A Review on the Seismic Performance Assessment of Steel Diagrid Structures

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ABSTRACT

In recent years, there is rapid increase in the construction of high rise structures due to the increase in population, high cost of land and restriction in horizontal growth due to less space. The advancements in the development of technological solutions and construction methods of high rise structures led to the innovative structural systems. One of the important criteria that need to be considered in the design of high rise structures is minimization of lateral loads. Hence, the importance of lateral load resisting system increased than structural systems that resist gravitational loads. Lateral loading due to wind and earthquake are the major factors that have to be considered in the design of high-rise structures. Diagrid structural system is recognized as a unique system in construction of high rise structures which is a variation of tubular structures. It consists of inclined members instead of vertical columns in conventional structures to carry both gravity and lateral loads. It gains popularity due to its structural efficiency and aesthetic potential gained by its unique geometric configuration. The present work reviews studies regarding seismic performance assessment of steel diagrid structures, studies on seismic performance factors of steel diagrid structures, impact of shear-lag effect and comparative studies on diagrids. Diagrids are found to be an efficient structural system for high rise structures in terms of structural efficiency as well as aesthetics. Also, it provides more economy, in terms of consumption of steel, thus making it cost-effective and eco-friendly.

Keywords: diagrid; seismic performance assessment; shear lag effect

1 INTRODUCTION

The demand for the space in densely populated land areas has led to the increase in the construction of high-rise structures. Advancements in structural engineering and construction technology have increased the height of structures which accelerated the construction of tall structures. The enhancement in the improvement of construction methods has pushed the limit of height of the structures making it more relevant and feasible. Thus, there is a need for systems that resist lateral loads than structural systems that resist gravitational loads. The major factors that have to be considered in the design of high-rise structures are lateral loads due to wind and earthquake. These are resisted by exterior structural system or interior structural system. The systems that resists lateral loads includes rigid frames, braced frames, belt and outrigger truss system and framed tube structures.

In recent years, diagrid structural system has gain popularity in the design of tall buildings. Diagrid system is recognized as a unique exterior structural system. It is a variation of tubular structures. These structures employ inclined members to carry both gravity and lateral loads. The inclined members are called diagonals that forms the outer perimeter of the structure. The diagrid system is an evolution of braced tube structures. The absence

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of vertical columns in the perimeter of building is the main difference of diagrid structures from that of braced tube structure. Shear can be carried by the diagonals located on the perimeter that avoids the need for shear rigidity cores. The configuration and efficiency of a diagrid system reduces the number of structural element required on the facade of the building providing less obstruction to the outside view. The structural efficiency also helps in avoiding interior and corner columns which allows for flexible floor plans.

1.1 DIAGRID COMPONENTS

Nodes: The nodes are the joints that connect all members. They can be formed by bolting or welding the ends of the members to a gusset plate. It can either be hinged or fixed depending upon conditions.

Diagonal members: These are the members that helps to transfer both lateral and gravity loads through axial action. Diagonal members can be made of steel, concrete, timber and composite members. The most commonly used are steel diagonals.

Ring Beams: The nodes are connected together at floor levels by the exterior floor beams called the ring beams. The ring beams play an important role in non-linear behaviour of the structure and in the formation of plastic hinge.

The frame of the diagrid is divided into a number of modules called diagrid modules along the height of the structure. The basic element of the diagrid system is the triangulated element. Triangulated element consists of two inclined diagonals and a horizontal ring beam as shown in Fig. 1. The diagrids are not necessarily formed in every single floor. The absence of columns from the exterior frame provides open facade that facilitates more entry of light which in turn gives more space so that architect can work with. These structures have considerable lateral stiffness which in turn reduces the need for auxiliary lateral systems like outrigger system that mostly carries the gravity loads. The gravity and lateral loads due to wind or earthquakes are carried by diagonals through axial compression or tension forces. When compared to the traditional moment frame structures, which carry shear through bending, diagrids efficiently reduces deformations due to the axial action of diagonal members. Diagrids provide both bending and shear rigidity. The angle of diagonal and topology of diagrid are the two key factors that have impact on lateral stiffness and efficiency of diagrids. Diagonal angle can be effectively adjusted which helps to improves the lateral stiffness and the linear and non-linear response of the structure under extreme and service loads. Finding an optimal diagonal angle for a diagrid structure is an essential step in the design process and it depends on several factors such as story height, aspect ratio, lateral load distribution and locality of the building. Even though the diagrid systems are increasingly used in tall buildings, the current codes do not consider them as independent structural system. Some examples of diagrid structures are shown in FIg.2.

