Evaluating Damage Spectra for Steel Braced Frames Due to Near-Field and Far-Field Earthquakes

A. Yousefi, B. Mohebi, M. A. Rostamkhani

***Abstract*—**Recent ground motion records demonstrate that the near-field earthquakes have various properties compared to far-field earthquakes. In general, most of these properties are affected by an important phenomenon called 'forward directivity' in near-fault earthquakes. Measuring structural damages are one of the common activities administered after an earthquake. Predicting the amount of damage caused by the earthquake as well as determining the vulnerability of the structure is extremely significant. In order to measure the amount of structural damages, instead of calculating the acceleration and velocity spectrum, it is possible to use the damage spectra of the structure. The damage spectrum is a kind of nonlinear spectrum that is drawn by setting the nonlinear parameters related to the single degree of freedom structures and its dynamic analysis under the specific record and measuring damage of any structure. In this study, the damage spectra of steel structures have been drawn. For this purpose, different kinds of concentric and eccentric braced structures with various ductility coefficients in hard and soft soil under near-field and far-field ground motion records have been considered using the Krawinkler and Zohrei damage index. The results indicate that, by increasing the structures' fundamental period, the amount of damage increases under the near-field earthquakes compared to far-field earthquakes. In addition, by increasing the structure ductility, the amount of damage based on near-field and far-field earthquakes decreases noticeably. Furthermore, in concentric braced structures, the amount of damage under the near-field earthquakes is almost two times more than the amount of damage in eccentrically braced structures especially for fundamental periods larger than 0.6 s.

***Keywords*—**Damage spectra, damage index, forward directivity, near-field earthquakes, far-field earthquakes.

I. Introduction

RECENTLY, for describing the behavior of structures during seismic excitations, many damage parameters have been introduced. Moreover, some criteria were developed to reveal the damage state of structures to illustrate the ultimate capacity of structural members. Researchers proposed different damage index to quantify designing procedure. Banon and Veneziano [1] offered the damage index based on cumulative deformation of evaluation structures and ductility invoices. According to this index, which has the highest usage in steel structures and can be calculated by an earthquake, it is necessary to determine the damage due to loss of structural strength, stiffness, and energy [2]. Park and Ang [3] introduced a cumulative index and considered both the deformation and the effect of energy. Kratzig and Meskouris [4] showed that the maximum flexibility of deformation cannot be a suitable criterion to determine the appropriate measure of damages so to use the structural response parameters such as the concentration of ductility and energy dissipation of hysteresis. Powell and Allahabadi [5] concluded an index of earthquake losses associated with estimating demand response parameters compared with the structural capacity. Ghobara et al. [6] offered damage index based on stiffness parameter that is calculated with two nonlinear static analyses. This index considered effects of structure stiffness before and after the earthquake. Bozorgnia and Bertero [7] introduced two modified damage spectra for an inelastic single degree of freedom system using hundreds of records. Estekanchi and Arjomandi [8] computed the performance of damage indexes in steel moment-resisting frames using nonlinear time history analyses.

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II. Characteristics of Ground Motion Records

Studies showed that the required displacement of near-field earthquakes is very high due to the actions of a large energy in a short time by near-field earthquakes. Characteristics of the near-field earthquakes are related to seismic source mechanisms, the direction of fault rupture toward the site, and direction of fault slip. The most important distinguishing characteristics of the near-field earthquakes is the production of pulses due to directivity and fling step effects. These pulses of movement typically include one or more distinct pulses in time history of acceleration, velocity, and displacement. These characteristics in near-field earthquakes are quite different from far-field earthquakes. Near-field earthquakes have higher acceleration and more limited frequency content in higher frequency values compared to the far-field earthquakes. The mapping of these earthquakes, especially under influence of the forward directivity effect, included long-period pulses with a strong amplitude which was often seen at the beginning of the earthquake. Anderson and Naeim [9] showed that near-field earthquakes with a pulse can significantly induce a response in their building. Somerville [10] agreed that conditions lead to forward and backward directivity will be provided as a parameter. Alavi and Krawinkler [11] evaluated effects of near-field earthquakes by providing three different models of each pulse in the behavior of the structures and its impact on the structures with higher fundamental periods.

