Malaysian Journal of Civil Engineering 28 Special Issue (2):130-139(2016)

REVIEW PAPER

FRAMEWORK FOR EVALUATING LATERAL RESISTANCE OF DIAGRID WITH BASE COLUMN

Roslida Abd. Samat*, Chua Fong Teng, Nur Akmal Hayati Mohd Mustakim, Fatin Izzaidah Anuar & Sariffuddin Saad

Department of Structures and Materials, Faculty of Civil Engineering , Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

*Corresponding Author: *roslida@utm.my*

Abstract: Development in highrise building construction had lead to the emergence of diagrid system which currently has gained popularity among the designers. Diagrid which is a portmanteau of diagonal grid is a framework of diagonally intersecting members at the exterior of a structure that lends to high structural efficiency in terms of resisting gravity and lateral loads, resulting in less steel consumption. The new aesthetic appearance of the diagrid has triggered the new interest in architecture. However, most structures of diagrid systems had been designed with full triangulated members from the ground level to the top of the buildings which cause a limited interior room at the ground level and limited spacing for entrance. The usage of vertical columns at ground level that are connected to diagrid members at the upper floor is an alternative to increase both interior room and spacing for entrance at ground level. This raises the question on the efficiency of this type of diagrid system in resisting the lateral load. Thus, a review on the framework is carried out to study the efficiency of this type of diagrid system in reducing the lateral displacement both statically and dynamically.

Keywords: *Diagrid, lateral displacement, highrise building, base column, tall building system*

1.0 Introduction

The combination of “diagonal” and “grid” words produce the term “diagrid” which refers to a structural system that is single-thickness in nature and gains its structural integrity through the use of triangulation (Boake, 2014). The triangulated member formation is achieved when the floor edge beams tie into the gird that receives and transfers the loads such as gravity and lateral forces from multiple sources and directions throughout its configuration in a distributive and uniform manner. The diagrid structural efficiency and its elegant brand new appearance contribute to the popularity of the diagrid system as the desired tall building system in the current millennium.

Diagrid structural system is the evolution of braced tube structure (Yadav and Garg, 2015). Historically, the approach of diagonal bracing with X configuration installed along the entire exterior perimeter surface of the braced tubular structure system was introduced in the late 1960s for the 100-story tall John Hancock Center building in Chicago. The strategy of constructing the diagonals at the exterior perimeter surfaces of the building maximizes their structural effectiveness and is much more effective than confining diagonals to narrower building cores. However, the diagonal pattern of the X bracing is not appealing as it obstructs the outdoor scenery view from the interior building. In contrast, diagrid with its structural effectiveness and lattice-like appearance is perceived as being aesthetics and elegant. Diagrid requires less number of elements on the perimeter of the building and makes less obstruction to the outside view. Another advantage of diagrid is it allows the architects to design building with more variety shape and unique which opens new aesthetic potential for tall building architecture (Moon, 2009). Most of diagrid structures are fabricated from steel and only a few of them are built with concrete. The earliest diagrid structure is the 13-story IBM Building in Pittsburgh (Figure 1) built in the early 1960s (Moon *et al.*, 2007). Until now there are a lot of buildings with several kind of shapes that apply diagrid system (Boake, 2014). Examples of buildings with unique element such as irregular angle and nonlinear shape are Swiss Re (30 St. Mary Axe) in London, Capital Gate in Abu Dhabi and CCTV in Beijing as shown in Figure 1.

IBM Building
(United Steelworks)

Swiss Re
(30 St. Mary Axe)

Capital Gate

CCTV

Figure 1: Some of the buildings that implement diagrid system (Boake, 2014).

