

A Review on Structural Performance of Diagrid Structural System for High Rise Buildings

Akshat ¹, Gurpreet Singh ²Post Graduate Student, Department of Civil Engineering, Chandigarh University, Gharuan, Mohali, Punjab, India ¹Assistant Professor, Department of Civil Engineering, Chandigarh University, Gharuan, Mohali, Punjab, India ²

ABSTRACT: The rapid growth of urban population and limitation of available land, the taller structures are preferable nowadays. So when the height of structure increases then the consideration of lateral load is very much important. For that the lateral load resisting system becomes more important than the structural system that resists the gravitational loads. Lateral load resistance of structure is provided by interior structural system or exterior structural system. Usually shear wall core, braced frame and their combination with frames are interior system, where lateral load is resisted by centrally located elements. While framed tube, braced tube structural system resist lateral loads by elements provided on periphery of structure. It is very important that the selected structural system is such that the structural elements are utilized effectively while satisfying design requirements. Recently the diagrid structural system is widely used for tall buildings due to its structural efficiency and aesthetic potential provided by the unique geometric configuration of the system. This paper reviews research published on the structural performance of diagrid system. A first step toward a systematic and comprehensive study is that regular patterns are compared to alternative geometrical configurations, obtained by changing the angle of diagonals (variable-angle, VA) as well as by changing the number of diagonal (variable-density, VD) along the building height. Further it discusses about the different diagrid patterns generated and designed for an assumed building; and how the resulting diagrid structures are assessed under gravity and wind loads and various performance parameters are evaluated on the basis of the analyses results.

KEYWORDS: Diagrid Structural System, Variable Angle Diagrid, Variable Density Diagrid, Granularity, Structural Design, Secondary Bracing System, Non-linear Pushover Analysis.

I. INTRODUCTION

Tall commercial buildings are primarily a response to the intense pressure on the available land. Advances in materials, construction technology, analytical methods and structural systems for analysis and design accelerated the development of tall structures. The lateral loading due to wind and earthquake is the major factor that causes the design of high-rise buildings. These lateral loads are resisted by exterior structural system or interior structural system. The lateral load resisting systems that are widely used are mainly rigid frame, shear wall, wall-frame, braced tube system, outrigger system, diagrid system and tubular system. Recent trend shows that the diagrid structural system is becoming popular in the design of tall buildings due to its inherent structural and architectural advantages. Diagrid is an exterior structural system in which all perimeter vertical columns are eliminated and consists of only inclined columns on the façade of the building. Shear and over-turning moment developed are resisted by axial action of these diagonals compared to bending of vertical columns in framed tube structure.

Vertical columns in the core are designed for carrying gravity loads only and the diagrid is useful for both gravity and lateral loading. Diagonalized applications of structural steel members for providing efficient solutions both in terms of strength and stiffness are not new, however nowadays a renewed interest in it and a wide spread application of diagrid is registered with reference to large span and high rise buildings, particularly when they are characterized by complex geometries and curved shapes.

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The diagrid systems are the evolution of braced tube structures. The major difference between a braced tube building and a diagrid building is that, there are no vertical columns present in the perimeter of diagrid building. The diagonal members in diagrid structures act both as inclined columns and as bracing elements and due to their triangulated configuration, mainly internal axial forces arise in the members. Diagrid structures do not need high shear rigidity cores because shear can be carried by the diagrids located on the perimeter.

The concept of diagrid is not new at all; people have always been intuitively familiar with the inherent stability of triangular structures. Placement of diagonals is the oldest and most natural solution in steel structures, and has widespread applications, receiving great popularity among engineers and architects; however the past architects considered diagonals highly obstructive and usually embedded them within the building interior cores.

II. DIAGRID STRUCTURE

Diagrid (diagonal grids) structure is a system of triangulated beams, straight or curved and horizontal ring that together make up a structural system for a skyscrapers (Tall Building). In short, it is made up of intersecting diagonal and horizontal components. It requires less structural steel than a conventional steel frame. 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% structural steel weight when compared to a conventional moment-frame structure.

