# Diagrid Structural System for Tall Buildings: State of the Art Review

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**Abstract -** *Over the past decade several research works have been carried out about diagrid buildings. Having established the importance of diagrid structures, researchers and practitioners have developed advanced design strategies to make diagrid structural systems efficient and economical. The structural efficiency and flexibility in architectural planning makes diagrid an innovative structural system for tall buildings. Several studies have pointed out the design methodology to be followed and researches have been carried out about the joint connections as well. Hence the purpose of this paper is to provide a systematic summary of the existing research achievements of the diagrid structural system for tall buildings.*

***Key Words***: Diagrid structural system, Framed structures, Lateral loads, Optimum diagonal angle, Concrete filled steel tube

## 1. INTRODUCTION

The increase in the number of high-rise buildings is contributed mainly by the evolution of efficient structural system, advances in construction technology, scarcity and high cost of urban land and also the advancement in computational techniques which allows the analysis and design of complex structures less time consuming and easy. Along with gravitational loading lateral loads such as wind loads and seismic loads proves to be major governing factor in the design of high-rise buildings. In order to resist lateral loads in tall structures mainly interior structural systems and exterior structural systems are provided. The widely used internal lateral load resisting systems are: rigid frame, braced frame, shear wall and outrigger structure. The exterior systems are: tubular structure and diagrid structure.

Out of many framed structures the uniqueness that differentiate diagrid is the ability to form wide range of non-rectilinear geometric structures which includes angles and curves. This makes diagrids as an excellent architectural choice in the creation of contemporary buildings. Diagrid is particular form of space truss, which does not have any conventional column on the exterior periphery of the structure. The efficiency of diagrids in sustaining lateral loads makes it an innovative and reliable technology. A series of triangulated truss system is formed by the diagonal columns and horizontal beams which facilitate efficient load transfer and increases stability. Deshpande et al. [22] compared diagrid structures to conventional structures. The authors came to the conclusion that diagrid has better overall performance in terms of efficiency as well as sustainability. Diagrid was found to have less deflection, used less steel and was eco-friendlier. More recently, diagrids are getting more and more attention owing to their unique form and properties. The unique compositional characteristics of diagrids provide great structural efficiency and aesthetic potential [15]. Swiss Re Tower in London is one of the latest examples of diagrid structures.

**Fig -1**: Swiss Re Tower. [14]

Boake [25] explained the fact that even though the first building to use a diagrid was constructed around 1965 in Pittsburgh the method was not really used again until around the year 2000 when several high-profile projects were in their design phase. The first building to use diagrid was the IBM Building constructed in 1965 at Pittsburgh. Its aesthetic appearance was enhanced by providing glazing system and resulted in oddly shaped windows.

## 2. DIAGRID CONFIGURATION AND DESIGN

### 2.1 Diagonal angle

Moon [16] explained the practical design guidelines. The methodology followed by Moon [16] was stiffness-based design methodology. This methodology was used to determine the preliminary member sizes for the diagonals. Moon [15] studied the optimal configuration of structural systems for tall buildings and in his study, he investigates optimal configurations of today's prevalent structural systems for tall buildings. Among various structural systems developed for tall buildings, the systems with diagonals are generally more efficient because they carry lateral loads by their primary structural members' axial actions [24]. From the studies it is evident that by placing the lateral load system throughout the perimeter of the building the overall efficiency of the system can be maximised. Varying angles as well as uniform angles are studied in order to determine the optimum angle so as to form an efficient configuration. By varying the diagrid angles, the system's efficiency can be further increased. Seismic performance of diagrid systems highly depends upon the diagonal angles. Moreover, increasing the diagonal angles will increase the related ductility ratios [23]. Moon [16] explained the practical design guidelines and optimal configuration for diagrid system. The optimal angle is usually unique for any particular building. The performance of the structure is influenced by brace angle and aspect ratio [13]. Lee et al. [4] used a Solid Isotropic Material with Penalization optimization approach to find the optimal topology and diagonal angle of a two-dimensional triangulated diagrid mesh under static and dynamic loadings. Hence authors recommend a formal optimization approach for finding the optimal diagonal angle for any particular diagrid structure. Moon [16] suggest that the optimal angle may vary from structure to structure and also depends on the height to width ratio. Jani and Patel [14] in their study carried out analysis of 40, 50, 60, 70 and 80 storey diagrid structure and determined that the optimal angle structure ranges between 65 degrees to 75 degrees. Panchal et al [21] conducted a similar study to determine the optimum angle and concluded that Diagrid angle in the region of 65° to 75° provides more stiffness to the diagrid structural system. Milana et al [9] quantified the considerable reduction of steel compared to traditional forms of construction like outrigger structures., three geometric configurations with inclination of diagonal members of 42°, 60°and 75° were used in the analysis and concluded that the one with the best overall behaviour results to be the one with 60°diagonal element inclination.

