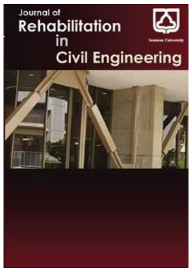
Journal of Rehabilitation in Civil Engineering 6-1 (2018) 58-69

journal homepage: http://civiljournal.semnan.ac.ir/



Effects of Ground Motion Directionality on the Seismic Behavior of Mid-rise Concrete Buildings with Considering Unequal Live-Load Distribution in Height

H. Noori[1] and M.M. Memarpour[2]*

1. M.Sc. of Earthquake Engineering, Department of Civil Engineering, Faculty of Engineering & Technology, Imam Khomeini International University, Qazvin, Iran

2. Assistant Professor, Department of Civil Engineering, Faculty of Engineering & Technology, Imam Khomeini International University, Qazvin, Iran

Corresponding author: *memarpour@eng.ikiu.ac.ir*

ARTICLE INFO

Article history:
Received: 18 June 2017
Accepted: 05 September 2017

Keywords:
Directionality,
Concrete 3D Frame,
Mid-Rise,
Irregularity,
Incident Angle.

ABSTRACT

The incident angle of ground motion is one of the sources of uncertainty in the seismic response of buildings. Moreover, understanding the structural response to the impose ground motion may cause significant changes in the maximum response of buildings. In order to investigate the influence of the spatial distribution of orthogonal components of earthquake strong motion on the structural responses, three 15-story buildings were analyzed in this study using the time-history method. A significant live load (750 kg/m^2) is imposed at different vertical levels of the structures. The imposed load was combined with ground motion excitations in the range of 0 to 90 degrees. The response of structure was investigated using roof drift index and inter-story drift ratio. Results demonstrate the orientation of seismic excitation and considering the maximum values of roof drift index, which correspond to the critical direction increase roof drift index between 8 to 12 percent. Furthermore, the inter-story drift ratio increased between 30 to 33 percent due to the orientation of excitation and considering the maximum values of the inter-story drift ratio, which correspond to the critical direction.

1. Introduction

The incident angle of seismic excitation imposed on a structure located in seismic regions is one of the uncertainty sources in structural analyses and designs. These uncertainties in site conditions, earthquake epicenter, and wave propagation properties make this hypothesis reasonable that the earthquake may impose different actions on

DOI: 10.22075/JRCE.2017.11679.1198

the structure in different incident angles. Investigation of the incident angle of orthogonal components of the earthquake on a structure and considering the maximum values of demands which correspond to the critical direction of demands is an important problem because the structure may experience more demands on a direction that necessarily doesn't lay down on the axis of analysis.

Many researchers have focused on the incident angle of excitation, which is briefly presented here. In 1974 Penzien and Watabe's researches showed that the most intensity of earthquake components occurs in the epicenter direction [1]. Due to the uncertainty of epicenter direction toward the location of a structure, research efforts focused on the direction of the maximum response experienced in a building [2-3]. Also, Davila and Cruz studied maximum actions occurred in a concrete frame components under linear-dynamic analysis in different directions and compared results with results which are brought from combinations of responses on two major directions. They concluded that SRSS of responses in two major directions estimates demands 25 percent less than which is obtained from analyses in different directions [4]. In 2005 a formulation presented for the critical angle of incident and maximum response which obtained imposing the three component ground motions [5]. Results show critical actions in the displacement of the elements and nodes vary up to 80 percent, considering different incident angles. Developing non-linear processing lead researchers to study non-linear behavior of structures under directional excitation. Rigato and Medina studied the the effect of incident angles on columns drift and ductility demands of regular and irregular buildings. They showed that these effects increase structure responses from 10 to 60 percent [6]. Also, Contaglo et al. demonstrate that concrete structures suffer irregularity in the plan are vulnerable to the incident angle of excitation considerably. However, structures with a regular plan less affect by directional excitations [7]. Some new researches in directionality effects of seismic excitation focused on building responses incorporating damage index. Emami and Halabian imposed orthogonal components of ground motion in a range of angles to three 3D concrete frames with the regular plan and considered rotation of response receiving axes to find a maximum response. They showed that directionality effects increase ductility demand and damage index between 10 to 30 percent [8]. Also, Kalkan et al. studied the rotation of ground motions pairs on a set of symmetric and asymmetric structures. He concluded that For a given ground motions pairs, rotation angle leading to maximum elastic response is different than that for maximum inelastic response [9].

