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# COMPARISON OF DAMAGE INDEXES IN NONLINEAR TIME HISTORY ANALYSIS OF STEEL MOMENT FRAMES

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## ABSTRACT

Damage indexes consider different aspects of structural response with the objective of producing a quantitative measure of structural damage. In this paper, damage indexes based on deformation, energy, modal parameters and low cycle fatigue behavior are investigated in order to find a correlation between their numerical values. Selected damage indexes are compared by applying them in the nonlinear analysis of various low rise steel frames subjected to a set of seven earthquake accelerograms corresponding to a specific soil condition. Correlations between various indexes have been presented graphically and approximate conversion formulas are also provided.

**Keywords:** Damage index, steel moment frame, earthquake assessment, low cyclic fatigue

## 1. INTRODUCTION

Quantitative measurement of structural damage during earthquakes has always been a challenging problem to the structural engineers. Various damage indexes have been proposed with the objective of quantifying the structural damage in prototype and model structures subjected to seismic excitation. These indexes make use of different parameters such as drift, datural period of structure, energy absorption and cyclic fatigue in estimating the damage level. For instance, Krawinkler and Zohrei [1] proposed a damage index that uses the concept of cyclic fatigue; Park and Ang [2, 3] proposed another damage index that is a combination of noncumulative deformation and energy concepts. Another combined damage index was introduced by Bozorgnia and Bertero [4-6]. A group of indexes which consider the changes in structural period during vibration time was brought in by Dipasquale and Cakmak [7-9]. On the other hand, structural damage has a physical interpretation from the structural engineering view point, i.e. losing the ability to resist external forces and ultimately becoming unstable. At service level, damage is also interpreted as the level of nonstructural damage that results from excessive building deformations. Considering the common concept of damage, the question arises about how these damage indexes are correlated and weather some indexes can be predicted based on the value of some others.

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In this paper some of the most commonly used damage indexes have been screened according to their significance and practical use. In the next step, these indexes have been measures by applying them in the nonlinear time-history analysis of a group of steel moment frames under selected seismic excitations. The correlation between these damage indexes has been studied by comparing their average values in various cases to two main indexes selected as base indexes. These include drift and Bozorgnia and Bertero index. A series of equations are presented in each case that enables one to estimate some damage indexes based on the value of others. The correlation coefficients and consistency of the results obtained from each damage index as compared to other ones are also studied.

## 2. THEORY AND CONCEPTS OF THE DAMAGE INDEXES

Several physical responses of structures have been used as indicators of damage at the structural level which are called damage parameters. Each damage index uses specific damage parameters and the parameters used to categorize the damage index. The structural responses used as damage parameters can be classified as:

1. Plastic deformation of elements or structure
2. Energy Dissipation through hysteretic behavior in the elements: Structural elements have limited capacity to dissipate energy in cyclic manner prior to failure. The amount of dissipated energy serves as an indicator of the damage occurred during loading.
3. Low cyclic fatigue of the elements: The structural damage could be assessed by the cyclic fatigue theory. Because of the nature of seismic response and large relative deformations involved, low cyclic fatigue theory is used in structural and earthquake engineering.
4. Changes in dynamical parameter of structure such as the first natural period of the structure.

Damage indexes are usually normalized so that their value is equal to zero when there is no damage and is equal to unity when total collapse or failure occurs. On the other hand a damage parameter is a quantity that is used for estimating the damage. A damage index can involve a combination of one or more damage variables in its calculation. As a result, in order to calculate damage indexes, damage parameters should also be normalized. The normalization of damage variables could be based on one of the following approaches:

1. The demand versus capacity approach is based on estimation of certain demand on a structure, sub-structure or member, and estimation of the corresponding capacity. This kind of normalization was more popular few years before. Several well known indexes like Park and Ang [2] use this kind of normalization.
2. In the second approach, the calculated degradation of a certain structural parameter, like stiffness or energy dissipation or natural period of structure, is compared with a predetermined critical value, and is usually expressed as a percentage of the initial value corresponding to the undamaged state or the last stage value as a damaged state.

Damage indexes can be classified from different viewpoints such as ‘Local - global’ indexes or 'Cumulative and non cumulative'. A local damage index is an indicator of damage for a part of structure such as an element or a story while a global index considers the damage to of the structure in whole. In order to determine an index for the entire structure from the local indexes, a method to weight these local values into a global parameter is necessary. In this paper a method in which local indexes are weighted by the local energy absorption as introduced by park and Ang [2] is used. Capturing the accumulation of damage sustained during dynamic loading is also of particular interest to structural engineers. Those indexes that can calculate the accumulation of damage are called cumulative indexes. In this paper some of the more versatile and significant damage indexes have been studied. The concepts of these indexes are summarized in the next section.

