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LIFE CYCLE ANALYSIS IN THE SEISMIC DESIGN AND MAINTENANCE POLICIES OF BUILDINGS WITH HYSTERETIC ENERGY DISSIPATORS

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SUMMARY

An approach is presented for the establishment of seismic design criteria and maintenance policies for structural systems with energy-dissipating devices. The formulation is presented under a life-cycle framework, which permits to account for the process of damage accumulation and for the resulting evolution of the mechanical properties of the systems studied. The methods proposed are illustrated through their application to several case studies. Some conclusions are reached about the variables affecting the conditions of useful applicability of the systems studied in practical cases.

INTRODUCTION

According to the performance-based seismic-design criteria, design requirements based on spectral accelerations or lateral force coefficients for given assumptions about over-strength ratios and available ductilities should be replaced by recommendations formulated in terms of more direct indicators of safety levels and expected damage, both in structural and in non-structural elements. Typical instances of such indicators are the ratios of deformation demand to deformation capacity, the low-cycle-fatigue indexes and the ratios of stiffness- and strength degradation; all of these at the local, story or global level. Acceptable values of these indicators may be arrived at through optimization studies intended to balance initial investments with expected present values of potential future costs. This sets the basis for the life-cycle approach to earthquake-resistant design and maintenance policies. According to this approach, the arrangement of the structural frame, the mechanical properties of each of its elements, the characteristics of non-structural elements and their connections to the structural system are chosen having in mind possible sequences of seismic events, damage patterns and repair and maintenance actions.

The influence of EDD's on structural response, damage accumulation and long-term reliability depends on a number of variables related to the relative contributions of those elements and of the structural members to the lateral stiffnesses and strengths of a combined system. It depends as well on the policies adopted for repair of the SM's and of replacement of the EDD's. It is assumed that, according to those policies, repair and replacement actions depend on the levels of damage accumulated as a consequence of previous earthquakes.

Presenting criteria and tools for optimum decision-making (design, construction and maintenance) in problems of the type described in the foregoing paragraph, and illustrating their application to specific cases are the objectives of this study. Thus, the article starts by establishing the proposed life- describe the complex stochastic process of earthquake occurrences, system responses and damage accumulation cycle optimization framework, identifying the relevant variables. Then, a probabilistic model is presented to, accompanied by the corresponding repair and maintenance actions. Reference is made to a previously proposed equivalence criterion to approximately represent multistory building-frames with EDD's by single-story systems, for the purpose of obtaining estimates of the influence of those devices on the response of the combined structures. The single-story systems are then applied to estimate damage accumulation functions of the detailed systems to be optimized. Finally, the use of the concepts and tools developed is exemplified by applying them to a number of specific case

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studies. The results of this analysis are discussed, and their possible implications on recommend practical criteria are identified.

The applicability of several concepts and models presented in the following is restricted to the case of hysteretic EDD's. However the general formulation and the probabilistic tools developed are valid for more general conditions.

OPTIMIZATION FRAMEWORK

Consider a system to be built at a site where earthquakes of different intensities occur in time in accordance with a stochastic process of known form and parameters. Assume also that design requirements of the system are expressed in terms of a set of nonlinear pseudo-acceleration response spectra for different values of the global ductility index that can be developed by the combined system of structural members and EDD's. This index is determined by the distribution, along the height of the structure, of the relative contributions of both types of elements to the lateral story stiffnesses and strengths of the combined system.

When an earthquake of sufficiently high intensity occurs, elements of both types may undergo significant damage. At each location, a damage increment takes place, which is a function of the number of deformation cycles and of the frequency distribution of their amplitudes, as well as of the local residual damage when the earthquake starts. Repair actions on the frame members and preventive-replacement measures on the EDD's are undertaken whenever empirical evidence or theoretical assessment lead to consider that current damage levels at individual elements or portions of the system may have reached critical acceptance thresholds.

Let C be the initial cost of a system of interest, T_i , i = 1, ..., ∞ the (random) times of occurrence of earthquakes that may affect it, and L_i , i = ,..., ∞ the losses associated with those earthquakes; they include damage and failure consequences as well as repair and maintenance actions. The following objective function must be minimized:

$$U = C + E\left[\sum_{i=1}^{\infty} L_i\, e^{-\gamma T_i}\right] \qquad [1]$$

Here, E stands for expected value and γ is an adequate discount rate.

