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Correlation Between Structural Performance Levels and Damage Indexes in Steel Frames Subjected to Earthquakes

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Abstract. *Various damage indexes have been introduced in recent years incorporating different parameters for estimating structural damage. Amongst these indexes, Plastic Ductility and Drift have been the center of attention of standards and building codes, like FEMA-356, because of their straightforward physical interpretation and ease of calculation. In this paper, several steel moment frames have been considered and their responses have been evaluated under a set of scaled earthquakes. A group of various damage indexes, which included cumulative and non cumulative, cyclic fatigue based, deformation based and modal parameter based, has been considered and the damage to structures has been evaluated on their basis. On the other hand, the performance levels of the frames have been estimated on the basis of the FEMA-356 standard. Based on these results, the correlation between FEMA performance levels and the values of damage indexes has been studied and some polynomial equations have been proposed. These simple equations can be used to estimate the value of the damage indexes from FEMA performance levels. Also, the range of each damage index for each FEMA performance level has been determined. At last, based on the concepts underlying each damage index, the indications of some important aspects of the structure response correlated to each FEMA performance level are investigated.*

Keywords: *Seismic assessment; Structural damage index; FEMA-356; Performance levels.*

INTRODUCTION

Many different damage indexes have been introduced in recent years and each of them utilizes some parameters to estimate the structural damage. Each of these indexes could give some useful information on structural damage, considering the underlying assumptions and application limits introduced by their developers.

Amongst these indexes, the Plastic Ductility Damage Index is at the center of attention of standards such as FEMA [1] because of the simplicity in calculation and tangible physical concept. This index was developed by Powell and Allahabadi [2].

Considering that the Plastic Ductility Index has certain weaknesses, such as elimination of damage caused by the cumulative effect of seismic excitations, the correlation between the Plastic Ductility Index, which is the basis of FEMA performance level determination and other damage indexes, will be of great importance. As a matter of fact, this correlation provides a sense of the level of consistency and reliability of the FEMA performance levels in the prediction of structural damage under seismic excitations.

THEORY AND CONCEPTS OF THE DAMAGE INDEXES

Several physical responses of structures have been used as an indicator of damage at the structural level, which are called damage parameters. Each damage index uses some damage parameters and the types of used parameter categorize each specific damage index. The structural responses used as damage parameters can be classified as:

1. Plastic deformation of structure;
2. Energy dissipation, which is the capacity of a

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member to dissipate energy through hysteretic behavior. Structural elements have a limited capacity to dissipate energy in a cyclic manner prior to failure. The amount of energy dissipated serves as an indicator of how much damage has occurred during loading;
3. Cyclic fatigue of the structure;
4. Change in the dynamic parameters of the 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 equal to unity when total collapse or failure occurs to the structure. On the other hand, a damage variable is a quantity that is used for estimating the damage. This variable could be an indicator of the above physical response, while a damage index can make use of a combination of one or more damage variables in its calculation. Because of this, in order to numerically calculate damage indexes, damage variables should be normalized. The normalization of damage variables can be based on one of the following approaches:

1. The demand versus capacity approach. In this approach, the seismic demand of the structure, substructure or member compares with the corresponding capacity. This kind of normalization is more popular and several well known indexes, like Park and Ang [3,4], use this kind of normalization.
2. In the second approach, the calculated degradation of certain structural variables, like stiffness, energy dissipation or the natural period of the structure, is compared with a predetermined critical value and is usually expressed as a percentage of the initial value corresponding to the undamaged state.

In addition to the method of damage index normalization, some other points of view can be used to classify damage indexes, such as:

- Local versus global:
  A local damage index is an indicator of damage for a part of a structure, such as an element or a story, while a global index gives an estimate of overall damage to the structure. In order to determine an index for the entire structure from local indexes, a method to weigh these local values into a global parameter is necessary. In this paper, a method that weights local indexes by local energy absorption, introduced by Park and Ang [3], is used.
- Cumulative and non cumulative:
  Capturing the accumulation of damage sustained during dynamic loading is of particular interest to structural engineers. Those indexes that can consider the accumulation effect of seismic excitation to structural damages are called cumulative indexes.

In this paper, some more practical and prevailing damage indexes have been studied. The concepts of these indexes are summarized in the next sections.

Non Cumulative Indexes

Powell and Allahabadi [2] define structural damage in terms of plastic ductility, which is shown in Equation 1. This index is defined at element level and some methods, like weighted averaging or using the maximum value of member indexes as the storey index, can be used to globalize it. The simple concept and ease of usage make this index a popular one for engineers and researchers.

