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Application of damage spectra as seismic intensity measures in endurance time method for steel moment-resisting frames

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Abstract. In seismic resistant design of moment frames, the structure behavior under earthquakes has to be examined considering various damage criteria. Damage indices can be estimated by Endurance Time (ET) method with minimum computational effort. The quality of this estimation can be improved in different ways. In this paper, the graphs of a certain damage index versus natural period of the structure, called damage spectra, are produced applying intensifying ET records and scaled Ground Motions (GM). Then, the excitation duration of ET acceleration functions (target time) is modified in order to reach acceptable consistency between ET and GM damage spectra. Moreover, various damage indices of a steel moment frame at two hazard levels are evaluated via nonlinear time-history analyses of the structure under scaled earthquakes and ET records. It is observed that the frame damage estimation can be improved by modifying the target time of ET records based on damage spectra. In addition, in most cases, there are negligible discrepancies between values of frame damage indices corresponding to ground motions and ET acceleration functions with the damage-based target time.

1. Introduction

In recent years, performance-based seismic design has been introduced in earthquake engineering, and many damage parameters have been accounted to describe the behavior of structures during seismic excitations. These parameters commonly include inter-story drift, plastic deformation, and cumulative energy dissipation of structural members. Although damage parameters were beneficial, some other criteria were developed to reveal the damage state of structures, comprising of the ratio between damage parameters and the ultimate capacity of structural members. These criteria, called damage indices, are quantities varying from zero to one corresponding to elastic behavior and state of collapse, respectively.

Researchers have proposed different damage indices. Krawinkler and Zohrei [1] examined local buckling in some steel members and attributed the deterioration in strength, stiffness, and energy dissipation to plastic rotations. They introduced damage indices based on relative deterioration. Powell and Allahabadi [2] suggested a ductility-based damage index involving plastic deformation, which had a simple concept and an easy computational method. Cosenza et al. [3] defined another damage index for the Elastic-Perfectly-Plastic (EPP) behavior to consider the effect of cumulative energy dissipation on the structural damage. This energy-based damage index depended on the number of cycles which include inelastic deformations. The most popular and practical damage index was presented by Park et al. [4] for Reinforced Concrete

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(RC) buildings, which was almost the combination of ductility-based and energy-based damage criteria. Bozorgnia and Bertero [5] prescribed improved damage indices on the basis of correcting the value of Park-Ang index ($\mathrm{DI_{PA}}$) for both slight and sever damage states.

Thereafter, Ladjinovic and Folic [6] proposed a new damage index by modifying the well-known $\mathrm{DI_{PA}}$, incorporating the cumulative plastic excursion. This index was adjusted to be exactly zero for elastic responses and one for the entire collapse of structures. Moreover, its parameters could be calculated independently. Later, Estekanchi and Arjomandi [7,8] evaluated the mentioned damage indices in steel moment frames and obtained the correlation between them and performance levels. In addition, Datta and Ghosh [9] generated design spectra at different hazard levels based on $\mathrm{DI_{PA}}$.

Damage spectra were generated [10] to evaluate the damage potential of various earthquake accelerograms. A damage spectrum is variation of a certain damage index versus natural period of the Single-Degree-Of-Freedom (SDOF) system, considering that other system dynamic properties are constant and a certain earthquake record is applied. This spectrum can be extended to different levels of excitations and can be employed in the seismic performance assessment of both existing and new structures. Zhai et al. [11] depicted various damage spectra relating to systems and earthquakes with different dynamic features.

Nonlinear dynamic analyses are applied to make a realistic prediction of structural behavior during seismic excitations and to incorporate almost any type of material and geometrical behavior. Many researchers severely advise to use nonlinear dynamic analyses to take into account strong-motion duration effect and behavioral complications such as fatigue, hysteresis energy dissipation, and cyclic deformation. Nonlinear time history analyses, which are time-consuming procedures, especially for the systems with a high degree of freedom, would be carried out in order to calculate most damage indices accurately. The Endurance Time (ET) method can be effectively used to reduce the computational effort needed to determine damage values of structures under various earthquake accelerograms at different hazard levels [12].

In the ET method, the structure is subjected to intensifying dynamic excitation, whose response is evaluated using time history analysis [13]. The damage indices of the structure can also be determined during the excitation, and the performance of the structure will be judged based on the endurance time at which some damage indices reach the maximum acceptable value. In addition, the definite time related to each hazard level can be detected such that the response spectrum of the ET records up until that time agrees with the target spectrum at that hazard level. This time, called target time, depends on the type of both the response and target spectrum, which were initially accounted for linear acceleration response and code spectrum, respectively [13].

The purpose of this paper is to apply damage spectra to modify the target time in ET method, which leads to the improvement of the damage estimation of steel moment frames by the ET method. Considering this goal, average damage spectra of Ground Motions (GM) and ET acceleration functions at two levels of excitation were generated, and the target time of ET series for each hazard level was modified in such a way that ET damage spectra coincide with GM spectra. Then, damage indices of a steel moment frame were estimated using the ET method with damage-based target time; furthermore, the accuracy of this estimation was discussed.

2. The concept of endurance time method

In the Endurance Time (ET) method, a structure is subjected to an artificial intensifying accelerogram, and its damage criteria are evaluated during excitation by nonlinear time history analysis. The time at which the selected damage criterion reaches its ultimate acceptable value–having to do with the seismic performance level assigned for the structure–will be the endurance time, which is used to determine the seismic performance of the structure [14].