DAMAGE ACCUMULATION

a) Conventional frame members

The mechanical behavior of the structural members subjected to alternating-sign deformation cycles is represented by constitutive force-deformation functions as shown in Figure 1. The model [Esteva, Díaz and García, 1998] considers that both local strengths and stiffnesses in each loading direction deteriorate gradually, as functions of the damage accumulated in that direction. The model is defined by six parameters: F_y, K_1, K_2, X_F, a and η. The first three are respectively the yield strength and the tangent stiffnesses before and after yielding; they determine the force-deformation envelope curve. X_F is the deformation associated with the peak value of the load, while a and η take into account the effect of the cyclic fatigue.

According to the model proposed

$$\beta = a\sum_{t=1}^{N}\frac{X_i}{X_F} \qquad [2]$$

and

$$D = 1.0 - \exp(-\gamma\beta) \qquad [3]$$

are the low-cycle-fatigue index and the damage index, respectively, which measure the degradation of the internal force corresponding to the maximum deformation amplitude reached during previous loading cycles

(See Figure 1). X_i is the deformation-amplitude in the direction of interest during the i-th cycle and N is the number of cycles. These functions are used here to represent the degrading hysteretic behaviour of plastic hinges at critical sections of flexural members. On the basis of experimental evidence given by Wang and Shah [1987], a was taken equal to unity, and η equal to 0.602. Esteva and Díaz [1993] present a description of the modified model.

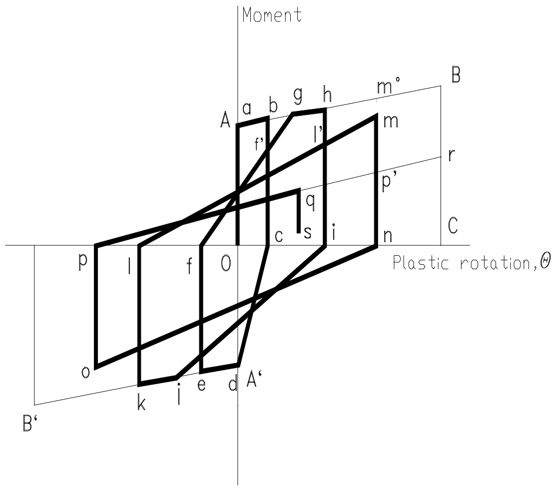

Fig.1 Stiffness-degrading functions for plastic-hinge rotation

b) Energy dissipating devices

A bilinear model with stable hysteresis loops for a large number of cycles is used to represent the cyclic behavior of energy-dissipating devices. The form and the parameters of the model adopted here are consistent with the laboratory tests performed on assemblages of U-shaped devices developed by Aguirre and Sánchez [1992]. An expression of the form given by Equation 4 was fitted to their results:

$$N_F(x) = \exp(px^{-r} - q) \quad [4]$$

Here, $N_F(x)$ is the number of cycles to failure under a sequence of cycles with a constant amplitude equal to x(cm); p = 128, r = 0.02 and q = 121.

c) Global damage

For the purposes of reliability analysis of a multistory building, the combined influence of the damage experienced at the local level by the members of the conventional frame and by the EDD´s must be expressed by an adequate indicator of the global damage experienced by the system. In this article, the structural systems studied were represented by means of simplified single-story models. Therefore, the state of damage in each system was described by its corresponding global damage index, D (Eq. 3).

DAMAGE ACCUMULATION UNDER RANDOM EARTHQUAKE OCCURRENCES

For simplicity, the discussion that follows refers to a single-story system with one EDD.

Just after the occurrence of the j-th earthquake, the damage accumulated on the EDD equals D_{dj}, while that affecting the structural frame is equal to D_{fj}. After the (j+1)-th event, these values become respectively $D_{d(j+1)} = D_{dj} + \delta_{d(j+1)}$ and $D_{f(j+1)} = D_{fj} + \delta_{f(j+1)}$, where $\delta_{d(j+1)}$ and $\delta_{f(j+1)}$ are the corresponding damage increments.

