innovative and up-to-date form stemming from building technologies and materials. The construction of the curved and angular form skyscraper was started in 2001 and completed in December 2003 and opened in April 2004. Its construction was completed quickly, but due to some inconveniences, it became a construction site where the people around it feared and reacted in this process. The reason this; the glazing/glass that surrounds the building is quite heavy and has often fallen during construction (Leon Rodriguez, Morales, and Margaria, 2014). After completed its construction, it succeeded to become one of the most iconic and most important urban symbols of the city with its design in a short time. At the same time, the building has brought a new prominence to the region with regards to its architecture, ecology and silhouette. The skyscraper, which is one of the most developed and tallest towers in Europe and completed with a cost of £138 million, has a height of 180 meters and was built as 41 floors, 1 of which was underground. The building was built on a floor area of 47,950 m². The curved form of the structure is less massive

than a square-shaped skyscraper, and due to its form, it allows the wind to circulate around it. As it causes less wind circulation on the ground, it creates a living space around the ring structure. The building consisting 41 floors and built with modern diagrid steel structure upon the advice of Arup engineering, is considered as the first ecological skyscraper in London. Due to its unique and brave design, Gherkin Tower has been deemed worthy of many architectural awards such as Stirling Award, Regional Award of London, Emporis Skyscraper Award. Gherkin Tower is today the headquarters of many large companies, including some offices of Swiss Re and Sky News. At the same time, some of the very popular television and radio shows are shot here. Meeting halls and offices can be hired on daily and hourly basis in Gherkin Tower. Considering the real estate values, offices are rented monthly for 999-1499 £ per person.



Figure 23. Construction aspect of the building (Munro, 2004).

Figure 24. Completed aspect of the building (Taken by the author, 2020).

4.1. Structural Information

With the opportunities of technology, from the point of Shukhov's using hyperbolic (double curvature surface) surfaces to make structures higher with lighter and less material and based on the philosophy of making these curves lighter by dividing them into triangular surfaces, there is a combination of steel and glass in Gherkin Tower, which is planned by Foster has a unique curved form. In the building used as commercial building, it creates a social space for Swiss Re and other tenants with its restaurant at 39th story and the bar covered with the dome, which is considered the crown of the building at 40th story. It offers the opportunity to watch panoramic views of London with its steel-glass dome design of 360° lamella grid form.

These social levels, starting from the 38th floor, are surrounded by a steel and glass dome structure of 30-meters in diameter and rise 22 meters from the support above the perimeter diagrid. The steel-glass dome is formed from the connection of fabricated triangular steel profiles intersecting with each other via the nodes of 360°. The efficiency of this structural arrangement is made with very few steel elements, which are only 110mm x 150mm in the section. Gross superstructure floor area is (incl. lightwells) 74,300 m². 46,450 m² of the commercial building, which is built on a net area of 47,950 m², is used as office and 1,400 m² is used as retail. The storey plans of the building, which is used as an office building today, are 50m in diameter on the ground. The largest floor is 56m and the highest floor is 25m in diameter. The storey height of the office floors is 4.15m. The floor/slab of the building is 160mm thick composite flooring. Besides, the improved floor plate provides vibration dynamics due to increased rib hardness. Columns are 508 mm on the ground and 273 mm on 36-38 floors. 333pc of 750 mm piles were used in the foundation of the skyscraper. Xstell was designed by Arup for the structural system. The total steel weight used was 8,358 tons (Munro, 2004). "The building has 40 stories, globally 180 m tall with; it is circular in plan with diameter changing along the elevation, equal to 56 m at its widest point, at the 20th story, reducing to 49 m at ground level and to 30 m at the 38th level, where a steel and glass dome tops off the building" (Mele, Toreno, Brandonisio, and De Luca, 2014). The façade siding consists of 5500 of 24.000 m² flat triangle and diamond-shaped glass panels. The steel structure with the diagrid system is in an angular, triangular form that does not contain traditional bearing elements such as columns inside and gives design freedom in the interior (Binder, 2006). A total of 8,358 tons of steel used in the building (from Arup Xsteel model); Used as 29% is in the diagrid, 24% core columns, 47% beams (Munro, 2004).

