Analysis and Design of High Rise Structure using Diagrid Frame Structure

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Abstract: As the height of building increases lateral loads goes on increasing and become more effective than gravitational loads. diagrid structural system is widely used due its structural efficiency and aesthetic potential due to its unique geometric configuration. Experimental analysis using finite element approach of high rise building with different diagrid angles is done to obtain most efficient angle of steel diagrid structure. Analysis and design of high rise building with varying number of storey and comparison of analysis results in terms of time period, top storey displacement and inter-storey drift is presented. Seismic analysis of high rise building with steel Diagrid system with uniform and varying angles of Diagrid is done and found safe. For 40, 50, 60, 70 and 80 story high structure with aspect ratio ranging from 4.3 to 8.7. For 40, 50 and 60 story structures uniform diagonal angle 63°. For 70 and 80 story structures uniform diagonal angle 69°. Hence this is concluded that as height increases aspect ratio increases which tends to increase the optimal angle. Stiffness based manual design for diagonal Diagrid members is also carried out.

Key Words: High rise building, Seismic analysis, Steel Diagrid, Stiffness based design, IS: 800- 2007

1. INTRODUCTION:

The rapid growths of urban population and its pressure on limited space have considerably influenced the residential development of city. The high cost of land, the desire to avoid a continuous urban spread, and the need to preserve important agricultural productive land have all contributed to develop residential buildings upward. As the height of building increase, the lateral load resisting system becomes more important than the structural system that resists the gravitational loads. The lateral load resisting systems that are widely used are: rigid frame, shear wall, wall-frame, braced tube system, outrigger system and tubular system. Recently, the Diagrid – Diagonal Grid – structural system is widely used for tall steel buildings due to its structural efficiency and aesthetic potential provided by the unique geometric configuration of the system.

Diagrid is a particular form of space truss. It consists of perimeter grid made up of a series of triangulated truss system. Diagrid is formed by intersecting the diagonal and horizontal components. Diagrid has good appearance and it is easily recognized. The configuration and efficiency of a Diagrid system reduce the number of structural element required on the façade of the buildings, therefore less obstruction to the outside view. The structural efficiency of Diagrid system also helps in avoiding interior and corner columns, therefore allowing significant flexibility with the floor plan. Perimeter "Diagrid" system saves approximately 20 percent of the structural steel weight when compared to a conventional moment-frame structure.

In diagrid structural system gravity loads and lateral forces resisted by the diagonal members due to their triangulated configuration. Diagrid structures carry lateral shear by axial action of diagonal members; So, Diagrid are more effective in minimizing shear deformation. Lateral shear can be carried by the diagonal members located on periphery; therefore Diagrid structures generally not need high shear rigidity, Jani[7].

1.1 History:

Early designs of tall buildings recognized the effectiveness of diagonal bracing members in resisting lateral forces. Most of the structural systems deployed for early tall buildings were steel frames with diagonal bracings of various configurations such as X, K, and chevron. However, while the structural importance of diagonals was well recognized, the aesthetic potential of them was not appreciated since they were considered obstructive for viewing the outdoors. Thus, diagonals were generally embedded within the building cores which were usually located in the interior of the building.

A major departure from this design approach occurred when braced tubular structures were introduced in the late 1960s. For the 100story tall John Hancock Center in Chicago, the diagonals were located along the entire exterior perimeter surfaces of the building in order to maximize their structural effectiveness and capitalize on the aesthetic innovation. This strategy is much more effective than confining diagonals to narrower building cores. Despite the clear symbiosis between structural action and aesthetic intent of the Hancock Tower, this overall design approach has not emerged as the sole aesthetic preference of architects, Moon [2].

