The effect of far field and near field earthquakes on the hysteresis energy and relative displacement of steel moment resisting frame structures

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Abstract Various types of research studies show that other parameters are also involved in seismic response of structures and only the force–displacement issue in elastic or even bilinear elastic perfectly plastic states is not capable of justifying the entire seismic behaviors of structures. Therefore, researchers are seeking to propose a new method in the seismic design of structures. In this regard and during the last two decades, the subject of energy has been highly taken into consideration, because by advances obtained in this method a lot of proposed parameters and behaviors in seismic design of structures have become justifiable and applicable in design process. In the current research, nonlinear dynamic analysis has been conducted under Loma Prieta, Landers, and Northridge earthquakes in far and near field on three ordinary moment resisting frames structures with 3, 6, and 12 stories in SAP2000 (VER 16.0.0) software. Hysteresis energy distribution and maximum relative displacements in buildings stories were extracted. The obtained results showed that *near-fault earthquakes* result in larger relative displacements of stories than *far-fault*.

Keywords Relative displacement · Far and near fault earthquakes · Seismic design of structures · Nonlinear dynamic analysis

1 Introduction

One of the great challenges of human in the history of his habitation on Earth has been dealing with natural disasters and protecting life and property against these events. Iran is among the high seismically active countries of the world. In the recent years, a *large earthquake with big loss of life and massive financial losses* has struck one part of the country *every 5 years* on average, and unfortunately, now Iran is amongst the countries in which earthquake is always accompanied by the possibility of high life's losses.

Various types of research studies show that other parameters are also involved in seismic response of structures and only the force–displacement issue in elastic or even bilinear elastic perfectly plastic states is not capable of justifying the entire seismic behaviors of structures. Therefore, researchers are seeking for proposing a new method in the seismic design of structures. Moreover, it has been found that the destructive effects of the earthquake are highly influenced by the input seismic energy to the structure during earthquake which its prediction is not completely possible by nonlinear response spectra or even displacement.

Housner [1] proposed, for the first time, an analysis of *limit state energy-based design*, in which the adequate energy absorbing capacity of structure against strong earthquakes was proposed as a safety and health factor of the structure. He said that a *portion of the earthquake* input energy is dissipated during earthquake, and a portion remains as kinetic and strain energy.

Investigating input energy, hysteresis energy and the ratio of cumulative hysteresis energy to input energy for multi degree of freedom (MDOF) and single degree of freedom (SDOF) structures, 3 and 10 stories with different structural characteristics subjected to four recorded earthquakes, McKevitt et al. [2] concluded that the energies that are

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dissipated during inelastic deformation are dependent to force–deformation properties, yielding strength, and damping, and the input energy percentage dissipated by hysteresis action, is almost the same for different records [3, 4].

Zahrah and Hall [5] studied affecting parameters on seismic energy absorption in single degree of freedom systems and concluded that ductility alone does not account for parameters of *strong ground motion duration*, frequency content, and cumulative plastic deformation.

Akiyama [6] published a book in the field of limit state design of structures, in which the fundamental principles of energy method were described using the method proposed by Housner and accordingly Akiyama presented a method for the design of steel structures [6]. Akbas [7] presented a method for designing steel frames, in which the energy dissipation capacity of frame members such as beam and column are first obtained based on former experimental studies on rigid full-scale frames. Then using an empirical formula, the amount of damping energy is calculated as a percentage of input energy and the difference between input and damping energies is defined as hysteresis energy. Through this energy distribution along the *height of building* and calculation of each beam contribution to the hysteresis energy, beam sections are obtained and columns are also designed based on capacity design conception. In addition, Amiri et al. [8] studied energy distribution and hysteresis damage within a number of reinforced concrete moment frames with shear wall designed based on regulations of *Earthquake-Resistant Design of Buildings* (Third edition, *STANDARD 2800*) [9]. They concluded that despite the uniform distribution of strength along the height, the distribution of hysteresis energy, damage, and relative displacement in height are not exposed to strong uniform movements and the mentioned parameters concentration is seen in one or two stories [10–12].

Results from performed studies showed that approximately all parameters affecting the seismic behavior of structures find justification in the form of energy conception. Structures enter the inelastic region subjected to effect of destructive earthquakes. Therefore, the study of inelastic behavior of structures subjected to these earthquakes seems to be necessary. The current research aims to investigate how the relative displacement and hysteresis energy are distributed among stories of *steel buildings with moment resisting* frames designed in accordance with building design based on regulations of *Earthquake-Resistant Design of Buildings* (Third edition, *STANDARD 2800*) [7].

