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A Comparative Study on Seismic Performance of Hexagrid, Diagrid and Tubular Structural Systems

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Abstract

Hexagrid structural system is an innovated system with structural behavior which is similar to a tubular system. In this paper, a numerical study is conducted to estimate the seismic performance of horizontal hexagrid concerning the combined horizontal and vertical hexagrid, tubular and diagrid structural systems. First 30 and 50 story buildings are modeled using ETABS, then pushover and nonlinear dynamic analyses are performed on buildings using PERFORM 3D. Results indicate that the horizontal hexagrid system under nonlinear dynamic analysis has the least roof displacement; buildings capacity curves also demonstrate that the horizontal hexagrid is the most efficient system, as it brings lowest roof displacement along with high energy dissipation.

Keywords High-rise Building, Lateral Resisting System, Hexagrid System, Nonlinear Static and Dynamic Analysis, Seismic Performance

1. Introduce

The functional and aesthetic requirements for tall buildings are the main purposes for development of the structural systems for these types of buildings. Structural systems for tall buildings have undergone dramatic changes since the demise of the conventional rigid frames in the 1960s as the predominated type of structural system for steel or concrete tall buildings. With the emergence of the tubular forms steel conforming to the International Style, such changes in the structural form and organization of tall buildings were necessitated by the emerging architectural trends in design in conjunction with the economic demands [1]. Early designs of tall buildings recognized the effectiveness of diagonal bracing members in resisting lateral forces [2]. The purpose of this paper is to investigate their apparent superior structural efficiency with respect to performance and behavior as seismic force-resisting systems in high seismic regions. Under moderate to extreme earthquake ground shaking demands, typical seismic force-resisting systems must provide sufficient ductility and energy dissipation characteristics to provide life safety against collapse while undergoing inelastic frame deformations.

Tube structures represented a dramatic change in the design of steel-framed buildings to enable them remain strong enough to resist the lateral forces of wind and earthquake acting on the building, which used load bearing exterior or perimeter walls to support these forces [3]. Other types of tube constructions such as grid structures (i.e., diagrid and hexagrid systems), are inspired by this type of arranging bearing elements.

The aim of this study is to compare seismic performance of hexagrid structural system with diagrid and tube systems. To this end, eight 3-D buildings have been modeled using four structural systems of horizontal hexagrid, combined horizontal and vertical hexagrid, diagrid and tubular systems. Each structure was modeled in a 50 story and a 30 story building to derive more accurate results depending on the height to plan dimensions. First, the capacity of eight models have been compared through nonlinear static pushover analyses, then the roof displacement of each model have been studied under near fault ground acceleration in PERFORM-3D software [4].

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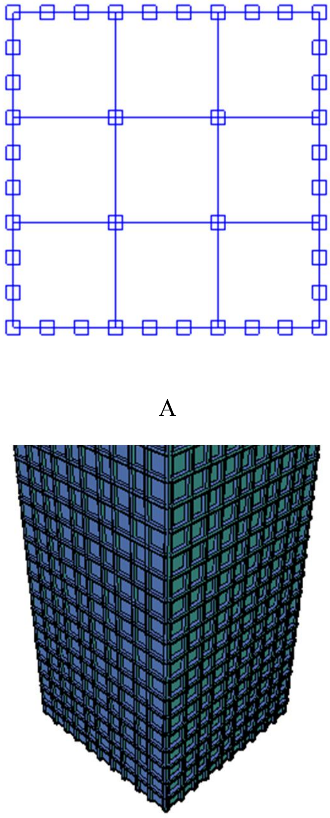
2. Framed Tube

Framed tube is a system where in perimeter beams and columns are designed in order to resist lateral loads. Buildings with this kind of structural system are designed to act like a hollow cantilevered box perpendicular to ground. This system was first introduced by Fazlur Rahman Khan [5]. The first example of tube is 43-story Dewitt-chestnut apartment building in Chicago [6]. The primary characteristic of a tube is the employment of closely spaced columns interconnected by deep spandrels so that the whole building works as a huge vertical cantilever. The efficiency of this system is derived from the great number of rigid joints acting along the periphery of the building. Lateral loading is carried by the exterior tube, while the gravity loading is shared between the tube and the interior columns [7]. An apparent problem in this type of structural system is the closely located columns which impede the interior view of the building. A schematic plan and perspective of this system is shown in Figure 1.



A

B

Figure 1 framed tube structure A. plan B. 3D view

The floor system, considered as a rigid diaphragm, distributes the loads to various elements according to their stiffness. In tube structures, typically, the strong bending direction of columns is aligned along the face of the building to benefit the most from their individual bending action. The frames parallel to the lateral load act as web of the perforated tube, while the frames normal to the loads act as flanges. Although the structure has a tube like form, its behavior is much more complex than that of a solid tube; unlike a solid tube it is subjected to shear lag effects [8]. The influence of shear lag is to increase axial stresses in the corner columns and reduce the same in the inner columns of both the flange and the web panels as shown in Figure 2.

