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Seismic assessment of nature-inspired hexagrid lateral load-resisting system

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Abstract: This paper provides a general perspective of the seismic performance of a nature-inspired, honey-comb grid structural system, known as a hexagrid, under near-field ground motions. Seismic performance of this skeleton is then compared to that of a bundled-tube, as a conventional and efficient load-resisting system in order to provide a better perception of the seismic behavior of a hexagrid skeleton. Two 20-story buildings with bundled-tube and hexagrid skeleton were studied. Nonlinear behavior of the structures was investigated through 3-D finite element computer models and nonlinear time history analyses by subjecting the models to seven three-component records of scaled near-field ground motions. Distribution of peak inter story drift and corner beam-column joint rotations were calculated and compared. Results indicated that by replacing the exterior columns of the bundled-tube system with inclined beam-column elements of nature-inspired hexagons, lateral stiffness of the building increased and it would tolerate less deformations before global dynamic instability is reached. The presence of inclined columns in the hexagrid skeleton helped to concentrate local nonlinearities in ring beams rather than exterior columns.

Keywords: high-rise steel structure; hexagrid structure; performance assessment; nonlinear seismic analysis

1 Introduction

The structural design of tall buildings in such a way that eliminates façade columns and combines the gravity and lateral load carrying systems has been given significant attention in recent years (Asadi and Adeli, 2018; Lee and Kim, 2017; Mashhadiali and Kheyroddin, 2013). Traditionally, moment frames, outriggers and tube-type systems are utilized as load carrying systems in tall buildings (Elnashai and Di Sarno, 2008; Mele *et al*., 2004). The main obstacle in implementing a moment frame system is the closely spaced columns at the perimeter of the building. In order to achieve more efficient structural systems, tube-type structures are introduced. Locating the major part of the lateral load resisting elements at the farthest distance from the center of the building, is the main idea in constructing tube-type systems. Framed-tube, braced-tube and bundled-tube systems are the main systems of tube-type structural systems (Kwan, 1994; Stafford and Coull, 1991; Parker and Wood, 2013). Bundled-tube systems are used in buildings that are wide in plan to increase the tube action efficiency. As the plan dimensions increase, the framed-tube system becomes less efficient. The bundled-tube system implements the idea of a cluster of tubes, thus this structural system is the preferred choice in cases where the building is wide in plan or has irregularities in height (Gunel and Ilgin, 2007). Grid structures are another class of tube-type structures, which eliminate façade columns. The two best known types of this class of structural systems are diagrid and hexagrid. Diagrid and hexagrid structures can carry both gravity and lateral loads by means of their inclined members, thus the need of implementing columns in the perimeter of the structures is eliminated by using these grid patterns instead. The triangular grid of a diagrid structure is an axial force-dominated structure, whereas hexagrids are bending-dominated structural patterns. Hexagonal cell structures form a large number of natural structures such as balsa, cork and beehives. Numerous studies have been done which indicate the benefits of hexagonal structures and make them an efficient system for man-made composites, materials and also on a large scale, as a load resisting skeleton (Montuori *et al*., 2015). Moreover, recent trends for structural design are toward bio-inspired forms, where the structural elements of a skeleton help the natural flow of forces. Several studies have been done in the field of nature-inspired load resisting systems for both regular patterns (Epstein and Adeeb, 2008) or irregular ones (Melle *et al*., 2016). The structural elements of a regular horizontal hexagrid skeleton, which is the subject of this study, are shown in Fig. 1.

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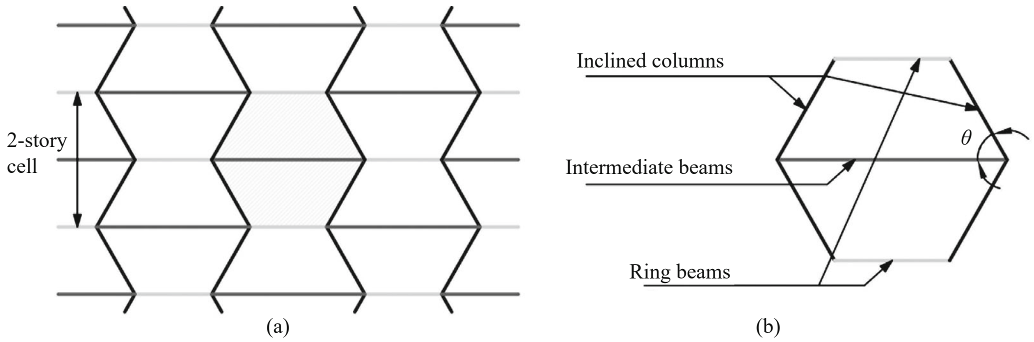

Fig. 1 Main structural elements of a hexagrid and its hexagonal cell

According to Fig. 1, members of a hexagrid skeleton are as follows: inclined columns, intermediate beams and ring beams. The angle of inclined columns depends on different parameters such as acting loads, which are discussed in previous studies (Montuori *et al*., 2015). The height of hexagonal cells is another variable which is selected based on design priorities. Figure 1 depicts a two-story height hexagonal cell.

A simple and well-known idea for the preliminary design stage of a tall building, is considering the whole structure as a cantilever beam. Baker (2013) formulated total actions on a tall building, simplified as a cantilever beam, as a combination of bending and shear deformations, which is given in Eq. (1).

$$\delta_{\text{tot}} = \delta_{\text{bending}} + \delta_{\text{shearing}} = \frac{q \cdot H^4}{8 \cdot EI} + \frac{q \cdot H^2}{2 \cdot GA} \cdot \chi \qquad (1)$$

where H is the building height (or the beam height), and A and I are the area and moment of inertia of the building cross section, respectively. E and G are the axial and shear moduli, respectively. χ refers to the shear modification factor. For the grid structures, in order to maintain the basic idea of equivalent cantilever beam, and to account for the discrete nature of structural grids acting as flanges and webs of the equivalent beam, EI and GA could be replaced by $(EI)_{\text{grid}}$ and $(GA)_{\text{grid}}$, respectively. This methodology that deals with frame tube panels as equivalent orthotropic membranes, was first proposed by Kwan (1994) and simplified the analysis procedure of a framed tube system as a continuous structure, as follows:

$$\delta_{\text{tot}} = \delta_{\text{bending}} + \delta_{\text{shearing}} = \frac{q \cdot H^4}{8 \cdot (EI)_{\text{grid}}} + \frac{q \cdot H^2}{2 \cdot (GA)_{\text{grid}}} \cdot \chi \qquad (2)$$

where the grid pattern can be a rectangle, as in a bundled-tube skeleton or a hexagonal pattern as in a hexagrid structure.