Fault propagation to the site with a velocity close to the shear wave velocity can make the most of the energy from the fault with a big impulse into the site that this impulse appears at the beginning of time history of the earthquake. If the site is in the direction of the fault to move it, these waves arrive and make a big reduction in the time waves from the fault reach to site (forward directivity), but if the site is in contrary to direction, the opposite situation occurs, and causes waves apart from each other and with more time to reach the site (backward directivity). In result of this phenomenon, large pulse of motion is clearly seen in the velocity and displacement time history. It can be seen that the maximum ground acceleration, velocity, and displacement of this backward directivity record are significantly smaller than their corresponding values of the forward directivity record [11].

III. Damage Spectra

The damage spectra are a kind of nonlinear spectra that are drawn by setting the nonlinear parameters related to the single degree of freedom structures, and its dynamic analysis under the specific record and measuring damage of each structure. Structural performance and amount of damage can be calculated with damage indexes. Damage spectra show the damage index changes versus period for a single degree of freedom structures that are subject to ground motion records. One of the methods available to estimate the structural damages is the functions called damage index. Damage index is a well-defined normal value, and its value will be zero if the structure remains elastic and will be one if there is a potential for structural collapse. Other areas of the structural performance such as life safety and collapse prevention have a damage index value between zero and one [12].

Park and Ang [3] presented one of the most famous and most practical methods for calculating the damage index. According to their research, the index of structural damages under seismic loads combined multiple recursive tension and stress cycles can be defined as follows:

$$DI_{P\&A} = \frac{D_m}{D_u} + \beta \frac{\int dE}{Q_y D_u} \tag{1}$$

where D_m is the maximum displacement response under earthquake desired, Q_y is the yield strength of structural models, dE is the cyclic energy losses and β is a positive constant factor. This index is a cumulative index that simultaneously considers the effect of deformation and energy. After several years, Kunnath and et al. [13] correct this damage index and (2) has been presented. Although this index was calibrated for concrete elements, due to obvious physical concepts that are used for damage assessment of concrete and steel structures:

$$DI = \frac{Q_m - Q_y}{Q_u - Q_y} + \beta_e \frac{\int dE}{M_y Q_u} \tag{2}$$

damage index in structures. Their approach includes two types of consideration, the first based on the balance between demands on the structure and its capacity, and the second based on the degradation of structural property. Using these techniques, a damage index can be estimated. Equation (3) illustrates one of the damage index predictions, which can be used in steel structures.

$$P_f = \{D > \gamma\} = P\left\{C\sum_{i=1}^{n} (\Delta\delta_{pi})^c > \gamma\right\} \tag{3}$$

where u_{max} and u_y, respectively are equal to maximum deformation and deformation submission, u_{pon} is equal to maximum deformation of the system under cyclic load and μ is displacement ductility demand by an earthquake. This index is a cumulative index.

Krawinkler and Zohrei [2] introduced a damage index that has the highest usage in steel structures because all experiments performed to calibrate the relationship between the steel I sections. According to this index that can be calculated by an earthquake, it is necessary to determine the damage due to loss of structural strength, stiffness, and energy. For this purpose, the concept of low-cycle fatigue is used as (4), which simply implies a probability of member collapse.

$$P_f = \{D > \gamma\} = P\left\{C\sum_{i=1}^{n} (\Delta\delta_{pi})^c > \gamma\right\} \tag{4}$$

where γ is the acceptable extent of damage, n is the number of cycles of failure, c and C are parameters of structural failure, and $\Delta\delta_{pi}$ is the plastic deformation of the i^{th} cycle.

IV. Performance Levels and Its Relationship to the Damage Index

Performance levels of the structure evaluate with the calculation of two variables relative displacement and plastic deformation. To compare the performance levels with Krawinkler and Zohrei's damage index, each performance levels experimentally is determined with a value between zero and one. These values are shown in Table I [14]. In this table, A-B is a linear state, IO is immediate occupancy, DC is damage control, LS is life safety, LSR is limited safety, CP is collapse prevention and C shows collapsed state.

TABLE I
PERFORMANCE LEVELS ASSOCIATED WITH KRAWINKLER AND ZOHREI'S DAMAGE INDEX [14]

Performance levels	A-B	IO	DC	LS	LSR	CP	C
Damage index	0	0.17	0.33	0.5	0.67	0.83	1

V. Results and Discussion

In this paper, the damage spectra in hard soil were calculated using seven near-field earthquakes, where relative distance of seismic stations to the center of an earthquake is less than 15 km, and seven far-field earthquake, where relative distance of seismic stations to the center of an earthquake is more than 15 km. Moreover, for comparison of the results of

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soil effects, the damage spectra in soft soil were calculated using six near-field earthquakes and seven far-field earthquakes. It is notable that all the near-field ground motion records had forward directivity effects. Selected ground motion records had been scaled according to ASCE/SEI 41-13 [15].