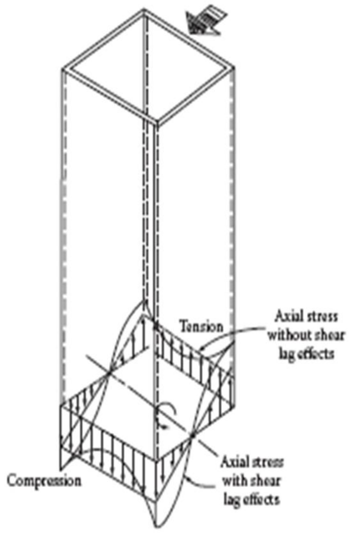


Figure 2 influence of shear lag on tube behavior [8]

Any other developments in tube-like systems have attempted to decrease the shear lag effect and, therefore, increase the structural efficiency.

3. Diagrid

In recent years, new and emerging architectural building designs have been put forward geometrical and structural system frame definitions consisting of triangulated sloped column and spandrel beam frame configurations called “diagrids” shown in Figure 3. These triangulated diagrid frames are most often placed on the building perimeter creating efficient structural systems in resisting both gravity and lateral loads [9]. In the typical triangulated configuration of the steel diagrid framed system, both gravity and lateral loads are distributed in the sloped column and spandrel beam elements primarily in axial compression and tension [9].

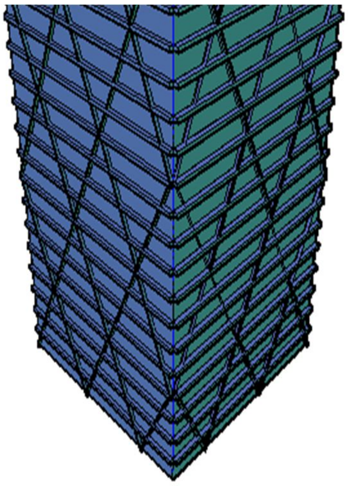


Figure 3 3D view of diagrid structural system

The difference between conventional exterior-braced frame structures and the current diagrid structures is that for diagrid structures, almost all the conventional vertical columns are eliminated. Because of the diagonal members in the diagrid structural systems, it is possible to carry gravity loads as well as lateral forces owing to their triangulated configuration. The configuration and efficiency of a diagrid system reduce the number of structural elements required on the façade of the building, therefore allowing significant flexibility with the floor plan. Perimeter diagrid system saves approximately 20 percent structural steel weight compared to a conventional moment-frame structure [10].

4. Hexagrid

Another new system invented by Nejad and Kim [2] is Beehive or Hexagrid system for tall buildings. This system, very similar with diagrid system, which is configured by locating hexagons along the exterior perimeter surface of the building in order to maximize the structural effectiveness, as well as the aesthetic appearance. Therefore, this system acts like a tube. According to the loading direction, the planes of the building act like the flange or web of the building. The hexagrid system offers several advantages in addition to eliminating perimeter columns. Most notably, it optimizes each structural element. Typically, columns are used to provide vertical load carrying capacity, and diagonals are participating in the vertical load transfer, and the lateral load under ideal assumption in a typical high-rise [2]. In a hexagrid system the two functions are working together, diagonal members of hexagons carry both gravity and lateral loads and they act like a sloped column. Thus, the need of exterior columns in this system has been eliminated. The corner columns also can be eliminated in case of architecture demand.

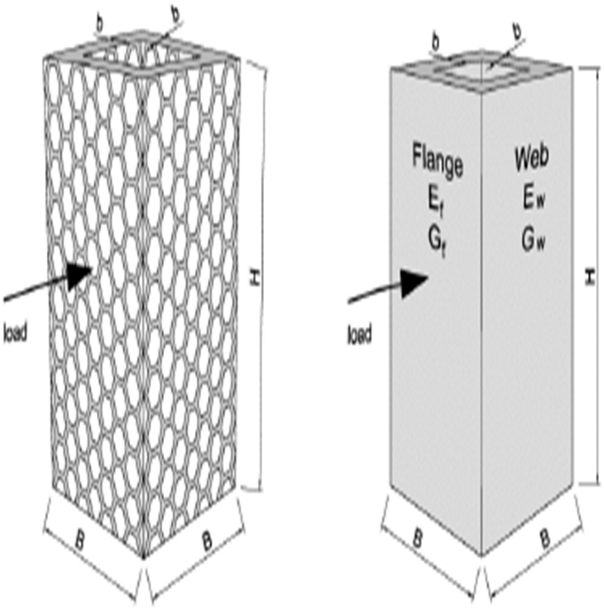


Figure 4 tube performance of hexagrid structure A.horizontal hexagrid B.equivalent solid

Hexagons can arrange in either vertical or horizontal directions and make vertical or horizontal grids respectively. Previous studies, [2,11], have examined seismic performance of vertical hexagrid. In this study, seismic performance of horizontal hexagrid and combined horizontal and vertical hexagrid has investigated. A schematic view of horizontal and vertical hexagrid is illustrated in Figure 5.

In this study, the behavior of horizontal hexagrid, combined horizontal, and vertical hexagrid are investigated and compared to framed tube and diagrid structural systems. In the combined horizontal and vertical hexagrid models, the horizontal hexagons transformed to vertical ones through a transitional story in the middle height of the building.