Tianjin International Plaza (Sinosteel Plaza) is the first project where a hexagrid skeleton is used as the lateral load resisting system in a high-rise building (Fu *et al*., 2012). Connection of hexagonal cells in this project is considered as rigid connections to ensure the structure stability. Stiffness of the hexagrid structure under vertical and horizontal loading conditions was also studied by Fu *et al*. (2012). While a hexagrid structure shows higher stiffness under lateral loading compared to other conventional lateral load resisting systems, low stiffness in the vertical direction of a hexagrid structure is attributed to the contribution of bending moment and shear force in inclined columns. Another appealing aspect of a Sinosteel structural system is the transition of external load resisting system from the hexagrid at the bottom stories, to the diagrid at the top stories by means of a transition zone which incorporates several stories. Different structural patterns used in this building are shown in Fig. 2 (Montuori *et al*., 2015).

Mashhadiali and Kheyroddin (2014) studied progressive collapse of a hexagrid skeleton and compared the resistance of this skeleton towards progressive collapse with diagrid structures by examining local failure of their structural elements. They found that a hexagrid skeleton, due to its geometrical configuration, exhibits higher resistance. Montuori *et al*. (2015) evaluated mechanical properties of hexagrid structures

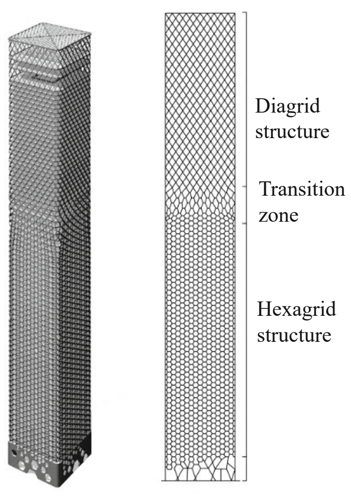

Fig. 2 Sinosteel international plaza: (a) 3-D perspective; (b) exterior load resisting systems, (Montuori *et al*., 2015)

and proposed a stiffness-based methodology for design of hexagrid structures and evaluated the application of this methodology in the design of hexagrid skeleton for tall buildings. Mele *et al*. (2016) assessed the applicability of hexagrid patterns and other non-conventional structural patterns as load resisting systems for tall buildings. Mashhadiali and Kheyroddin quantified the response modification factor of vertical patterns of a hexagrid structure (Mashhadiali and Kheyroddin, 2019). Based on their study, a response modification factor of four can satisfy the acceptance criteria of the FEMA P695 (2009) methodology. However, performance of a hexagrid skeleton under near-field ground motions has not been thoroughly studied in the literature yet. The importance of studying the nonlinear behavior of tall buildings under near-field ground motions is that these types of tremors impose large inelastic demands on structural elements in a few cycles (Kalkan and Kunnath, 2006). Hence, it is the energy dissipation mechanism of the structural system that could help buildings avoid reaching global dynamic instability under large-amplitude velocity pulses of near-field ground motions. Furthermore, tall buildings are known as long-period structures which are especially vulnerable under long-period ground motions.

From this brief review it becomes clear that nonlinear response assessment of a hexagrid skeleton under seismic excitations and how the structure would undergo dynamic instability is of a great importance. This research therefore aimed to assess the inelastic response of a hexagrid skeleton under near-field ground motions. In order to gain comprehensive knowledge about the seismic performance of this nature-inspired skeleton, the inelastic response of a bundled tube skeleton is assessed as well, and results from nonlinear analyses are compared to those of the hexagrid skeleton.

2 Numerical modeling

Hexagrid structures can be combined with a tube-type skeleton and make a hybrid skeleton which benefits from the advantages of tube-type structures and aesthetic aspects of hexagonal cells. In this study, first the bundled tube skeleton is designed. The interior load resisting system is kept the same for both bundled-tube and hexagrid skeletons. Therefore, the only difference in the studied structural systems is the arrangement of exterior load bearing elements. In this way, a comprehensive knowledge about the inherit differences between hexagrid structural system and bundled tubes, which arose from their different geometrical configurations, could be obtained. Another advantage of utilizing the same structural sections in both buildings becomes clear in studying formation of plastic hinges. Plastic hinge mechanisms provide a tangible illustration about weaknesses of different structural elements in hexagrid and bundled tube skeletons, and will be discussed later. A framework which illustrates the steps of this study is shown in Fig. 3.

The remainder of this paper is devoted to the design and analysis procedure of the structures and is organized as follows: structural configuration of each skeleton and design details are represented in Section 2.1. Nonlinear models incorporated in finite element models are discussed in the analysis method section. Information about the selected ground motions are presented in ground motion selection part. After evaluating the analyses results in the results section, final discussions and conclusions are given, different limitations which the authors encountered and their preferred solutions are discussed. Finally, ideas for extending this research and some hints are given.

