13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1261

VULNERABILITY AND DAMAGE ANALYSES OF EXISTING BUILDINGS

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SUMMARY

The assessment of seismic performance of buildings under future earthquakes is becoming an important problem in earthquake engineering. Some important buildings are considerably old and therefore their strengths and ductilities are less than strength and ductility demands. Such buildings must be strengthened to resist future earthquakes. At first the structural model must be developed and then based on seismic hazard and seismic risk analysis or code quantities, the design (or control) parameters are determined. Other step is defining the damage indices. Then the nonlinear dynamic analysis is carried out. Finally based on numerical results one can determine the amount and how of strengthening. In this paper some damage indices are reviewed and then a formulation is presented for considering the importance of columns and lower stories failure. As an example an existing building is analyzed.

INTRODUCTION

In the conventional design method, the elements are usually determined on the basis of demand strength and then the limitations on the deflections are controlled for serviceability. However the important point is that structural performance of the structure under earthquake motions is tightly associated with the level of structural damages. Seismic performance of some important structures located on the fault zones is a problem that engineers face in practice. Also there are many structures that have been designed and constructed prior to the adoption of reliable seismic codes. Seismic performance of these kinds of structures must be carried out precisely.

For assessing the actual performance of structures during earthquakes, the nonlinear dynamic analysis is required. Then the damage indices of building must be calculated, using appropriate damage models. Damage indices are numerical representation of damage state of the structures. These models are usually based on the maximum deformations, hysteretic energies and structural deteriorations. Damage indices are suitable tools for quantifying numerically the damage in structures sustained under earthquake loading. Many researchers have defined various damage indices. Damage indices may be defined locally for elements or globally for whole the structure.

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Williams and Sexsmith [1] and and Ghobarah et al. [2] carried out an extensive review of defined damage indices for various types of structures. Vulnerability of an existing structure based on seismic hazard analysis has been assessed by Golafshani et al. [3]. Also the amount of strengthening in some elements has been proposed based on the equivalent energy idea. Bakhshi et al. [4] presented the complete procedure of the seismic assessment of existing structures based on push-over and dynamic analyses. There was relatively good agreement between the results of both push-over and dynamic analyses for the case studied. However for assessing the strength and ductility of various elements and for determining the difference between the existing and demand strengths, nonlinear dynamic analysis is required.

Some retrofitting techniques such as steel jacketing, fiber elements and base isolation were reviewed by Bakhshi et al. [5]. Also the effect of strengthening on the behavior of structures was investigated. It was emphasized that an appropriate distribution of strength and ductility by retrofitting can substantially improve the seismic performance of the existing structures.

Park-Ang damage index [6], considered in IDARC [7], is the most usual damage index for damage analysis of reinforced concrete structures. It can be calculated in the element, story and overall scales. An important point is that the damage indices of stories are calculated based on hysteretic energy weighting factors and therefore the structural importance of beams and columns are the same. Also overall damage index of structure is calculated by summation of the story damage indices on the basis of hysteretic energy of each story.

Seismic vulnerability and damage analysis of special structures have been carried out successfully using IDARC program by Tabeshpour et al. [8]. The key idea of structural modeling of the special structures is to develop a simplified 2-D model using beam-column elements based on moment-curvature in some plane sections. Appropriate results have been achieved by nonlinear dynamic analysis of these simplified models.

DAMAGE INDICES

In order to retrofit decision, it is necessary to quantify the structural damage. Therefore many damage models have been developed. Damage index is a mathematical model for quantitative description of the damage state of the structures and in most cases it has a correlation with the actual damage in earthquakes.

There are various ways to categorize the damage indices. The simplest way is the correlation between damage indices and observed damage. For example Park et.al [6,9] classified the structural damage as : None, Minor, Moderate, Severe and Collapse. Similarly Bracci et al. [10] defined the following categorization: Undamaged or minor damage, Repairable, Irrepairable, Collapsed. The above classification can be used for retrofit decision making.

Many damage indices have been defined. According to state-of-the art of damage indices carried out by Williams and Sexsmith [1] and Ghobarah et al. [2], a relatively complete classification is given in appendix. In the following section a formulation is presented for considering the importance of columns and thus failure of lower stories. This approach can be considered for each local index. However Park-Ang damage model is considered in this paper. Therefore Park-Ang damage index is reviewed herein.

Park-Ang Damage Model

The most usual damage index is the Park-Ang model. It is defined as combination of maximum deformation and hysteretic energy:

$$DI = \frac{\delta_m}{\delta_u} + \frac{\beta}{\delta_u P_y} \int dE_h \qquad (1)$$

in which δ_m is the maximum deformation of the element (nonlinear dynamic analysis), δ_u is the ultimate deformation (push-over analysis), β is a model constant parameter (0.1-.015), $\int dE_h$ is the hysteretic energy absorbed by the element during the earthquake, P_y is the yield strength of the element. Park-Ang damage model can be extended to the story and overall scales, by summation of damage indices as follows:

$$SDI_j = \sum_{k=1}^{m_j} \lambda_{kj} . DI_{kj} \qquad , \qquad \lambda_{kj} = \frac{E_{kj}}{\sum_{i=1}^{m_j} E_{ij}} \tag{2}$$

in which SDI_j is the damage index of the j-th story, DI_{kj} is the damage index of the k-th element of the j-th story, E_{kj} is the hysteretic energy of the k-th element of the j-th story, $E_j = \sum_{i=1}^{m_j} E_{ij}$ is the hysteretic energy of the j-th story, and m_j is number of the elements of the j-th story. Also the overall damage index is:

$$ODI = \sum_{i=1}^{N} \lambda_i (SDI_i) \qquad , \qquad \lambda_i = \frac{E_i}{\sum_{s=1}^{N} E_s} \tag{3}$$

where ODI is the overall damage index, $E_T = \sum_{s=1}^{N} E_s$ is the overall hysteretic energy, and N is number of the stories. Park-Ang damage indices for various damage states are shown in table (1).

Table 1. The relation between damage index and damage state

Degree of Damage	Damage Index	State of Building
Slight	< 0.1	No Damage
Minor	0.1-0.25	Minor Damage
Moderate	0.25-0.4	Repairable
Severe	0.4-1.0	Beyond Repair
Collapse	>1.0	Loss of Building

Some researchers have suggested using a value of *Damage Index*= 0.8 to represent collapse. An important point in IDARC is that the overall and story Park-Ang damage indices are calculated based on the hysteretic energy dissipated in members and the effect of more important members and stories is not considered. Here a procedure is presented that indicates how to consider this effect and also a numerical study is carried out through an example.

Park- Ang Damage Index Based on Importance of Elements and Stories

The fundamental philosophy of seismic design is based on weak beam and strong column. This approach must be followed in the structural strengthening or retrofitting. In IDARC the overall and story damage indices are calculated based on elements hysteretic energies and therefore the importance of columns is not considered. Also lower stories are more important than upper stories. Here a formulation is presented that considers these problems. The method is based on Park-Ang model.

First the damage indices for all elements are calculated. Defining α_j^c and α_j^b as weighting factors for columns and beams of the *j*-th story respectively, the new damage index for the *j*-th story is:

$$SDI_j = \alpha_j^c DI_j^c + \alpha_j^b DI_j^b \tag{4}$$

in which DI_j^c and DI_j^b are columns and beams damage indices of the *j*-th story respectively:

$$\lambda_{kj}^c = \frac{E_{kj}^c}{\sum_{i=1}^{n_j^c} E_{ij}^c} \quad , \quad DI_j^c = \sum_{k=1}^{n_{cj}} \lambda_{kj}^c DI_{kj}^c \tag{5}$$

$$\lambda_{kj}^b = \frac{E_{kj}^b}{\sum_{i=1}^{n_j^b} E_{ij}^b} \quad , \quad DI_j^b = \sum_{k=1}^{n_{cj}} \lambda_{kj}^b DI_{kj}^b \tag{6}$$

where DI_{kj}^c and DI_{kj}^b are the damage indices of k-th column and beam of the j-th story, E_{kj}^c and E_{kj}^b are column and beam hysteretic energies respectively, n_j^c and n_j^b are the number of columns and beams in the j-th story and $E_j^c = \sum_{i=1}^{n_j^c} E_{ij}^c$ and $E_j^b = \sum_{i=1}^{n_j^b} E_{ij}^b$ are the hysteretic energy of columns and beams in the i-th story. Like previous the overall damage index is defined as:

$$ODI_{new} = \frac{\sum_{i=1}^{N} (\alpha_i^c \lambda_i^c DI_i^c + \alpha_i^b \lambda_i^b DI_i^b)}{\sum_{k=1}^{N} (\alpha_k^c + \alpha_k^b)} \tag{7}$$

where

$$\lambda_i^c = \frac{E_i^c}{\sum_{k=1}^{N} E_k^c} \quad , \quad \lambda_i^b = \frac{E_i^b}{\sum_{k=1}^{N} E_k^b} \tag{8}$$

Now to use of the results of Park-Ang damage index model, α_j^c and α_j^b are such calibrated that the overall damage index in two states (uniform importance and element importance) be the same. For this purpose these factors are multiplied by $\frac{ODI}{ODI_{new}}$.

For the seismic vulnerability assessment of existing buildings and determining the strategy of strengthening one can use the story damage index. If story damage index is calculated based on element importance (weak beam- strong column) then the philosophy of strengthening and design will be the same.

CASE STUDY

As an example an existing building is selected. The building is a ten-story reinforced concrete frame structure. A typical floor plan and two dimensional frame of each direction are shown in Figure 1. The one-way slab is supported by five frames in the N-S direction. There are four and five similar frames in E-W and N-S directions respectively.