However, recently the use of perimeter diagonals – thus the term "Diagrid" – for structural effectiveness and lattice-like aesthetics has generated renewed interest in architectural and structural designers of tall buildings. The difference between conventional exterior-braced frame structures and current Diagrid structures is that, for Diagrid structures, almost all the conventional vertical columns are eliminated. This is possible because the diagonal members in Diagrid structural systems can carry gravity loads as well as lateral forces due to their triangulated configuration in a distributive and uniform manner. Compared with conventional framed tubular structures without diagonals, Diagrid structures are much more effective 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. The Diagrid can be compared with another prevalent structural system, the outrigger structures. Properly designed, an outrigger structure is effective in reducing the overturning moment and drift of the building. However, the addition of the outrigger trusses between the shear core and exterior columns does not add lateral shear rigidity to the core. Thus, tall buildings that employ outrigger systems still require cores having significant shear rigidity, Moon [2].
The Diagrid structures provides both bending and shear rigidity. Thus, unlike outrigger structures, Diagrid structures do not need high shear rigidity cores because shear can be carried by the Diagrid located on the perimeter, even though super tall buildings with a Diagrid system can be further strengthened and stiffened by engaging the core, generating a system similar to a tube-in-tube. An early example of today's Diagrid-like structure is the IBM Building of 1963 in Pittsburgh. With its 13-story building height, this building was not given much attention by architects and engineers, and it was not designed as a three-dimensional system as is done at present. In the early 1980s Humana Headquarters competition, a Diagrid structure was proposed by Sir Norman Foster. However, the winning entry at that time was a historicist building of the post-modern style designed by Michael Graves. Only recently have notable Diagrid tall buildings been commissioned, Moon [2].

1.2 Present Scenario :

Examples are the 30 St. Mary Axe in London also known as the Swiss Re Building (fig. 1 a) and the Hearst Headquarters in New York, both by Sir Norman Foster, Moon [2]. CCTV headquarter Beijing (fig.1 b) , Guangzhou Twin Towers in Guangzhou(fig. 2 a) and O-14 Building in Dubai (fig. 2 b) by RUR Architecture employ reinforced concrete Diagrid as their primary lateral load-resisting systems.

Fig -1-a: Figure

Fig -1-b: Figure

2. Literature Review:

M. M. Ali and K. S. Moon,[1]presented a general review of structural systems for tall buildings. A new system-based broad classification is presented as exterior versus interior structures. Author studied Evolution of structural systems considering its architectural forms and aesthetics. The focus of author is on new & existing trends in high rise buildings such as Diagrid structures and outrigger system structures. Supplementary damping systems are as well discussed. He studied from conventional rigid frame to more resent re-formed "out-of-the-box" structural form such as aerodynamics and twisted forms. Future of tall buildings in structural development point of view is discussed briefly.

K. S. Moon *et al.*,[2]examined the influence of the diagonal angle on the behaviour of Diagrid type structures. It was found that, for 60-story Diagrid structures having an aspect ratio of about 7, the optimal range of Diagrid angle is from about 65° to 75°. For 42-story buildings having an aspect ratio of about 5, the range is lower by around 10° because the importance of bending to the total lateral displacement is reduced as the building height decreases. A stiffness-based methodology for determining preliminary design sizes for the diagonals was introduced and applied to a representative set of steel buildings. Results for displacement and required steel tonnage demonstrate the practical usefulness of the proposed preliminary design method. These values are shown to be useful for architects and engineers as guidelines for preliminary design. Associated architectural and constructability issues of Diagrid structures are also discussed here.

K. S. Moon,[3]examined the influence of the different configurations of the diagonals on the behavior of Diagrid structures. For uniform angle Diagrid structures, it was found that, as a building becomes taller, the optimal angle also increases because the design of a taller structure with a large height-to-width aspect ratio tends to behave more like a bending beam, and steeper angle diagonals resist bending moments more efficiently by their axial actions. For the tall Diagrid structures, with aspect ratios ranging from about 4 to 9, the range of the optimal angle is from approximately 60 to 70 degrees. The design methodology is applied to a set of Diagrid structures 40, 50, 60, 70, and 80 stories tall. Author also investigated the potential of Diagrid structures with varying angle diagonals. It was found that the Diagrid angle configuration that becomes gradually steeper towards the base of the building generates a more economical design in terms of material usage than the uniform angle configuration for Diagrid structures with an aspect ratio larger than about 7. However, for Diagrid structures with an aspect ratio smaller than about 7, it was found that the uniform angle diagonals produce the most economical design.

K. S. Moon,[4]presents a stiffness-based design methodology for determining preliminary member sizes of steel Diagrid structures for tall buildings. The methodology is applied to Diagrid of various heights and grid geometries to determine the optimal grid configuration of the Diagrid structure within a certain height range. Author also presents various strategies to improve constructability of Diagrid through prefabrication of the nodes. For the 60-story Diagrid, it was found that the uniform angle configuration produces more efficient design than the varying angle configuration, and this is also true for the 40- and 50story Diagrid. However, this is no longer true for the 70- and 80-story Diagrid structures. For the Diagrid structures, with height-to-width aspect ratios bigger than about 7, gradually changing Diagrid angles with the uniform optimal angle as a median angle value produces more efficient design than the uniform angle design cases.