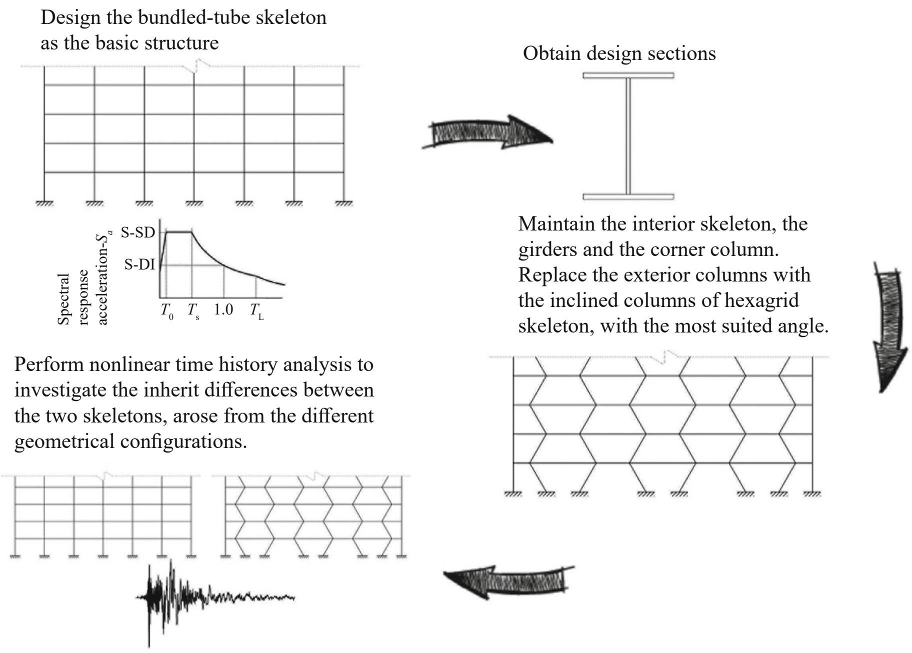

Fig. 3 Framework for assessing the inherit differences between studied skeletons

2.1 Description of structures

Two 20-story buildings are studied in this research, and typical floor plans are presented in Fig. 4. The bundled tube skeleton consists of six-bay perimeter moment-resisting frames with the span length of 6 meters in the *X* and *Y* directions. From Fig. 4, it is observed that the exterior columns of a building with a hexagrid skeleton are eliminated.

As illustrated in Fig. 1, θ is the angle of the inclined members of hexagrid skeleton with respect to azimuth and is one of the important variables in design of hexagrid structures. Different ranges are suggested for θ in the literature. Angles between 40°-50° are suggested for inclined members of vertical hexagonal cells and 50-70 for horizontal cells θ = 60° is implemented in this study in order to reach maximum efficiency of hexagonal patterns (Montuori *et al*., 2015).

Both buildings are symmetrical in plan and there are no irregularities in plan or elevation of the buildings. Simple connections are shown with dashed lines and thick lines depict moment frames. The interior structural system is the same for both models. The exterior structural configuration of each skeleton is shown in Fig. 5. Plastic hinges assigned to each component are represented in Fig. 5 as well. Detailed discussion about the concentrated plasticity is presented in following sections.

The buildings are assumed to be located on soil type II, $\overline{v}_s = 375 - 750$ m / s, ($\overline{v}_s$ denotes velocity of shear wave) with high seismicity risk according to the Iranian code of practice 2800 (2014). Structural members are designed to resist floors dead and live loads of 0.5 t/m^2 and 0.2 t/m^2, respectively. Seismic mass includes 100% of dead load, as well as 20% of live load combined. The studied structures are first modeled and designed in a finite element program (SAP 2000, 2013). For the sake of investigating the effects of hexagonal cells in seismic response of the skeletons, the interior component sections are kept the same for both models. One majority of the studied finite element models is that they are modeled as three-dimensional structures, hence the effects of wave propagation are well considered while performing nonlinear time history analyses. Furthermore, the effect of beam-column joints are considered through rigid offsets between the interconnected beam and column elements (Raheem *et al*., 2018). Tables 1 and 2 display designed sections of the structural elements for exterior and interior skeletons, respectively. Figure 6 represents a schematic view of each section type. Box sections are implemented for columns and inclined members of a hexagrid skeleton to resist bi-directional bending.

Modal dynamic properties of the structures including modal periods and corresponding participating masses

