Seismic Damage Index for Classification of Structural Damage – Closing the Loop

R. Sinha & S. R. Shiradhonkar
Indian Institute of Technology Bombay, Mumbai, India

SUMMARY:
Damage indices proposed in published literature quantify local and global structural damage of buildings, subject to base excitations, on a scale ranging from zero to unity; where zero score represents undamaged state and unity represents collapse damage state of the building. This quantification helps in assessing seismic performance of the building through analytical methods and helps in several applications such as selecting retrofitting options. However, damage indices are not adequately correlated to post-earthquake damage states that are defined based on observational methods. This paper evaluates the correlation between analytical damage indices and observational damage states. From this study it is seen that damage indices accurately capture the status of an almost undamaged building or a heavily damaged building. However, the damage indices do not provide accurate assessment of the intermediate damage states, which are of most interest for retrofitting after an earthquake.

Keywords: Seismic damage index, damage assessment, damage state, seismic capacity assessment

1. INTRODUCTION

The quantification of damage to reinforced concrete buildings due to earthquakes has utmost importance. Seismic damage indices are widely used to predict possible damage. These damage indices have been formulated using response parameters of the structure that are obtained through analytical evaluation of structural response. The damage index typically normalizes the damage on a scale of 0 to 1, where zero represents undamaged state while unity represents collapse state of the building. The seismic damage indices are used in the field of vulnerability assessment, post-earthquake damage assessment, decision regarding retrofitting of structures and performance evaluation of structure. In all such applications, the threshold values of seismic damage indices play a very important role. The threshold values of the damage index can be determine by comparing different damage levels of the analytical model with the corresponding damage states. The threshold values of damage indices also influence the shape of vulnerability curves. They may also affect decisions related to reoccupation of damaged buildings after an earthquake. These values also have great importance in taking decisions related to repair and retrofitting of the building. Hence, quantification of the relationship between damage index, which quantifies the damage using analytical models, and the damage states, which provide categorization of observed seismic damage is very important.

Damage states have been developed for evaluating seismic intensity of an area after an earthquake (such as EMS-98 (1998)). However use of damage states has been extended to post earthquake damage assessment, vulnerability assessment of the structure, loss estimation and rehabilitation/ retrofitting of the structure. The damage states are based on observational methods for assessment of the building damage and provide categorization of damage in the structure from undamaged to complete damaged (collapse) state. Therefore damage states provide understanding of the post-earthquake condition of the building.

Several damage indices for reinforced concrete buildings, such as Park and Ang (1985) index, flexural damage ratio (FDR) (Banon et al., (1981), and Wang and Shah (1987)) index, have been proposed in published literature. Among these, the damage index proposed by Park and Ang (1985) has been correlated to the collapse state of buildings. However, this damage index has not been correlated to intermediate damage states. The other damage indices have not been rigorously correlated to any of the damage states.

Table 2.1. Selected Damage Indices with Parameter Values Chosen for Example Buildings

