A CAPACITY-BASED GLOBAL SEISMIC DAMAGE INDEX FOR REINFORCED CONCRETE FRAME BUILDINGS

S. R. Shiradhonkar¹ and R. Sinha²

ABSTRACT

Quantification and classification of seismic damage in RC buildings are of prime importance in vulnerability assessment and loss estimation. Seismic damage index has been widely used to classify damage to RC buildings. A well-calibrated seismic damage index allows the designer of a new building to achieve desired performance objective and choose failure mechanisms by suppressing undesired failure modes. In this paper, a comprehensive global seismic damage index representing the complete range of damage has been proposed. The new index is capable of identifying a wide range of moderate damage states of RC buildings in addition to the typically identified extensive damage state. The effect of the relative contribution of damage in beams and columns on load carrying capacity of the building is incorporated using a reduction index. The accurate identification of moderate damage states makes the new index suitable for assessing higher-level performance objectives such as immediate occupancy. The building assessments using the proposed damage index are found to have greater accuracy than the widely used Park-Ang global seismic damage index.

¹Former Graduate Student Researcher, Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India 400076 (saurabh.coep@gmail.com)
²Professor, Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India 400076 (rsinha@civil.iitb.ac.in)

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Quantification and classification of seismic damage in RC buildings are of prime importance in vulnerability assessment and loss estimation. Seismic damage index has been widely used to classify damage to RC buildings. A well-calibrated seismic damage index allows the designer of a new building to achieve desired performance objective and choose failure mechanisms by suppressing undesired failure modes. In this paper, a comprehensive global seismic damage index representing the complete range of damage has been proposed. The new index is capable of identifying a wide range of moderate damage states of RC buildings in addition to the typically identified extensive damage state. The effect of the relative contribution of damage in beams and columns on load carrying capacity of the building is incorporated using a reduction index. The accurate identification of moderate damage states makes the new index suitable for assessing higher-level performance objectives such as immediate occupancy. The building assessments using the proposed damage index are found to have greater accuracy than the widely used Park and Ang global seismic damage index.

Introduction

Classification of structural damage in RC buildings due to earthquakes is of prime importance in the field of vulnerability assessment, loss estimation and to define performance levels [1] for the design of new buildings. A well-designed RC building dissipates input seismic energy by distributed hinge formation in beams and columns and thereby avoids the early formation of collapse mechanism. The distributed damage patterns can be formed in several ways [2, 3] and the extent of reduction in lateral resistance experienced by the building depends on the distribution of the plastic hinges in various members. The cyclic nature of earthquake excitation causes additional reduction in strength and stiffness of the members after initiation of damage, and thereby further reduction in seismic capacity of the building.

Seismic damage indices have been commonly used for the representation of loss in load carrying capacity of the members (local damage index) and that of a complete building (global damage index). These seismic damage indices, whose value typically vary between zero and one.
or more, are found to accurately predict the vulnerability of buildings when they are likely to remain undamaged (index value close to zero) or are likely to experience extensive damage (index value close to unity or higher). However, a previous study [2] has found that the available seismic damage indices accurately capture severe to collapse damage states but may be highly inaccurate for moderate damage levels. Also, in the widely-used methods, the global seismic damage index is determined by the predefined weighted average of member damage indices [4]. Thus, the global seismic damage does not explicitly take into consideration the residual capacity of the building after damage.

This paper presents a criterion for classification of moderate seismic damage states using damage index. The paper proposes a new generalized seismic damage index based on residual seismic capacity. In an earlier study, the authors [5] had proposed a new member seismic damage index that identifies a wide range of moderate damage states of an RC member. In this paper, the proposed seismic damage index is shown to be suitable for differentiating a variety of moderate damage states of the building. A reduction index has been proposed to incorporate the effect of the relative contribution of damage in beams and columns on load carrying capacity of the building. Example building assessment results have been compared with widely used Park-Ang global seismic damage index [6] in order to examine the accuracy of identification of moderate damage states. The identification of moderate seismic damage using the proposed index can be useful for the design of buildings where higher performance levels, such as Immediate Occupancy level, is required.

