Research

Investigating the Pattern of Plastic Hinge Formation in Steel Moment Frames Under Near-field and Far-field Earthquakes

Mohammad Saleh Estakhri *, Ali Nikkhoo

Department Civil Engineering Department, University of Science and Culture, Tehran, Iran.

*Correspondence should be addressed to Mohammad Saleh Estakhri, Department Civil Engineering Department, University of Science and Culture, Tehran, Iran. Tel: (+98) 9190025410; Email: mohammad.s.estakhri@gmail.com

ABSTRACT

In this study after modeling three types of 3, 5 and 8-story frames with 2, 3 and 4 spans by Sap2000 using two categories of earthquake records of far-field and near-field for different levels of peak ground acceleration (PGA), the process of forming plastic hinges has been investigated and evaluated by performing nonlinear time history analysis. The obtained results showed that the first plastic hinges were formed in the 3-story frames in the lower stories and in the case of the 5 and 8-story frames in the middle stories. Also, by applying the higher PGA, the formation of hinges in the upper floors of the frames is developed. furthermore, the frequency corresponding to the formation of the first collapse prevention (CP) hinge in the case of the 3-story frame with 2, 3, and 4 span is equal to 1.11, 1.31, and 1.22 Hz, in the case of the 5-story frame it is equal to 0.85, 1.03, and 0.94 Hz, and in the case of the 8-story frame it is equal to 0.44, 0.42, and 0.4 Hz, respectively. Other results showed that the behavior of 3-story frames under the effect of far-field records and the behavior of 5 and 8-story frames under the effect of near-field records are in higher dynamic instability conditions. Also, with the increase of spans and the number of floors, the possibility of damage and dynamic instability in the frames has increased. For all frames with different story numbers, by increasing the number of spans from 2 to 4, an increase of 5.88, 22.4 and 38.3% has been obtained respectively in the number of hinges formed in the frame.

Keywords: plastic hinge, moment frame, nonlinear time-history analysis, near-field and far-field earthquake

1. INTRODUCTION

In general, there are two methods for structural health monitoring, which include destructive and non-destructive methods. In the destructive method, by spending high costs, it is possible to identify the location or severity of the damage. High cost, time consuming and low accuracy are among the weak points of this method. The second method for monitoring the health of the structure is to use non-destructive methods. This method can be done without spending high costs and without the need to

perform executive operations, with high accuracy and based on the information and properties of the structure. One of the important topics in the field of research related to the health monitoring of structures is the identification of damage-sensitive features. Features are parameters or characteristics that are extracted from methods related to failure detection and make it possible to evaluate the behavior of structures in a healthy or damaged state. In monitoring the health of structures, in order to detect damage, methods based on the frequency responses of the structure have a higher advantage compared to other methods based on temporal or modal data [1,2].

In monitoring the health of the structure, the main assumption is that the occurrence of an earthquake is the cause of damage to the structure. It is also important that the occurrence of earthquakes in the near-field or far-field will not cause similar and identical damage to the structure due to the presence of some parameters such as directivity effects (in the case of records in the near-field) and permanent displacement (in the case of records in the far-field).

Therefore, when the natural frequency of the structure coincides with the high-domain regions of the Fourier spectrum of the earthquake record, the wide-amplitude responses will be occurred. This can be interpreted according to the phenomenon of resonance. In general, earthquake can lead to non-linear behavior in various structural components of steel moment frames. Non-linear behavior is one of the signs of changes in the performance characteristics of the structure. Also, identification of nonlinear behavior can be used in the diagnosis of failure of structural systems, including steel moment frames. In such a way that in the conditions of applying seismic loading (occurrence of an earthquake), depending on the magnitude and intensity of the earthquake, the formation of plastic hinges in members and connections will be seen. In this condition, the members and joints of the structure experience a significant reduction in stiffness. According to equation 1, the period of the natural modes of the structure will increase and the frequency of the modes of the structure will decrease (based on equation 2).

Therefore, as a result of seismic loading and according to the changes in the frequency of the main modes of the structure, for different levels of PGA from the earthquake record, the manner and position of the formation of plastic joints in the structure will be changed. In this situation, it is possible to identify the position and type of the plastic hinge created in the frame by applying different earthquake records, with different PGAs, and achieve the pattern of plastic hinge formation in the steel moment frame. In the following relations, m, k, T and f are mass, stiffness, period and frequency of the structure respectively. It is important that due to the application of lateral loads such as earthquakes, bending moments and shear forces are created in the beams and columns of the structure. By increasing the amount of PGA, formation of plastic hinges in the beam and columns will be possible.

The ideal situation is to observe the principle of weak beam-strong column, according to which, plastic hinges are formed first in beams and then in columns, that can delay the collapse of the structure. It should be noted that in moment frames, the PMM hinge (interaction of axial force and bending moment) is often assigned to the columns and the M hinge to the beams. Figure 1 shows the locations of possible hinges. Therefore, in the present study, an attempt has been made to obtain the pattern of plastic hinge formation in steel moment frames by applying two categories of earthquake records of the near-field and far-field at different levels of PGA. After that, through the identified pattern, the changes made in the frequency of the main modes of the structure has been identified.

$$T = 2\pi \sqrt{\frac{m}{k}} \qquad (1)$$

$$f = \frac{1}{T} \qquad (2)$$
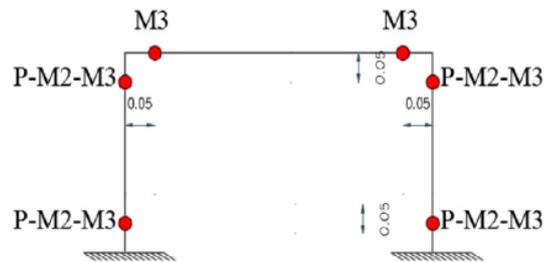
Figure1. The possible position of hinges in the moment frame [2]

Among the natural disasters that occur all over the world, earthquakes are one of the most complicated events that have claimed the lives of many people throughout human history, and it is considered one of the most destructive loads that will be applied to a structure during its lifetime. Therefore, one of the important goals in the field of structural and earthquake engineering is to establish sufficient safety for the structure under possible loadings during its useful length. Predicting and preventing the complete destruction of the structure and correctly estimating the behavior of the structures against the earthquake is considered one of the most important challenges for engineers in seismic design. Steel moment frames are considered as a very flexible system that can withstand the inelastic behavior of multiple members of the structure under strong earthquakes. The most desirable design process is that inelastic behavior occurs in the form of plastic hinges in the beams and near the connection of the beam to the column. In a building with a correct structural configuration, it is necessary to first form joints in several floors so that the intensity of the seismic demand for the total movement is not concentrated in one floor and is distributed throughout the structure. As a result, the amount of deformation in different points will be limited and the strains of the desired member will reach to such a level that it can be tolerated by the relevant element.

K Ahmadi et al. [3] identified damage in concrete girders of bridges by using squared time-frequency distribution and neural network. In their research, by using signal processing tools and artificial intelligence, features sensitive to damages have been extracted in such a way that the presence of damage, its severity and its location can be determined only by using the vibration response signals received from a sensor with a very high accuracy of about 99% and an error percentage of less than 1%. Based on the presented method, first by using the squared time-frequency function, the response signals received from the structure with different scenarios in healthy and damaged states with different percentages were processed, then using these data as input, the desired neural network has been trained and the corresponding outputs has been determined. In order to evaluate, validate and ensure the performance of the proposed method, the numerical model of a concrete beam and also the numerical model of Shahid Madani bridge of Tabriz in the normal and noisy state have been used. The results show the high detection accuracy of this method and the lowest error rate in determining the health of the structure as well as identifying the position of the damaged element. Sadeghian et al. [4] investigated damage in structures by updating the finite element model by benefiting from the changes in the wavelet coefficients of the correlation function. The wavelet conversion coefficients obtained in this research have been updated in the range of natural frequencies and also in the vicinity of resonances where damping and incomplete measurements do not have a significant effect on the parameter estimation results, in order to identify damage in the target structure. The proposed algorithm is used to estimate the structural parameters of the frame model. By solving the sensitivity equation using the least squares method, the finite element model of the structure has been updated to estimate the location and severity of structural damage simultaneously. The ability of the method has been studied numerically, on the frame structure, in several damage scenarios. The results show the power of the method in detecting damage against modeling and mass measurement errors by adding random errors to the simulation of damaged model data and mass parameters. Kourehli [5] investigated the health monitoring of steel frame