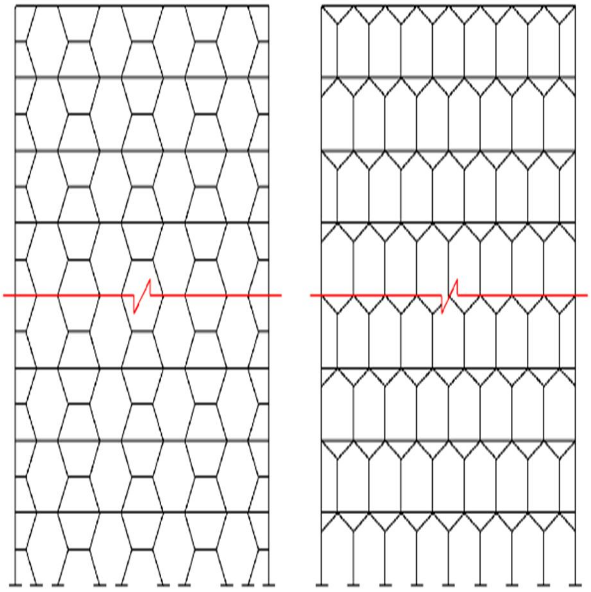


Figure 5 hexagrid structure A. horizontal hexagrid B. Vertical hexagrid

5. The numerical analysis method

In the present study, computer models with 30 story and 50 story height with the tube framed system, diagrid, horizontal hexagrid, and combined horizontal and vertical hexagrid are investigated. Typical plan of models and elevation of each system is shown in Figure 6 and 7 respectively. The diagrid is composed of sloping columns modularized for every two stories. To compare the seismic performance of computer models, the model structures is designed for similar loads. Structures is designed with the dead and live loads of 7.75 KN/m2 and 2 KN/m2 respectively. The perimeter beams, Hexagrid and diagrid elements are designed with box hollow sections. The floor slabs are considered as rigid diaphragms. The internal beams of all models are designed with IPE sections in order to lower the weight of the building. In all model structures, columns, beams, and grid members are made of ST37 (Fy= 2400 Kg/cm2) steel. Table 1 depicts the geometrical properties of studied models.

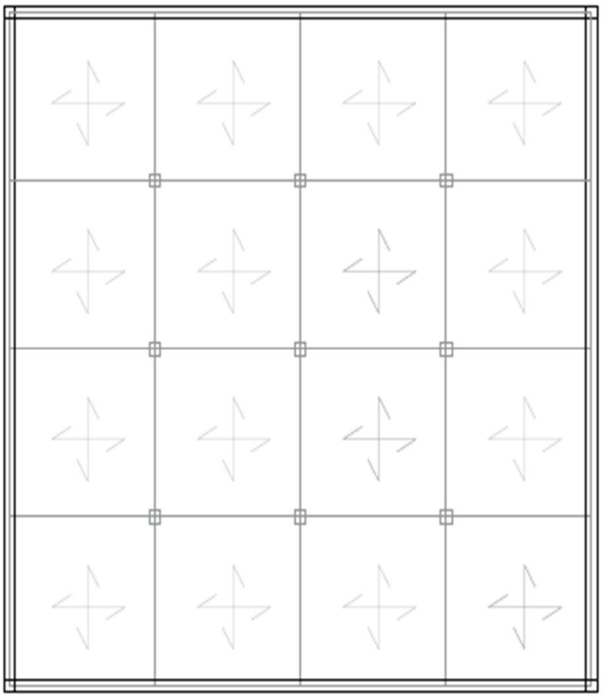


Figure 6 typical plan for models

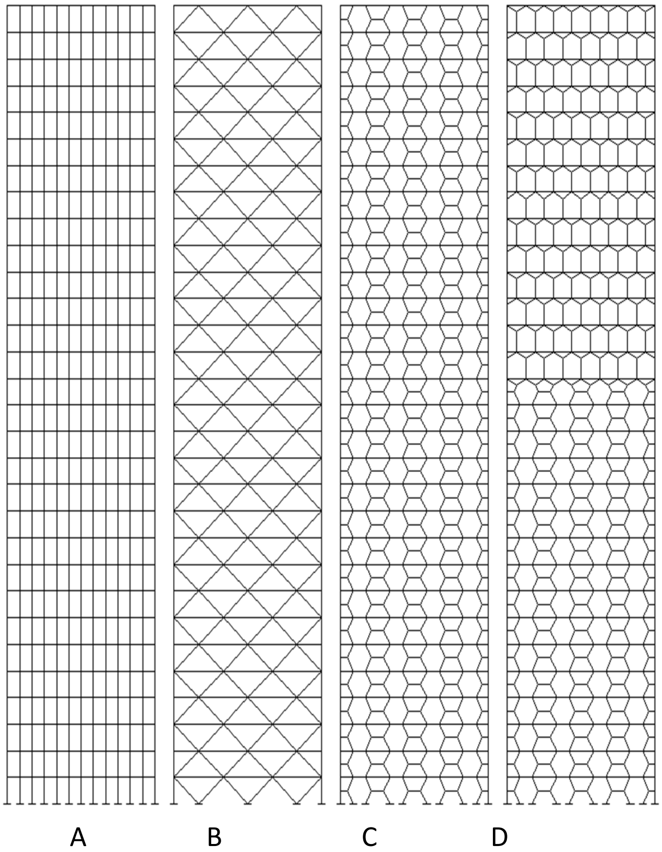


Figure 7 2D elevation of each structural system A. framed tube B. diagrid C. horizontal hexagrid D.combined horizontal and vertical hexagrid

Table 1 geomtrical properties of studied models

Story height (m)	Gravity bearing span length (m)		Number of gravity span in each direction
3.464	6		4
Number of lateral span in each direction			
Framed tube system	Diagrid system	Horizontal hexagrid system	Combined horizontal and vertical hexagrid
12	4	4	4

