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SEISMIC DAMAGE ANALYSIS AND DESIGN OF REINFORCED CONCRETE BUILDINGS FOR TOLERABLE DAMAGE

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SUMMARY

A seismic damage model is developed for reinforced concrete structures in which the structural damage is expressed as a linear combination of the maximum deformation and the hysteretic energy dissipation. Based on an extensive damage analysis of various reinforced concrete buildings, a seismic intensity scale is also derived to describe the potential destructiveness of ground motion; it is a simple function of the rms acceleration and strong-motion duration. The proposed damage model is calibrated with observed building damages from past earthquakes. On this basis, a design procedure is developed for reinforced concrete buildings with an explicit tolerable level of structural damage.

INTRODUCTION

In the aseismic design of reinforced concrete structures, some level of damage would be expected and permitted against a moderate earthquake that can be expected over the life of a structure, whereas structural collapse should be prevented under a severe earthquake defined by a relatively long recurrence period. Clearly, in order to assure seismic safety and limit the potential damage of reinforced concrete buildings, the failure mechanism of structural systems under dynamic earthquake loadings needs to be delineated and incorporated in the development of aseismic design provisions. Under earthquake loadings, reinforced concrete structures are generally damaged by a combination of repeated stress reversals and high stress excursions. Accordingly, a seismic damage model is developed as a function of the maximum deformation and the effect of cyclic loadings.

The proposed damage model is calibrated with observed building damages from past earthquakes. On this basis, a detailed aseismic design procedure is developed to limit the potential damage to a tolerable level.

DAMAGE ANALYSIS

Damage Index Consistent with the behavior of reinforced concrete described above, seismic structural damage is expressed as a linear combination of the damage caused by excessive deformation and that contributed by repeated oscillations. This may be expressed in terms of a "damage index."

$$D = \frac{\delta_m}{\delta_u} + \frac{\beta}{Q_y \delta_u} \int dE \tag{1}$$

in which values of damage index, D, are such that $D \geq 1.0$ signifies collapse or total damage; δ_m = the maximum response deformation; δ_u = the ultimate deformation under monotonic loading; Q_y = yield strength; $\int dE$ = dissipated hysteretic energy; and β = a non-negative constant. Structural damage, therefore, is a function of the responses δ_m and $\int dE$, that are dependent on the loading history, and the parameters δ_u, β, and Q_y, that specify the structural capacity. Based on an analysis of a large number of reinforced concrete components, the scatter of the ultimate value of D was observed to have a mean value of 1.0 and a c.o.v. of 0.50 (for details, see Ref. 1).

In addition to the member and story-level damage measures defined by Eq. 1, an indicator for assessing the overall damage sustained by a building is also needed. Such an indicator should reflect the damage concentration in the weakest part of a building, e.g., the first story or top story as frequently observed, as well as the distributed damage throughout the building such as in a weak-beam-type building. It is well recognized that the damage distribution is closely correlated with the absorbed energy distribution (Ref. 2). Therefore, the overall damage may be expressed as the sum of the damage indices of each story, D_i, weighted by the corresponding energy contribution factor λ_i, namely,

$$D_T = \sum_i \lambda_i D_i \tag{2}$$

where, $\lambda_i = E_i / \sum E_i$; in which E_i is the total absorbed energy (including the potential energy of the ith story.

A random vibration method for hysteretic systems (Ref. 3) is used to obtain the response parameters, i.e., δ_m and $\int dE$ in Eq. 1. The earthquake excitation is modeled as a filtered shot noise process described by the Kanai-Tajimi spectrum having a time varying envelope function.

<u>Ground Motion Parameters</u> Based on the analyses of columns under seismic excitations with various combinations of intensity and duration, the following "characteristic intensity" was found to be appropriate for representing the damage potential of ground motion:

$$I_c = A_{rms}^{1.5}\, t_o^{0.5} \tag{3}$$

where: A_{rms} = the rms ground acceleration; and
t_o = the strong-motion duration.

A linear relationship is also observed between the damage of MDF reinforced concrete buildings and the intensity I_c. All the buildings have three bays and consist of three-story frames, including a typical weak-column-type frame, a weak-beam-type frame, and a "rocking-shear-wall" type design. The linear relationship between I_c and $\overline{D}$ appears to hold for both story-level and overall damage indices. Details are given in Ref. 1.