If D_{fj} exceeds a given threshold, designated here as D_{rf}, the frame is repaired in such a manner as to eliminate the damage accumulated, thus restoring its initial strength and stiffness, R_f and K_f. It is assumed that the damage level on the frame can be assessed on the basis of the evidence of physical deterioration, while that on the EDD's is inferred from the estimated value of the low-cycle-fatigue index. This information is used to implement the preventive strategy of replacing the EDD after the occurrence of a number of high-intensity earthquakes, on the basis of a threshold value Drd, to be defined later.

Whether the process of occurrence of earthquake ground motions with different characteristics considers some kind of correlation with previous history or ignores it, the levels of damage accumulated D_{fj} and D_{dj}, $j = 1, ..., \infty$, at the end of the j-th earthquake occur as events of a Markov process. The transition probabilities from (D_{fj}, D_{dj}) to ($D_{f(j+1)}$, $D_{d(j+1)}$) are obtained from the probability density functions of $\delta_{f(j+1)}$ and $\delta d_{(j+1)}$, which depend on D_{fj}, D_{dj} and on the probability density function of Y_{j+1}, the intensity of the (j+1)-th event.

In order to determine the conditional probability density functions of $D_{f(j+1)}$ and $D_{d(j+1)}$, given the values corresponding to the end of the j-th earthquake, it is necessary both, to calculate the joint probability density function of the waiting time to the (j+1)-th earthquake and its intensity, and to determine the damage states D'_{fi} and D'_{di} of the system's components after carrying out the operations of repairing the conventional frame members and/or replacing the EDD's. The conditional probability functions obtained in this manner are integrated recursively in order to obtain the marginal probability distributions of all D_{fj} and D_{dj}. Details are presented by Esteva and Díaz [1993].

Due to the amount of computational work needed to perform the recursive integrations mentioned in the foregoing paragraph we opt to use a Monte Carlo simulation approach. This consists in developing at the outset a set of damage accumulation functions for different alternatives regarding the mechanical properties of the structural system of interest. The damage accumulation function is described in terms of the form and parameters of the conditional probability density function of the damage index at the end of an earthquake, as a function of its initial value and the intensity of that earthquake. If adequate simplifying assumptions about these forms are adopted, Monte Carlo simulations of the damage accumulation process for random earthquake intensity sequences can be performed directly from the damage accumulation function, instead of having to make a detailed simulation of structural response for each event.

SIMPLIFIED STRUCTURAL MODELS

For the purpose of dynamic-response calculations, the mechanical properties of the structural and energy-dissipating elements and the gravitational loads acting on the system were taken equal to their expected values. Once these values were derived on the basis of the nominal design parameters and the assumed statistical parameters and safety factors, an equivalent single-story model was assumed to represent the “real” system for the purpose of performing a life-cycle optimization analysis.

Díaz-López and Esteva [1991] present an equivalence criterion to determine the properties of simplified one-bay single-story frame systems used as references to estimate the responses of “real” multistory frame-buildings. The criterion assumes that the mechanical properties of both the real systems and their simplified models are imperfectly known. The means and variances of the mechanical properties of the simplified model are derived from those of the detailed model of the system. The equivalence criterion aims at preserving the most important global properties of the “real” systems; namely, natural period, lateral strength and stiffness, and degradation function similar to that given by Equations 2 and 3.

CASE STUDIES

The concepts presented above were applied to the optimization analysis of three reinforced concrete buildings: five, ten and fifteen-story high, respectively (Figure 2). It is assumed that they are intended for construction on soft soil sites in the valley of Mexico, where local soil conditions are similar to those of the recording site of the accelerogram SCT850919EW, which will be used to define the seismic excitations considered in the analysis that follows.

The seismic excitations considered were characterized by evolutionary intensity and frequency content functions similar to those of the SCT record mentioned above. The seismic hazard at the building sites was expressed by means of the rates of exceedance of ground motion intensities, y; the latter are measured by the maximum ordinate of the linear pseudo-acceleration response spectrum for damping equal to 0.05 of critical. From previous studies, the rate of exceedance was obtained as $\nu(y) = 30 \exp(-y^{0.32})$, where y is expressed in units of cm/s^2.

