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COLLAPSE ASSESSMENT OF BUILDING STRUCTURES USING DAMAGE INDEX

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SUMMARY

Nonlinear dynamic analyses were performed for five and ten-story multi-degree-of-freedom systems where the story collapse was assessed by means of damage index. A parametric study was carried out to characterize the effect of different levels of hysteretic energy dissipation demand on the seismic damage to reinforced concrete structures. In the analysis, the base shear yield strength was gradually decreased until one of the stories came to collapse. The additional strength requirement imposed by the inclusion of energy demand in assessing seismic damage was investigated and the structural behavior of the system leading to its collapse was also examined in detail. The results indicate that simple measures of ductility demand may not fully capture the effect of cyclic loading since it fails to account for the increased energy demand when high inelastic excursions occur in both loading directions while a damage index that combines the effect of maximum deformation and cumulative hysteretic energy demands should give a better assessment of seismic response.

INTRODUCTION

The earthquake engineering community recognizes the need to improve current seismic codes and design methods in light of the recent inadequate behavior of buildings. Part of this may be attributed to simplified design methods such as equivalent static force procedure which fails to account for the cyclic load effect usually encountered during earthquakes. It has been widely recognized however that cyclic loading has significant effect on the cumulative damage to structures [1-5]. Such shortcoming may be overcome by adopting a more adequate means of assessing seismic damage which can be done by using a damage index that combines the effects of maximum deformation and inelastic energy dissipation.

The main objective of this study is to incorporate cumulative damage concepts in assessing seismic response of building structures by considering the combined effect of maximum deformation and cumulative dissipated hysteretic energy. Focus is given to the assessment of collapse which from the observed earthquake damage in the past could happen at different stories of the building. The additional strength requirement imposed by the inclusion of energy demand in assessing seismic damage and the structural behavior leading to its collapse are also examined in detail.

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METHODOLOGY

Analytical model of the structure

The structural model analyzed is a multi-degree-of-freedom (MDOF) system as shown in Fig. 1. The beams and floor systems are assumed to be rigid with the mass idealized to be concentrated at the floor levels and uniformly distributed along the height of the building. The system, described as finite rotation model, has rotational springs at both ends of the columns and each level has a single degree of freedom indicated by rotation angle ϕ.

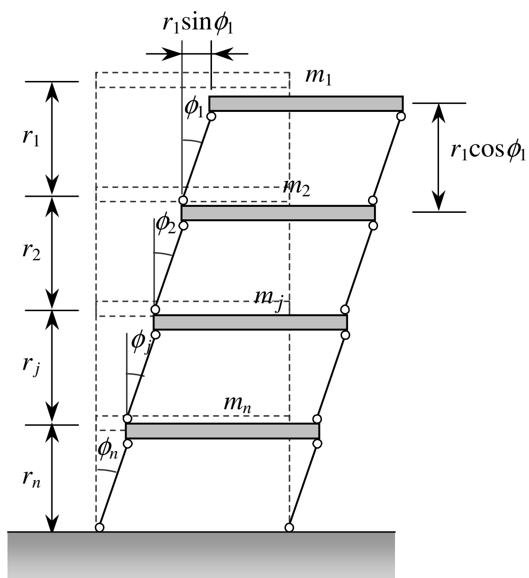


Fig. 1 MDOF model of the structure.

The system was considered to be made of reinforced concrete (RC) material with a uniform story height of r = 4 m. Two cases were analyzed: a short-period building with the number of stories n = 5, and a long-period building with n = 10.

The fundamental natural period of the building T was computed as $0.1n$ which is equal to 0.5 sec and 1.0 sec for the five and ten-story models, respectively. These represent intermediate values between the periods calculated from the US and Japanese codes for 20 and 40 m high RC buildings.

The lateral strength was based on the Ai distribution stipulated in the Japanese code [6] and the lateral stiffness has parabolic distribution such that the fundamental mode shape is inverted triangle. The viscous damping coefficient was chosen such that the fraction of critical damping is 0.05 in the elastic range and proportional to the tangent stiffness in the inelastic region.

Equation of motion

The motion of the structural model being analyzed is governed by the following equation where the j–th level is counted from the top for ease of computer programming.

$$[I_t]\{\ddot{\phi}\} + [I_n]\{\dot{\phi}^2\} + \{c\dot{\phi}\} + \{M_r\} = \ddot{x}\{H\} + (g + \ddot{y})\{V\} \tag{1}$$

where:

$$[I_t]=\begin{bmatrix} m_1 r_1^2 & m_1 r_1 r_2 \cos(\phi_1-\phi_2) & \cdots & m_1 r_1 r_n \cos(\phi_1-\phi_n) \\ m_1 r_1 r_2 \cos(\phi_2-\phi_1) & (m_1+m_2) r_2^2 & \cdots & (m_1+m_2) r_2 r_n \cos(\phi_2-\phi_n) \\ \vdots & \vdots & \ddots & \vdots \\ m_1 r_1 r_n \cos(\phi_n-\phi_1) & (m_1+m_2) r_2 r_n \cos(\phi_n-\phi_{2)} & \cdots & (\sum_1^n m_j) r_n^2 \end{bmatrix} \quad (2)$$