2 Energy-based design philosophy

Energy-based design of earthquake resistant structures or earthquake-resistant limit-state design of structures are based on the presumption that prediction of energy demand

during an earthquake or a set of earthquakes, or the expression of energy capacity of a structural member or system is possible.

Energy equations are written as follows:

$$E_I = (E_K + E_S) + (E_D + E_H) \quad (1)$$

where E_I is input energy, E_K is kinetic energy, E_D is dissipated energy caused by equivalent hysteretic linear viscous damping, E_H is dissipated energy in residual plastic deformation, and E_S is the elastic strain energy. Generally, due to the close relation between input energy value (E_I) and the square root of the area under the gravity acceleration curve, the time history of input energy follows earthquake characteristics.

E_H is the energy dissipated in the inelastic behavior of system after yielding of members. Due to the direct relation of damages to the structure with hysteretic energy, this part of energy is the most important component of energy equation. The amount of energy applied to structure and its absorption and dissipation amount can represent the overall performance of the structure against earthquake, but it does not present a model for its behavior. In other words, the amount of hysteretic energy (E_H) in a structure is the index of damage level or its ductility, but it cannot represent the distribution of damage within various components of the structure or the mechanism of yielding or collapsing, whereas, energy distribution in the structure largely follows the structural model and its characteristics. Damage distribution in a high-rise building is corresponding to distribution of strength within its height. The presence of a weak story leads to damage concentration in that story and collapse of the structure. Therefore, the basic principle is the optimal distribution of energy dissipation in the building that is corresponding to damage distribution and appropriate distribution of resistance. The type of ground motion and the site predominant period could also be effective in changing damage distribution pattern, and these issues must be taken into consideration in selecting design earthquake.

Viscous damping energy (E_D) not only has no influence on the structural damage, but also leads to damage reduction and is considered as the desirable component of the energy equation. Kinetic energy (E_K) has no effect on the structural damage but it can be taken into account as an index of non-structural damages. Elastic strain energy (E_S) has no effect on the structural damages. This energy is stored as elastic work (the product of force to displacement up to elastic limit) in members and reaches zero after the end of earthquake.

3 Modeling

In order to study and investigate how the energy is distributed in the building with moment resisting frame system, a 3, 6, and 12-story structures with an identical story

height of 3 m for all stories were selected as short, medium, and high-rise structures, respectively. Then, the structures were loaded by equivalent static force procedure in similar conditions and based on the standard of *Earthquake-Resistant Design of Buildings* (Third edition, *STANDARD 2800*) [9] and sixth debate in 2014.

First, three structures were subjected to equivalent static loading in SAP200 (VER 16.0.0) software, then these structures were analyzed nonlinearly in PERFORM-3D (VER 5.0) software under Loma Prieta, Landers, and Northridge earthquakes in far and near fields. The story height for all structures is constant and equal to 3 m and the frames span width has been considered to be 4 m. All stories dead and live loads have been considered to be equal to 308 and 200 kg/m², respectively, and the roof dead and live loads were considered to be 227 and 150 kg/m², respectively.

In addition, external walls are of earthen wall type with a thickness of 25 cm and unit surface weight of 645 kg/m². The building use is residential with medium importance degree ($I = 1$) that is placed on type-II soil.

4 Characteristics of the selected acceleration records

In order to conduct nonlinear dynamic time-history analysis, it is required to select earthquake records. The amount of input energy to structure is much influenced by earthquake record rather than structure properties.

To achieve this, three earthquake acceleration records were selected. Nine records were considered for near fault and nine records for far fault cases. It is noteworthy that for being consistent with site conditions, all of these records were selected of soils with the same type (type-II soil). The relatively complete characteristics of these records are presented in Table 1.

According to the considered assumptions in the current study, the location of structures is of high seismicity, and thus the entire selected far fault acceleration records are scaled to 0.35 g with respect to standard 2800, third edition [9]. Moreover, in order to maintain the power of acceleration records and equalizing of relative risk, the entire near fault acceleration records are scaled to 1.5 times the standard spectra i.e., equal to 0.525 g.