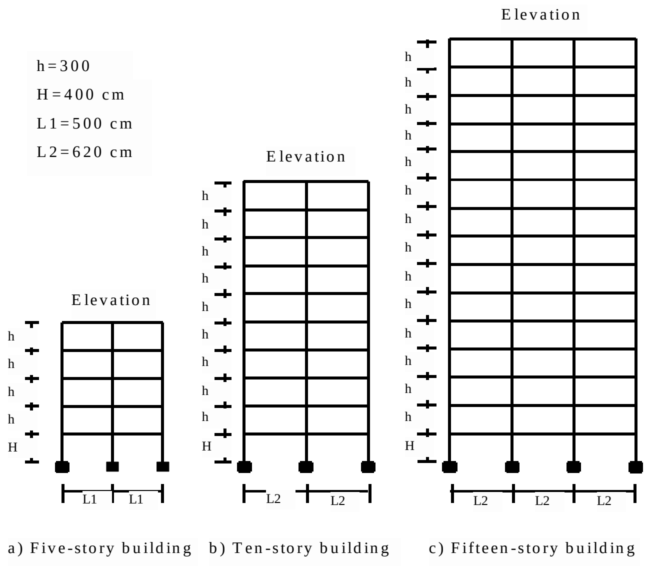

Fig. 2 Systems studied

The behavior of the reinforced concrete members was represented by the model described before. According to the comments presented by Esteva et al [1998], the predicted values of the stiffness and strength degradation of those members are excessively large, thus leading to excessively large responses and damage levels. The case studies are presented, however, because of the value of the qualitative conclusions extracted from the results.

According to previous studies the initial construction cost of the frame system, C, is related to the nominal value of the seismic design coefficient (base-shear ratio), c, in accordance with the equation $C = C_0 (1 + 0.14 N c^{1.4})^{0.4}$, where N is the number of stories and C_0 is the value of C for c = 0. The cost of installing an energy-dissipating device of the type proposed by Aguirre and Sánchez [1992] is equal to $1.306 P^{0.68}$, where P is the lateral yield strength in Newtons and the cost is expressed in 1997 US dollars. The repair-cost of the structural and non-structural elements at a given story were assumed to vary linearly with the global damage index. Costs associated with loss of income or impairment of functionality during repair works were not included in the evaluation of the utility function U (Equation 1).

DAMAGE FUNCTIONS

The Monte Carlo approach was used to obtain the damage functions. A typical set of cumulative damage functions is displayed in Figure 3, corresponding to the single-story model for a 10-story building. The graphs at the left represent expected values of the final damage index on the conventional frame, D_{fc}, while those at the right show values of the parameter α of a beta probability density function associated with that damage index. This parameter is related to the first two moments of the distribution as follows:

$$\alpha = \left(1 - \frac{\overline{D}_{fc} - D_{ic}}{1 - D_{ic}}\right)\left(\frac{(\overline{D}_{fc} - D_{ic})(1 - \overline{D}_{fc})}{\sigma^2_{D_{fc}}} - 1\right) \quad [5]$$

Here, $\overline{D}_{fc}$ and $\sigma_{D_{fc}}$ are respectively the mean and standard deviation of D_{fc}.

The relative contributions, r_R and r_K, of the energy-dissipating elements to the lateral strength and stiffness at each story are both equal to 0.75 of the values corresponding to the combined system. The curves at the left are represented as functions of the initial damage, D_{ic}, on the conventional frame for different values of the ratio y/y_m, where y is the earthquake intensity as defined above and ym is the intensity of the SCT850919EW record. The curves at the right are represented as functions of y/y_m for different values of D_{ic}. Each pair of sets of curves corresponds to a given value of D_{id}, the initial damage on the energy-dissipating system.

Empirical functions for the expected values and coefficients of variation of the accumulated damage are shown by the smooth curves presented in Fig. 6 The corresponding mathematical expressions have been given by Esteva, Díaz and García [1998].