### *2.1 Non Cumulative local Damage Indexes*

Plastic ductility based indexes are one of the most prominent indexes in this category. Powell and Allahabadi [10] define structural damage in terms of plastic ductility as shown in Eq. (1). The simple concept and ease of use make this index a popular one between engineers and researchers.

$$DI_{\mu} = \frac{u_{\max} - u_y}{u_{mon} - u_y} = \frac{\mu - 1}{\mu_{mon} - 1} \tag{1}$$

### *2.2 Non Cumulative global Damage Indexes*

Structural drift is among the most well known indexes in this category. This index is defined as the ratio between the maximum displacement of structure at the target point, and the story height.

$$DI_{Drift} = \frac{\Delta_m}{H} \tag{2}$$

### *2.3 Combined indexes*

### *2.3.1 Modified version of Park and Ang index*

Park and Ang introduced their index in 1985 [2]. This index was a combination of ductility and energy absorption capacity indexes. After some years Kunnath et al. [11] modify the original index and represent it in the form of Eq. (3). Although this index was calibrated for concrete elements, this index is used for damage assessment of both concrete and steel structures because of its clear physical concept. The index is well known among all researchers and is one of the most popular indexes.

$$D = \frac{\phi_m - \phi_y}{\phi_u - \phi_y} + \beta_e \frac{\int dE}{M_y \phi_u} \tag{3}$$

### *2.3.2 Bozorgnia and Bertero*

Bozorgnia and Bertero [4-6] introduced two improved damage indexes for a generic inelastic SDF system. These damage indexes are given in Eqs. (4) through 6.

$$\mu_H = \frac{E_H}{F_y u_y} + 1 \tag{4}$$

$$DI_1 = \frac{(1-\alpha_1)(\mu - \mu_e)}{\mu_{mon} - 1} + \alpha_1 \frac{\mu_H - 1}{\mu_{Hmon} - 1} \tag{5}$$

$$DI_2 = \frac{(1-\alpha_2)(\mu - \mu_e)}{\mu_{mon} - 1} + \alpha_2 (\frac{\mu_H - 1}{\mu_{Hmon} - 1})^{1/2} \tag{6}$$

Where $0 < \alpha_1 < 1$ And $0 < \alpha_2 < 1$ are Bozorgnia and Bertero coefficients.

### *2.4 Damage indexes based on modal parameters*

#### *2.4.1 Maximum softening index*

Dipasquale and Cakmak [7] define the maximum softening for the one-dimensional case, where only the fundamental eigen frequency is considered. The index is given by

$$D_m = 1 - \frac{T_{und}}{T_m} \tag{7}$$

The maximum softening demonstrates a measure of combination of both the stiffness degradation and plasticity effect.

#### *2.4.2 Plastic softening index*

Dipasquale and Cakmak [8, 9] define the plastic softening index as follows:

$$D_{pl} = 1 - \frac{T_{dam}^2}{T_m^2} \tag{8}$$

The plastic softening is essentially a measure of plastic deformation and soil interactions occurring during the earthquake.

### *2.5 Cyclic Fatigue Local Damage Indexes*

#### *2.5.1 Krawinkler and Zohrei*

In order to assess the reliability of structures subjected to severe ground motions, it is necessary to evaluate failure modes which lead to cyclic deterioration in strength, stiffness and energy dissipation capacity. It is convenient to use cumulative damage models to predict the probability of failure in cyclically loaded materials or structural elements. Krawinkler and Zohrei [1] introduced a well known damage index as given in Eq. (9). They used three kinds of deterioration in an element to define its damage, i.e. strength, stiffness and energy dissipation capacity.

$$\Delta d = A(\Delta\delta_p)^a \tag{9}$$

$A$ and $a$ are Krawinkler and Zohrei parameters which depend on the properties of the structural component and can be obtained from some graphs which they calibrated from experimental test on some I shaped steel specimens.

## 3. FRAME MODELS

For the purpose of this study, several 2D intermediate steel moment frames that can be considered as typical office building frames were designed based on LRFD method of UBC-97 [12]. Frame sections have been selected from ordinary W sections that are commonly used in office buildings frames. There are two groups of designs based on the lateral loading and drift limitation shown in Table 1.

Table 1. Frame design groups

| Design group | Response spectrum | Drift criteria |
|---|---|---|
| A | LS damage spectrum-2800-NEHRP | FEMA-ASCE7-2800 |
| B | IO damage spectrum | FEMA |

In the Life Safety [13] damage spectrum [14] level, Iranian 2800 standard [15] and NEHRP response spectrum are almost same and the structures designed based on those codes turned out to have the same member properties [16]. In order to cover a range of model geometries, structures with various geometries are selected as shown in Figure 1. All of the bay widths are 6 meter and the story height of all frames is 3.6 meter which is common in office buildings. Some frame’s design properties are shown in Table 2. Also in order to cover a broader range of lateral stiffness and strengths, several frames have been designed to remain at IO level when subjected to the design level earthquake as shown in Table 2. All frames have been designed considering a response reduction factor, $R$, of 6 corresponding to ordinary moment frames.

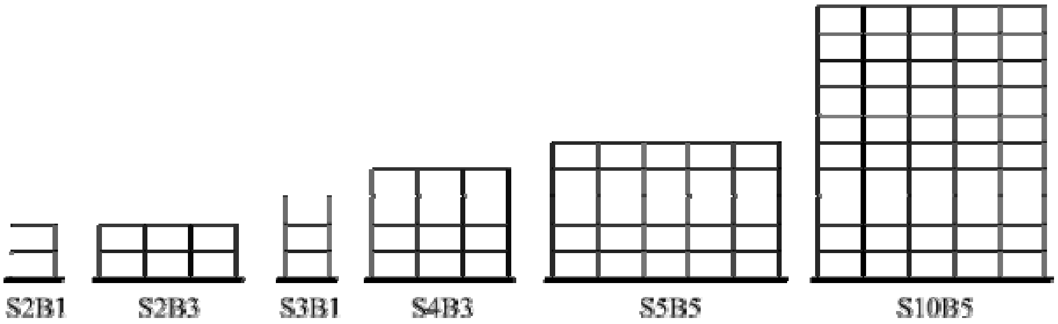


Figure 1. Frame geometries

Three frames named as F2D2A3s1b are designed with the geometry S3B1 and different loading and based on ASD method from AISC-89 [17]. Lateral loading of that frames are based on Iranian 2800 standard response spectrum. The normal frame has design PGA equal to 0.35g but the weak and strong frames have half and twice of normal PGA [18]. The frames design properties can be seen in Table 2.