2.0 How Diagrid Systems Work

2.1 Load Distribution in Diagrid Systems

There are two types of loads acting on building which are gravity load and lateral load. The lateral load occurs due to wind or earthquake. Both gravity and lateral loads from any direction are received and transmitted by the diagonal diagrid members throughout their triangulated configuration to foundation (Jani and Patel, 2013). Most of the lateral load is resisted by the diagonal members of the exterior diagrid frame while the gravity load is resisted by both the exterior diagrid frame and interior frame of a building. Horizontal elements that connect to the triangulated elements are added to prevent it from buckling due to its supporting of different type of loads (Lemons and Alvarado, 2011). The floor plates that are connected to the diagrid diagonal members transfer the vertical gravity load to the diagonal members, that flows through the diagrid system into the foundation. However, the floor plates do not receive any load either gravity or lateral loads dispite being connected to the diagonal diagrid members (Lemons and Alvarado, 2011). Study on 36 storey diagrid building models by Jani and Patel (2013) shows that the base shear due to wind load is higher compared to earthquake load.

2.2 Lateral Resistance

The structural performance of diagrid system can be evaluated based on the efficiency of the system to resist the lateral force. Shear lag and lateral displacement are major issues in the design of highrise building. Leonard (2007) and Moon (2014) found that the shear lag coefficient increases as the slope of the diagrid members increases. According to Moon (2014), the shear lag increment becomes rapid when the angle is higher than 70°, but, interestingly, the shear lag effect of the diagrid structure was less than the tubular structure. The increase of the slope of the diagrid members also causes drastic change to the lateral deflection (Leonard, 2007). However, there is no relationship between shear lag and the lateral displacement of diagrid structure as some of the diarid buildings with higher shear lag was found to have smaller deflection at the top of the buildings than diagrid buildings that experienced less shear lag (Leonard, 2007).

Lateral displacement of high rise building is due to the lateral force from wind or earthquake. The importance of wind load analysis increases as the higher the building is. Jani and Patel (2013) observed that the storey shear in x-direction and y-direction due to dynamic wind load is higher compared to earthquake load. Among the 36, 50, 60, 70 and 80 storey diagrid models studied, 80 storey model recorded the highest top displacement and inter-storey drift (the difference in lateral deflection between two adjacent stories of a building) in both x- and y-axis due to dynamic wind load. This shows that both of the values increase when the building height is increased. According to Mehmet and Huseyin (2014), estimation of wind loads for a building that has more than 40 storeys should consider the dynamic response of the building that is usually known by using wind tunnel test.

2.3 Node Connection in Diagrid System

Node connects the diagonal members and beam of the building. It is an important element that must be designed carefully as failure of the nodes may lead to building failure. The node connection has high stress which is generated from gravity and lateral load. In general, the function of node is to provide the load path through the members or to receive the load from four incoming diagonal members including horizontal beam at each side (total of 6 connections) (Boake, 2004). Thus, the joints of diagrid structure between diagonal members and horizontal beam are difficult to fabricate resulting these joints of diagrid to be more expensive than the joints of conventional structures (Boake, 2013a).

Technically, if a purely triangulated truss structure is designed, the center of the node need not be rigid and can be constructed as a hinge or pin connection (Moon, 2009). According to Hammida (2015), pin node will be used for symmetrical structure as the structure has balance load, while rigid node will be used if the node needs to assist the structure to support during the construction process. Rigid nodes or moment resisting connections are not normally used in standard triangulated truss designs (Boake, 2013b). The joints of the diagrid structure can be welded or bolted depending on what appearance is required for the design. If the structure is to be exposed, welding can provide better aesthetic value, but requires more skillful workers. In contrast if the structure will be clad or concealed like Hearsts tower, bolting will be a better choice and it provides speedy erection on site. (Hammida, 2015). The nodes are usually being fabricated to reduce the difficulties of erection on site because some nodes take many tonnes in weight and can be lifted and turned only with a crane (Boake,2013b).

Decision to choose the design details of the diagrid node can be made based on cyclic performance under lateral load which is determined by experiment (Kim *et al.*, 2011). According to Jung (2014), welding methods and design details did not affect the initial stiffness and yielding stress of diagrid under cyclic loading significantly, but instead affected the failure mode and energy dissipation of the nodes.