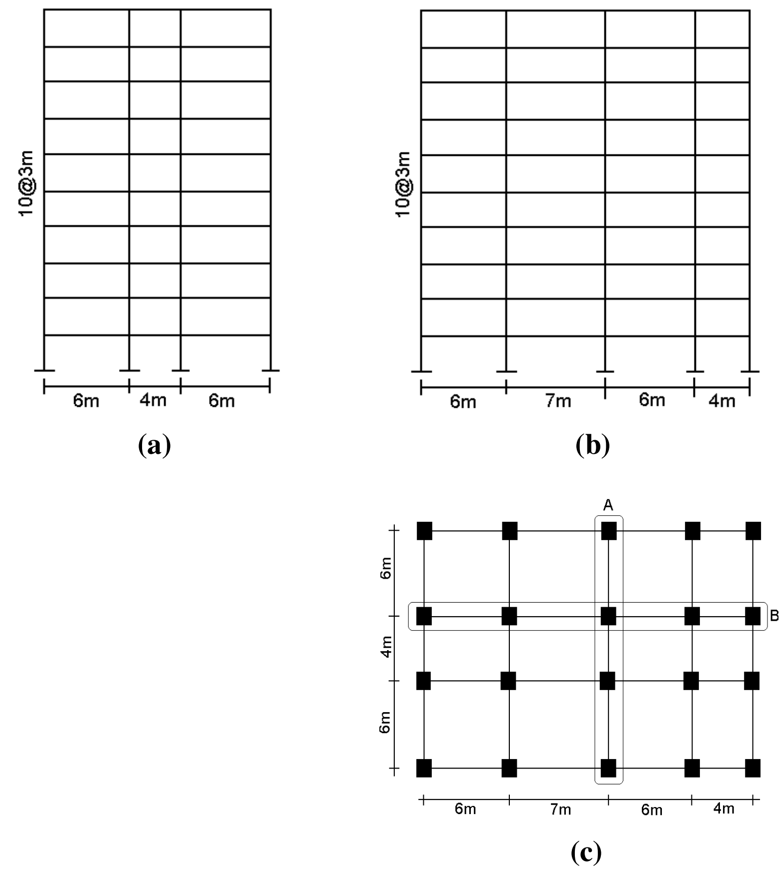

Figure 1: Modeling of frames (a , b), and typical plan (c)

Although the frame system is able to carry gravity loads and has some capacity to resist earthquakes, but its resistance is not sufficient. At first it must be determined the frame that govern the capacity of the building. For this purpose the nonlinear seismic analysis and damage evaluation of both frames A and B must be carried out. Damage analyses of the frames, performed using the IDARC computer program, show that the N-S frames are critical. Therefore frame A is selected as a basis for damage analysis and determining the strengthening strategies.

The inelastic behavior of reinforced concrete elements (stiffness degrading, strength deterioration, and pinching) is considered. In this study the inelastic behavior of concrete elements is determined by using tri-linear skeleton curve and three model parameters. The uncertainties in the structural parameters such as concrete compressive strength, concrete Young's modulus, steel yielding strength and viscous damping ratio must be considered. The viscous damping ratio is assumed to be uniformly distributed and other parameters are modeled by a normal distribution. Five sets of structural parameters are selected randomly within two standard derivations around the mean value. Also three acceleration time histories are selected. Each set of structural parameters is combined with all of the time histories and therefore fifteen samples of the structure- earthquake are established. For each sample, levels of PGA between 0.1 g and 0.7 g are considered.

The seismic hazard analysis shows that the appropriate PGA is equal to 0.4 g. For example using Tabas earthquake time history and considering the appropriate PGA, the nonlinear seismic responses of the building are presented.

Displacement response of each floor is shown in Figure 2. It is clear that the 3rd and 5th stories are more critical than the 1st and 2nd stories. The displacements of the five lower stories are out of the desired limit. The hysteretic behavior of the stories is shown in Figure 3. The base shear is about 5.5% of the total weight of the building. Demand ductility in the 3rd floor is very high as same as 5th floor. The responses of upper stories are in the desired limit. Figure 4 shows the damage indices of beams and columns for all stories. It is seen that the non-uniform importance for structural elements causes the damage indices to change compared to the uniform distribution based on hysteretic energy. The damage index of the columns of the 1st story comes near the damage index of the columns of the 3rd story. Such variations in the damage indices impel the strengthening strategies to the strong column-weak beam idea. For example in the 2nd story the damage indices of columns and beams are equal for the uniform distribution. But in the state of the non-uniform distribution, the damage indices of columns and beams differ 22%. The damage indices of the all columns and all beams are shown in Figure 5. Optimum distribution of strength and stiffness is an important point in the structural design. A nearly uniform distribution for inter-story drifts is helpful to achieve this goal. But in practice, constructional limitations violate this idea. Therefore there is a considerable difference between the maximum inter-story drift and overall drift. For example the related maximum inter-story drift and overall drift to ODI=0.4 are 6% and 2.7% respectively (Figure 6). The difference represents the amount of deformation concentration. By using this approach one can find the soft story (s). Determining the soft story(s) is important to decide for strengthening. It is clear that the peak ground acceleration (PGA) affects the overall damage of the building. Figure 7 shows the effect of PGA on the overall damage index. The related PGA to the structural collapse is equal to 0.62 g for Tabas earthquake time history. More detailed results of damage are shown is Figure 8. The curve representing story damage indices versus PGA is very helpful for determining the weak stories. It is seen that for PGAs equal to 0.4 g and 0.6 g the weakest stories are the 3rd and the 1st respectively. It means that the statistic study must be carried out and the mean valves of damage indices be selected.