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

The drift ratio, which is the most practical index between engineers, can be put in this category of indexes. This index is defined as the ratio between the maximum displacement of the structure at the target point and the storey height, and is a naturally global index.

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

Combined Indexes

Modified Version of Park and Ang Index

Park and Ang introduced their index in 1985 for the first time [3,4]. The index is a combination of ductility and energy absorption capacity parameters. After some years, Kunnath et al. [5] modified the original index and represented it as Equation 3. Although this index was calibrated for concrete elements, it is used for damage assessment of both concrete and steel structures, because of its clear physical concepts. The index is well known and is among the most popular indexes.

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

Bozorgnia and Bertero 2001

Bozorgnia and Bertero [6-8] introduced two improved damage indexes for a generic inelastic SDF system. These damage indexes are defined as follows:

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

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

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

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

Damage Indexes Based on Modal Parameters

Maximum Softening Index

Dipasquale and Cakmak [9] define the maximum softening for a 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 is, essentially, a measure of a combination of both the stiffness degradation and plasticity effect.

Plastic Softening Index

Dipasquale and Cakmak [10,11] define the plastic softening index as follows:

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

Plastic softening is, essentially, a measure of plastic deformation and soil interaction occurring during an earthquake.

Cyclic Fatigue Local Damage Indexes

Krawinkler and Zohrei 1983

In order to assess the reliability of structures subjected to severe ground motion, it is necessary to evaluate failure modes, which lead to cyclic deterioration in the 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 introduced their index, as shown in Equation 9 [12], and used three kinds of deterioration measure in structure elements to define its damage:

- Strength;
- Stiffness;
- 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. These parameters can be calculated from some relations, which were obtained from experimental tests on I shaped steel specimens, originally conducted by Krawinkler and Zohrei [12].

FEMA PERFORMANCE LEVELS

FEMA 356 defines the performance levels of a structure at several stages [1]:

1. Linear limit: The structure response restricted to linear limit;
2. Immediate occupancy structural performance level: The structure will be safe to occupy after the earthquake;
3. Damage control structural performance range: A damage state between life safety and immediate occupancy performance level;
4. Life safety structural performance level: Structure is damaged but retains a margin against onset of partial or total collapse;
5. Limited safety structural performance range: A damage state between collapse prevention and life safety performance level;
6. Collapse prevention structural performance level: The structure continues to support gravity loads but retains no margin against collapse;
7. Collapsed.

The performance level of a structure is assessed by evaluating two damage variables:

1. Drift: Drift is the top deflection of a structure over the height of the structure and is a natural global index;
2. Plastic deformation normalized by yield deformation: The maximum local indexes of the structure should not be greater than the limits defined by the standard.

To compare the FEMA discrete performance stages with damage indexes, each FEMA performance level is tentatively assigned to a value between zero and one. Proper scaling of these performance levels requires further investigation, however, for the purpose of this preliminary investigation, a linear scale has been considered. The assigned values are shown in Table 1. Also, in order to avoid the problems associated with including double criteria in calculating the numerical value of performance levels, only the plastic deformation criteria have been used in structural assessment and the drift criteria have not been considered.

FRAME MODELS

For the purpose of this study, several 2D intermediate steel moment frames, which can be considered as

Table 1. Damage indexes assigned to FEMA performance levels.

Fema Performance Level	A-B	IO	DC	LS	LSR	CP	C
Fema Damage Index	0	0.17	0.33	0.5	0.67	0.83	1

similar to typical office building frames, were designed, based on the LRFD method on UBC-97 [13]. Frame sections have been selected from ordinary W sections, which are commonly used in office building frames, and the connection between beams and columns is rigid. The gravitational loading is calculated, based on the Iranian National Building Codes (INBC), but earthquake loads are evaluated by various different approaches. There are two groups of design, based on the lateral loading and drift limitation shown in Table 2. In the LS damage spectrum level [14], the Iranian 2800 standard and the NEHRP response spectrum are almost the same and the structures designed, based on those codes, turned out to have the same member properties [15]. To gain broader results, structures with various geometries are selected, as shown in Figure 1. All of the bay widths are 6 meters and the storey height of all frames is 3.6 meters. Some important frame design results are shown in Table 2.