Park and Ang Global Seismic Damage Index

The commonly used Park-Ang [6] member seismic damage index ($D_{memb}$) is obtained by linear combination of displacement and energy terms, and is expressed as,

$$D_{memb} = \frac{\phi_m - \phi_y}{\phi_y - \phi_f} + \beta \int \frac{dE}{\phi_f M_y}$$

where, $\phi_m$, $\phi_y$ and $\phi_f$ represent maximum, yield and ultimate curvature of the member. Parameters $M_y$ and $\int dE$ represent yield moment and dissipated hysteretic energy, respectively. Global seismic damage index [4] of the building is expressed as the average of member damage indices, weighted by the local hysteretic energy dissipation. The global seismic damage index is formulated as,

$$GDI_{Hyst} = \frac{\sum_{i=1}^{n} D_i E_i}{\sum_{i=1}^{n} E_i}$$

in which $D_i$ and $E_i$ are the member damage index and energy absorbed by member $i$, respectively, while $n$ is a total number of members in the building. The Park-Ang damage index is found to accurately identify buildings that are undamaged and that are severely damaged or have collapsed. However, studies show that the Park-Ang damage index does not accurately identify moderately
damaged buildings or help to assess the usability of buildings in this damage state [2]. This inability is due to lack of quantification of parameters of member seismic damage at intermediate damage states and corresponding cumulative hysteretic energy. The lack quantification of member seismic damage also leads to inconsistent estimates of global damage index determined from hysteretic energy-weighted average formulation (Eq. 2).

**Proposed Capacity-based Seismic Damage Index for RC Structural Members**

In a previous study [5], the authors have proposed a capacity-based member seismic damage index. The damage index is formulated as a non-linear combination of deformation and normalized hysteretic energy terms in order to incorporate both the effect of flexural deformation and cyclic damage. The proposed member seismic damage index is given as [5],

\[
D_{\text{proposed}} = D_1 + D_2 - D_1D_2 \quad \text{with} \quad D_1 = \frac{\phi_m}{\phi_f} \quad \text{and} \quad D_2 = \beta \frac{\int dE}{C_p \phi_y M_y} \tag{3}
\]

where \(D_1\) is the deformation component of the damage index and captures initiation of damage, and \(D_2\) captures reduction in strength caused by damage accumulation due to cyclic loading. The control parameter \((C_p)\) represents incremental damage under cyclic loading, and depends on normalized hysteretic energy and strength reduction factor \(\beta\), between limiting damage index values. Parameter \(\beta\) has been obtained based on observed loss of strength during quasi-cyclic experiments at collapse state of the member. The following equation [7] is used to estimate \(\beta\),

\[
\beta = \left\{ 0.37\eta_0 + 0.36 \left( \frac{\rho_1 f_y}{0.85 f_c} - 0.2 \right)^2 \right\}^{0.99}
\]

The non-linear relationship between damage index \(D\) and damage components \(D_1\) and \(D_2\) allows flexibility to incorporate variation in hysteretic energy. In this study, the control parameter \((C_p)\) of proposed seismic damage index has been determined at key member damage states, representing specific residual seismic capacity as discussed later. The occurrence of key member damage states has been identified for limiting values of extreme fiber compressive strains [8 and 9].

Based on above, for column members, the following equations to determine the control parameters \((C_p)\) and ultimate curvature ductility \((\mu_\phi)\) are proposed.

Control parameter, \(C_p = 21.49\eta_0 + \rho_w^{-0.052} - 2.248 \left( \frac{\rho_1 f_y}{0.85 f_c} \right) \tag{5}\)

Ultimate curvature ductility, \(\mu_\phi = \left\{ 0.445\eta_0^{-0.896} + \left( \frac{\rho_1 f_y}{0.85 f_c} \right)^{0.019} \left( \frac{\rho_1 f_y}{0.85 f_c} \right)^{-0.338} \right\} \tag{6}\)
For beam members, the following equation is proposed.

\[
C_p = 3.855 - 14.680 \left( \frac{\rho f_y}{0.85 f_c} \right) + 33.970 \left( \frac{\rho f_y}{0.85 f_c} \right)^2
\]

(7)

For both beams and columns, the proposed member seismic damage index varies between 0 to 0.44 for slight, 0.44 to 0.66 for moderate and >0.66 for severe damage states. These member damage states represent the occurrence of narrow cracks on the surface of concrete, initial spalling of cover concrete and significant spalling of cover concrete along with exposed reinforcement bars, respectively [5].

