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Diagrid- An Innovative Technique for High Rise Structure

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Abstract—*Construction of multi-storey building is increasing nowadays throughout the world. This is because of advances in construction methodology, materials, analysis and design software. "DIAGRID"- Diagonalised Grid structure have emerged as one of the most innovative and adaptable approach to structural building in this millennium. Diagrid is a particular form of space truss having design principle of cantilever. It consist of perimeter grid made up of series of triangulated truss system. Diagrid is formed by intersecting the diagonal and horizontal components. The diagonal members of diagrid can carry both gravity load as well as lateral load by axial action as in truss. Architects always try for new complex structures. Diagrid system gives wide range structural efficiency and has aesthetic potential. The triangulated module can also be of diamond shaped. It includes the Hearst Tower in New York, Guangzhou West Tower in Guangzhou, and Capital Gate Tower in Abu Dhabi. The aim of this paper is to present diagrid structures, comparison of different diagrid structure with conventional structures. Effect of the change in the angle of twist, angle of tilt, tampered shaped structure, freeform etc. are also investigated in this paper.*

1. INTRODUCTION

The development and growth of tall buildings around the world in populated cities is increasing day by day. It is due to continuous urban sprawl, availability of more rental areas with less environmental damage, constructional cost efficiency and the need to preserve the agricultural land. Diagrid - Diagonalised grid structures is one of the emerging innovative concept to design tall buildings. Diagrid not only gives more stiffness but also resist the lateral forces (due to wind and seismic) and gravity load by axial action. It is a particular form of space truss consisting of perimeter grid made up of triangular structural system [1].

Diagrid- a word formed by combination of "diagonal" and "grid" [2]. Architects designated Diagrid as a "totally new trend". Vladimar Shukhov, a Russian Engineer, built the first diagrid structure known as Hyperboid Structure shown in Figure 1 in 1896. The tower is now known as Shukhov Tower (Fig. 2). On his visit to some of Shukhov projects Ian Ritchie, a renowned British Architect, commented, "Vladimar Shukhov pioneered new analytical methods in many different fields. Shukhov left a lasting legacy to early Soviet Russia constructivism".

Figure 1. Hyperboid Structure

Figure 2. Shukhov Tower

The aim of this paper is to present diagrid structures, comparison of different diagrid structures with conventional structures. Effect of change in the angle of twist, angle of tilt, tampered shaped structure, freeform etc. are also investigated in this paper.

2. STRUCTURAL SIGNIFICANCE

It is said that when there is problem there is a development. The basic idea for developing a diagrid sytem is to eliminate vertical columns. Vertical columns carry only gravity loads and incapable of providing lateral stability[3]. A tall building should resist both gravity loads and lateral loads (due to wind, earthquake, etc.). Diagrid system provides this facility. This structural system resist both, gravity and lateral loads, by the action of axial forces in an effective manner. Diagrid structures act like free standing cantilevers and become more susceptible to lateral loads as their height to base ratio increases [4]. Therefore, these are subdivided longitudinally into modules according to repetitive diagrid pattern [5]. The parameters, an Architect and Structural Engineer, takes into account while planning and designing a Diagrid Structure includes height of diagrid, angle made by diagonals, rate of twist, angle of tilt, angle of taper, degree of fluctuation of freeform, etc.

2.1 The height of diagrid structures

According to heights of structures, buildings are classified in 3 groups [6]

Figure 3. Tornado Tower, 200 m, Doha, Qatar

Figure 4. Hearst Tower, 183 m, New York, USA

Table 1: Category of Building [6]

Sr. No.	Building	Storey height (in m)
1	Mid-Rise Buildings	<120
2	High Buildings	120-500
3	Super High Buildings	>500

From Figure 5, it was observed that the height of building has increased in the last decade. Among the tallest buildings in the world, 76% are within the range of 50–70 stories which stand in the second group. The number of mid-rise buildings is also increasing day by day in diagrid structure. This is because these structure became popular in tall structure and soon can be applied to mid-rise building. Super high towers (>500m) clearly illustrates capabilities in constructing towers in diagrid structures because these structures can resist gravity and lateral loads more effectively which is a serious problem in high rise structures [5].

2.2 Diagrid' angles

The structural design of diagrid structure is greatly influenced by the angle of diagonals. With the deviation of angle of diagonals from optimum condition, not only the required amount of steel increases significantly [7] but also storey drift of structure, storey shear and top storey displacement changes. Therefore, it is very necessary for an Engineer to obtain the optimum angle of diagonals in diagrid structure in order to obtain a safe structural design of diagrid.

For maximum bending rigidity, the angle made by column should be 90^0 and for maximum shear rigidity, it is 35^0. It is expected that optimum angle of diagrid falls in this range [8]. Tall building of high aspect ratio (height/width) behave like bending beams whereas short buildings with low aspect ratio behave like shear beams. Thus, it is expected that, increase in building height increases the optimal angle of diagonals [8].

