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A Study on Seismic Performance of Hexagrid Structures

P A Krishnan, Renjith Kumar, Prasad J S

Abstract— **This paper presents a study on seismic performance of hexagrid structures. Hexagrid structures are tubular type structures, in which structural steel is provided along the periphery of the structure. This eliminates the need for corner and interior columns in the structure. Lateral load resistance of such structures are achieved by axial or truss action of members provided along the periphery of structures. In this paper, first a study with both horizontal and vertical orientation is done and it was found that the latter is more efficient. For evaluating seismic performance of the structure, equivalent static method (static method), pushover analysis and time history method (dynamic methods) are adopted. Analysis is performed on 18 and 24 storey structures of regular pattern and 36 storey structure of varying density and varying angle is modelled in ETABS 2016, conforming to IS 1893: 2016. Module size of each structure is varied to obtain optimum module density. Parameters like storey displacement, drift, base shear etc are used to evaluate structural performance of each structure. It was found that the model with varying density is the most efficient with more stiffening in the middle portion compared to other models.**

Index Terms— **Base shear, Hexagrid structure, Equivalent static analysis, Pushover analysis, Time history analysis, Tubular structures, Storey drift**

I. INTRODUCTION

Advances in construction technology, materials, structural systems and analytical methods for analysis and design facilitated the growth of high rise buildings. Structural design of high rise buildings is governed by lateral loads due to wind or earthquake. 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.

Hexagrid structure is the arrangement of hexagrids in the outer periphery of the structure. Hexagrid structures is inspired by honeycomb occurring in our nature and can also be called as "Beehive structure". Hexagrid structures can meet the architectural, aesthetic and constructional requirements in modem constructions for high rise buildings. Hexagrid structures have an easily recognisable good appearance. The structural efficiency of the system renders interior and corner columns unnecessary, therefore allowing significant flexibility with the floor plan. The column free structure of hexagrid structural system offers several advantages such as high architectural flexibility with enormous day lighting due to its large free façade surface. Architecturally, the absence of columns in the corners of the building enables great panoramic views and extends the useful space from the interior.

II. LITERATURE SURVEY

The nonlinear performance of steel diagrid structures using static, time-history, and incremental dynamic analysis was studied (**Asadi et al.**).Various cross sections for the inclined members of the diagrid structural system was considered. The diagrids are found to have a substantial collapse capacity and lateral stiffness.

Models circular in plan was analysed with different aspect ratio (**Kamath et al.**). The objective was to study the performance characteristics of diagrid structures using nonlinear static pushover analysis. The models studied are circular in plan with aspect ratio H/B varying from 2.67 to 4.26. The three different angles of external brace considered are 59^o, 71^o and 78^o. The width of the base is kept constant at 12 m and height of the structure is varied accordingly. The nonlinear behavior of the elements is modelled using plastic hinges based on moment-curvature relationship as described in FEMA 356 guidelines. Seismic response of structure in terms of base shear and roof displacement corresponding to performance point were evaluated using nonlinear static analysis and the results are compared. For 71^o brace angle model, base shear at performance shows an increase in all the aspect ratio considered in the study. We can therefore say that the performance of the structure is influenced by brace angle and aspect ratio.

The progressive collapse-resisting capacity of hexagrid structural system and the common diagrid system was carried out based on the local failure of the structural elements in the story above the ground **(Ali et al.).** In this study, push down and time history analyses were carried out to evaluate the nonlinear static and dynamic behaviors, respectively. The analysis results state that the hexagrid has enough potential of force redistribution to resist progressive collapse due to its special configuration and show that dynamic amplification factor could be larger than 2. Push down curves report that it is ductile and the diagrid is brittle. The location of plastic hinge formations clarifies completely the behavior of both structural systems and illustrate that the mega corner column increases the capacity of structure against progressive collapse. It is found that as buckling is prevented, behavior of both structural systems improves.

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The possibility of adopting variable patterns for diagrid structures was stated, thereby achieving great structural efficiency (**Giovanni et al.**). The scientific contributions prior to this paper studied mainly regular diagrids, i.e. patterns characterized by constant geometrical attributes of the base module (width and height, angle, scale). In this paper, a first step toward a systematic and comprehensive study of geometrical patterns for diagrids is provided. For this purpose, diagrid structures characterized by 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.

Based on the equivalent static analysis it was found that both Hexagrid and Pentagrid structural systems perform better in the case of lateral loads and also both system exhibits increasing efficiency with increase in the number of unit cells in the horizontal direction (**Taranath et al.**). Here, the proposed pentagrid system performs better than the Hexagrid system. Nevertheless, it is observed that with increase in height, the efficiency of Hexagrid bracing system increases while the efficiency of pentagrid system decreases.