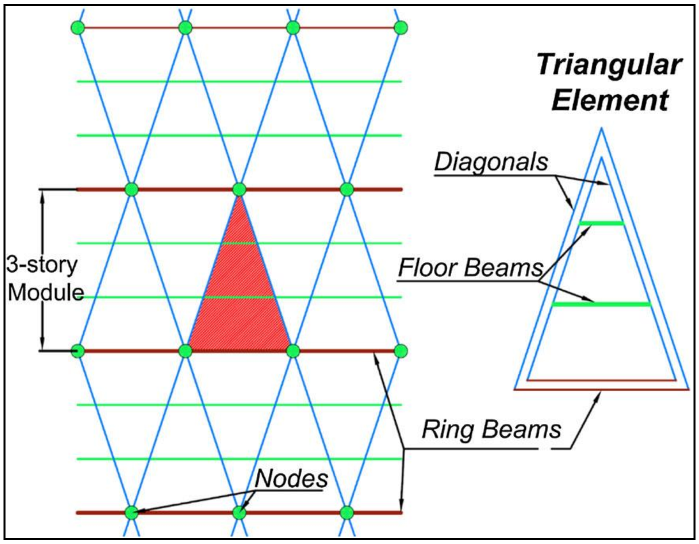


Fig.1: Representation of a 3-storey diagrid module and a triangular element (Asadi and Adeli 2016)

1.2 MATERIALS USED FOR DIAGRID STRUCTURES

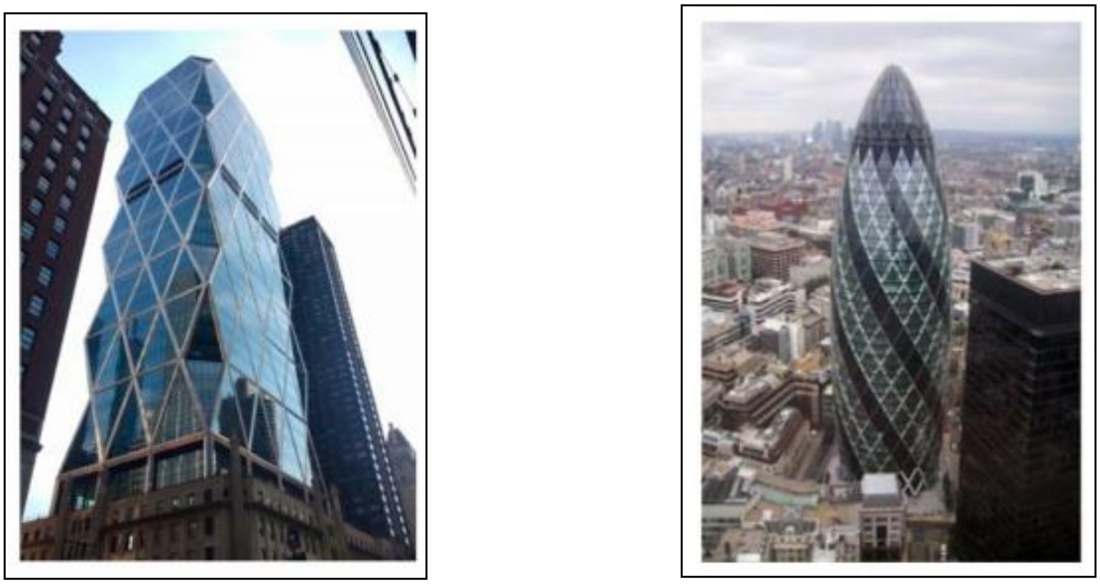
The diagrids can be constructed using variety of materials like steel, concrete, timber and composites. The unit weight of the material, availability of the material, lead time, erection time, flexibility, durability, labour cost and fire resistance are the criteria used for material selection. Majority uses steel. The predominant use of steel in diagonal member is due to easy fabrication and faster construction sequence compared to other materials. The diagonal members are supposed to take both tension and compression forces. Since concrete is weak in tension, the huge tension forces created during process can cause severe problems. Another reason for not using concrete is the constructability issues. This happens when connections to nodes are hard to fabricate and construct on site. The costly framework and slow construction are the main disadvantages of concrete diagrid structure. The use of composite section can help solve tension issues. Another alternate is to use pre-stress concrete. Applying pre-loading compression force, the concrete will be still in compressive state when the actual loading is causing tension in the element thereby reducing the failure due to concrete cracking and rupture in tension. But this not much adapted due to the cost of construction.