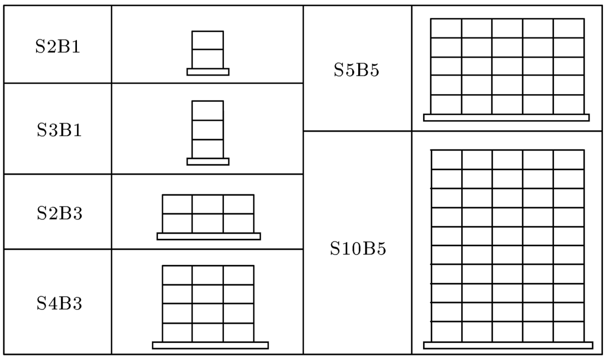


Figure 1. Frame geometries.

Table 2. Frame design groups.

Design Group	Reponse Spectrum	Drift Criteria
A	LS damage spectrum-2800-NEHRP	FEMA-ASCE7-2800
B	IO damage spectrum	FEMA

Three of the frames (F2D2A3s1b_x) are designed with geometry S3B1, different lateral loading levels, and sections designed based on INBC, which is similar to the ASD method of AISC-89 [16]. The lateral loading of these frames are based on the Iranian 2800 standard response spectrum. The normal frame has a standard design PGA equal to 0.35 g, but the weak and strong frames have half and twice the standard design PGA [17]. Frames design properties can be seen in Table 3.

EARTHQUAKE RECORDS

The earthquake records used in this study are from seven earthquakes selected from twenty records proposed in FEMA-440 [18] for site class C. These records have been suggested in FEMA-440 for time history analysis in the assessment of structures. To gain a better result, these records are scaled to match the Iranian 2800 standard response spectrum [19]. The ground motion records and scaling factors are listed in Table 4.

Table 3. Frame design properties

Structure	Natural Period	Base Shear Over the Weight of Structure	Controlled by Stress/Drift
S2B1_A	1.04	0.07	Stress
S2B1_B	0.30	0.44	Drift
S3B1_A	1.41	0.05	Stress
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_strong	0.68	0.11	Drift
F2D2A3s1b_normal	0.96	0.08	Drift
F2D2A3s1b_weak	1.28	0.06	Drift

Table 4. Ground motions records on site class C.

No	Data	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

DAMAGE PREDICTION OF FRAMES

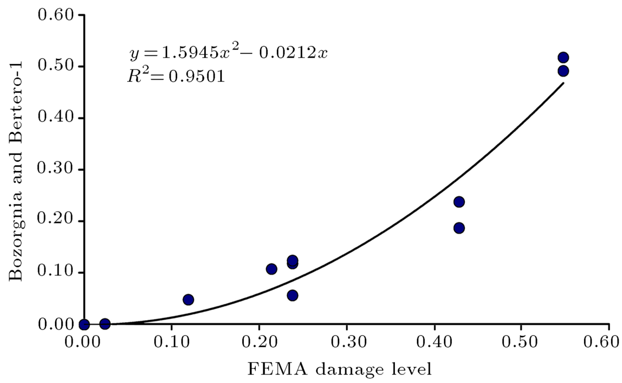
A finite element software, named OPENSEES [20], was used to create models of the proposed structures. The structural elements are modeled with displacement beam column elements, which define distributed elastic plastic sections all along the element [21]. Five integration points in each element are used to evaluate the response of the element. The section of the element is a fiber section, the section within which is divided into uniaxial fibers. Those fibers represent uniaxial force-deformation relationships. Materials are modeled with the STEEL01 object in OPENSEES [21]. This material object is used to construct a uniaxial bilinear steel material object with a small strain hardening ratio.

Some of the indexes needed to be modified for each element, such as the Krawinkler and Zohrei indexes. The parameters used in these indexes depend on the section of the element and, in order to use them for elements which do not have the same properties as the base element, their parameters have to be modified on the basis of solid mechanics principles [16]. The indexes which use the energy capacity of elements like Bozorgnia and Bertero, and Park and Ang, and those which use the cyclic capacity of members like Krawinkler and Zohrei, are more accurate for low damages; therefore, they are calibrated to equal zero on no structural damage and one on ten percent of total structural damage [22]. The nonlinear time history method was used to predict the performance level of frames [1]. All modeling properties and parameters are applied on the basis of the FEMA-356 standard.