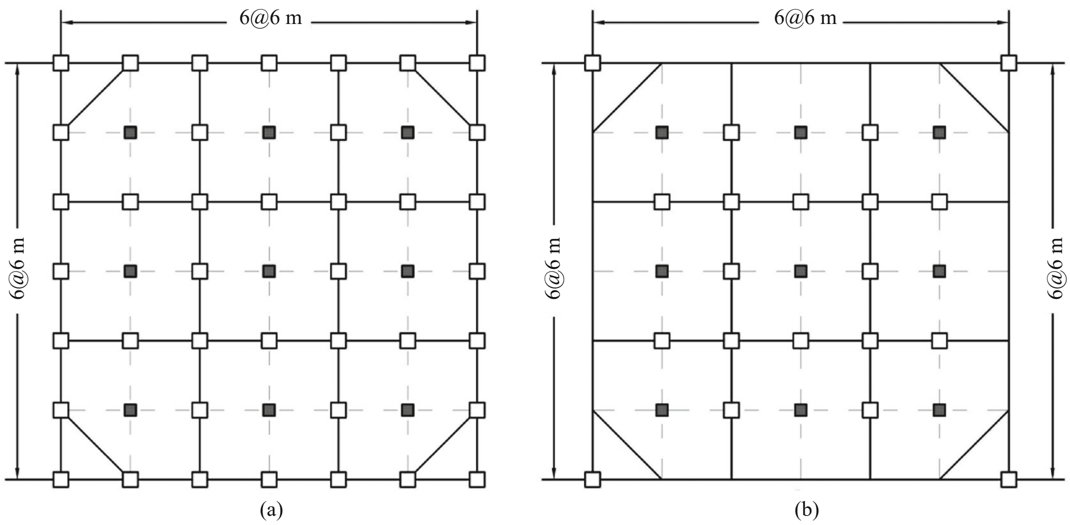

Fig. 4 Plan configuration of the studied models: (a) bundled tube; (b) hexagrid

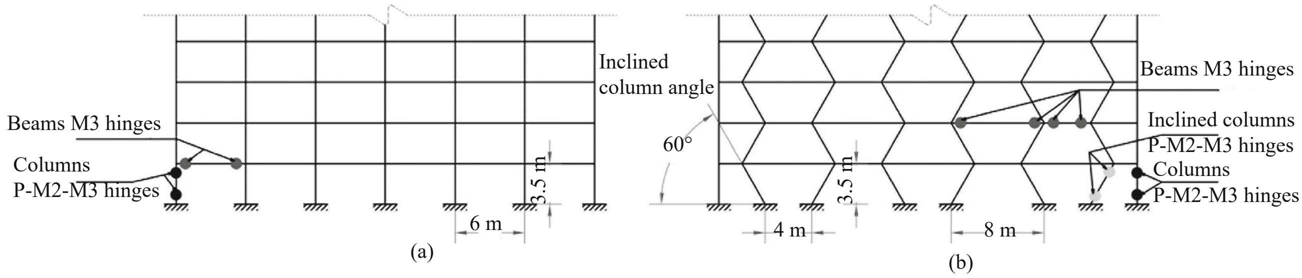

Fig. 5 Facade of the studied structures: (a) bundled tube; (b) hexagrid

were obtained as given in Table 3. It can be inferred from Table 3 that a hexagrid structural system has inherently higher stiffness compared to a bundled-tube skeleton, which is consistent with previous studies (Mashhadiali and Kheyroddin, 2013).

Table 1 Properties of the designed exterior columns and girders sections

Story number	Exterior columns (mm)	Girders (mm)
1–5	Box 600×30	B 500×15×350×25
6–10	Box 550×25	B 450×15×350×25
11–15	Box 500×20	B 450×10×350×25
16–20	Box 450×15	B 400×10×300×20

2.2 Analysis method

Nonlinear time history analyses of a three-dimensional finite element model of the skeletons are performed using SAP2000 (2013). Through approaches for assessing the nonlinear behavior of the elements, as elastic element with concentrated plasticity is used in this study. Based on the concentrated plasticity approach, the inelastic behavior of structural elements is concentrated in two plastic hinges lumped at the two ends of the structural member and the member is assumed to perform linearly through its length (ATC/72-1, 2010; Nguyen and Kim, 2018). Salgado and Guner (2018) provided a comparison between different approaches accounting for material nonlinear behavior. Typical plastic hinges, assigned to different structural components, are shown in Fig. 5.

Table 2 Properties of the interior structural sections

Story number	Interior columns (pinned bents)	Interior columns (rigid bents)	Interior beams (pinned bents)	Interior beams (rigid bents)
1–5	Box 500×25	Box 600×30	B 350×10×150×00	B 500×15×350×25
6–10	Box 450×20	Box 550×25	B 350×10×150×00	B 450×15×350×25
11–15	Box 400×15	Box 500×20	B 350×10×150×00	B 450×10×350×25
16–20	Box 350×15	Box 450×15	B 350×10×150×00	B 400×10×300×20

Table 3 First six elastic modal periods of the studied structures

	Hexagrid skeleton		Bundled tube skeleton	
	Modal period	Participating mass ratio	Modal period	Participating mass ratio
1st and 2nd modes *X* and *Y*- translation	2.81	0.73	2.49	0.72
3rd mode Rotation about the *Z*-axis	1.92	0.20	2.23	0.21
4th an 5th modes *X* and *Y*- translation	1.01	0.12	0.82	0.12
6th mode Rotation about the *Z*-axis	0.71	0.03	0.69	0.03

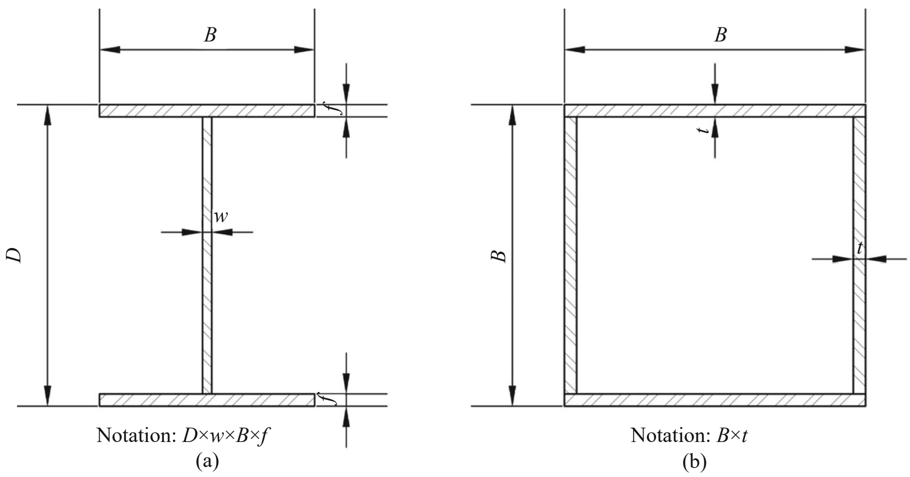

Fig. 6 Schematic of the implemented sections: (a) built up girders; (b) built up column boxes

The backbone curve is used as a force-deformation relationship reference for defining the bounds of hysteretic response of the structural components (FEMA 440, 2005). Component models in this research work utilized backbone curves of the types shown in Fig. 7 per the recommendations of the ASCE/SEI 41-13 (Seismic Evaluation and Retrofit of Existing Buildings, 2013) and FEMA 440 (2005). According to Fig. 7, hinge yielding is achieved at point *B*. Ultimate capacity of the hinge is also reached at point *C*. Residual strength and total failure are achieved at points *D* and *E*, respectively. Performance levels of the building structures are shown in Fig. 7 as well.

For inclined elements of hexagrids, as they are bending-dominated elements (Montuori *et al*., 2015), P-M-M hinges are considered with a reduction factor of 0.8 for calculating nonlinear modeling parameters *a*, *b*, and *c* in order to account for uncertainties involved in the connections of the inclined members. M3 hinges are assigned to clamped beams and P-M-M hinges are assigned to columns. As it is predicted that columns of gravity frames undergo severe axial force under the selected ground motion records, the axial hinges are also assigned to the middle height of these columns. The back bone curve of this type of plastic hinge is shown in Fig. 7(a). Figure 7(b) also represents the defined back bone curve for flexural governed beam-columns.

The Hilber-Hughes-Tailor (HHT) direct integration method as an unconditionally stable method (Hilber *et al*., 1977) is employed in nonlinear time history analysis. According to the HHT method, α is assumed to be 0.333.