1.3 MERITS OF DIAGRID STRUCTURES

- The absence of column in the interior and exterior of diagrids allows for more clear and free space hence can design unique floor plans.
- The glass facades of interior columns allow huge amounts of day lighting into the structures.
- The use of diagrids results in about 20% reduction in the consumption of steel when compared to braced frame structures.
- They are sustainable in terms of energy efficiency, low environmental cost and efficient use of available resources.
- The structures are aesthetically dominant and make maximum exploitation of structural material.
- A diagrid structure has the capability to redistribute load than a moment frame structure.

1.4 DEMERITS OF DIAGRID STRUCTURES

- The fabrications of joints are more complicated when compared to orthogonal and results in additional costs.
- Erection of nodes is a difficult process.
- The diagrid construction techniques are yet to be explored.
- Lack of availability of skilled workers for constructing diagrid structures.



a) b)

Fig.2: Examples of diagrid structures: a) Hearst Tower, USA (Scaramozzino et al. 2020);
b) Swiss Re Tower, UK (Li et al. 2017);

This paper reviews studies regarding seismic performance assessment of steel diagrid structures, studies on seismic performance factors of steel digarid structures, impact of shear-lag effect and comparative studies on diagrids.

2 SEISMIC PERFORMANCE ASSESSMENT STUDIES ON STEEL DIAGRIDS

Seismic performance defines a structures ability to sustain its main functions at and after a particular earthquake. A structure can be considered safe if it does not harm the lives and well-being of those in or around it by partially or completely collapsing. Seismic performance assessment is a powerful tool of earthquake engineering which helps to gain a better understanding of seismic performance of building. Heshmati et al. (2020) evaluated the seismic performance of diagrid structures with varying angles. Also, the capability of diagrids on addition of diagrid cores was investigated. The result of pushover analysis showed that when diagrid angles are lower than the core, interior tube act as a backup load-resisting system after yielding of perimeter tube. Most diagrids were capable of undergoing large deformations without abrupt collapse in the whole structure. The performance of diagrid structures was acceptable under maximum considered earthquake motions and the deformations were within the allowable range. The mean drift was found to be less than the maximum allowable drifts as stated in tall building codes. Non-linear time history analysis was used for obtaining residual drifts that have to be controlled in tall structures in-order to avoid post-earthquake deformations that are likely to cause excessive damages. This also requires excessive downtime for performing the repair. It was found that the peak residual drifts were below the limit range of 1% as per tall building codes.

For diagrid structures, no specific criteria were introduced for their performance assessment and loss estimation. Asadi et al. (2018) investigated non-linear performance of steel diagrid structures. They defined three performance levels for each structural member as per FEMA 356 and carried out a series of non-linear static analysis on all models. It was found that the diagrids showed larger lateral stiffness and smaller fundamental period. After the formation of first plastic hinge, the stiffness was found to decrease. With the increase in lateral load, plastic hinge reaches higher performance levels. When the load capacity increased to ultimate load beyond which failure mechanism takes place i.e., collapse point, there occurs a sharp reduction in lateral stiffness leading to excessive deformation.

