Performance assessment of hexagrid structural system

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Abstract. The progression of innovation and advancement of economy of the world have brought new period of tall structures. Different types of structural systems pose challenges which are being faced by the structural engineers and architects in terms of innovation in structural system. Hexagrid is one among them. This system is adopted in tall buildings due to their structural efficiency and architectural potentials. Hexagrid encloses intersection of diagonal and horizontal or vertical members. This system is very similar to that of diagrid system and is configured by locating hexagons along the periphery of the building. This study aims to compare between hexagrid structural systems with different patterns and to find the optimal pattern which resists the lateral loads in hexagrid structural system. The use of hexagrids in a skyscraper is a relatively new idea. As such, more is yet to be explored in such a system.

1. Introduction
1.1. General
In recent years, fundamental economic growth of tall buildings is due to the quick development of populace, significant expense of land, improvement in the perspective on city and limitation in the horizontal growth due to less space. Today, it is difficult to envision a significant city without tall structures. Recent design trends pose new challenges in providing a structural framework with requirements of strength, stiffness and stability against the loads that are being experienced by the structures over the life cycle.

A significant purpose of this arrangement is to present a framework that is capable of minimizing lateral loads. The need for opposing lateral loads is more significant contrasted with withstanding gravity for elevated structures. These days, the structural systems ought to be so that it responds to the architecturally aesthetic prerequisites as well as it is structurally efficient. A framework which opposes both gravity and lateral loads with the same structural component can be considered as a productive structural framework.

The most effective framework for tall structures has been the tube-type structural systems. The diagrid system with tubular behaviour was found to be structurally efficient and architecturally sound. The diagonals provided around the perimeter of the building acts as a façade, which helps in providing the aesthetic view of the structure. To enhance the effectiveness of the tube type structures, another framework known as "Hexagrid" was introduced and was first proposed in literature published in 2012 [1]. Hexagrid system is the new emphasis of the exoskeleton tubular framework. The framework is comprised of a system of multi-storey tall hex-angled truss system [2]. It highlights modules composed of hexagon-shaped structural elements on the periphery of the structure to determine both
lateral and gravitational forces to a similar fashion as that of diagrids. Hexagrid structures are rising as a new trend for elevated structures in the modern period of architecture.

In contradistinction to diagrid systems, the amount of research conducted on hexagrid systems is very few. The hexagonal pattern was first introduced in Sino-steel International Plaza located in China. A couple of other structures in which hexagonal patterns implemented are as shown in the Figure 1.

1.2. Hexagrid system
This system bears a resemblance to diagrid system, in which the hexagons are situated along the outermost periphery of the building which bears the purpose of enhancing the structural productiveness and aesthetic appearance. Therefore, this system resembles a tube. Hexagrids encompass intersection of diagonal and horizontal or vertical members to form six node hexagonal grids which are obliged by mega columns located on the corner of the structure. They transfer both lateral as well as gravity loads. This type of innovative system eradicates the necessity of external vertical columns in elevated structures that offer a great scenic view from the inner side of the structure. The columns present at the corner can also be eliminated to achieve architectural demand. Also, the load paths are uninterrupted and continuous [3]. Hexagrids helps in 10-15% of reduction in steel. The diagonal assumes a significant role in the behaviour of hexagonal framework as it determines the stress distribution resisting internal forces. Hexagrids are more compelling in minimization of shear deformation as they carry shear by axial action of diagonal members, unlike conventional tall buildings which carry shear by the bending of vertical columns and horizontal spandrels. The hexagrid structural system provides both bending as well as shear rigidity. But, it does not require high shear rigidity cores as shear is being carried by hexagon elements that are located on the exterior periphery of the structure. Subsequently, hexagrid framework can be reviewed as an ideal framework for elevated buildings. Hexagrid framework shall take the form in two patterns are shown in Figure 2 [7].
2. Building configuration
2.1. Building description and modelling
A square building of plan area 1296 m² and size 36m x 36m is considered. The building consists of 36 stories with uniform storey height of 3.6 m. The inclined columns are provided at a spacing of 6 m along the perimeter. The support conditions of interior columns are fixed and that of exterior hexagrid is hinged. The floor slab is subjected to a live load of 2.5 kN/m². The computations for the design earthquake load is based on zone factor of 0.16, importance factor 1, medium soil and response reduction factor 5 [4]. The structure is modelled and analyzed in ETABS 2016. The plan of the structure is as shown below in the Figure 3.
Table 1. Size of typical members of 36 storey hexagrid structure.

| Storey                  | Diagonal Columns (same for all storey) | Interior Columns | Beams (same for all storey) |
|-------------------------|----------------------------------------|-------------------|-----------------------------|
| From 30th – 36th storey | 825 mm Pipe sections with 50mm thickness | 1500 mm x 1500 mm | B1 and B3 = ISMB550 to ISWB600 |
|                         |                                        |                   | B2 = ISWB600 with           |
| From 12th – 29th storey | 1650 mm x 1650 mm                      |                   | top and bottom cover        |
| From 1st – 11th storey  | 1800 mm x 1800 mm                      |                   | plate of 220 x 50 mm        |

Figure 4 shows the details of internal column which opposes the gravity loads [5]. The member sizes can be lowered by the consideration of higher strength of structural steel.