## 2.2 Preliminary analysis and design

To propose a practical form for the building, engineers need to have an approximate method in order to determine the preliminary sizes of the structural members quickly. Hence number of approximate preliminary design procedures were mentioned in number of studied one of them is of Moon et al. [16]. The authors introduced a simple design methodology to find the required cross-sectional areas of diagonals approximately considering a lateral stiffness-based design criterion. The allowable maximum displacement was given as H/500 where H is the height of structure [10]. The diagrid structure is divided into a number of diagrid modules (a group of adjacent stories) along the height. This diagrid modules were interconnected using diagonals. Diagrid structures do not need high shear rigidity cores because shear can be carried by the diagrids located on the perimeter [21]. Approximate cross sections of diagonals are calculated for the web and flange diagrids (diagrids parallel and perpendicular to the lateral force, respectively) based on the stiffness criterion. The authors report reasonable accuracy compared with using a linear finite element (FE) package for tall diagrid structures with an aspect ratio equal to or greater than five and diagonal angle in the range 60° to 70°. Moon [16] revised the method slightly by introducing a factor to include the contribution of web diagonals to bending rigidity. Mele et al [7] propose a simplified analysis method by dividing the diagrids into a number of triangular elements. Hasnet, A [1]. Analysed buildings with vertical and stiffness irregularity subjected to lateral loading and concluded that complex shaped buildings are getting popular, but they carry a risk of sustaining damages during earthquakes. Hence for their safe construction proper care should be given for the dynamic behaviour of the buildings. Moehle, J.P [11] studied seismic response of vertically irregular structure and concluded that certain parameters like storey drift changed abruptly on reaching the irregularity. Stiffness and strength approaches are both necessary and unavoidable; they are not separately sufficient for an exhaustive sizing process of the diagonal members [8]. Lee and shin [5] performed nonlinear static push over analysis using ABAQUS software to verify the structural and economic superiority of convex shaped diagrids over flat-shaped and concave diagrids.

## 2.3 Joints in diagrids

The most complex part in the design of diagrid structures are the Joints. Joints connection may vary depending upon the type of material used and the amount of loading acting on the structure. Diagrid columns can be constructed with different type of materials like Steel, reinforced concrete and CFST tubes. Each of the material have different type of joint connection. The joints have to be stiff and also capable of transferring the axial loading effectively to the adjacent members [27]. Ling et al [18] investigated the behaviour of the intersecting connection of CFST columns in diagrid structure, a typical reduced scale planner connection specimen is tested under monotonic compressive loading. Experimental results as well as numerical simulation concluded that the intersecting CFST connection was able to develop fully plastic deformation with sufficient capacities. Huang et al [3] conducted a number of experiments on eight circular CFST diagrid node specimens under monotonic static axial compressive loading. Two types of CFST connections are tested In CFST connections, elliptical steel bearing plate is welded to the four intersecting columns to resist axial compressive loads. Two different details are used to strengthen the connections (i) a lining plate with a ring reinforcing plate, it consists of four semi-tubular lining plates which are welded at the intersecting ends at each column, and one ring reinforcing plate at the centre of the connection.(ii) flange plates, it consists of four semi-ring flange plates which are welded to the columns and then they are connecting each other with bolts. All these components are strengthening the confinement effect of the structural members. So as to improve the load bearing capacity of the connections. Compared to flange plates lining plates offers more confinement effect. Huang et al [3] suggests that failure occurs in these connections are mainly depends on the interacting angle between the columns. For the specimen with an interacting angle of 20°then steel tube bulging occurs within the connection zone. But specimen with an interacting angle of 35° the failure occurs in the column zone. Therefore, the connection with smaller interacting angle requires appropriate reinforcement such as increasing the thickness of the steel tube or the elliptical plate to avoid failure.

Zhou et al [26] conducted study in RC diagrid structures and x-shaped reinforced concrete joints were provided in the experimental study. These joints consist of four diagonal columns and horizontal girders. volumetric ratio of the stirrups loading patterns are the main design factors for x-shaped reinforced concrete joints. Expanding deformation may occurs at the joint concrete region under loads. The stirrups confine the lateral expanding deformation. So, joints with normal volumetric ratio of stirrups are designed for large stiffness and high load bearing capacity.