P-delta effects in line with large displacements are considered in the analysis procedure. The importance of considering P-delta effects in modeling and nonlinear analysis of structures has been discussed in the literature (Krawinkler, 2006).

2.3 Ground motion selection

The selected ensemble of ground motions contains seven three-component near-field records according to FEMA P-695 (2009). Ground motions are obtained from the PEER ground motion database (PEER) and selected in such a way that covers both forward and backward directivity effects with magnitudes ranging from 6.5 to 7.5 (Qu *et al*., 2011). All the ground motions selected are within a distance of less than 20 km from the rupture plane to account for near-field characteristics. Krinitzsky and Chang (1988) represented a classification regarding the magnitude of earthquakes and their related radius in which the near field effects are evident. According to their study for earthquakes with magnitude of 6.0, near field effects can be better observed within a radius of 25 km. As the magnitude of earthquakes increases, this radius decreases. From Table 4, the 1979 Imperial Valley earthquake has the least magnitude in the selected ground motion ensemble, i.e., 6.53. Therefore, selecting ground motion records within a distance less than 20 km would conservatively take into account the effects of near field ground motion records.

The selected ground motion records are scaled according to the specified provisions of IS 2800-4 (2014). A comparison is done according to Kurama (2003) for different ground motion scaling methods. According to this study, both near-field and far-field records need to be scaled to adequately define the damage potential of a specific site condition and structural characteristics. Some scaling methods are appropriate for near-field records and some for far-field records. However, the ground motion scaling method should be chosen in such a way that it introduces no significant scattering in the analyses results. In this study, two horizontal components of the selected ground motion records are utilized in the ground motion scaling procedure. The calculated scale factor is then applied to horizontal and vertical components of the ground motions. Therefore, all three components of each ground motion are scaled by the same scale factor. Ground motions properties are given in Table 4. Horizontal response spectra of the scaled ground motions along with the average and design spectrum are illustrated in Fig. 8.

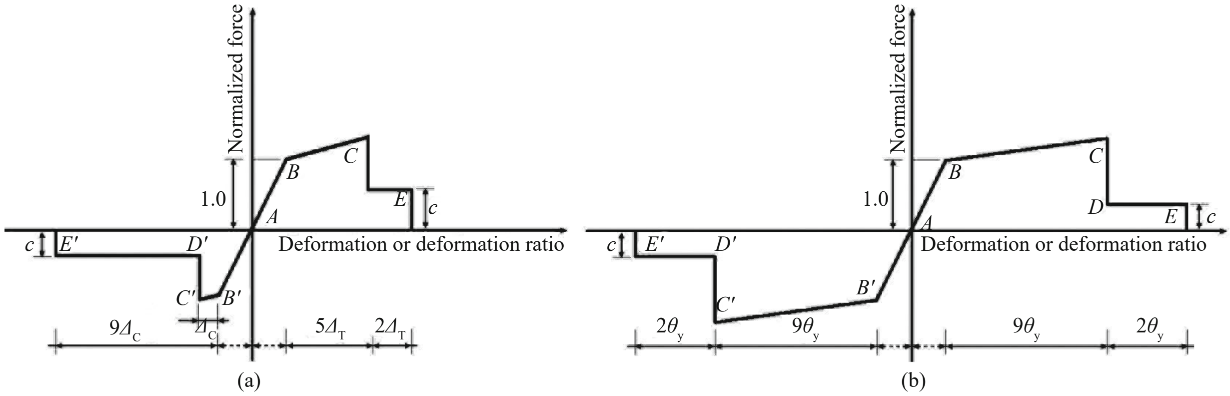

Fig. 7 Nonlinear behavior of a typical beam-column adapted from ASCE/SEI 41-13 (a) axial-force governed gravity columns; (b) flexural columns (ASCE 41-13, 2012)

3 Results

In this section, the responses of the structures are discussed. Peak inter-story drift, maximum amount of corner columns-beam joint rotation and plastic hinge mechanisms are studied as the main computational responses of buildings under seismic excitations. A comparison is also performed between the studied models for each calculated response parameter.

3.1 Peak inter-story drift distribution

Basic parameters which can better illustrate seismic performance of the studied structures are discussed herein. First, maximum inter story drift of each structure under the selected ensemble of ground motion records is studied. Figure 9 indicates the maximum inter story drift ratio of buildings in the *X* and *Y* directions, which are correspond to fault parallel (LN) and fault normal (TR) components of selected ground motion records, respectively. From Fig. 9 it is inferred that the hexagrid structure performed more uniformly under ground motion excitations, and the dispersion of the story drift ratios was less than those of the bundled tube skeleton. Mean peak story drift distributions exceed the drift limit of 2% specified by Iranian code 2800 (2014). Therefore, a multistory side-sway mechanism is predicted for the bottom two-fifth height of buildings. Dispersion of peak drift distributions is evident at the top half height of the bundled tube system, whereas this dispersion is notable at the bottom half height of the hexagrid skeleton, indicating that the hexagrid skeleton perform better in controlling lateral displacements at the top stories.

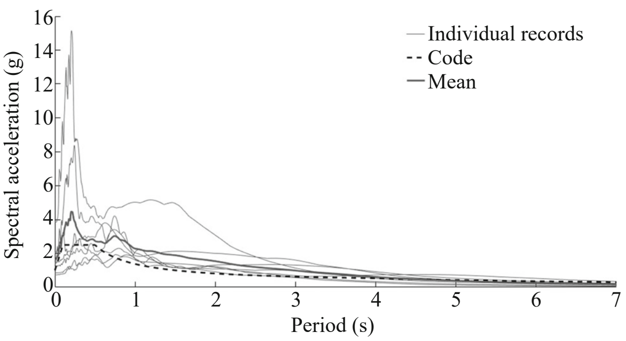

Fig. 8 Horizontal response spectra of scaled ground motions and design spectrum for the bundled tube skeleton

Table 5 represents maximum inter story drift of the bundled tube and hexagrid structures under each ground motion to better investigate their differences in nonlinear response. As can be seen, the structures showed nearly the same maximum drift under E#07 ground motion and the maximum difference in peak drift is attributed to the

