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DAMAGE MEASURES FOR PERFORMANCE-BASED SEISMIC EVALUATION OF RC FRAME STRUCTURES

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ABSTRACT

In performance-based earthquake engineering, deformation based methods such as member plastic rotation and inter-story drift ratio are recommended in guideline documents such as FEMA-356 for evaluating structural performance. Such response quantities, however, don't provide insight into the state of damage in the structure. Yet, damage at a certain local level in the system can result in unexpected structural damage which may lead to partial failure or structural collapse – a condition that may not be immediately evident from standard deformation measures. Local damage is associated with many parameters at the element and constitutive level. Therefore this study introduces a material-based structural damage model to evaluate the performance of RC frame structures subjected to strong ground motions.

Introduction

Growing interest in performance-based seismic engineering due to both economic considerations and safety concerns has led to the need to develop more precise methods to measure structural damage. While several efforts to define component and system damage has appeared in the literature (Chung et al, 1989; Krawinkler and Zohrei, 1983; Legeron et al, 2005; Park et al, 1985, 1988), very few damage models have been implemented in performance-based seismic assessment. Current guideline documents such as FEMA356 (REF) utilized inter-story drift ratio and plastic rotation to establish building performance levels such as immediate occupancy, life safety, and collapse prevention. While these measures provide information on the deformation of elements and the displaced profiles at critical states, they are inadequate in themselves to provide an assessment of the state of damage or proximity to collapse. An alternative methodology to measure structural damage based on material response states is proposed in this paper.

Material-Based Structural Damage

Since the response of common structural engineering materials such as steel and RC from the elastic state to failure is represented by yielding, plastic or irreversible behavior, crack growth, and fatigue during monotonic and cyclic loading, it is possible to represent such deterioration

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phenomena by a numerical model which can be incorporated in fiber-based discretization of a section for material-based damage estimation at the element level.

Damage Modeling at Constitutive Level

In this section, a damage model is introduced at the material level that is related to the response of the section deformation. This deformation is characterized by the stress and strain in the fibers of the cross-section.

Damage in Concrete Fiber

Strains at the threshold of damage initiation, attainment of compressive strength, and residual strength of crushed concrete are defined as damage parameters. In the present study, damage is considered only in the core concrete because it was determined that calibrating the damage state to the compression damage in the core was a better indicator of section damage than incorporating deterioration in both core and cover concrete. Other measures of concrete damage such as tensile cracking was found to be inessential since the corresponding response in the unconfined concrete fiber is reflected in reinforcing steel. Moreover, the response in compression governs the section damage in the concrete core. The constitutive model proposed by Mander et al. (1988) is used to evaluate the stress-strain response of the confined concrete.

Damage in concrete is initiated when bond and mortar micro cracks occur under loading. It usually happens quite early since concrete is a brittle material, so the strain at the damage initiation will generally be small. In compression, damage evolution is suspended when the cracks close during unloading. Upon reloading, damage accumulation continues when the previous unloading point is reached. However, an examination of cyclic stress-strain response of plain concrete suggests that a simple model based on the monotonic stress-strain curve is feasible. Ignoring the damage resulting from tensile cracking, a simple bilinear model is proposed in Eq. 1 and 2 assuming that the damage index is 1.0 when accumulated plastic strain reaches the strain at the residual strength:

$$D_{ci} = \frac{D_{cu}(f - f_{cd})}{(f_{cu} - f_{cd})} \text{ for } \varepsilon \le \varepsilon_{cu} \tag{1}$$

$$D_{ci} = 1 + \frac{(1 - D_{cu})(f - f_{cf})}{(f_{cf} - f_{cu})} \text{ for } \varepsilon > \varepsilon_{cu} \tag{2}$$