Generation of ET acceleration functions is a kind of optimization problem, in which the target function is the integration of squared differences between ET spectral response and template spectral response (Eq. (1)). The time span of ET excitation at which the target function has to be minimized is called basic target time, which is frequently considered 10 s. The ET response spectra, which depend on time duration of ET excitation, or target time, are typically linear or nonlinear acceleration response spectra. Template spectra can be code-based spectra or average acceleration response spectra relating to several real earthquakes. The ET accelerograms will be induced such that their linear spectral acceleration is proportional with the excitation duration (Eq. (2)) [15]:

$$\min F(a_g) = \int_0^{T_{\max}} \left[S_a(T,t_b) - S_{aT}(T)\right]^2 dT, \qquad (1)$$

$$S_a(T,t) = \frac{t}{t_b} S_{aT}(T). \qquad (2)$$

In Eqs. (1) and (2), T is the period of SDOF system, t is the time duration of ET excitation, t_b shows basic target time, and S_a as well as S_{aT} are ET linear spectral acceleration and template spectral acceleration, respectively. Additionally, $F(a_g)$ indicates the error of correlation between ET response spectrum and the template spectrum.

Every target time in ET method corresponds to a particular ET response spectrum, which can be compatible with a target spectrum–used to scale the earthquakes in a seismic dynamic analysis–at a certain hazard level. In other words, for distinct hazard levels, different target times will be specified such that ET response spectra related to those target times conform to the target spectra at those levels of excitation. With this in mind, seismic responses of structures can be determined at various levels of excitation through just one ET analysis. Therefore, the ET method dramatically reduces the computational effort needed in nonlinear dynamic analyses in an acceptable way.

The ET analysis, in comparison with spectral or pushover analyses, is able to take into account the effect of strong-motion duration and behavioral complications such as buckling, hysteresis energy dissipation, and cyclic deformation. Moreover, compared to conventional time history analyses, which directly apply ground motions, ET method is an adequate alternative to decrease the computational demand with a reasonable precision. This is because only three ET records are imposed on the structure, and the average response time history will be obtained to assess the performance of the structure at various hazard levels. Consequently, ET records have been used in the seismic assessment of various structures and in the generation of several types of spectra.

For instance, Valamanesh and Estekanchi [16] examined a number of steel moment frames under bidirectional seismic loading and estimated the seismic response by the ET method. They verified the results by comparing ET responses with those obtained by nonlinear time history analyses. Similarly, Hariri et al. [17] investigated seismic performance of several steel moment frames using time history, incremental dynamic, and endurance time methods, which approve acceptable accuracy of ET method. Likewise, Mirzai et al. [18] successfully employed ET method in performance-based design of steel frames. Mashayekhi and Estekanchi [19] generated effective-number-of-cycles spectra with ET and ground motions accelerograms. Furthermore, they modified the target time of some ET series based on duration consistency.

In this study, the spectra suggested in ASCE/SEI7-10 [20] for Design Basis Earthquake (DBE) and Maximum Considered Earthquake (MCE) hazard levels are considered as target spectra. And, "ETA20inx" records [21]–a type of ET acceleration functions–with different target times are applied to produce ET spectra. Moreover, some other ET accelerograms–namely, ETA20a, "ETA20e", and "ETA40g" records [21]–are tacitly used for comparative study.

Since "ETA20inx" records have been optimized to fit the average of GM nonlinear response spectra–corresponding to 20 records in FEMA–440 [22] on soil type C–its response spectra are not much consistent with code spectra (target spectra). For further accuracy, specific target time for every system period (T) and hazard level will be computed such that the average of ET linear acceleration response spectrum is equal to the average of target spectrum in the periodic range of $0.2T$-$1.5T$. In this paper, the target time obtained under this procedure is recognized as S_a-based target time. In Figure 1, the ET linear response spectra related to different target times together with target spectra are conveyed. Moreover, the ET response spectra scaled at DBE and MCE hazard levels using S_a-based target time are displayed in Figure 2.

3. Damage spectra

Damage spectrum is a variation of certain damage index against natural period of SDOF system under

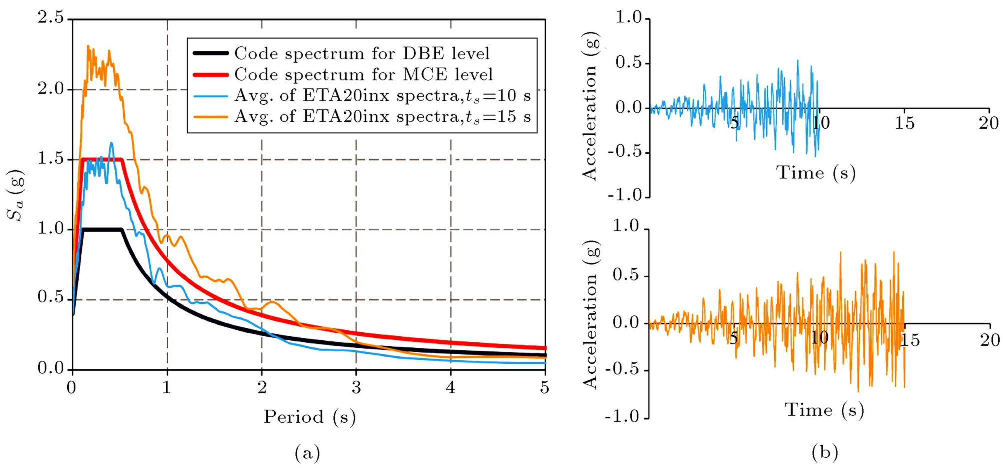


Figure 1. (a) Target spectra and average of response spectra of ETA20inx records at different target time. (b) Typical ETA20inx acceleration function.