Damage Index	Type and Characteristics	Formulation	Parameter Values
Powell and Allahabadi (1988)	Deformation based-Non cumulative	$D = \frac{\mu_m - 1}{\mu_u - 1}$ (2.1)	
Modified Flexural Damage Ratio (MFDR) Roufaiel and Meyer (1987)	Stiffness based-Non cumulative: Flexural damage ratio (FDR) and MFDR have similar characteristics	$MFDR = \frac{\frac{\phi_m}{M_m} - \frac{\phi_y}{M_y}}{\frac{\phi_u}{M_u} - \frac{\phi_y}{M_y}}$ (2.2)	
Wang and Shah (1987)	Deformation based-cumulative: based on exponential function of cumulative cyclic inelastic deformation Damage index is evaluated for two values.	$D = \frac{e^{\eta\beta} - 1}{e^{\eta} - 1}, \ \beta = C \sum_{i=1}^{N} \frac{\theta_i}{\theta_u}$ (2.3)	C = 0.15, η = -3 & -1
Mehanny and Deierlein (2001)	Deformation based-cumulative: uses powered terms of cumulative plastic rotations and concept of primary (PHC) and follower (FHC) load cycles to trace out loading history effects	$D_\theta^+ = \frac{\left(\theta_p^+\|_{current\ PHC}\right)^\alpha + \left(\sum_{i=1}^{n^+} \theta_p^+\|_{FHC,i}\right)^\beta}{(\theta_{pu}^+)^\alpha + \left(\sum_{i=1}^{n^+} \theta_p^+\|_{FHC,i}\right)^\beta},$ $D = \sqrt[\gamma]{(D_\theta^+)^\gamma + (D_\theta^-)^\gamma}$ (2.4)	α =1, β =1.5, γ = 6
Colombo and Negro (2005)	Combined DI: uses exponential and hyperbolic functions of energy term.	$D = 1 - f(\beta_1, \mu) \cdot f(\beta_2, \int dE_{duct}) \cdot f(\beta_3, \int dE_{br})$ $f(\beta_1, \mu) = \left(1 - \frac{\theta_m}{\theta_u}\right)^{1/\beta_1}$ $f(\beta_2, \int dE_{duct}) = 0.5\left(1 - tanh\left(\beta_2 \frac{\int dE}{E_u^*} - \pi\right)\right)$ $f(\beta_3, \int dE_{br}) = exp\left(-\beta_3 \frac{\int dE}{E_u^*}\right)$ (2.5)	α =1, β_1=0.1, β_2 = 2.4, β_3 = 0.1, γ = 0.8
Park and Ang (1985)	Combined DI: Kunnath et al. and Chai et al. have similar formulations	$D = \frac{\theta_m}{\theta_u} + \frac{\beta}{M_y \theta_u} \int dE$ (2.6)	β = 0.4
Niu and Ren (1966)	Combined DI: similar to Park and Ang damage index but formulated with different constants	$D = \frac{\theta_m}{\theta_u} + \alpha \left(\frac{E}{E_u}\right)^\beta$ (2.7)	α = 0.1387, β = 0.0814

This paper analyzes the correlation between damage indices and damage states for entire range of damage index values for two example structures. The ability of these damage indices in identifying minor, moderate and collapse damage states of the buildings has been investigated in the paper.

2. DAMAGE INDICES

Williams and Sexsmith (1995), Ghobarah et al. (1999) and Padilla et al. (2009) have carried out comprehensive reviews of available damage indices. Kappos (1997) has provided elaborative classification of damage indices based on response parameters, formulation and use of damage indices. The damage indices have been classified as local damage indices and global damage indices based on their use in quantifying damage in individual members or entire building, respectively. Cosenza and Manfredi (2000) provided classification of the damage indices based on the type of analytical model used in calculating the damage index. The paper also evaluates the correlation between damage indices and damage states for assessing the condition of the structure and for decision making related to retrofitting and repairing of the damaged structure. The damage indices based on member-type model are classified as deformation-based damage indices; energy-based damage indices and combined damage indices. Other damage indices based on SDOF approximation, dynamic characteristics of the buildings and micro-level modelling of an element are not considered in this study.

Borg and Rossetto (2010) used scoring system to rank available damage indices based on their abilities to quantify global damage and to identify critical damage location. The main objective of the scoring system was to select a few damage indices useful in repair and retrofitting decision making. Energy and deformation combined damage indices scored high in the ranking system and therefore only combined damage indices were evaluated with example buildings. However, to understand the behavior of existing damage indices in capturing various damage states of buildings, the important damage indices considered in this paper are given in Table 2.1.

The global damage indices and story-level damage indices are evaluated from a combination of local damage indices. Park et al. (1985) expressed overall damage of a building as average of local indices weighted by the local energy absorption and therefore higher weightage is given to more heavily damaged members, as given in Eqn. 2.8.

$$D_{story} = \frac{\sum_{i=1}^{N} D_i E_i}{\sum_{i=1}^{N} E_i} \ , \ D_{global} = \frac{\sum_{story,i=1}^{N} D_{story,i} E_{istory,i}}{\sum_{story,i=1}^{N} E_{story,i}} \tag{2.8}$$

Bracci et al. (1989) proposed global damage index formulation as a function of the fraction of total gravity load supported by various members. This definition gives more weightage to the damage at the base of structure and in the columns, as given in Eqn. 2.9.

$$D_{story} = \frac{\sum_{i=1}^{N} W_i D_i^{b+1}}{\sum_{i=1}^{N} W_i D_i^{b}} \ , \ D_{global} = \frac{\sum_{story,i=1}^{N} W_{story,i} D_{story,i}^{b+1}}{\sum_{story,i=1}^{N} W_{story,i} D_{story,i}^{b}} \tag{2.9}$$

3. DAMAGE STATES

The damage states, with clear definition of the damage and failure mechanisms, allow users to evaluate post-earthquake status of buildings and also provide categorization of the damage for further use, such as for assessing seismic intensity. The damage states developed on the basis of cost-ratio or damage factor effectively link ground motion parameters such as the peak ground acceleration to structural and non-structural damage and consequently to the cost of damage; which are useful in estimating economic losses.