Considering directionality effects as applied in previous researches result in severe demands on building with irregularity in plan, so the question then arises: "what happen if directionality effects be considered in building with irregularity in height?" to answer this question, three 15-story 3D concrete frames are proposed with same beams and columns section, and different irregularity pattern in height and a set of dynamic analyses are performed using rotated ground motions. Inter story drift and roof drift index of three structures is studied. Ground motions are rotated to 0, 15, 30, 45, and 60 degrees and characteristics of the structures are recorded considering directionality effects (orientation of seismic excitation and considering the maximum values of demands which correspond to the critical direction). Also, responses of two ordinary axes are combined in various methods, such as 100-30, 100-40, SRSS and 1.2 multiple to maximum response of two major axes to find the best fitting to the responses recorded considering directionality.

2. Development of the Numerical Models

The framework, which is described below, consists of modeling three 15-story concrete building. Story height for all models is constant of 3.2m and similar plans at all story levels assigned. In these structures, there is one story with a live load equal to 750 kg/m2 to make height irregularity. This considerable live load location differs in three structures. In this paper, three structures are indicated by M2, M7, and M13, which denote to the assignment of the considerable live load on the 2nd story, the 7th story and the 13th story respectively. Live load in other stories assumed 200 kg/m2 and the dead load considered for all stories is 450 kg/m2.A lateral resisting system of special moment frames with rigid diaphragms was used. Structures designed based on Iranian National Building code [10]. Soil properties assumed to be very dense soil, according to the Iranian Code of Practice for Seismic Resistant Design of Building [11]. Ground acceleration for the site selected according to high seismic risk regions equal to

0.35g [11]. Selection of 750 kg/m2 as the considerable live load is based on this assumption that a library with fixed shelves located at a particular level. It is the minimum live load for the library with fixed shelves recommended by the Iranian National Building code [10]. The plans of the models shown in figure1 and section dimensions are presented in table1. Models sections are designed so that to have the same section properties. Also, Columns designed so that total reinforcing area doesn't exceed 3 percent of the total cross section area.

Table 1. Beams and columns section dimensions

Story	Beam(cm)	Column(cm)
15	40X50	40X40
14	40X50	40X40
13	40X50	40X40
12	40X50	50X50
11	40X50	50X50
10	40X50	50X50
9	60X40	60X60
8	60X40	60X60
7	60X40	60X60
6	70X30	70X70
5	70X30	70X70
4	70X30	70X70
3	80x30	80X80
2	80x30	80X80
1	80x30	80X80

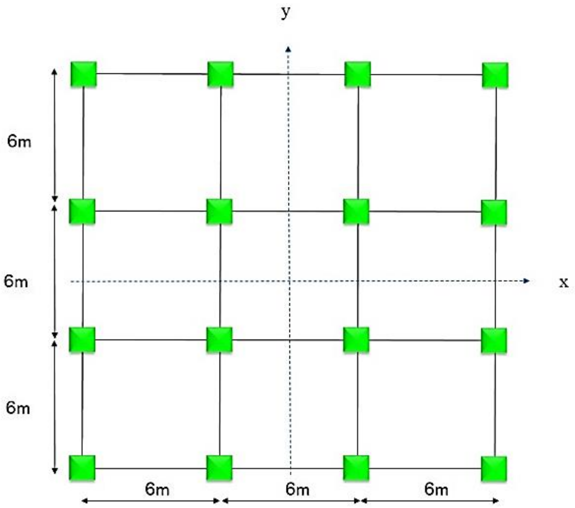


Fig. 1. Plan of 15 story concrete building.

3. Ground Motion Selection

In this study, a set of ground motion, including three records with five different rotation angle (0, 15, 30, 45, 60) is used in this study.

Table 2. Properties of selected ground motions.

Earthquake Name	Year	Station Name	5-95% Duration (sec)	Magnitude	Mechanism	Rjb (km)	Rrup (km)	Vs30 (m/sec)
"Kobe	1995	"Morigawachi"	55.2	6.9	strike slip	24.78	24.78	256
"Manjil	1990	"Abbar"	29.1	7.37	strike slip	12.55	12.55	723.95
"Tabas	1978	"Boshrooyeh"	19.5	7.35	Reverse	24.07	28.79	324.57

These records scaled so that the response spectrum of each ground motion matches with the design spectrum of the Iranian Code of Practice for Seismic Resistant Design of Building [11]. Selected Ground motions must be representative of site properties, so selected ground motions are proportional to a site with a very dense soil [11]. The ground motions provided from PEER[1] database. Properties of selected ground motions are mentioned in table2.