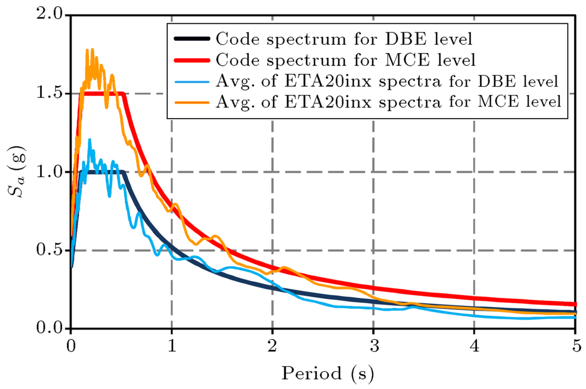


Figure 2. Average of response spectra of ETA20inx records scaled at DBE and MCE levels using S_a-based target time.

definite earthquake excitation, where other system dynamic properties are constant. Hence, three items should be determined to produce damage spectrum: (1) the type of damage index, (2) the assumed dynamic characteristics of SDOF system, and (3) the earthquake record.

Among all damage indices, "Modified Park-Ang" Damage Index (DI_m) has been selected in this study, since this index becomes exactly zero in the case of system elastic behavior, and it becomes one when the system collapses under uniformly increasing lateral deformation. In addition, the parameters of the index can be calculated or assumed to be independent of other indices [23]. Because there is a nearly good correlation between the values of DI_m and $\mathrm{DI}_{\mathrm{PA}}$ in the range of 0.2-0.8 and because Park-Ang index has already been verified by experimental researches [4], parameter DI_m will correctly represent the seismic performance of structures.

In Eq. (3), the formulation of DI_m is represented:

$$\mathrm{DI}_m = \frac{\mu - 1}{\mu_u - 1} + \alpha\beta \frac{E_h}{F_y u_y (\mu_u - 1)},$$

$$\alpha = 1 - \frac{\mu_c}{\mu_{ac}},$$

$$\mu_c = \frac{u_{c,\max}}{u_y},$$

$$\mu_{ac} = 1 + \frac{\sum_i |u^+_{p,i}| + \sum_i |u^-_{p,i}|}{u_y}, \tag{3}$$

where μ is maximum ductility, which is the ratio of maximum to yield displacement, demanded by earthquake excitation; μ_u is the ultimate ductility capacity of the structure under uniformly increasing lateral deformation, reported in FEMA-356 [24] for structural members; E_h, F_y, and u_y are the cumulative energy dissipation demanded by earthquake excitation, yield strength, and yield displacement of the structure, respectively. According to Cosenza et al. [3], coefficient β varies between 0.025 and 0.25, and it can be taken 0.15 for steel members. In addition, complicated coefficient α includes cyclic ductility (μ_c) and accumulative ductility (μ_{ac}). μ_c quantity contains maximum excursion of deformation ($u_{c,\max}$) when plastic responses exist and will be assumed zero in elastic behavior. Parameter μ_{ac} depends on the sum of absolute plastic excursion ($|u_{p,i}|$) all through the cyclic deformation (the $u_{p,i}$ parameter represents the plastic excursion in ith cycle).

All dynamic properties of SDOF system should be constant to induce damage spectrum, except for natural period, which varies in the range of 0.2-3 s. In this paper, system mass (m), damping ratio (x), and μ_u are considered 1 kg, 5%, and 10, respectively, to generate damage spectra. Given DIm formulation, the dominators of two fractions have the same expression including μ_u parameter, which makes the development of the damage spectra more comfortable for other values of ductility capacity. Material hysteresis behavior is supposed to be Elastic-Perfectly-Plastic (EPP), and earthquake coefficient (C)–the ratio of yield strength to the weight of system–takes different values of 0.1, 0.15, 0.2, and 0.25 according to ASCE/SEI7-10 [20] advice.

For the production of GM damage spectra, 21 earthquake records, suggested in FEMA-695 [25] for Site Class C, have been selected including far-field and near-field ground motions. These real accelerograms are scaled at DBE and MCE hazard levels, such that the average of GM and target linear response spectra become equal in the periodic range of $0.2T$-$1.5T$. For instance, GM damage spectra for $C = 0.15$ and DBE level, together with their average and deviation, are illustrated in Figure 3. Nonlinear time history analyses have been performed to properly depict these graphs.

As was mentioned in the previous part, three "ETA20inx" records are chosen to generate ET damage

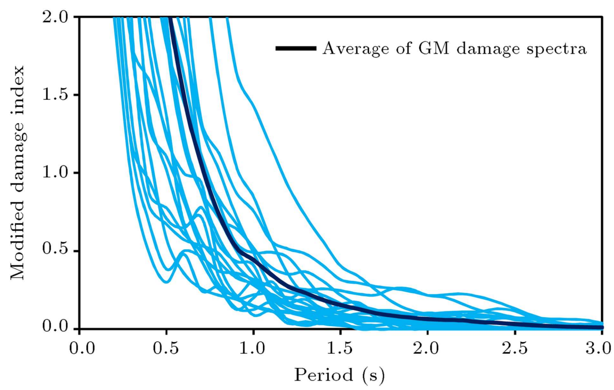


Figure 3. Damage spectra of 21 records in FEMA-695 (Site Class C) corresponding to DI_m, $m = 1$ kg, $x = 5\%$, $\beta = 0.15$, $\mu_u = 10$, $C = 0.15$, EPP behavior, and DBE level.

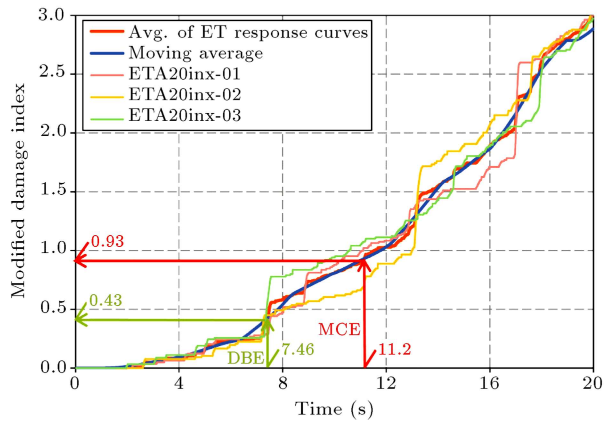


Figure 4. Moving average of damage time history for ETA20inx records: $x = 5\%$, $C = 0.2$, $T = 0.6$ s, $\mu_u = 10$, and EPP behavior.