2.4 Materials

Selection of material for the construction of a structure is an important issue in design. Steel, concrete and composite materials are three types of materials that are available for diagrid construction. According to the Rathod and Saha (2015), steel is mostly used for the construction of high rise diagrid structure. This is because steel systems offer speed in construction, less weight (Chandwani *et al.*, 2012), besides being easier to construct, has simple joint, less use of formwork and suitable with sustainability concept (Rathod and Saha, 2015). Concrete material which can be used either in precast or cast-in-situ, is not popular among designers. The weight of concrete increases the dead load on the foundations but concrete offers great safety against structural fire damage (Mohan, 2011). Until now, only a few buildings with concrete diagrid system have been built which are Atlas Building (2006), Poly Real Estate Head-quarters (2007), Yellow Building (2008) and O-14 Tower (2010), Burj Doha (2012) and 170 Amsterdam Ave in New York (2014).

3.0 Diagonal Angle of Diagrid System

3.1 Uniform Diagonal Angle

Diagonal angle which is the angle measured from horizontal line to the inclined member of the diagrid, is an important element that influences the performance and efficiency of the diagrid system. Hearst Building is an example of a building that utilizes diagrid with uniform angle while Lotte Super Tower in Seoul is built with varying angled diagrid.

The diagonal angle that minimises the lateral displacement of the diagrid structures is called as optimum angle. Diagrid system with four corner columns and diagrid system without corner columns have different optimum angles (Moon *et al.*, 2007). The optimum angle where the maximum displacement requirement for the structures is satisfied lies between 53^o to 76^o and between 63^o to 76^o when the structure was with four corner columns and when the structure was without corner columns, respectively. The range of the optimum angle of the diagrid structure without corner columns have shifted upward because the diagonal members had to provide both shear rigidity and bending rigidity when the vertical columns were eliminated. Another factor that influences the optimum angle is the height of buildings. The optimum range of diagrid angle is from about 65^o to 75^o when the diagrid structures were having 60 stories with aspect ratio of about 7, while for 42-storey building, the optimal range of diagrid angle was decreased by 10^o since the bending resistance due to lateral force was reduced when building height decreased (Moon *et al.*, 2007). For 40 storey buildings with 36m x 36 m footprint, diagrid structures with 60^o inclination of the diagonal members had the best overall performance in terms of strength, stiffness and ductility besides the most saving of steel weight when compared to the diagrid structures with 42^o and 75^o inclination of the diagonal members (Milana *et al.*, 2014).

3.2 Varying Diagonal Angles

A study on the performance of different geometrical patterns for diagrids of 90 story buildings with three different geometrical patterns: regular patterns, patterns with changing angle of diagonal (variable-angle, VA) with height and patterns with changing number of diagonal (variable-density, VD) along the building height was conducted by

Montuori *et al.* (2014). These models were exerted by both gravity and wind loads and were evaluated based on the lateral displacement and structural weight of the system. The regular diagrid of 60° and 70° angle and variable angle diagrid systems were found to be efficient whereas the diagrid with variable density was efficient only for the cases where the diagrid was denser at the lower part of the building and less dense at the upper part. According to Moon (2011a), efficient diagrid structures is acheived when uniform angle diagonals is used for 40-, 50- and 60-story structures, while vertically varying diagonals is used for 70-story and taller diagrid structures with a height–to-width aspect ratio greater than 7 .