$$[I_n]=\begin{bmatrix} 0 & m_1 r_1 r_2 \sin(\phi_1-\phi_2) & \cdots & m_1 r_1 r_n \sin(\phi_1-\phi_n) \\ m_1 r_1 r_2 \sin(\phi_2-\phi_1) & 0 & \cdots & (m_1+m_2) r_2 r_n \sin(\phi_2-\phi_n) \\ \vdots & \vdots & \ddots & \vdots \\ m_1 r_1 r_n \sin(\phi_n-\phi_1) & (m_1+m_2) r_2 r_n \sin(\phi_n-\phi_{2)} & \cdots & 0 \end{bmatrix} \quad (3)$$

$$\{\phi\}=\begin{Bmatrix} \phi_1 \\ \phi_2 \\ \vdots \\ \phi_n \end{Bmatrix} \qquad \{c\dot{\phi}\}=\begin{Bmatrix} c_1\dot{\phi}_1 \\ c_2\dot{\phi}_2 \\ \vdots \\ c_n\dot{\phi}_n \end{Bmatrix} \qquad \{M_r\}=\begin{Bmatrix} M_1(\phi_1) \\ M_2(\phi_2) \\ \vdots \\ M_n(\phi_n) \end{Bmatrix} \quad (4)$$

$$\{V\}=\begin{Bmatrix} m_1 r_1 \sin\phi_1 \\ (m_1+m_2) r_2 \sin\phi_2 \\ \vdots \\ (\sum_1^n m_j) r_n \sin\phi_n \end{Bmatrix} \qquad \{H\}=\begin{Bmatrix} m_1 r_1 \cos\phi_1 \\ (m_1+m_2) r_2 \cos\phi_2 \\ \vdots \\ (\sum_1^n m_j) r_n \cos\phi_n \end{Bmatrix} \quad (5)$$

where:

m_j	:	mass of the *j*-th level
r_j	:	height of the *j*-th level
ϕ_j	:	rotation angle of the *j*-th level
c_j	:	viscous damping coefficient of the *j*-th level
$M_j(\phi_j)$	:	restoring moment of the *j*-th level
$\ddot{x}$	:	horizontal ground acceleration
$\ddot{y}$	:	vertical ground acceleration
g	:	acceleration due to gravity

In the succeeding sections, the term story is counted from the base of the structure as is conventionally the case.

Restoring moment characteristics
Fig. 2 shows the trilinear skeleton curve for the hysteretic system used in the analysis. Also shown are the values of the parameters used to define the backbone curve.

The hysteresis model used was that developed by Takeda et.al. [7] based on experimental studies done on RC members and includes (a) stiffness changes at flexural cracking and yielding, (b) hysteresis rules for the inner hysteresis loops, and (c) unloading stiffness degradation. The Takeda model was originally formulated to simulate the behavior of RC members. Certain modifications were therefore made to describe the response at the story level. For instance, unloading before yielding takes place towards the origin instead of the point representing the cracking load in the other direction.

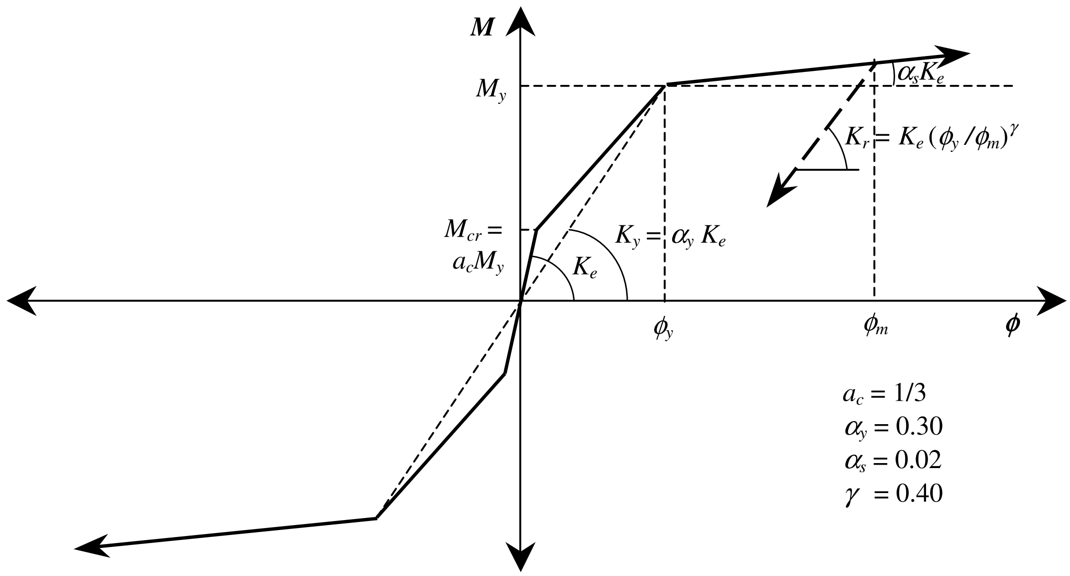


Fig. 2 Trilinear skeleton curve of the restoring moment-rotation relation.