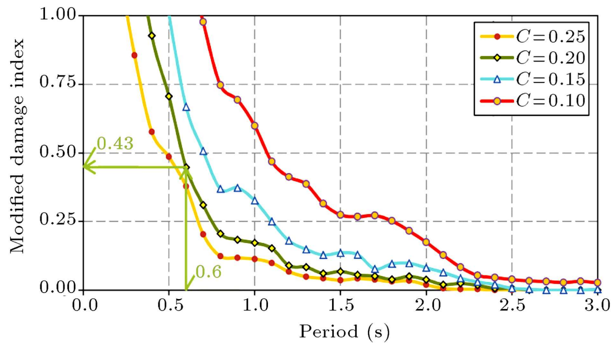
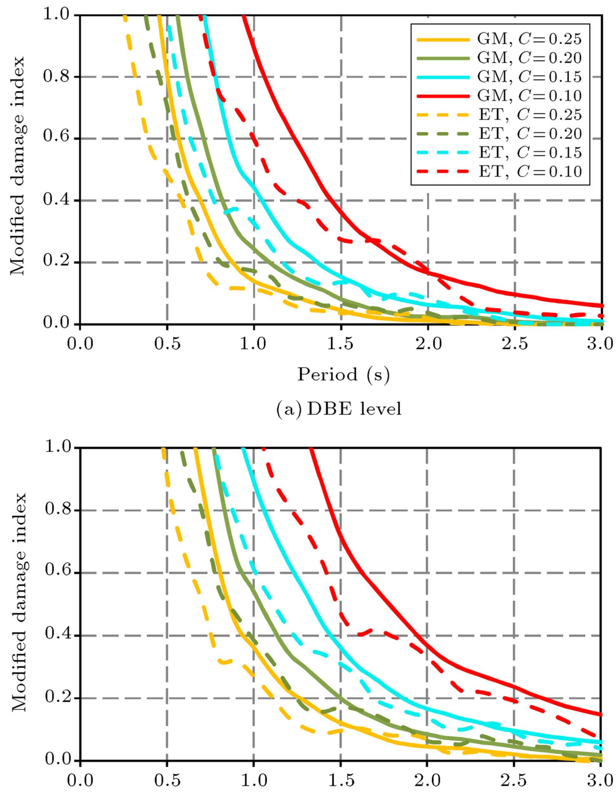


Figure 5. Average damage spectra for ETA20inx records: $x = 5\%$, $\mu_u = 10$, EPP behavior, and DBE level.

spectra. The diagram of maximum damage index of certain SDOF system subjected to each ET record versus ET excitation duration will be damage time history. The moving average of three cases of damage time history will represent system damage index at distinct hazard levels through knowing the S_a-based target time corresponding to each hazard level and each system period. A moving average of ET response curves for a system with $T = 0.6$ s and $C = 0.2$ is displayed in Figure 4. As it is shown, the system damage index at different levels of excitation can be obtained by producing only three damage response diagrams. For example, the damage value at DBE level–whose related target time will be 7.46 s–is 0.43 that agrees with the corresponding damage spectrum (Figure 5).

Theoretically speaking, SDOF systems with different natural periods can have the same yield strength, resulting in the same earthquake coefficient (C), in which case, the more flexible the system is, the less its damage index will be. However, in a practical context, decreasing the stiffness of a structure accompanies the reduction of strength, which might increase or decrease the damage index. These obvious facts can be seen in Figure 5.



(a) DBE level

(b) MCE level

Figure 6. Comparison between ETA20inx and GM damage spectra: $x = 5\%$, $\mu_u = 10$, and EPP behavior.

4. Comparison among damage spectra

For the evaluation of the potential of ET records in estimating the damage state of structures, it is useful to compare the average of ET and GM damage spectra with each other. This comparison is presented in Figure 6 for damage values between zero and one, which are meaningful quantities. As it depicts, "ETA20inx" acceleration functions generally underestimate the damage index at both DBE and MCE hazard levels. Furthermore, the discrepancy between ET and GM spectra increases in the periodic range of 0.7-1.5 s and diminishes for long-period structures. There are two possible ways to achieve more consistency: modifying the target time of ET records or generating new ET excitation functions.

It is also beneficial to examine the effect of excitation level on damage spectra. The higher level of ET or GM excitations causes more damage values. The special case is the exact coincidence of the GM damage spectrum related to DBE level and $C = 0.1$ with the one related to MCE level and $C = 0.15$. This could be because both earthquake accelerograms and system yield strength are multiplied by the same number (1.5); hence, mathematically, the damage index and damage spectrum stay unchanged.

Table 1. The S_a-based and damage-based target times for different ET series and hazard levels.

Series	DBE level		MCE level	
	S_a-based t_t	Damage-based t_t	S_a-based t_t	Damage-based t_t
ETA20e	8.20	9.92	12.30	14.20
ETA20in	8.42	10.32	12.63	14.78
ETA40g	10.00	11.00	15.00	15.70

5. Modifying the target time based on damage spectra

In the previous sections, ET damage spectra were depicted using the S_a-based target time, and their discrepancy with average of GM damage spectra was investigated. One way to make ET damage spectra compatible with real GM spectra is perhaps to change the target time. In other words, damage spectrum can be used as intensity measure to modify the target time in ET method. In this regard, the ratio between the average of GM damage spectrum and that of ET in the range of 0-3 s will be calculated for each value of coefficient C, and the results are averaged to acquire "spectral damage ratio" at a specific hazard level. Then, the average of the S_a-based target time corresponding to that hazard level is multiplied by the spectral damage ratio to reach a new target time. Afterwards, the ET damage spectra based on the new target time can be induced, and the procedure will be repeated until the spectral damage ratio lies between 0.95 and 1.05. The last target time, called the damage-based target time, is presented in Table 1 for different ET series (ETA20e, ETA20inx, and ETA40g) and two hazard levels.