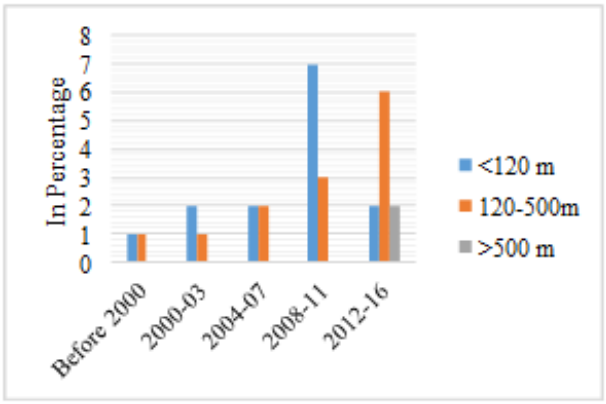

Figure 5. Height of Building in different time span

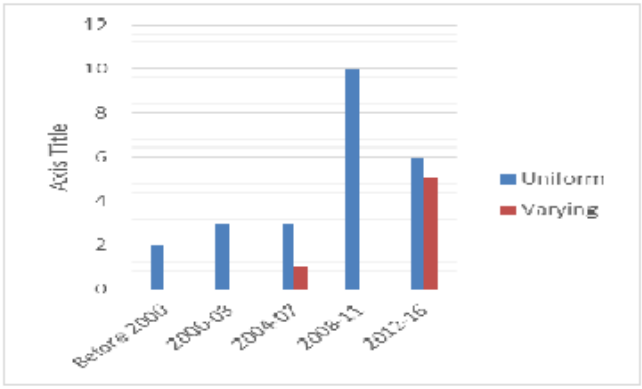

Figure 6. Comparison of Angle of Diagonals

From the Figure 6, it is clearly seen that varying diagonal angle has increased because of economic considerations, efficiency and sustainability concepts. The varying angle concept proves very helpful in structural efficiency.

2.3 Diagrid' plans and forms

A recent architectural phenomenon is employing twisted forms for tall buildings [10]. For example, Fig. 7 shows one such structure. Twisted forms of structure are not structurally beneficial in terms of static response. Fig. 8 shows a twisted tower with a square plan. The moment of inertia of a square plan do not change with the angle of twist in a solid tower. But, the lateral stiffness of the twisted tower is smaller than that of the straight tower if structures considered are of many framed members [11]. Generally, buildings are constructed vertically i.e. orthogonal to the ground. When a building is tilted, it indicates a serious problem. The Leaning Tower of Pisa Fig. 9 is a famous example of tilted buildings due to differential settlements. Today's Architects intentionally designed and built tilted buildings in order to produce more dramatic architecture. Capital Gate Fig. 10 is one such example. The structural performance of a tilted tall building is dependent upon its structural system and angle of tilt. If the angle of tilt is ranging from 0 to 13 degrees, it do not influence lateral stiffness of tilted diagrid. It is seen that the lateral

deformation of tilted structures is because of wind loads and eccentric distribution of gravity loads. Through careful construction planning, the gravity-induced deformation can substantially be reduced [11].

Figure 7. Shanghai tower model

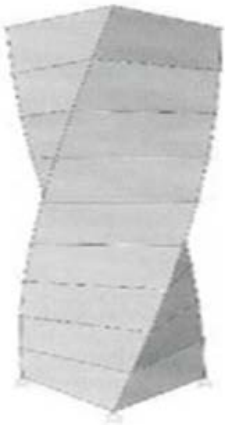

Figure 8. Twisted Tower

Figure 09. Leaning Tower Of Pisa

Figure 10. Capital Gate

For tall buildings, tapered forms provide many advantageous aspects for structural systems as compared to prismatic forms. As we move towards the base of the building, the magnitudes of shear and overturning moments due to lateral forces grows. To resist these, tapered building with more base width is desirable because it helps to increase the lateral stiffness and reduce lateral loads. Also, when compared to prismatic tall buildings, tapered tall buildings are less susceptible to severe across-wind direction vibrations caused by vortex-shedding. Architecturally, tapered building are more desirable for mixed used tall building [12]. To maximize comforts for occupant's living space should not too far away from natural light whereas natural light is less important in office functions. Therefore, to work well architecturally tapered tall building with commercial office on lower and residential functions on higher level is most favourable. Some of tapered diagrid structures are. Guangzhou International Finance Centre and John Hancock center in Chicago as shown in Fig. 11 & 12 resp.

Figure 11. Guangzhou International Finance Centre

Figure 12. John Hancock center in Chicago

Freeform is another widely used concept in diagrid structural system. In this type, the plan of building is not of any standard geometry shape or of regular form. Earlier, it was difficult to analyze and design irregular freeform building. With the advancement in technology, software many freeform tall structures are designed and constructed also [13].