Definition of collapse

A number of damage indices have been proposed by previous researchers but one that captures the combined effect of deformation and dissipated energy demand should give a better assessment of the cyclic load effect. One such index was that developed by Park and Ang [8] based on experimental studies and extensive calibration with observed damage in actual buildings. The Park and Ang damage index expressed in terms of moment-rotation relation and normalized rotation angle (ductility factor) is given by the following equation:

$$DI = \frac{\mu_m}{\mu_u} + \beta \frac{\int dE_h}{M_y \phi_y \mu_u} \tag{6}$$

where:

- μ_m : maximum ductility demand
- μ_u : ultimate ductility capacity under monotonic loading
- dE_h : incremental dissipated hysteretic energy
- M_y : yield moment capacity
- ϕ_y : yield rotation angle
- β : a dimensionless constant, and
  - $DI < 0.4$: represents reparable damage
  - $0.4 \le DI < 1.0$: represents damage beyond repair
  - $DI \ge 1.0$: represents total collapse

The ultimate ductility capacity μ_u of the system is defined to be equal to 4 which may represent systems of medium ductility. In determining the value of parameter β, Park and Ang [8] proposed a regression equation in terms of variables such as shear span ratio, axial stress, steel and confinement ratio, and material strength.

In the parametric study, four values of parameter β were used to characterize the contribution level of the energy demand to the damage. First, $\beta = 0$ means the effect of hysteretic energy is not considered (i.e., only deformation). A value of 0.05 as suggested by Park et. al. [9] for RC components was also considered. Williams and Sexmith [10] noted that the values of β obtained from the proposed regression equation could be too small to characterize the effect of dissipated hysteretic energy. Therefore, $\beta = 0.10$ and $\beta = 0.15$ which represents the median of experimental values as cited by Teran-Gilmore [11], were used as well.

Although further studies are needed to determine appropriate values of parameter β especially at the story level and for a given story ductility capacity, this study was motivated by the need to investigate the merits of including hysteretic energy in evaluating seismic damage to building structures.

Nonlinear dynamic analysis

Nonlinear dynamic analysis was carried out for the analytical model of the structure where the base shear yield strength was gradually decreased until one of the stories came to collapse. The collapse of a certain story was considered to occur when the damage index *DI* defined by Eq.(6) reaches a value of 1. A total of six (6) earthquake records were chosen for the dynamic analyses and are given in Table 1. All horizontal ground motions were multiplied by a factor such that the peak ground velocity (PGV) becomes scaled to 50 cm/s. The resulting scaled input ground motions are shown in Fig. 3.

Table 1 Selected earthquake ground motions (original records)

Ground motion	Comp.	Notation	PGA	PGV (cm/s)
El Centro – 1940	N-S	ELCEN	0.35g	33.5
Hachinohe – 1968	N-S	HACH	0.23g	34.1
Kobe JMA – 1995	N-S	KOBE	0.84g	90.2
SCT – 1985	E-W	SCT	0.16g	60.5
Sylmar – 1994	N-S	SYLM	0.84g	128.9
Fukiai - 1995	N240E	FUKI	0.70g	57.4

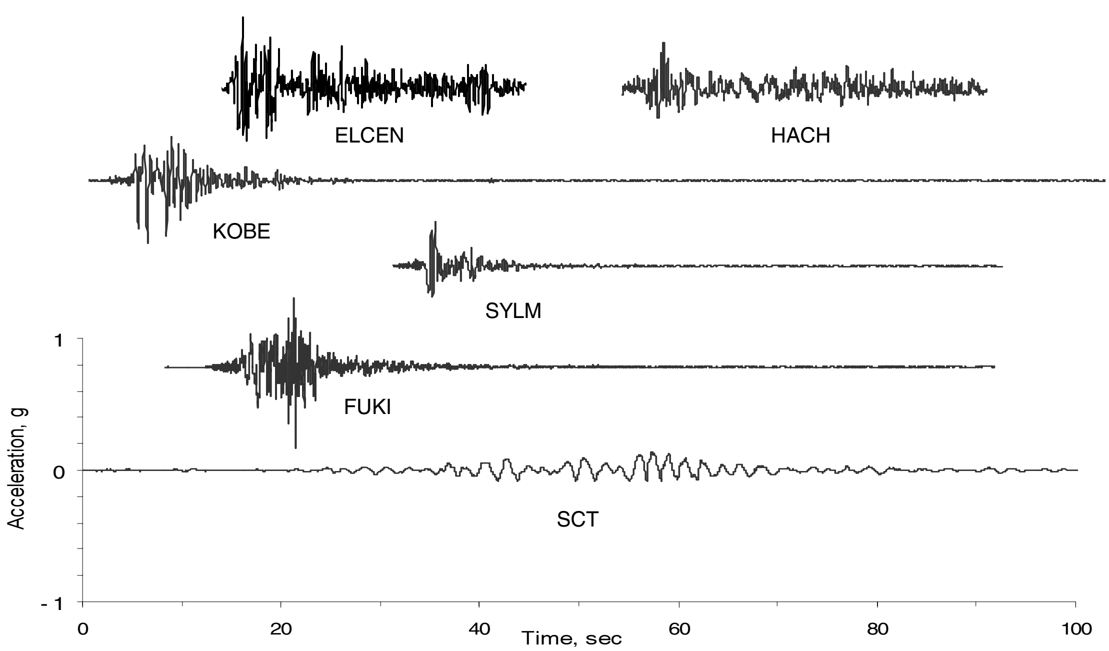


Fig. 3 Scaled input ground motions.