Table 2 seismic parameters considered in the design process

Structural system	tube	diagrid	Horizontal-hexa	Combined-hexa
Response modification factor (R)	7.5	5	6	6
Over strength factor (Ω)	2.5	3	2.5	2.5

Table 3 fundamental period of model buildings

Structural system	tube		Diagrid		Horizontal-Hexa		Combined Hexa	
No. of story	30	50	30	50	30	50	30	50
Period (s)	4.99	6.63	2.45	4.12	3.85	5.01	5.01	4.57

The buildings are assumed to be located at high seismic zone hazard and soil type II, having zone factor of 0.35. The importance factor of 1 is assumed for buildings. The models are designed according to Iran's 2800 seismic provisions [12]. The design seismic load was computed based on the parameters mentioned in Table 2. Structural member design is performed using ETABS program [13]. The force-deformation relationship of typical column element modeling is shown in Figure 9 for both axial stress-strain and flexural moment relationships. Beam and diagonal members' connections in diagrid models are assumed as hinge connections. In the framed tube models, internal beams have simple connection to the external columns and perimeter beams have been rigidly connected to the columns. In the hexagrid structural system, the grids elements had rigid connection to each other and simple connection to the perimeter beams. Fundamental period of each model is mentioned in Table 3.

6. Verification

To ensure the validity of the modeling process, verification has been done. To this end, a 30 story building with the horizontal hexagrid structural system is modeled and results (including steel weight, maximum roof displacement and shear mode displacement) are compared to the ones obtained in the reference no. 10. The geometric properties of the studied model is represented in Table 4. Plan and elevation view of the building are demonstrated in figure 8.

Table 4 Geometric parameters for model structure [11]

description	value
Story height	4 m typical
Width	28 m
Beam span	7 m typical
Beam spacing	3.5 m typical
Floor live load	500 Kg/m2
Floor dead load	600 Kg/m2

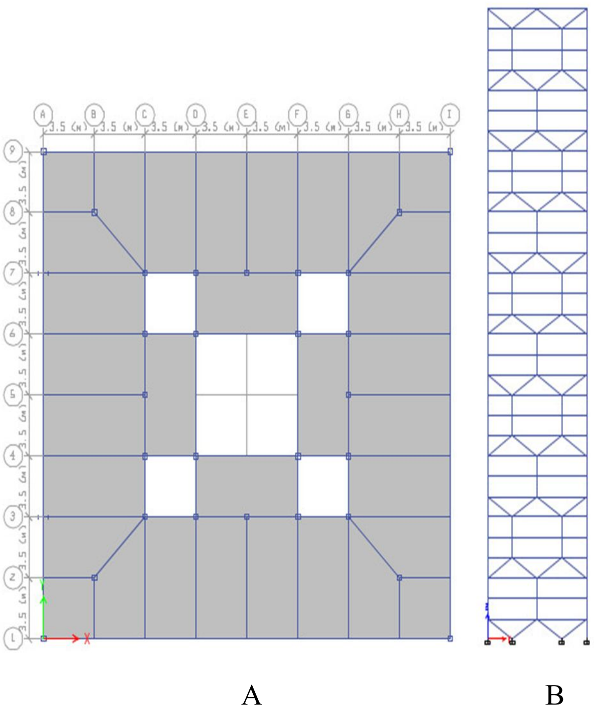


Figure 8 Reference model A. plan B.Elevation

Table 5 verification results

	Reference article	Studied model	Discrepancy (%)
Steel weight (ton)	4593.1	4433.43	3.47
Maximum roof displacement (m)	0.25	0.26	4
Shear mode of displacement (m)	0.2	0.2003	1

Results obtained from the verified model are represented in Table 5. As it can be inferred from Table 5, results have an acceptable dispersion from the ones obtained in the reference article.

7. Pushover analysis

For nonlinear analysis of bending members, force-deformation curve provided in FEMA-356 [14] was used as shown in Figure 9 (A). The parameters a, b, and c vary depending on the width-thickness ratio of the structural members, and are determined based on the guidelines provided in the Tables 5-6 and 5-7 of the FEMA-356 [14]. The post-yield stiffness of 3% was generally used for modeling of bending members. For nonlinear analysis of bracing members, the generalized load-deformation curves recommended in the FEMA-274 [14] and shown in Figure 9 (B) were used.