4.0 Advantages of Diagrid System

4.1 Bending Moment and Shear

Diagrid structures have large stiffness, strength and quite brittle compared to the tubular structure (Kim and Lee, 2012). Diagrid structures are much more effective in minimizing shear deformation when compared with conventional framed tubular structures without diagonals because diagrid structures carry shear by axial action of the diagonal members, while conventional framed tubular structures carry shear by the bending of the vertical columns (Moon *et al.*, 2007). The placement of the diagonals on its periphery further, provides better resistance of diagrid to lateral loads (Bhale and Salunke, 2016). Both bending and shear rigidity are provided by the perimeter diagrid without requiring high shear rigidity core. However, diagrid system can be further strengthened and stiffened by engaging the core by the concept of tube-in-tube system even in supertall buildings. (Ali and Moon, 2007). Yadav and Garg (2015) found that the ratio of bending moments and shear forces in interior beams between the diagrid and the conventional building varies from 0.54 to 0.82 and from 0.72 to 1.12, respectively, which proved that the shear force and bending moment in interior beams were reduced effectively in all the floors in diagrid structures. In addition, the bending moment value in the interior column in diagrid structure is reduced , but the axial force in interior column is increased in comparison to conventional structure (Yadav and Garg, 2015). The internal columns in diagrid carry only gravity force while the seismic load is resisted by external diagonal column. In conventional frame building, both internal and external columns resist both gravity and seismic load. (Bhale and Salunke, 2016).

4.2 Steel Consumption

The effectiveness of diagrid in minimizing the shear deformation allows less steel consumption in the construction of high rise structures. Diagrid system saves approximately 20 percent of the structural steel weight if compared to conventional rigid frame structure (Leonard, 2007; Lemaons and Alvarade,2011). In diagrid structure, the steel weight decreases as the brace slope increases. (Kim, 2010). Diagrid with 75^o

reduced structural steel weight by 33 percent compared to diagrid with 42^{o} and 60^{o}. Reduced weight of the superstructure can translate into a reduced load on the foundation (Singh *et al.*, 2014).

4.3 Adaptability of Diagrid in Complex Building Shape

Another advantage of diagrid is it is buildable and suitable for buildings that have complex shape such as twisted, tilted and freeform buildings. The strength of diagrid structure with a circular plan shape is higher than the strength of a conventional square plan building due to the reduction of shear lag effect (Kim and Lee, 2012). Twisted, tilted and freeform diagrid structure have less lateral stiffness than the conventional building. Interestingly, twisted tower performed better in dynamic response with respect to across-wind direction (Moon, 2011b). On the contrary, the lateral stiffness of any structural system will increase if the structure building is tapered and in fact, as the angle of taper increases the lateral stiffness will also be increased due to the reduction of applied wind load (Moon, 2011b). The ”Bow” or Encana Tower in Canada is an example of adaptability of diagrid system in an actual curved form building (Charnish *et al.*, 2008).

4.4 Other advantages of diagrid

The unique appearance of skyscrapper that employs diagrid system has caused diagrid building to emerge as a new aesthetic trend of tall building. The elimination of almost all the vertical columns that is allowed in the diagrid system provides variety of open floor plans. Diagrid system is classified as an exterior structure that has high structural efficiency as it is capable to resist both lateral and gravity loads due to its triangulated member configuration (Ali and Moon, 2007). Diagrid system has redundancy in design which provides alternate load paths in the event of a structural failure (Boake, 2014). Diagrid system is capable to transfer load from a failed portion of structure to another structure that can minimize the structural failure of tall building. According to McCain (n.d.), diagrid structure has better ability to redistribute load than a moment frame tall building. In addition, diagrid system allows high amount of natural sunlight that cut the cost in electricity during day time, and thus, contribute in the sustainability of a tall building. Diagrid building is found to have the same reduction of lateral displacement as a building that uses other tall building system, but at lesser amount of steel consumption (Milana *et al.*, 2015). In addition, the usage of steel in diagrid building allows offsite prefabrication, the reduction of site waste and the high recycling rates of the materials which fulfill the sustainability concept (Milana *et al.*, 2014). According to Milana *et al.* (2014), the Hearst Tower in New York City that was built using 85% recycled steel and consumes 25% less energy than an equivalent office building had been awarded “green diagrid building” and is the first building to receive “gold rating” award under US Green Building Council’s Leadership.