RESULTS AND DISCUSSION

Yield strength capacity at collapse

In the dynamic analysis, the yield strength of the system was gradually decreased until one of the stories came to collapse, i.e., $DI \geq 1$. This yield strength expressed in terms of acceleration due to gravity will be referred to as the collapse base shear coefficient C_{bc} in the succeeding discussion.

Figs. 4 and 5 show the values of C_{bc} corresponding to the range of parameter β considered in this study for the five and ten-story models, respectively. The values of C_{bc} obtained from the analysis are accurate to three decimal places but it should be noted that these values do not necessarily correspond to the strength demand imposed by the original earthquake excitations due to the scaling of input ground motions made. The back analysis done (i.e., reduction of the yield strength capacity until collapse) allows the determination of the additional seismic demand imposed by the inclusion of the effect of hysteretic energy dissipation on the cumulative damage.

Based from the results of the analysis, a stepwise increase of 0.05 in the value of β generally corresponds to an average increase of about 0.02 in the value of C_{bc} for n = 5. In the case of the ten-story model, the variation of C_{bc} is less sensitive to parameter β and results to an approximate increase of 0.01 in C_{bc} per 0.05 increment of β. This can be seen in Fig. 5 where the C_{bc} - β plots for different excitations are relatively more flat compared to those in Fig. 4. It should be noted however that the incremental increase in seismic demand depends on the characteristics of earthquake excitation (i.e., amplitude, duration and frequency content). For example, for the five-story model, ELCEN, KOBE and HACH ground motions which have relatively rich frequency content causes higher increase in strength demand when compared to the other input ground motions used.

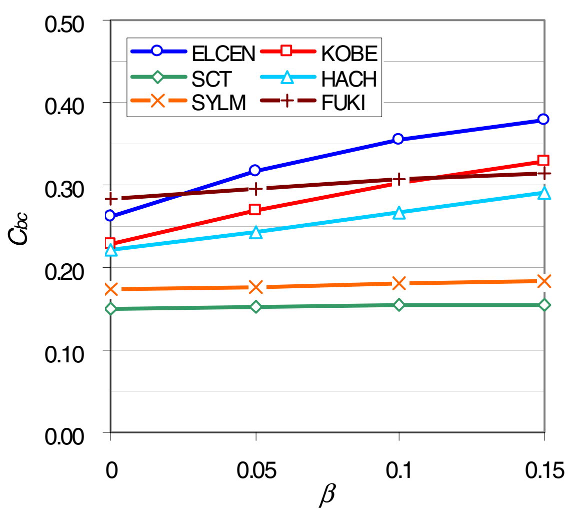


Fig. 4 Collapse base shear coefficient C_{bc} for different values of β, n = 5.

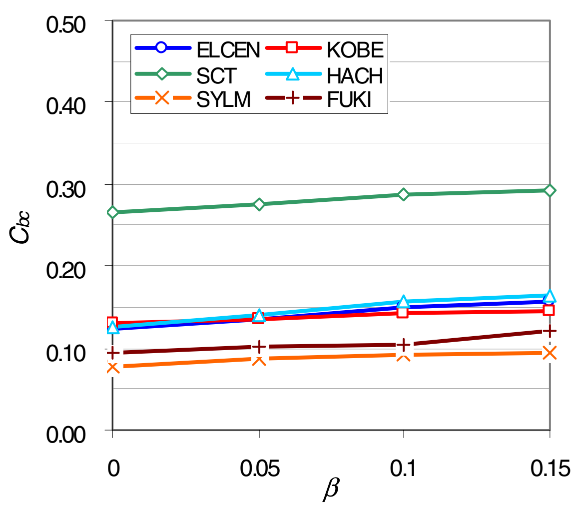


Fig. 5 Collapse base shear coefficient C_{bc} for different values of β, n = 10.

The results obtained are consistent with the trend of decreasing seismic demand from short to longer period buildings as what may be observed in a typical response spectrum of single-degree-of-freedom (SDOF) system. An exception occurs in the case of SCT ground motion where the values of C_{bc} obtained for a period of T = 1.0 sec (Fig. 5) is higher compared to that of T = 0.5 sec (Fig. 4). This can be attributed to the frequency content of SCT ground motion which is harmonic in nature. It is known that an increase in seismic response can occur when the natural period of the system is close to the predominant period of the ground motion, a phenomenon often referred to as frequency resonance.

Collapse behavior

In assessing the seismic performance of building structures, the prediction and quantification of the structural behavior at different limit states is very important. In this study, focus was given to the description of structural behavior that influences its collapse since this is the most critical limit state as it poses threat to human safety.

The distribution of damage along the building height when a story collapses was first investigated and is shown in Figs. 6 and 7 for n = 5 and n = 10, respectively. The collapse indicated by $DI \geq 1$ usually happens at the first story except in the case of ELCEN when n = 5 and KOBE and in one case of FUKI when n = 10. For these exceptional cases, the collapse happens in one of the upper stories which may be attributed to higher-mode effects and damage concentration due to formation of plastic hinge.