** Representation of Residual Structural Strength using Reduction Index**

In order to quantify the effect of distributed as well as concentrated member damage on lateral resistance of the building, the Reduction Index (RI), has been formulated as,

\[
RI = \frac{1}{\sqrt{2}} \sqrt{RI_{stiffness}^2 + RI_{base shear}^2} = \frac{1}{\sqrt{2}} \sqrt{\left( \frac{K_{iniundam} - K_{failundam}}{K_{iniundam} - K_{failundam}} \right)^2 + \left( \frac{V_{b_undam} - V_{b_dam}}{V_{b_undam}} \right)^2}
\]

(8)

where \( K_{iniundam} \) and \( K_{failundam} \) are the initial secant stiffness of pushover curves of undamaged and damaged structures, respectively, as shown in Fig. 1. \( K_{failundam} \) is secant stiffness at collapse of undamaged state pushover curve. \( V_{b_undam} \) and \( V_{b_dam} \) are base shear capacities of the undamaged and damaged buildings as shown in the Fig. 1. The factor of \( 1/\sqrt{2} \) ensures convergence of Reduction Index to unity as building reaches collapse state. The value of reduction index varies between 0 and 1; where 0 represents undamaged building and 1 represents a substantial loss in load capacity of the building.

![Figure 1. Definition of parameters for Reduction Index](image)

** Simulation of Damage Cases and Estimation of Reduction Index**

For the development of new global seismic damage index, various damage cases have been obtained from nonlinear numerical simulations of example building frames. Three representative example building frames have been selected from published literature, and a pool of damage cases have been developed along with their reduction indices.
The example building frames have been chosen to represent a variety of seismic design practices. The chosen buildings are regular in plan and elevation but have different plan dimensions, number of stories and story heights. Example Building 1 [10] is designed for commercial occupancy while Example Buildings 2 [11] and 3 [12] are designed for residential occupancy. The span to depth ratios of beams in Example Building 1 is higher than those of Example Buildings 2 and 3. The response of beams and columns of Example Building 1 is dominated by flexural deformation. In Example Buildings 2 and 3, when subjected to strong base excitations, the central shorter spans capture the possibility of shear failure due to large end moments developed due to the adjacent beam members. Example Building 1 is designed as a ductile strong column-weak beam frame as per Canadian standards, Example Buildings 2 is designed as per Chinese standards while Example Building 3 is designed as per Indian standards. Numerical investigations in this study have been carried out by modelling the buildings as 2-D frames using IDARC-2D v7.

Table 1. PGAs of base motions for non-linear time history analysis

<table>
<thead>
<tr>
<th>Ground Motion</th>
<th>Example Building 1</th>
<th>Example Building 2</th>
<th>Example Building 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Centro 1940, N-S</td>
<td>0.25 g, 0.375 g, 0.50 g, 0.625 g, 0.75 g, 0.875 g, 1.00 g and 1.125 g</td>
<td>0.125 g, 0.25 g, 0.375 g, 0.525 g and 0.625 g</td>
<td>0.10 g, 0.20 g, 0.30 g, 0.40 g, 0.50 g, 0.60 g, 0.65 g and 0.70 g</td>
</tr>
<tr>
<td>Taft 1952, Component 21</td>
<td>0.15 g, 0.25 g, 0.37 g, 0.50 g, 0.625 g, 0.75 g and 0.875 g</td>
<td>0.04 g, 0.08 g, 0.125 g, 0.18 g, 0.25 g, 0.315 g, 0.375 g and 0.50 g</td>
<td>0.10 g, 0.20 g, 0.30 g, 0.40 g, 0.50 g and 0.60 g</td>
</tr>
<tr>
<td>Northridge 1994, Component 90</td>
<td>0.25 g, 0.375 g, 0.50 g, 0.625 g, 0.75 g, 0.875 g, 1.00 g, 1.25 g, 1.50 g, 1.75 g and 2.00 g</td>
<td>0.125 g, 0.25 g, 0.375 g, 0.50 g, 0.57 g, 0.625 g, 0.75 g, 0.875 g and 1.00 g</td>
<td>0.10 g, 0.20 g, 0.30 g, 0.40 g, 0.50 g, 0.60 g, 0.70 g, 0.80 g, 0.90 g, 1.00 g, 1.25 g, 1.50 g, 1.75 g and 2.00 g</td>
</tr>
<tr>
<td>Chi-Chi 1999, Component 90</td>
<td>0.25 g, 0.375 g, 0.50 g, 0.625 g, 0.75 g, 0.875 g, 1.00 g, 1.25 g and 1.50 g</td>
<td>0.125 g, 0.25 g, 0.375 g, 0.50 g, 0.54 g, 0.58 g, 0.625 g, 0.68 g and 0.75 g</td>
<td>0.125 g, 0.25 g, 0.375 g, 0.50 g, 0.625 g, 0.875 g, 1.00 g and 1.125 g</td>
</tr>
</tbody>
</table>