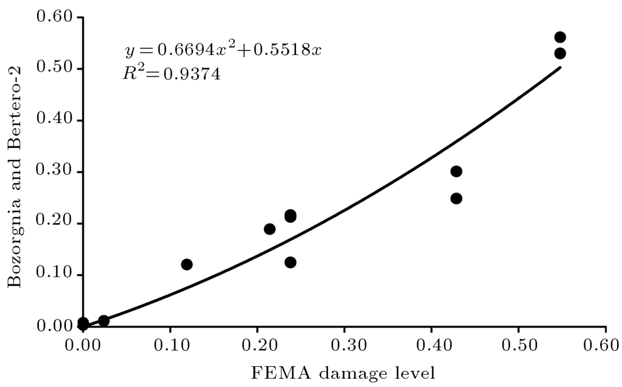
CORRELATION BETWEEN FEMA PERFORMANCE LEVELS AND DAMAGE INDEXES

In this section, the correlation between FEMA-356 performance levels and some prominent damage indexes are investigated. For this purpose, several nonlinear time history analyses have been done and, using the results of these analyses, the structural damage indexes were evaluated. On the other hand, the performance levels of structures under each earthquake have been calculated using FEMA guidelines. At last, the results are summarized in the figures that are presented below. In Figures 2 to 6, each point presents the average of structural response under 7 scaled earthquakes.

As can be seen in Figures 2 to 6, the correlation of FEMA performance levels with Bozorgnia and Bertero, Park and Ang, Krawinkler and Zohrei, and Drift,

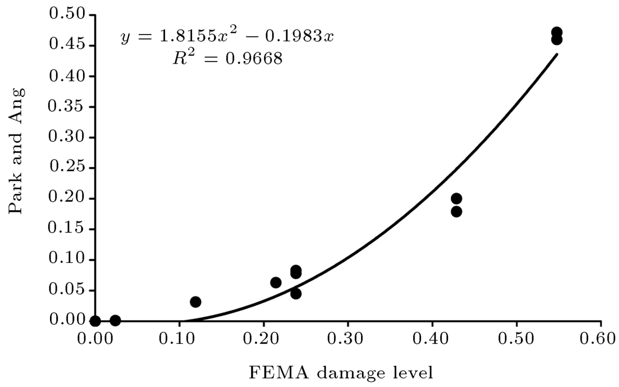


(a) Bozorgnia and Bertero-1

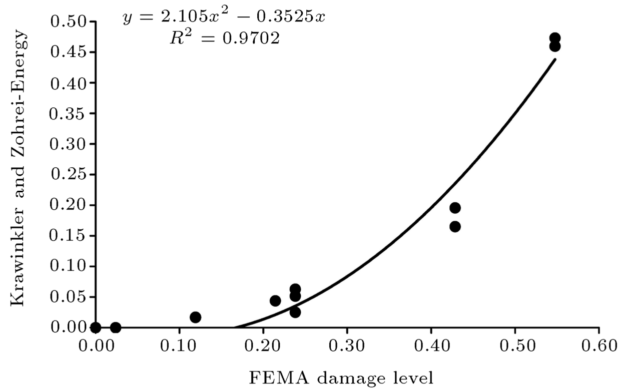


(b) Bozorgnia and Bertero-1

Figure 2. Correlation between combined damage indexes and FEMA performance levels.

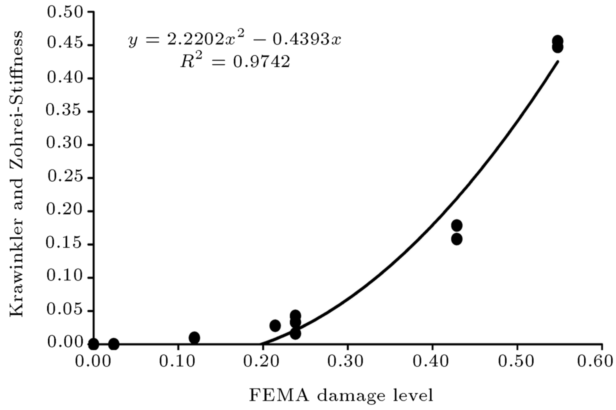


(a)

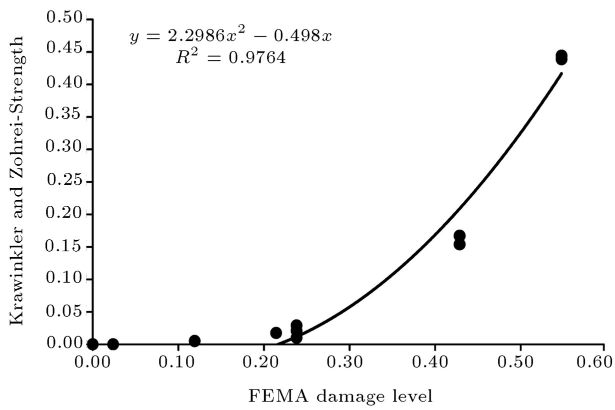


(b)

Figure 3. Correlation between (a) combined damage index Park and Ang, (b) low cyclic fatigue base damage index Krawinkler and Zohrei-energy, and FEMA performance level.