Figure 13. Central Chinese Television Tower (CCTV)

Figure 14. Diagrid Freeform Tall Building

The choice of supporting freeform depends on specific situation and very often diagrid are employed as primary structural system for freeform see Fig. 13 [10]. The diagrid structural system has great potential for freeform because triangular structural geometric can specify any irregular freeform tower more accurately without distortion Figure 14. The rate of lateral stiffness reduction increases with increase of degree of fluctuation in freeform diagrid [10]. Hence,

shapes of freeform should be determined for architectural and structural performance.

2.4 Diagrid Material

Diagrid is a particular form of space truss consisting of perimeter grid made up of series of triangular module. This module can also be of diamond shaped. The important point for a diagrid structure system is selection of material for the structure. The materials available for the construction of diagrid are:-

1. Steel
2. Concrete
3. Composite (steel filled with concrete)

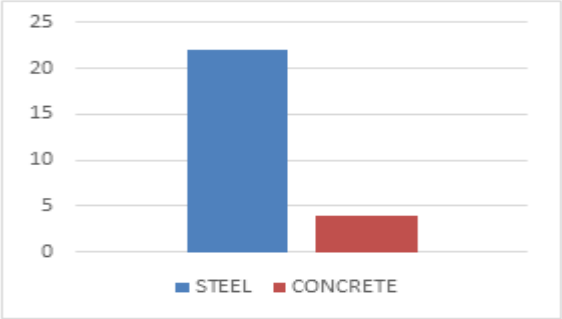

Figure 15. Comparison of Materials

From the above figure, steel is mostly used for the construction of high rise diagrid structure Fig. 15. Steel grids are more popular because of easier and faster construction, simpler joints, less expensive formwork and agreement with sustainability concepts [6].

2.5 Steel Diagrid

For tall buildings, construction of steel diagrid is more challenging and complex when compared to conventional structural system. This is because of the fact that the joints of diagrid is more complicated as of conventional structural system. A diagrid structure is a cantilever beam fixed on ground subdivided longitudinally into modules (triangular or diamond) according to the repetitive diagrid pattern.

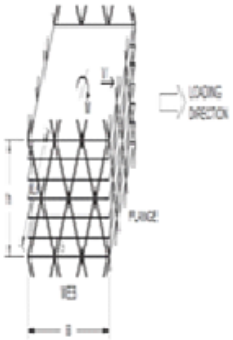

Figure 16. Typical Diagrid Module

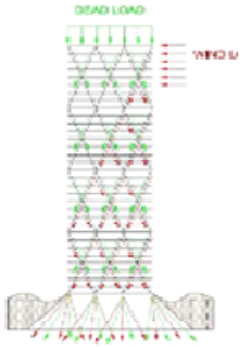

Figure 17. The distribution of load in diagrid structure

The faces act as either web planes (i.e., planes parallel to wind) or flange planes (i.e., planes perpendicular to wind depending on direction of loading Fig. 16. As mentioned earlier diagrid is particular form of truss and hence are assumed as pin-connected. They resist the transverse shear and moment through axial action only Fig. 17. Therefore, the design problem reduces to determining the cross-sectional area of typical web and flange members for each module [8].

The construction of diagrid structure becomes complicated because of node. The joints of diagrid structures are more complicated and tend to be more expensive than those of conventional orthogonal structures. To minimize the cost of construction, prefabrication of nodal elements is necessary. It seen from studies, the nodes become stressed due to simultaneous tensile and compressive forces and additional moment due to the couple axial forces when subjected to lateral load due to wind and earthquake [14]. The governing failure of diagrid node is combined mechanism of axial force and additional moment from the two axial forces Fig. 18.

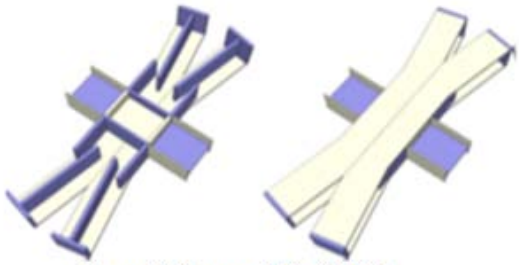

Figure 18. Proposed Diagrid Node

2.6 Concrete Diagrid

Presently numerous tall buildings are in construction and the most challenging use of the diagrid structure is in creation of model in different forms i.e. in twisted, tapered, tilted, freeform, etc. Typically, the building uses a substantial vertical concrete core to carry straight run elevator access through the building. Concrete a material widely used to carry the compression loads, is used in diagrid system to carry the gravity load coming from the structure. To design the concrete core, it requires extra engineering to ascertain the structural integrity of the building [6].