Although the average of ET and GM damage spectra can be almost equal-by modifying target time in ET method–the trend of these spectra might be still distinct. Therefore, ET damage spectra based on the damage-based target time have been compared with GM spectra in Figure 7. As can be seen, the discrepancy between the damage values related to ET and GM accelerograms is reduced to less than 0.1, which is acceptable value in practical applications. Therefore, damage spectrum can be an appropriate intensity measure to produce a new target time which is more helpful than S_a-based target time to estimate the damage state of structures.

6. Structural application of damage-based target time

It is interesting to use the damage-based target time obtained in the previous section to estimate various damage indices of a real frame by the ET method. It is also important to compare these damage values with those acquired by GM records or ET series with the S_a-based target time. In this study, a steel moment frame

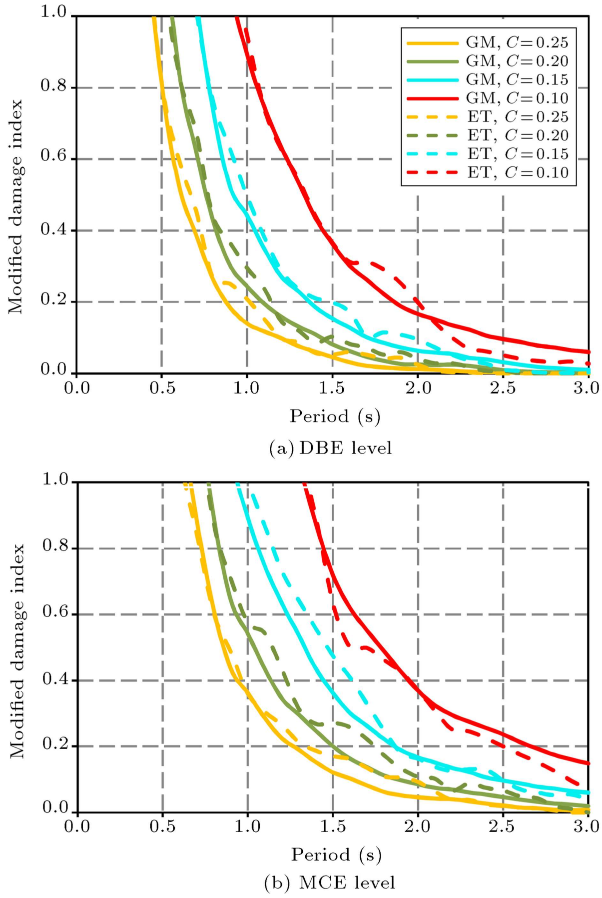


Figure 7. Comparison between modified ETA20inx and GM damage spectra: $x = 5\%$, $\mu_u = 10$, and EPP behavior.

is investigated, and its damage indices are evaluated applying the mentioned methods.

6.1. Design of steel moment frame

According to ANSI/AISC360-10 [26] and LRFD method, a two-dimensional steel moment frame with three stories and one bay has been designed in which the drift is the controlling item. The frame sections are selected from usual rolled W sections, and the used material is ST-37. Moreover, the fundamental period of the frame is 0.86 s. Other important properties of the frame are shown in Figure 8.

Dead and live loads are assigned similar to those in office buildings. For an ordinary design, the seismic loading is specified based on Iranian Seismic Standard [27], considering seismic zone factor, reflection coefficient, importance factor, and reduction coefficient,

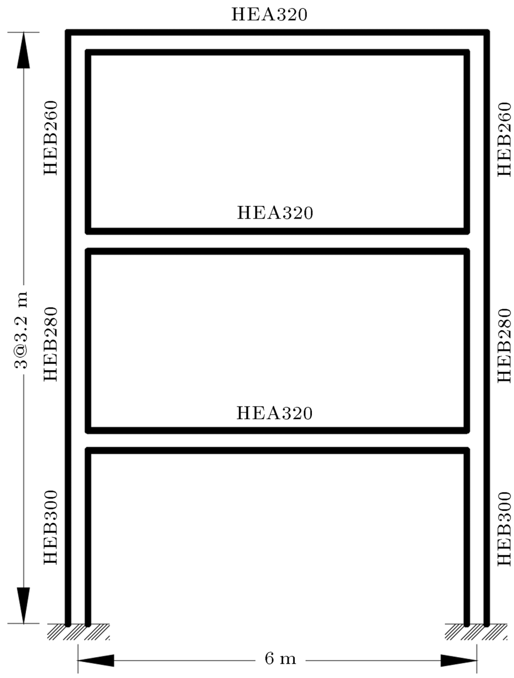


Figure 8. The steel moment frame geometry.

which are equal to 0.35, 2.5, 1, and 5, respectively. All frame connections are rigid, and the panel zones are strengthened by an enough number of stiffeners.

6.2. Seismic analysis procedure

The "OPENSEES" software [28] will be very useful to carry out nonlinear dynamic analysis of the frame, which is the best method proposed in seismic design codes. Therefore, in this study, the OPENSEES model of the frame with nonlinear beam-column elements, uniaxial fiber sections, and STEEL01 material has been prepared. The strain hardening coefficient is assumed 0.01 to make the material behavior similar to EPP behavior. Each member is equally divided into four elements by defining five recorded points–where damage indices are calculated–for the member and seven integration points for every element. The recorded points as well as a typical fiber section of structural members are displayed in Figure 9.