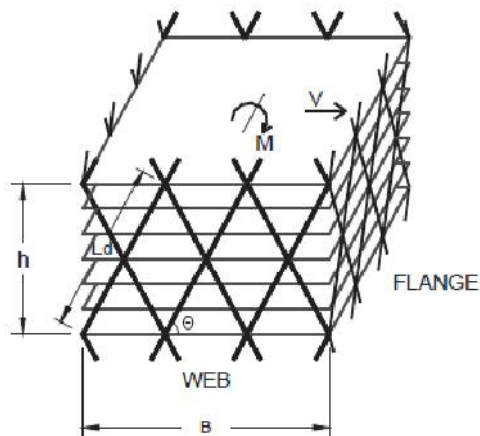


Fig. 1. Diagrid Structure
(Source - K. S. Moon, 2011)

The diagonal members in diagrid structural systems can carry gravity loads as well as lateral forces due to their triangulated configuration. Diagrid structures are more effective in minimizing shear deformation because they carry lateral shear by axial action of diagonal members. Diagrid structures generally do not need high shear rigidity cores because lateral shear can be carried by the diagonal members located on the periphery. The famous examples of diagrid structure all around the world are the Swiss Re in London, Hearst Tower in New York, Cyclone Tower in Asan (Korea), Capital Gate Tower in Abu Dhabi and Jinling Tower in China as shown in Fig 2.

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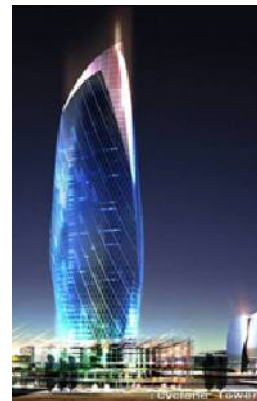
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(a)



(b)



(c)



(d)



(e)

Fig. 2. Diagrid buildings: (a) Swiss Re in London, (b) Hearst Tower in New York, (c) Cyclone Tower in Asan (Korea), (d) Capital Gate Tower in Abu Dhabi and (e) Jinling Tower in China.
(Source - K. Jani & P. V. Patel, 2013)

Merits of Diagrid Structural System

1. The diagrid structures have mostly column free exterior and interior, hence free and clear, unique floor plans are possible.
2. The glass facades and dearth of interior columns allow generous amounts of day lighting into the structure.
3. The use of diagrids results in roughly 1/5th reduction in steel as compared to braced frame structures.
4. The construction techniques involved are simple, yet they need to be perfect.
5. The diagrids makes maximum exploitation of the structural material.
6. The diagrid structures are aesthetically dominant and expressive.

Demerits of Diagrid Structural System

1. As of yet, the diagrid construction techniques are not thoroughly explored.

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2. Lack of availability of skilled workers. Construction crews have little or no experience creating a diagrid skyscraper.
3. The diagrid can dominate aesthetically, which can be an issue depending upon design intent.
4. It is hard to design windows that create a regular language from floor to floor.
5. The diagrid is heavy-handed if not executed properly.
6. There is a height limitation of 100 storeys for diagrid constructed of steel and 60 storeys for diagrid constructed of concrete.

III. LITERATURE REVIEW

Technical papers of various journals from India and abroad are studied to understand the importance and necessity of this research in consideration of wind and seismic resistant design. It presents a brief summary of the literature review. Following review of literature gives an outlook on the behaviour of diagrid structural system in high rise building.

In 2017, E. K. Julistiono investigated the structural pattern's granularity variation to optimize a vertical structure. The old research has been performed by applying different patterns on perimeter of the vertical structure to optimize its performance. Results obtained from previous researches showed that triangular pattern has the optimum efficiency. This study was on the effect of granularity variation of triangular pattern on the perimeter of the building to optimize its structural efficiency. Granularity was the main focus of the study which was manipulated again and again to increase the efficiency of the structure. For carrying out the investigation of performance of granularity patterns medium and high rise buildings were considered as the case studies. Examination of performance of each pattern was made under two loading conditions i.e. vertical and horizontal loads. For each case, triangular patterns were modelled using CAD modelling in three different degrees of granularity. Optimization was performed using structural design and optimization software. Results obtained were then compared and analyzed to study the effect of structural pattern's granularity variation on the efficiency of the structure. Overall, it was concluded that greater granularity was more efficient in resisting vertical loads while for lateral loads, there was no significant effect of variation of granularity to the structural efficiency. Also, it was observed that smaller granularity performs better than the larger ones.