J. Kim and Y. H. Lee,[5]designed and seismic responses were evaluated using nonlinear static and dynamic analyses for 36-storey Diagrid structures with various slopes of external braces. A tubular structure and a Diagrid structure with buckling-restrained braces were also designed with the same design loads, and their seismic performances were compared with those of the Diagrid structures. According to the analysis results, the Diagrid structures showed higher strength with smaller ductility compared with the tubular structure. It was also observed that as the slope of braces increased the shear lag effect increased and the lateral strength decreased. Both the strength and ductility of Diagrid structures increased significantly when the diagonal members were replaced by buckling-restrained braces.

K. S. Moon,[6]proposed a stiffness-based design methodology for determining preliminary member sizes for the braced tube structures was introduced and applied to a representative set of steel buildings. Results for displacement and required steel tonnage demonstrate the practical usefulness of the proposed preliminary design method. Empirical guidelines for assessing the relative contribution of bending and shear deformation to the total lateral displacement of braced tube tall structures were derived. With the formula, the preliminary member sizing process is essentially automated. Compared with a conventional strength-based iterative methodology, a stiffness-based methodology is more efficient for today's relatively light and flexible structures such as tall buildings, the design of which is governed by stiffness rather than strength. In addition, while the iteration process in the conventional method does not guarantee that the selected design uses the least amount of structural material to meet the design requirements, the proposed methodology generates the design with the minimum amount of structural material. Author also examined the influence of the diagonal angle on the structural design of braced tube structures. It was found that the typically adopted angles ranging from about 40° to 50° are close to the optimal angle. Simplemember sizing methodology and other topics discussed will be very useful to engineers for the preliminary design of braced tube structures.

K. Jani and P. V. Patel, [7]presented analysis and design of 36, 50, 60, 70 and 80 storey Diagrid steel building. A regular floor plan of 36 m × 36 m size is considered. ETABS software is used for modelling and analysis of structural members. IS 800:2007 is used for design of all the structural members considering all load combinations. Dynamic along wind and across wind are considered for analysis and design of the structure. Comparison of analysis results in terms of time period, top storey displacement and inter-storey drift is presented. From the study it is observed that most of the lateral load is resisted by Diagrid columns on the periphery, while gravity load is resisted by both the internal columns and peripheral diagonal columns. Due to increase in lever arm of peripheral diagonal columns, Diagrid structural system is more effective in lateral load resistance. Lateral and gravity load are resisted by axial force in diagonal members on periphery of structure, which make system more effective. Diagrid structural system provides more flexibility in planning interior space and facade of the building.

3. Results and Discussion:

Sr .No.	Name of Author	Work Done	Results
1	M.M.Ali and K. S. Moon [1]	Brief history and classifications Resent trends in tall buildings. of tall building structural systems as interior and exterior systems. Recent development in the form of tall building. The future of structural developments in tall buildings is envisioned briefly	Different high rise buildings have been investigated by author and concluded that the tall building phenomenon will continue in a greater scale to meet the needs of the growing population in future large cities. "out-of-the-box" architectural design trends, such as aerodynamic and twisted forms should be seriously investigated in terms of their structural efficiency and economy.

Sr .No.	Name of Author	Work Done	Results
2	K. Jani and P. Patel [7]	Analysis and design of 36, 50, 60, 70 and 80 storey diagrid steel building is presented. A regular floor plan of 36 m × 36 m. ETABS software is used for modelling and analysis. IS 800:2007 is used for design of all the structural members.	Comparison of analysis results in terms of time period, top storey displacement and inter-storey drift is presented. Most of Lateral loads carried by diagrid. Gravity loads by both diagrid and internal columns.