5 Results and discussion

The considered models in the dissertation were analyzed first through linear static analysis using SAP200 software, and after obtaining stress ratios of structure elements which were in the range of 0.9–1, they were evaluated by

PERFORM-3D software under far and near fault earthquake records in the nonlinear range of behavior.

In this project, acceleration records of three earthquakes were selected. In order to study the actual influence of these earthquakes on the structure, all three components of accelerations records i.e., two horizontal components and one vertical component were used. Therefore, the structure was first subjected to each horizontal component (X) and (Y) separately, and then it was subjected to both horizontal components (XY) simultaneously, and finally, it was subjected to the combined effect of the two horizontal and one vertical components (XYZ). Due to the lack of cantilever and long span beams usage and the lack of concentrated (point) load on the beams, the vertical component had no significant effect on the results and the structure showed identical results under two-component and three-component records, therefore, the results of three-component records are not presented separately.

5.1 Hysteresis energy distribution in stories

The amount of hysteretic energy in a structure is the index of damage level in structure or its ductility, but it is not capable to represent the distribution of damage within various components of the structure or the mechanism of yielding or collapsing. After applying all intended records and conducting nonlinear dynamic analysis, the percentage of hysteretic energy of each story was calculated for all records. In the studied models, beams enter into inelastic region due to their two-end-restrained design, and thus together with columns they contribute to structure hysteretic energy.

In this section, the distribution percentage of hysteresis energy in 3, 6, and 12-story structures are presented once under all the one horizontal component records (X), one horizontal component records (Y), and two horizontal component (XY), and once subjected to the average of the one horizontal component records (X), one horizontal component records (Y), and two horizontal component (XY) in the forms of separate diagrams (Figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18).

The investigation of diagrams indicates that in the 3-story structure, under far and near fault earthquakes, about half of the energy has been absorbed by the members of the second story, and additionally, under both far fault and near fault earthquake records, the amount of hysteresis energy absorption was approximately equal.

In the 6-story structure (structure with medium height), under far and near fault earthquakes, it is observed that the first story had no contribution to the hysteresis energy absorption, and under the effect of earthquake records, the maximum amount of hysteresis energy absorption and

Table 1 Characteristics of studied earthquake records

Earthquake record	Site properties	Distance (km)	PGA (g)	PGV (cm/S)	PGD (cm)	Duration (s)
Far fault						
Landers-far-X	Soil	69.21	0.114	55.891	32.274	49.98
Landers-far-Y	Soil	69.21	0.146	47.526	17.469	49.98
Landers-far-Z	Soil	69.21	0.089	43.225	12.828	49.98
Loma Prieta-far-X	Soil	71.23	0.098	35.903	9.159	39.99
Loma Prieta-far-Y	Soil	71.23	0.113	40.596	16.161	39.99
Loma Prieta-far-Z	Soil	71.23	0.043	54.81	12.556	39.99
Northridge-far-X	Soil	53.24	0.1	19.340	1.940	31.98
Northridge-far-Y	Soil	53.24	0.094	24.458	3.859	31.98
Northridge-far-Z	Soil	53.24	0.07	14.70	1.153	31.98
Near fault						
Landers-near-X	Soil	11.03	0.273	52.169	17.378	43.98
Landers-near-Y	Soil	11.03	0.283	78.999	28.832	43.98
Landers-near-Z	Soil	11.03	0.18	43.232	17.654	43.98
Loma Prieta-near-X	Soil	0.16	0.644	45.614	7.696	39.985
Loma Prieta-near-Y	Soil	0.16	0.482	51.81	13.912	39.985
Loma Prieta-near-Z	Soil	0.16	0.457	22.399	14.911	39.985
Northridge-near-X	Soil	9.87	0.262	51.786	12.065	60.01
Northridge-near-Y	Soil	9.87	0.381	52.249	4.903	60.01
Northridge-near-Z	Soil	9.87	0.181	17.557	4.375	60.01

Fig. 1 Hysteresis energy of 3-story structure under (X) component of far and near fault records **Fig. 2** Hysteresis energy of 3-story structure under average (X) component of far and near fault records

consequently damage concentration had occurred in the penultimate story i.e., the fifth story.

Hysteresis energy distribution diagrams for the 12-story structure represent that under near fault earthquakes, the maximum hysteresis energy concentration is observed in the eleventh story and under far fault earthquakes, the hysteresis energy concentration and consequently the damage concentration are observed in the third and eleventh stories. Moreover, it is observed that under most of earthquake records, the damage distribution has not been inconsiderable in fifth to ninth stories.