where D_{ci} is the concrete damage index at the i^{th} concrete fiber, D_{cu} denotes the damage index at the corresponding compressive strength, f_{cd} is the strength at damage initiation, f_{cu} is the concrete compressive strength, f_{cf} is the residual strength, and ε_{cu} denotes strain at concrete compressive strength. As shown in Figure 1, the damage rate changes at the peak compressive strength according to D_{cu} which can be determined by the ratio of the degraded strength at the failure ($f_{cu} - f_{cf}$) to the compressive strength (f_{cu}) denoted by D_{cu} as follows:

$$D_{cu} = \frac{\varepsilon_{cu} - \varepsilon_{cd}}{\varepsilon_{cf} - \varepsilon_{cd}} \tag{3}$$

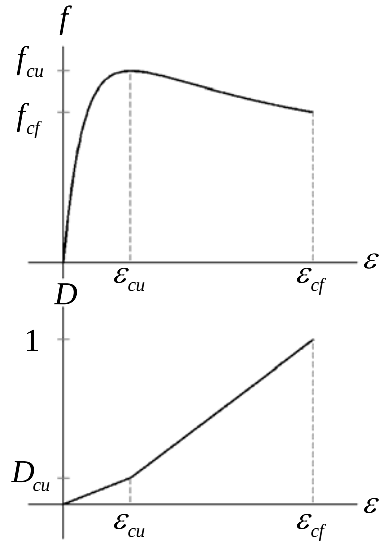


Figure 1. Stress-strain response of confined concrete and corresponding damage evolution

The proposed bilinear model is an idealization of the nonlinear damage evolution process, but it is expected that ongoing calibration and validation studies will serve to improve the model.

Damage in Reinforcing Steel Fiber

While the response of reinforcing steel beyond the elastic phase is described through yielding, hardening, softening, and fracture under monotonic loading, these monotonic parameters are inadequate to incorporate random cyclic effects such as strength degradation because steel is vulnerable to fatigue damage under seismic loads. It is more efficient to consider damage due to cyclic fatigue since it encompasses the combined effect of multiple damage parameters. Buckling of reinforcing bars is an important phenomenon that occurs under both monotonic and cyclic loading however, a cyclic fatigue model can also include buckling effects.

Therefore Miner's (1945) linear damage rule shown in Eq. 3 is applied to compute damage in reinforcing steel fiber:

$$D_{si} = \frac{1}{\sum_{j=1}^{n} (2N_f)_j} \tag{3}$$

where D_{si} denotes the damage index in the ith steel fiber, and $(2N_f)_j$ denotes the number of half-cycles to failure at the plastic strain amplitude corresponding cycle j which is described in Coffin (1954, 1971) and Mason (1965). Further details to find $(2N_f)_j$ can be also found in Kunnath et al (2009). D_{si} is initialized to zero until the cumulative plastic strain attains the damage initiation threshold and it reaches unity (ideally) when the rebar is fractured.

Structural Damage at Story Level

Damage is computed at each story level to facilitate the assessment of structural performance under earthquake loads. However, it is necessary to first generate damage at the element level from the section damage at the fiber level discussed in the previous section.

Damage at the Element Level

It is reasonable to consider the damage index of the most critical fibers for concrete and reinforcing steel as representative damage indices for each section as defined below:

$$D_{cx}^{B} = \max(D_{ci}^{B}),\ D_{sx}^{B} = \max(D_{si}^{B}) \tag{4}$$

$$D_{cx}^{C} = \max(D_{ci}^{C}),\ D_{sx}^{C} = \max(D_{si}^{C}) \tag{5}$$

where D_{cx} and D_{sx} denotes concrete and reinforcing steel damage index respectively on the x^{th} element for each story and superscripts B and C denote beam and column elements. For a n story frame structure with m bays, $x = 1, 2 \ldots.m$ for beams and $x = 1, 2\ldots\ m+1$ for columns for each story. It is assumed that the failure of any critical concrete or reinforcing steel fiber leads to section failure in the member. This assumption may be conservative if the concrete crushing strain is achieved prior to the fatigue failure of the reinforcing bar; however, the ultimate compressive strain in confined concrete is a severe damage state that also impacts the damage in the bar. Since the failure of a local member detected by the proposed damage model at the material level progressively affects adjacent members, it does provide a measure of system damage. Hence the damage index at the material level can govern the damage index at the element as well as the system level.