In this study, four single degree of freedom systems including Concentric Braced Frames (CBF) and Eccentric Braced Frame (EBF) were modeled using OpenSees [16] software. Fig. 1 presents the type of frames used in this study.

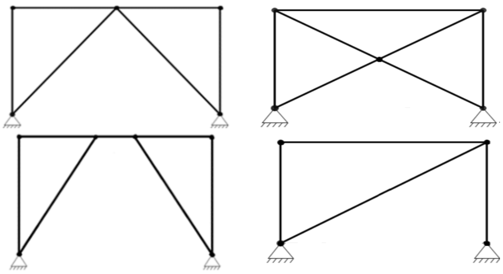
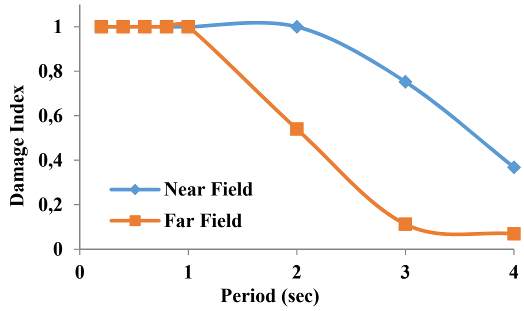


Fig. 1 CBF and EBF frames considered in the study

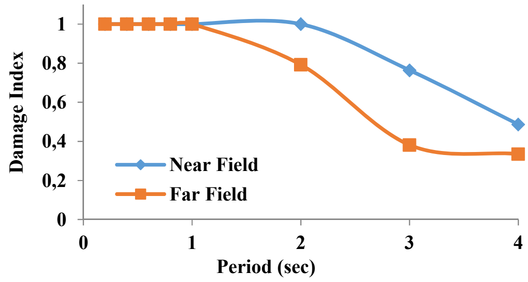
Damage spectra are plotted for each of these frames for three levels of different ductility including μ=2, μ=3.5, and μ=5 considering two types of hard soil and soft soil. All structural elements are assumed as a type Nonlinear-Beam-Column element with Steel02 material.

According to the results of Fig. 2, for μ=2 in hard soil and soft soil for most of the spectrum, the amount of damages related to the near-field and far-field ground motion records for fundamental periods less than 1 sec, is greater than 1 and the structure will collapse in this period. Furthermore, for a fundamental period equal to 2 and 3 sec under near-field ground motion records of Northridge, Imperial Valley, Luma Prieta, Landers and Tabas, the amount of damages is above 1. In most of the spectra with increasing the fundamental period of structures, the amount of damage index decreases. The amount of damages for all periods is greater than that caused more damages to the structures in both hard and soft soil under near-field and far-field ground motion records.

According to Fig. 3, for the X-braced frame with μ=3.5 in the soft and hard soil for periods less than 4.0 sec, the amount of damages in the most spectrum is greater than 1 and the structure will collapse. In hard soil for all periods except the Morgan Hill earthquake, the amount of damage under near-field record is more than far-field records. In soft soil in all earthquakes for all periods, the amount of damages under near-field records is more than far-field records except the Northridge earthquake for a fundamental period of 6.0 to 8.0 sec and Luma Prieta earthquake for a period of 4.0 to 1.0 sec. According to Fig. 4, for the X-braced frame with μ=5 in hard soil, for the Northridge, Luma Prieta and San Fernando earthquakes under both near-field and far-field records and the Landers earthquake under far-field record for periods less than 2.0 sec, the amount of damages is above 1. In all earthquakes in the hard soil for all periods, the amount of damage to the structure under near-field records is greater than far-field records. The average damage spectra, under near-field and far-field earthquakes, for X-braced frame considering different coefficients of ductility are shown in Figs. 2-4.