(a)



(b)

Figure 4. Correlation between low cyclic fatigue base damage indexes and FEMA performance level.

follows a second degree curve with reasonably good correlation. The results of maximum and plastic softening are somewhat more scattered. Also, the initial zero damage segment is remarkable in drift and plastic ductility indexes. The numerical range of each damage index correlated to FEMA-356 performance levels can be derived using the above graphs. Therefore, using the relation obtained above, the value of each damage index correlated to FEMA performance levels can be summarized in Table 5.

By using the results shown in Table 5, the damage index that could be assigned to each FEMA

Table 5. The estimated value of damage indexes correlated to FEMA performance levels.

FEMA-356 Performance Level	A-B	IO	DC	LS	LSR
Bozorgnia and Bertero-1	0.00	0.04	0.17	0.39	0.70
Bozorgnia and Bertero-2	0.00	0.11	0.25	0.44	0.67
Park and Ang	0.00	0.02	0.13	0.35	0.68
Krawinkler and Zohrei-energy	0.00	0.00	0.11	0.35	0.71
Krawinkler and Zohrei-stiffness	0.00	0.00	0.10	0.34	0.70
Krawinkler and Zohrei-strength	0.00	0.00	0.09	0.33	0.70
Maximum softening	0.00	0.18	0.34	0.51	0.67
Plastic softening	0.00	0.30	0.51	0.63	0.66
Plastic ductility	0.00	0.00	0.11	0.34	0.68
Drift	0.00	0.00	0.08	0.32	0.69

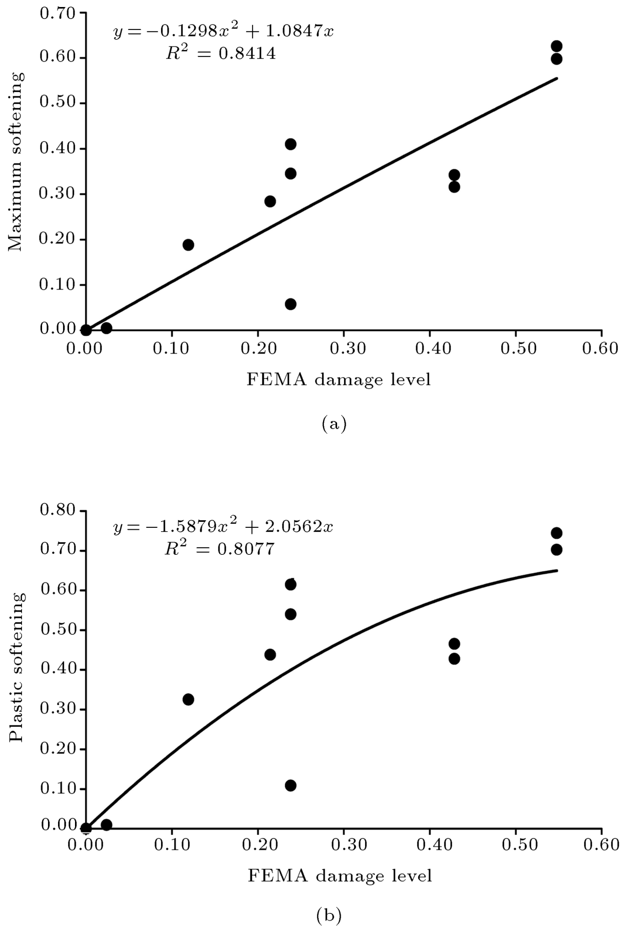


Figure 5. Correlation between modal parameter base damage indexes and FEMA performance level.