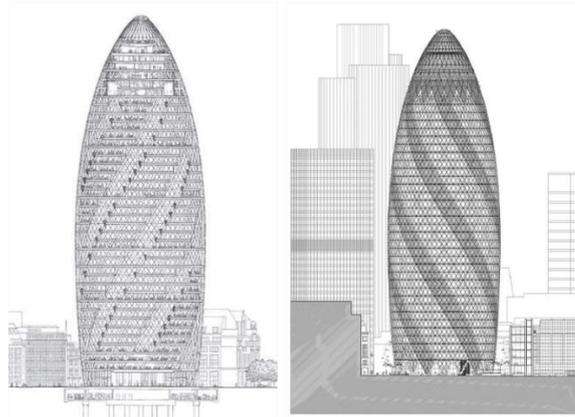


Figure 25. Gherkin Tower drawings(Massey,2014).

4.1.1. Design of The Nodes

Arup Company, that provided engineering services together with Foster in the design of Gherkin Tower, preferred the diagrid system as the structural system in the structure. It designed 360° steel nodes to simplify the construction process of the angularly rising and curved skyscraper and connect the diagrid frame. These nodes are used at the intersections of the structural elements and the load is transferred to other elements.

The nodes contain 3 steel plates welded at different angles. The connections helped easy and cost-effective construction of the diagrid. These nodes are prepared as factory pre-produced like modules. The center of the node is made of solid steel block of 240x140mm. The diagrid itself contains tubular steel sections that provide vertical support to the floor by following the scrolls of the building and bring the superiority of the office space without columns. The local geometry of the connection varies at each floor level due to different floor diameters (Boake,2014).

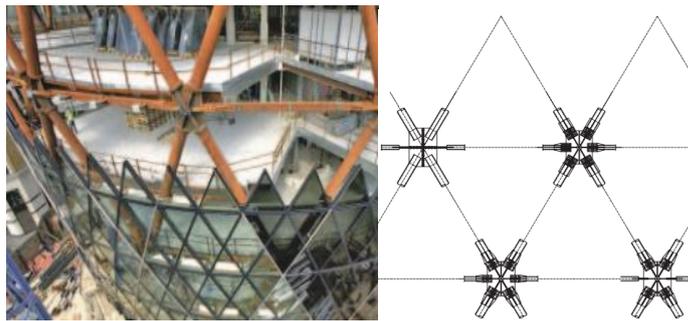


Figure 26. Node design (Munro, 2004).

4.1.2. Design of Module Size/Dimension

A module of four floors from tip to tip of the diagrid is used on the Swiss Re Tower. In this instance, the relatively small module is required in order to allow for the use of straight diagrid members to achieve the appearance of a curved shape without necessitating the bending of the members. The tighter module also contributes to the intention to spiral the darker blue ventilation shafts up the volume of the building. The changing building shape results in an increasingly steeper grid angle toward the top of the building(Boake,2014). The angle of the diagonals allows for a natural and direct flow of loads through the structure and down to the foundation of the building.



Figure 27. Module dimension of Gherkin Tower(Boake,2014).

4.1.3. Less Steel Usage

“When considering the efficiency of a diagrid structure, it is important to take a very holistic view of the project. Diagrid buildings such as the Hearst Magazine Tower and the Gherkin Tower have been reported to use 20% less structural steel than a conventional moment-framed building. While this is important in terms of project and environmental costs, it must be recognized that diagrids increase the fabrication costs due to the use of specialized connections – the nodes – even though these are normally prefabricated. From the point of view of fabrication and cost, the module size and consistency has a direct impact on the design and fabrication of the nodes. Larger modules require fewer nodes. As the fabrication costs of the nodes are likely to greatly exceed the base cost of the steel, larger modules can offer fabrication and erection savings” (Boake,2014).

5. Interaction of Structural System with Architectural Design in Gherkin Tower

Gherkin Tower, also known as 30 St Mary Axe, is the first full diagrid commercial building. Skyscraper is not only an ambitious and interesting building. It is one of the sustainable green buildings with its architectural and structural system design. Due to its distinctive form in the heart of the City of London, it is an instantly recognizable structure even on the horizon/skyline. It has a sustainable design that will serve as a model for all skyscrapers in Europe's leading financial centers. It was built with an environmentally friendly approach that reduces energy consumption. The relationship of the building, which has a high environmental strategy, with the street is well established by the architect; it is separated from other skyscrapers with its sitting areas, landscape elements and a public square. It is a lively skyscraper that keeps urban life and office life interconnected due to the social spaces/social domains it contains.