The influence of the different configurations of the diagonals on the behavior of diagrid structures was studied **(Moon et al.**). For uniform angle diagrid structures, it was found that, as a building becomes taller, the optimal angle also increases because the design of a taller structure with a large height-to-width aspect ratio tends to behave more like a bending beam, and steeper angle diagonals resist bending moments more efficiently by their axial actions. For the tall diagrid structures, with aspect ratios ranging from about 4 to 9, the range of the optimal angle is from approximately 60 to 70 degrees. This paper also investigated the potential of diagrid structures with varying angle diagonals. It was found that the diagrid angle configuration that becomes gradually steeper towards the base of the building generates a more economical design in terms of material usage than the uniform angle configuration for diagrid structures with an aspect ratio larger than about 7. However, for diagrid structures with an aspect ratio smaller than about 7, it was found that the uniform angle diagonals produce the most economical design.

Based on the literature review, the following conclusions are reached. There has been no significant study on variable pattern hexagrid structures and its efficiency. In a study conducted by Giovanni[7], the efficiency of variable angles and variable density diagrids were discussed. This can be applied to the hexagrid structural system also. The traditional method of attaining stiffness and strength requirements in tall steel structures is by reducing the material cross section or by reducing the strength of the material as we approach the top of the building. From the studies it can be learned that reducing a few members or varying diagonal angle will also serve as alternate options. For this analysis results from regular sized hexagrids are very much required. In variable angle models, the approach is to keep the median value of angles provided, to be same as that of the optimum angle from the regular hexagrids

III. STRUCTURAL BEHAVIOR

The irregular architectural style in high rise buildings due to hexagonal grid system can be effectively used for load transfer mechanism. Structures with inclined columns couple significant lateral and torsional stiffness and strength capacity to remarkable material economy, thus allowing for tremendous structural efficiency. In a hexagrid structure the hexagons can be oriented in two patterns, vertical and horizontal as shown below.

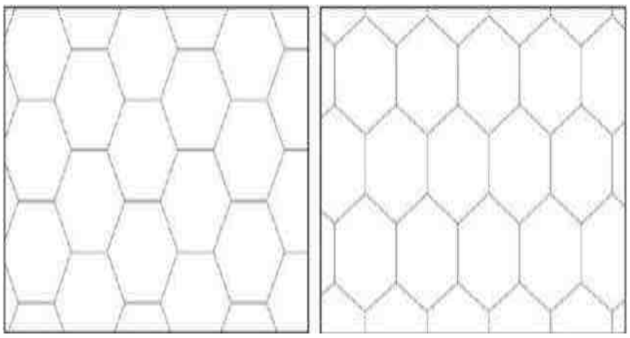


Figure 1: Horizontal and vertical hexagrid system

The rationale behind the design strategy adopting variable angle (VA) patterns is that the share of bending and shear stiffness demands in a hexagrid building is a function of the building slenderness, and, for a given building, it varies along elevation. Since the module angle strongly affects both the bending and the shear stiffness of the hexagrid structure, it is likely that the most efficient hexagrid structures should be characterized by variable angle configurations. In particular, it is expected that the diagonal angle should be steeper at the upper levels, than at lower levels.

IV. MODEL DETAILS

The plan area of the building is 1296 sq.m. The building has storey height of 3.6 m and the dimension of building is 36m x 36m. Both 18 and 24 storey buildings have to be modelled for regular pattern and a 36 storey model for varying angle and varying density models. The grade of steel used is Fe 250. The end conditions of hexagrids are hinged and that of vertical columns are fixed. The live load on floor slab is 2.5 kN/m^2. The design earthquake load is computed based on medium soil, importance factor 1, response reduction factor of 4 and the zone factor as 0.16 as per IS 1893 (Part 1):2016. The load combinations are taken from IS 800:2007 for limit state of collapse and limit state of serviceability.

To make maximum utilization of the material the members of the hexagrid are modelled to take load through axial action. The end conditions of the hexagrid members are provided as pinned, so that no moment is transferred to the member. The member is subjected to axial tension and axial compressive forces and therefore size of the members is reduced. There are four module patterns: vertical hexagrids (VH), horizontal hexagrids (HH), varying angle (VA) and varying density (VD). The models in the first two patterns are named according to the number of storeys required to form an additional hexagrid layer.