joints using wavelet transformation. After the damaged frames are excited under earthquake accelerogram, the time history of velocity response in different degrees of freedom is obtained and decomposed using wavelet transform. After analyzing the time history of the structure's response, the detail coefficients have been obtained. Examining these coefficients indicates that the maximum detail coefficient has been obtained at the time of causing damage to the connections. In other words, the proposed method has been able to identify the occurrence of damage in the beam-column connections of steel frames with high accuracy. Haseli and Kheiri [6] used reduced interference distribution functions and tensor method to diagnose seismic damage in the concrete bridge of Kordestan-Mullasadra street. The results of this study showed that, based on the signals recorded by the hypothetical displacement sensor, the most vulnerable middle pier of the Kurdistan Bridge - Mulla Sadra Street is the middle pier number 8. Sahib al-Zaman et al. [7] evaluated the effects of plastic hinge modeling of rigid connections on the progressive failure resistance of steel moment frames. The obtained results show that by defining and applying plastic hinges at the joints, beams and columns, the structure shows less resistance to progressive damage and the structure's resistance is closer to its real value. The simultaneous modeling of plastic hinges for connections and members has a

minimum of 20% and a maximum of 37% effect on the reduction of the structure's resistance against progressive failure. Therefore, modeling of plastic hinges of joints and members at the same time should be considered as a principle. Khalili et al. [8] predicted the plastic hinge length of reinforced concrete bridge foundations using artificial neural network algorithms. The results of this study showed that the neural network algorithm will be highly accurate in predicting the necessary parameters to predict the length of the plastic hinge. Huras et al. [9] numerically analyzed the formation of plastic hinges in moment frames under the effect of an earthquake. The results of this study showed that under the effect of earthquakes with different intensities, the period of plastic hinges and their type and position in moment frames will be changed. Therefore, to monitor the health of the structure, it is very efficient and beneficial to check the formation position and the type of plastic hinges. Considering the significant volume of studies conducted in the field of structural health monitoring, as well as significant studies in the field of evaluating the seismic behavior of various structures with regard to the position of the formation of plastic hinges, it indicates the importance of the subject studied in the present research. In this study, the main goal is to investigate the pattern of plastic hinge formation in steel moment frames due to near-field and far-field earthquakes. A topic that has been less paid attention to by researchers in this field.

2. MATERIALS AND METHODS

The investigated models are introduced in nFm form, which are showed in table 1. In this nomenclature, n represents the number of floors, F represents the steel moment frame and m represents the number of spans. It should be noted that after analyzing the frames, the type and position of the plastic hinges will be recorded at the same time as the main mode frequency of the frame. According to the number of analyzes performed, it is possible to obtain the pattern of plastic hinge formation in steel moment frames under the effect of near and far field records. Therefore, the basic answers considered in the current research include the following:
- ✓ The type of plastic hinges formed for different earthquake levels

- ✓ The position of forming plastic hinges for different earthquake levels
- ✓ The main mode frequency of the studied frames

Gravity loading for the frames was applied based on Iran National Building Code (6th topic) [10]. It is important to note that as 2D frames would be analyzed, a frame has been selected from the 3D structure. The frames studied in the current research include 3, 5 and 8-story frames with 2, 3 and 4 spans. The height of the 3, 5, and 8-story frames is 9.6, 16, and 25.6 meters, respectively. Also, the width of 2, 3 and 4-span frames is equal to 11.5 (5.5+5), 15 (5.5+5+4.5) and 19.5 meters (5.5+5+4.5+5.5) respectively. The hinges introduced to beams and columns are automatically defined and assigned to

the frame. The hinges assigned to the beam element are of M3 type and the hinges assigned to the column element are of P-M2-M3 type. All hinges are considered at distances of 0.033 from the two ends of the element. According to the application of two sets of triple earthquake records, the final reflection of the frame is equal to the maximum response of the frame according to the applied records. Based on the obtained results, the most reflections of the studied frames regarding the records of the near and far-field are respectively related to the Loma prieta and Northridge earthquake records. Therefore, here, the results have been obtained only for two records of Loma prieta (reflection of the records of the near-

field) and Northridge (reflection of the records of the far-field). It should be noted that in all models Rayleigh damping is determined according to the period of the main mode of the structure and the integration method is the Hilbert-Hughes-Taylor method. In order to select the earthquake accelerograms for structural analysis, the pulses of the velocity and displacement components of the earthquake records were visually compared and the records with more and stronger pulses were selected. These earthquake maps were obtained from PEER earthquake database. Totally, 3 earthquake records of the near and 3 far-field were selected, whose characteristics are presented in table 2.

Table 1. Modeled steel moment frames.

Name	Steel Moment Frame
3F2	**3-Story, 2-Span**
3F3	**3-Story, 3-Span**
3F4	**3-Story, 4-Span**
5F2	**5-Story, 2-Span**
5F3	**5-Story, 3-Span**
5F4	**5-Story, 4-Span**
8F2	**8-Story, 2-Span**
8F3	**8-Story, 3-Span**
8F4	**8-Story, 4-Span**

Table 2. Earthquake records of near and far-field used for time history analysis

	Earthquake records	Magnitude	PGA
Far-field	Big bear(1992)	4.7	**0.531**
	Northern(1941)	5.7	**0.561**
	Northridge(1994)	6.7	**0.563**
Near-field	Northridge-JFP(1994)	6.7	**0.416**
	Loma prieta(1989)	6.93	**0.376**
	Northridge – Syl(1994)	6.93	**0.340**

2.1. Verification

In order to ensure the modeling of steel frames, the period related to the main mode of 3, 5 and 8-story 2-span frames was obtained by Sap2000 and compared with the period resulted from relationships of steel moment frame presented in the Iranian seismic code (called 2800 standard [11]). Figure 2 shows the image of three frames studied in this research. The period of the first mode of the studied frames can be

compared in Table 3 with the results obtained based on the practical period relationship of Iranian seismic code. It can be seen that the maximum difference between the period obtained from the software models and the period calculated based on Iranian seismic code is equal to 2.3%. This insignificant difference indicates the acceptable accuracy of the modeling process.
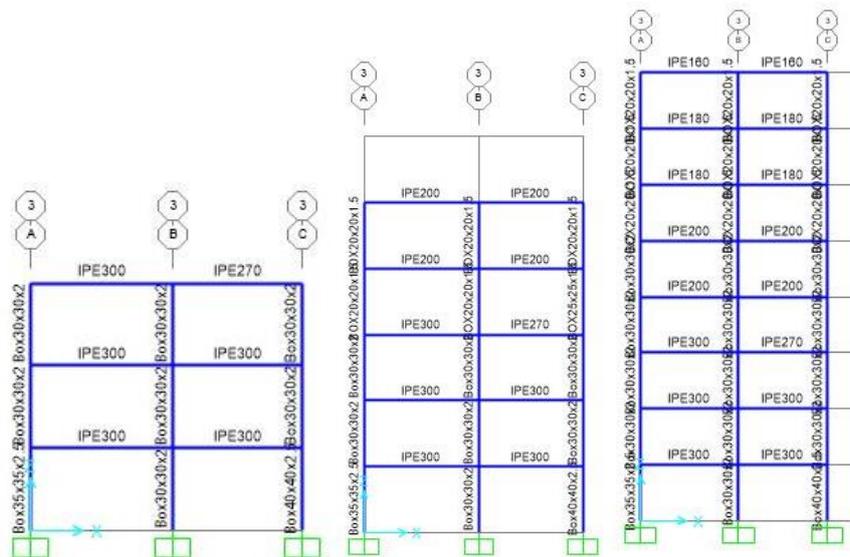
**Figure 2.** Schematic image of frames used for verification

