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A Review on Novel Structural Development in Tall Building: Diagrid Structure

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Abstract —*The development of new structural concepts for the evolution of tall building structural systems have been towards stiffness and lightness. The structural systems have become further lighter and safer. Structural systems are more efficient now and this is significantly influenced by its geometrical configuration. Therefore, after selection of appropriate structural system it should be configured properly to increase the structural efficiency. It is also wiser to reduce the forces and dissipate the magnitude of vibrations rather than directly standing them. one of the main governing criteria for structural design of high rise structure is lateral loads which are due to wind and earthquake. The resistance towards lateral load is provided by interior structural systems and exterior structural systems. From the many structural systems, available for tall building the diagonalized grid structure have emerged more effective as the primary structural members carry lateral loads by axial action. the structural effectiveness is increased as the primary structural member is located on the perimeter of the building. A review paper is presented discussing the effectiveness of diagrid structural system having different story heights, variable diagrid angles, variable density diagrid system. Optimum diagrid angle range is discussed and depicted that variable angle pattern is better than regular diagrid pattern and regular diagrid angle is better than regular frame structure. Lastly, analysis result like displacements, story drift and story shear of a simple frame and diagrid structural system are compared.*

Keywords*- High rise structure, Tall structural systems, Diagrid system, Variable angle, Variable density system.*

I. INTRODUCTION

The rapid growths of urban population and consequent pressure on limited space have considerably influenced the residential development of city. The high cost of land, the desire to avoid a continuous urban sprawl, and the need to preserve important agricultural production have all contributed to drive residential buildings upward. It is difficult to distinguish the characteristics of a building which categorize it as tall. Tall building cannot be defined in specific terms related to height or number of floors. From the structural point of view a building is considered as tall when its structural analysis and design are affected by the lateral loads particularly sway caused by such loads. Lateral loading due to wind or earthquake are governing in design of high rise buildings along with gravitational loading. As the height of building increase, the lateral load resisting system becomes more important than the structural system that resists the gravitational loads. The growth of high rise buildings is contributed by the evolution of efficient structural system, advances in construction technology, scarcity of urban land and advances computational techniques. For tall structures, interior structural systems and exterior structural systems are provided to resist the lateral loads.

II. CLASSIFICATION OF TALL BUILDING STRUCTURAL SYSTEMS

Structural system in tall buildings can be divided into two broad categories: Interior structures and Exterior structures (Fig. 1). This classification is based on distribution of components of the primary lateral load resisting system over building. An interior structure is when its major part of lateral load resisting system is located within interior of structure and an exterior structure is, if the major part of lateral load resisting system is located at the building perimeter.

A. Classification of tall building structural system

1. Interior Structures
   - Shear Wall/shear Trusses
   - Core Supported Outrigger structure
   - Moment-Resisting frame (MRF)
2. Exterior Structures:
   - Diagrid system
   - Bundled Tube
   - Braced Tube
   - Space Trusses
   - Framed Tube System
   - Tube-In-Tube