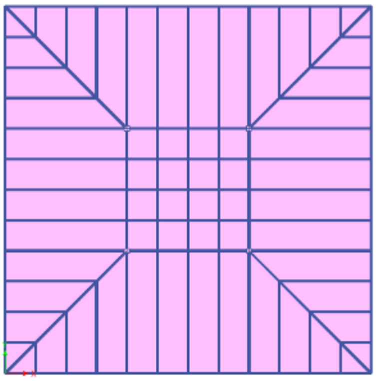


Figure 2: General plan view

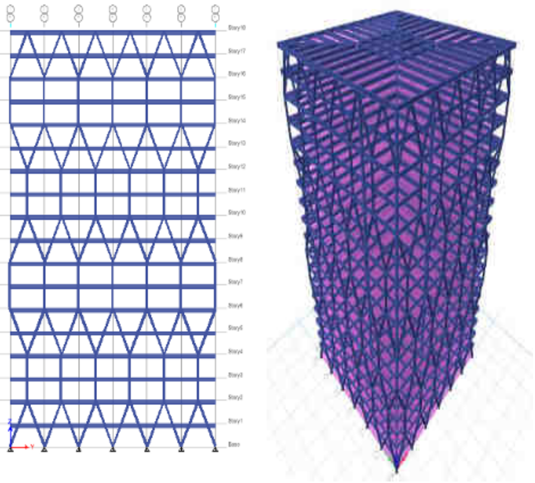
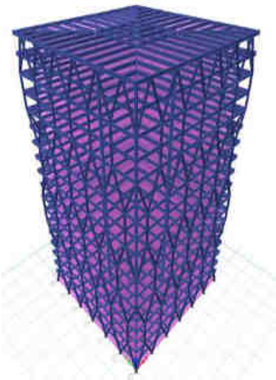


Figure 3: Elevation and 3D view

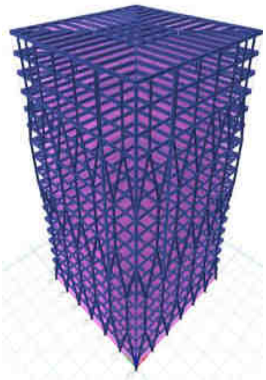
Table.1 Details of models

Model pattern	Model name	Model designation	No. of stories
Vertical Hexagrids	2VH 18	4-storey module	18
	3VH 18	6-storey module	18
	2VH 24	4-storey module	24
	3VH 24	6-storey module	24
Horizontal Hexagrids	2HH 18	4-storey module	18
	3HH 18	6-storey module	18
Variable Angle	VA1	60°,70°,78°	36
	VA2	70°,78°,80°	36
	VA3	65°,72°,76°	36
Variable Density	VD1	Inner Stiffened	36
	VD2	Outer Stiffened	36

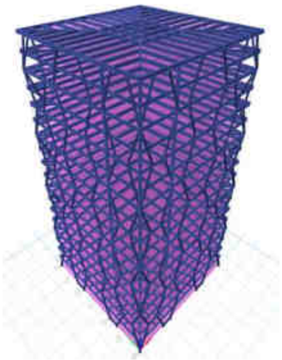
Cross sections of steel sections provided to the structure are obtained from initial design performed using ETABS 2016. For 18 storey models, pipe sections with 425 mm dia and 25 mm thickness was used for storeys up to 12, for the hexagrid part. For remaining storeys 375 mm dia with 12 mm thickness was used. Similarly for 24 storey building, pipe sections with 425 mm dia and 25 mm thick and 375 mm dia with 12 mm thickness was used respectively.