Table 4 Properties of the selected ensemble of ground motion records

Event name	Station	Year	Magnitude (M_w)	Component	PGA/PGV (1/s)	PGV/PGD (1/s)
Tabas	Tabas	1978	7.4	LN	8.2	1.47
				TR	6.8	1.17
				UP	14.46	1.05
Bam	Bam	2003	6.6	LN	10.41	2.50
				TR	6.29	3.51
				UP	24.87	3.86
Imperial Valley	El Centro Array #6	1979	6.53	LN	6.21	2.37
				TR	3.88	1.58
				UP	28.06	1.93
	El Centro Array #7			LN	6.99	2.01
				TR	4.10	2.18
				UP	19.85	2.75
	Meloland Overpass (MEL)			LN	4.26	2.92
				TR	3.2	2.79
				UP	10.01	2.74
Northridge	Jensen Filter Plant (JFP)	1994	6.7	LN	5.89	4.01
				TR	3.94	2.47
				UP	11.59	4.16
	New hall- W.Pico			LN	4.73	4.18
				TR	4.81	1.63
				UP	7.65	2.78

*LN refers to the fault-parallel component of record

*TR refers to the fault-normal component of record

JFP ground motion record. Mean inter story drift of the bundled tube system was about 7% greater than that of the hexagrid structure.

3.2 Peak beam-column joint rotation

Figure 10 illustrates beam-column joint rotations of corner columns. Total beam-column joint rotations, including elastic and plastic rotations, for each four of the corner columns are taken into account. Maximum demands of both skeletons represented nearly the same distribution over the bottom stories, except that a gap is evident in the bottom two-fifth height of the hexagrid skeleton. The maximum demand of beam-column joint rotation for the bundled tube skeleton is greater than that of the hexagrid, while the sensitivity of the bundled tube system to input ground motions is less when compared to the hexagrid skeleton.

3.3 Plastic hinge mechanism

Formation of plastic hinges illustrates vulnerability of different structural members under input energy. For a given ground motion, the velocity pulse caused a sudden increase in the amount of released energy. The structural system has to dissipate this input energy while maintaining desired performance levels. This is the point where different structural systems are distinguished by their ability to tolerate the input energy according to their special structural details or materials. In order to better understand the behavior of the hexagrid and bundled tube skeletons under large amounts of input energy, formation of plastic hinges and their corresponding performance level are investigated herein.

Plastic hinge states for Tabas and E#07 ground motions as well as the fault-normal velocity time histories are depicted in Fig. 11. Plastic hinges are captured at the peak velocity of ground motions, which is depicted by a dot in velocity time histories of corresponding earthquakes. Energy flux of Tabas and #E07 ground motions are also illustrated in Fig. 12. As can be deduced from Fig. 12, input energy of Tabas ground motion continues to increase while the hexagrid skeleton reaches its dynamic instability. It is inferred that girders undergo severe deformations in the hexagrid skeleton. Comparing the state of plastic hinges at the exterior columns of the bundled-tube skeleton and inclined members of the hexagrid structure, reveals that columns of the bundled-tube skeleton undergo more deformations. Furthermore, in the hexagrid skeleton, input inelastic demand of ring beams is more than that of intermediate beams. This implies different structural detailing for these two types of beams so that they would reach nearly the same performance level at a given input intensity.

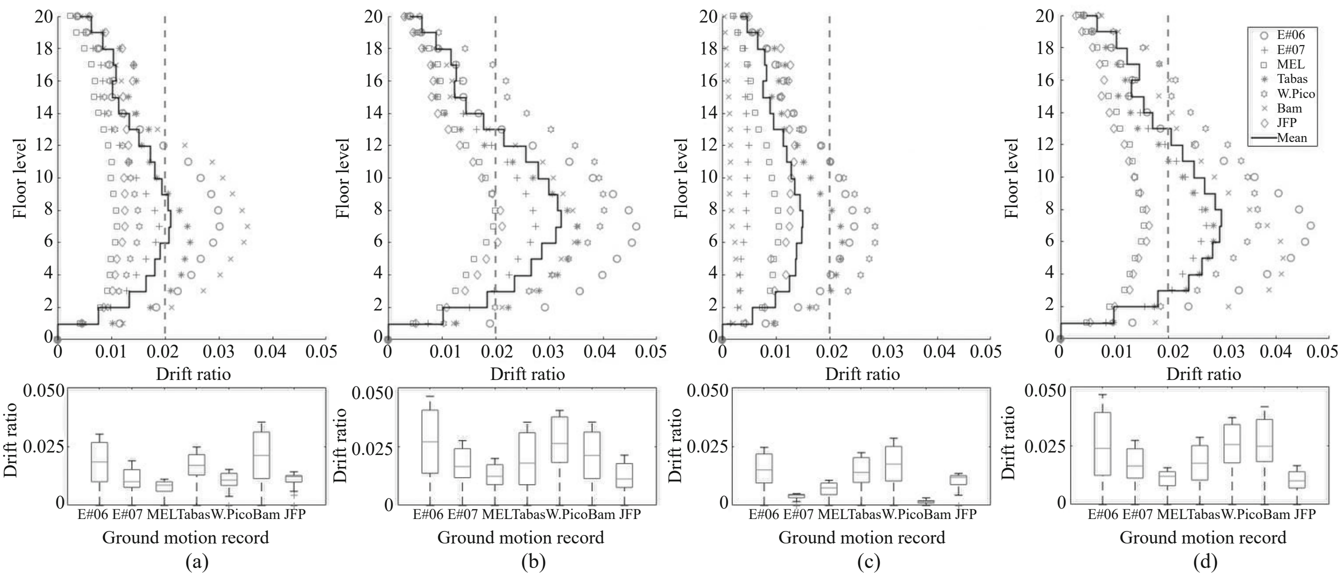

Fig. 9 Peak inter story drift distribution over the height of bundled tube structure corresponding to: (a) LN; (b) TR and hexagrid structure corresponding to: (c) LN and (d) TR components of ground motion records