Sr .No.	Name of Author	Work Done	Results
3	K. S. Moon et al.[2]	Structurally optimal range of angles of diagonal members is investigated for typical 60-, 42- and 20-story buildings, using a conventional iterative design approach. Then,a simple methodology for determining preliminary diagrid member sizes is introduced and applied to the previous set of buildings. Lastly, the design parameters generated with this procedure are verified and compared with the previous set.	Author examined the influence of the diagonal angle on the behaviour of diagrid type structures. It was found that, for 60-story diagrid structures having an aspect ratio of about 7, the optimal range of diagrid angle is from about 65° to 75°. For 42-story buildings having an aspect ratio of about 5, the range is lower by around 10° because the importance of bending to the total lateral displacement is reduced as the building height decreases. Compared with a conventional strength-based iterative methodology, a stiffness-based methodology is more efficient for today's relatively light and flexible structures such as tall buildings.

Sr No.	Name of Author	Work Done	Results
4	J. Kim and Y. H. Lee [5]	36-storey diagrid structures with various slopes of external braces were designed and their seismic responses were evaluated using nonlinear static and dynamic analyses.A tubular structure and a diagrid structure with buckling-restrained braces were also designed with the same design loads, and their seismic performances were compared with those of the diagrid structures.	It was observed that as the slope of braces increased the shear lag effect increased and the lateral strength decreased. The diagrid structures with the brace angle between 60° to 70° seemed to be most efficient in resisting lateral as well as gravity loads. The diagrid structure with a circular plan shape showed higher strength than the diagrid structure with a square plan as a result of decrease in shear lag phenomenon.The diagrid structures showed higher strength than the tubular structure.

Sr .No.	Name of Author	Work Done	Results
5	K. S. Moon [6]	A stiffness-based design methodology for determining preliminary member sizes for the braced tube structures was introduced and applied to a representative set of steel buildings. The design methodology presented in the preceding sections is applied to 40, 50, 60, 70, and 80 story braced tube structures, with height-to-width aspect ratios ranging from 4.3 to 8.7.	Diagonal angle of braced tube in structures, It was found that the typically adopted angles ranging from about 40° to 50° are close to the optimal angle. Compared with a conventional strength-based iterative methodology, a stiffness-based methodology is more efficient for today's relatively light and flexible structures such as tall buildings, the design of which is governed by stiffness rather than strength. proposed methodology generates the design with the minimum amount of structural material

Sr .No.	Name of Author	Work Done	Results
6	K. S. Moon [3]	Characteristics and stiffness-based preliminary design methodology of diagrid structures are discussed. The design methodology is applied to a set of diagrid structures, 40, 50, 60, 70, and 80 stories tall. 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 with a different height and to investigate the structural potential of Diagrid with changing angles.	For uniform angle diagrid structures, it was found that, as a building becomes taller, the optimal angle also increases. For the tall diagrid structures, with aspect ratios ranging from about 4 to 9, the range of the optimal angle is from approximately 60 to 70 degrees. It was found that the diagrid angle configuration that becomes gradually steeper towards the base of the building generates a more economical design in terms of material usage than the uniform angle configuration for diagrid structures with an aspect ratio larger than about 7.for building aspect ratio smaller than 7 uniform angle diagonals produce the most economical design.

Sr .No.	Name of Author	Work Done	Results
7	K. S. Moon [4]	Author presents a stiffness-based design methodology for determining preliminary member sizes of steel diagrid structures for tall buildings. The methodology is applied to diagrid of various heights and grid geometries to determine the optimal grid con-figuration of the diagrid structure. within a certain height range. Various strategies to improve constructability of diagrid through prefabrication of the nodes are also presented.	Diagrid structure of 36m x 36m in plan. Stiffness-based design methodology.40, 50, 60, 70 and 80 story high structure with aspect ratio ranging from 4.3 to 8.7. For 40 and 50 and 60 story structures uniform diagonal angle 63° and Varying Angles (73, 69 & 63 degrees). For 70 and 80 story structures uniform diagonal angle 69° and Varying Angles (73, 69 & 63 degrees), but varying angles produces more efficient design.

4. Conclusion

To minimize the effect of lateral loads in high rise buildings diagrid structure is one of the best solution. Studies have been done in diagrid structure with typical floor plans and with uniform angles of diagrid. Different combinations of diagrid angles are also examined. This combinations are analysed in order to obtain optimal diagrid angle for a particular height. For 40, 50, 60, 70 and 80 story high structure with aspect ratio ranging from 4.3 to 8.7. For 40, 50 and 60 story structures uniform diagonal angle 63°. For 70 and 80 story structures uniform diagonal angle 69°. Hence this is concluded that as height increases aspect ratio increases which tends to increase the optimal angle.

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