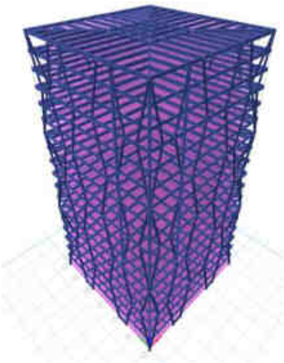
2VH 18



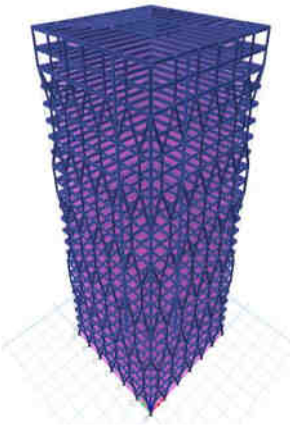
3VH 18



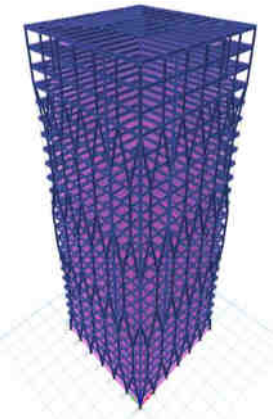
2HH 18



3HH18

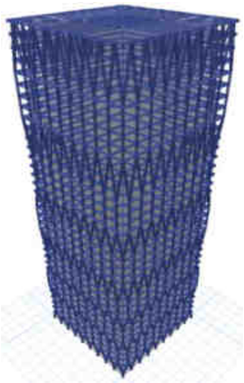


2VH 24

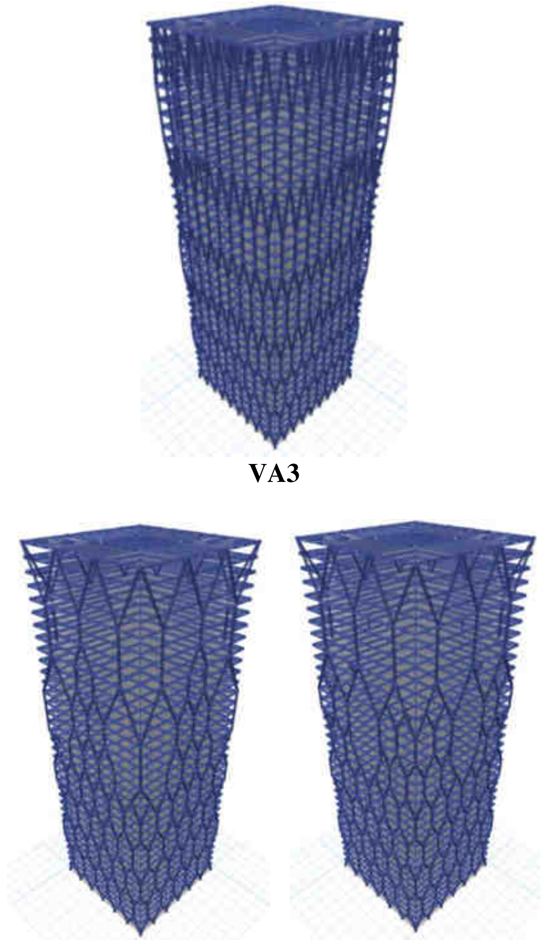


3VH 24

VA1



VA2


VA3

VD1 VD2

Figure 4: 3D view of all models

The building elevation is subdivided into macro-modules, with the hexagrid angle kept constant in each macro-module. Since 36 storey structures are considered, each macro-module is made of 12 storeys, thus dividing the elevation into three parts. The steepest angle will be provided to the uppermost module. The optimal angle obtained in the regular pattern hexagrid analysis will be used as the diagonal angle for the center module. In the VA1 model, the first macro-module (angle = 60°) extends from 0 to 36 m, encompassing 12 storeys; the second macro-module, (angle = 70°) extends from 36 m to 72 m, encompassing 12 storeys; finally, the third macro-module (angle = 78°) extends from 72 m to 108 m, encompassing the last 12 storeys. A similar approach is used for VA2 and VA3 models.

Also, two approaches in variable density models are adopted here. Primary aim of the variable density models is to gradually reduce the number of diagonal members required as we move to the top. In the VD1 pattern, the geometry followed in the bottom macro-module is gradually reduced by maintaining members only in the centre of the middle macro-module. Subsequently hexagrids with bigger module density will appear on the edges of the structure. Whereas, in the VD2 pattern, members are provided on both edges of the structure in the central macro-module. As a result hexagrids with bigger module density are formed at the central macro-module. For the VA and VD parameter models, 375mm dia, 20mm thick pipe Section are used for the hexagrids.

V. RESULTS

A. Equivalent static method:

1. Load distribution:

We can observe an almost equal distribution of gravity loads, among the external hexagrid system and internal core. Vertical hexagrids show an improved distribution of gravity loads when compared to horizontal hexagrids.

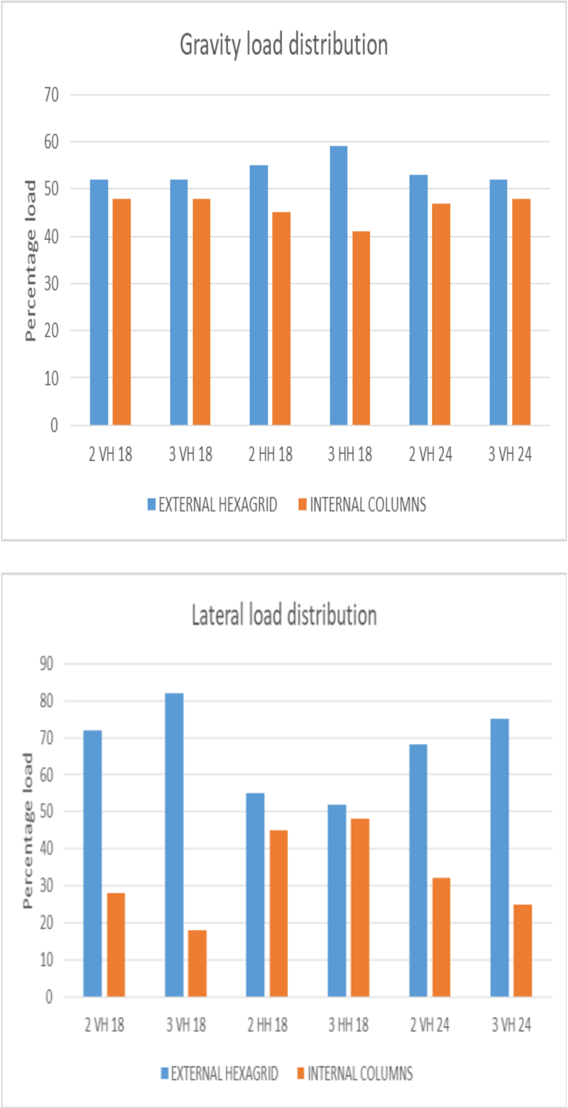


Figure 5: Gravity and lateral load distribution

Almost 70-80 % of lateral load are resisted by external hexagrid system, for vertical hexagrids. Also with increase in module size, more lateral loads are resisted in case of vertical hexagrids. For horizontal hexagrids, lateral loads are resisted almost equally among internal core and external hexagrid system.