There are a number of damage state definitions in published literature. Hill and Rossetto (2008) reviewed the suitability of available damage states in seismic loss estimation. Whitman (1973) developed damage states based on damage cost data from the 1971 San Fernando earthquake. Several damage states have been proposed based on damage factors. ATC 20 (1985) used expert opinion to predict the losses from earthquakes. It provided broad classification of damages states for safety evaluation of damaged buildings after an earthquake. HAZUS (1999) used predefined set of cost ratios for buildings to forecast the damage and loss in buildings due to future earthquakes. On the other hand, FEMA 273 (1997) provided damage classification based on expected performance of structure in terms of building safety and serviceability after an earthquake.

In order to correlate damage indices with the damage in actual buildings through damage states; the damage states should be defined with limiting values of measurable engineering parameters, capable of representing both global and local damage. The thresholds of the engineering parameters can be derived from experimental and/or observational studies. However, available damage states are based on damage factor, on engineering judgement or on experimental calibration using very limited data. The available damage states neither define damage states in terms of structural response parameters nor explicitly consider the differences in building lateral load resisting system and damage to non-structural elements. Hence, only limited attempts are made to correlate damage states with the damage indices. For example, Rossetto and Elnashai (2003) developed a relationship between damage state definitions and inter-story drifts using experimental observations. .

Table 3.1. Structural Damage Category Definition for Various Building Elements

Damage States	Column	Beam
S5	Crushing of core concrete at joints, relative movement with respect to slab and other columns (cracks > 3 mm)	Crushing of concrete at supports, excessive deflection
S4	Diagonal/Torsional cracks in concrete core (0.5 to 3 mm), opening of tie bars, bucking of longitudinal bars	Reinforcement and concrete bond is broken, cracks in the core concrete (0.5 to 3 mm), shear tie bar have failed
S3	Major portion of outer layer of concrete is spalled but core is intact except for hairline cracks (0.2 to 0.5 mm)	Major portion of outer layer of concrete is spalled but core is intact except for hairline cracks (0.2 to 0.5 mm)
S4	Visible cracks (0.1 to 0.2 mm)	Visible shear cracks (near support) or tension cracks (at bottom) (0.1 to 0.2 mm)
S1	Very fine cracks (less than 0.1 mm)	Very fine cracks (less than 0.1 mm)
S0	No observable damage	No observable damage

Table 3.2. Definition of Building Category (for Non-Collapsed Buildings)

Damage States	Building Type – Concrete Framed Building
S5-Collapse	More than 50% columns have S5 damage, rest in any category
S4-Extensive	About 25% columns have S4 damage and rest in lower category
S3-Moderate	About 25% columns have S3 damage and rest in lower category
S4-Light	About 25% columns have S2 damage and rest in lower category
S1-Slight	About 25% columns have S1 damage and rest in lower category
S0-None	Less than 5% or no columns have S1 damage, rest in S0 category

In this paper, the following damage state definition from loss estimation developed after the Bhuj Earthquake (2001) by Sinha and Goyal (2004) has been used. In this member damage states (Table 3.1) are based on crack-widths in members and structural damage states (Table 3.2) are estimated from combination of damaged members.

4. METHODOLOGY AND EXAMPLE BUILDINGS

The damage indices and damage states have been evaluated for two example buildings from published literature. The first example building is a regular 2 bay-2 story ductile concrete building, taken from experimental study by Filiatrault et al. (1998). Shake table tastings were carried out to simulate the effect of earthquake using N04W component of Western Washington earthquake recorded at Olympia, Washington. IDARC-2D version 7.0 has been used for analytical modelling of example structures. Bilinear moment curvature relationships have been used during the analysis. The peak responses obtained from analytical model is found to show good agreement with the corresponding experimental responses.

To study the correlation between damage indices and damage states, nonlinear time history analyses of the example building has been performed for five real earthquake ground motions, viz. ElCentro, Taft, Chile, Chi-Chi and Northridge. Consecutive analyses are carried out using accelerograms scaled to 0.21g, 0.42g, 0.63g, 0.84g and 1.05g and each base excitation is separated by time duration of 10s to damp out the response due to the previous excitation. Similar base excitation was applied during the experimental investigation of the building by Filiatrault et al. (1998). The incremental base excitations ensure that there is gradual increase of damage from no damage to complete (collapse) damage state.