Table 2. Frame designed properties

| Structure | Natural period | Base shear over the weight of structure | Controled by |
|---|---|---|---|
| S2B1_A | 1.04 | 0.07 | Steress |
| S2B1_B | 0.30 | 0.44 | Drift |
| S3B1_A | 1.41 | 0.05 | Steress |
| S3B1_B | 0.34 | 0.43 | Drift |
| S2B3_A | 1.07 | 0.07 | Stress |
| S2B3_B | 0.27 | 0.42 | Drift |
| S4B3_A | 1.75 | 0.04 | Stress |
| S4B3_B | 0.42 | 0.43 | Drift |
| S5B5_A | 1.99 | 0.04 | Stress |
| S5B5_B | 0.45 | 0.43 | Drift |
| S10B5_A | 3.28 | 0.02 | Stress |
| S10B5_B | 0.67 | 0.37 | Drift |
| F2D2A3s1b_Srong | 0.68 | 0.11 | Drift |
| F2D2A3s1b_Normal | 0.96 | 0.08 | Drift |
| F2D2A3s1b_Weak | 1.28 | 0.06 | Drift |

## 4. EARTHQUAKE RECORDS

Records used on this study are seven earthquakes selected from a set of twenty records used in FEMA 440 [19] for site class C that have relatively similar response spectrum in comparison to soil type II in Iranian code 2800 standard. These records are selected on the basis of near unity scale factor with the acceptable scaling range between 0.5 and 2 when matched against Iranian code 2800 soil type II standard response spectrum. These ground motion records are listed in Table 3 and their scaled response spectrums are shown in Figure 2. All records are scaled for the periodic range between 0.1 to 1.6 second to have response spectrums with minimum difference with the Iranian code 2800 standard response spectrum for soil type II. The scaling over the periodic range lead to a response spectrum which have not a fine correlation with the purposed spectrum but the finest one for set of structures on the scaled periodic range.

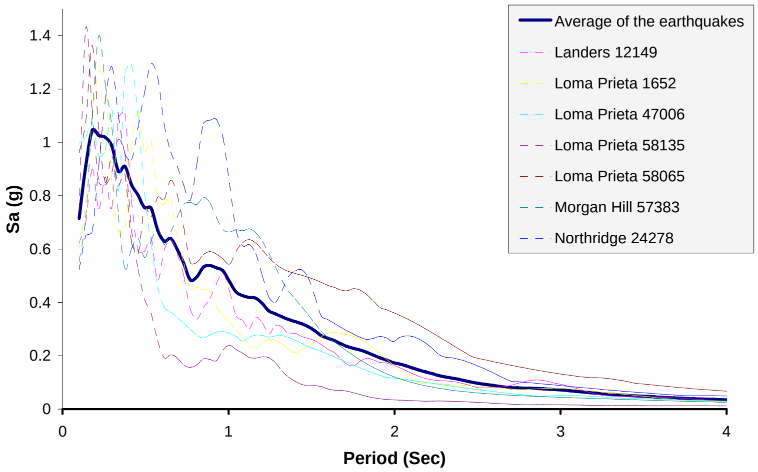


Figure 2. Response spectrums of the scaled accelerograms

Table 3. Ground Motions Records on Site Class C

| No | Date | Earthquake Name | Magnitude (Ms) | Station Number | Component (deg) | PGA (g) | Scale factor |
|---|---|---|---|---|---|---|---|
| 1 | 01/17/94 | Northridge | 6.8 | 24278 | 360 | 0.51 | 0.91 |
| 2 | 06/28/92 | Landers | 7.5 | 12149 | 0 | 0.17 | 2.00 |
| 3 | 04/24/84 | Morgan Hill | 6.1 | 57383 | 90 | 0.29 | 1.18 |
| 4 | 10/17/89 | Loma Prieta | 7.1 | 1652 | 270 | 0.24 | 1.56 |
| 5 | 10/17/89 | Loma Prieta | 7.1 | 47006 | 67 | 0.36 | 1.18 |
| 6 | 10/17/89 | Loma Prieta | 7.1 | 58135 | 360 | 0.44 | 0.80 |
| 7 | 10/17/89 | Loma Prieta | 7.1 | 58065 | 0 | 0.50 | 1.22 |

## 5. DAMAGE PREDICTION OF FRAMES BASED ON THE DAMAGE INDEXES

### *5.1 Structural modeling*

The ‘OPENSEES’ finite element software [20] was used in order to create numerical model of structures. Beam and column elements are modeled with displacement beam-column element type that defines a distributed elastic-plastic section all along the element [21]. Five integration points in each element is used to evaluate the response of the element. These responses include the energy dissipated in the element, plastic deformations and cyclic fatigue calculations. The section of element is a fiber section in which the height of the I section is divided into uniaxial fibers. Those fibers represent uniaxial force-deformation relationships. Materials are modeled with the STEEL01 object in OPENSEES which is used to construct a uniaxial bilinear steel material object with strain hardening ratio [20].