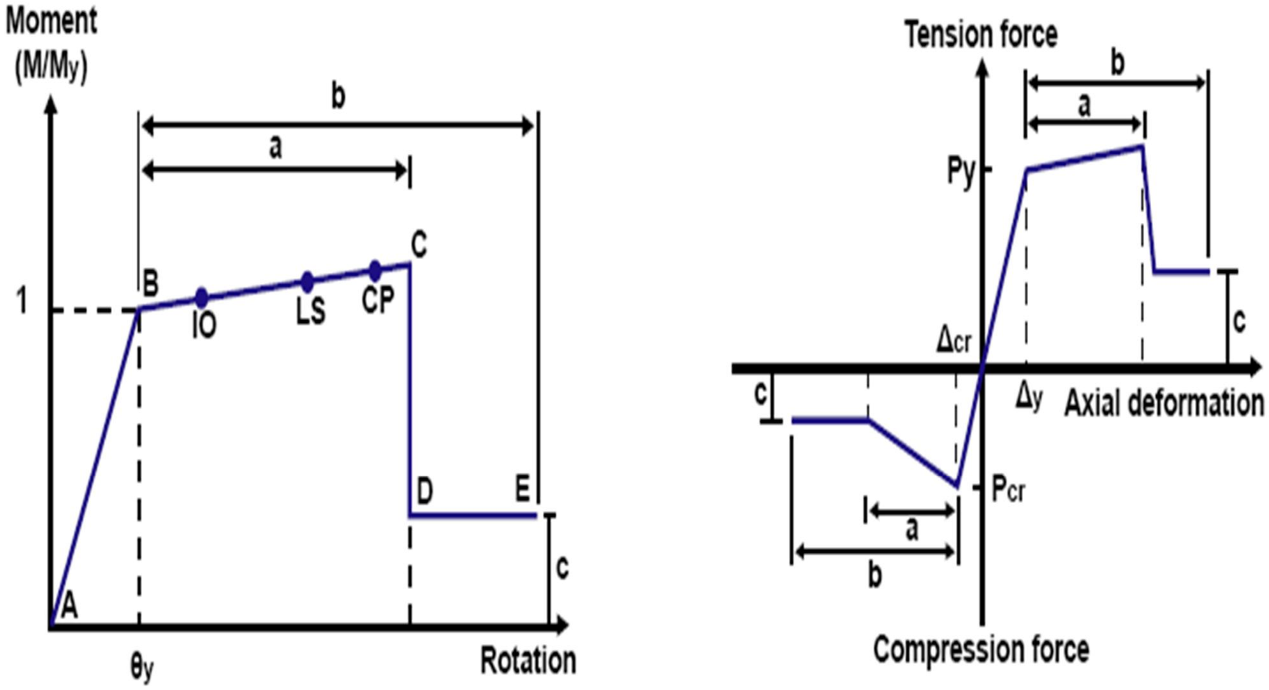


Figure 9 nonlinear force-deformation relationships for structural members [15]

8. Nonlinear dynamic analysis

Nonlinear response is evaluated for a near fault ground motion record. This ground motion scaled based on the ground motion scaling requirements of Iran's 2800 seismic provisions [12]. Table 6, represents the properties of the ground motion record used for nonlinear dynamic analyses. Figure 10, depicts the pseudo acceleration response spectrum of this ground motion record. The directivity of rupture has played a great role in the ground motions. Rupture began at the depth of 19Km below the surface and propagated up dip toward the north on a plane dipping at about 42 degree from the horizontal. The rupture plan has a length along strike about 18Km and up deep bottom (South-West) and top (North-East) edges of the rupture are 20Km and 6Km respectively, with most of the rupture confined to depth of 12Km or more [16]. The normalization factors used to scaling the ground motion record for each model structure, are noted in Table 7.

Table 6 properties of earthquake record used for nonlinear dynamic analysis

Earthquake	Date	Station	Magnitude	Distance from fault	PGA (g)
Northridge	1994	LADam	6.69	5.92	0.427