In 2017, H. U. Lee & Y. C. Kim studied the preliminary design of tall building structures with a hexagrid system. The recently developed hexagrid system constitutes an innovative shape from both architectural and structural perspectives. In this study, the characteristics of tall hexagrid tubular buildings were investigated. Main focus of this investigation was on the size and patterns of hexagrid modules. The study proposed a sizing formula based on stiffness-design criteria of members in the preliminary design stage. For examining the structural behaviour of tall building with a hexagrid system, 234 m high, 60 storey buildings were designed which composed of diagonal, horizontal and vertical members. The number of storeys in a module were used as study perimeter. The study was focused only on the structural aspects of the hexagrid system.

In 2017, T. H. Kim et al. developed a building structural system using an IsoTruss[®] grid. A structure was developed using an IsoTruss[®] grid (ITG) system and its behaviour is compared with that of a diagrid system. Exterior columns were placed vertically and obliquely which were connected in a zigzag manner over the height of the building. The main role of exterior columns was that the more free space can be allocated in a building. A 64-storey building was analyzed with diagrid and ITG to assess the structural efficiency of the system. Also, for the structural design of the diagrid and ITG system stiffness based criteria was adopted. Its feasibility was studied in terms of control of the lateral displacement at the top of the building and steel tonnage for the columns in the exterior frame. From the results of analyses it was observed that the structural performance of the suggested system was similar to that of the diagrid system.

In 2016, K. Kamath et al. studied the performance of a diagrid structure using non-linear static pushover analysis. The models studied were circular in plan with aspect ratio H/B whose value varies from 2.67 to 4.26. The angles of external braces considered for the study were 59°, 71° and 78°. The width of the base was taken as 12 m which was

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kept constant while height of the structure was varied correspondingly. The non-linear behaviour of the elements was modelled using plastic hinges based on moment curvature relationship as per FEMA 356 guidelines [3]. For analyses, the structure was subjected to monotonically increasing lateral load till the target displacement was reached. The pushover analysis was carried out using displacement control method in which the displacement of the top storey of the structure was incremented step by step, such that required horizontal forces pushes the structure laterally. Under this study, seismic response of the structure was analyzed using non-linear static analysis. Base shear and roof displacement were the parameters evaluated for the study of seismic response of the structure. There was an effective impact of brace angle and aspect ratio on the performance of the structure.

In 2015, R. D. Deshpande et al. compared conventional and diagrid structural systems. ETABS software was used for modelling and analyses of structural members. Dynamic along wind and across wind were considered for analyses and design of the structure. The main objective of the study was to compare the efficiencies of conventional and diagrid structural building. Diagrid structure system performs better across all the criteria of performance evaluation, such as efficiency, expressiveness and sustainability. Structure had comparatively less deflection as compared to the same designed conventional building. Weight of the structure was reduced to greater extent, due to which structure was more resistive towards the lateral forces. Diagrid structures are cost effective and eco-friendly. Diagrid used 11247 tonnes of steel which was 28% less as compared to the conventional orthogonal building which used 15255 tonnes. In comparison to conventional structure, diagrid structure had more opening area, less deflection and 28% less usage of steel.

In 2014, D. Lee & S. Shin analyzed advanced high strength steel tube diagrid using TRIZ and non-linear pushover analysis. The goal of the study was to provide a good indication of TRIZ methodologies and to evaluate new high performance steel diagrid details to resolve the problematic aspects of steel diagrid structures such as the concentration of stress at the ends of the tube contacted to cap plates. The steel diagrid system considered for the study had a tensile stress of 800 MPa and a low yielding ratio can be applied. TRIZ is a problem-solving, analysis and forecasting tool. A so-called DSDI which stands for “Define”, “Solve”, “Design” and “Implement”. TRIZ procedure was introduced by POSCO steel company in 2008 to develop manufacturing technologies related to steel.