2.2. Building patterns
The patterns considered for the study are listed below in figures 5 and 6. The models are divided based on the patterns, storey height and hexagrid density. A total of 12 patterns are observed and analyzed.
3. Results and discussion
The response spectrum analysis results of all hexagrid patterns are compared and presented in this section.

3.1. Time period

Figure 5. Vertical Patterns of Hexagrid structure.

Figure 6. Horizontal Patterns of Hexagrid structure.

Figure 7. (a) Time period of vertical hexagrid buildings.

Figure 7. (b) Time period of horizontal hexagrid buildings.
In vertical hexagrid, as the module size increases, time period decreases as shown in Figure 7(a). In horizontal hexagrids, as the module size increases, time period decreases as shown in Figure 7(b). From figures 7(c) and 7(d) it is found that vertical hexagrids give lesser time period when compared to horizontal hexagrids.

3.2. Storey displacement

The displacement decreases in vertical hexagrid when both the module size and angle increases as shown in Figure 8(a). The same is noticed in horizontal hexagrid as shown in Figure 8(b).
Figure 8. (b) Storey Displacement of horizontal hexagrid buildings.

Figure 8. (c) Storey Displacement of vertical and horizontal hexagrid buildings.

Figure 8. (d) Storey Displacement of vertical and horizontal hexagrid buildings with angles decreased.
In both the figures 8(c) and 8(d), it is noted that vertical hexagrids displaced lesser than that of the horizontal hexagrids. It is observed that the displacement increases in both vertical as well as horizontal hexagrids when the angle decreases as shown in Figure 8(d).

It is concluded that the vertical hexagrids of larger module size are preferred over horizontal hexagrids.

3.3. Storey drift

Figure 9. (a) Storey Drift of Vertical hexagrid buildings.

Figure 9. (b) Storey Drift of Horizontal hexagrid buildings.
In vertical hexagrid, with an increase in module size, there is a decrease in the drift as shown in Figure 9(a). Also, the drift decreases with an increase in module size and angle in horizontal hexagrid as shown in Figure 9(b). From both figures 9(c) and 9(d), the vertical hexagrids are found to have lesser storey drift when compared to horizontal hexagrids. It is observed in Figure 9(d) that as the angle decreases, the storey drift is found to increase in both vertical and horizontal hexagrid structures. Therefore, it is concluded to prefer vertical hexagrids with larger module size over horizontal hexagrids.

3.4. Load distribution
As seen in Figure 10(a), the gravity load is evenly distributed between the internal core and perimeter columns in horizontal hexagrid. The vertical hexagrid turned out to take a higher gravity load compared to horizontal hexagrid. In Figure 10(b), as the angle is decreased, it is seen that the gravity load is distributed equally between the interior core and perimeter columns in vertical hexagrid. While in horizontal hexagrid, the distribution of gravity load is more towards the interior columns.
Figure 10. (a) Gravity load distribution in both vertical & horizontal hexagrid buildings.

Figure 10. (b) Gravity load distribution in both vertical & horizontal hexagrid buildings with angles decreased.

Figure 10. (c) Lateral load distribution in both vertical & horizontal hexagrid buildings.
As seen in Figure 10(c), the majority of the lateral loads are opposed by the perimeter diagonals in vertical hexagrid. But the lateral load is found to be resisted by the interior columns in horizontal hexagrid. In Figure 10(d), as the angle decreases, it is noted that the majority of the lateral loads are taken by the perimeter diagonals in vertical hexagrid. Whereas in horizontal hexagrid, some of the lateral load is found to be distributed to the perimeter diagonals.

The conclusion derived from the response spectrum analysis by observing all the above results is that vertical hexagrid building of larger module size is preferred over horizontal hexagrids.

4. Conclusions
The purpose of the work is to contrast between hexagrid frameworks with different patterns and to obtain the optimal pattern. Four parameters are considered for the comparative study. The following results obtained from the study are:

- The displacement values decrease as module size increases in both vertical and horizontal hexagrids. It is observed that as the angle decreases, displacement values increases in both vertical and horizontal hexagrids.
- The drift values decrease in both vertical and horizontal hexagrids as module size increases. As the angle decreases, it is observed that the drift values increases in both vertical and horizontal hexagrids.
- There is an equitable distribution of gravity load between the internal core and perimeter columns in horizontal hexagrid. The vertical hexagrids turned out to take a higher gravity load compared to horizontal hexagrids.
- Most of the lateral load is found to be resisted by the perimeter columns in vertical hexagrid. But the lateral load is found to be resisted by the interior columns in horizontal hexagrids. As the angle decreases, some of the lateral load is found to be distributed to the perimeter diagonals in the horizontal hexagrid structure.

Vertical hexagrids of larger module size gives better performance compared to horizontal hexagrid structure.
5. References

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