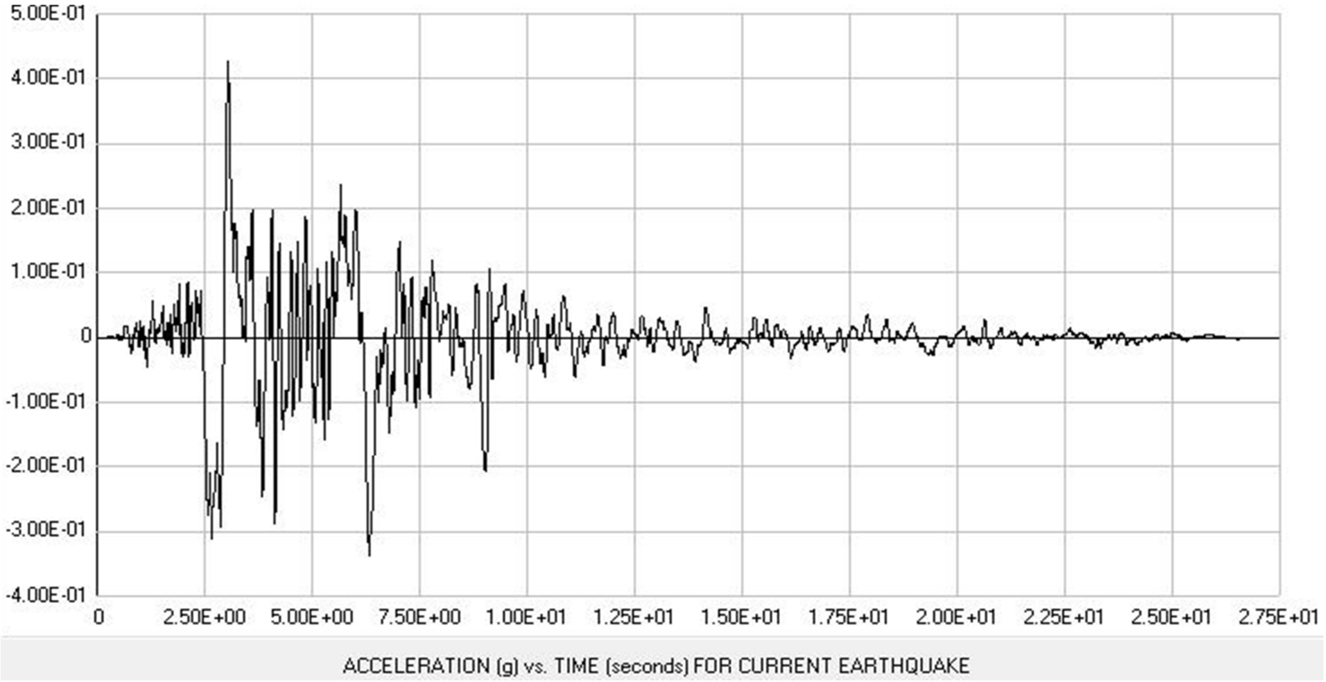


Figure 10 pseudo acceleration response spectrum of the selected ground motion record

Table 7 scale factors used for scaling the ground motions

Structural system	tube		Diagrid		Horizontal-Hexa		Combined Hexa	
No. of story	30	50	30	50	30	50	30	50
Normalization factor	0.933	1	0.868	0.9	0.893	0.945	0.945	0.921