Calibration of Damage Index In developing a rational design criterion, the tolerable damage state as well as the ultimate damage state (i.e., building collapse) should be identified. For this purpose, the proposed damage index is calibrated with respect to the observed damage of nine reinforced concrete buildings that were moderately or severely damaged during the 1971 San Fernando and the 1978 Miyagiken-Oki earthquakes. The buildings are listed in Table 1 with the observed seismic damage descriptions. The building details and results of extensive damage inspection of these buildings are available in the U. S. Department of Commerce (Ref. 4) (building A) and the Architectural Institute of Japan (Ref. 5) (buildings B to I). Table 1 also gives the calculated overall damage indices D_T and the corresponding ground motion intensity in terms of I_c. The same results are also summarized in Fig. 1, which are used as the basis for calibrating the damage index D. In light of the above calibration results, structures with an overall damage index of $D_T \leq 0.4$ may be considered to be reparable, whereas buildings with $D_T > 0.4$ represent damage beyond repair, and $D_T \geq 1.0$ represents total collapse.

Table 1 List of Damaged Buildings

Name of Building	Number of Stories	Observed Damage	Ground Motion I_c	Damage Index D_T
A. Olive View Hospital	6	Collapse*	0.31	1.47
B. Taiyo Gyogyo Building	3	Collapse*	0.23	1.05
C. Tohoku Togyo University	4	Moderate*	0.12	0.48
D. Saigo School	2	Minor	0.19	0.22
E. Tonan High School	3	Moderate*	0.19	0.39
F. Kinoshita Menko Building	3	Severe*	0.23	0.85
G. Obisan Office Building	3	Collapse*	0.23	1.25
H. Fukushi Kaikan Building	2	Very Minor	0.12	0.02
I. Izumi High School	3	Minor	0.23	0.27

*Subsequently demolished

DAMAGE-LIMITING DESIGN

Design Procedure From the above calibration results, an overall damage level of $D_T = 0.4$ is suggested as the tolerable level of damage for reinforced concrete buildings. A damage-limiting aseismic design procedure has been developed to achieve a uniform damage of D = 0.4 by properly selecting both the strength and ductility of the structural members.

In the proposed procedure, the base shear coefficient, C_B, is regarded as a design variable. Following the strength specification, the degree of structural ductility (necessary to limit damage at D = 0.4) is determined according to the selected value of C_B and the design earthquake intensity.

For weak-column-type buildings, the following linear lateral force distribution is used (following the UBC Code);

$$F_i = C_B W \frac{w_i h_i}{\sum_j w_j h_j} \tag{4}$$

in which, F_i = lateral force at the ith floor; C_B = selected base shear coefficient; W = total weight of the building; h_i = height of the ith floor from the base; and w_i = weight of the ith floor.

In the case of weak-beam-type buildings, the strength requirement may be applied to the whole building rather than to each story. Thus,

$$\sum M_i = h_e C_B W \tag{5}$$

where,

$$h_e = \frac{\sum w_i h^2{}_i}{\sum w_i h_i} \tag{6}$$

in which, M_i = yield moment of the hinged component; and h_e = equivalent height of building.

The above design is then verified for ductility requirements (Ref. 1). These requirements are related explicitly to the tolerable damage of D=0.4.

Design Examples Four three-bay reinforced concrete frames are designed according to the proposed procedure. Designs obtained with the proposed procedure are then evaluated through damage analyses. The dimensions of the frames are shown in Fig. 2. Frames A and B are weak-column-type frames, whereas Frames A′ and B′ are weak-beam-type structures. All the frames have a uniform story weight of 420 kips and uniform story height of 12 feet. A design seismic load of characteristic intensity I_c = 0.15 is assumed for all the frames, which corresponds approximately to a peak acceleration of 0.4g (for California earthquakes). The predominant period of the ground motion is assumed to be T_G = 0.4 sec. (hard soil condition). Nominal concrete strength of f'_c = 3 ksi and reinforcing steel strength of f_y = 50 ksi are prescribed. The major design parameters are listed in Table 2.