4. The methodology of Directionality Considerations

The method, which is described here, previously used by Emami and Halabian to calculate the maximum response of structures. In the first step, the pair of ground motion sets are rotated by rotation matric of 0, 15, 30, 45 and 60 degrees. This method for rotation previously used by Baker [12]. Then the pair of rotated ground motions is imposed on the buildings, and linear time history analysis is performed. The next step, the responses of the building, which depended to displacement corresponding to the major axes (0 and 90 degrees) is recorded. In the last step, primary axes are rotated to directions between 0 to 180 degrees (with 30 degrees increment) so that the responses that are recorded in the previous step are projected on new axes using equation1.

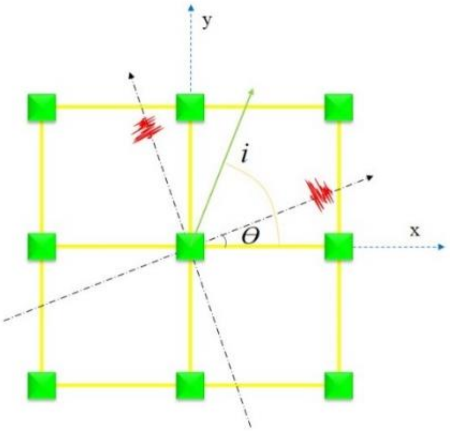


Fig. 2. Schematic view for directionality concept.

In other word, the responses for all directions of excitation are captured, and every response is projected in all possible direction in the plane. In fact, a polar approach substitute with a Cartesian coordinate system to record the maximum demand.

$$D^{i}_{t,\theta} = D^{x}_{t,\theta} \cos i + D^{y}_{t,\theta} \sin i \qquad (1)$$

In equation1, $D^{i}_{t,\theta}$ is the projected response of the structure for imposing the rotated ground

---

[1] Pacific earthquake engineering center

motion excitation with the angle of Θ on new oriented axes rotated with the angle of i . $D^{x}_{t,\theta}$ and $D^{y}_{t,\theta}$ are the responses of the structure for imposing for imposing the rotated ground motion excitation with the angle of Θ on primary axes. Subscript t in this equation indicates time in the ground motion time history.

In this study, two displacement-based responses captured: inter story drift ratio and roof drift index. Assuming $D^{i}_{m,\theta}$ shows maximum displacement projected on i direction during a time-history and H indicates the height of a story, Then inter-story drift ratio is calculated by Equation2:

$$\Delta^{\theta}_{m,i} = \frac{D^{\theta}_{m,i}}{H} \tag{2}$$

In this equation $\Delta^{\theta}_{m,i}$ shows the maximum inter-story drift ratio in i direction for imposing the rotated ground motion excitation with the angle of θ. Replacing roof displacement and height of the structure with story displacement and height of structure respectively in equation2, it yields roof drift index. Figure 3 shows the imposed excitation and corresponding displacement demand on structure plan, schematically.

5. The Software Used for Numerical Modeling

For numerical modeling and section designing, CSI Etabs V 15.0.0 is utilized [13]. This software is capable of performing linear time-history analysis by direct integration. Also, Etabs is able to rotate ground-motions with a degree of interest. Etabs provide various kinds of methods to solve dynamic equations, so Hilber-Hughes-Taylor method was utilized in this study. Five percent Rayleigh damping considered for two modes include 90% of the participated modal mass in dynamic analysis. Figure 3 shows a 3D view of one of the models.

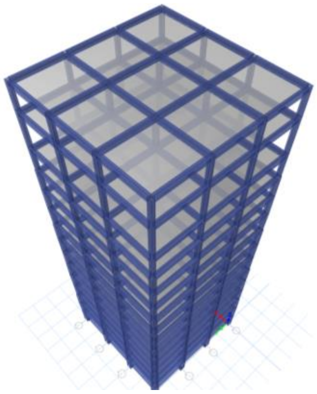


Fig. 3. 3D view of modeled buildings.

6. Modal and Time-History Analysis

Before performing time-history analysis, modal analysis is done to evaluate the modal behavior of models. In Table 3 period of vibration modes of the structures is mentioned.

Table 3. period of vibration modes.

Structure / Mode	M2 (sec)	M7 (sec)	M13 (sec)
1	2.461	2.388	2.428
2	2.461	2.388	2.428
3	2.067	2.012	2.042

To transform linear displacement recorded by analysis to equivalent nonlinear displacement, all values multiplied by Cd factor, which recommended by the Iranian Code of Practice for Seismic Resistant Design of Building. Based on this code, the factor value for special moment frames is 5.5.