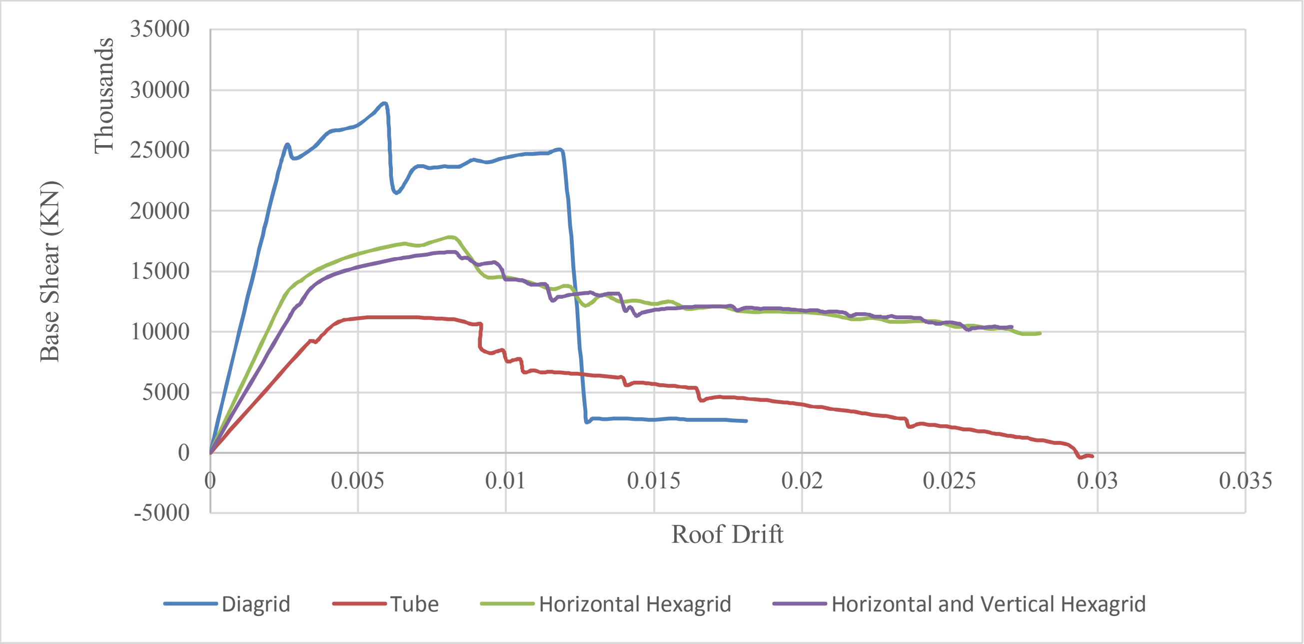


Figure 11 capacity curves for the 30 story height structures

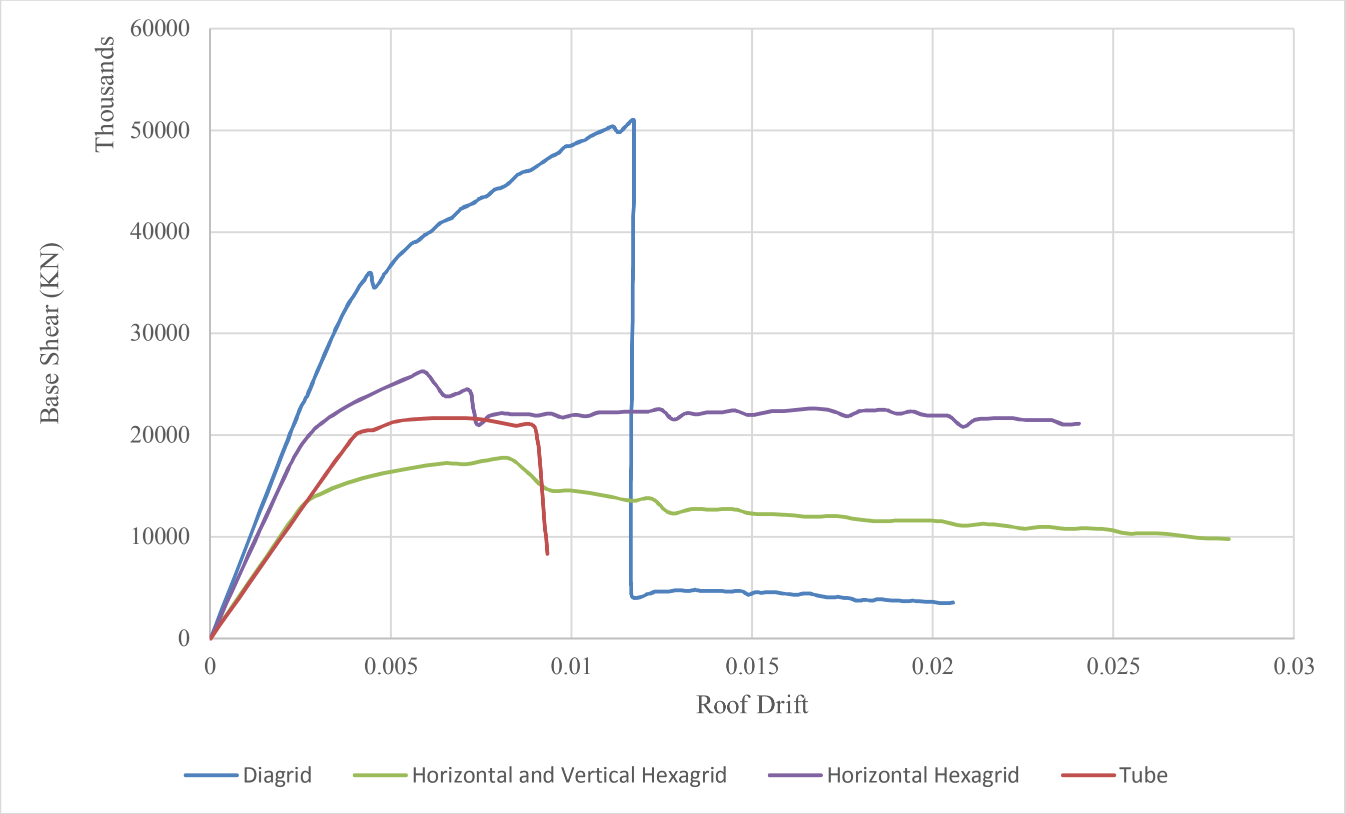


Figure 12 capacity curves for the 50 story height structures

9. Results

In this section, numerical results from the nonlinear static and dynamic analyses were investigated. Figure *11* and Figure 12 depict capacity curves for 30 and 50 story height structures respectively. According to the capacity curves illustrated in Figures 11 and 12, the diagrid system has the most stiffness, which is about 3 times greater than the stiffness of the tube system for 30 story models. Horizontal hexagrid system and combined hexagrid system, have a median stiffness between tube and diagrid structural systems. The progress of the capacity curve of the combined horizontal and vertical hexagrid structural system in the horizontal line depicts the high ductility of this structural system, which has a positive effect on the energy absorption of the building. The framed tube system represented large permanent displacement after earthquake, which means that in this system, the structural elements specially columns undergone major nonlinearity. However, for the other structures in this study, the permanent displacements of the structural elements are neglected. Figure 13 and Figure 14 show roof displacement of the studied models under nonlinear dynamic analyses for 30 and 50 story height structures, respectively. The largest roof displacement in each model is represented in Table 8 in order to make better comparison.

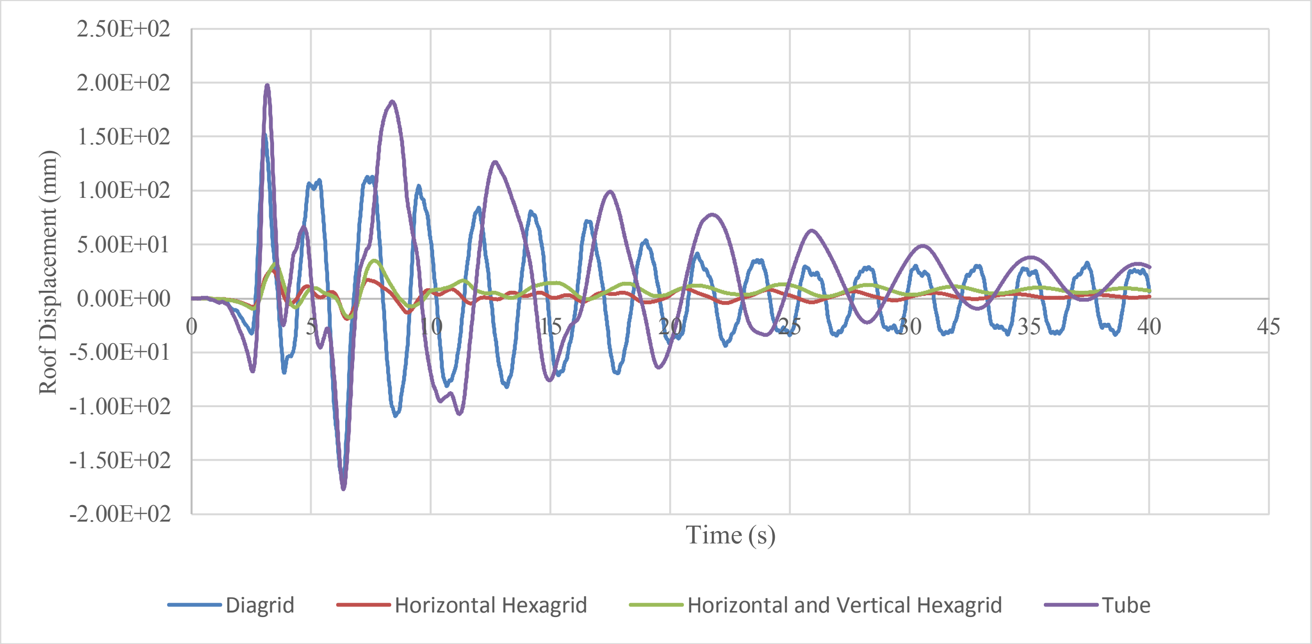


Figure 13 Rood displacement of studied models under nonlinear dynamic analysis for 30 story height structures