### *5.2 Calibration of damage indexes*

Some of the indexes, such as Krawinkler and Zohrei index, need to be scaled for each element. The parameters used in these indexes depend on the cross section of the element and in order to use the original parameters for elements with different properties as compared to the tested elements, these are modified on the basis of solid mechanics principles [22].

The indexes which make use of energy capacity of elements, such as Bozorgnia and Bertero or Park and Ang, and those that make use of the cyclic capacity of members, such as Krawinkler and Zohrei, are more accurate in predicting low levels of damage. For cyclic fatigue damage indexes of Krawinkler and Zohrei [1], some discussion has been required about the reliability of damage prediction. They compared numerical and experimental models and the comparison shows that the numerical models show more damage for structures after the 10% deterioration and the numerical models have an inaccurate estimation of damage in the range of over 15% deterioration. Therefore, in this paper, these damage indexes are calibrated to equal zero in no structural damage range and to equal one on ten percent of total structural damage. This modification is achieved by using ten percent of the structural member capacity against cyclic loadings as the ultimate capacity of the member [23].

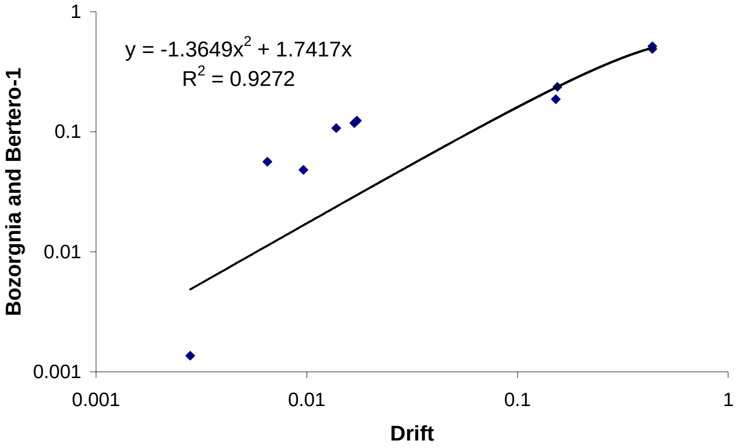
## 6. THE CORRELATION BETWEEN DAMAGE INDEXES

One of the most versatile and popular damage indexes in structural engineering is drift which is used in all building codes as serviceability index and as an important parameter in design procedures. The question that arises is that how accurately and reliably it can estimate the damage of structures and how it can correlate with the other prominent damage indexes.

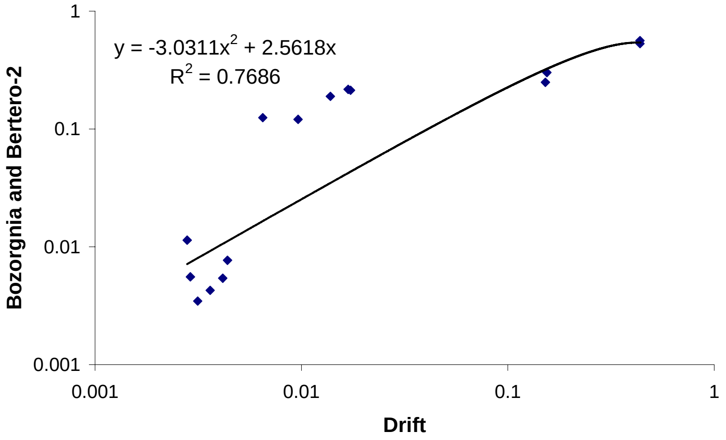
Figures 3 through 6 show the correlation between drift and the studied damage indexes. Each point on these figures corresponds to a series of analyses where the intended structure is assessed under 7 scaled earthquakes and the values of the damage indexes are averaged.

The best fit equations are presented that enable one to estimate various indexes based on the drift of the structure. Considering the fact that the energy dissipation and displacement are related to each other by a second degree relation, the energy or cyclic fatigue based indexes can be expected to show an approximate second degree relation to drift. On the other hand, the displacement based indexes almost follow a linear correlation to drift. The modal parameters based indexes have more complicated and diversified relation to drift that cannot be simply anticipated. All fitting curves are set to pass through the origin of coordinates.