Table 3. Verification results

frame	Iranian seismic code	Sap2000	Difference%
Period of first mode of 3-story frame (sec)	0.545	0.541	**0.73**
Period of first mode of 5-story frame (sec)	0.8	0.787	**1.6**
Period of first mode of 8-story frame (sec)	1.138	1.111	**2.3**

3. RESULTS AND DISCUSSION

The results include the frequency of the frame's main mode and the position of plastic hinges in the studied frames. The results have been analyzed and evaluated separately for 3, 5 and 8-story frames. After that, it was tried to use the obtained results to obtain the pattern of plastic hinge formation according to the frequency value in each category of the studied frames. Therefore, the formation of plastic hinges for different levels of PGA for 3, 5 and 8-story frames (2-3-4 spans) is provided. Due to the significant number of samples, in this section, only the images of the formation of plastic hinges of selected models are displayed. Based on the obtained results, as the number of hinges formed in the frames under the effect of far-field earthquake is higher, it can be concluded that for 3-story frames the behavior of the frame under the effect of the records of the far-field is more critical compared to the near-field. Also, the results showed that with the formation of plastic hinges, the main mode frequency of the frame has

decreased. This issue is justified due to the reduction of the stiffness of the frame by formation of plastic hinges. Considering that the CP hinge represents the start of failure in the frame, according to the frequency corresponding to the formation of the plastic hinge at the threshold of collapse, it is possible to monitor the health of the frame. for frequency values lower than the frequency corresponding to the formation of the first plastic hinge, the failure of the structure will be definitely occurred. Furthermore, it is observed that the frequency corresponding to the formation of the first CP plastic hinge for the 3-story frame with 2, 3, and 4 spans is equal to 1.11, 1.31, and 1.22 Hz, respectively. In other words, in these frames, if the frequency of the frame, due to the formation of the plastic hinge and reduction of stiffness, is lower than the frequency values corresponding to the formation of the first CP joint of the frame, the collapse or destruction of the 3-story frame will be occurred.