Figure 28. Zone Skyline(Building The Gherkin Press,2007).

Dominic Munro, a design associate with Arup who was deeply involved with the project, wrote in an article for *Stålbyggnad*: “The project shows the ability of structural steel to enable radical architectural ideas to be realized” (Boake,2014).

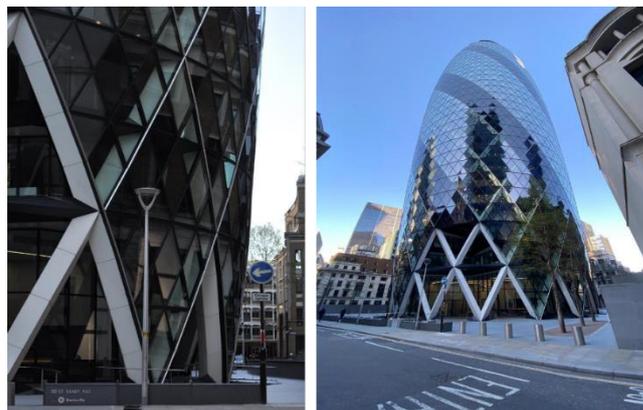


Figure 29. Gherkin Tower. (30St Mary Axe)(Taken by the author,2020).

5.1.Architectural Form

Gherkin Tower that located in the heart of London's financial center has become one of the landmarks and symbols of the region with its challenging design, is considered as the first ecological skyscraper of London. The architect of the building, Foster + Partners, wanted to obtain an impressive form that manifests itself, distinct from the old buildings around, as well as being modern and stylish. In order to create an assertive structure, angularly rising diagrid structure design has emerged with the support of Arup Company. Since the angular rise of the bearing system gives the structure an aesthetic appearance, the steel construction is emphasized on the facade.



Figure 30. Gherkin Tower and its environment (Taken by the author, 2020).

Gherkin, composed of a triangular diamond-shaped glass curtain wall/glass curtain façade with angular braces, has a length of 180 meters and is 40 floors. The roof of the tower, which is in a circular plan that narrows as it rises from the ground to the top, is covered with a dome. Starting from 38th floor, there are restaurant and bar floors with 360-degree panoramic views of the Empire Square to create a social environment for office workers and visitors.



Figure 31. Bar floor of Gherkin Tower(Taken by the author,2020).

Although the building is high, a structural success has been achieved against wind load. One of the reasons for this success is to decide its curvature as a result of passing many wind simulation tests while creating the form of the building. Compared to a rectangular structure, the wind turbulence at the plaza level is low, a social living space has been created for people on the ground. As are at the top of the skyscraper, there are cafes and outdoor sitting areas on the ground floor.

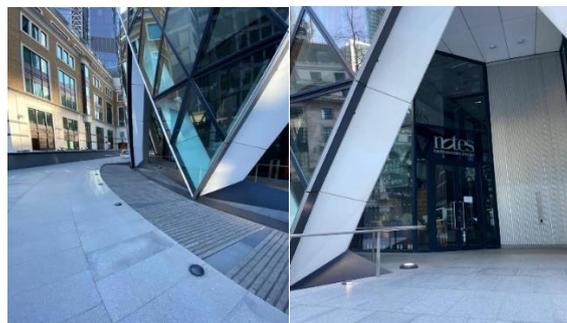


Figure 32. Gherkin Tower ground floor social areas(Taken by the author,2020).

In the Gherkin Tower building, the height of the entrance floor is arranged as 7 meters and the height of office floors are arranged as 4.15 meters. All of the floor plans with form are differently designed by Foster. Each floor in the skyscraper turns at an angle of 5 degrees. Also 6 triangular pieces have been removed from the circular floor plans and light wells have been built in order to benefit from sunlight in these spans. At which angle the spans will join with

the walls varies throughout the structure due to the rotation of the floors. Even this situation sounds interesting when experiencing the structure, it makes it quite challenging in terms of design.