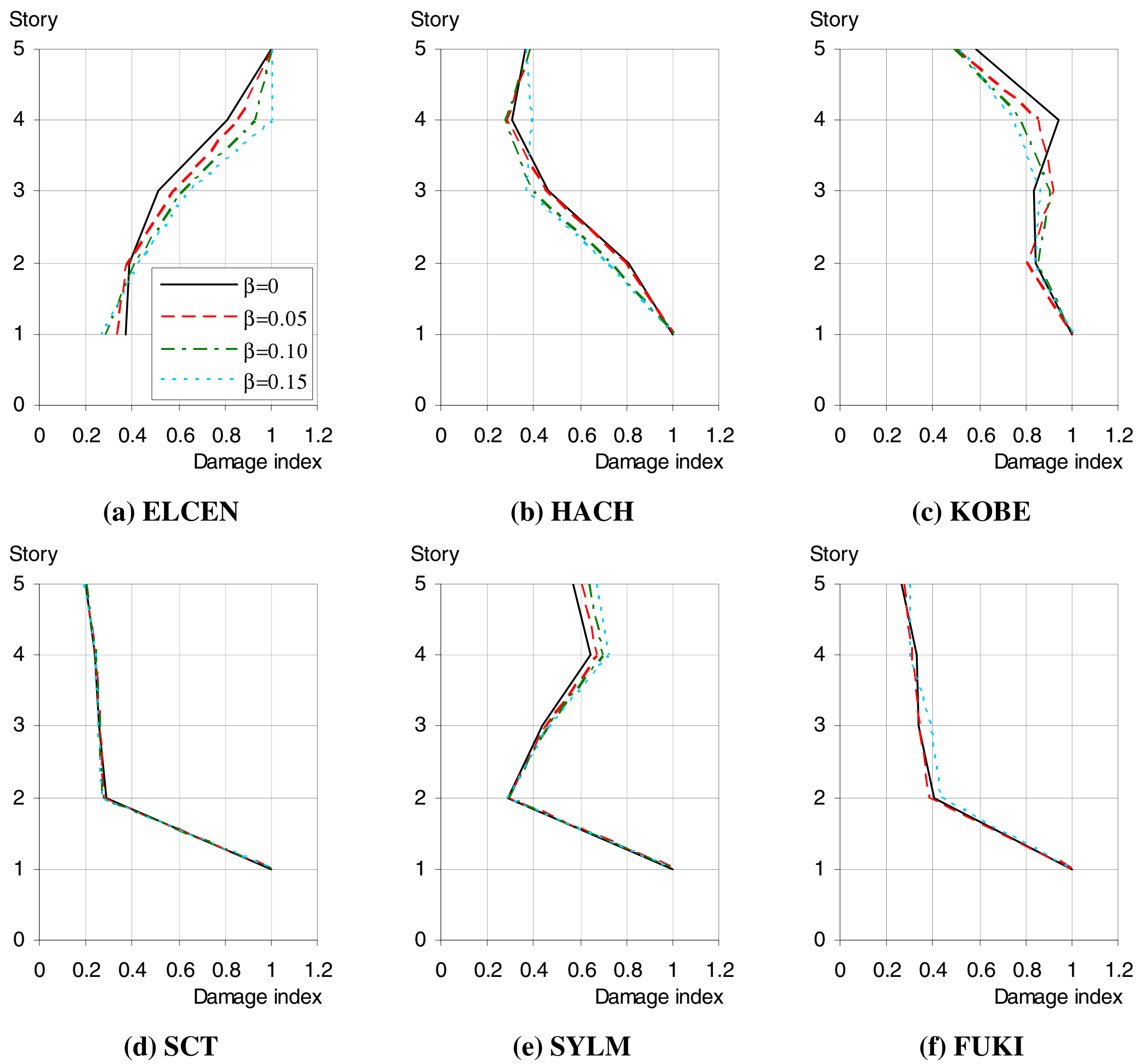
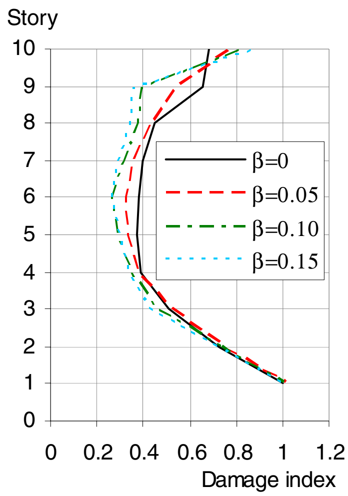
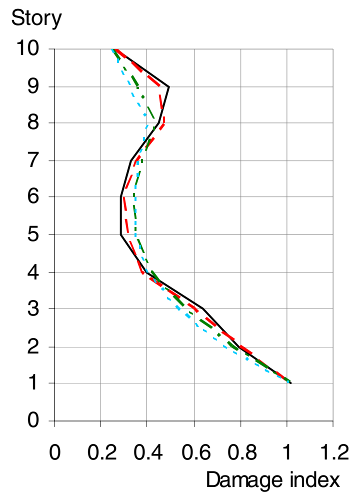


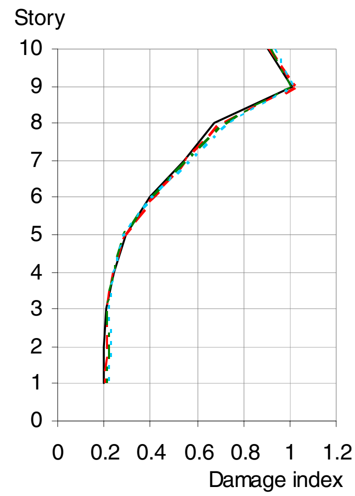
Fig. 6 Distribution of damage index along the height of five-story model.