Figure 19. Aldar HQ

Figure 20. The Bow

Aldar HQ in Abu Dhabi, Fig. 19, is 8 floor base module, which is capable of forming to the curves required by the circular disk design of the tower. For the stability of the structure due to the eccentric loading, a concrete core is used although the building is symmetric.

The Bow in Canada [15] is one such diagrid structure using concrete core. The building frame consist of structural steel beams with concrete on steel deck. The gravity column of this structure is of structural steel, Figure 20.

3. ARCHITECTURAL PERSPECTIVE OF DIAGRID

Today architect mostly prefer to design a complex-shaped tall building involving a new structural system. In such a case, a trend for tall structure, Diagrid has emerged. This section provides a basic difference between the conventional orthogonal structure and diagrid structure. Conventional structure is composed of slab, beam, vertical columns, etc., subjected to flexure (bending due to load on beam), torsion and shear i.e. it is designed to resist all the above. Whereas in case of Diagrid structural system, all vertical columns are eliminated and inclined columns (diagonals) inclined at specific angle is used. Thereby, they are subjected to only axial forces (tensile or compression) and are designed accordingly. In diagrid structural system, not only lateral forces (due to wind or earthquake) but also gravity load are resisted by axial forces developed in diagonal, Fig. 25. The diagonals are provided on the perimeter of the structure. Diagrid system gives wide range structural efficiency and has aesthetic potential. As far material is concerned, diagrid used less material than conventional structure [2]. The weight of steel required in diagrid structure is 33% less than that of conventional building. Because of this, number of interior column in a structure is decreased thereby allowing much flexibility on the design plan. Hence, diagrid provide a new variety for architect and structural engineer to designed complex-shaped tall building. The structural elevation of Aldar HQ is shown below Fig. 21.

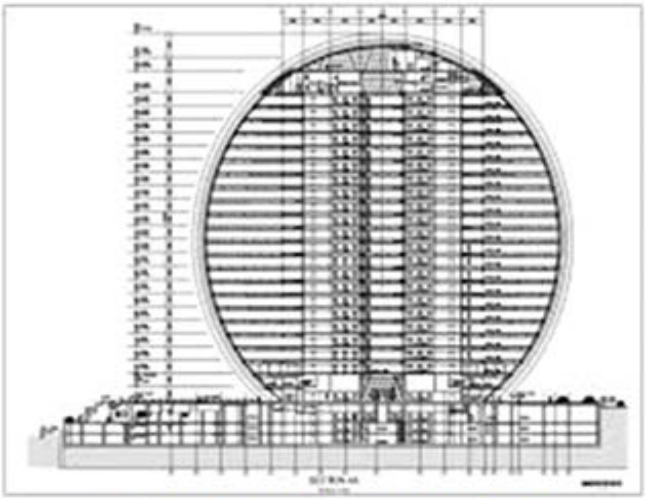

Figure 21. Structural Elevation of Aldar HQ

4. ADVANTAGES OF DIAGRID OVER CONVENTIONAL BUILDING:

The observations can be made by comparing Diagrid building with Conventional building are as follows [2]:

- **Structural performance**

Diagrid building shows less lateral displacement and drift in comparison to conventional building.

- **Material saving property**

The volume of concrete used in both building is approx. same, but diagrid shows more economical in terms of steel used. Diagrid building saves about 33% steel without affecting the structural efficiency.

- **Better resistance to lateral loads**

Diagrid shows better resistance to lateral loads as diagonal columns on its periphery and due to this, inner columns get relaxed and carry only gravity loads. While in conventional building both inner and outer column are designed for both gravity and lateral loads.

- **Aesthetic look**

In comparison to conventional building, diagrid buildings are more aesthetic in look and it becomes important for high rise buildings.

5. CONCLUSIONS

Diagrid - Diagonalised grid structures is one of the emerging innovative concept to design tall buildings. Diagrid- a word formed by combination of “diagonal” and “grid”. Diagrid structures act like free standing cantilevers and resist both, gravity and lateral loads, by the action of axial forces in an effective manner.

The Optimal angle of diagonal increases with the increase in height of structure. These structures are seen in different forms like twisted, tilted, tapered, freeform, etc. It is observed that, lateral stiffness of the twisted tower is smaller than that of the straight tower if structures considered are of many framed members. The structural performance of a tilted tall building is dependent upon its structural system and angle of tilt. If the angle of tilt is ranging from 0 to 13 degrees, it do not influence lateral stiffness of tilted diagrid. Tapered tall buildings are less susceptible to severe across-wind direction vibrations caused by vortex-shedding. In case of freeform diagrid, the rate of lateral stiffness reduction increases with increase of degree of fluctuation. Steel diagrid proves more economic than concrete. It is observed that, in diagrid 33% less steel is required than conventional building. Also, architecturally diagrid structures give more aesthetic than conventional building.

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