The second example building is a regular 3 bay-6 story structure with first long story, and is taken from an experimental investigation conducted by Lu (2002). In this building, proportioning of the structural members was carried out by following capacity design procedures for strong column-weak beam design as per Eurocode 8 (EC8). Consecutive analyses are carried out by scaling the abovementioned accelerograms to 0.1g, 0.3g, 0.6g, 0.9g and 1.2g, and each base excitation is separated by a period of 10s. Tri-linear moment curvature relationships are used for this building. The peak displacement responses obtained from analytical model has shown good agreement with the corresponding experimental responses for base excitations with peak acceleration of 0.1g and 0.3g ElCentro excitation.

4.1. Evaluation of damage indices

The time-history response of both the example buildings from each base excitation is used to calculate the member-level, story-level and global damage indices. The expressions used for evaluation of damage indices are summarised in Table 2.1. The story-level and global damage indices are calculated using both energy and gravity load formulations. For gravity load formulation, the value of exponent *b* in Eqn. 2.9 is taken as unity.

4.2. Evaluation of damage states

In order to calculate the maximum width of crack in member due to maximum moments during base excitations, the formulation proposed by Gergely and Lutz (1968) has been used. This crack width formulation is based on a regression analysis of a large number of tests from different sources. The crack-width for given moment is given by

$$W_{max} = 0.076\,\beta f_s \sqrt[3]{d_c A_e} \times 10^{-3} \text{ inches} \tag{4.1}$$

Where, β is ratio of distance between neutral axis and tension face to distance between neutral axis and centroid of reinforcing steel, f_s is stress in steel, d_c is distance from center of bar to extreme tension fiber (in inches) and A_e is the effective stretched concrete area (in^2). This formulation is valid up to yield point of steel. The same expression has been also used to evaluate the crack widths corresponding to post-yield moments. For moments greater than yield moments, the stress in steel is calculated by the product of strain in steel and initial modulus of elasticity.

5. RESULTS AND DISCUSSIONS

For effective comparison of results, the damage indices are divided into two groups: Powell-Allahabadi, MFDR and Wang-Shah are included in the 1st group; while Mehanny-Deierlein, Colombo-Negro, Park-Ang and Niu- Ren are included in the 2nd group.

Figs. 5.1 and 5.2 shows the time-history of global damage indices of groups 1 and 2, respectively, for example building 1 subjected to ElCentro base excitation. In this building, the first yielding occurs at the start of 0.42g base excitation (at around 75s) and the complete failure occurs just after the start of 0.84g base excitation (at 227.6s). Similarly, Figs. 5.3 and 5.4 represent the time-history of global damage indices of groups 1 and 2, respectively, for example building 2 subjected to Taft base excitation. For this building, the first yielding occurs at the start of 0.3g base excitation (at around 34s) and the complete failure occurs at the start of 0.9 g base excitation (at 108.3s). From Figs. 5.1 to 5.4, it can be observed that all global damage indices accurately identify the first yielding through a sudden jump in the index value.

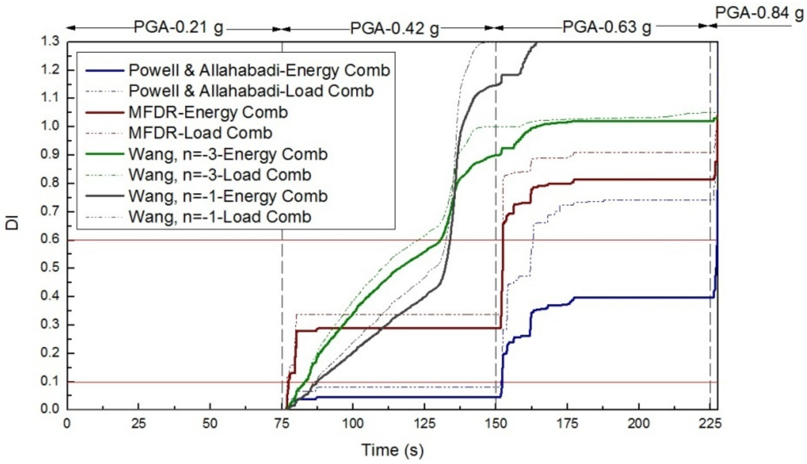

Figure 5.1. Global Damage Indices for Group 1, for example building 1 (ElCentro excitation)