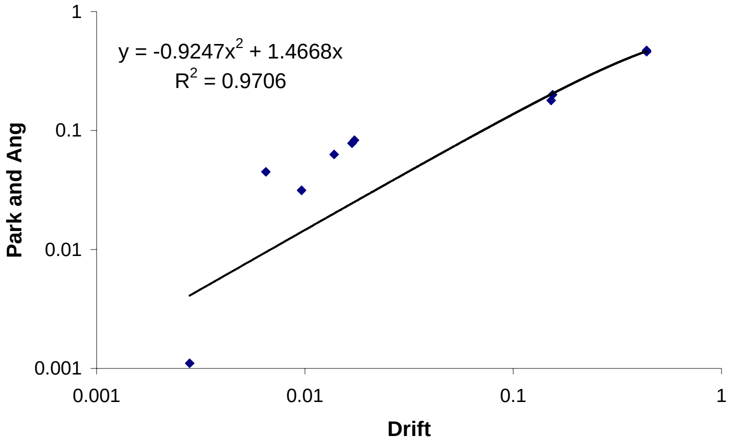
In the Figures 3 the combined indexes of Bozorgnia and Bertero are correlated with the drift index. The combined indexes assume damage parameters of structure as a combination of energy dissipations and plastic deformations in the structure. This underlying definition causes two specific trends in the correlation curves. The cumulative dissipation part has a greater portion from the deformation base part of the damage index in structures with low lateral drift; therefore the predicted damage by combined damage indexes is more than those for drift index. On the other hand the greater portion of non cumulative damages leads closer value for damage indexes estimated by the combined and drift indexes in the structures which have larger value of drift.



(a)

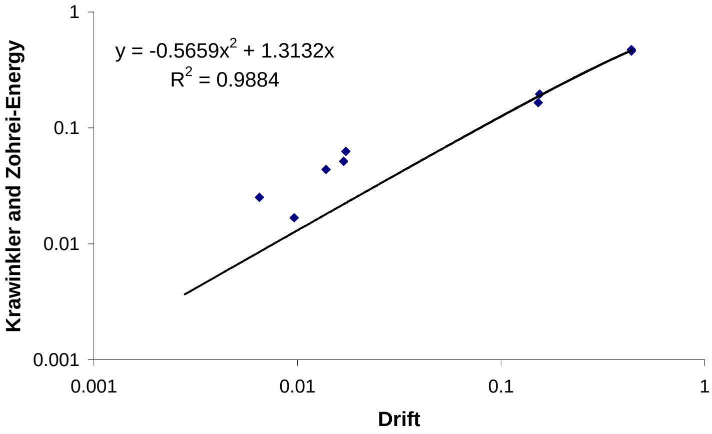


(b)

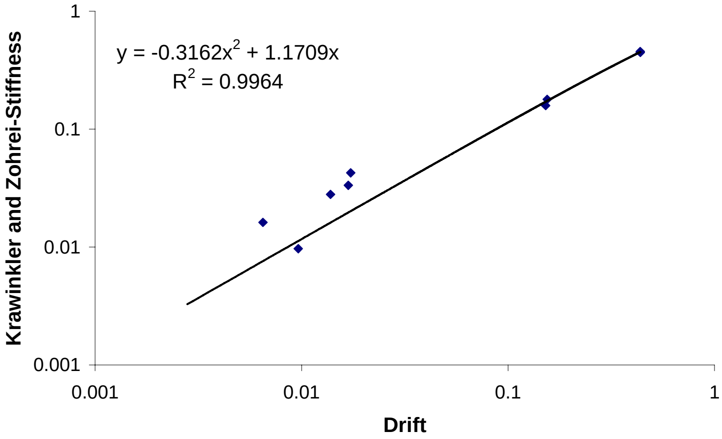


(c)

Figure 3. Correlation between Drift and combined damage indexes (a) Bozorgnia and Bertero-1 (b) Bozorgnia and Bertero-2 (c) Park and Ang



(a)



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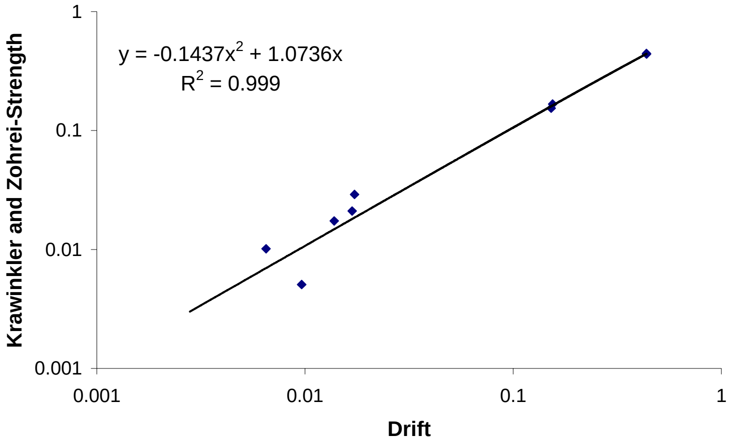


(c)

Figure 4. Correlation between Drift and low cyclic fatigue Krawinkler and Zohrei damage indexes (a) Krawinkler and Zohrei-Energy (b) Krawinkler and Zohrei-Stiffness (b) Krawinkler and Zohrei-Strength

Figures 4 show the correlation between cyclic fatigue indexes and drift index. Since all of the cyclic fatigue indexes use Coffin-Manson and Palmgren-Miner relation in order to predict the number of cycles in which the element fails, the general trend of damage levels are almost the same and difference between the curves is slight and just from difference in the rate of damage development. Two specific trends exist in these comparison curves. This movement from a primary low drift trend to high drift trend is because of the cumulative effect of deformations. In Figure 5 the correlation of Plastic Ductility and Drift index has been depicted. It can be seen that while a reasonable overall correlation exists between the values of the two indexes, in the low drift range, the correlation degrades.