In addition, two vertical load combinations in the nonlinear dynamic analysis are examined according to ASCE/SEI7-10 [20], considering the geometrical nonlinear behavior or secondary moments. The story mass is distributed to the beam ends as lumped masses. Additionally, Rayleigh damping is supposed, including the damping ratio equal to 0.05 and the frequencies of the first and second vibration modes of the frame. Moreover, the ductility capacity of structural elements is determined based on FEMA-356 report [24].

ET records and scaled real earthquakes are separately imposed on the frame; thereafter, the time history of moment and plastic rotation at recorded points as well as inter-story drifts are computed. Eventually,

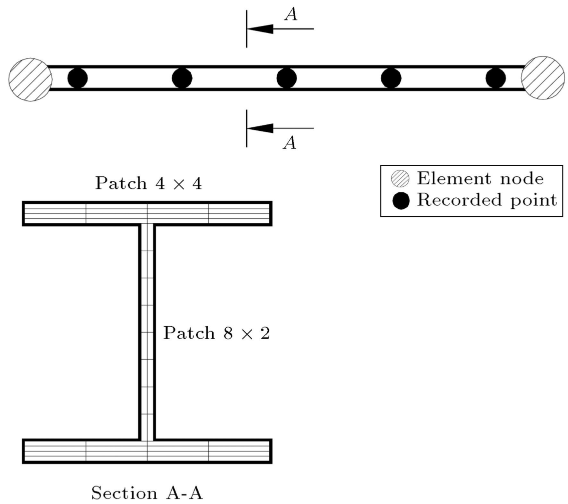


Figure 9. Recorded points and a fiber section of a member.

through applying a post processor piece of software induced for this research, various damage indices at each recorded point are calculated.

6.3. Presentation of used damage indices

The mentioned damage index, DI_m, is calculated for frame members, considering section rotation (θ) and yield moment (M_y), instead of deformation (u) and yield strength (F_y) in DI_m formulation, respectively. In addition to "Modified Park-Ang" damage criterion, some well-known damage indices are used to evaluate the damage state of the frame.

The first damage index is the inter-story drift defined as the ratio of the story relative displacement to the story height. The drift ratio ($\mathrm{DI}_{\mathrm{drift}}$) used in this study is the proportion of maximum inter-story drift to drift capacity (C_{drift}), which agrees with the damage index definition. This index is given in Eq. (4):

$$\mathrm{DI}_{\mathrm{drift}} = \left(\frac{\Delta_{\max}}{H}\right)/(C_{\mathrm{drift}}), \tag{4}$$

where H is the story height and $\Delta_{\max}$ is the maximum relative displacement between the top and bottom of the story. Drift capacity is usually presumed 0.05 for steel frames [24].

The next damage criterion is "Krawinkler-Zohrei" index (DI_{KZ}), the proportion of cumulated cyclic deterioration ($\sum \Delta \mathbf{d_i}$) to the ultimate deterioration capacity (Δd_c). This index attributes deterioration (Δd) in terms of strength, stiffness, and energy dissipation to the plastic rotation ($\Delta\theta_p$). The related formulations are presented in Eq. (5), where parameters a and A are constant depending on the properties of the structural member, assumed 1.226 and 0.930 for energy dissipation, where strength and stiffness deterioration have been neglected. The parameter $\Delta\theta_{pc}$ indicates maximum plastic rotation of a section during the pushover analysis of the frame:

$$\mathrm{DI}_{KZ}=\frac{\sum\Delta d_i}{\Delta d_c},$$

$$\Delta d=A(\Delta\theta_p)^a,$$

$$\Delta d_c=A(\Delta\theta_{pc})^a. \qquad (5)$$

Two damage parameters applied directly in some damage criteria (such as DI_m) are presented in Eq. (6), where $\mathrm{DI}_{\mathrm{duc}}$ and $\mathrm{DI}_{\mathrm{eng}}$ indicate ductility-based and energy-based damage indices, respectively. Furthermore, the expression in the dominator of $\mathrm{DI}_{\mathrm{eng}}$ is the ultimate energy dissipation capacity of the structure, with EPP behavior under uniformly increasing lateral deformation, where θ_y and M_y are yield rotation and yield moment of a section, respectively. All other quantities were defined previously:

$$\mathrm{DI}_{\mathrm{duc}}=\frac{\mu-1}{\mu_u-1},$$

$$\mathrm{DI}_{\mathrm{eng}}=\frac{E_h}{\theta_y M_y(\mu_u-1)}. \qquad (6)$$

The next popular damage index is "Park-Ang" index ($\mathrm{DI}_{\mathrm{PA}}$), containing both ductility and energy dissipation of structural members. The $\mathrm{DI}_{\mathrm{PA}}$ formulation is given in Eq. (7); all parameters have been explained in the prior sections. Moreover, the interpretation of $\mathrm{DI}_{\mathrm{PA}}$ values was represented by Ladjinovic and Folic [6]:

$$\mathrm{DI}_{\mathrm{PA}}=\frac{\mu}{\mu_u}+\beta\frac{E_h}{M_y\theta_y\mu_u}. \qquad (7)$$

The last damage criteria used in this study are "Bozorgnia-Bertero" indices (DI_1 and DI_2). They are almost similar to DI_m index, but many nonlinear analyses as well as regression analysis are needed to evaluate their modifying coefficients (α_1 and α_2) for each earthquake excitation. These indices are shown in Eq. (8):

$$\mathrm{DI}_1=(1-\alpha_1)\mathrm{DI}_{\mathrm{duc}}+\alpha_1\mathrm{DI}_{\mathrm{eng}},$$

$$\mathrm{DI}_2=(1-\alpha_2)\mathrm{DI}_{\mathrm{duc}}+\alpha_2\sqrt{\mathrm{DI}_{\mathrm{eng}}}. \qquad (8)$$

6.4. Comparison and discussion

When the designing, modeling, and seismic analysis of the frame were performed, the explained damage indices at recorded points for a certain earthquake record will be calculated, similar to the procedure of damage computation for SDOF systems. The maximum value of each damage index, for example DI_m, related to every structural member is considered as the damage index of that member, which can be averaged for distinct excitations. The damage indices of the panel zones will be zero because of preparing enough number of stiffeners [29].