2. Storey displacement

As module size increases displacement of vertical as well as horizontal hexagrids decreases, but the displacement values for horizontal hexagrids are much higher than vertical hexagrids. The obtained values of displacements are almost twice as that of vertical hexagrids. So it is preferable to have vertical hexagrids with larger module size.

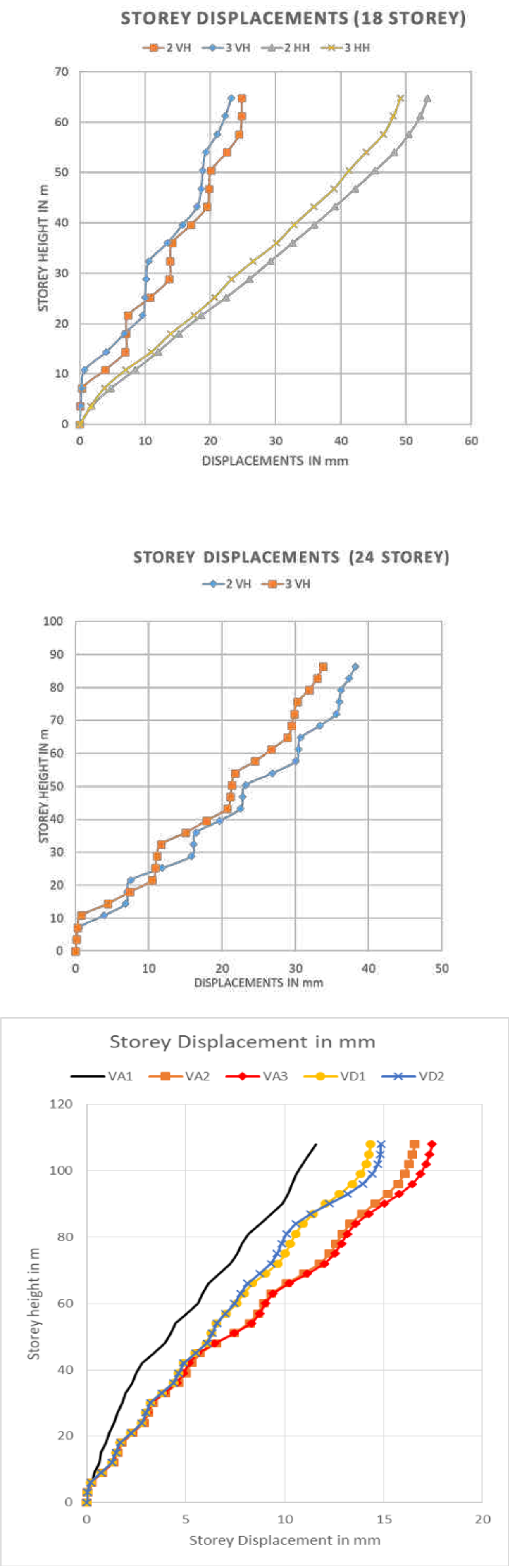


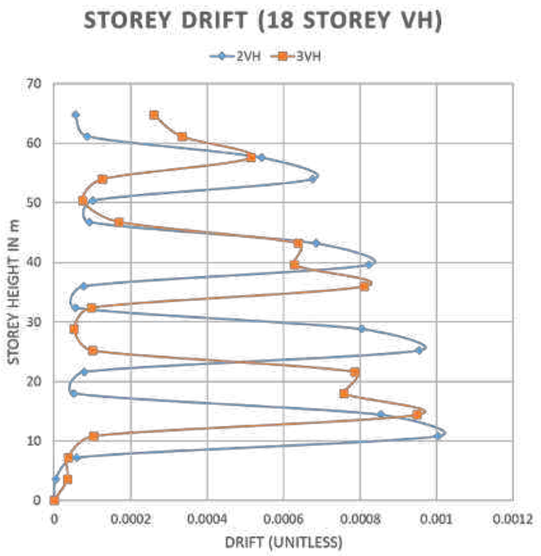
Figure 6: Storey displacements

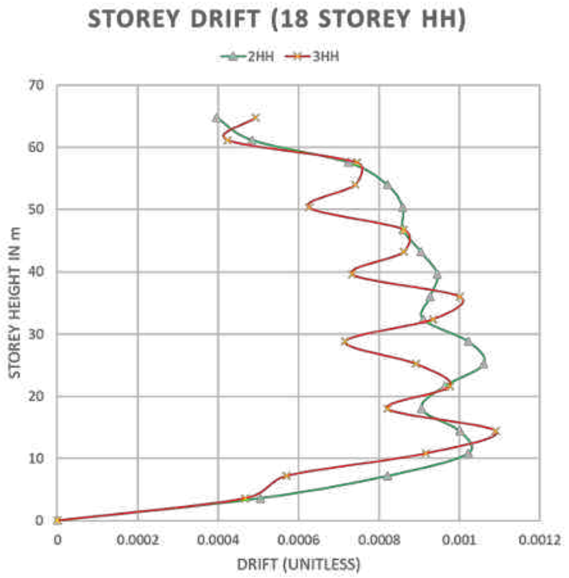
The graphical representation of displacement at each storey level is shown in Fig 6. As per IS: 1893 (Part 1) -2016, the maximum allowable displacement is given by H/500, where H is the overall height of the structure. All the displacement values are found to be well within the permissible limits.

The variable density approach is showing less displacements when compared to other approach. The VA1 model is showing the least displacements because of its less inclined diagonal members. Thus gradually increasing the diagonal angles causes an increase in the displacement values. Even though there is significant reduction in materials provided in variable density models, the displacement values are found to be much less, making it efficient than variable angle hexagrids.

3. Storey drifts