Table 2. Damage indices of elements

PGA (g)	1st story		2nd story		3rd story		4th story		5th story	
	Beam	column	Beam	column	Beam	column	Beam	column	Beam	column
0.1	0.004	0.019	0.006	0.021	0.003	0.034	0.003	0.028	0.000	0.052
0.2	0.025	0.050	0.028	0.052	0.008	0.176	0.010	0.070	0.001	0.085
0.3	0.070	0.137	0.085	0.110	0.038	0.242	0.056	0.147	0.006	0.226
0.4	0.111	0.238	0.173	0.178	0.078	0.351	0.090	0.223	0.016	0.313
0.5	0.208	0.318	0.193	0.211	0.127	0.387	0.147	0.285	0.030	0.385
0.6	0.325	0.39	0.334	0.245	0.131	0.448	0.148	0.313	0.041	0.432
0.65	0.216	0.549	0.390	0.435	0.060	4.72	0.112	0.341	0.023	0.401
0.7	0.338	8.09	0.359	0.378	0.052	0.555	0.095	0.265	0.020	0.346
PGA (g)	6th story		7th story		8th story		9th story		10th story	
	Beam	column	Beam	column	Beam	column	Beam	column	Beam	column
0.1	0.001	0.34	0.001	0.034	0.001	0.016	0.012	0.000	0.000	0.000
0.2	0.003	0.028	0.002	0.102	0.001	0.026	0.001	0.000	0.005	0.000
0.3	0.002	0.079	0.014	0.057	0.000	0.036	0.013	0.000	0.006	0.000
0.4	0.007	0.172	0.019	0.053	0.002	0.052	0.009	0.002	0.006	0.000
0.5	0.009	0.21	0.013	0.66	0.003	0.058	0.19	0.001	0.001	0.006
0.6	0.009	0.233	0.010	0.078	0.002	0.049	0.001	0.002	0.002	0.005
0.65	0.005	0.209	0.007	0.078	0.002	0.049	0.012	0.001	0.001	0.005
0.7	0.008	0.172	0.007	0.081	0.002	0.050	0.010	0.001	0.001	0.005