With DSDI TRIZ procedure new structural details of the existing diagrid structures can be obtained in structural design of mega structures. It can also be applied to architectural or civil design. DSDI TRIZ can be effectively utilized to investigate the appropriate shapes of structures and their possibilities in the beginning stages of structural design, when the best solution cannot be easily obtained by typical structural design. According to the evaluated results of DSDI TRIZ, a convex diagrid was evaluated as an improvement on the flat shaped diagrid which was the current best solution. The structural and economic superiority of the convex diagrid was verified using non-linear static pushover analysis for which ABAQUS software was used. From the study results, it was confirmed that the TRIZ process can be a strong idea generation tool for developing structural details to improve the behaviour of existing structures.

In 2014, G. M. Montuori et al. studied the geometrical patterns provided for the diagrid structures. For this purpose, diagrid structures of regular patterns were compared to different geometrical configurations, which were obtained by changing the angle of diagonals (variable-angle i.e. VA) and the number of diagonals (variable-density i.e. VD) along the height of the building. Eight kinds of the geometrical patterns were developed for the systematic and comprehensive study. The diagrid patterns generated for the building model were analyzed using FEM numerical models, by means of SAP2000 computer code. The diagrid patterns were designed for a 90 storey building model. The resulting diagrid structure was analyzed under gravity [10] [11] and wind [12] loads and various performance parameters were evaluated on the basis of analyses results.

For complete assessment of the structural performance exhibited by different diagrid patterns, the major response parameters were thoroughly examined and compared, which had been obtained by processing the results of analyses. Specifically, the following parameters were considered for assessment: horizontal displacement (u), interstorey drift ratio (d_h) and strength demand to capacity ratio in the diagonal members (DCR_{dg}) which is defined as the tension/compression axial force under design loads normalized to the yield/buckling capacity of the relevant member.

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In 2014, G. M. Montuori et al. investigated secondary bracing systems for diagrid structures in tall buildings. A framework was defined for assessing the structural issues in the design of tall buildings. For establishing the need of a specific secondary bracing system a methodology was presented. Design criteria for SBS was adopted and applied to some of the building models. A 90 storey building model was considered for the study. A properly designed secondary bracing system (SBS) was added to the diagrid building model because local deformation within the module height requires this which allows the transfer of horizontal forces to the diagrid nodes through the load path. It involves the axial stiffness of the SBS members instead of the flexural stiffness of the diagrid diagonal elements. Secondary bracing system also stabilizes the columns of gravity load resisting system (i.e. core columns) at the intermediate levels between two panel points. SBS consists of four concentric braced frames along the two orthogonal building direction for each diagrid building designed. A twofold design criterion had been adopted: (i) to comply with the imposed drift limitations and (ii) to stabilize the core gravity columns. All the diagrid patterns were compared with each other in terms of structural weight and performances to obtain the results regarding their efficiency potentials.

The outcomes of the proposed simplified procedures, both for assessing SBS necessity and for the consequent SBS member design, had been compared to the structural response of the diagrid building models, obtained without and with SBS, demonstrating both the accuracy of the proposed formulations and the primary importance of the discussed local questions. In fact, all analyzed diagrid models exhibited problems concerning stability of interior columns (i.e. multi-storey buckling modes) and/or local flexibility (excessive interstorey drift); the above local problems were completely solved after the introduction of a SBS at the central core location, and, against a modest increase of structural weight (about 3%), any flexural engagements in the diagrid member was eliminated.