Table 5 Maximum inter story drift of structures under each earthquake

	Max drift (%)							
	E06	E07	MEL	Tabas	W. Pico	Bam	JFP	Mean
Bundled tube	4.62	2.74	1.99	3.53	4.02	3.53	2.13	3.21
Hexagrid	4.65	2.71	1.56	2.85	3.68	4.14	1.65	2.99
Difference (%)	0.79	1.00	21.64	19.29	8.47	14.77	22.50	6.70

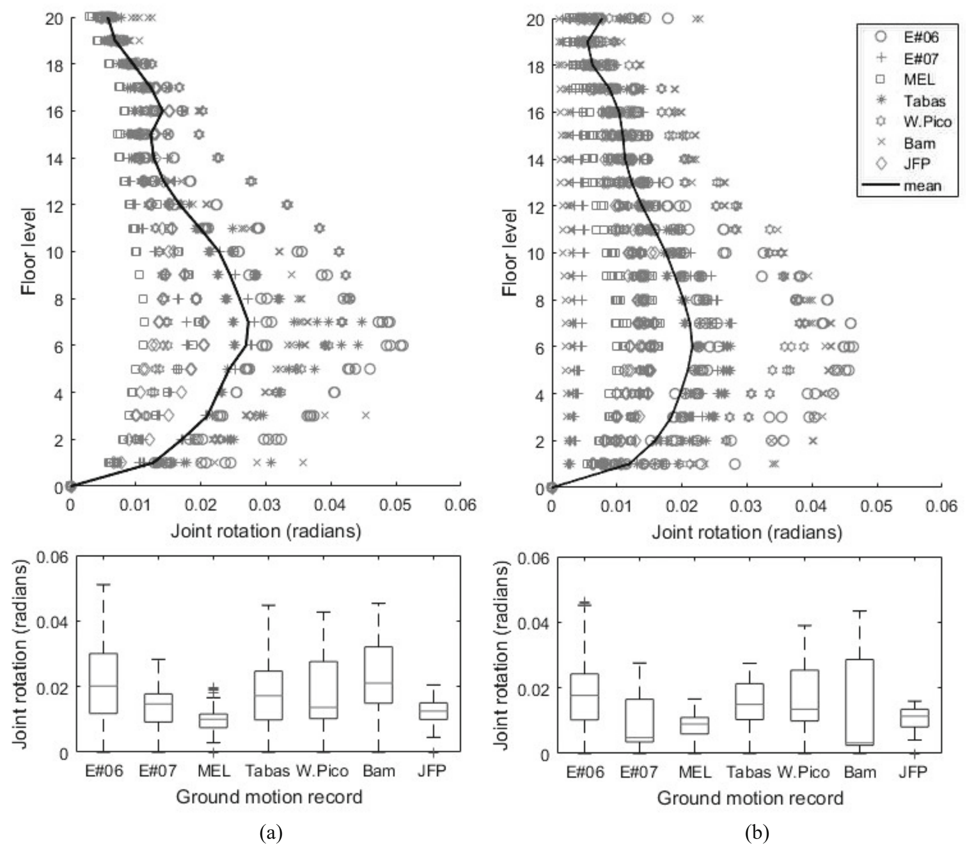

Fig. 10 Corner columns beam-column joint rotation: (a) bundled tube; (b) hexagrid