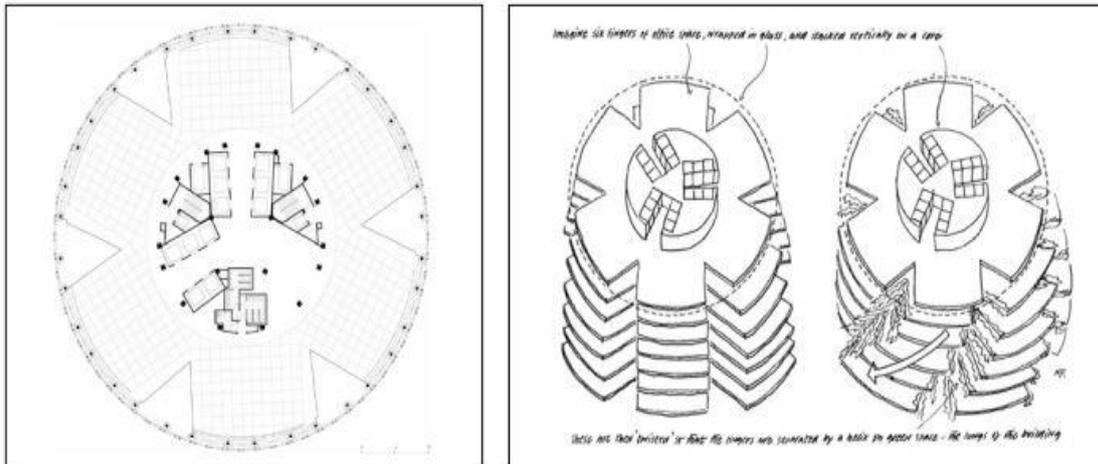


Figure 33. The Sketch showing the rotation of floors drawn by Foster + Partners(Boake,2014).



Figure 34. View of Gherkin Tower turning angle from the ground floor(Taken by the author,2020).

One of the advantages of the diagrid structure system used in the skyscraper is that there are no traditional columns in the structure. In this way, clear and spacious areas with large span have been created in the interior. Usage area has reached maximum efficiency for offices and common areas.



Figure 35. Skyscraper entrance hall and office floors inside(Taken by the author,2019).

5.2. Façade

Many diagrid buildings, especially those with curvilinear forms, tend to use triangular glasses on their facades. Triangular geometry is often preferred in these types of structures, for reasons such as its manifesting the curve more comfortably when used in different sizes on curvilinear and tilt/curved surfaces and being more applicable than square glasses and traditional walls. Gherkin Tower is one of the buildings with this triangular glass curtain-wall/glass façade. The integrity of the façade with structure is achieved by using a triangular-diamond-shaped transparent double wall glass façade in the form rising angularly. Besides adding an aesthetic value to facade designs, angular rise of structural elements in the building and the possibility of coming into prominence provide designers convenience in facade arrangements. Although the glass system itself is more expensive than the traditional curtain wall system, the use of glass in such curvilinear facades is a much more economical option. After negotiations with the facade engineers for skyscraper, it was decided to apply double glazing in the building and 5500 pieces of glass equal to 24.000 m² which is about the size of 5 football fields were used. The reason of using gray glasses is to reduce the

burning effect of the sun. While the outer wall is composed of triangular glass claddings and profiles, the inner walls are mostly composed of dividing elements and doors. Also, one of the factors that make Gherkin Tower an ecological building is that some parts of the windows in the curtain wall/siding covering the spiral form can be opened and closed. There are 792 mechanical windows that can be opened in light wells for ventilation and fresh air flow in the building. Considering the climate and weather conditions, the building is naturally ventilated by these folding mechanical glasses. In this way, the energy consumption used for ventilation is reduced. The modules are left empty in the entrance parts of the building and the cafe on the ground floor, and the entrance is provided through these spaces.



Figure 36.Gherkin Tower Entrance



Figure 37. Gherkin Tower façade and points of entry(Taken by the author,2020).

5.3. Façade Cleaning

Special methods are required for facade cleaning in curvilinear and tilt structures such as Gherkin Tower in London. In order to clean the facade of Gherkin, a rotating extendable crane to the top of the tower has been designed. The crane designed for Gherkin runs on a rail set parallel to the building form. With this crane operated at certain intervals, the exterior of the office building can be cleaned easily. Also, crane rails are designed to be a feature of the tower top design. This cleaning device is operated with cables attached to the curtain wall of the tower at certain points along the height of the tower. Additional foam rings are used to prevent the cables from hitting or damaging the glass and the tower's mullions.



Figure 38. Rail and crane used for facade cleaning of Gherkin Tower(Boake,2014).