In 2013, K. Jani & P. V. Patel analyzed and designed diagrid structural system for high rise steel buildings. A 36 storey diagrid steel building was adopted for the study. Also, 50, 60, 70 and 80 storey diagrid steel structures are analyzed and designed for the investigation. ETABS software was used for modelling and analyses of the structure. All the members of the structure were designed using IS 800:2007 [9]. All the load combinations were considered during design and analyses of the model. Structural design of the building was governed by lateral loads due to wind [12] or earthquake [7]. Lateral load acting over the structure was resisted by interior and structural system. Interior structural system consists of usually shear wall core, braced frame and their combination with frames where lateral load was resisted by centrally located elements while exterior structural system consists of framed tube and braced frame where lateral load was resisted by elements provided on the periphery of the structure. It was observed that most of the lateral load was resisted by diagrid columns on the periphery, while gravity load was resisted by both the internal columns and the peripheral diagonal columns. So, internal columns should be designed for the vertical load only. A framed tube consists of closely spaced vertical columns while diagrid structure consists of inclined columns on the façade of the building. Due to inclined columns lateral loads were resisted by axial action of the diagonal compared to bending of vertical columns in a framed tube structure. Diagonal structures generally do not require core because lateral shear can be carried by diagonals on the periphery of the building. Due to increase in lever arm of peripheral diagonal columns, diagrid structural system was more effective in resisting the lateral load due to wind or earthquake.

In 2011, K. S. Moon studied the structural performance of the diagrid systems in complex shaped tall buildings. The complex shaped tall building models considered for the study was twisted tower, tilted towers and freeform towers. The complex shaped tall building models were designed with diagrid systems, and their structural performance and efficiency potential was studied. For the study of impacts for variation of geometric configurations of complex shaped tall buildings. Parametric structural models were used for the study of rate of twisting and angle of tilting. On the basis of results obtained, design considerations are studied for using the diagrid system efficiently in complex shaped tall buildings.

The diagrid structure was modelled as a cantilever beam on the ground. It was subdivided longitudinally into modules according to the repetitive diagrid pattern. Each module was defined by a single level of diagrids that extend over multiple storeys. In order to estimate the lateral rigidity provided by diagrids more accurately, all the required lateral stiffness was allocated to the perimeter diagrids, and core structures, were only gravity systems in this study.

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IV. SUMMARY OF LITERATURE

From the literatures reviewed it was revealed that:

1. Diagrid performs better across all the criterions of performance evaluation, such as efficiency, expressiveness and sustainability.
2. Diagrid structures have higher stiffness than other structures.
3. Diagrid structures have less deflection as compared to the conventional structures.
4. Weight of the structure gets reduced to a greater extent due to which structure has more resistance to lateral forces.
5. Displacement on each storey, storey drift and storey shear are observed to be less in diagrid structures as compared to conventional structures.
6. Diagrid structure gives more aesthetic look and gives more of interior space. Due to less number of columns, façade of the building can also be planned more efficiently.
7. Greater granularity of structural pattern is more efficient for resisting vertical loads. While for lateral loads, variation of granularity has no significant impact to the structural efficiency, although smaller granularity tends to perform better.
8. Lateral load is resisted by diagrid columns on the periphery, while gravity load is resisted by both the internal columns and peripheral diagonal columns. So, internal columns need to be designed for vertical load only.
9. 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.
10. Diagrid structure system provides more economy in terms of consumption of steel as compared to other structural system. So, diagrid structure is cost effective and eco-friendly.

V. GAPS IN LITERATURES

After study of various national and international researches papers on the behaviour and performance of the diagrid structural system, the gaps and problems which are still not studied, are mentioned below:

1. From the earlier research work till now, various researchers have carried out study for geometrically regular shaped building by incorporating diagrid structural system. However, there is an absence of scientific research dealing with performance of diagrid structural system in High rise Building especially with geometrically irregular and unsymmetrical shape in plan.
2. Mostly the analysis of the high rise building has done under the seismic zone 3. There is few researches been done in zone IV and zone V.
3. The analysis of the models had done in grid models only. No researchers have done by taking actual plan of the building.
4. Nowadays using modern softwares we can analyze the buildings by various non-linear methods, such as time history analysis. But, non-linear time history analysis for high rise structure has not yet studied.
5. Damping and diagrid structural system can also be used combinedly to resist more of the lateral forces acting over the structure. Till yet this type of system is not studied in any literature.

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