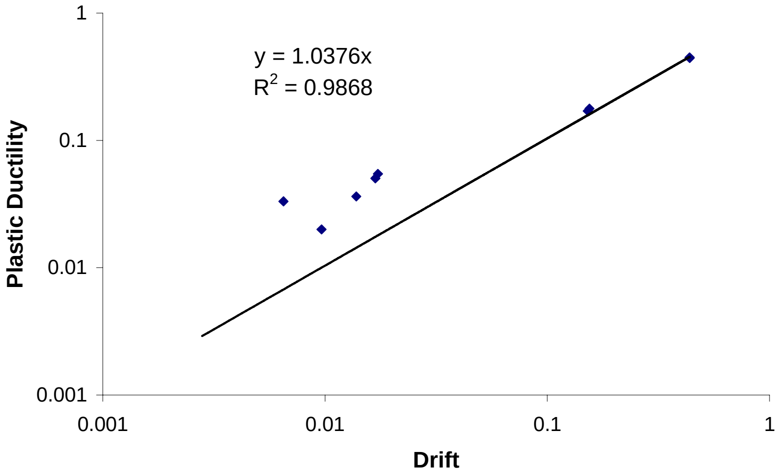
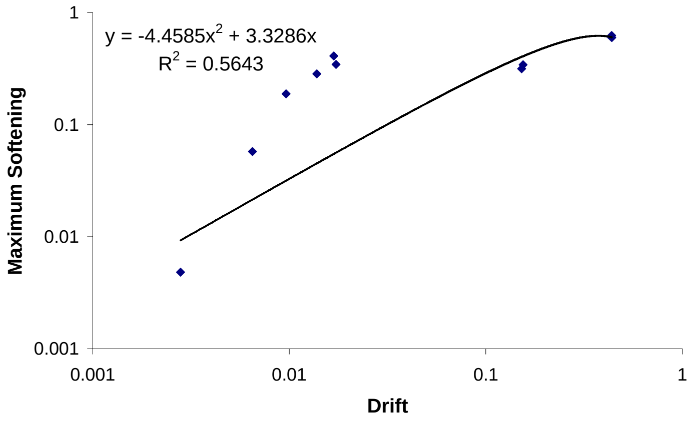


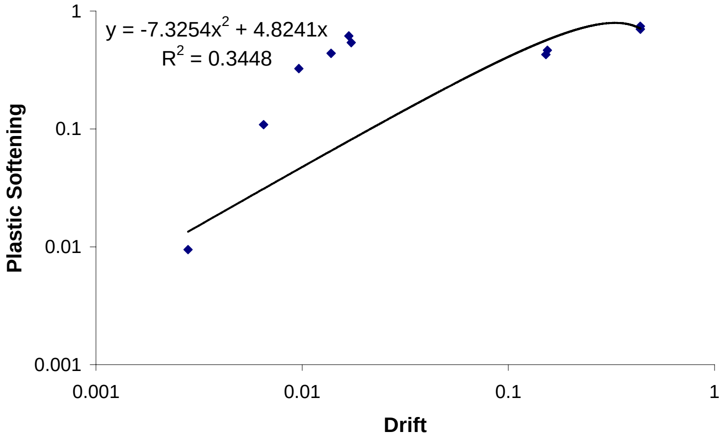
Figure 5. Correlation between Drift and a deformation base damage index Plastic Ductility

In Figure 6 a correlation have been made between drift and modal parameter based indexes. The structures which have less drift under a specific earthquake are more rigid and have lower value of natural period. The modal parameter based indexes compare the natural period of structure with damage or undamaged structure, thus it is predictable that they are more sensitive in the case of stiffer structures. As can be seen in this figure, the correlation between modal parameters based indexes with the drift index is rather poor and these indexes cannot be reliably predicted based on the drift index.

In general it should be mentioned that the drift index cannot be considered the best index where upon, the other indexes can be best estimated. As discussed before, it does not account for the cumulative effect of cyclic deformations and in spite of its clear physical meaning and versatility; it is not to be considered a comprehensive damage index. It seems that better estimations on damage levels can be obtained by using more comprehensive damage indexes that include more aspects of structural response.



(a) Maximum softening

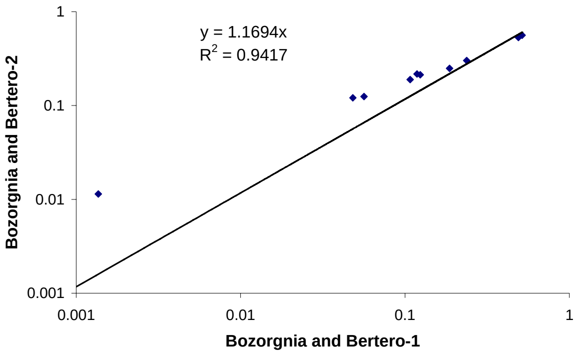


(b) Plastic softening

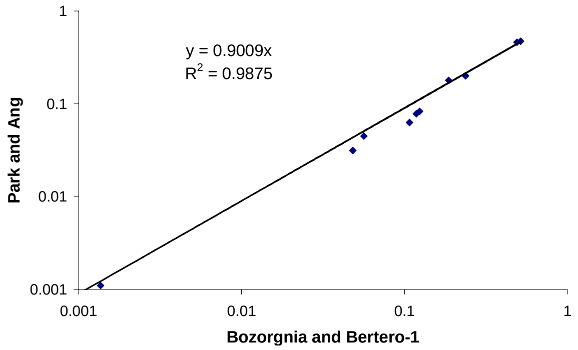
Figure 6. Correlation between Drift and modal parameter base damage indexes