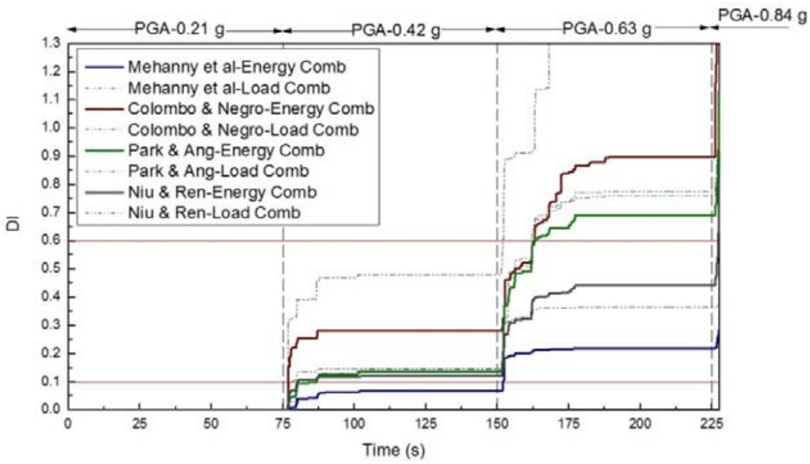

Figure 5.2. Global Damage Indices for Group 2, for example building 1 (ElCentro excitation)

When complete failure occurs, all damage indices either reach close to or exceed unity, except for Mehanny-Deierlein damage index. The deformation-based Powell-Allahabadi damage index and stiffness-based MFDR damage index do not consider cumulative damage of beams and the damage index values are dominated by damage in columns. This is observable in response to example building 2 where the damage, at the end of 0.3g base excitation, is concentrated in beams, while both these show low value of the damage index.

The widely used Park and Ang damage index quantifies damage as a linear combination of maximum deformation and hysteretic energy and is therefore expected to consider the accumulation and distribution of the damage in beams. However, Park and Ang as well as Niu and Ren indices do not show a significant increase in index values when damage are concentrated in beams at the end of 0.42g and 0.3g base excitations in example buildings 1 and 2, respectively. In fact, both these combined damage indices are dominated by the deformation term and therefore, sudden jump in damage indices is observed for 0.63 g and 0.9 g base excitations; which correspond to damages in columns. The combined damage index by Colombo and Negro uses exponential and hyperbolic functions of energy, but has also failed to capture the gradual increase in damage. However, the exponential function causes sudden rise in damage index value at failure state or at near failure state of the buildings.

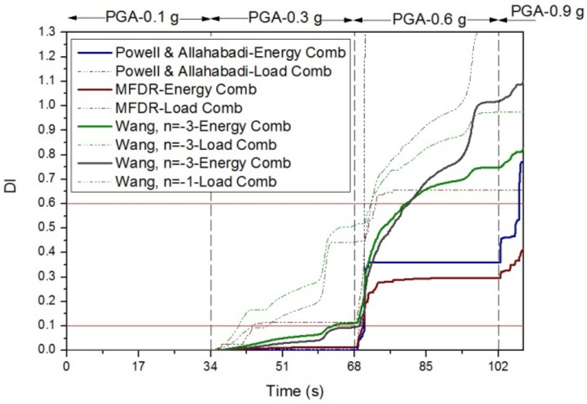

Figure 5.3. Group 1 Global Damage Indices for example building 2 (Taft excitation)

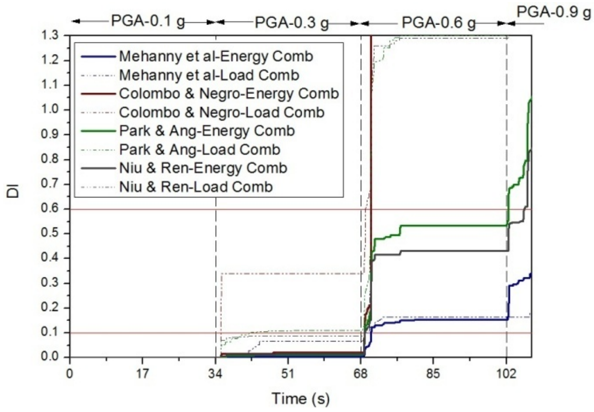

Figure 5.4. Group 2 Global Damage Indices for example building 2 (Taft excitation)

all these damage indices, the Wang and Shah damage index has shown gradual increase in damage index values from start of the damage to failure stage of structure for chosen values of η. However, this damage index is very sensitive to the values of η and shows wide verity of results for different values of η. Since the criteria for selection of η for different structural types is not available, the use of this damage index poses other problems.