- Exoskeleton Super Frames

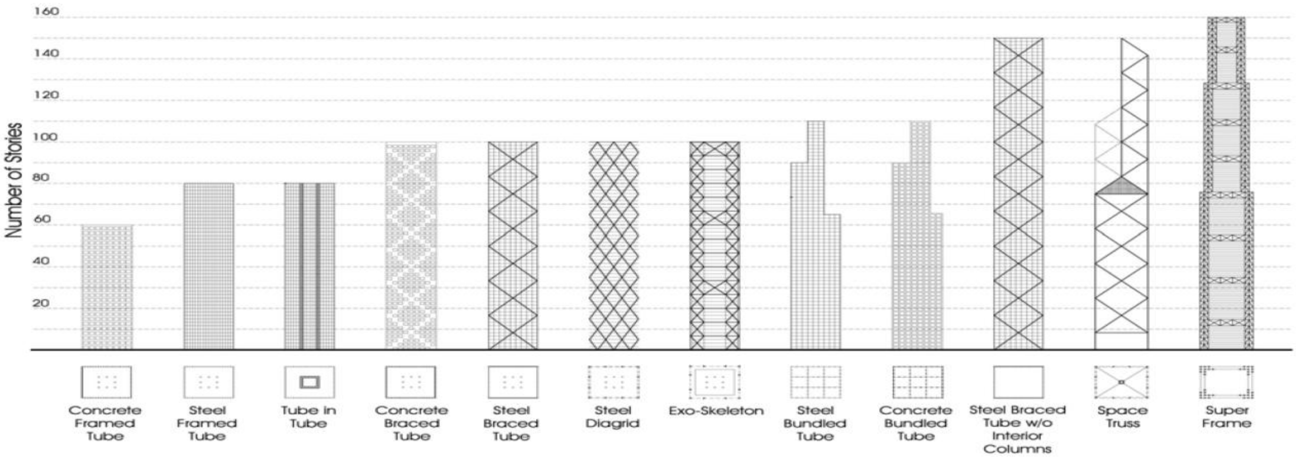


Figure 1. Exterior Structure

- Super Frames

III. DIAGRID SYSTEM

Recently, the diagrid structural system with their structural efficiency of an evolved version of tubular systems and exclusive geometric configuration, have been budding as a new artistic trend for tall buildings. Initial designs of tall buildings accepted the usefulness of diagonal bracing members in counteracting lateral forces with various arrangements such as X, K and V. However, diagonals had a structural importance but aesthetical potential was not appreciated considering it obstructive in view. Thus, diagonals were usually fixed within the building cores which were usually located in the interior of the building. The diagrid is a specific form of space truss. It consists of exterior grid made up of a series of triangulated truss system and the diagrid system is formed by intersecting the diagonal and horizontal components.

The diagrid systems are the further development of braced tube structures, the difference between standard exterior-braced frame structures and present diagrid structures is that the mega-diagonal members are spread over the elevation, giving rise to closely spaced diagonal elements and letting the complete removal of the vertical columns. Therefore, the diagonal members in diagrid structures act both as inclined columns and as bracing elements, and carry gravity loads as well as lateral forces; due to their triangular configuration, mainly internal axial forces develop in the members, thus lessening shear racking effects. Compared [2] with conventional framed tubular structures without diagonals, diagrid structures are much more operative in minimizing shear deformation because they carry shear by axial action of the diagonal members, while conventional tubular structures carry shear by the bending of the vertical columns and horizontal spandrels.

Another structural system for today's tall buildings is outrigger system with either reinforced concrete cores or steel braced cores. An [2] outrigger structure is effective in reducing moment and drift below outriggers. But the system does not provide shear rigidity, whereas diagrid structure provides both shear and bending rigidity. Thus, outrigger needs cores of higher rigidity whereas diagrid structure does not need higher rigidity cores because they carry shear by diagonal grids located on the perimeter.

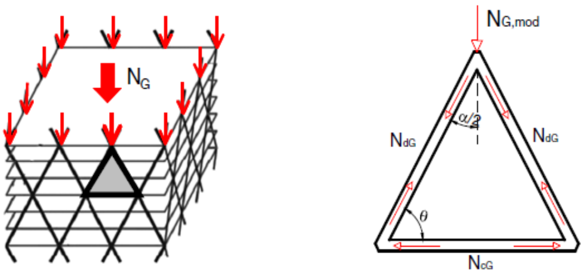
A. Diagrid Variations

- Regular Diagrid: Assuming a diagrid module with constant angle along the height, the resulting pattern is characterized by constant module size and uniform density [1].
- Variable angle Diagrid (VA): The basis behind the design strategy adopting variable angle (VA) patterns is that the share of bending and shear stiffness demands in a diagrid building is a function of the building dimension, and, for a given building, it varies along elevation thus varying angle diagrid system is designed [1].
- Variable density Diagrid (VD): An alternative design strategy is proposed, consisting in a variable density (VD) geometry of the structural configuration: the decrease of stiffness and strength demands along the elevation is addressed by reducing the number of diagonals going from the building base to the top [1].