7. Results and Discussion

Three numerical models of 15-story buildings, which designed to resist gravity and lateral design loads, is proposed. In every building at a particular story level, a considerable live load (750 kg/m2) is imposed, which represents a library with fixed shelves. This considerable live load incorporated in the 2nd story, the 7th story and the 13th story respectively, for structure M2, structure M7 and structure M13. Three pairs of ground motions are rotated to five different angles (0, 15, 30, 45 and 60 degrees) and imposed uniformly at the base of the structures. Dynamic analyses performed and maximum Inter-story drift and roof drift index is recorded in all possible directions in the plane. Then the maximum responses captured using this method are compared with responses from the traditional approach (excitation and response receiving axes be the same and on the direction of 0 or 90 degrees).

Table 4. Comparison of roof drift indexes values of directionality analysis and traditional method.

Model	M13			M7			M2			
Record	Directionality	Max (x,y)	%	Directionality	Max (x,y)	%	Directionality	Max (x,y)	%	Average for each record
Kobe	0.0066	0.0065	1.339	0.0069	0.0067	1.747	0.0060	0.0059	1.25	1.44
Manjil	0.0061	0.0051	19.44	0.0061	0.0061	0	0.0060	0.0053	14.4	11.26
Tabas	0.0094	0.0080	16.22	0.0095	0.0079	19.68	0.0088	0.0080	9.85	15.24
	Average		12.33	Average		7.142	Average		8.49	

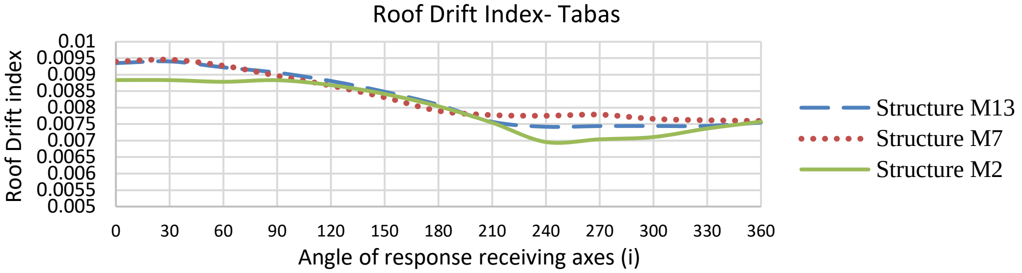


Fig. 4. Comparison of roof drift index for different response receiving axes angle-Tabas.

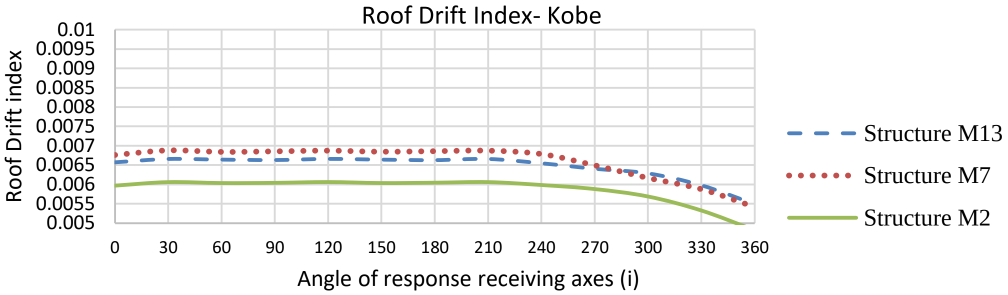


Fig. 5. comparison of roof drift index for different response receiving axes angle-Kobe.

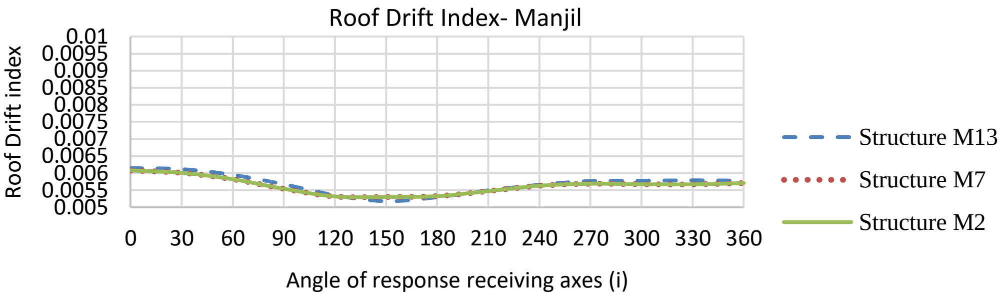


Fig. 6. comparison of roof drift index for different response receiving axes angle-Manjil**.**

Figures 4 to 6 show the response of the roof drift index for three structures and three ground motions. In this figures Structure M13, Structure M7, and Structure M2 respectively denote that considerable live load (750 kg/m2) is imposed on the 13th story, the 7th story, and the 2nd story.