0.1g

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0.3g

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0.5g

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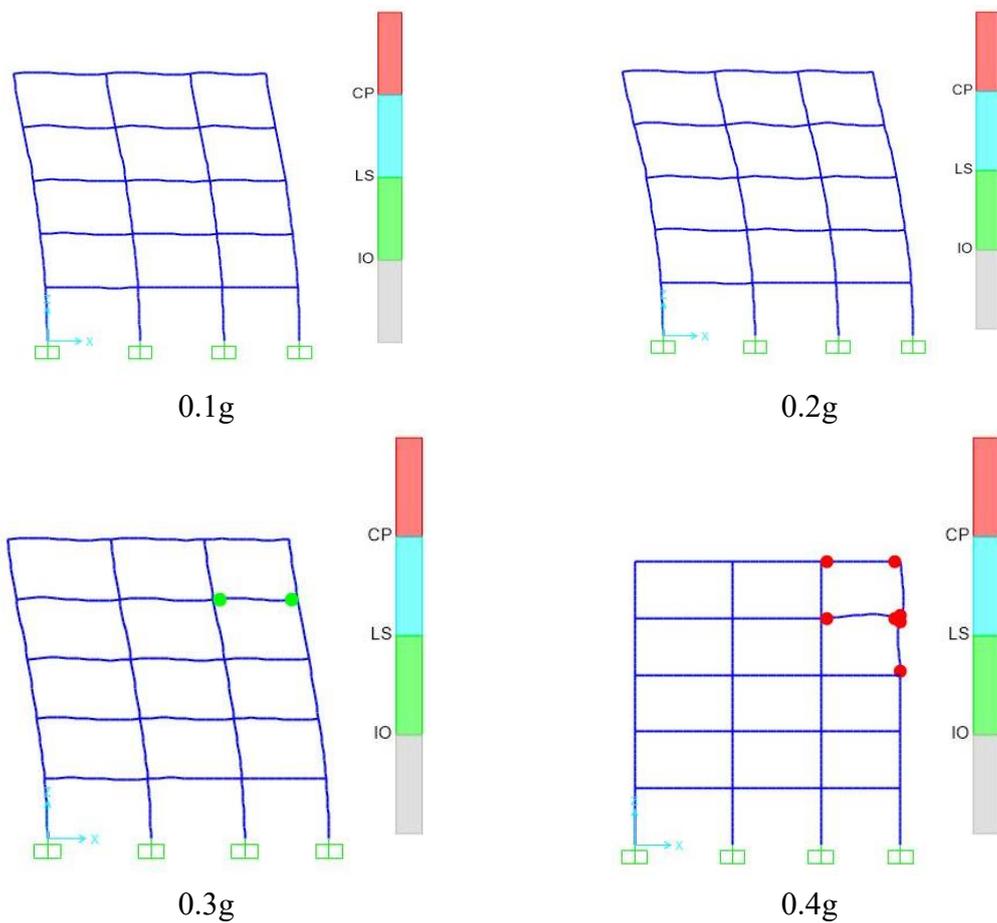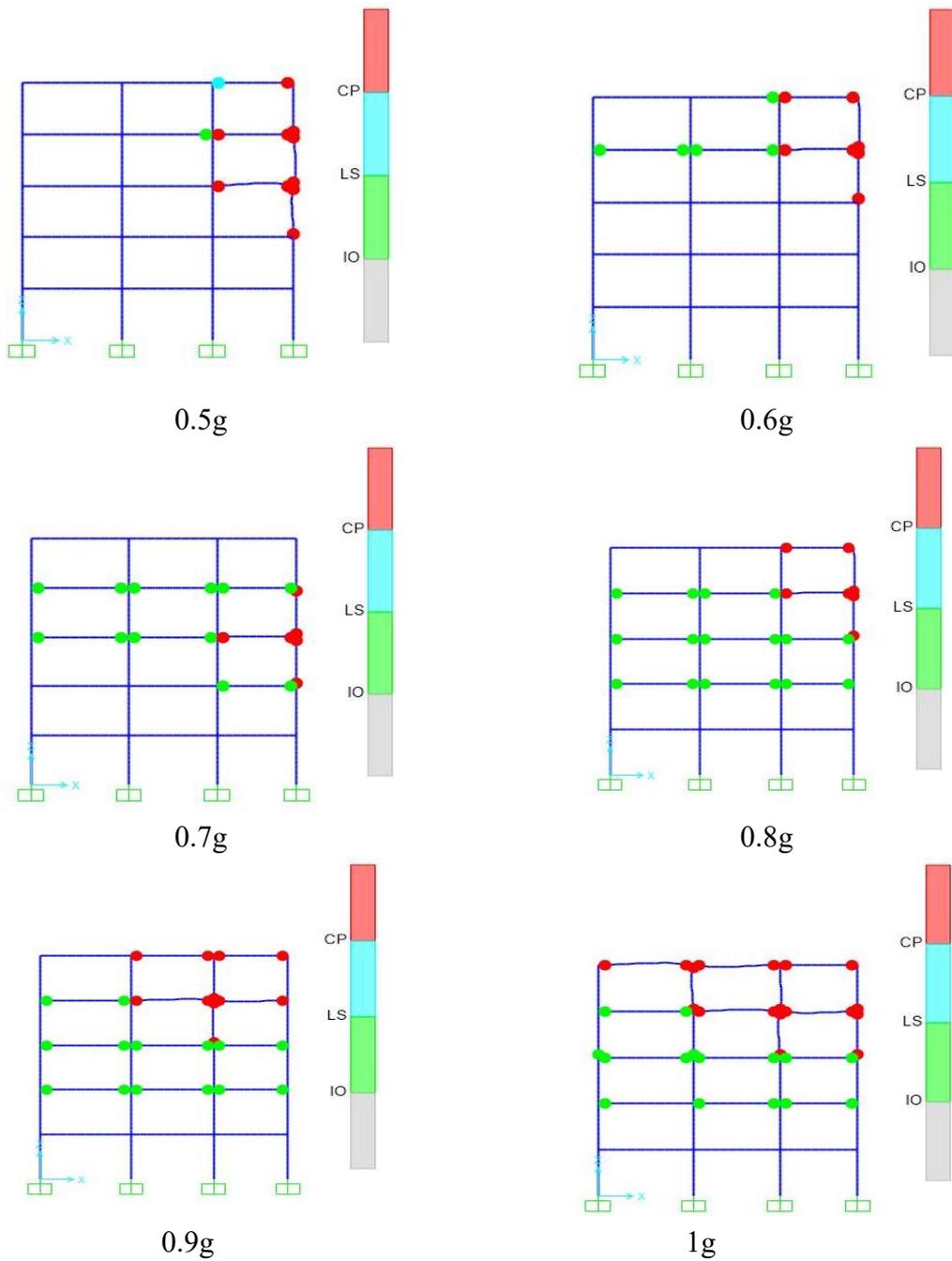0.9g   1g
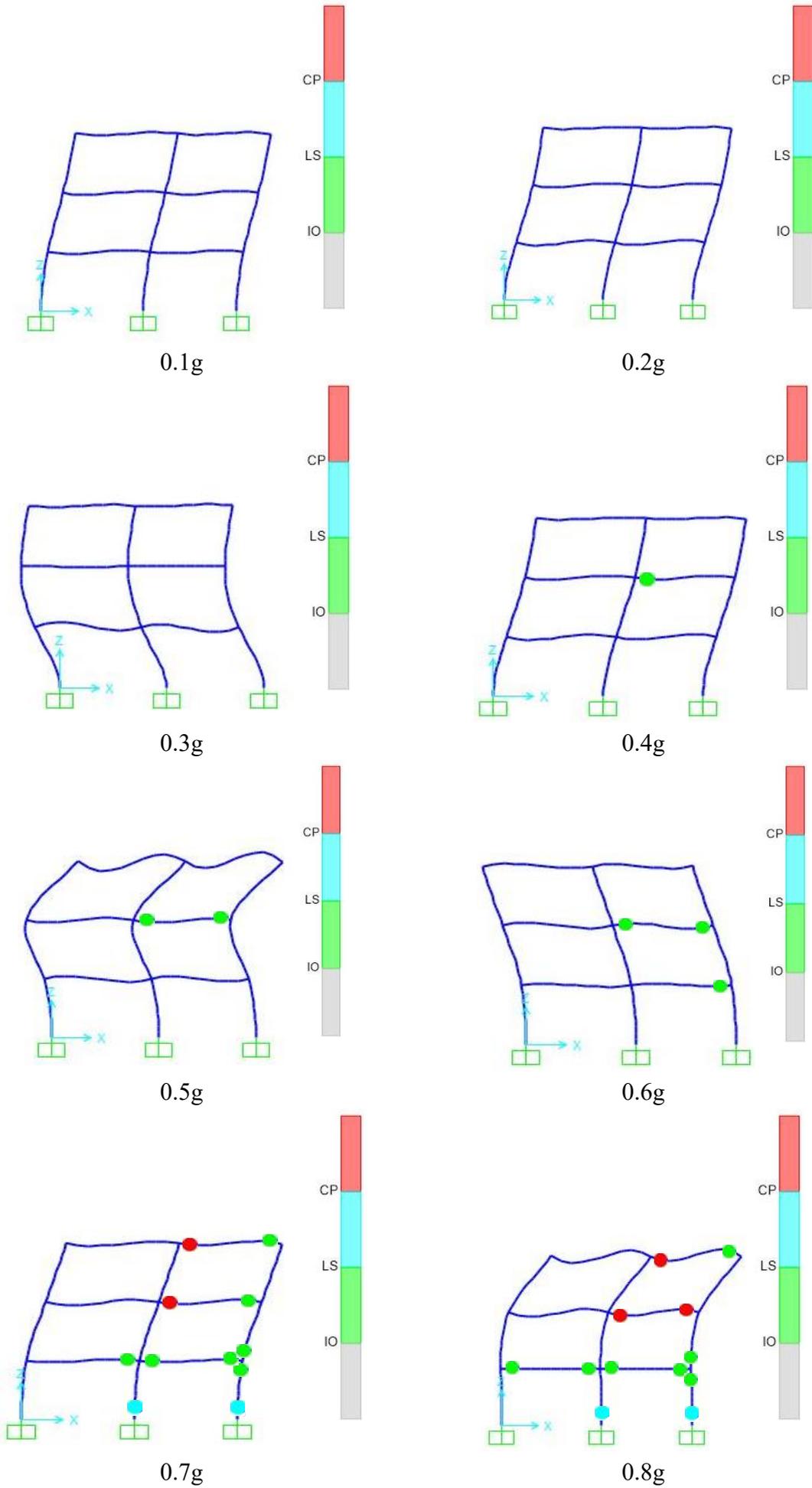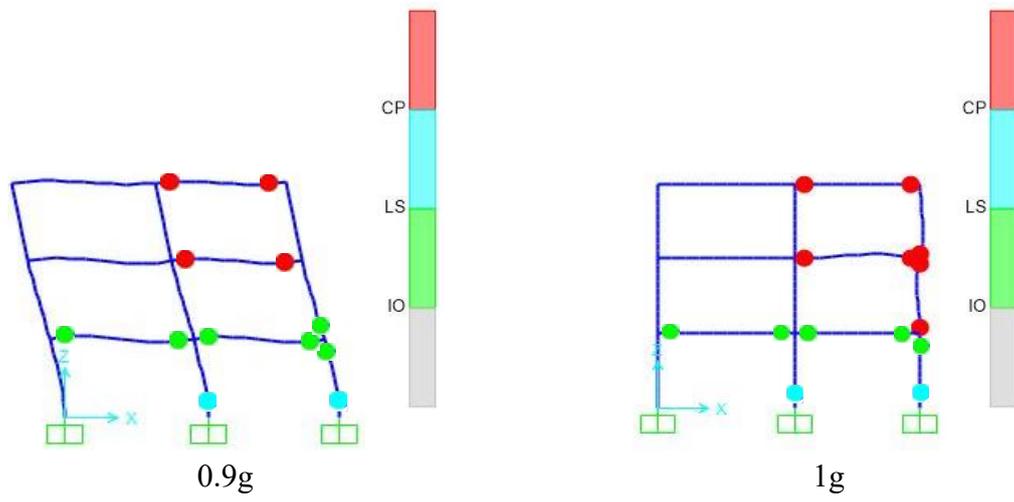
Figure 3. Formation process of plastic hinges in a 3-story, 2-span frames for different earthquake levels near-field Loma prieta.
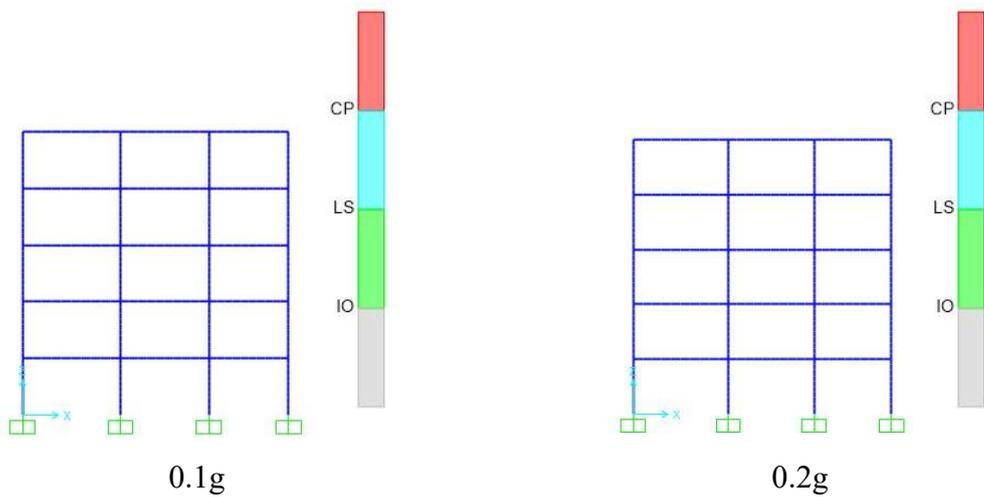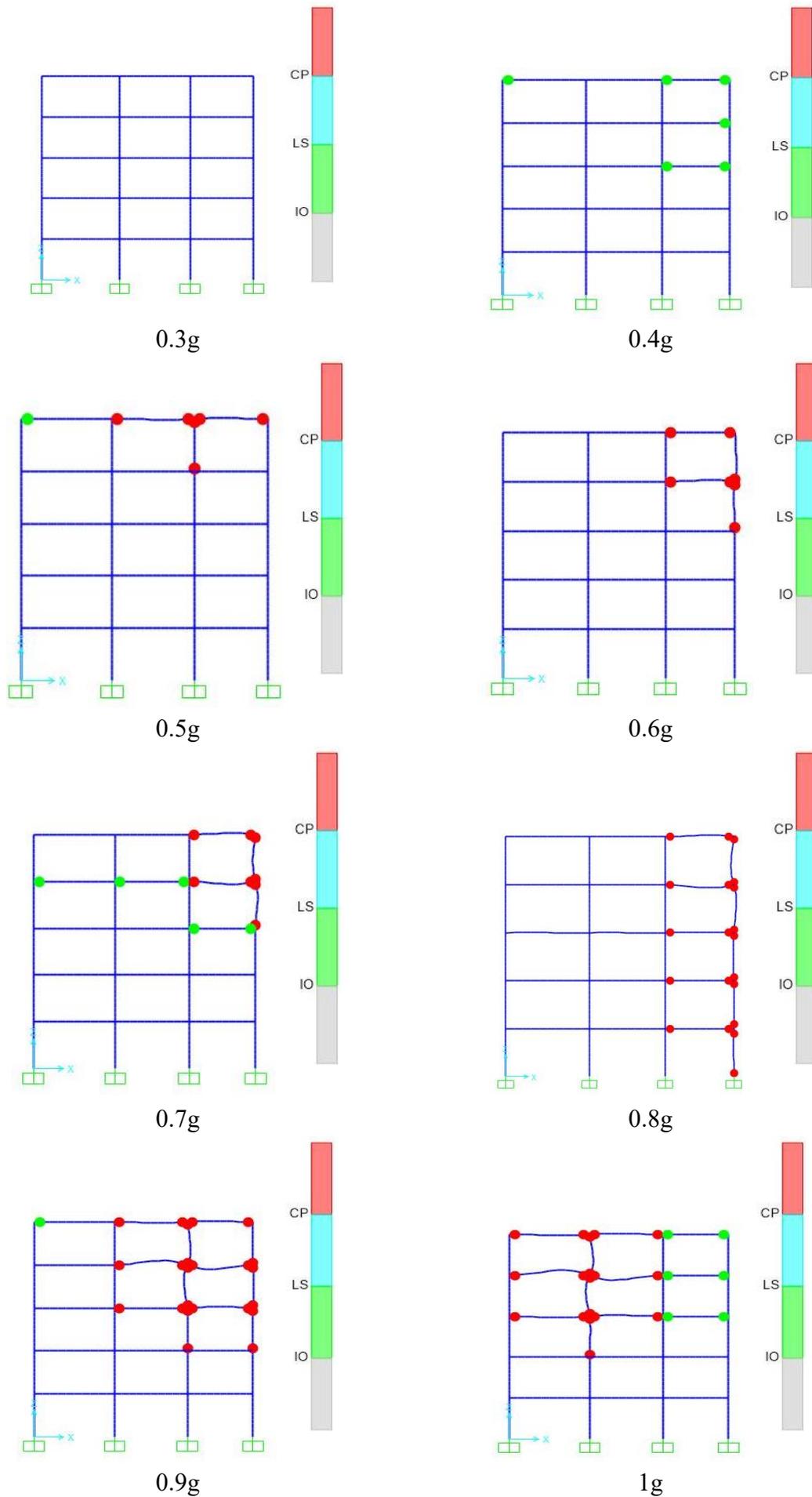