The combination of individual section damage to compute the element damage requires the implementation of weighting factors. In the study, based on studying different weighting factors, it was determined that the damage index itself is quite effective to be regarded as the weighing factor in estimating section damage. This approach has also been used previously by Bracci et al. (1989). In Eq. 6 and 7, w_{cx} and w_{sx} denotes the weighting factor for the damage index of the extreme concrete and steel fiber for the x$^{\text{th}}$ element on each story respectively.

$$w_{cx}^{B} = \frac{D_{cx}^{B}}{(D_{sx}^{B} + D_{cx}^{B})},\ w_{sx}^{B} = \frac{D_{sx}^{B}}{(D_{sx}^{B} + D_{cx}^{B})} \tag{6}$$

$$w_{cx}^{C} = \frac{D_{cx}^{C}}{(D_{sx}^{C} + D_{cx}^{C})},\ w_{sx}^{C} = \frac{D_{sx}^{C}}{(D_{sx}^{C} + D_{cx}^{C})} \tag{7}$$

Finally, the damage index of x$^{\text{th}}$ beam and column element (D_{x}^{B}, D_{x}^{C}) is estimated as follows:

$$D_{x}^{B} = D_{sx}^{B} w_{sx}^{B} + D_{cx}^{B} w_{cx}^{B},\ D_{x}^{C} = D_{sx}^{C} w_{sx}^{C} + D_{cx}^{C} w_{cx}^{C} \tag{8}$$

Damage at the Story Level

The same concept of using the damage index as weighting factor can be applied in computing the damage for each story as described in Eq. 9:

$$D_y^B = \frac{\sum_{x=1}^{m}\left(D_x^B\right)^2}{\sum_{x=1}^{m} D_x^B},\ D_y^C = \frac{\sum_{x=1}^{m}\left(D_x^C\right)^2}{\sum_{x=1}^{m} D_x^C} \tag{9}$$

where D_y^B and D_y^C denotes the damage index for the y^{th} story of a n-story frame structure. In seismic structural design and analysis, a moment resistant frame system is designed by employing a strong-column and weak-beam concept to avoid undesirable failure during strong earthquakes. Accordingly, columns should remain elastic so as to keep the system stable while beam elements absorb inelastic energy by hinge formation at the ends of each element. Therefore, it is necessary to impose a higher weighting factor for the failure of column elements compared to beams. Assuming that a story fails when the combine damage index of the columns in that story reaches 0.5, the story damage index for column (D_y^C) needs to be updated as given in Eq. 10. In the range $D_y^C < 0.5$, D_y^C can be adjusted by an interpolation function:

$$D_y^C = \begin{cases} 1\ (D_y^C \geq 0.5) \\ \text{adjusted by interpolation}\ \ (D_y^C < 0.5) \end{cases} \tag{10}$$

Eq. 11 shows the damage index of the y^{th} story using the weighted beam and column damage index of each story.

$$D_y = \frac{\left(D_y^B\right)^2 + \left(D_y^C\right)^2}{D_y^B + D_y^C} \tag{11}$$

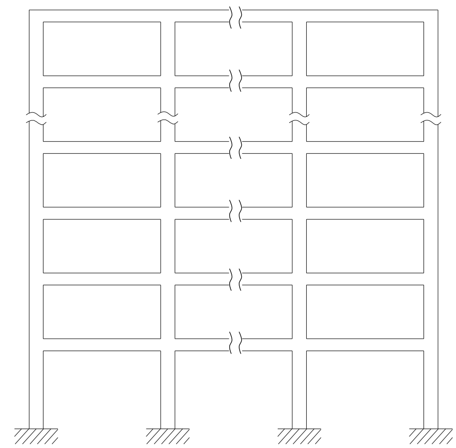
In the current study, the distribution of damage across story levels is considered adequate to assess overall structural damage. This is consistent with current engineering practice that evaluates peak inter-story drift as the critical damage measure. For more details about weighting factors, weighted story and system damage, refer to Heo (2009).