OPTIMIZATION ANALYSIS

The design and maintenance variables considered in the optimization analysis were the seismic design coefficient and the pre-established threshold values of the story damage levels whose exceedance would lead to repair and/or replacement actions. These threshold values are D_{rc} and D_{rd} for the elements of the conventional frame and of the energy-dissipating system, respectively. The values of r_R and r_K were fixed at 0.75.

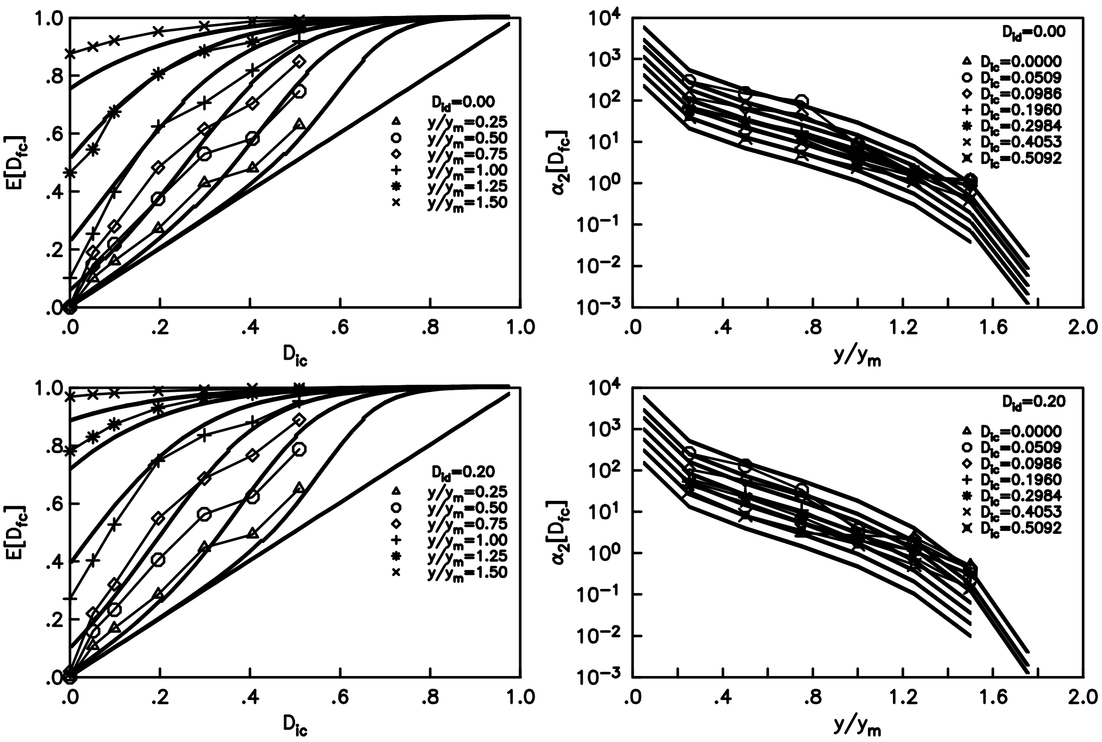

Fig. 3 Cumulative damage functions for simplified model of ten-story building

For each combination of the free variables (the seismic design coefficient c and the threshold values D_{rc} and D_{rd}), an estimate is obtained of the negative utility U, given by Equation 1. The estimate is obtained by Monte Carlo simulation.

The estimation starts by simulating a number of seismic histories, each consisting of the times of occurrence and the intensities of the corresponding events. Damage levels on the conventional frame members and the energy-dissipating devices at the end of each event are obtained by Monte Carlo simulation, taking into account the intensity of the ground motion and the damage levels on both groups of elements at the beginning of the ground motion. Repair or replacement actions are taken, if adequate, after comparing the resulting damage levels with the pre-established threshold values. The initial conditions for the next earthquake to occur are determined. The corresponding costs are then obtained and used to calculate the value of the corresponding term inside the parenthesis in Equation 1. After doing this for a sufficiently large sample of seismic histories, the expected value in that equation can be obtained.