A large number of nonlinear simulations of the example buildings have been carried out to stimulate different damage situations from undamaged to collapse states. Ground motions of four different recorded earthquakes namely, El Centro, Taft, Northridge, and Chi-Chi have been selected from COSMOS (2001) strong motion database. These ground motions have been selected to represent a wide range of frequencies, as represented by their central frequency and shape factor [13]. For the selected ground motions, the central frequencies are 7.2 rad/s, 6.2 rad/s, 7.5 rad/s and 9.5 rad/s, respectively, while the shape factors are 0.68, 0.64, 0.63, 0.69, respectively. Thus, the selected ground motions contain a wide range of frequencies around central frequencies. A total of 103 damage cases have been simulated by subjecting the example buildings to ground motions of different Peak Ground Accelerations (PGAs). The PGAs of the different ground motions used
Estimation of Reduction Index for Damaged Buildings

Reduction indices of the example buildings have been determined from capacity curves using incremental dynamic analyses (IDA) [14] up to maximum inter-story drift of 3% [15]. The IDA procedure for first two analyses is illustrated in Fig. 2. The dynamic capacity curves for the undamaged state are also estimated for each ground motion. Fig. 3 shows the dynamic capacity curves for undamaged and damaged cases of Example Building 1 for El Centro base excitation.

![Figure 2. Illustrative scheme of nonlinear dynamic analysis with incrementally increasing PGAs to determine dynamic capacity curve of damaged buildings](image)

![Figure 3. Dynamic capacity curves of undamaged and damaged Example Building 1 for El Centro base excitation](image)

Proposed Global Seismic Damage Index

Global seismic damage index that incorporates reduction in seismic capacity has been developed from the consideration of mechanistic behavior of RC buildings subjected to base excitation. A well designed RC building dissipates most of the energy through hinges in the beams before the formation of plastic hinges in the columns. The Park-Ang hysteretic energy-weighted average formulation (Eq. 2) assigns equal weightage to the damage in beams and columns. In the scenario where damage is well distributed in the beams, and the columns are relatively undamaged, seismic damage index estimated as per Eq. 2 has excessive contribution from seismic damage indices of the beams than those of the columns. This is because the more energy is dissipated through the damage in beams compared to the damage in columns. However, the damage in columns contributes more significantly to the reduction in seismic capacity of the damaged building.
In this study, in order to understand the contribution of damage in beams and column to reduction in seismic capacity, damage indices of the column (DI_{col}) and beam joint (DI_{beam jts}) groups are estimated using the following formula, for the 103 considered damage cases.

\[ DI_{col} = \frac{\sum_{i} D_{i} E_{i}}{\sum_{i} E_{i}} \quad \text{and} \quad DI_{beam jts} = \frac{\sum_{i} D_{i} E_{i}}{\sum_{i} E_{i}} \]  \hspace{1cm} (9)

Fig. 4 shows damage indices of column and beam groups against the reduction index. The dotted line in Fig. 4 indicates seismic damage index of beam groups while the solid line indicates seismic damage index of column groups. From Fig. 4, it is observed that seismic damage indices of both the column and beam joint groups increase with the reduction index. However, the increase in seismic damage index of the column group with the reduction index is more rapid compared to that of the beam joint group. Thus, the reduction in seismic capacity is mainly contributed by damage to columns. The damage in beam joints adds to the reduction in seismic capacity caused by the columns. In scenarios where beam joints suffer substantial damage and columns remain undamaged; the reduction in seismic capacity of the building is not substantial. Thus, the ultimate reduction in seismic capacity is governed by substantial damage to columns. Therefore, the global seismic damage index is estimated from seismic damage indices of the column and beam joint groups. The global seismic damage index is expressed as,

\[ GDI_{proposed} = \begin{cases} DI_{col} + DI_{beam jts} - DI_{col} \times DI_{beam jts} & \text{if } DI_{col} > DI_{beam jts} \\ \sum_{i} D_{i} E_{i} & \text{if } DI_{col} < DI_{beam jts} \end{cases} \]  \hspace{1cm} (10)

\[ GDI_{proposed} = \frac{\sum_{i} D_{i} E_{i}}{\sum_{i} E_{i}} \]

![Figure 4. Comparison of seismic damage indices of column and beam joint groups (Eq. 9) with Reduction Index (Eq. 8)](image)

**Comparison of Proposed and Park-Ang Global Seismic Damage Indices**

For each damage case, proposed member damage indices are determined by estimating control parameters (C_p) of column and beam members using Eq. 5 and 7, respectively. The ultimate curvature ductility of column members is estimated using Eq. 6. For beam members, the axial load ratio in Eq. 6 is taken as 0.05. The proposed global seismic damage index (Eq. 10) and Park-Ang
seismic damage index (Eq. 2) have been estimated from the simulation results. Fig. 5 shows the estimated values of proposed global seismic damage index and global Park-Ang seismic damage index from the simulations.