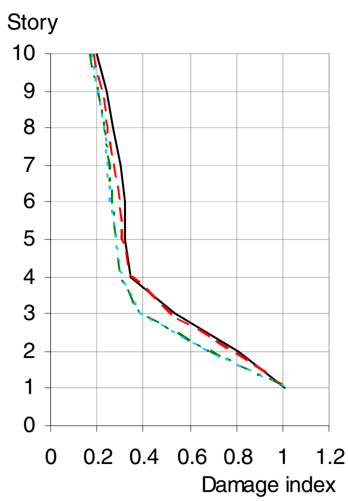
(a) ELCEN



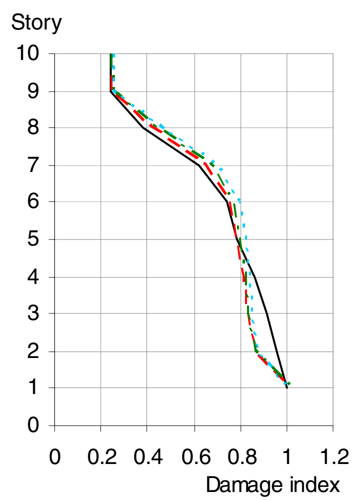
(b) HACH



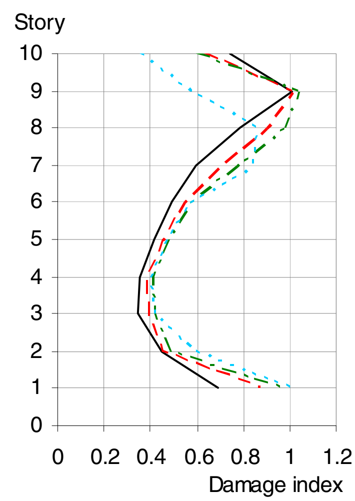
(c) KOBE



(d) SCT



(e) SYLM

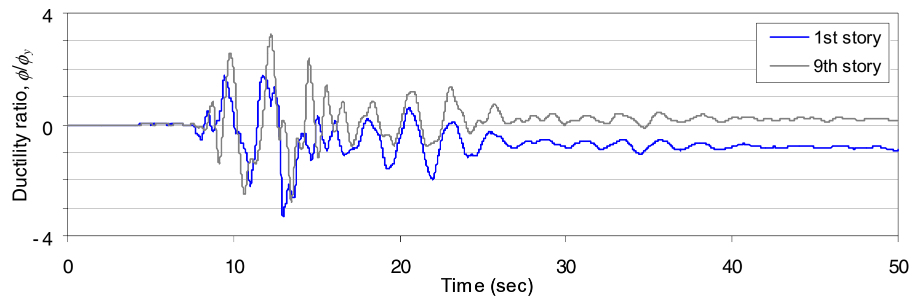


(f) FUKI

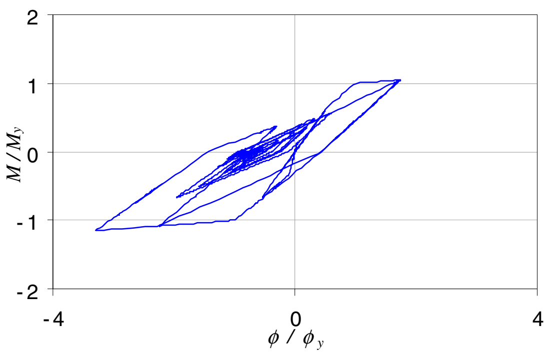
Fig. 7 Distribution of damage index along the height of ten-story model.

The case of FUKI when n = 10 is especially interesting because a change in the collapsing story happens when β is increased from 0.10 to 0.15 as can be seen in Fig. 7.f. This is due to the difference in the strength demand requirement for systems with different energy dissipation capacity characterized by the parameter β. The values of C_{bc} corresponding to β = 0.10 and 0.15 are 0.104 and 0.120, respectively. At these two levels of base shear yield strength, the upper stories of the system behave somewhat differently to FUKI excitation. Referring to Fig. 7.f, at C_{bc} = 0.104 (β = 0.10) aside from the first story, concentration of damage (ductility and energy demands) also happens at the 8th and 9th stories leading to the collapse of the latter. On the other hand, at C_{bc} = 0.120 (β = 0.15), damage concentration in the upper part of the building is shifted to the 7th and 8th stories which eventually leads to the collapse of first story where the seismic damage is even greater.

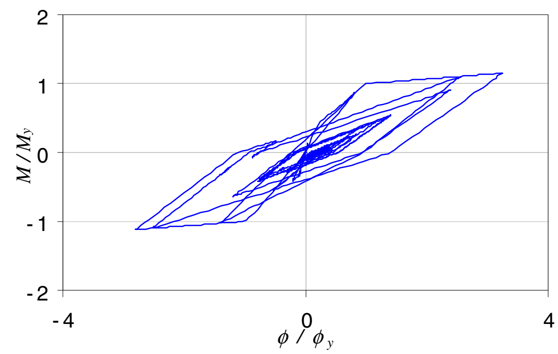
This collapse behavior can also be verified from Figs. 8 and 9 where the deformation time histories (part a) and hysteresis curves of the 1st and 9th stories (parts b and c) are shown for C_{bc} equal to 0.104 and 0.120, respectively.