Kim et al [28] studied the steel joints through number of experiments. The node core is designed with a box type section such as H-section. It consists of two diagonal brace members, side stiffeners, centre stiffener. The flanges are attached at the node section. The web braces are not continuous therefore the axial forces from the webs are transferred to side stiffeners at the node. Failure mechanism of a diagrid node is governed by combined mechanism of axial force and additional moment from the two axial forces. For the design of joints consider stiffener configuration, welding method, overlapping length of stiffeners as fundamental parameters. Rounded stiffeners offer reduction of the strain concentration near the side stiffener ends. FP welding method is recommended for the flange to flange welds in order to avoid detrimental behaviour. PP welding method is recommended for remaining welds for load transfer mechanism. Overlapping length of stiffeners also plays an important role in structural performance of diagrid structures. Overlapped length that beyond standard length is recommended for adequate safety.

## 3. TYPES OF DIAGRID STRUCTURES

### 3.1 Concrete diagrids

Due to the ease in construction and fabrication steel sections commonly W-shaped and circular or square hollow structural sections are used for diagonals of a diagrid structure. The added advantage of steel since it can withstand large tension as well as moderate compressive strength also attribute to the fact of preferring steel over concrete for diagrid structures. However, a number of diagrid structures have been built with concrete. Some common examples are the 20-story 170 Amsterdam Avenue building in New York City completed in 2014 is an example of exposed concrete diagrids where the large concrete diagonals form the exterior of building, the so-called exoskeleton. Yet little research has been reported on concrete diagrid frames [17]. Hence the scope of research is more for concrete diagrids.

### 3.2 Steel diagrids

The most common form of diagrid frames are steel frames. The advantage of ease in fabrication and construction paved the way for steel frames over concrete frames. The sections commonly used are rectangular HSS, rounded HSS and wide flanges [20]. The weight and size of the sections are made so as to resist the high bending loads. They can be quickly erected and the cost of labour for the installation is low. One of the major disadvantages that can be attributed against steel is that since steel sections are factory made the flexibility of construction complex shaped structures is limited. Majority of diagrid structures built today is of steel.

### 3.3 CFST diagrids

The new type of composite construction of Concrete Filled Steel Tubular elements used as diagrid frames is gaining importance in recent years. The combined structural performance of steel as well as concrete justifies the use of CFST in diagrid frames [29]. They can be further strengthened using Fibre reinforced polymer [19]. Completed in 2010, the 103-story Guangzhou West Tower aka the Guangzhou International Finance Centre in China is known as the tallest diagrid structure built. The structure consists of an RC internal core and an exterior curved-shaped concrete-filled steel tubular (CFST) diagrid frame. Huang et al [13] conducted Experimental and Numerical Investigation of the Axial Behaviour of Connection in CFST Diagrid Structures. But however very little research study has been conducted in using CFST as diagrid frames.

## 4. SUSTAINABILITY OF DIAGRID STRUCTURES

The Leadership in Energy and Environmental Design (LEED) uses a rating system to evaluate the sustainability of a new or constructed building based on material, energy and water efficiency, environmental quality, and innovative design criteria. The inclined members of the diagrid carry most of the lateral loads and hence the interior columns may be designed for gravity loading only which leads to less consumption of steel [6]. Also, the diagrid offers flexibility in designing complex geometrical forms which can create beautiful architectural buildings. The other sustainability feature of Diagrid has been the large column less spaces which may be used as rental spaces or can be allocated to sky gardens, atriums, and so forth. Also, the structural efficiency lead to reduced use of structural material. One of the examples of a LEED gold rated diagrid building is The Bow Tower completed in 2012. It is a 47-m and 57-story steel diagrid office building with unique curved shape and distinctive sustainable features. It is the tallest building in Calgary, Canada. Charnish and McDonnell [2] claimed that a great deal of thought and design effort was placed on creating a progressive sustainable building within Canada. Multi-story sky gardens were incorporated into the building at three separate levels to provide added green space. And finally, in order to maximize sunlight several studies were also done to position the building accordingly.

## 5. CONCLUSION

The mechanism of load transfer, structural style and aesthetic appearance of diagrid structures are very different form orthogonal structures. The design of safe joint connection is an important step in the design of diagrid structures. Better seismic resistance of the structure makes it ideal in seismic vulnerable areas as well. Many studies prove that diagrid not only enhances strength and stiffness but also improves the ductile capacity of the structure. Hence the potential of diagrids to become more popular in the construction of high rise and mid-rise buildings is high as the new technology in the field of construction will aid the complex construction to become easier. The flexibility of using diagrids to form architecturally complex shaped structures has been recognised all over the world. A limitation to this is the lack of specific design procedures for the safe and conservative design.

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