5.4. Atriums and Lighting

One of the performance targets of Gherkin Tower has been to use daylight at the highest level inside the whole structure. In accordance with this purpose, 6 triangles were removed from the floor/storey plans with a circular form and rotating at an angle of 5 degrees and atriums were formed in those areas. These atriums have light wells that control and purify the air, divide the building into fire safety zones. Every 6 floors are combined with a light well. The atriums are connected vertically, but each floor deviates from the previous level at an angle of 5 degrees and forms a spiral structure.



Figure 39. Light wells (Foster+Partners).

By means of the light wells, the people working in the office make maximum use of the daylight that reaches the center of the circular floor plan. These light wells created at the same time have become stress relieving and city-view spaces where office workers can relax during the day. These luminous areas provide strong visual connections between floors and create a natural focus for offices. Atriums designed on each floor are connected vertically to each other in order to create a series of informal interstitial spaces that spiral the building. Atriums, which are a natural social focus for refreshment points and meeting areas, function as the building's livers. The reason for this is that the glass panels in the light wells can be opened and the interior can be ventilated naturally. Light wells are interrupted on every six floors, thus it makes easy to pull the air out in the building.



Figure 40. Light wells (Foster+Partners).

Diagrid structure on the facades are formed by the intersection of the steel tubes framing the light wells. These steels that follow the slope of the building to increase the column-free office space also keep the structure stable.(Figure 40.)

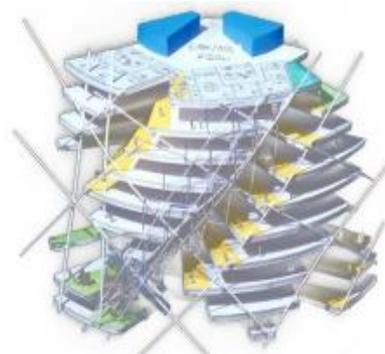


Figure 41. Structural system and light wells (Balci, 2013).

5.5. Ventilation

The façade of the Gherkin Tower's being equipped with complete double-skin façade triangular glasses and the opening and closing feature of the windows in the light well areas according to the weather conditions is an important pillar of the ventilation system and it is important in terms of energy saving, air circulation and increasing indoor air quality. In the building; 6 atriums have been created on each floor in order to lighting, make use of maximum daylight in the offices, to bring the daylight to the core of the circular form. The opening of the glasses in the atriums created in line with this objective significantly contributes to the ventilation in the building. The air is more easily dispersed in the structure due to the 5 degrees rotation of the floors and the atriums cut every 6 floors. At the same time, the aerodynamic form of the building provides an economical and sustainable contribution that helps natural ventilation in light wells, significantly reducing the use of air conditioning. Opening and closing of the windows passing through the light wells on the facade for ventilation creates a healthy indoor environment and produces different pressures with the wind. External pressure differences created by twisted winds help the building use its unique natural ventilation system. 792 openable mechanical windows are used for the ventilation of the building and the flow of fresh air in the light wells.



Figure 42. Ventilation system of Gherkin Tower(Shen,2009)

“All of this helps to reduce the building’s heating and cooling loads and its total energy needs. Within the double skin façade are blinds that can intercept solar radiation, at a 15% solar transmission rate, and the building can then reclaim heat from the solar radiation or reject it depending on the cooling or heating needs of the building . The blinds are computer controlled to raise or change their tilt depending on input data. The windows of the building are also computer controlled and are designed to open when the external temperature is between 20 degrees Celsius and 26 degrees Celsius and the wind speed is less than 10 mph . The glass panels in the atriums are also tinted to reduce glare and solar gain”(Shen,2009).

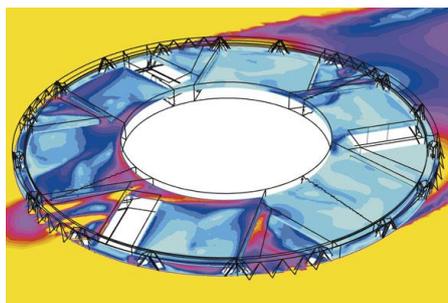


Figure 43. Thermal analysis showing the contribution of the presence of light wells(Sahin Karagöz,2016).