IV. METHODOLOGY

Diagrid structures boast diagonal bracing on the perimeter of the building to provide the building with lateral stiffness. Because diagonal bracing is located further from the center of the building, it also provides more stiffness than if they were located in the core of building. However, the diagonal braces also serve to carry gravity loads, eliminating the need for vertical columns in building. The diagonal braces carry both lateral and gravity loads axially, provide a more efficient structural response than other systems that depend on bending capacity of vertical columns. This reduction in the number of vertical columns is the main architectural selling point of diagrid structures, as it lends itself to open floor plans and unobstructed views for building occupants. The diagonals can also be integrated into facade and help define aesthetic vision of building for observers.

As shown in the studies by Moon et al.2007 and Moon 2008, the diagrid module under gravity load G is subjected to downward force (NG, mod) it causes both diagonal member in compression and horizontal member in tension. (Fig. 2).

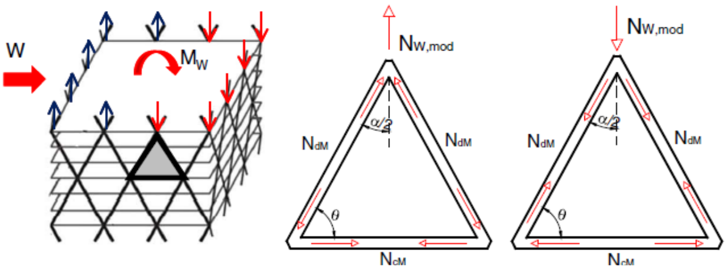


$$N_{dG} = \frac{N_{G,\mathrm{mod}}}{2\cos(90-\theta)}$$

$$N_{cG} = \frac{N_{G,\mathrm{mod}}}{2} \cdot \tan(90-\theta)$$

Figure 2. Diagrid module: Effect of gravity load

Under horizontal load W (Fig. 3), the overturning moment Mw causes vertical forces in the apex joint of the diagrid modules, the direction and intensity of force is more for module located on windward side and less for module located on web sides.

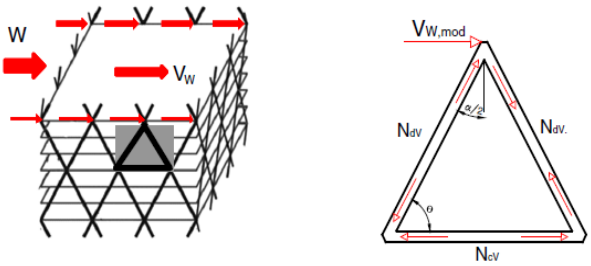


$$N_{dM} = \frac{N_{w,\mathrm{mod}}}{2\cos(90-\theta)}$$

$$N_{cM} = \frac{N_{W,\mathrm{mod}}}{2} \cdot \tan(90-\theta)$$

Figure 3. Diagrid module: Effect of overturning moment

The global shear V_w (Fig. 4) causes a horizontal force in the apex joint of the diagrid modules, $V_{(w,\ mod)}$, which intensity depends on the position of the module with respect to the direction of wind load, since the shear force V_w is mainly absorbed by the modules located on the web facades.



$$N_{dV} = \frac{V_{w,\mathrm{mod}}}{2\sin(90-\theta)}$$

$$N_{cV} = \frac{V_{w,\mathrm{mod}}}{2\sin(90-\theta)} \cdot \cos\theta$$

Figure 4. Diagrid module: Effect of shear force

Since the triangle module usually expands over a certain number of stories, transfer of loads to the module occurs at every floor level, and thus also concentrated loads along the diagonal length are present (Fig. 5); As a consequence, bending moment and shear force are expected due to this load condition. However, the introduction of a horizontal member at each floor girder to diagonal intersection, an intermediate chord, allows for the absorption of the force component orthogonal to the diagonal direction, thus preserving the usual axial force condition.