In the next step, the Bozorgnia and Bertero-1 index is selected as the base index and its correlation with other indexes is studied. In Figures 7 to 10, each point is related to a structure which was assessed under 7 scaled earthquakes and the values of the damage indexes are averaged. By using the relations presented in Figure 7 through 10, each damage index can be estimated based on the Bozorgnia and Bertero-1 damage index. As can be seen in Figure 7, the correlation of Bozorgnia-Bertero-2 and Park-Ang indexes with Bozorgnia-Bertero-1 is quite good as expected. Krawinkler-Zohrei indexes show some divergence in the low damage range and their values are generally lower than what is predicted by Bozorgnia-Bertero-1 index as shown in figures 8. Plastic ductility shows better correlation to Bozorgnia-Bertero-1 index as compared to drift index (Figure 9). Modal parameter based indexes also show better relation with Bozorgnia-Bertero-1 index as shown in figure 10 when compared to drift index (see Figure 6), but the correlation is still unsatisfactory.

It should be noted that the correlation provided in this research should be applied with appropriate precaution and careful consideration of the scope and limitations of this study. While each damage index has its own significance and merit, it is believed that knowledge of approximate correlation between various damage indexes can be quite useful and add to the insight when performing seismic resistant design of structures.

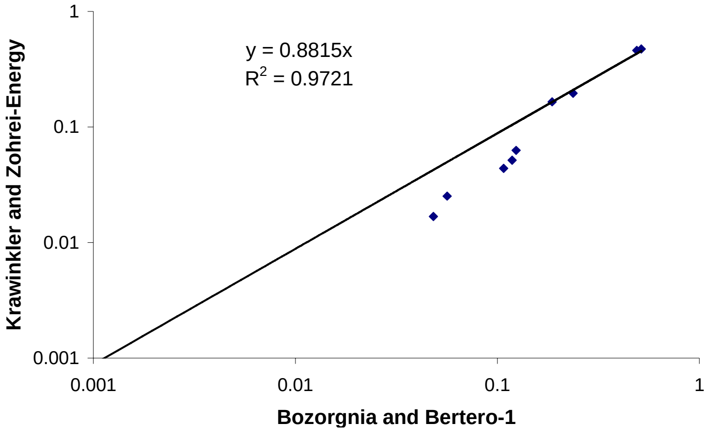


(a) Bozorgnia and Bertero-2

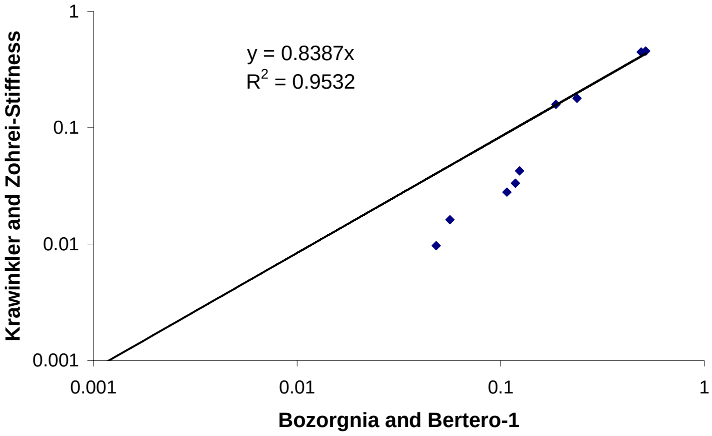


(b) Park and Ang

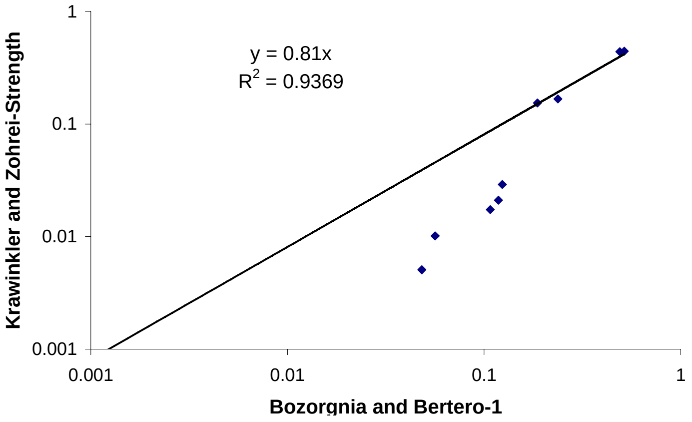
Figure 7. Correlation between Bozorgnia and Bertero-1 and combined damage indexes



(a) Krawinkler and Zohrei-Energy



(b) Krawinkler and Zohrei-Stiffness



(c) Krawinkler and Zohrei-Strength

Figure 8. Correlation between Bozorgnia and Bertero-1 and Krawinkler and Zohrei low cyclic fatigue damage indexesm and Bozorgnia and Bertero-1