(a) Time histories of normalized rotation angle

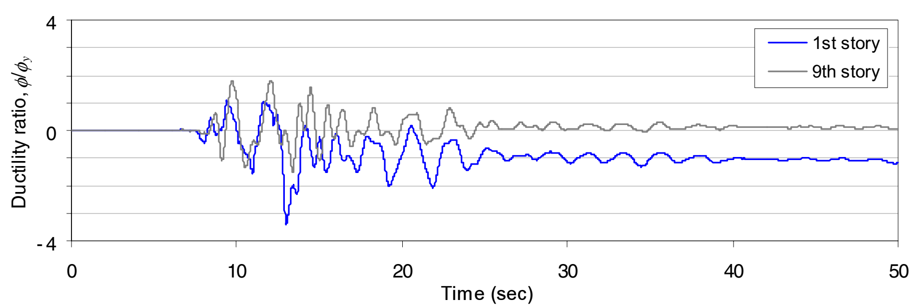


(b) Hysteresis curve of 1st story

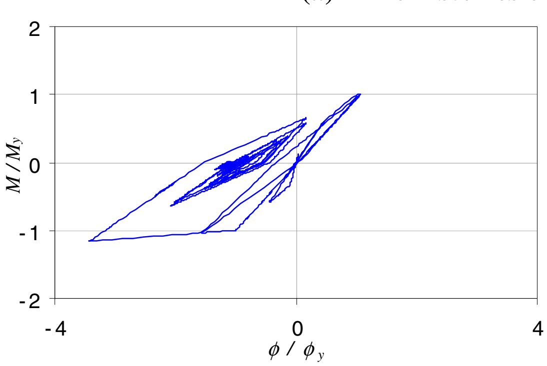


(c) Hysteresis curve of 9th story

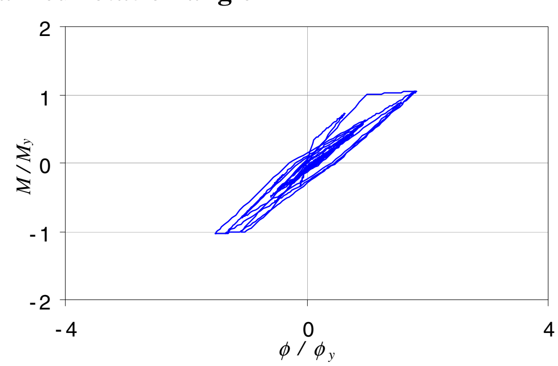
Fig. 8 Seismic response of 1st and 9th stories – FUKI, C_{bc} = 0.104, β = 0.10.



(a) Time histories of normalized rotation angle



(b) Hysteresis curve of 1st story



(c) Hysteresis curve of 9th story

Fig. 9 Seismic response of 1st and 9th stories – FUKI, C_{bc} = 0.120, β = 0.15.

In the case of C_{bc} = 0.104, although the maximum ductility demands, which occur in the opposite directions for the 1st and 9th stories are almost the same, the energy absorbed by the latter is much higher as indicated by larger hysteresis loops in Fig. 8.c, leading to its eventual collapse. This is one shortcoming of the maximum ductility demand as a simple measure in assessing seismic response in that it fails to account for the higher absorbed energy that occurs when large inelastic deformations occur in both directions of cyclic loading. Furthermore, Estes and Anderson [12] have pointed out that multiple inelastic excursions, even below the maximum deformation could still cause significant damage.

In the case of C_{bc} = 0.120, the seismic demand becomes concentrated mainly in the first story as can be seen in Fig. 7.f. This can also be verified from the hysteresis curve of the 1st story where the highest ductility demand happens (Figs. 9.b). On the other hand, the plastic deformation in the other stories including the 9th story (Figs. 9.c), have not progressed far into the inelastic region with the maximum ductility demands ranging only from 1.3 to 2.6.

In order to have a better picture of the distribution of damage along the height of the building for the two cases discussed above, the energy time histories of the structure have been plotted in Figs. 10 and 11 where the individual cumulative dissipated hysteretic energies of each story are shown.