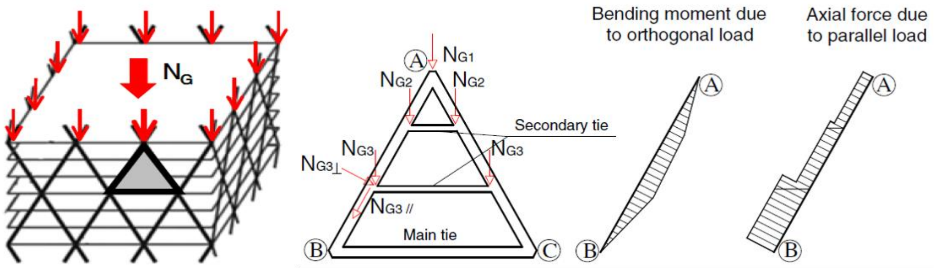


Figure 5. Diagrid module: Effect of concentrated loads

V. LITERATURE REVIEW

In the field of structural engineering, it has been generally known that diagrid structural systems are usually appropriate for resistance against eminent lateral forces. The paper aims at briefing the several investigations and their conclusions that have been carried out in the field of diagrid structures.

In 2014, Montuori et al. carried an organized study of geometrical patterns for diagrids. For this purpose, diagrid structures having unvarying patterns are compared to another geometrical configuration, found by changing the angle of diagonals (variable angle, VA) as well as by altering the number of diagonal (variable-density, VD) along the building elevation. The author generated eight different model buildings which are assessed under gravity and wind loads and various performance constraints are evaluated. The assessment in terms of structural weights and performances finally permits for debating productivity of the different patterns. In this paper the author proposes handy and quick analytical tools for preliminary sizing of diagrid members, where the geometrical and mechanical limitations which govern the load path, resisting mechanisms and deformation modes, are clearly identified. The need for secondary stability system (SBS) for reducing the inter-story drifts and stabilizing the core gravity columns is checked. With this regard, it has been shown that ordinary concentric braced frames located in the interior core are sufficient for drastically reducing the inter-story drifts, with a very slight increase (3%) of the structural weight.

In 2010, Kim and Lee studied the seismic performance of 36 storey diagrid structure with various brace angles using nonlinear static and dynamic analysis. The results were equated with those of a tubular structure and a diagrid structure with secondary bracing system. According to the result the authors observed that as the slope of braces enlarged the shear lag effect increased and the lateral strength reduced. Authors deduced that diagrid between 60° to 70° seemed to be most effective in resisting lateral as well as gravity loads. They also deduce that the diagrid structure with circular plan showed higher strength than the diagrid structure with a square plan as a result of decrease in shear lag phenomenon. The diagrid structure showed higher strength than the tubular structure. The result also showed that the behaviours of diagrid under lateral load were highly brittle caused by buckling of braces and to overcome this they suggest to replace diagonal members with buckling restrained braces.

In 2014, Panchal et al. applied design methodology to a set of diagrid structure which consist of 24, 36, 48 and 60 stories. The diagrid structure of each storey height is designed with diagonals placed at various uniform angles as well as gradually changing angles along the building height in order to determine the optimal uniform angle for each structure potential of diagrid with changing angles. The comparison of analysis of results in terms of top storey displacement, storey drift, time period, angle of diagrid and steel and concrete consumption is presented by author. Author concludes that the diagrid angle in the region of 65° to 75° provides more stiffness to the structure and storey drift and storey shear is very much lesser. This region of angle provides more economic structure in terms of consumption of steel and concrete.