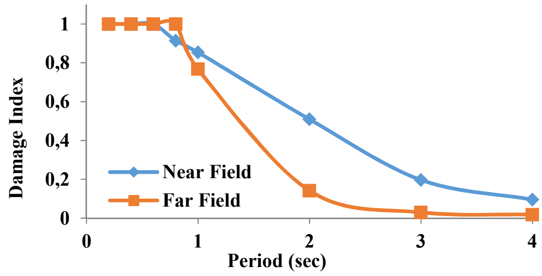


(a)

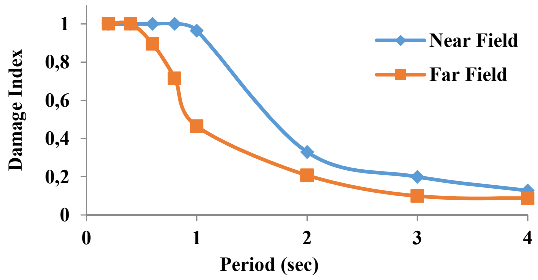


(b)

Fig. 2 Average damage spectra of X-braced frame with μ=2, (a) soft (b) hard soil

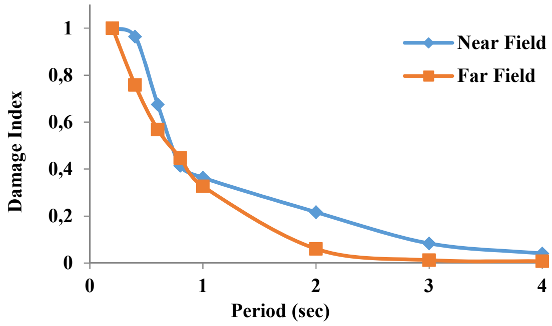


(a)

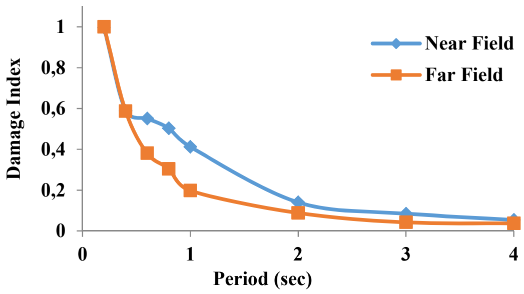


(b)

Fig. 3 Average damage spectra of the X-braced frame with μ=3.5, (a) soft (b) hard soil



(a)



(b)

Fig. 4 Average damage spectra of the X-braced frame with μ=5, (a) soft (b) hard soil

TABLE II
THE AVERAGE DAMAGE RATIO UNDER NEAR-FIELD TO FAR-FIELD RECORDS FOR STEEL BRACED FRAMES IN HARD SOIL

		$DI_{Near\text{-}field}/DI_{Far\text{-}field}$		
		T≤ 0.6	0.6 <T≤ 1	1 <T≤ 4
μ=2	X-brace	1	1	1.28
	Chevron	1	1	1.25
	Eccentric	1	1.05	2
μ=3.5	X-brace	1.04	1.30	1.82
	Chevron	1	1.29	1.80
	Eccentric	1.09	1.41	2.30
μ=5	X-brace	1.09	1.66	1.88
	Chevron	1.10	1.64	1.90
	Eccentric	1.23	1.60	2.5

TABLE III
THE AVERAGE DAMAGE RATIO UNDER NEAR-FIELD TO FAR-FIELD RECORDS FOR STEEL BRACED FRAMES IN SOFT SOIL

		$DI_{Near\text{-}field}/DI_{Far\text{-}field}$		
		T≤ 0.6	0.6 <T≤ 1	1 <T≤ 4
μ=2	X-brace	1	1	1.81
	Chevron	1	1	1.77
	Eccentric	1	1.02	1.67
μ=3.5	X-brace	1	1	1.56
	Chevron	1	1	1.61
	Eccentric	1	1.32	2.4
μ=5	X-brace	1.11	1.10	1.70
	Chevron	1	1	1.81
	Eccentric	1	1	1.77

Tables II and III present the average damage ratio under near-field to far-field records for steel braced frames in the hard and soft soil, respectively. The following table is one of the most important results of this research. These tables can be used to obtain the amount of damage in the steel structures with types of braced frames under near-field and far-field records in both hard and soft soil. For this purpose, it is enough that amounts of structural damage under far-field records multiply to the coefficients in the tables.

VI. CONCLUSION

In this paper, the damage spectra for braced frames for three levels of different ductility including μ=2, μ=3.5, and μ=5 were evaluated. For this purpose, four type of Concentric Braced Frames (CBF) and Eccentric Braced Frame (EBF) in the soft and hard soil type were assumed. In order to assess damage spectra, nonlinear dynamic analyses were applied using OpenSees software subjected to both near-field and far-field earthquakes. The novelty of this study is performing two important tables which can be used to obtain the amount of damage in the steel structures with types of braced frames under near-field and far-field records in both hard and soft soil. This amount can be calculated by multiplying the amounts of structural damage under one area to the coefficients in the tables.

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