0.1g   0.2g

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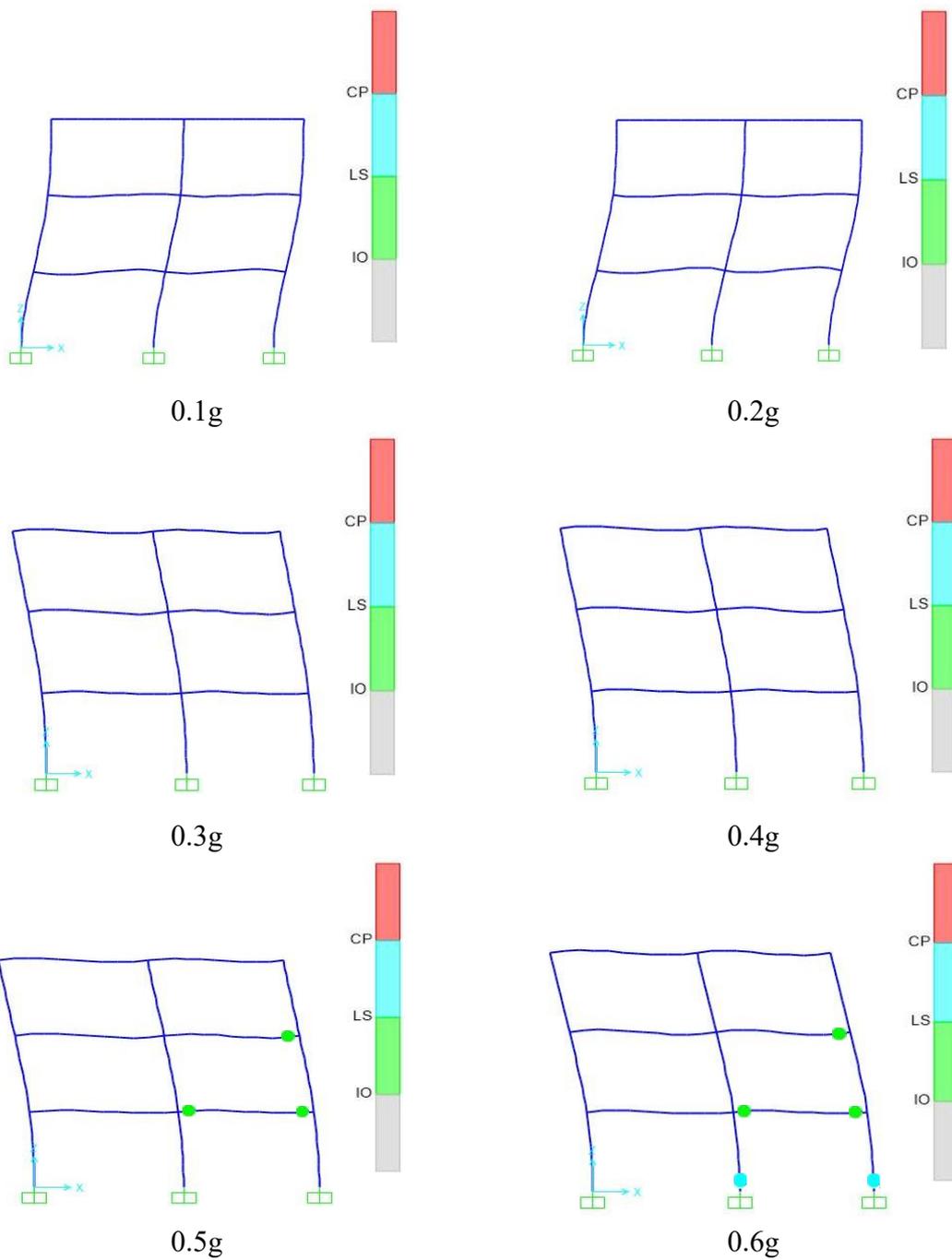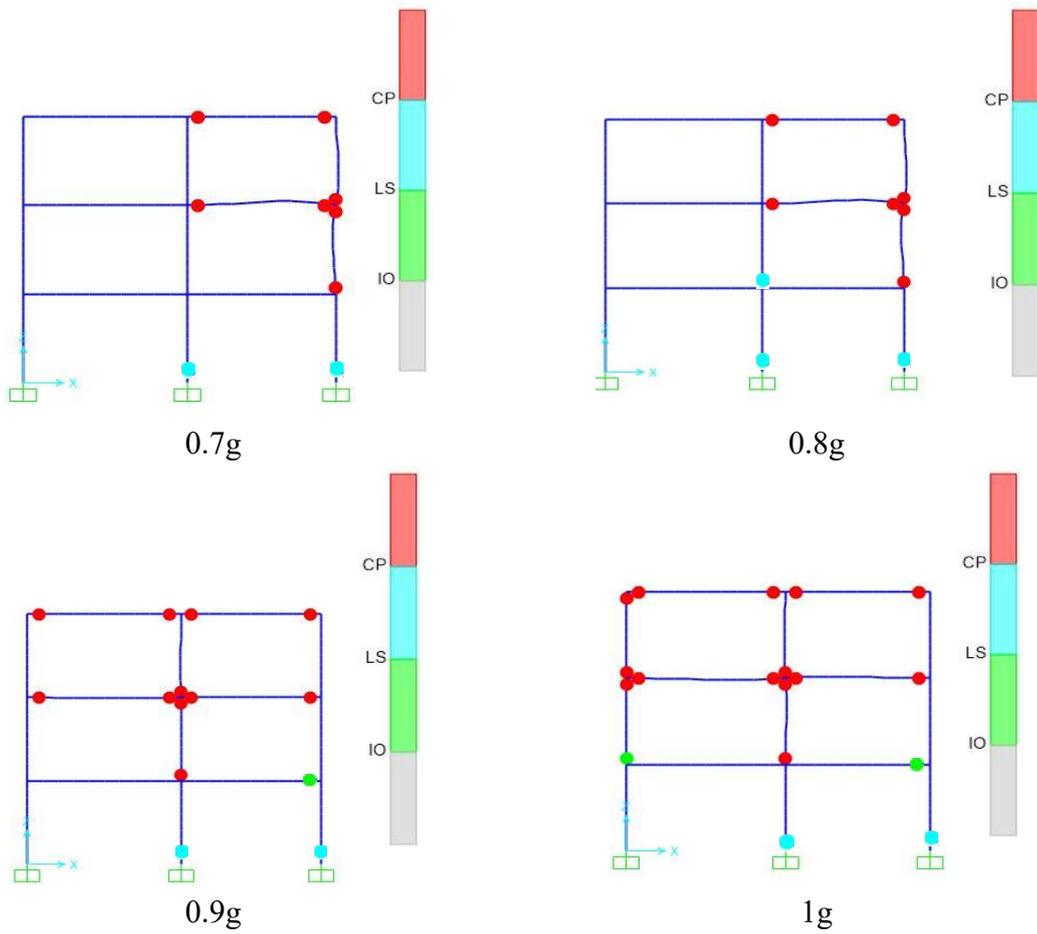
Figure 4. Formation process of plastic hinges in a 3-story, 2-span frames for different earthquake levels far-field Northridge