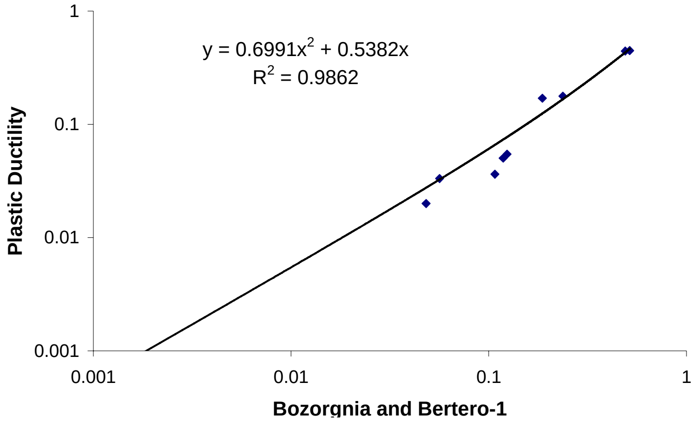
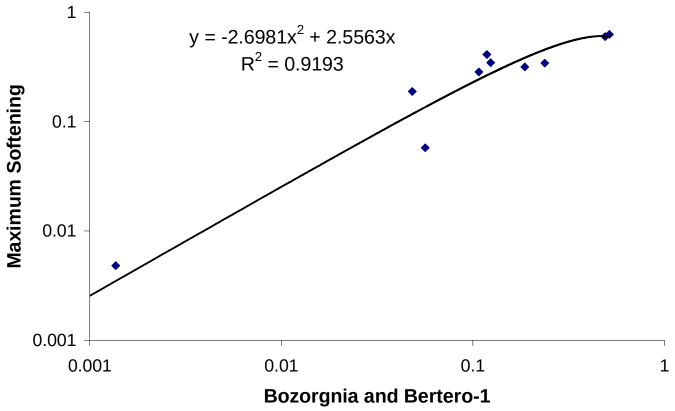
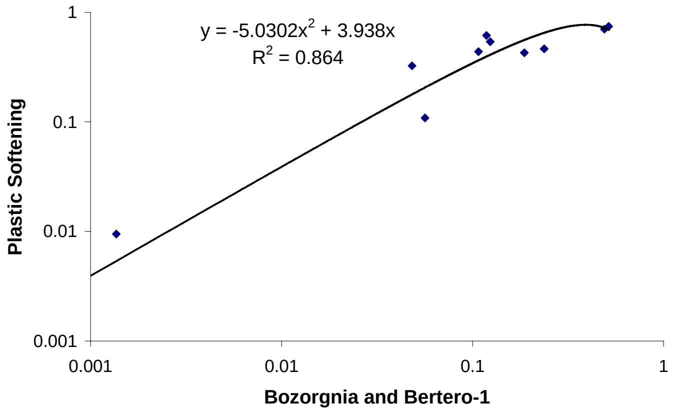


Figure 9. Correlation between Bozorgnia and Bertero-1, and a deformation base damage index Plastic Ductility



(a) Maximum softening



(b) Plastic softening

Figure 10. Correlation between modal parameter base damage indexes, and Bozorgnia and Bertero-1

## 7. CONCLUSIONS

Damage indexes consider different aspects of structural response with the objective of producing a quantitative measure of structural damage. Calculation of most damage indexes involves complicated and time consuming computations that are neither economical nor feasible in concurrent structural engineering practice. For steel moment frames, it is possible to estimate the value of many of these damage indexes based on drift index with acceptable accuracy. Using the equations presented in this paper, the structural damage caused by cyclic fatigue theory or energy dissipation capacity can be estimated based on the maximum drift of the structure. In this way, the damage level of steel moment frames subjected a specific level of earthquake loading can be approximated by using a simple linear analysis.

It is shown that in the cases studied in this research, the Bozorgnia-Bertero, Park-Ang and Krawinkler-Zohrei show a relatively satisfactory correlation with maximum drift index. Some indexes such as modal parameters based indexes and plastic ductility index are less satisfactorily correlated to drift index. It is also shown that better correlation between indexes can be achieved by using more comprehensive indexes such as Bozorgnia-Bertero as the base index. This index shows a much improved correlation with other indexes in general. The correlation with modal parameters based indexes, while improved, remains poor in this case either.

## SYMBOLS

| | |
|---|---|
| $dE$ | Element energy absorption |
| $E_{Hn}$ | Hysteretic energy demanded by earthquake ground motion |
| $E_{Hmon}$ | The hysteretic energy capacity under monotonically increasing lateral deformation |
| $H$ | Structural height |
| $M_y$ | Yield moment |
| $R$ | Response reduction factor in linear analysis |
| $T_{und}$ | Period of undamaged structure |
| $T_{dam}$ | Period of damaged structure |
| $T_m$ | Maximum period of structure |
| $\beta_e$ | Park and Ang coefficient which has range 0.1- 0.5 |
| $\Delta d$ | Element deterioration |
| $\Delta_m$ | Deformation of the target point |
| $\Delta\delta_p$ | Plastic deformation |
| $\mu$ | Displacement ductility demanded by earthquake ground motion, $\mu = u_{\max}/u_y$ |
| $\mu_{mon}$ | The monotonic ductility capacity, $\mu_{mon} = u_{mon}/u_y$ |
| $\mu_e$ | Maximum elastic portion of deformation, $\mu_e = u_{elastic}/u_y$ , $\mu_e = 1$ for inelastic |

behavior and $\mu_e = \mu$ if the response remains elastic $\mu < 1$

$\phi_m$ Maximum curvature in the member

$\phi_y$ Yield curvature in the member

$\phi_u$ Ultimate curvature before totally damaged

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