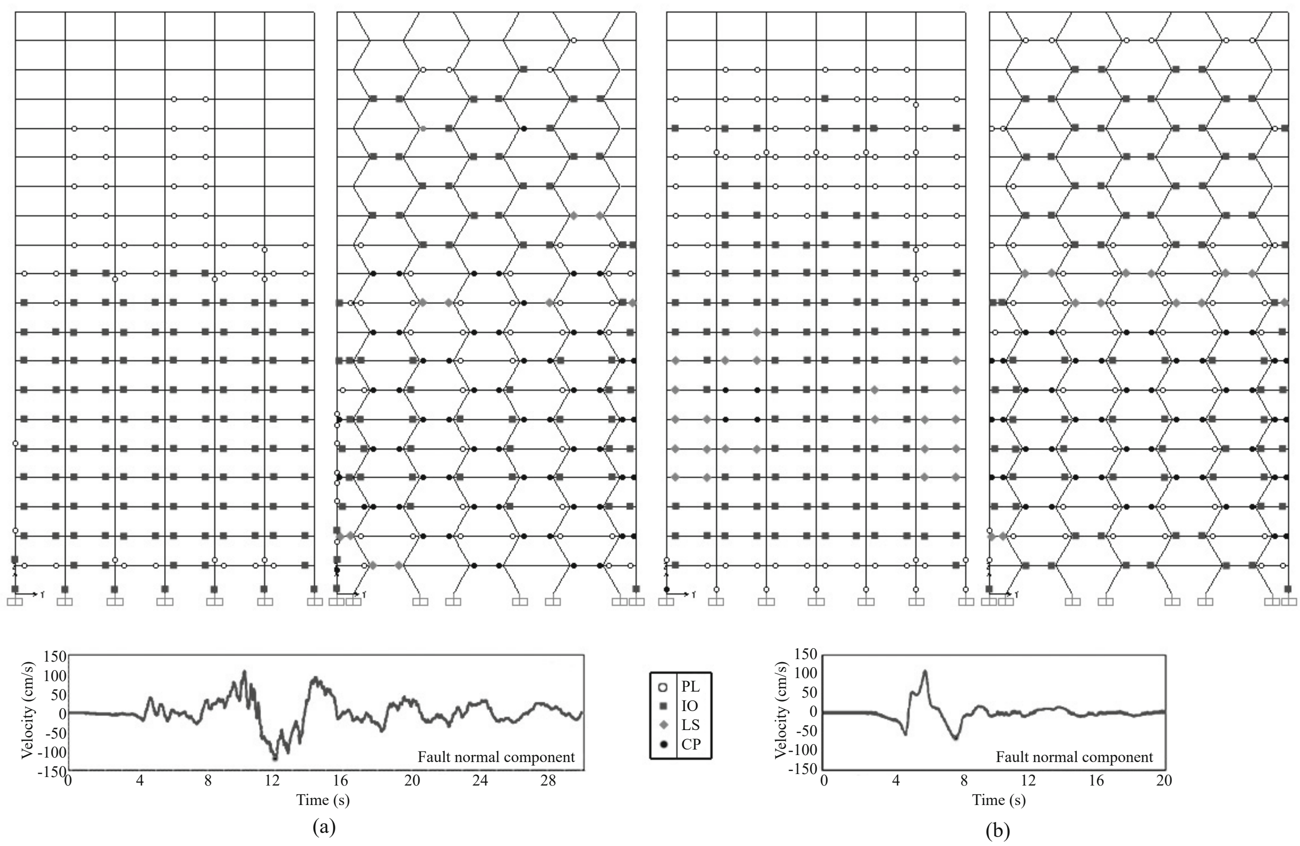

Fig. 11 State of the plastic hinges at the peak velocity of earthquakes: (a) Tabas; (b) E#07

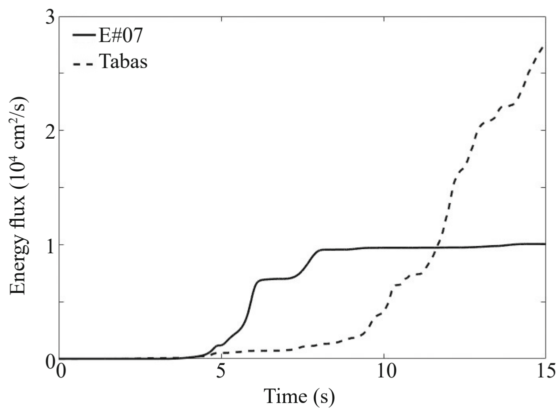

Fig. 12 Flux energy curve of Tabas and #E07 earthquakes

4 Discussion

Nature is a source of inspiration especially for structural engineers in order to design bio-inspired structures. Hexagrid is one of the nature-inspired structural systems which has drawn the attention of researchers in recent years. Different studies have been done in the field of hexagrid mechanical properties and its application in tall buildings′ structures. However, nonlinear behavior of this skeleton is not well understood. In the first stage of design of this skeleton, some parameters have to be selected such as the angle of inclined beam-columns and height of the hexagonal cells. Previous studies suggested different angles, based on which the present study assumed an angle of 60° with respect to azimuth for inclined members. Horizontal cells were considered as 2-story cells, since cells with higher or lower height caused the hexagrid structure to have a period of vibration radically different from that of the bundled tube skeleton and this would lead to improper comparison of the structures′ performance under seismic excitations. The main goal of this study was to evaluate nonlinear performance of the hexagrid skeleton as a lateral load resisting system in a tall building. Hence nonlinear properties of structural elements needed to be precisely modeled. One of the limitations was that there were no data on the experimental analysis of nonlinear behavior of hexagrid structures in the literature. Therefore, the specified backbone curves of FEMA-440 (2005) were utilized as a force-deformation relationship. To account for uncertainties involved in the material nonlinearities and due to the lack of data on nonlinear behavior of inclined members of a hexagrid, a reduction factor of 0.8 was considered for the modelling parameters calculated from considerations of FEMA-440 (2005).

Finite element models of buildings were developed through SAP 2000 software. Modal and nonlinear time history analyses were utilized to assess the behavior of skeletons. Structural sections of hexagrid structure were chosen to be the same as the bundled tube system to ensure that the differences in modal properties and nonlinear responses between the hexagrid and bundled tube systems arose only from their different geometrical configurations.

Near-field ground motions were selected to examine nonlinear response of studied skeletons. The ensemble of ground motions in this study contained seven three-component of near-field ground motion records, the magnitude of which ranged from 6.5–7.5. All three components of ground motions were scaled by the same scale factor. The following results are obtained from nonlinear time history analyses:

1. Hexagrid skeletons exhibited less dispersion for inter-story drift demands under different seismic excitations, which is a merit of this structural system. This may be perceived as independency of this skeleton to input excitation.

2. Rotation of corner beam-columns joints depicted that for both structures, peak rotations occur in the middle stories and the number of mean rotations for a bundled tube system was greater than that of a hexagrid structural system. Furthermore, the hexagrid skeleton exhibited more uniform joint rotations along the height of the building, which decreases the probability of unexpected beam-column joint failure.

3. Formation of plastic hinges showed that the inclined beam-columns of a hexagrid structure help concentrate local nonlinearities in the girders rather than the exterior columns. Hence, girders of the hexagrid skeleton are more vulnerable when compared to those of the bundled tube and need elaborate detailing. However, the story beams of the hexagrid structure should be designed in a way to arrive at the yield point prior to the inclined columns.

As this study revealed, peak drift dispersion was lower for the bundled tube skeleton at the bottom stories and for the hexagrid skeleton at the top stories. Therefore, it may be possible to make use of both structures in the perimeter of a single building but at different levels to get the advantages of both load resisting systems. Another important aspect of implementing a hexagrid skeleton as the load bearing system, is ring beams which are subjected to great moment demands imposed from inclined members. Different structural details may be applicable for these elements, such as tapered beams or reduced beam sections. However, this is not a trivial task as different solutions need to be considered and the most promising one which meets most of design considerations should be taken as the preferred solution.

5 Conclusions

From the above discussion it becomes clear that the field of structural framing for tall buildings is a challenging yet appealing trend. Different geometrical patterns could be considered and their advantages and disadvantages assessed through nonlinear analyses. The energy dissipation mechanism of a selected pattern should be such that utilizes the capacity of inferior structural elements to withstand input inelastic demand.

This study aimed to assess the applicability of hexagonal patterns as they are good candidates for providing the desired lateral rigidity. To extend the findings of this study, further research is needed for simultaneous usage of conventional rectangular and hexagonal grids where optimizing techniques can help researchers to find the most appropriate grid pattern according to the input inelastic demands. Furthermore, apart from implementing regular grid patterns, it is a wise choice to mimic how nature and natural structures withstand forces and implement those natural irregular patterns and strategies in structural framing of tall buildings.

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