Non-linear time history analysis was carried out and the ratio of maximum inter-storey drift (IDR_{max}) to average inter-storey drift (IDR_{avg}) was used as an indicator to assess the performance. The mean inter-storey drift and ratio of maximum inter-storey drift to average inter-storey drift (IDR_{max}/IDR_{avg}) was relatively lower when compared to concentrically braced frames (CBF). The higher values of these parameters indicate more concentrated damage and more chances of soft-storey mechanism. The mean IDR_{max} for diagrids under design basis earthquake (DBE) and maximum considered earthquake (MCE) was 1.27 and 2.02% respectively which was lower when compared to similar structures such as CBF's in higher seismic region which shows that diagrids are less prone to soft-storey failure. The presence of incomplete module reduces the stiffness of such stories that causes increase in the concentration of deformation in them. This also affects the location of plastic hinges. It was found that the unique efficient configuration, in which diagonals carry both gravity and lateral loads, diagrids show substantial capacity against collapse. They showed lower expected total loss. The non-structural components were the main contributor to the total loss as these components are more prone to excessive spectral acceleration.

Kim and Lee (2010) studied earthquake response of diagrid structures with various slopes of external braces and responses were evaluated using nonlinear static and dynamic analyses. The results were compared with that of tubular structures. When the slope of the diagonals increased, the fundamental period also increased. Pushover analysis was carried out for diagrid structures. It showed that the diagrid structures generally have large stiffness and strength compared with the tubular structure designed with the same loads which is due to the large redundancy inherent to diagrid structures. They showed brittle behaviour compared with the tubular structures. It was observed that, the maximum base shear the diagrid structure could sustain decreased as slope increased. Brace angle between 60° to 70° was found to be effective in resisting both gravity and lateral loading. Pushover analysis was carried out for diagrid structures with buckling restrained braces which showed that the structure with braces have smaller stiffness but higher strength than the original structure with conventional steel braces. They also showed ductile behaviour much larger than tubular structure.

Asadi and Adeli (2018) investigated non-linear behaviour and design of mid-to-high rise steel diagrid structures. These were compared with corresponding moment resisting frames and concentrically braced frames. It was observed that inclination of diagonals has significant impact on the weight of the structure. It was observed that, appropriate diagrid angle reduced the weight of the structure and found that diagrids was lighter than moment resisting frames (MRF) and concentrically braced frames (CBF). This may be due to the presence of large columns in those structures. MRF showed the largest amount of lateral displacements and story drift. Diagrid models have lower story drift than CBF. The mean fundamental period was less for diagrids than MRF and CBF. Mean initial stiffness for diagrids were considerably larger when compared to MRF and CBF. Also, diagrids showed smaller ductility compared to MRF in non-linear behaviour which needs to be addressed. The addition of passive dampers can help to solve this issue. Installation of passive or semi-active control systems at inclined corner diagonal can help improve overall ductility.

The progressive collapse resisting capacities for tall diagrid building was evaluated by Kwon and Kim (2014) using arbitrary column removal scenario. The load factor exceeded 1.0 for every model which indicates that the structures are safe when one or two pairs of diagrids are removed from a corner. When the twist angle increased, the maximum load factor also increased. Non-linear dynamic analysis showed that all models remained stable after vertical vibration. The over strength factor was increased when twist angle increased. The adjusted collapse margin ratio decreased when twist angle increased which implies that the seismic safety decreases as twist angle increases. As twist angle increased, the seismic fragility decreased.

Kim and Lee (2009) studied the progressive collapse capacity of tube-type structures such as diagrid and tubular structures. The analysis was carried out by removing first-storey columns. The analysis showed that progressive collapse tended to occur when perimeter columns more than 11% were removed. The addition of corner columns did not contributed to increase in strength but helped to reduce failed members.

3 STUDIES ON SEISMIC PERFORMANCE FACTORS OF STEEL DIAGRID STRUCTURES

Seismic performance factors are used to estimate strength and deformation demands on seismic-force resisting systems that are designed using linear methods of analysis. The seismic performance factors include response modification factor, over strength factor and deflection amplification factor. Response modification factor (R) determines non-linear performance of building structure during strong earthquakes. This indicates the ability of a structure to dissipate energy through inelastic behaviour. Over strength factor (Ωo) is an amplification factor applied to forces in certain elements in the same load path. It is required to prevent a weak link from occurring prior to full energy dissipation and helps to remain safe during powerful tremors and reduces elastic strength demand. Deflection Amplification Factor (Cd) predicts maximum deformation from that produced by the design seismic forces.