Table 5.1. Crack Widths and Damage States for Example Building 1 (0.21g-0.42g-0.63g-0.84g)

Base Acc.	0.21g	0.42g	0.63g	0.84g	0.21g	0.42g	0.63g	0.84g
Time	0s-75s	75s-150s	150s-225s	> 225s	0s-75s	75s-150s	150s-225s	> 225s
	Crack Width (mm)				Damage States			
Col1	0.172	0.688	7.031	7.456	2	4	5	5
Col2	0.186	2.173	4.591	8.489	2	4	5	5
Col3	0.172	0.800	7.456	7.456	2	4	5	5
Col4	0.059	0.176	0.244	0.249	1	2	3	3
Col5	0.047	0.154	0.174	0.244	1	2	2	3
Col6	0.000	0.000	0.000	0.000	1	1	1	1
	Final Global Damage States				2	4	5	5

The damage in columns is dominated by deformation and dissipate small amount of hysteretic energy from undamaged to collapse condition. In global damage indices, gravity load formulation gives more weightage to damage in columns and, therefore, damage indices which are dominated by deformation term give higher values of gravity load global damage indices than hysteretic energy global damage indices. All damage indices except Wang and Shah damage index show higher values for gravity load formulation than the hysteretic energy formulation. This result is more evident in example building 2 for excitations at 0.6g and 0.9g, where damage is mainly concentrated in columns.

To examine the ability of existing damage indices in identify the various damage states of the structure, which provides qualitative description of structural condition from undamaged to collapse state; the damage states of both example buildings from analytical models are evaluated using Table 3.2. Crack widths of individual members, at the end of each base excitation are calculated using Eqn. 4.1. These crack widths are used to assign damage state to individual member as per Table 3.1.

For example building 1, the maximum crack widths in the columns and corresponding damage states are summarised in the Table 5.1. Table 5.2 summarize global damage state of example building 1 when evaluated from damage states of members, as per damage condition given in Table 3.2. It is found that the damage states at the end of 0.21g, 0.42g, 0.63g and 0.84g are light, extensive, collapse and collapse, respectively. In this building, none of the members had yielded at the end of 0.21g base excitation. Therefore, all damage indices show no damage state of the structure at the end of 0.21g excitation. At the end of 0.42g base excitation, the damage state changes immediately from light to extensive damage state. However, all the damage indices except Wang and Shah damage index show relatively small increase in damage index values between 0.21g and 0.42g base excitations. Finally, for collapse damage state at the end of 0.63g base excitation, all damage indices except Mehanny and Deierlein, show substantial increase in damage index values and these damage indices reach values approaching unity for complete collapse of the structure at the end of 0.84g base excitation. Thus, the damage indices show substantial increment in their values for extensive and collapse damage states.

Table 5.2. Comparison of Damage States and Damage Indices for Example Building 1 (0.21g-0.42g-0.63g-0.84g)

Damage States	0.21g	0.42g	0.63g	0.84g	0.21g	0.42g	0.63g	0.84g
	2	4	5	5	2	4	5	5
	Light	Extensive	Collapse	Collapse	Light	Extensive	Collapse	Collapse
	Hysteretic Global Damage Index (Eqn. 2.8)				Gravity Load Global Damage Index (Eqn. 2.9)			
Powell and Allahabadi	0	0.05	0.40	0.78	0	0.08	0.74	1.41
MFDR	0	0.29	0.81	1.05	0	0.34	0.91	0.99
Wang and Shah (η = −3)	0	0.90	1.02	1.03	0	1.00	1.05	1.05
Wang and Shah (η = −1)	0	1.15	1.54	1.55	0	1.30	1.56	1.56
Mehanny and Deierlein	0	0.07	0.22	0.29	0	0.14	0.36	0.37
Colombo and Negro	0	0.28	0.90	87.69	0	0.48	3.91	1287.02
Park and Ang	0	0.14	0.69	1.13	0	0.15	0.77	1.44
Niu and Ren	0	0.12	0.44	0.82	0	0.15	0.76	1.43