Structural Damage Simulation: A Case Study

The proposed damage formulation is now applied to assess the seismic performance of a 5-bay, 12-story reinforced concrete moment frame building. The building is designed to seismic hazard for Site Class D in a location near San Francisco (*37º 6' 29" N, 122º 5' 9" W*). The short period spectral acceleration for the site is determined to be S_s = *1.5* and the corresponding mapped spectral value at a period of 1.0 sec is S_1 = *0.669*. The design base shear is computed as *V = 2268.7 kips*. Details of a typical exterior frame that is considered in the evaluation is summarized in Table 1.

Table 1. Configuration and reinforcing details of multistory frame

Story		Column	Beam
1~3	Size	34×34	34×30
	Long reinf.	20-1.27dia	14-1.27dia
	Trans reinf.	0.5dia@5.28	0.5dia@7.50
4~6	Size	32×32	32×28
	Long Reinf.	16-1.27dia	14-1.27dia
	Trans reinf.	0.375dia@6.00	0.5dia@7.00
7~8	Size	30×30	30×26
	Long reinf.	16-1.128 dia	16-1.128 dia
	Trans reinf.	0.375dia@6.00	0.5dia@6.50
9~10	Size	28×28	28×22
	Long reinf.	16-1.128dia	16-1.128 dia
	Trans reinf.	0.375dia@6.00	0.5dia@5.50
11~12	Size	22×22	22×18
	Long. reinf.	16-1.128dia	14-1.128 dia
	Trans reinf.	0.375dia@5.44	0.5dia@4.50



Units: inch, kip

The building frame is subjected to three separate ground motions whose primary characteristics are specified in Table 2. The ground motions were selected so as to induce different degrees of damage in the structure. The 5% damped response spectra of the selected ground motions are shown in Figure 2. Also shown in the figure are the periods corresponding to the first 3 vibration modes.

Table 2. Ground motion details

Eq. ID	EQ. Name	Year	Station	*M*	*ClstD*	PGA (g)
EQ1	Hector Mine	1999	Hector	7.13	11.66	0.34
EQ2	Imperial Valley-06	1979	Meloland Overpass FF	6.53	0.07	0.30
EQ3	Chi-Chi, Taiwan	1999	TCU068	7.62	0.32	0.57