In 2011, Moon in the paper covers the earlier studies on diagrids by considering more effective diagrid arrangements which involve less amount of structural material to meet design necessities. Author has studied diagrid structures of uniform and several varying angle configurations to get more efficient geometric configurations of the system. Thus, this paper presented material saving workable structural design approaches for tall buildings of diagrid systems. It was found that varying angle arrangements can yield more efficient diagrid structures for very tall buildings. Structural consideration has been a governing factor of the studies presented in this paper. However, the most effective structural results may not best satisfy other design necessities. Complete design integration approach between the structural and other building systems should be followed throughout the design process.

In 2014, Panchal and Patel has carried out a comparative analysis and design of 20 storey diagrid structural system building and simple frame building. ETABS software is used for modelling and analysis of the structure. Some conclusion given by author from the study are like, the lateral load is counterattacked by diagonal columns the top storey displacement, story drift, storey shear is very much less in diagrid structure than simple frame structure. Other is the member size used in the simple frame is higher than diagrid structure, thus the diagrid structural system is economical. Lastly diagrid structural system offers more flexibility in planning interior space and façade of the building.

In 2008, Moon carried out stiffness-based design methodology for diagrid structure and braced-frame buildings and the result obtained for displacement and required steel tonnage demonstrate that braced-frame structure has more displacement and steel requirement as compared to diagrid structural system. Author also examined the geometric configuration of braced tube and diagrid structure in which it was found that optimal angle for diagrid structures it was between 60-70 degrees whereas for braced frame it was between 40-50 degrees.

In 2007, Ali and Moon analyses the development of tall building’s structural systems and the technological driving force behind tall building developments. For the primary structural systems, a new classification – interior structures and – exterior structures are presented in this paper. While most illustrative structural systems for tall buildings are discussed, the emphasis in this review paper is on present trends such as diagrid structures and outrigger systems. Auxiliary damping systems controlling building motion are also discussed. Further, modern “out-of-the-box” architectural design trends, such as aerodynamic and twisted forms, which directly or indirectly affect the structural performance of tall buildings, are also studied in this paper.

In 2012, Moon investigated the optimum configurations of today’s widespread structural systems for tall buildings. When the lateral load resisting system is situated at the periphery of the building, the efficiency system can be increased, this is because the entire building depth can be used to resist lateral loads. Among numerous structural systems developed for tall buildings, the systems with diagonals are generally more efficient. The systems that use bracing are the Diagrid, Outrigger structure and Braced tube. From this author conclude that the effectiveness of a particular structural system selected for a tall building is significantly influenced by its configuration. The importance of the studies on optimal configuration of tall building structural systems cannot be exaggerated to save our limited resources and construct more workable built environments.

VI. CONCLUTION OF LITERATURE REVIEW

Reviewed papers have designed different storey structures with different diagrid angles taking regular, variable angle diagrid structures. Comparison is done between terms like storey drift, time period, angle of diagrid, steel and concrete consumption. Results depict that variable angle system are effective than regular diagrid structures and regular diagrid is better than regular frame structure. The diagrid structure reduces column count which provides more rentable space in the same plane area as that of framed system. Results also depict the requirement of the study of the diagrid structural system combined with different cores to increase its effectiveness and height.

VII. COMPARISON OF DIAGIRD STRUCTURE WITH SIMPLE FRAME STRUCTURE

Comparison of diagrid structure with simple frame structure is carried out using ETABS to check that diagrid is better than a simple frame structure.

A. Building configuration
- Plan dimension- 36mt. X 36mt.
- Storey height- 3.5mt.
- Number of floors- 48
- Steel grade- Fe250
- Concrete grade- M 30
- Live load- 4 KN/m^2

MEMBER	MEMBER NOS.	DIAGRID STRUCTURE	SIMPLE FRAME STRUCTURE
BEAM	Beam A	700 X 250 X 50	700 X 250 X 50
	Beam B	700 X 250 X 75	700 X 250 X 75
COLUMN	C1(INT.)	2000 X 2000	2000 X 2000
	C2 (EXT.)	-	550 X 550
DIAGRID	D1	Exterior Dia. 750mm Interior Dia. 50mm	–

Table 1. Member sizes

B. The wind loading is computed based on the basic wind speed of 39 m/sec and terrain category III as per IS:875 (III)- 1997

C. The design earthquake load is computed based on the zone factor of 0.16, medium soil, importance factor of 1 and response reduction factor of 5.