In this study, the average and maximum values of each damage index for structural members are evaluated to compare the damage results having to do with GM records and ET excitations. These comparative damage values at DBE hazard level are gathered in Table 2, relating to GM and ET records with S_a-based and damage-based target times. Apparently, $\mathrm{DI}_{\mathrm{duc}}$ and $\mathrm{DI}_{\mathrm{eng}}$ parameters have minimum and maximum values among all damage criteria, respectively. In addition, some parameters–namely DI_m, $\mathrm{DI}_{\mathrm{PA}}$, DI_1, DI_2, and $\mathrm{DI}_{\mathrm{drift}}$–refer to the same damage grade in most cases of the study.

As was previously mentioned, in the ET method, damage indices of members can be simultaneously evaluated for various levels of excitations. Additionally, a few numbers of accelerograms will be imposed on the frame. Hence, the analysis time will be considerably reduced. It is noteworthy that the damage values of "ETA20e" and "ETA20inx" series will be close to each other, since they have been generated based on real earthquakes.

The values of damage index DI_m for all structural members are demonstrated in Figure 10, correspond-

Table 2. Average and maximum damage values of the frame members with respect to GM and ET records with S_a-based and damage-based target times at DBE level.

Damage index	**GM**		**S_a-based ET**		**Damage-based ET**	
	Average	**Max.**	**Average**	**Max.**	**Average**	**Max.**
$\mathrm{DI}_{\mathrm{duc}}$	0.119	0.255	0.060	0.173	0.096	0.251
$\mathrm{DI}_{\mathrm{eng}}$	0.683	1.000	0.158	0.372	0.328	0.902
DI_m	0.185	0.453	0.070	0.176	0.125	0.292
$\mathrm{DI}_{\mathrm{PA}}$	0.211	0.502	0.081	0.208	0.140	0.322
DI_1	0.283	0.715	0.088	0.201	0.163	0.404
DI_2	0.233	0.465	0.146	0.284	0.219	0.444
DI_{kz}	0.414	1.000	0.084	0.223	0.178	0.535
$\mathrm{DI}_{\mathrm{drift}}$	0.360	0.420	0.240	0.280	0.300	0.340

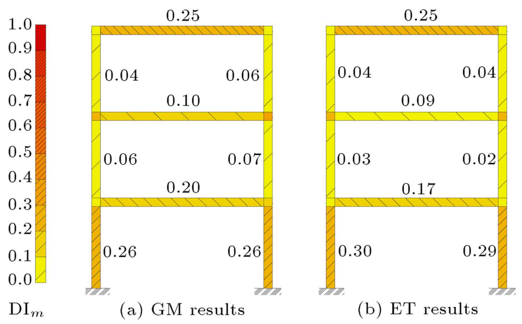


Figure 10. Comparison between DI$_m$ values of frame members under GM and ETA20inx records with damage-based target time at DBE level.

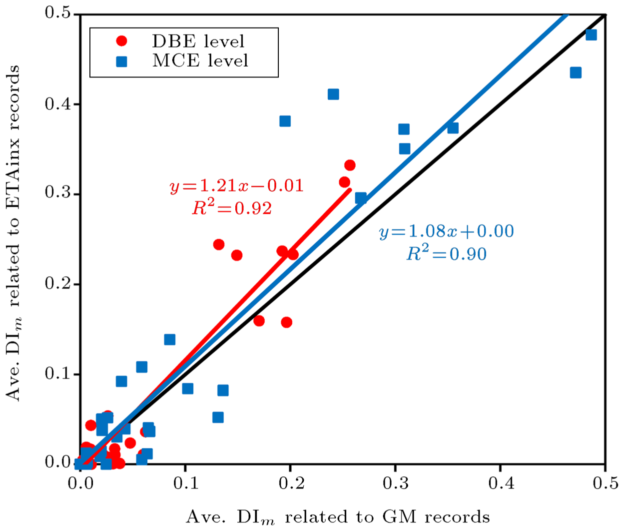


Figure 11. Comparison between DI$_m$ values related to GM and ETA20inx records, with damage-based target time, at recorded points of the frame.

ing to GM records and "ETA20inx" series with the damage-based target time. As it reveals, the elements in the first story have received most of the damage. Additionally, the damage estimation by the ET method can be acceptable. For more details, in Figure 11, damage values at recorded points of the frame, connected to GM records, have been compared with those of ET series at two levels of excitation, where the trend line is close to the bisector, and R-square coefficient is near to one, which indicates the reliability of ET results.

The comparison among damage criteria relating to GM records and ET accelerograms with S_a-based and damage-based target times will be important in order to survey both the accuracy and improvement of the ET method in which damage spectrum is applied as intensity measure to modify the target time. Therefore, the average damage of structural members for the mentioned three cases at two hazard levels is illustrated in Figure 12. As can be seen, the usage of damage-based target time considerably reforms the damage estimation by ET method.