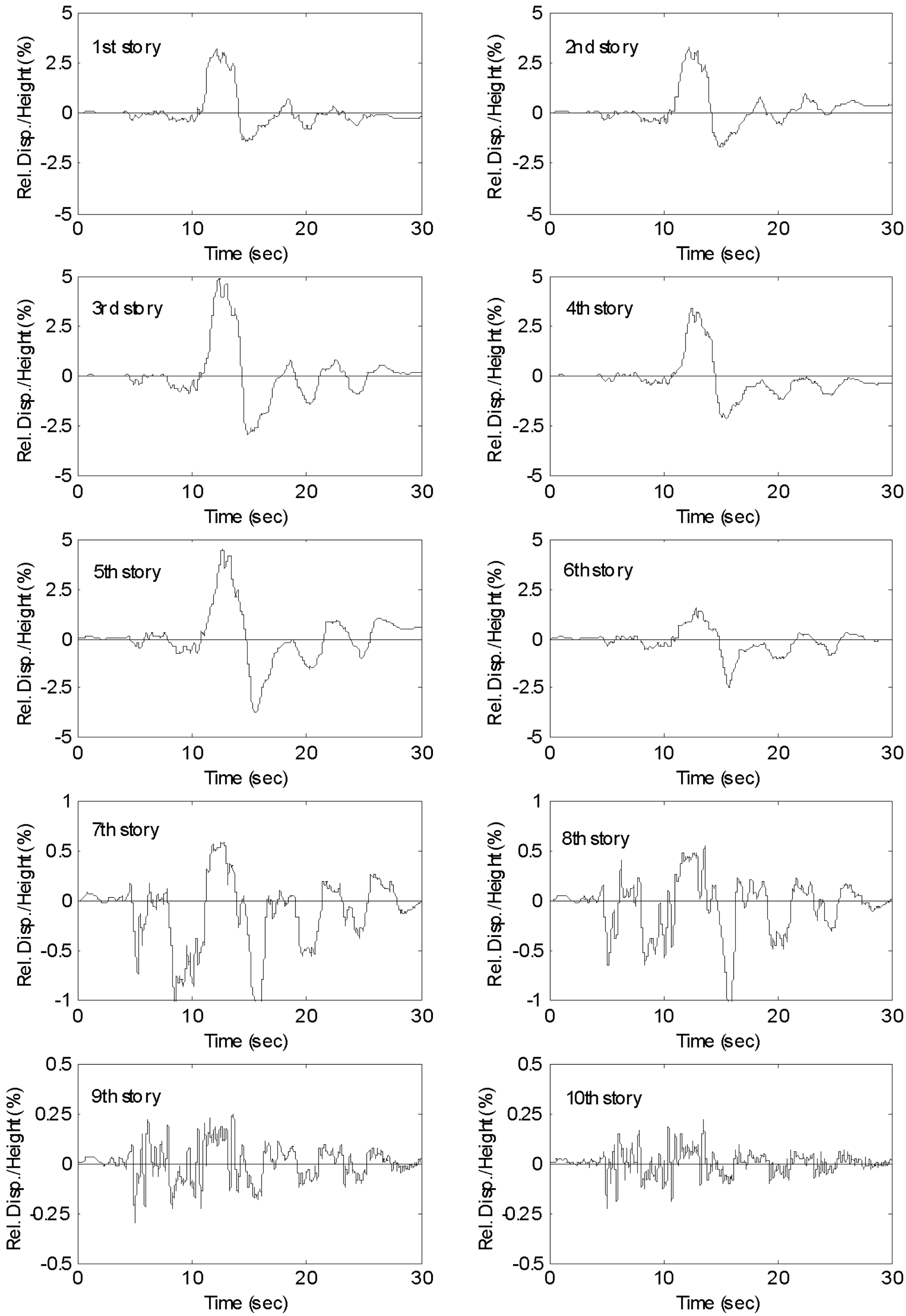

Figure 2: Normalized relative displacement of stories

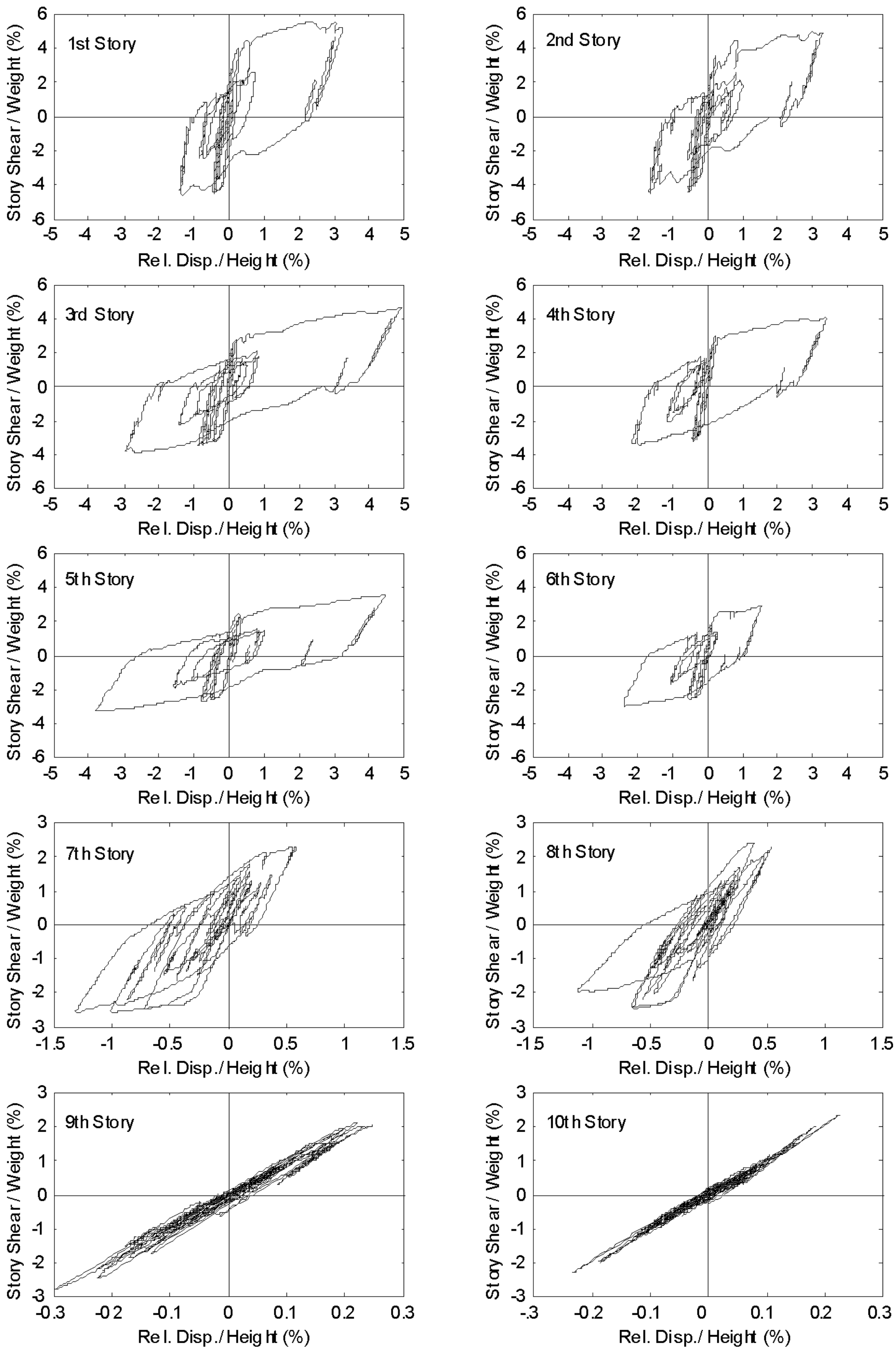

Figure 3: Hysteretic behavior of stories

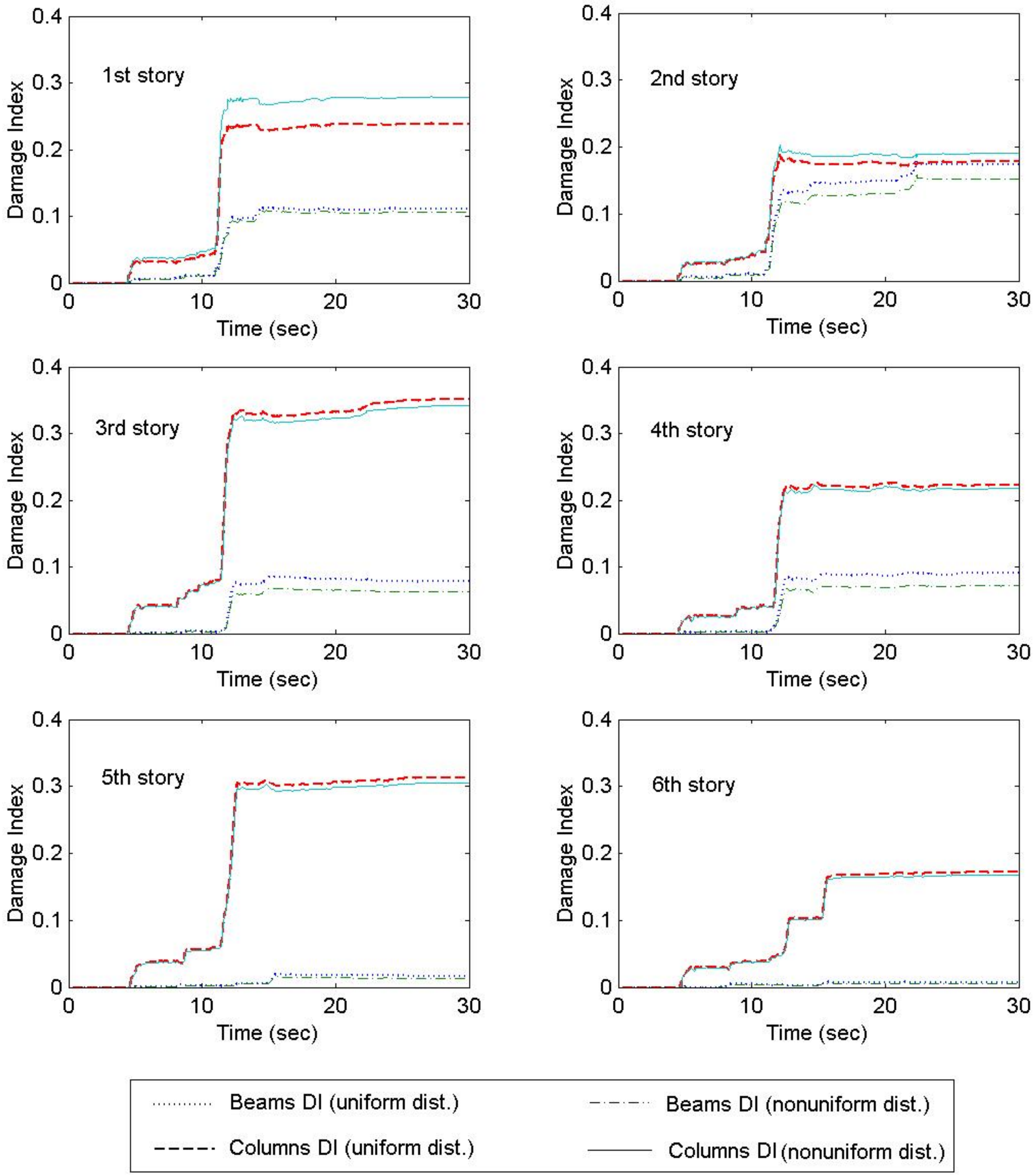

Figure 4: Damage history of stories for two distributions of element importance

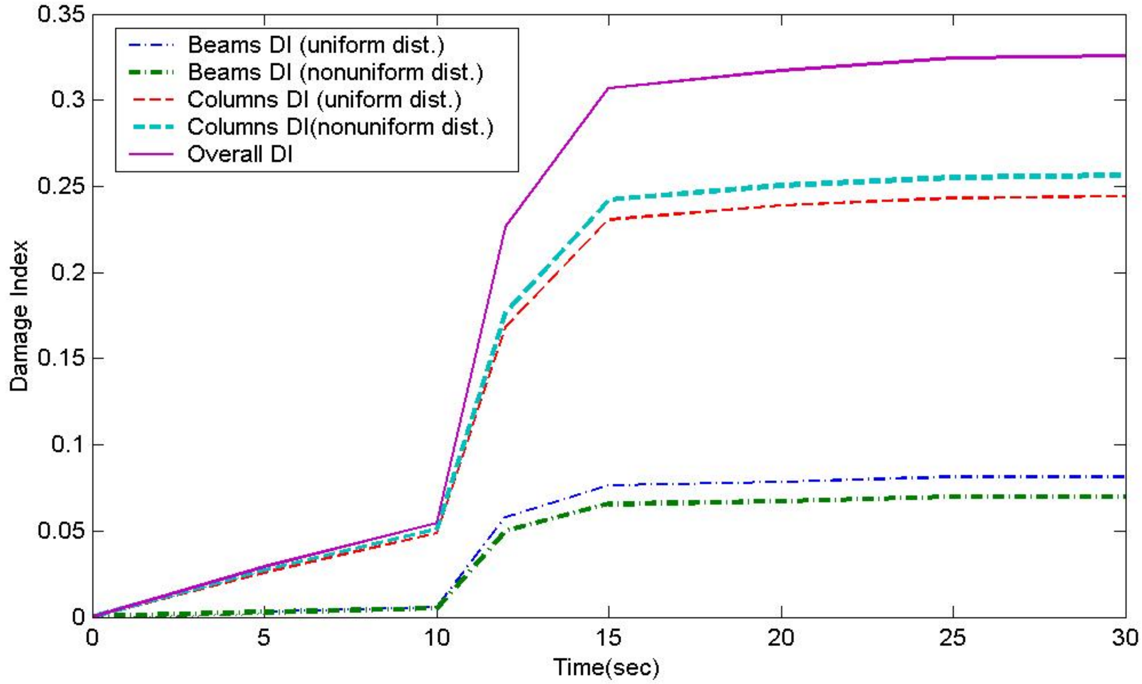

Figure 5: The history of the overall, beams and columns damage indices

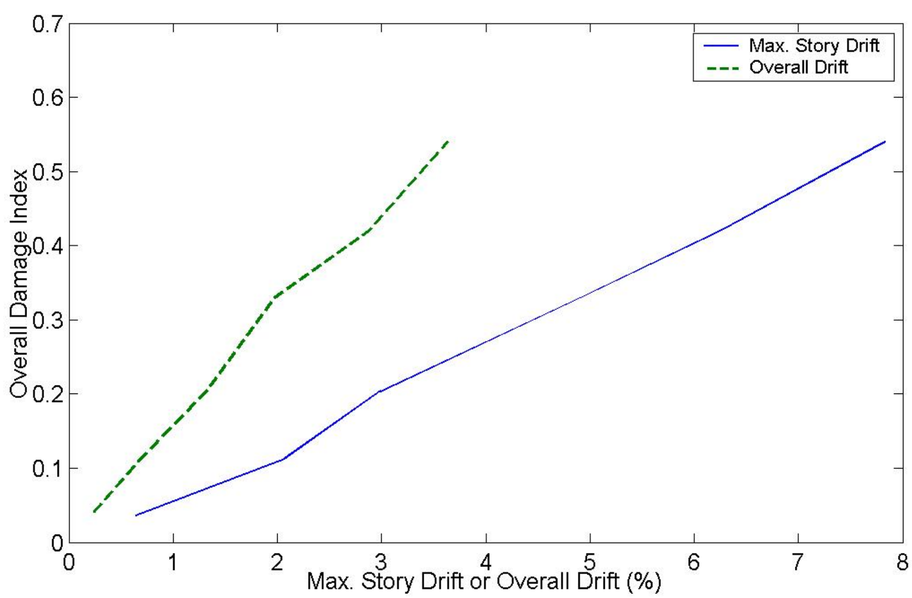