5.2 Stories' relative displacement

The results of relative displacement of stories for 3, 6, and 12-story structures were calculated, and the maximum values of relative displacement of stories for far and near fault earthquakes are shown by transferring the results obtained from PERFORM-3D to MS-Excel software. These diagrams are presented as the distribution of the percentage change of relative displacement of structures in stories and in two X and Y directions under one-component and two-component records, separately (Figs. 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30).

Fig. 3 Hysteresis energy of 3-story structure under (Y) component of far and near fault records

Fig. 6 Hysteresis energy of 3-story structure under average (XY) component of far and near fault records

Fig. 4 Hysteresis energy of 3-story structure under average (Y) component of far and near fault records

Fig. 7 Hysteresis energy of 6-story structure under (X) component of far and near fault records

Fig. 5 Hysteresis energy of 3-story structure under (XY) component of far and near fault records

Fig. 8 Hysteresis energy of 6-story structure under average (X) component of far and near fault records

It can be seen from diagrams that the maximum relative displacements in the near fault earthquakes for 3, 6, and 12 story-structures are equal to 2.69, 2.67, and 2.59%, respectively and for far fault records, these values for 3, 6, and 12 story-structures are equal to 2.42, 1.67, 2.49%, respectively indicating higher displacement demands in short, medium, and high-rise structures under near fault earthquakes. Moreover, it is seen that the relative displacement diagrams for one-component and two-

component records are very close to each other and a little difference is observed between them.

6 Conclusions

In the current research, three multi story (3, 6, and 12 stories) steel buildings with ordinary moment resisting frame subjected to far and near fault earthquakes were

Fig. 9 Hysteresis energy of 6-story structure under (Y) component of far and near fault records

Fig. 12 Hysteresis energy of 6-story structure under average (XY) component of far and near fault records

Fig. 10 Hysteresis energy of 6-story structure under average (Y) component of far and near fault records

Fig. 13 Hysteresis energy of 12-story structure under (X) component of far and near fault records

Fig. 11 Hysteresis energy of 6-story structure under (XY) component of far and near fault records

Fig. 14 Hysteresis energy of 12-story structure under average (X) component of far and near fault records

investigated, and the following results obtained from their nonlinear dynamic analysis.

- (a) By investigating the results of hysteresis energy distribution, it was observed that the lower stories contribution to hysteresis energy is higher in short buildings, and by increasing in the building height, the contribution of upper stories increases.

- (b) It could be concluded from the diagrams that the relative displacement of stories caused by near fault records is considerably different from those of far fault records.
- (c) According to the performed studies, as the near fault records have pulses with long period, they have more impact on the structures in comparison to far fault

Fig. 15 Hysteresis energy of 12-story structure under (Y) component of far and near fault records

Fig. 16 Hysteresis energy of 12-story structure under average (Y) component of far and near fault records

Fig. 17 Hysteresis energy of 12-story structure under (XY) component of far and near fault records

records. The obtained results indicate the higher relative displacements in stories in the case of near fault earthquakes compared to far fault ones.

Fig. 18 Hysteresis energy of 12-story structure under average (XY) component of far and near fault records

Fig. 19 Maximum relative displacement of 3-story structure in X direction under two-component record

Fig. 20 Maximum relative displacement of 3-story structure in X direction under X component record

- (d) In comparison to far fault records, the displacement demand of near fault earthquake records is higher, and thus the need for considering measures to

Fig. 21 Maximum relative displacement of 3-story structure in Y direction under two-component record

Fig. 24 Maximum relative displacement of 6-story structure in X direction under X component record

Fig. 22 Maximum relative displacement of 3-story structure in Y direction under Y component record

Fig. 25 Maximum relative displacement of 6-story structure in Y direction under two-component record

Fig. 23 Maximum relative displacement of 6-story structure in X direction under two-component record

Fig. 26 Maximum relative displacement of 6-story structure in Y direction under Y component record

Fig. 27 Maximum relative displacement of 12-story structure in X direction under two-component record

Fig. 28 Maximum relative displacement of 12-story structure in X direction under X component record

Fig. 29 Maximum relative displacement of 12-story structure in Y direction under two-component record

Fig. 30 Maximum relative displacement of 12-story structure in Y direction under Y component record

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construct structures in the near faults regions is completely obvious in standard 2800 [9].