As shown in figures 4 to 6, the effects of directionality are different for every ground motion. In table 4 results of the roof drift index for three models and three ground motions is shown. Also, according to table 4, it is determined that ground motion exciting in different angles and rotation of response receiving axes increase roof drift index up to 12.5%. Effects of directionality are minimum in the model which considerable live load is located on 7th story.

This paper focuses on the inter-story drift as well as roof drift index. Figure 7 shows the average of inter-story drift for three models as a profile of building height. In figure 7, the results of various methods for combining responses of two major axes are compared to results considering directionality. These methods are described in table5, and for every method, an abbreviation is allocated. For example, XYXY denotes the method that excitation is imposed in primary X, and Y direction and responses are recorded in the same directions. In table 7, mathematician expressions are used to give a better definition for the methods. In these expressions $\Delta^{\theta}_{m,i}$ indicate maximum inter-story drift ratio due to impose excitation rotated with an angle of Θ and aligned with axes rotated by an angle of i. In the last three rows of the table6 (related to SRSS, 100-30 and 100-40 manner), subscribe x or y indicate responses on primary X and Y axes.

Figure 7 shows the average of inter-story drift profile in height for the methods described in table5. In Figure 8 differences of inter-story drift between DD method (the method which directionality considered in both the direction of excitation and the direction of response) and other methods as a profile of building height is shown.

According to Figure7, the inter-story drift of the DD method is considerably higher than XYXY method (the traditional method which directionality ignored in both directions of excitation and direction of the response). The difference is about 19% to 27% toward story height level. This difference has two sources: excitation of ground motion in various angles and considering the maximum demand corresponding to the critical direction of the response. In order to study the effect of each source, the method DXY (the method which Directionality considered in the direction of excitation but ignored in the direction of the response) is defined. Conforming to results, determined that on average, 12% of the difference related to imposing excitation in different angles and 12% related to the rotation of response axes.

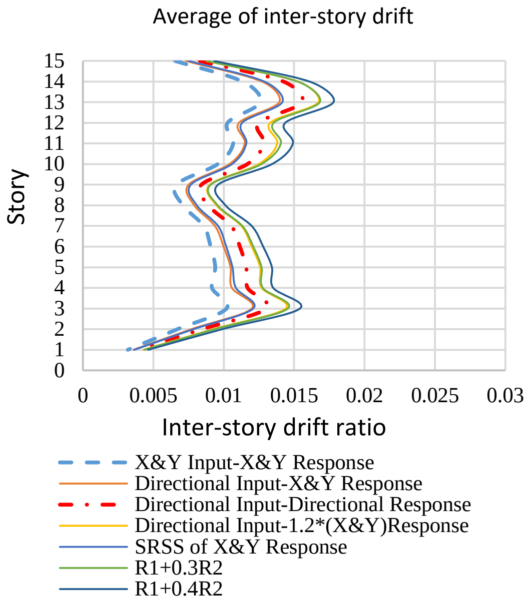


Fig. 7. Average of inter-story drift for different methods.

In addition, figure 7 shows inter-story drift value in the 3rd, and the 14th stories are more than other stories. These stories are located at one higher level than the story which considerable live load is imposed. This observation occurred due to the inertia of the presence of the considerable live load in the 2nd story and story 13th respectively in structure M2 and structure M13. The inherent inertia of the lower stories causes resists against the moving in line with the movement pattern of the entire structure. Thus an increase in demand happens in the upper stories.

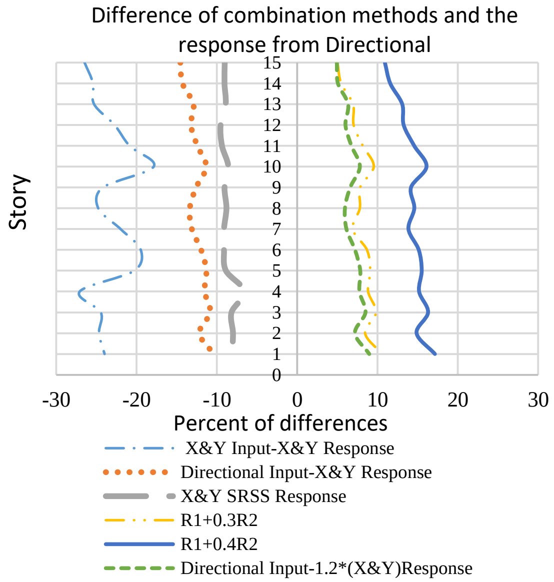


Fig. 8. Differences of response combining methods with responses from directionality