Table 2 Design Parameters for Frames

	A	B	A′	B′
Base Shear, C_B	0.3	0.4	0.12	0.1
Natural Period, T (sec.)	0.35	0.49	1.24	1.93
Ductility Index, R_d (%)	0.77	0.57	3.53	3.03

Damage analyses were performed assuming two values of the strong motion duration, t_o = 5 sec. and t_o = 15 sec. The corresponding values of the rms acceleration are 0.165g and 0.114g, respectively. The calculated story drifts (as a fraction of the interstory height) and damage indices are shown in Fig. 3. The design criterion of $\bar{D} \leq 0.4$ is satisfied reasonably well for both the weak-column-type frames (A and B) and weak-beam-type frames (A′ and B′).

The applicability of the proposed procedure should be limited to buildings with less than seven stories. For highrise buildings, e.g., higher than ten stories, the deviation of the story damage from the tolerable damage level of D = 0.4 may be unacceptably large; this may be attributed to the contribution of the higher modes to the building response.

SUMMARY AND CONCLUSIONS

A damage-limiting design procedure is proposed for reinforced concrete buildings. The tolerable damage state has been specified at $D \leq 0.4$ based on the damage analyses of nine reinforced concrete buildings damaged during past earthquakes. Accordingly, a design procedure has been developed to limit the potential damage at $D = 0.4$ by properly selecting both the strength and ductility of the structural members. The applicability of the proposed method to buildings up to seven stories was illustrated and verified to have $D \leq 0.4$. Also, a near uniform damage distribution with the target value of $\bar{D} = 0.4$ is achieved.

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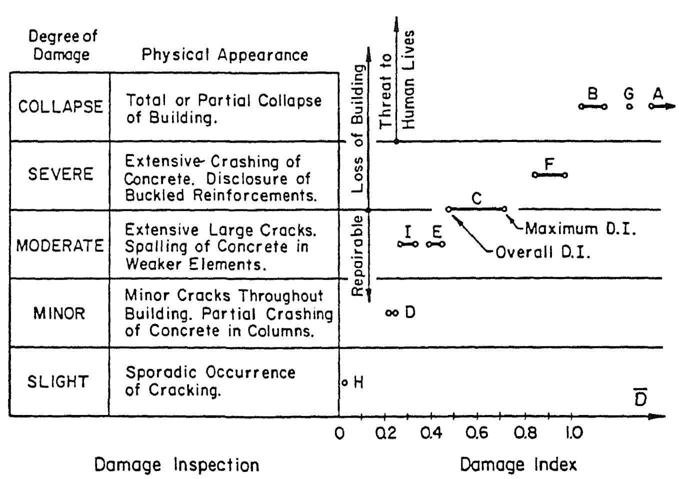

Fig. 1 Comparison of Calculated Damage Index with Damage Inspection

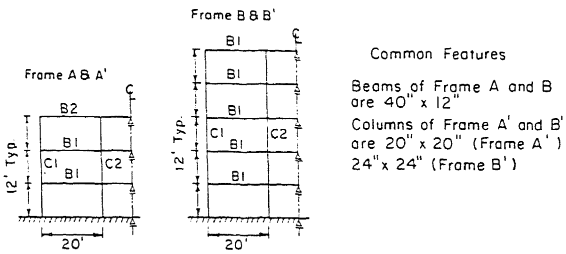

Fig. 2 Details of Frames

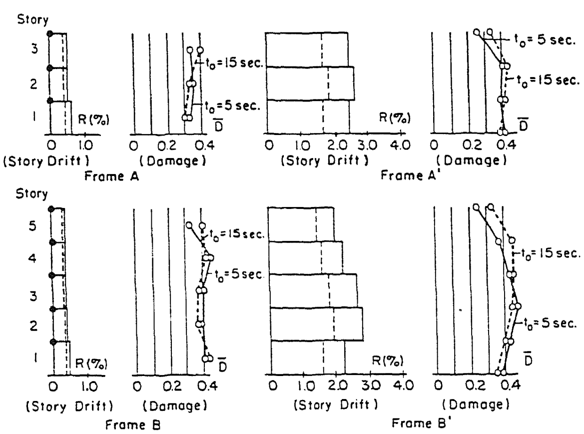

Fig. 3 Story Drift and Damage Index of Designed Frames