5.6. Wind Resistance

Structures resist many lateral forces such as wind load, earthquake waves and vibrations. Especially the structure’s being forced by wind load and the turbulence formed in the area where the structure stands on disrupting the comfort of the space are one of the most important problems to be considered in tall buildings such as 30 St Mary Axe. While choosing the structure and circular form of the building in Gherkin Tower, a number of turbulence simulations were made and design was made according to the simulation results.

As an advantage of its structure, Gherkin Tower resists the limitations of the area with its original form. The circular form of the office building, that decreases in diameter as it rises, is less massive than a rectangular block, creates an urban living space at street level. At the same time, while the aerodynamic form of the building shows minimal wind resistance, it makes the wind rotate around; this increases the environmental quality for people on the ground and reduces the load on the structure (Figure. 43).

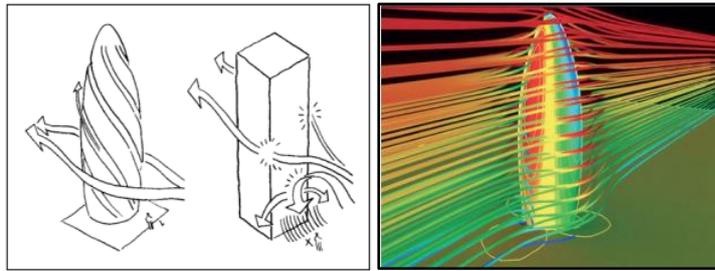


Figure 44. Relation of building form with wind (Boake,2014).

5.7. Lift System

There are 23 elevators in the 41-storey 30St Mary Axe office building to provide human circulation. 16 of them are passenger elevators (6 high rise, 5 mid-rise and 5 low rise), 2 fire fighters, 2 good lifts, 2 shuttle lifts for the top floor and 1 car park lift. Elevators can carry maximum of 378 people at a time and can travel at a speed of 6 meters per second. However, seen as a bard had been planned for the 40th floor this was not possible. The architects dealt with this by having the main lift only reach the 34th floor, and then having a push-from-below lift to the 39th floor.



Figure 45. Some elevators in Gherkin Tower(Taken by the Behzad,2020)

5.8. Fire Safety

In the event of fire in Gherkin Tower, fire-fighting systems have been developed. In case of fire in the building, fire warning is given by automatic heat and smoke detectors. Apart from the automatic fire alarm, there are also many manual fire buttons in the building. A sprinkler system with a deluge system at most 25 meters is used to respond with the fire. Sprinkler was used in 39 floors, but there is no sprinkler system in the dome. The windows in the light wells open automatically in case of fire and help to evacuate the smoke. At the same time, the atriums in the skyscraper includes an escape strategy based on a gradual variation, it is a safe area for evacuation and protection of people in case of fire. Another fire precaution in Gherkin is using special galvanized and fire-resistant partitions to prevent splashing of fire to other parts via central fire control system after the evacuation of people in the area where the fire occurred. With this fire barrier curtain, the area around the fire is closed automatically and the spread of fire is prevented to other areas.

5.9. Energy Saving

St Mary Axe is an environmentally progressive building. Its uncompromising modernity is allied toward a sensitivity to the natural environment. A comprehensive range of sustainable measures mean that the building will use 50% less energy than a traditional prestige office building. Fresh air is drawn up through the spiralling light-wells to naturally ventilate the office interiors and minimise reliance on artificial cooling and heating. The light-wells and the shape of the building maximise natural daylight, moderate the use of artificial lighting and allow views out from deep within the building. The interior atria are expressed on the exterior by the distinctive spiral bands of grey glazing (Foster+Partners, 2004). 30St Mary Axe is London's first environmental skyscraper. A comprehensive range of sustainable measures mean that the building will use 50 percent less energy than a traditional prestige office building. Fresh air is drawn up through the spiralling light-wells to naturally ventilation the office interiors and minimise reliance on artificial cooling and heating. The light-wells and the shape of the building maximise natural daylight, moderate the use of artificial lighting and allow views out from deep within the building (Binder,2006).

6. Conclusions

This study is focused on examining the diagrid structural system and its advantages, which are widely used in tall buildings today, over Gherkin Tower. Throughout the study, besides the advantages of the Gherkin Tower structural system, interaction of the diagrid structure with architectural design has been examined and supported by field work.

Diagrid structures become one of the preferred systems for designers and engineers in recent years in the construction of tall buildings where the limits of architecture and technology are pushed day by day.