5.0 Summary

The emergence of diagrid system as a new tall building system has sparked enthusiasm among the designers due to its many advantages. Diagrid system which is an exterior structural system, is effective in controlling the lateral displacement for tall building. Generally, a building should not have its lateral top deflection more than H/500, to fulfill the serviceability criteria and to ensure human comfort besides to avoid problems such as drainage and the falling of the cladding or window glass. Diagrid system is efficient in resisting lateral forces due to its large stiffness and dominant diagonal member's axial action. Other advantages of diagrid structures are the elimination of perimeter columns that allows more flexibility in interior plan, reduction in steel consumption, and the ability to corporate in complex building shapes.

Nonetheless, some buildings that have full diagrid structures face problems of their entrance at ground floor being obstructed by the diagrid structures besides having a limited space of the interior room for the users. The open space concept has to be employed at ground level or lobby as it is usually a public area. One way to resolve the problem is to introduce vertical columns at the ground level and the diagrid structure will start from the upper level. The vertical columns on the ground level will transmit the force from the diagrid system to the foundation. This raises the question on the performance and efficiency of the diagrid system in resisting the lateral force. In order to investigate the effect of the addition of the vertical columns at ground level and making the diagrid system to start from the top of the vertical columns, to the lateral displacement of high rise building, further research is required to identify the following:

- What is the range of height of the columns that can be used to retain the efficiency of the diagrid systems in resisting the lateral load?

- What is the most optimum spacing of the vertical columns with a uniform spacing arrangement to retain the efficiency of the diagrid systems in resisting the lateral load?

- What is the best arrangement of the vertical columns to retain the efficiency of the diagrid systems in resisting the lateral load?

- Is closely spaced vertical columns near to the corner of the building but further apart at other areas is better than a uniform spacing arrangement of the vertical columns to retain the efficiency of the diagrid systems in resisting the lateral load?

The results of the research will lead to:

- Determination of the optimum height of the columns to resist the lateral load effectively.

- Determination of the optimum spacing of the vertical columns with a uniform spacing to resist the lateral load effectively.
- Determination of the optimum type of arrangement of the vertical columns to resist the lateral load effectively.
- Determination of range of height and spacing of the uniformly spaced vertical columns that should be avoided as they cause the diagrid not to perform effectively.

References

Ali, M.M and Moon, K.S. (2007). Architectural Science Review: Structural Developments in Tall Buildings: Current Trends and Future Prospects. 50(3): 205-223.

Bhale, P and Salunke, P.J. (2016). Analytical Study and Design of Diagrid Building and Comparison With Conventional Frame Building. International Journal of Advanced Technology in Engineering and Science, Vol. No. 4, Issue No 01, January 2016

Boake, T. M. (2004). Elegant Structures : Diagrids take to the Sky, IABSE Symposium Report, IABSE Conference Nara, 2015: Elegance in Structures, pp. 1-8(8).

Boake, T. M. (2013a). Diagrids, the New Stablity System: Combining Architecture with Engineering. Aei 2013, 574–583. http://doi.org/10.1061/9780784412909.056

Boake, T. M. (2013b). Diagrid Structures: Innovation and Detailing. Structures and Architecture: New concepts, applications and challenges, CRC Press Pages 991–998, DOI: 10.1201/b15267-140

Boake, T. M. (2014). Diagrid Structure : Systems, Connection, Details. (A. Muler, Ed.). Germany: Deutsche Nationalbibliografie. Retrieved from http://dnb.dnb.de

Chandwani, V., Agrawal, V. and Gupta, N. K. (2012). Role of Conceptual Design in High Rise Buildings, 2(4), 556–560.

Charnish, B. and MCDonnell, T. (2008). The Bow: Unique Diagrid Structural System for a Sustainable Tall Building. CTBUH 8th World Congress, Dubai.