Sadeghi and Rofooei (2018) focused on quantifying the seismic performance factors of diagrids. The diagrid exhibited brittle behaviour on pushover analysis. With the increase in angle, the ductility ratio increased but the over strength factor reduced. They also investigated the effect of connection type on the behaviour of the structure and found that there was no significant influence on the stiffness. For better assessment of the effect of connection type, they defined performance index ratio. It is the ratio of median collapse drift ratio of pinned ended beam to median collapse drift ratio of rigid ended beam. It was found that the values of performance index were greater than 1 which indicated that pinned connection tolerates greater displacements before collapse than rigid ended. Therefore, replacing rigid by pinned ended will take larger displacements.

Rofooei and Seyedkazemi (2020) studied on the Evaluation of seismic performance factors for steel diagrid structural systems using FEMA P-695 and ATC-19 procedures. The seismic performance factors were calculated using ATC-19 coefficient method and FEMA P-695 was used for understanding the accuracy of computed factors. It was observed that the over strength and response modification factor decreased on increasing the number of stories and ductility factor increased. Mid-rise diagrid buildings were found to be more reliable than high-rise structures. At maximum considered earthquake, all models have adequate safety against collapse. There was reduction in median collapse capacity while increasing the stories of the building. The effect of span length and variation of diagrid angle was investigated and found that the seismic performance factors do not change significantly when span length was increased since the aspect ratio and diagonal angle was kept constant.

Haghighat and Ashtari (2019) aimed to evaluate the seismic performance factors as the current code lacks this. They evaluated it based on FEMA P695 methodology and Uang method. The response modification factor was estimated about 2.5. The overstrength factor considering only one performance group was equal to 2. The estimated deflection amplification factor was 2.5.

Mohsenian et al. (2020) aimed to assess the seismic reliability of diagrid structural system. They calculated demand and supply response modification factors for different diagrids with different storey heights. The maximum storey drifts in the last module were found to be larger than others. The structures remained elastic at the design basis earthquake (DBE) level. The drift values were less than the allowable limit of 2%. The evaluation of axial strain distribution implied that they perform higher than safety level under both hazard levels. A response modification factor of four was found to maintain acceptable for satisfactory performance of diagrds under design basis earthquake which can also perform higher than life safety for maximum considered earthquake. The results showed good seismic performance and reliability of diagrid systems as a cost-effective alternative to conventional lateral load resisting system in tall buildings.

4 STUDIES ON SHEAR LAG EFFECT

Framed tube system or braced tube system in skyscrapers act as its primary structural system. These structures are affected by shear lag effect. Shear lag is a non-linear distribution of stresses across the sides of the section. This can result in higher concentration of stresses at the corner columns than the inner columns of the side. This reduces the structural efficiency and increases the lateral displacement of the building when subjected to lateral loads. Johan Leonard (2007) investigated the influence of shear-lag in diagrd structures. The deflection at the top, stress distribution and shear lag ratio were analysed. The shear lag ratio at the base of the building increased non-linearly at the base while the stress distribution showed negative shear lag at the mid-height. For smaller diagrid angle, the shear lag was smaller than for larger diagrid angle. The weight of the structure was found to decrease as the angle of diagrid increased. Larger deflection was experienced for diagrids with higher optimal angle. The diagrid buildings with angles lower than the optimal angle range will have higher total structural weight. The increase in the number of bays decreased the deflection at the top but the shear lag ratio was found to increase with increase in the density. This is because increase in number of bays causes more variation in the axial stress distribution. The influence of shear lag on the lateral displacement was investigated and found that lower shear lag does not directly correspond to lateral deflection. Kim and Lee (2010) observed that the shear lag effect was lesser when compared to tubular structure. When brace angle increased, shear lag coefficients also increased. This becomes rapid when the brace angle becomes more than 70^{o}. Shi and Zhang (2019) proposed simplified calculations for diagrid structures taking in to consideration the shear lag effect. The diagrid was considered equivalent to continuous orthogonal elastic membrane. The stress function was constructed as simple analytical expression of stress derived by energy variation principle. The method provides effective solutions to key problems like optimization of the diagrid angle column and evaluation of shear lag effect.