Table 5.3. Comparison of Damage States and Damage Indices for Example Building 1 (0.21g-0.31g-0.42g-0.52g)

Damage States	0.21 g	0.31 g	0.42 g	0.52 g	0.21 g	0.31 g	0.42 g	0.52 g
	2	3	4	5	2	3	4	5
	Light	Moderate	Extensive	Collapse	Light	Moderate	Extensive	Collapse
	Hysteretic Global Damage Index (Eqn. 2.8)				Gravity Load Global Damage Index (Eqn. 2.9)			
Powell and Allahabadi	0	0.00	0.04	0.71	0	0.02	0.06	1.04
MFDR	0	0.07	0.28	0.77	0	0.10	0.28	0.73
Wang and Shah (η = −3)	0	0.15	0.91	0.97	0	0.29	0.94	0.98
Wang and Shah (η = −1)	0	0.08	1.01	1.15	0	0.16	1.05	1.11
Mehanny and Deierlein	0	0.00	0.06	0.28	0	0.01	0.13	0.22
Colombo and Negro	0	0.20	0.29	31.17	0	0.32	0.36	300.68
Park and Ang	0	0.03	0.13	0.85	0	0.05	0.14	0.96
Niu and Ren	0	0.05	0.12	0.77	0	0.08	0.12	1.96

To check the ability of damage indices in tracing moderate damage state of the structure, consecutive analysis are carried out for example building 1 using ElCentro base excitation scaled to 0.21g, 0.31g, 0.42g, 0.52g, 0.63g. In these analyses, the failure of structure occurred at the start of 0.52g due to accumulation of damage. The building experiences light, moderate, extensive and collapse damage states during 0.21g, 0.31g 0.42g and 0.52g base excitations. The damage states and corresponding damage indices of the building are compared in Table 5.3. From this table it can be seen that all damage indices have yielded low values for moderate damage state of the structure. The Wang and Shah damage index, which had identified extensive damage in the earlier analysis shown in Table 5.2 at the end of 0.42g base excitation, also shows very low increase in the damage index value at the end of 0.31g base excitation for this case. It is also seen that the damage indices experience sudden increase in their values at collapse state, but several of the damage indices have relatively low values for extensive damage state at the end of 0.42g) base excitation. Similar results are also observed for example building 2 (Table 5.4), whose detailed results are not presented due to space constraints.

Table 5.4. Comparison of Damage States and Damage Indices for Example Building 2 (0.1g-0.3g-0.6g-0.9g)

Damage States	0.1 g	0.3 g	0.6 g	0.9 g	0.1 g	0.3 g	0.6 g	0.9 g
	1	2	3	4	1	2	3	4
	Slight	Light	Moderate	Extensive	Slight	Light	Moderate	Extensive
	Hysteretic Global Damage Index (Eqn. 2.8)				Gravity Load Global Damage Index (Eqn. 2.9)			
Powell and Allahabadi	0	0.00	0.36	1.13	0	0.00	2.60	3.31
MFDR	0	0.01	0.30	0.43	0	0.12	0.66	0.64
Wang and Shah ($\eta = -3$)	0	0.11	0.75	0.83	0	0.51	0.97	0.97
Wang and Shah ($\eta = -1$)	0	0.09	1.02	1.10	0	0.44	1.32	1.33
Mehanny and Deierlein	0	0.00	0.15	0.35	0	0.07	0.16	0.19
Colombo and Negro	0	0.02	4.4E05	8.6E06	0	0.33	1.1E07	3.03E08
Park and Ang	0	0.01	0.53	1.39	0	0.22	1.32	2.97
Niu and Ren	0	0.01	0.43	1.17	0	0.09	1.38	2.93

6. CONCULSIONS

The paper has carried out a critical review of seismic damage indices to quantify damage due to base excitations. The paper has also evaluated the ability of the damage indices to predict damage states of a RC building. The paper has presented the results of analyses of two example RC buildings subjected to different intensities of several base excitations. It is seen that most damage indices adequately predict the undamaged and collapse damage states of the buildings. However, the damage indices fail to predict the gradual increase in damage between undamaged to slight, moderate and extensive damage states. Since after a damaging earthquake, a very large number of buildings are likely to be in these damage states, it can be concluded that the damage indices considered in this study have limited applicability in assessing low and moderate damage states using analytical methods.

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