Table 5. Average and standard deviation for differences of different methods and directionality analysis

Data	SRSS(%)	1.2Max(x,y) (%)	1.3R1+R2 (%)	1.4R1+R2 (%)
Average of absolute difference	9	8	9	15
Standard Deviation	2.2	2.9	5.5	7.1
C.V	0.25	0.39	0.65	0.49

Although the presence of considerable live load in the 13th and the 3rd stories causes increasing inter-story drift in the upper story, in the presence of live load in 7th story the value of inter-story drift in upper story is near adjacent stories. This happens because the produced inertia of the significant live load in the intermediate stories doesn't have any conflict with the total displacement of the structure, so no increase in inter-story drift has been observed.

Focusing on the profile of inter-story drift considering directionality in the direction of excitation and response axes (DD method), it is obvious that in stories which demands are considerably increased (the upper stories of stories, which considerable live load is located) effects of directionality increases.

Table 6. Definition of response receiving methods.

abbreviation	The Method brief description	Mathematical description of the methods
XYXY	X&Y Input-X&Y Response	$\Delta_{m,0}^{0}$
DXY	Directional Input- X&Y Response	$Max\{\Delta_{m,0}^{0}, \Delta_{m,0}^{15}, \Delta_{m,0}^{30}, \Delta_{m,0}^{45}, \Delta_{m,0}^{60}\}$
DD	Directional Input- Directional Response	$Max\{\max(\Delta_{m,0}^{0}, \Delta_{m,15}^{0}, \ldots, \Delta_{m,180}^{0}), \ldots, \max(\Delta_{m,0}^{60}, \Delta_{m,15}^{60}, \ldots, \Delta_{m,180}^{60})\}$
DMXY	Directional Input- 1.2 (X&Y)Response	$1.2 \times Max\{\Delta_{m,0}^{0}, \Delta_{m,0}^{15}, \Delta_{m,0}^{30}, \Delta_{m,0}^{45}, \Delta_{m,0}^{60}\}$
SRSS	X&Y SRSS Response	$Max\{\sqrt{{\Delta_{x,0}^{0}}^{2} + {\Delta_{y,0}^{0}}^{2}}, \sqrt{{\Delta_{x,0}^{15}}^{2} + {\Delta_{y,0}^{15}}^{2}}, \ldots\}$
100/30	R1+0.3R2	$Max\{\max(\Delta_{x,0}^{0} + 0.3\Delta_{x,0}^{0}, \Delta_{y,0}^{0} + 0.3\Delta_{x,0}^{0}), \ldots, \max(\Delta_{x,0}^{60} + 0.3\Delta_{x,0}^{60}, \Delta_{y,0}^{60} + 0.3\Delta_{x,0}^{60})\}$
100/40	R1+0.4R2	$Max\{\max(\Delta_{x,0}^{0} + 0.4\Delta_{x,0}^{0}, \Delta_{y,0}^{0} + 0.4\Delta_{x,0}^{0}), \ldots, \max(\Delta_{x,0}^{60} + 0.4\Delta_{x,0}^{60}, \Delta_{y,0}^{60} + 0.4\Delta_{x,0}^{60})\}$

In another word, more inter-story drift, more directionality effects in height.

According to observation, it can be concluded that the presence of considerable live load in middle stories brings less inter-story drift toward the top or down stories.

As mentioned, in this study, a set of response combination methods are used to evaluate the effectiveness of each method to predict the maximum probable response, calculated by directionality consideration (the DD method). In figure8 difference of each combination method with the DD method as a profile of the building, height has been shown. Some of these methods estimate the response greater or smaller than the response obtained using the DD method. These combination methods are defined in table5.

The average value of relative differences in comparison with the DD method and their standard deviations is presented in Table 5, for each method. As mentioned in table5, DMXY is the method with minimum differences with DD method. In DMXY method, excitation is imposed in all directions, and maximum response is multiplied by 1.2. Between various methods for combining the responses, The DMXY method with a smaller standard deviation value has the least difference compared with other methods.