Hammida,Y. Diagrid Structural Systems for Tall Buildings. www.slideshare.net/youssefhammida/diagrid-structure (online start from June 13, 2015)

Jani, K., and Patel, P. V. (2013). Analysis and design of diagrid structural system for high rise steel buildings. Procedia Engineering, 51, 92–100. http://doi.org/10.1016/j.proeng.2013.01.015

Jung, I. Y., Kim, Y. J., Ju, Y. K., Kim, S. D., and Kim, S. J., (2014). Experimental Investigation of Web-Continuous Diagrid Nodes under Cyclic Load. Engineering Structures, 69, 90-101.

Kim, J. and Lee, Y. (2012). Seismic performance evaluation of diagrid system buildings. The Structural design of tall and special buildings. 21: 736-749.

Kim, Y. J., Kim, M. H., Jung, I. Y., Ju, Y. K. and Kim, S. D. (2011). Experimental Investigation of The Cyclic Behavior of nodes in Diagrid Structures. Engineering Structures, 33, 2134-2144.

Lemons, K. and Alvarado, L. (2011). Typical Uses of the Diagrid from website Diagrid-Structural Variety-AE390 at https://sites.google.com/site/diagridstructuralvarietyae 390/

Leonard, J. (2007). Investigation of Shear Lag Effect in Highrise Buildings with Diagrid System Massachusetts Institute of Technology

McCain, I. (n.d.). Diagrid: Structural Efficiency & Increasng Popularity. from website Scribd at https://www.scribd.com/doc/307473552/DiaGrid-Structural-Efficiency-Increasing-Popularity

Mehmet, H. G. and Huseyin, E. I. (2014). Tall Buildings: Structural Systems and Aerodynamic Form. New York. Routledge.

Milana, G., Gkoumas, K., and Bontempi, F. (2014). Sustainability Concepts in the Design of High-Rise buildings : the case of Diagrid Systems, 170–179.

Milana, G., Olmati, P., Gkousmas, K. and Bontempi, F. (2015). Ultimate Capacity of Diagrid Systems for Tall Buildings in Nominal Configuration and Damaged state. Ŕ Periodica Polytechnica Civil Engineering 59(3), pp. 381–391.

Mohan, P. (2011). Diagrid: The language of modern day builder. Unpublished note. Civil Engineering Seminar: The Civil Engineering Lexicon.

Montuori G. M. , Mele, E., Brandonisio G. and Luca A. D. (2014). Geometrical Patterns for Diagrid Buildings: Exploring Alternative Design Strategies from The Structural Point of View. Engineering Structures, 71: 112-12

Moon K.S. (2011a). Sustainable Design of Diagrid Structural Systems for Tall Buildings. International Journal of Sustainable Building Technology and Urban Development, 2(1), 37-42.

Moon K.S. (2011b). Diagrid Structures for Complex-Shaped Tall Buildings. Procedia Engineering, 14, 1343-1350.

Moon, K.S, Connor, J.J. and Fernandez, J.E. (2007). Diagrid Structural Systems For Tall Buildings: Characteristics And Methodology For Preliminary Design, The Structural Design Of Tall And Special Buildings. 16, 205–230

Moon, K.S. (2009). Design and Construction of Steel Diagrid Structures. School of Architecture, Yale University, New Haven, Nordic Steel Construction Conference. Retrieved from http://www.nordicsteel2009.se/pdf/72.pdf

Moon, K.S. (2014). Comparative efficiency of structural systems for steel tall buildings. International Journal of High-Rise Buildings, 5(3), 230–237. http://doi.org/10.1080/2093761X.2014.948099

Rathod, N. G., and Saha, P. (2015). Diagrid- An Innovative Technique for High Rise Structure, 2(5), 394–399.

Yadav, S., and Garg, V. (2015). Advantage of Steel Diagrid Building Over Conventional Building, 3(1), 394–406.Alam, J.B., Dikshit, A.K., and Bandyopadhyay, M. (2004). *Sorption and Desorption of 2,4-D and Atrazine from Water Environment by Waste Tyre Rubber Granules and Its Management*. Global NEST: the International Journal 6: 105-115.