Figure 6: Maximum story drift and overall drift vs. overall damage index

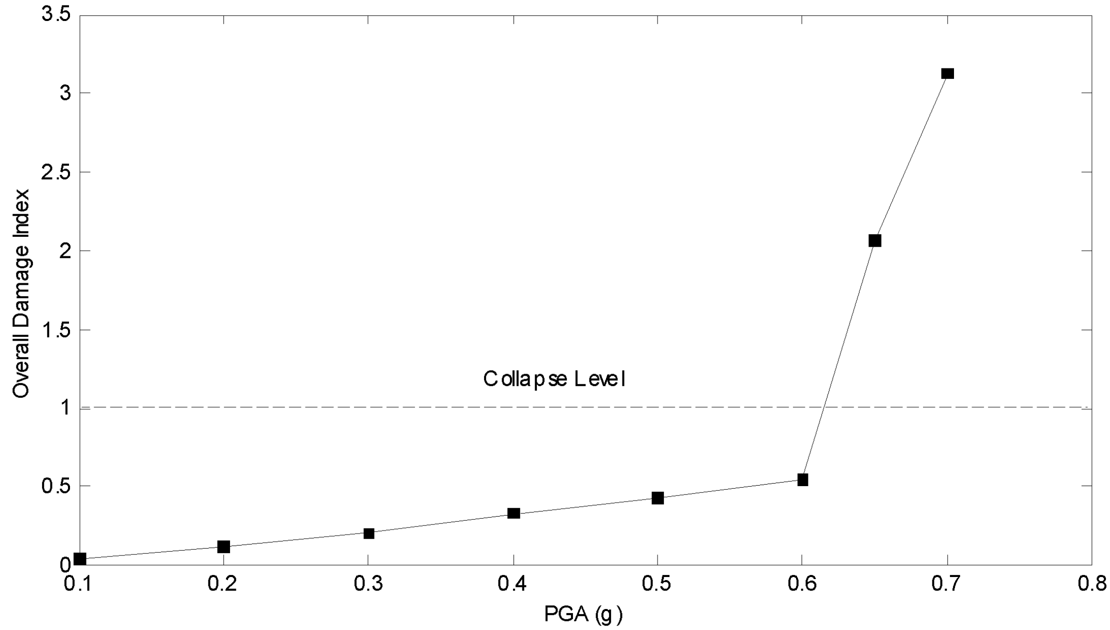

Figure 7: The effect of PGA on the overall damage index

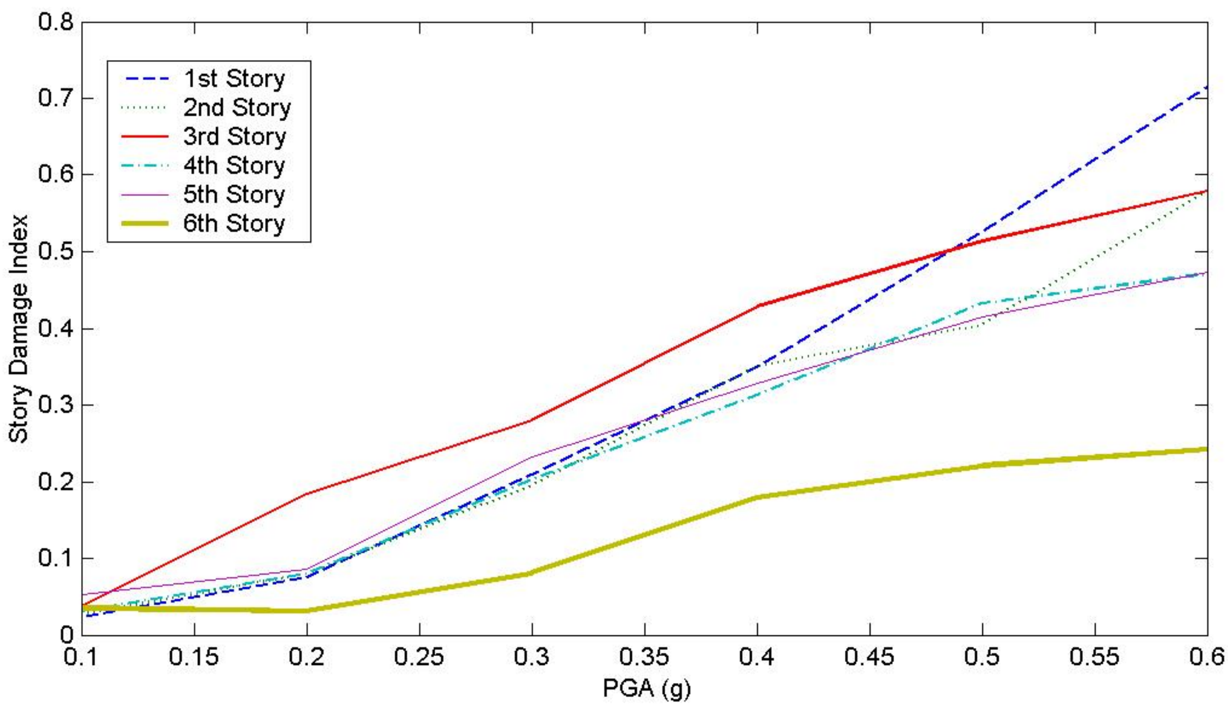

Figure 8: The effect of PGA on the story damage indices

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Appendix: Classification of Damage Indices.

- Damage Models
  - *1 – Local Damage Indices*
    - *1 – Non – Cumulative Indices*
      - 1 – Ductility Ratio (DR)
      - 2 – Interstory Drift (ID)
      - 3 – Slope Ratio (SR)
      - 4 – Flexural Damage Ratio (FDR)
      - 5 – Maximum Permanent Drift (MPD)
      - 6 – Pushover – Based Damage Index
    - *2 – Cumulative Damage Indices*
      - *1 – Deformation – Based Models*
        - 1 - Normalized Cumulative Rotation (NCR)
        - 2 - Cumulative Displacement Ductility
        - 3 – Normalized Cumulative PLastic Deformation
        - 4 - Maximum Deformation - Based Model
        - 5 – Low - cycle Fatigue Model
      - 2 – Energy – Based Models
      - *3 – Combined Models*
        - 1- Park - Ang Damage Index
        - 2 - Bracci et al. Damage Index
  - *2 – Global Damage Indices*
    - 1– Weighted Average Indices
    - *2 – Modal – Based Indices*
      - 1– Roufaiel – Meyer Global Model
      - 2 – Maximum Softening
      - 3 – Final Softening
    - *3 – Financial Indices*
      - 1 – Ratio of the repair cost to the replacement cost
      - 2 – Gunturi - Shah Financial Index