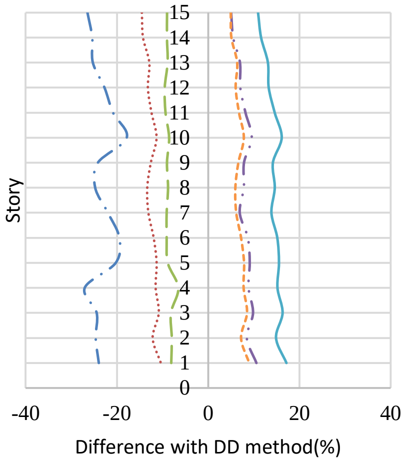


Fig. 15. Differences of response combining methods with responses from directionality–M2.

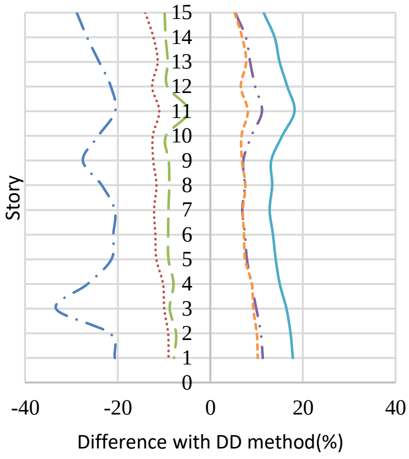


Fig. 16. Differences of response combining methods with responses from directionality–M7.

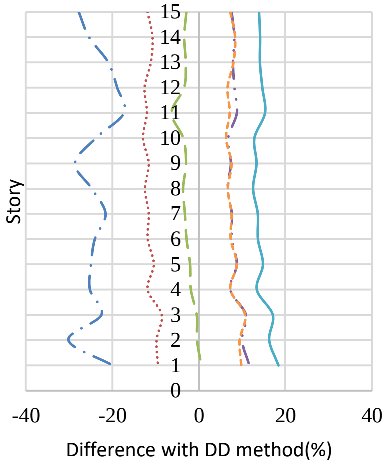


Fig. 17. Differences of response combining methods with responses from directionality–M13.

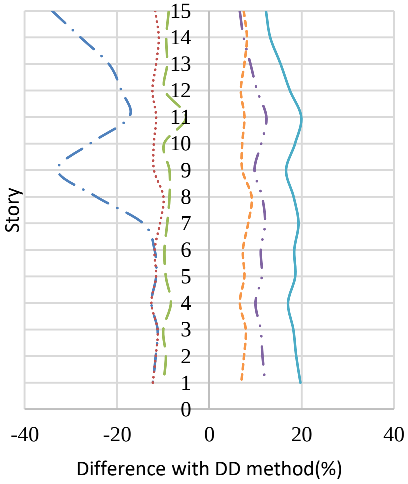


Fig. 18. Differences of response combining methods with responses from directionality–Kobe.

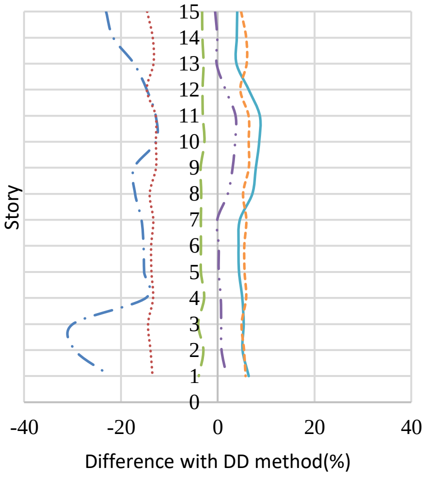


Fig. 19. Differences of response combining methods with responses from directionality–Manjil.

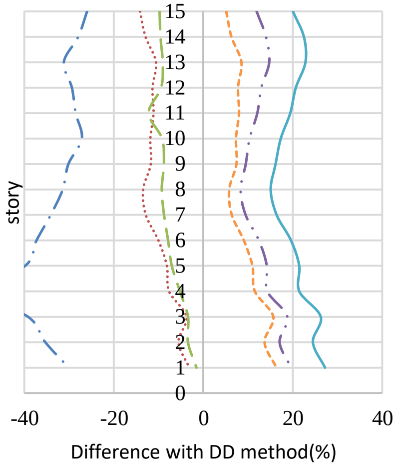


Fig. 20. Differences of response combining methods with responses from directionality–Tabas.

— · —	········	– · – ·	— · — ·	———	— — —
Directional Input-X&Y Response	Directional Input-X&Y Response	SRSS of X&Y Response	R1+0.3R2	R1+0.4R2	Directional Input- 1.2*(X&Y)Response

Figures 9 to 11 and figure 15 to 17 show inter-story drift and differences in the responses with the DD method, respectively for three models. Similarly, Figures 12 to 14 and figures 18 to 20 shows in the same values for three seismic events. It should be noted that results for every seismic event are the average of five time-history analyses under rotated excitations.