0.5g

0.6g

0.7g

0.8g

0.9g

1g

Figure 5. Formation process of plastic hinges in a 5-story, 3-span frames for different earthquake levels near-field Loma prieta
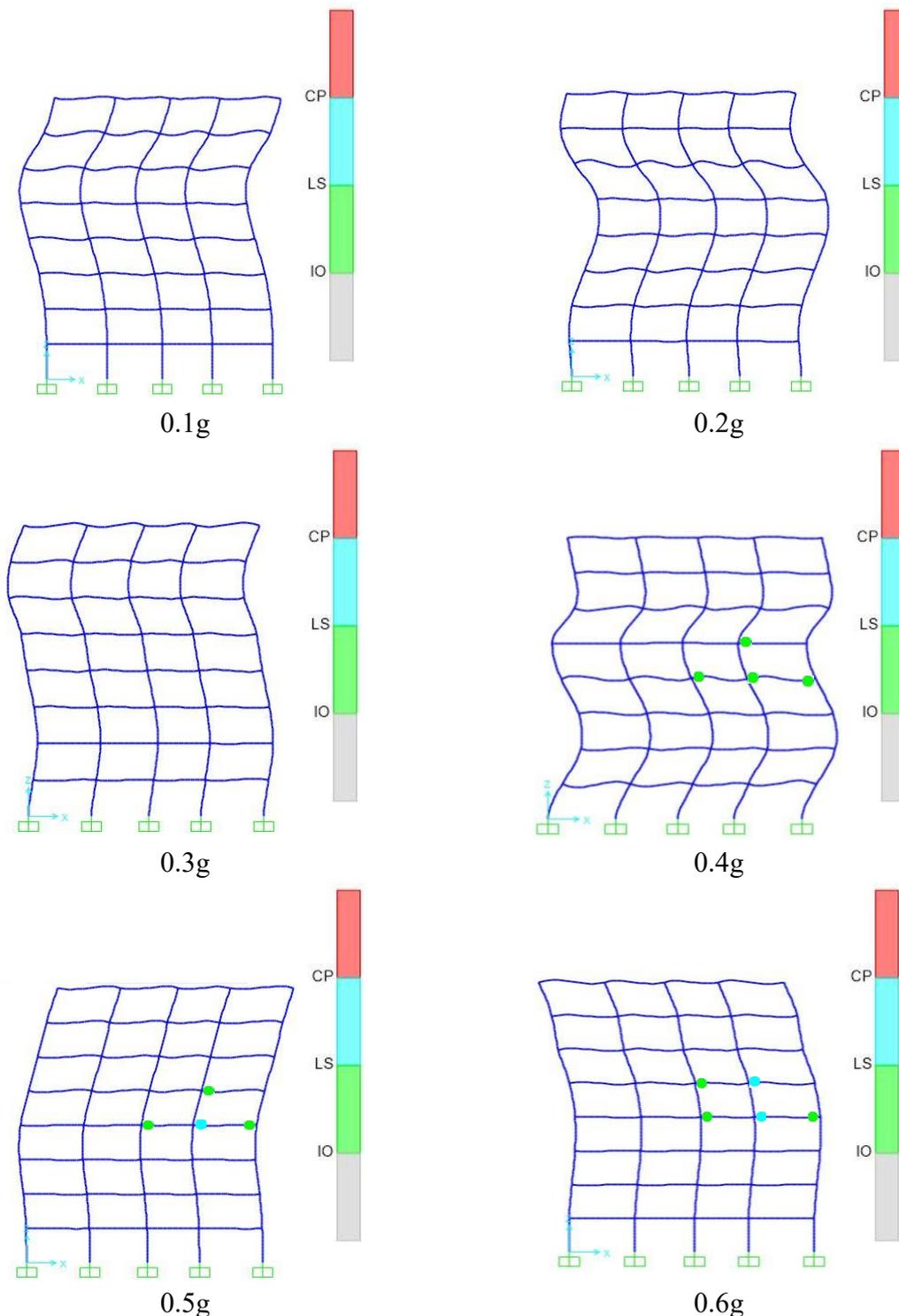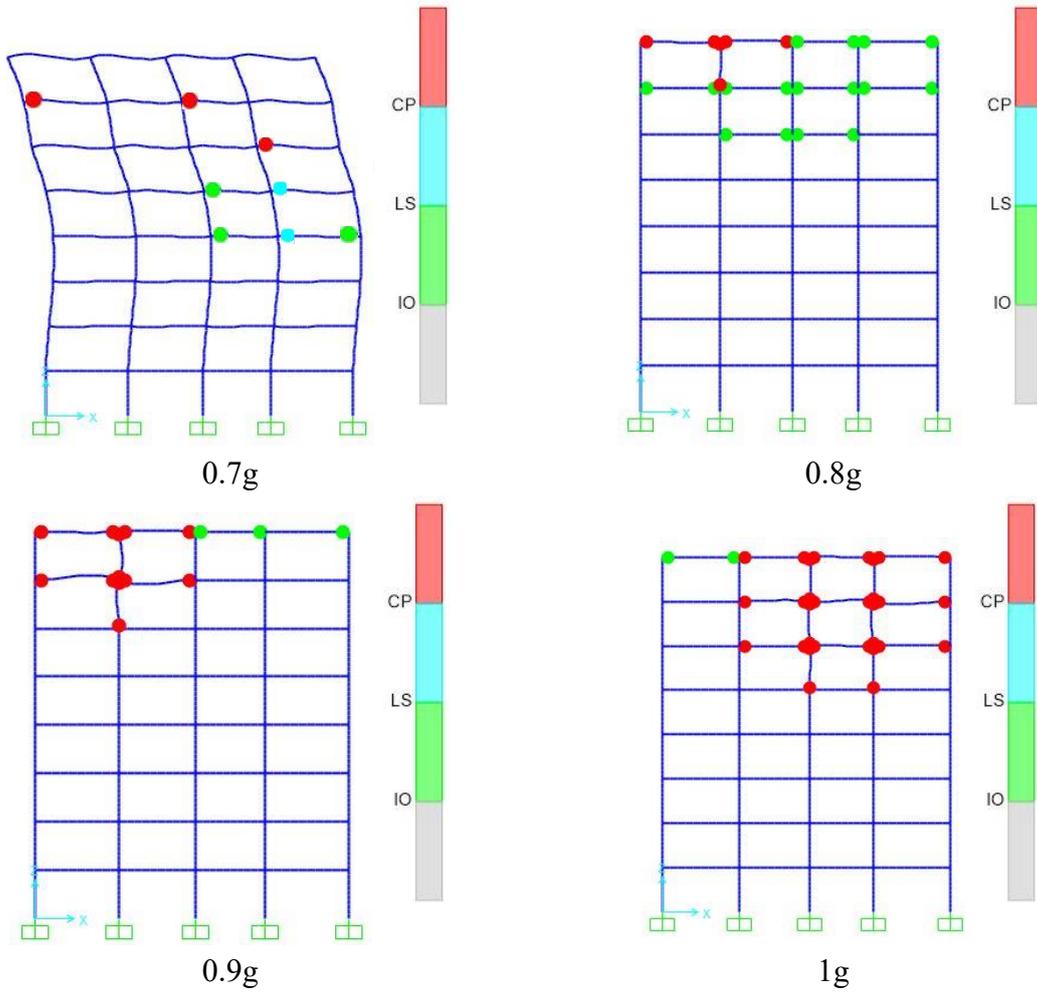
0.1g