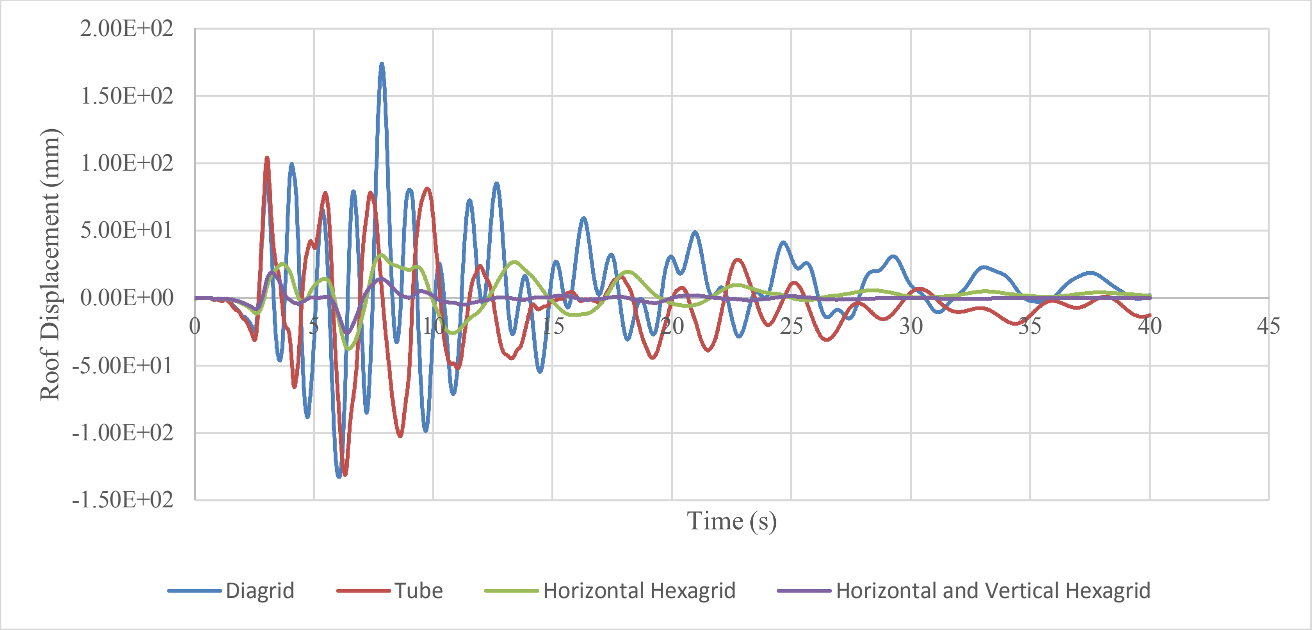


Figure 14 Rood displacement of studied models under nonlinear dynamic analysis for 50 story height structures

Table 8 maximum roof displacement of studied models under the given earthquake

Structural system	Tube		Diagrid		Horizontal Hexa		Combined Hexa	
No. of stories	30	50	30	50	30	50	30	50
Max roof disp (mm)	198.18	104.60	152.60	174.32	26.4	32.2	35.26	19.2

As can be inferred from Table 8, for 30 story buildings, the tube system represents the largest roof displacement, about 7 times more than the maximum roof drift of the horizontal hexagrid structural system which has the least roof displacement in 30 story buildings. For 50 story buildings, the diagrid structural system shows the largest roof drift, about 9 times greater than the maximum roof drift of the combined hexagrid which has the least roof displacement among 50 story buildings subjected to study.

10. Conclusions

Results obtained from the nonlinear dynamic analyses, demonstrated that using the hexagrid structural system, whether horizontal one or combined, the roof displacement of the building will decrease in comparison to tube and diagrid structures. Using the horizontal hexagrid system, the lateral roof displacement decreases about 7 times in comparison to the tube system, and 5 times in comparison to the diagrid structural system in a 30 story building. Moreover, by increasing the height of the models from 30 stories to 50 stories, the combined horizontal and the vertical hexagrid showed lower responses, and maximum roof displacement of the model used the combined horizontal and vertical hexagrid, was about 1.5 times less than the horizontal hexagrid system, for the 50 story models. Therefore, the hexagrid structural system leads to less lateral displacement compared to the tube and diagrid systems.

Due to the appropriate performance of the combined horizontal and vertical hexagrid system and its favorable energy dissipation according to capacity curves, it is suggested that the optimal location of the transitional story, which transforms horizontal grids to vertical ones, will be investigated and seismic performance of this type of hexagrid (with optimal location of the transitional zone) will be compared with other types of common structures for tall buildings.

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