The storey drift patterns of the hexagrid building seems to be undulating. This is because the shear force resisting capacity of each floor is varying largely. The drift is caused due to the shearing force occurring at each storey level. The drift values reduces with the increase in height of the building. With increase in module size the drift values of vertical hexagrids are decreasing.





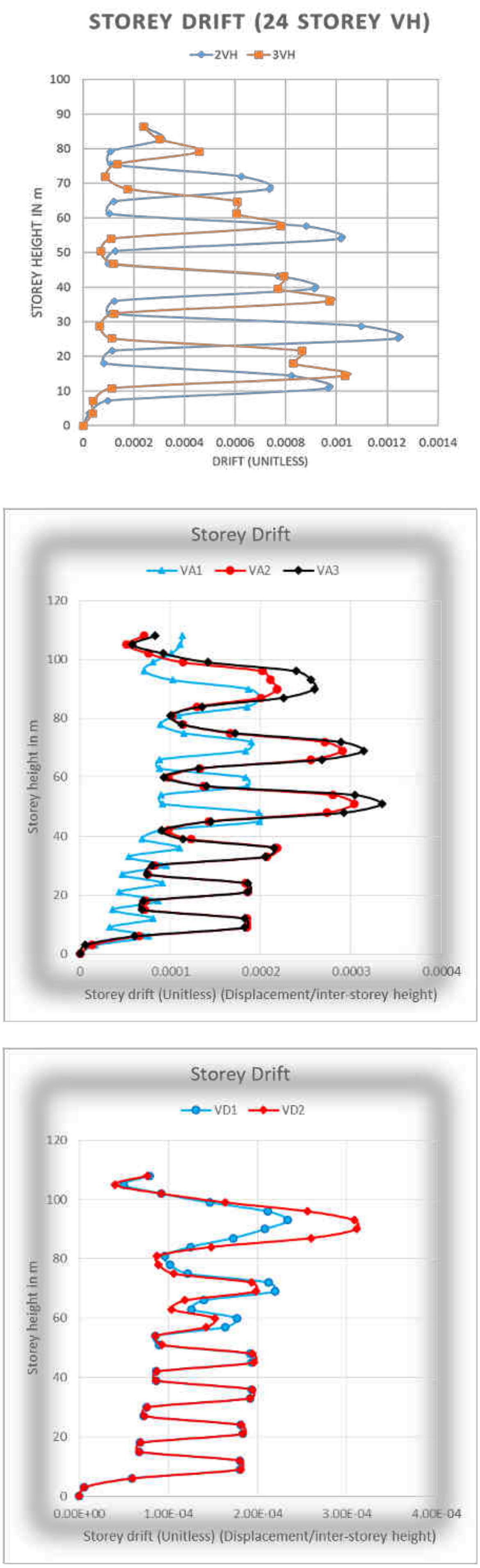


Figure 7: Storey drift values

As per IS 1893 (Part 1) 2016, the storey drift shall be less than 0.004 times the height of the storey. Thus the maximum permissible value of drift = 0.004 x 3m = 0.012m. The drift values obtained from the analysis of all models are well within this limit. Because of the truss (axial) action of the hexagrid, the net shear force and bending moment occurring in the members will be reduced and causes less value of drift.

The VA1 is showing a similar trend in the drift pattern as in the case of displacement. The less inclined diagonal members are causing less displacements thereby causes low drift values. As a result of the structural geometry provided to VD2 model there is a sudden increase in the drift value at certain locations. Whereas the VD1 model shows no such sudden increase or impact, making it more efficient among the other models.

4. Time Period

In vertical and horizontal hexagrids as the size of the module increases the time period of the building decreases. But horizontal hexagrids are exhibiting very high time period values, when compared with vertical hexagrids.