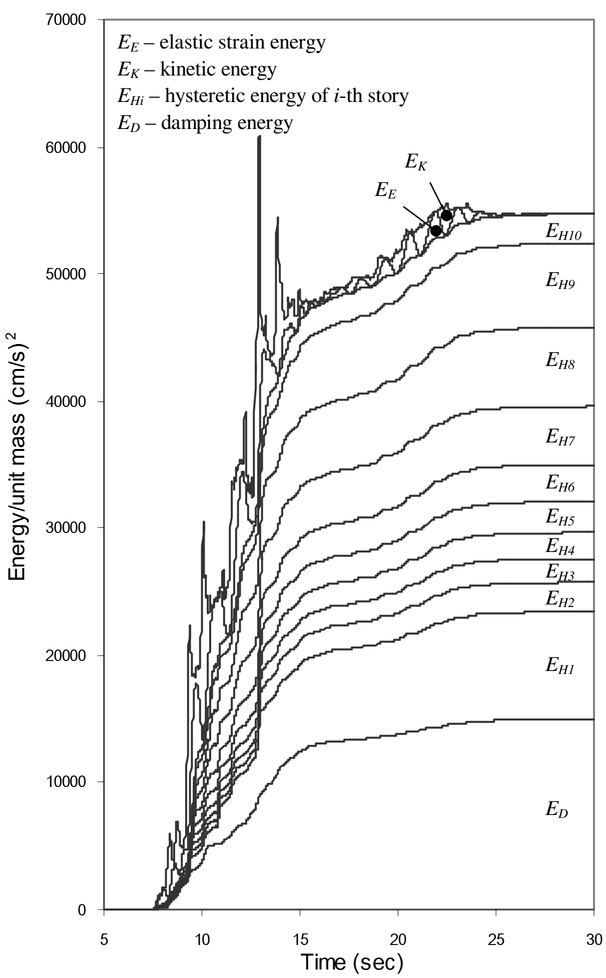


Fig. 10 Energy time histories – FUKI, C_{bc} = 0.104, β = 0.10.

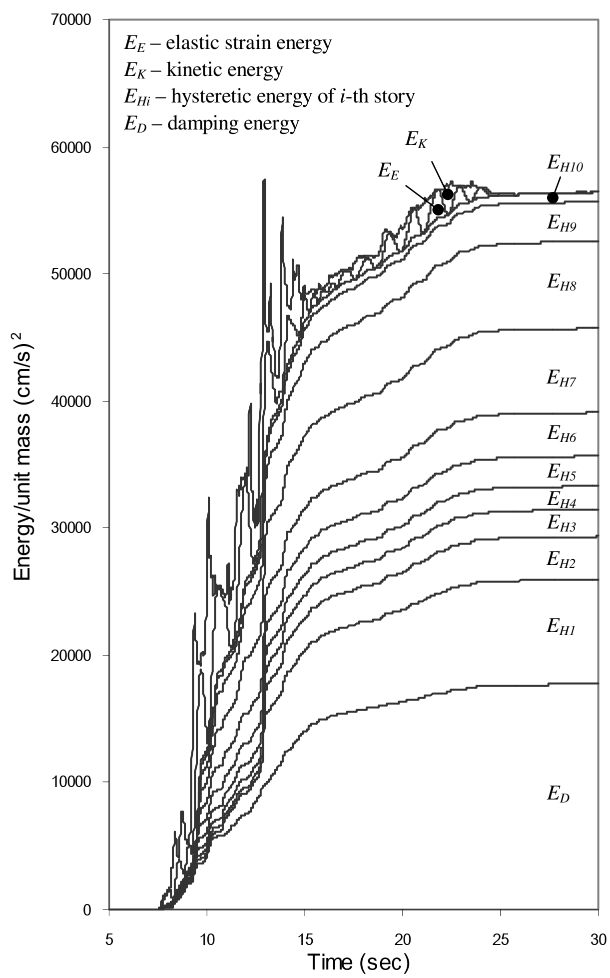


Fig. 11 Energy time histories – FUKI, C_{bc} = 0.120, β = 0.15.

The hysteretic energy indicated by E_{Hi} for the i-th story is representative of the combined effect of maximum deformation occurring in both directions and the number of load cycles which contributes to the cumulative fatigue damage. This energy quantity therefore also includes the effect of strong motion duration. From the time history of inelastic energy demand, the change in the response behavior along the building height including the trend in the collapsing story just examined can be clearly understood.

CONCLUSIONS

Nonlinear dynamic analysis was performed for five and ten-story MDOF systems where the story collapse was assessed by means of Park and Ang damage index. A parametric study was carried out to characterize the effect of different levels of hysteretic energy dissipation demand (or capacity) as denoted by parameter β to the seismic damage in reinforced concrete buildings. In the analysis, the base shear yield strength was gradually decreased until one of the stories came to collapse. This strength level expressed in terms of acceleration due to gravity was referred to as the collapse base shear coefficient C_{bc}.

Due to the nature of the objectives of this study, the structural model employed was the MDOF system which may be regarded as being representative of structures having strong beam-weak column connections. With this limitation in mind, the following conclusions are drawn from this study:

1. The increase in the collapse base shear coefficient per incremental increase in parameter β for short-period buildings is higher compared to longer period buildings. This trend is consistent with the trend of decreasing strength demand with increasing natural period as what may be normally observed in typical response spectra of SDOF systems.

2. The collapse base shear coefficient for a specific value of β depends on the characteristics of earthquake ground motion.

3. The collapse usually happens at the first story with few instances of collapse in the upper stories which may be attributed to higher mode effects and damage concentration due to formation of plastic hinges.

4. In extremely rare case, a change in the collapsing story may happen depending on the level of hysteretic energy dissipation capacity characterized by the parameter β resulting to different strength demands C_{bc}. The structure may then behave in a rather different manner based on these different levels of collapse capacity as can be seen in the time histories of deformation and energy demands.

5. Simple measures of maximum ductility demand may not fully capture the effect of cyclic loading since it fails to account for the increased dissipated hysteretic energy when high inelastic excursions happen in both loading directions. Moreover, it fails to account for the cumulative damage that occurs during cyclic deformation, which even at levels below the maximum response can still cause significant fatigue damage. A damage index that combines the effect of maximum deformation and cumulative hysteretic energy will therefore give a more appropriate assessment of seismic damage.

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