5 COMPARATIVE STUDIES ON DIAGRID STRUCTURES

A comparative study was conducted by Sun (2015) on the seismic performance between concrete diagrid and steel diagrid. Diagrid structures with varying parameters were taken into analysis. Dynamic modal analysis was performed on models to have an overview on mode shapes and their corresponding frequencies. Comparison of fundamental periods among steel concrete and outrigger system showed that steel diagrids were stiffer with a fundamental period due to its bigger mass. The mode shape illustrated that diagrids are susceptible to translational way. Response spectrum analysis compared top drift and top acceleration. Diagrid structural system was better in controlling top drift than moment and outrigger system. In the case of top acceleration, concrete models have lower top acceleration than steel. The performance of diagrids was lesser in satisfying top acceleration than the other two structures. Nayak et al. (2020) conducted a comparative study between 60 storey braced tube and diagrid structures. The structures were analysed for earthquake loads and wind loads. They observed that for earthquake and wind analysis, circular plan perform better in braced tube in terms of storey drift, storey displacement and base shear while square plan performs better in diagrids in terms of storey drift, storey displacement and base shear. Diagrids was found to have lower storey displacement and storey drift values and concluded that diagrids perform better than braced tube.

6 OTHER STUDIES

Montuori et al. (2014) defined a framework for assessing local structural issues in the design of diagrid tall buildings. The various local structural issues addressed are instability of interior columns and excessive inter-storey drifts. These mainly arise due to lack of flexural resistance since diagonals in diagrds are generally designed to carry only axial load. The flexural resistance is not enough to reduce multi-storey sway of interior gravity columns as well as excessive inter-storey drift of intra-module floors. They proposed a simple equation to check the flexural resistance of diagonals and equation to assess the need of additional systems. They analyzed a 90-storey building with different diagonal angles to test the efficiency of proposed formulation. Diagonal members with 70^o and 80^o have less inertia than required showing the necessity of secondary bracing systems (SBS). SBS's were designed such that it consists of four CBFs, to stabilize interior columns and limiting inter-storey drift. Results showed that there was a 3% increase of total structural weight but proven effective in limiting inter-storey drift.

Scaramozzino et al. (2020) carried out an updated review of diagrid structural systems were carried out in the study. Diagrids was found as efficient systems for tall buildings. The efficiency was due to the axial-dominated behavior of triangular element of the diagrid. Due to modularity characteristics and versatility, complex-shaped buildings can be constructed with excellent aesthetics. The structural performance of diagrids can be optimized based on geometrical features which are crucial for sustainability purposes. Diagrid structures with irregular shapes were analyzed and found that twisted, tilted, tapered and freeform diagrid system offers variety of architectural solutions for the design of unconventional tall buildings.

Jani and Patel (2013) analyzed and designed a 36 storey steel diagrid building. They also studied the load distribution. Most of the lateral load was resisted by diagrid columns on the periphery. Internal columns need to be designed only for vertical load. The loads are resisted by the axial action of diagonal members making the system more effective. The large interior space provides flexible planning.

Mele et al. (2012) proposed a hand-based method for the evaluation of axial stresses in diagrid members. The method was based on analysis of internal forces that arise in triangular element due to gravity and lateral loads. The method was applied to three case studies and found that there were equal stress levels in the diagonals and the design of steel members was governed by strength criteria. Diagonalized façade gave more horizontal stiffness.

7 CONCLUSION

The paper reviews studies on seismic performance assessment of steel diagrids. The review shows that diagrids are one among the best structural systems for high rise structures. It can be even used for the construction of irregular shaped structures. The structures with increasing diagrid angle showed better seismic performance and finding an optimal diagrid angle is a significant criterion in the design of diagrid structures. Also, current codes do not consider steel diagrid structures as an independent structure even though it is widely used. The unique efficient configuration in which the diagonals carry both lateral and gravity loads helps them to maintain substantial capacity against collapse. Diagrid structures have large stiffness and strength when compared with the tubular structure. Diagrid structures exhibits lesser shear lag effect when compared to other structural systems. Diagrids are less vulnerable to soft-storey mechanism. Researches regarding the impact of different parameters like diagrid angle, span length etc. on the seismic performance factors of diagrids are not thoroughly investigated. There is a need for extensive research in finding an angle that enhances response modification factor. The construction of diagrid structures were found as a sustainable alternative as lesser amount of construction material is required.

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