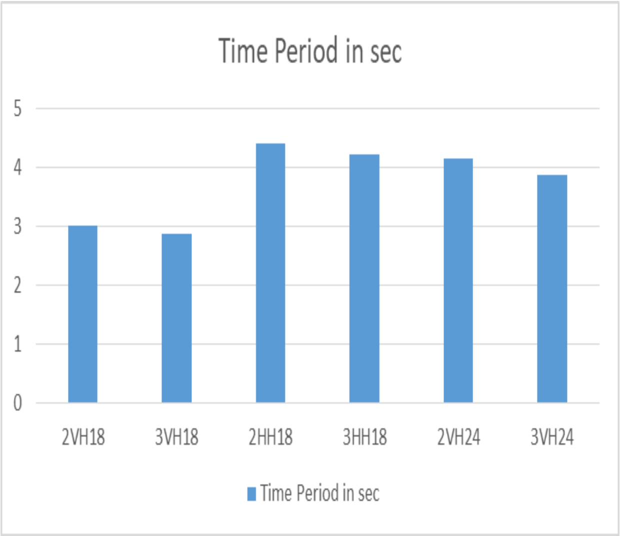


Figure 8: Time period of all models

Considering the efficiency of vertical hexagrids over horizontal ones, the further study is restricted to only vertical hexagrids.

B. Non-linear time history analysis:

The seismic data of seven previous earthquakes were used as the ground motion, namely Kobe, El Centro, Bhuj, Trinidad, Northridge, Landers and Friuli earthquakes on the models with parameter VA and VD.

The behaviour of a model under time history analysis, depends heavily on the type of ground motion used. As a result, different ground motion data tends to give different results from which a final conclusion cannot be obtained. So, the mean performance under all seven ground motions will be used as the criterion for arriving conclusions. The mean values of Base shear and Maximum displacement from the analysis of all seven ground motion data are as shown in Fig 8.

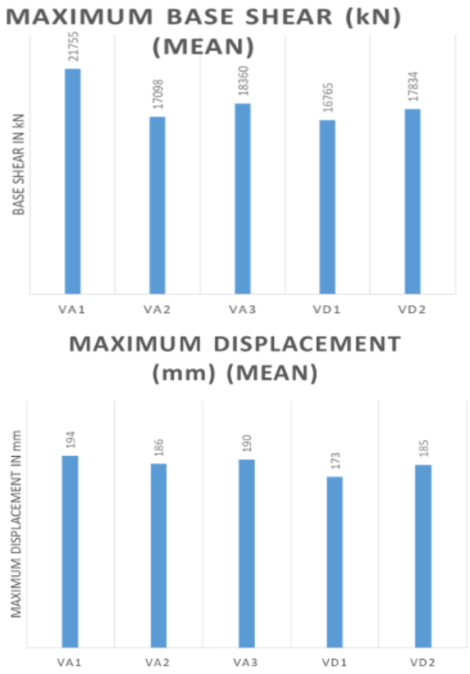
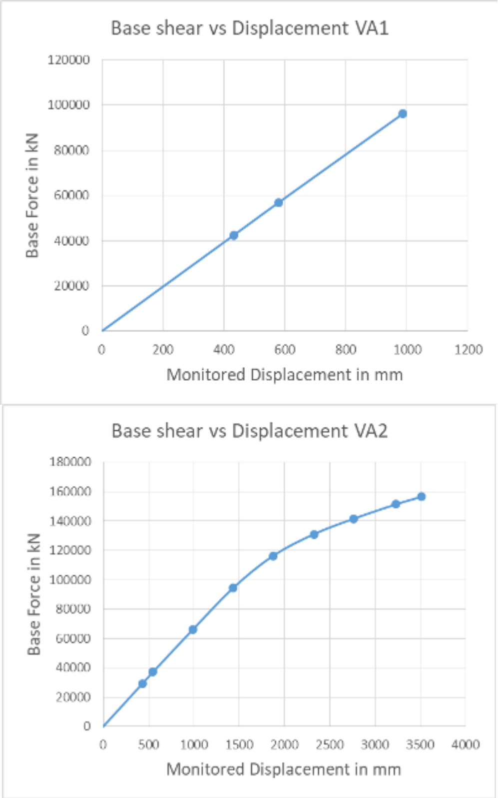


Figure 8: Results of time history analysis

C. Non Linear Pushover Analysis:

Displacement controlled non-linear pushover analysis is conducted on the building. The displacement v/s base shear graph for all models is shown in Fig 9. From the graph maximum base shear force that can be resisted by each model and the displacement each model undergo while resisting these forces are obtained. The hexagrid buildings are very stiff, so the pushover curve show very little deviation when it moves to the plastic region. Performance point obtained by the intersection of demand curve with the capacity curve is also compared (FEMA 440 Equivalent Linearization).