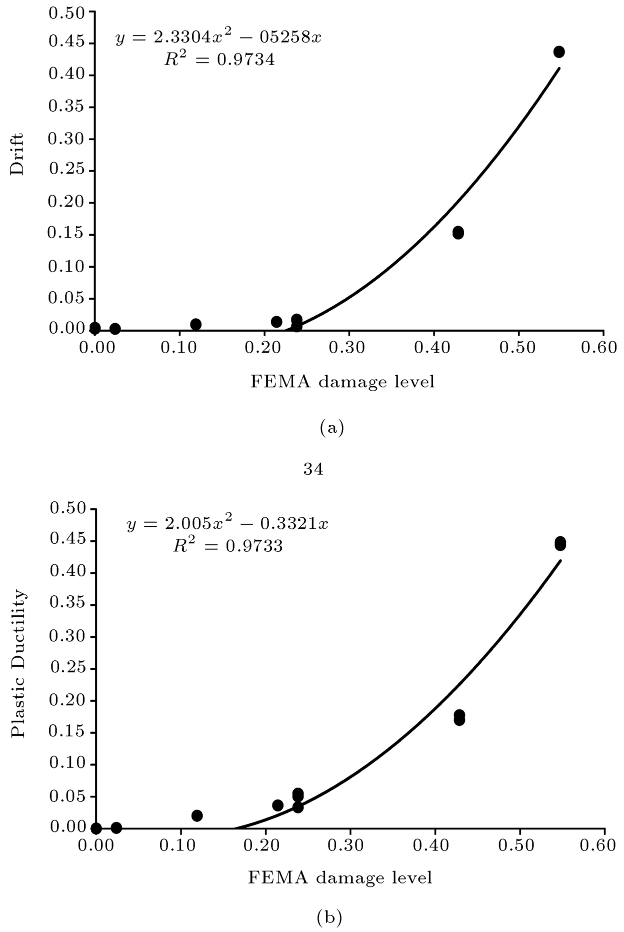


Figure 6. Correlation between deformation base damage indexes and FEMA performance level.

performance level could be estimated and the relation of intervals between the performance levels could be reached.

SUMMARY AND CONCLUSIONS

The results of this study show that prominent damage indexes can be estimated from equations, using the FEMA structural performance level as an input variable. Consequently, information, such as remaining structural energy absorption capacity, structural stiffness fatigue, structural strength fatigue and other information gained from damage indexes, can be estimated with reasonable accuracy by using FEMA performance levels.

By comparing the range of values obtained for various damage indexes in this study, the following conclusions can be made regarding the steel frames studied in this research:

- Steel frames at A-B performance level show a near zero damage index for all indexes.
- Frames at IO performance level show highly scattered results of 0.2-1.1% overall damage on the basis of combined indexes. The low cyclic fatigue indexes show no energy capacity, stiffness and strength degradation. In addition, about 22% increase in the period, as compared to the initial period of the structure, results in 18 to 30% damage, predicted by the modal parameter damage indexes. Modal parameter damage indexes are more sensitive indexes at low levels of damage, but a reasonably accurate correlation with FEMA damage levels cannot be established.
- Frames at LS performance level show 3.5-4.4% overall damage on the basis of combined indexes. The low cyclic fatigue indexes show 3.5% energy capacity degradation, 3.4% stiffness and 3.3% strength degradation. In addition, the modal parameter damage indexes show about 104% increase of period, in comparison to the initial period of the structure. Scatter of the results is much less at this level of damage and it can be expected that a relatively good estimation of various indexes can be obtained using the proposed correlation formulas at LS level.
- In general, damage indexes based on modal pa-

rameters do not show a good correlation with the FEMA index at lower damages. Also, low cycle fatigue based indexes do not show good correlation with the FEMA index at low damage levels and approximation formulas should be used with caution in these cases. Correlation of the FEMA index with the combined indexes studied in this research is within acceptable tolerance in the entire range of FEMA damage levels and their value can be estimated with reasonable accuracy using the provided formulas.

NOMENCLATURE

dE	element energy absorption
E_{Hn}	hysteretic energy demanded by earthquake ground motion
E_{Hmon}	the hysteretic energy capacity under monotonically increasing lateral deformation
F_y	maximum elastic force
H	structural height
M_y	yield moment
T_{und}	period of undamaged structure
T_{dam}	period of damaged structure
T_m	maximum period of structure
$U_{\max}$	maximum deformation capacity
U_{mon}	monotonic deformation capacity
U_y	maximum elastic deformation
β_e	Park and Ang coefficient which has a range of 0.1- 0.5
$\Delta\delta_p$	plastic deformation
Δd	element deterioration
Δ_m	deformation of the target point
μ	displacement ductility demanded by earthquake ground motion,$\mu = u_{\max}/u_y$
μ_{mon}	the monotonic ductility capacity, $\mu_{mon} = u_{mon}/u_y$
μ_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 $\mu < 1$
ϕ_m	maximum curvature in the member
ϕ_y	yield curvature in the member
ϕ_u	ultimate curvature before totally damaged

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