M: Moment magnitude; ClstD: Closest distance (km) from site to the ruptured area

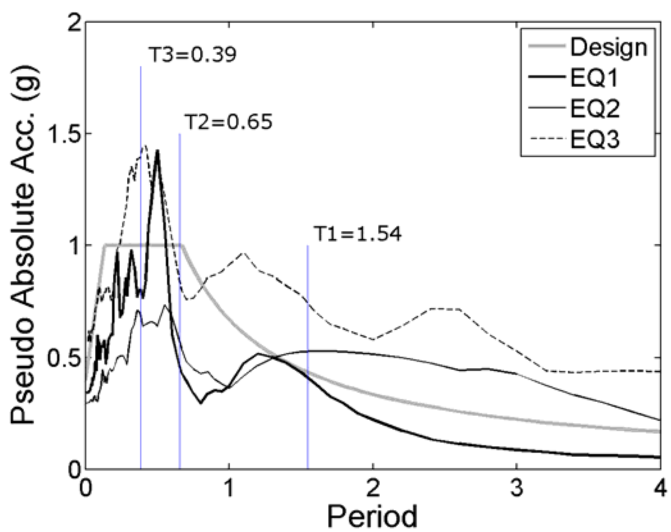
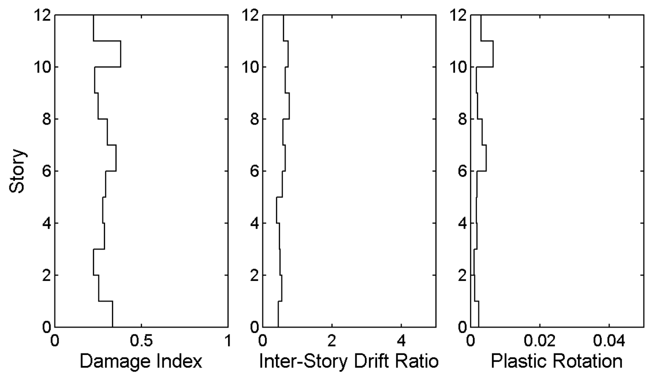
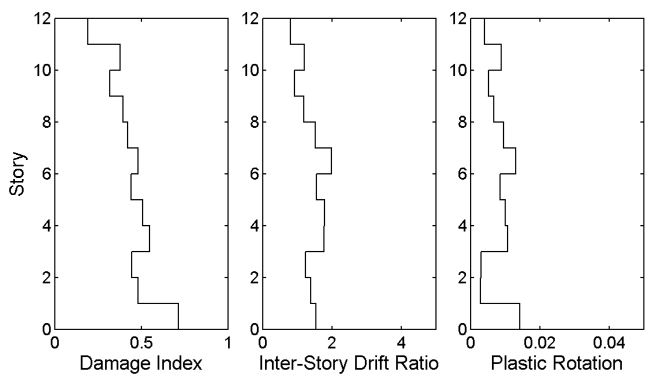


Figure 2. Response spectra of selection motions

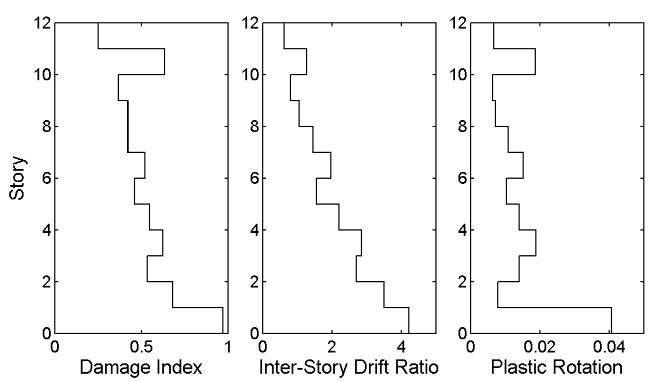
Results of the damage assessment are displayed in Figure 3. The computed damage indices are compared to interstory drifts and peak plastic rotation in the elements of the corresponding story. Each of the selected ground motions imposes increasing levels of deformation demands in the system. The results shown in Figure 3 indicate that the computed damage indices are reasonable estimates compared to either the member plastic rotation or the interstory drift demand. Plastic rotations reported in the figure are those computed in OpenSees (2010).



(a) Response to EQ1: Low damage



(b) Response to EQ2: Moderate Damage



(c) Response to EQ3: Severe Damage

Figure 3. Computed story level damage indices for three ground motions with increasing intensity and correlation with standard deformation measures

Conclusions

A material-based damage model to assess the performance of a reinforced concrete frame building is proposed. The model is suitable for use in nonlinear dynamic analysis of frames that is based on fiber discretization of a section. Damage computed at the section level is transformed into element, story and system damage through the use of weighting factors. The proposed model is applied in seismic assessment of a typical multistory frame subjected to different intensity ground motions and thereby resulting in different degrees of damage. Validation of the model is accomplished by comparison of the computed damage to well-known structural response measures such as interstory drift and member plastic rotation.

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