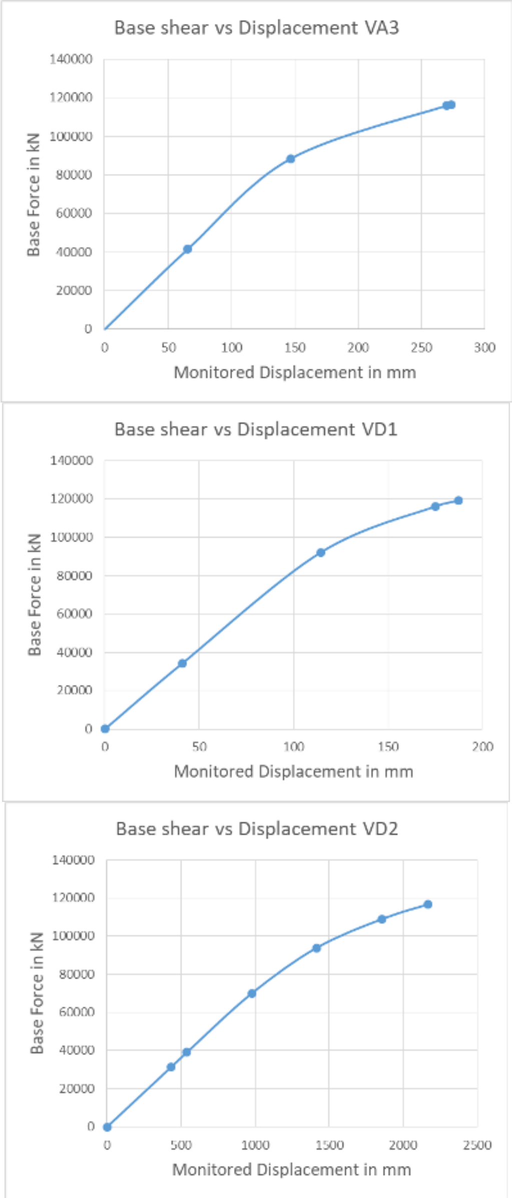


Figure 9: Base shear v/s monitored displacement

Table 2: Performance point from pushover results

Model	Performance Point	
	Base shear (kN)	Displacement (mm)
VA1	41,848	678
VA2	43,954	653
VA3	40,731	602
VD1	54,229	663
VD2	46,063	638

It is found that the pushover curve is initially linear, but it starts to deviate from linearity as the members undergo inelastic actions. The demand curve intersects the capacity curve within the elastic region for all the models. This proves that the structure has great resistance against lateral loads and has lot of reserve strength.

Among all the models, VD1 has the greatest base shear capacity. Compared to the variable angle models, variable density models are exhibiting increased capacity against lateral loads.

CONCLUSION

Hexagrid buildings provide great structural efficiency to the building and undergo very less displacement and drift. They resist the shear force and bending moment occurring in the building through axial action of its members. The gravity load is shared equally among the core and hexagrid system. And about 80% of the lateral load is resisted by the hexagrid system. The following results are obtained from the study on module size of both vertical and horizontal pattern hexagrid:

In vertical hexagrids, gravity load is distributed almost equally between external hexagrids and internal core, whereas in horizontal ones more gravity load is taken up by external hexagrids. With increase in module size in vertical hexagrids, more lateral loads are taken up by the external hexagrid. Compared to horizontal hexagrids, vertical hexagrids are undergoing less displacement and drift. Also with increase in module size, the displacement and drift values are decreasing.

In vertical and horizontal hexagrids the time period of the building decreases with increase in module size. But horizontal hexagrids are showing higher values of time period for same storey height and module size. From this analysis it is found that vertical hexagrids with increased module size showed better performance, i.e. 3 module vertical hexagrid.

From equivalent static analysis, variable density models showed lowest values of displacements and drifts among the different patterns. Variable angle models shows abrupt changes in drift and displacements, which is a drawback occurring due to sudden changes in inclination of diagonal members at certain locations. Stiffening the middle portion is found to be a better approach than stiffening the edge portions. Among the variable density models VD1 showed better results in static analysis.

From Time History Analysis**,** VD1 model is found to behave efficiently under all ground motions. The base shear experienced by members is lowered considerably in this model. This is due to the redistribution of axial forces effectively at the necessary locations. Providing higher diagonal angles for variable angle models is also found to reduce the base shear considerably. Still it has drawbacks due to sudden change in diagonal angles which causes high displacement values. The appropriate design against lateral loads is given by the VD1 model. Because of its highly stiffened middle portion, the displacements are very much reduced, which is very much required in actual ground excitations.

From Nonlinear Pushover Analysis, the performance point, where demand curve meets capacity curve, for all the models were found to be in elastic linear range. This shows that the structure has high reserve strength if plastic region is reached. The capacity of the variable angle models were found to be much lower than that of the variable density models.

After conducting the above three analysis on all the cases, VD1 models showed better performance. High lateral load resisting capacity and less deformations makes it highly efficient among the models.

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