Figure 5. Comparison between proposed global seismic damage index (Eq. 10) and global Park-Ang seismic damage index (Eq. 2)

From Fig. 5, it can be seen that there is a high correlation between the proposed global seismic damage indices and the global Park-Ang seismic damage index, implying that the proposed damage index can be easily implemented in existing software capable of evaluating the Park-Ang damage index. It can be noted that the correlation is nonlinear. When there is low damage, it can be seen that the Park-Ang damage index values are clustered in a narrow range of around 0.0 to 0.2. For these same cases, the proposed global damage index values range between 0.0 to 0.5. Similarly, damage cases of slight to moderate damage, where Park-Ang damage index values vary between 0.2 to 0.4 are found to have their corresponding values between 0.4 to 0.75 in the proposed global damage index. Review of damage details shows that there are a number of cases of overlap of index values when using Park-Ang damage index, which results in lower index values for higher damage state. However, in these cases, the proposed global damage index consistently estimates larger index for cases with higher damage. The proposed global damage index thus provides damage estimates that are more consistent, are able to correctly identify slight and moderate damage. The proposed index also provides a consistent transition from moderate to severe damage. The damage state classification for proposed global damage index has been compared with the Park-Ang damage index in Table 2.

Table 2. Limiting values of proposed seismic damage index

<table>
<thead>
<tr>
<th>Damage State</th>
<th>Global Park-Ang DI</th>
<th>Proposed Global DI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slight</td>
<td>GDI ≤ 0.1</td>
<td>GDI ≤ 0.35</td>
</tr>
<tr>
<td>Light</td>
<td>0.1 &lt; GDI ≤ 0.25</td>
<td>0.35 &lt; GDI ≤ 0.60</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.25 &lt; GDI ≤ 0.40</td>
<td>0.60 &lt; GDI ≤ 0.75</td>
</tr>
<tr>
<td>Extensive</td>
<td>GDI &gt; 0.40</td>
<td>GDI &gt; 0.75</td>
</tr>
</tbody>
</table>

Comparison of Reduction Index and Global Seismic Damage Index

Figs. 6 and 7 shows the relationship between the global Park-Ang damage index and proposed
global seismic damage index with reduction index, respectively. The correlation between the damage index and reduction index in the two cases is also shown. It is seen that there is a reasonable linear correlation between the proposed global damage index and the reduction index. However, the correlation in case of Park-Ang damage index is much lower. For damage cases with reduction index less than 0.45 (which represent 45% reduction in structure capacity), the Park-Ang global seismic damage index values are very low and are consistently lower than 0.5. However, from Figure 7, it can be seen that the proposed seismic damage index values range between 0 and 0.8. Using the proposed seismic damage index, Figure 7 shows that the reduction index remains nearly constant, and less than 0.2, when index values are between 0 to 0.35. These represent buildings that are reoccupiable after the earthquake, and thus correspond to Slight damage. When the reduction index increases from 0.20 to 0.4, the corresponding index values increase from 0.35 to 0.60 and represent Light damage.

Based on the above, it can be concluded that the proposed global seismic damage index accurately incorporates a reduction in seismic capacity and is capable of representing moderate damage states of the building. The proposed global damage index can be used to define a hierarchy of performance levels for the design of new buildings. It can also be used for sub-classification of moderate damage to assess their usability after damage. The losses can also be more accurately assessed for scenario development and other purposes using the proposed global damage index.

**Conclusions**

The paper discusses development new global seismic damage index that incorporates the reduction in seismic capacity due to damage. The global seismic damage index is expressed as a combination
of member seismic damage index. The contribution of damage to beams and columns on seismic resistance of buildings has been also investigated using a reduction index. The proposed global seismic damage index is expressed as a function of seismic damage indices of columns and beam joint groups. The proposed global seismic damage index varies between 0-0.35, 0.35-0.60, 0.60-0.75 and > 0.75 for Slight, Light, Moderate and Extensive damage states, respectively. The new index is capable of identifying a wide range of moderate damage states of RC buildings in addition to the typically identified extensive damage state. The proposed seismic damage index is found to have good correlation with the reduction index. The accurate identification of moderate damage states allows the design of a new building to choose failure mechanisms and suppress undesired failure modes.

References