D. Analysis result in terms of Storey Shear, Displacement, Inter-storey Drift are presented.

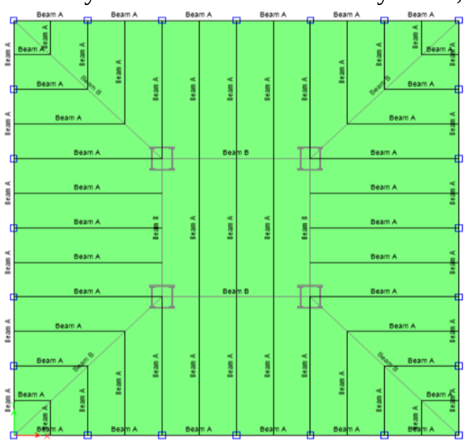


Figure 6. Floor Plan

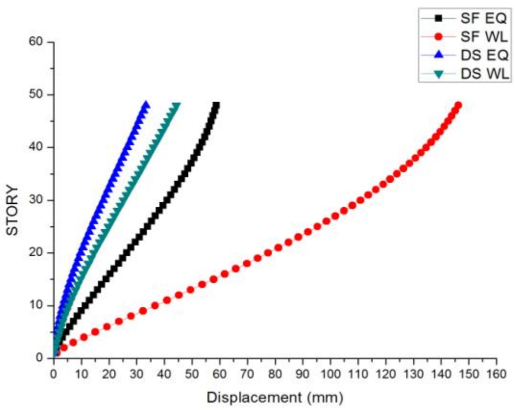


Figure 7. Story V/s Displacement Graph

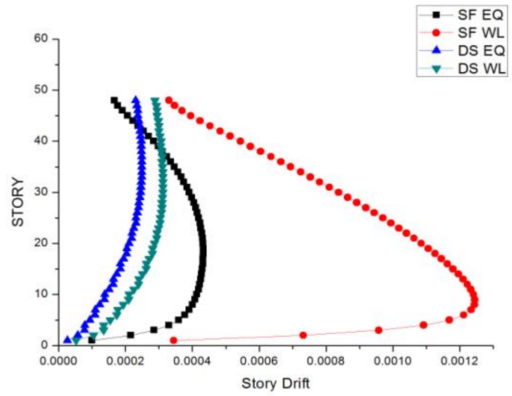


Figure 8. Story V/s Story Drift

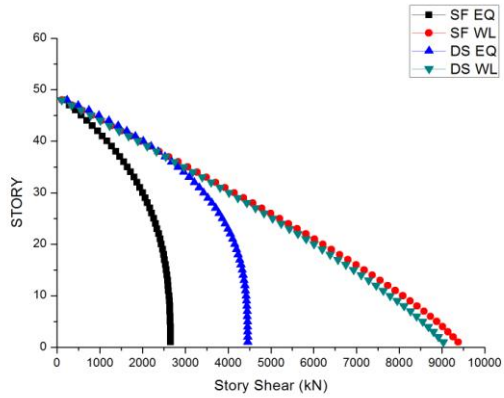


Figure 9. Story V/s Story Shear

VIII. DISCUSSION

- Figure 6 shows basic floor plan for the structures having Beam A and Beam B.
- Figure 7, 8 & 9 shows graph for story verses displacement, drift and shear respectively.
- As the lateral loads are resisted by diagonals the top story displacement is very less in diagrid structure as compared to the simple frame structure.
- The story drift and story shear is less for diagrid structural system.

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