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Figure 6. Formation process of plastic hinges in a 5-story, 3-span frames for different earthquake levels far-field Northridge
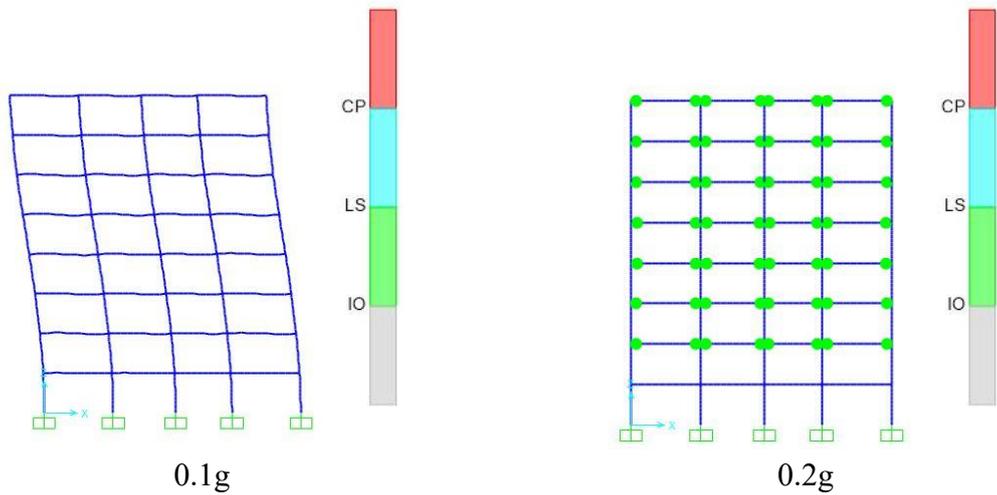
For the 5-story frames, the behavior of the frame under the effect of the records of the near-field is more critical compared to the records of the far-field, because the number of hinges formed under the effect of the record of the near-field is higher. Also, the results indicate that by formation of plastic hinges, the main mode frequency of the frame showed a decreasing trend. This issue can be justified by reduction of the stiffness of the frame due to formation of plastic hinges. Also, it can be seen that the frequency corresponding to the formation of the first plastic hinge (CP) for the 5-story frame with 2, 3, and 4 spans is equal to 0.85, 1.03, and 0.94 Hz, respectively. In other words, in these three types of frames, if the frequency of the frame becomes lower than the frequency values corresponding to the formation of the first CP hinge, due to the reduction of stiffness, the failure and total destruction of the frame will be occurred.

0.1g

0.2g

0.3g

0.4g

0.5g

0.6g

0.7g

0.8g

0.9g

1g

Figure 7. Formation process of plastic hinges in 8-story, 4-span frames for different earthquake levels near-field Loma prieta.

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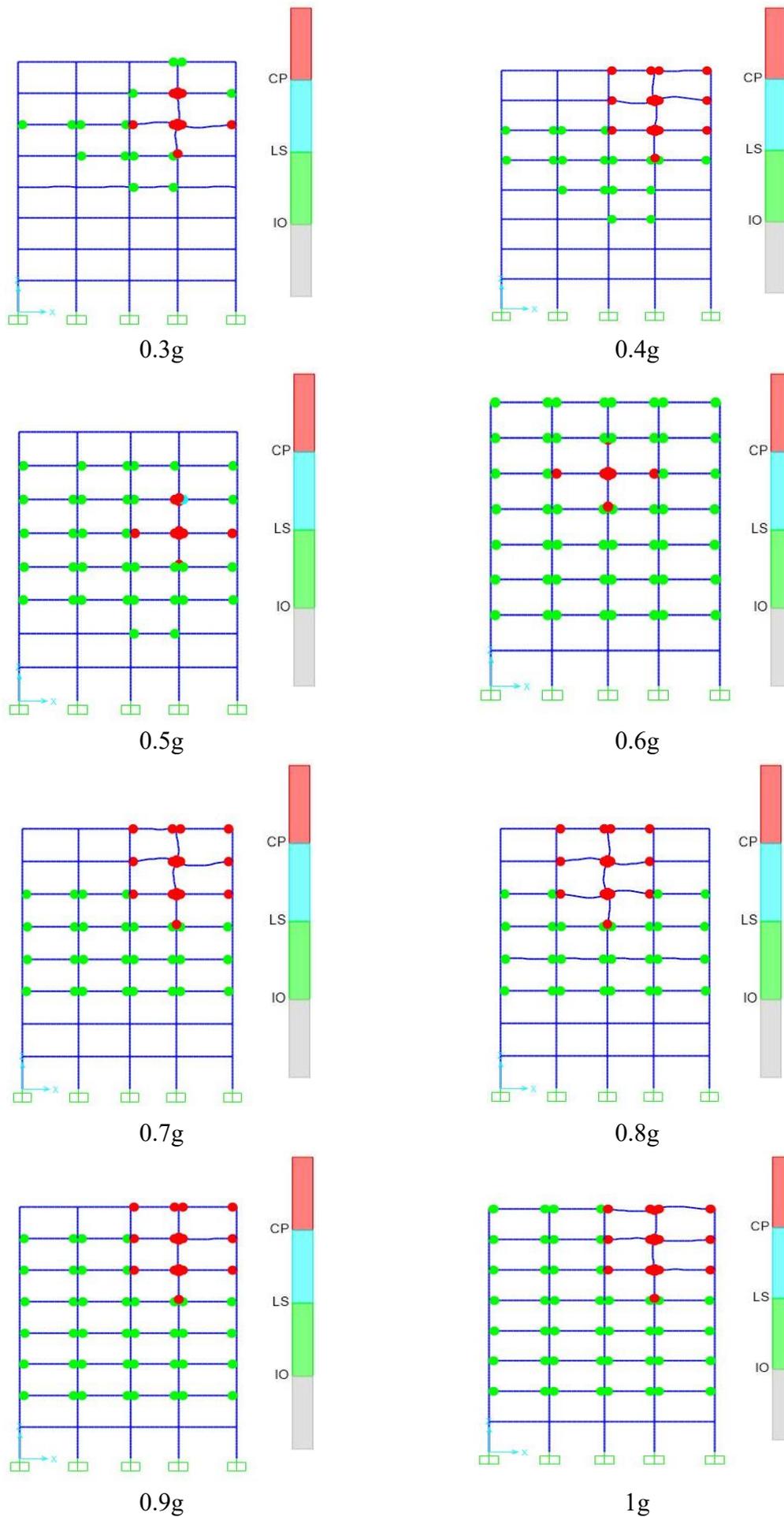
Figure 8. Formation process of plastic hinges in 8-story, 4-span frames for different earthquake levels far-field Northridge.