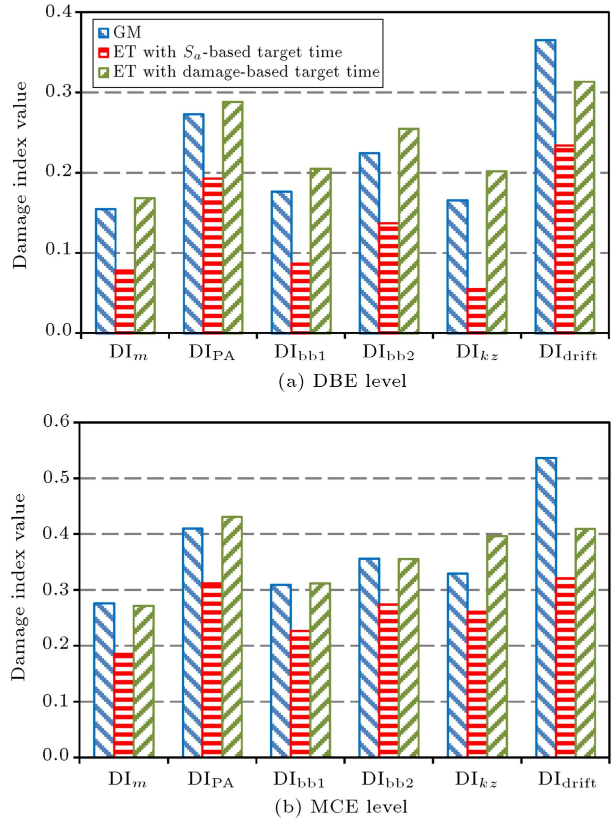


Figure 12. Comparison between the average of damage indices corresponding to GM and ETA20inx records, with the S_a-based and damage-based target times.

7. Conclusions

To sum up, by taking into account what was examined in this study, the following conclusions will be drawn:

- The estimation of damage spectra by Endurance Time (ET) method using S_a-based target time–corresponding to linear target spectra–is prone to a considerable inaccuracy, and in general, the system damage index is underestimated using this procedure;
- By modifying the target time of ET series on the basis of the damage spectra, using the ratio between the average of damage spectrum of scaled Ground Motions (GM) and that of ET records, ET damage spectra become much more consistent with GM damage spectra. Thus, damage spectrum can be applied as an intensity measure in ET method to modify the target time;
- The damage estimation of steel moment frames by the ET method can be highly improved by modifying the target time based on damage spectra. In general, it seems that the damage level of conventional structures might be estimated in an adequate faction through employing the method proposed in this research. Given the results, it is proposed to

generate ET excitation functions based on damage spectra, which can further improve the accuracy and reliability of damage estimation;

- The damage of steel moment frame at DBE and MCE hazard levels, examined in this study, will be roughly approximated by two ET acceleration functions, that is, "ETA20e" and "ETA20inx" records, with the damage-based target time.

Nomenclature

a	Krawinkler and Zohrei material-dependent constant
a_g	ET acceleration function
A	Krawinkler and Zohrei constant depending on section properties
C	Earthquake coefficient
C_{drift}	Drift capacity of the frame
DBE	Design basis earthquake
DI_1 and DI_2	Bozorgnia-Bertero damage indices
DI_{drift}	Drift ratio
DI_{duc}	Ductility-based damage index
DI_{eng}	Energy-based damage index
DI_{KZ}	Krawinkler-Zohrei damage index
DI_m	Modified Park-Ang damage index
DI_{PA}	Park-Ang damage index
EPP	Elastic-perfectly-plastic behavior
ET	Endurance time method
E_h	Hysteretic energy dissipation demanded by earthquake excitation
$F(a_g)$	The error of correlation between ET response spectrum and the target spectrum
F_y	Yield strength of a structure
GM	Ground motions
H	Height of story
LRFD	Load and Resistance Factor Design
m	Mass of a structure
MCE	Maximum Considered Earthquake
M_y	Yield moment of a section
RC	Reinforced Concrete
S_a	Spectral acceleration response
$S_a(T,t)$	The ET acceleration response at time t for structure with period T
$S_{aT}(T)$	Template acceleration response for structure with period T
SDOF	Single-Degree-Of-Freedom System
t	Time duration of ET record
t_b	Basic target time
t_t	Target time
T	The natural period of a structure
$u_{c,\max}$	Maximum cyclic deformation
$u_{p,i}$	Plastic deformation at ith cyclic
u_y	Yield displacement of a structure
α_1 and α_2	Bozorgnia-Bertero coefficients
β	Park-Ang coefficient
Δd_i	Element deterioration at ith cyclic
Δd_c	Ultimate deterioration capacity
$\Delta_{\max}$	Maximum story drift
$\Delta\theta_p$	Plastic rotation of a section
$\Delta\theta_{pc}$	Maximum plastic rotation of a section during the pushover analysis of a frame
θ_y	Yield rotation of a section
μ	Ductility demanded by earthquake excitation
μ_{ac}	Accumulated cyclic ductility of an element
μ_c	Cyclic ductility
μ_u	Ductility capacity of an element
x	Damping ratio

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Biographies

Mohammad Jalal Maleki-Amin was born in 1989. He was qualified in Shahid Danesh High School in Tehran, Iran, as the best student in the field of mathematics and physics in 2008. Subsequently, he entered Sharif University of Technology and began studying Civil Engineering. He achieved a BS degree in Civil Engineering and an MS degree in Structure Engineering in the years of 2012 and 2014, respectively. He successfully defended his MS degree thesis entitled "Application of Damage Spectra in the Estimation of Steel Moment Frames Damage by ET Method" in August 2014. He was ranked 2nd in the PhD Professional Examination, and is presently a PhD candidate in Structure Engineering in the faculty of Civil Engineering at Tehran University.

He has focused on some research areas comprising: performance-based design of steel and concrete structures, nonlinear dynamic analysis of buildings, seismic assessment and rehabilitation of existing structures, and damage estimation of steel frames.

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