8. Conclusion

Three numerical models of 15-story buildings that a considerable live load (750 kg/m2) is imposed on one story of each structure were proposed. The considerable live load respectively was located in the 3rd, the 7th and the 13th story of each building to investigate the effects of irregularity in the height of the buildings under time-history analyses. Effects of the incident angle of ground motions and considering demands corresponding to the critical direction of response are recorded, and results are compared to the traditional approach (constant incidence angle and considering two major axes as the critical direction). Roof drift index and inter-story drift ratio are recorded as demand for models and effects of considerable live load location on the demands are studied. In addition, some methods for the the response combination are used to find the best fitting to the responses, which are calculated considering directionality. Below statements are concluded:

- Considering directionality increases roof drift index in an average 9% and inter-story drift as 24% toward traditional approach.

- Results showed locating of considerable live load in story 13th, and story 2nd impose more demand on one story upper than the location of this load. This intense increase in inter-story drift profile did not record as considerable live load is located on the 7th story. Based on these results, it is concluded that the inertia of the existence of the considerable live load in the 2nd story and 13th story causes the increase inter-story drift in the upper story because this inertia resists moving as same as of whole building movement pattern. In the presence of this load on story 7th, as inertia does not make any disorder for whole building movement, inter-story drift in adjacent stories did not change.

- Results showed in cases which more demands are recorded, effects of directionality increased.

- In comparing methods of response combining, results of the method, which obtained by multiplying 1.2 to the maximum response on X and Y axes under imposing excitation in various directions, yields the nearest response to the responses obtained by directionality considerations.

- Record by record investigation of directionality considerations showed the considerable difference, so it is concluded that the intensity of directionality effects on response is depended on records properties; thus more researches seem beneficial to understand what properties of ground motions may affect on directionality considerations.

REFERENCES

[1] Penzien, J., Watabe, M. (1974) “Characteristics of 3-dimensional earthquake ground motions”. Earthquake Engineering & Structural Dynamics, 3(4):365–73.

[2] Menun, C., Der Kiureghian, A.(1998) "A Replacement for the 30%, 40%, and SRSS Rules for Multicomponent Seismic Analysis". Earthquake Spectra, 14(1):153–63.

[3] Wilson, EL., Suharwardy, I., Habibullah, A. (1995). "A Clarification of the Orthogonal Effects in a Three-Dimensional Seismic Analysis". Earthquake Spectra, 11(4):659–66.

[4] Davila, F., Cruz, E. (2004). "STUDY OF THE EFFECT OF IN-PLAN ASYMMETRY IN MULTISTORY BUILDINGS SUBJECTED TO UNI- AND BI-DIRECTIONAL SEISMIC MOTIONS". In Canada; 2004.

[5] Athanatopoulou, AM. (2005). "Critical orientation of three correlated seismic components". Engineering Structures, 27(2):301–312.

[6] Rigato, AB., Medina, RA. (2007). "Influence of angle of incidence on seismic demands for inelastic single-storey structures subjected to bi-directional ground motions". Engineering Structures, 29(10):2593–601.

[7] Cantagallo, C., Camata, G., Spacone, E. (2012). "The Effect of the Earthquake Incidence Angle on Seismic Demand of Reinforced Concrete Structures". In Lisboa; 2012.

[8] Emami, AR., Halabian, AM. (2015). "Spatial distribution of ductility demand and damage index in 3D RC frame structures considering directionality effects: Spatial Distribution of Ductility Demand and Damage Index". Struct Des Tall Spec Build. 24(16):941–61.

[9] Reyes, JC. Kalkan, E. (2013). "Significance of Rotating Ground Motions on Behavior of Symmetric- and Asymmetric-Plan Structures: Part I". Single-Story Structures. Earthq Spectra. 31(3):1591–612.

[10] MHUD. (2014). "Iranian National Building Code, part 10, steel structure design". Tehran: Ministry of Housing and Urban Development.

[11] BHRC. (2014). "Iranian code of practice for seismic resistance design of buildings: Standard no. 2800 (4th edition)". Building and Housing Research Center.

[12] MHUD. (2014). "Iranian National Building Code, part 6, loads on buildings". Tehran: Ministry of Housing and Urban Development.

[13] Baker, JW., (2007). "Quantitative Classification of Near-Fault Ground Motions Using Wavelet Analysis". Bulletin of the Seismological Society of America, 97(5):1486–501.

[14] Berkeley, CSI., (2015) . "Computer Program ETABS Ultimate 2015". Computers and Structures Inc., Berkeley, California.