Based on the results, it can be concluded that about the 8-story steel moment frames, the behavior of the frame under the effect of the records of the near-field is more critical compared to the records of the far-field. That is because the number of hinges formed in all the 8-story frames under the effect of near-field earthquake is more than the far-field ones. Also, the obtained results indicate that with the formation of plastic hinges -similar to the 3 and 5-story frames- the numerical value of the main mode frequency of the frame had a decreasing trend. This issue is justified by reduction of the frame stiffness due to the formation of plastic hinges. Furthermore, it can be seen that the frequency corresponding to the formation of the first plastic hinge (CP) for the 8-story frame with 2, 3, and 4-spans is equal to 0.44, 0.42, and 0.4 Hz, respectively. In other words, in these three frame types, if the frequency of the frame is lower than the frequency values corresponding to the formation of the first CP hinge, failure and collapse of the frame will be occurred. Tables 4 to 6 show the position of the formation of the first plastic

hinge in all the models. In order to investigate the effect of the height of the frame and the number of spans on plastic hinges formation, the average number of plastic joints formed under the effect of near and far-field is presented in table 7. The obtained results indicate that by increasing the number of spans, number of plastic hinges will be increased. In fact, in 3, 5 and 8-story frames, by increasing the number of spans from 2 to 4, number of hinges formed will be increased by 5.88%, 22.4% and 38.3% respectively. It can be seen that this increasing trend is more noticeable with increasing the height of the frame. Other results show that increasing the height of the structure can increase the number of hinges which made the frame unstable. By increasing the height of the frame from 3 to 8 floors, the number of plastic hinges formed in 2, 3, and 4-span frames has increased by 41.4%, 74.7%, and 61.7%, respectively. In other words, by increasing the number of spans and floors, the possibility of damage and dynamic instability in the frame has increased.

Table 4. Position of the formation of the first plastic hinge in the 8-story, 2-span frame under the near and far-field records

Performance level	8st-2sp-loma		8st-2sp-northridge	
	Frequency (Hz)	Location	Frequency (Hz)	Location
IO	10.58	4th floor	10.78	4th floor
LS	10.53	7th floor	10.7	6th floor
CP	10.35	5th floor	10.43	6th floor

Table 5. Position of the formation of the first plastic hinge in the 8-story, 3-span frame under the near and far-field record

Performance level	8st-3sp-loma		8st-3sp-northridge	
	Frequency (Hz)	Location	Frequency (Hz)	Location
IO	11.56	2nd floor	11.62	4th floor
LS	10.82	2nd floor	11.62	4th floor
CP	11.26	5th floor	11.19	5th floor

Table 6. Position of the formation of the first plastic hinge in the 8-story, 4-span frame under the near and far-field records.

Performance level	8st-4sp-loma		8st-4sp-northridge	
	Frequency (Hz)	Location	Frequency (Hz)	Location
IO	11.7	4th floor	11.73	2nd floor

LS	11.7	4th floor	11.5	**6th floor**
CP	11.31	5th floor	11.5	**4th floor**

Table 7. The average number of plastic hinges.

	3-Story	**5-Story**	**8-Story**
2-Span	17	26	**29**
3-Span	10.5	28.5	**41.5**
4-Span	18	33.5	47

4. CONCLUSION

The main goal of the current research is to investigate the pattern of plastic hinges formation in steel moment frames due to near and far-field earthquakes. Therefore, after modeling three types of frames with 3, 5 and 8 stories with 2, 3 and 4 spans by Sap2000, two categories of far and near earthquake records have been applied to the frames. Then the process of forming plastic hinges has been investigated and evaluated by performing nonlinear time-history analysis. It should be noted that this process has been carried for different levels of PGA records. After that, due to the reduction of the stiffness of the frame by formation of plastic hinges, the frequency corresponding to the formation of the first hinge at the CP level of the frame has been identified, and the effect of the height and spans on the process of the formation of plastic hinges has been investigated. It should be noted that due to the use of two sets of triple earthquake records, the final reflection of the frames for the records of the near-field has been obtained under the effect of the Loma prieta earthquake record. Also, the final reflection of the frames, according to the records of the far-field earthquake, has been obtained by Northridge earthquake record. Therefore, the results have been compared and evaluated only for these two earthquake records. The most important results obtained from this study are as follows:

1- In 3-story frames the first plastic hinges were formed in the lower floors of this frame, and in the 5- and 8-story frames, the first hinges were formed in the middle floors, which are developed in the upper floors by increasing the earthquake level (PGA).

2- The 3-story frames, under the effect of far-field records, and the 5 and 8-story frames, under the effect of near-field records of the earthquake, show more critical behavior and are exposed to more dynamic instability.

3- The frequency corresponding to formation of the first CP hinge in the 3-story frame with 2, 3, and 4 spans have been obtained in 1.11, 1.31, and 1.22 Hz, respectively. In other words, in these frames, if the frequency of the frame - due to the formation of the plastic hinge and reduction of stiffness - is lower than the frequency values corresponding to the formation of the first CP hinge, the failure and destruction of the 3-story frame will be occurred.

4- The frequency corresponding to the formation of the first CP plastic hinge for the 5-story frame with 2, 3, and 4 spans is equal to 0.85, 1.03, and 0.94 Hz, respectively. In other words, in these frames, if the frequency of the frame - due to the formation of the plastic hinge and reduction of stiffness - is lower than the frequency values corresponding to the formation of the first CP hinge, the failure and destruction of the 5-story frame will be occurred.

5- The frequency corresponding to the formation of the first CP plastic hinge for the 8-story frame with 2, 3, and 4 spans is equal to 0.44, 0.42, and 0.40 Hz, respectively. In other words, in these frames, if the frequency of the frame - due to the formation of the plastic hinge and reduction of stiffness - is lower than the frequency values corresponding to the formation of the first CP hinge, the failure and destruction of the 8-story frame will be occurred.

6- By formation of plastic hinges, in all the studied frames (3, 5 and 8-story), the numerical value of the main mode frequency of the frame has had a decreasing trend. This issue is justified by reduction of the stiffness of the frame due to the formation of plastic hinges.

7-By increasing the number of spans, number of plastic hinges formed in each of the studied frames has been increased. In fact, in 3, 5 and 8-story frames, by increasing the number of spans from 2 to 4, an increase of 5.88%, 22.4% and 38.3% in the number of hinges has been observed, respectively. This increasing trend is more noticeable by increasing the frame height.

8-By increasing the height of the frame, the number of plastic hinges will be increased and as a result, the structure will be placed in an unstable position. The obtained results show that by increasing the height of the frame from 3 to 8-story, the number of plastic hinges formed in 2, 3 and 4-span frames has increased by 41.4%, 74.7%, and 61.7%, respectively. In other words, by increasing the number of spans and height of the frame, the possibility of damage and dynamic instability has increased.

5. REFRENCES

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