The process leading to diagrid structures began with the search for more structural capacity with less material, less weight and less cost. Hyperbolic designs of Shukhov, together with his relevant calculations, proved this can be achieved by using double-curvature geometry-both in planar and volumetric sense. Almost half a century later, it continued with R.Buckminster Fuller's geodesic dome, thin-shell structures of E. Torroja, P. L. Nervi, F. Candela, Otto Frei and S.Ban's grid shell, which help also minimize the visual mass of building besides proving utterly efficient structural qualities. Further researches continued to be undertaken about not only covering larger and larger spans but, also, for constructing taller and taller buildings, providing the required structural efficiency. One of the results of these researches and relevant implementations, along with the wide use of computer software's is the "Diagrid System".

Diagrid structures provide many advantages such as use of much less material due to the double-curved geometry and the triangular tessellation, hence reducing the weight of the building, successfully transferring the loads in the structure to foundation through nodes and modules. Which can be prefabricated and assembled in a short time, therefore lessening the required construction period, etc. In diagrid systems, load transfer is carried out with diagonal beams without the need for vertical columns, a factor which is one of the most important architectural assets proving the freedom of space and flexibility of use. It was observed that the amount of structural steel usage decreased by 1/5 compared to traditional frame systems by using the diagrid structure in the Gherkin Tower building, which was examined in detail in the study. Since the structural materials are fabricated and mounted easily, the construction was completed in as short as 2 years. The structural diagrid system, that reaches the top from the ground, has given the facade an aesthetic, dominant and impressive identity besides increasing stability of the building: The diagrid system is emphasized on the facade, and an elegant image is obtained by using double skin transparent glasses, reflecting the surrounding built environment, mainly the historic part of London, of which it has become a "Foreign Companion".

The building has set an example for other buildings not only with its structural and architectural design but, also, due to its ecological design which made it sustainable enough to be considered the world's first green office building (Baytin,2010). Floor plans of the tower have been rotated at a certain angle, and some sections have been removed from the circular plan to certain angle, and some sections have been removed from the circular plan to create a triangular gap again. These spaces have been used as atrium and light well, benefitting. Natural daylight to the maximum extent, and reducing the need for energy significantly. The light wells with 792 mechanical openable glasses provide natural ventilation which can, also, serve as safe zones in case of a fire. The aerodynamic and contemporary form of the building, produces maximum resistance against the wind, prevents the wind from hitting the building and turning into the surrounding built environment as turbulence, in addition to adding dynamic power to the curvilinear structure(Baytin,2010).

Therefore, Gherkin Tower has become the most impressive and striking example of the fact that a structural system can be structurally very efficient, can serve sustainability principles, can help ecology of the environment, can add to the aesthetic value to the region through enriching architectural aesthetics of the building. In Türkiye, tendency for constructing office and commercial buildings as well as the mixed-use ones taller and taller has been increasing in recent years. However, the structural system utilized is, almost always, the reinforced concrete skeleton system, which makes the building very heavy and massy. Therefore, as the height of a tall building increases its cost follows it, not adding to its structural efficiency but to its weight, which, in turn, decreases it. As the course of its nature, the skeleton system has many columns, which hinder the provision of freedom in architectural space, let alone the flexibility necessary for dealing with possible changes of use in time. In addition, it is regretful to point out the fact that the due care for sustainability and ecological issues are not given in the design and construction of these buildings: on the contrary, most of the time invaluable ecological balance of the environment is damaged.

As was shown in the study, the diagrid structural system can be another alternative for constructing tall buildings in Türkiye, due to its above mentioned peculiarities and advantages. They could be built more economically and faster with this system, as criteria sufficient enough to overcome the hesitations about the material-steel- since the country imports structural steel for the time being. The author considers that the diagrid structural system will, also, allow for different climatically aware architectural designs, since Türkiye has seven geographical regions with different climatic features. Therefore, it is anticipated that this system, which has not yet been implemented in our country, will be used in the future due to its multiple advantages, underlying the possibility for variety of architectural design.

Acknowledgment: I would like to express my sincere thanks to Assoc.Prof.Dr. Nesil Baytin for her helpful critics and technical coordination during the study on this research. And we sincerely thanks to Assoc.Prof.Dr. Gökçen Firdevs Yücel Caymaz for their help and guidance.

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