The results of applying the procedure described above to the ten-story building are summarized in Figure 4. This figure is divided into four segments: the first from the left corresponds to the case of a building without an energy-dissipating system; the other three consider buildings that contain such a system. Each of these segments corresponds to a value of the damage-threshold level adopted for the replacement of the elements of that system. Three different seismic design coefficients are considered: 0.05, 0.10 and 0.15. From the results shown in this figure and from those corresponding to the five- and fifteen- story buildings, not shown here, it is found that the normalized utility values range from about 1.013 to 1.61, while they grow systematically with the number of stories. In general, they are significantly more sensitive to the seismic design coefficient than to the repair and replacement policy.

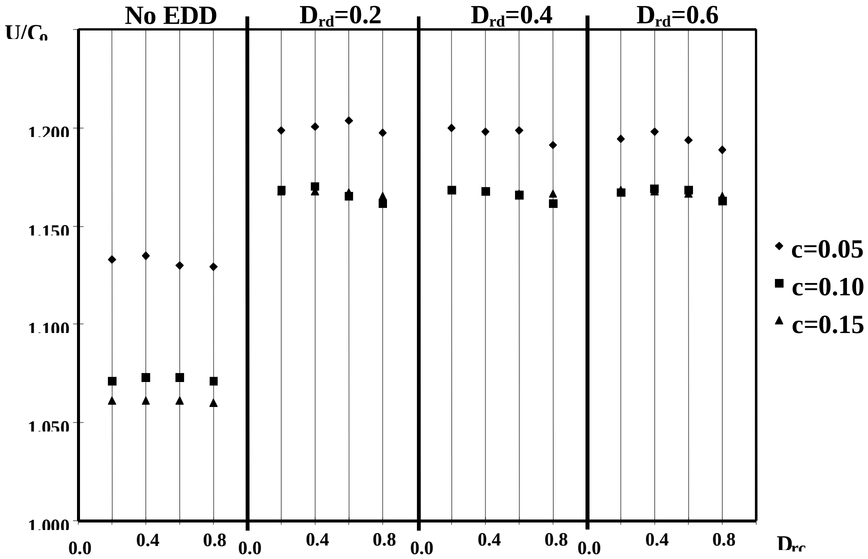

Fig. 4 Utility values for 10-story systems

A comparison of the values of the control variables leading to optimum values of the utility function is summarized in Table 1. Cases A and B correspond to the conventional frame building and to the system with energy-dissipating devices, respectively; N is the number of stories, and the other variables were defined above. For five-story systems the optimum solution corresponds to case B, with c = 0.10, D_{rc} = 0.8 and D_{rd} = 0.6. For N = 10 and N = 15, the optimum conditions correspond to case A, with c = 0.15 and D_{rc} equal to 0.8 and 0.2, respectively. In the last two cases, the negative utilities associated with case B systems were respectively 10 and 18 percent greater for the ten- and fifteen-story buildings than for the corresponding case A systems. These differences are smaller than those appearing between the initial costs of the corresponding systems. This means that, for the cases considered in the study, the use of energy-dissipating devices led to reductions in the expected costs of damage, but that these reductions were smaller than the additional costs arising from the use of those devices.

Table 1. Comparison of optimum utilities and control variables

N	Case	U	c	D_{rc}	D_{rd}
5	A	1.0135	0.15	0.8	-
	B	1.0116	0.10	0.8	0.6
10	A	1.0602	0.15	0.8	-
	B	1.1613	0.10	0.8	0.4
15	A	1.1018	0.15	0.2	-
	B	1.2887	0.10	0.8	0.6

CONCLUSIONS

An approach to the establishment of optimum seismic design criteria and repair and maintenance policies for structural systems with energy-dissipating devices has been formulated under the framework of a life-cycle analysis. From the case studies presented, it is concluded that the life-cycle approach serves to decide about the convenience of using energy-dissipating devices in specific cases.

The conditions under which the use of those devices may be advantageous are strongly influenced by the costs of damage and maintenance actions.

These costs should include those of consequences such as loss of functionality or interruption of activities during the repair or replacement actions. Consequences of this type were not considered in the cases studied here.

For some of those cases the increments in initial cost associated with the use of energy-dissipating devices exceeded the benefits arising from the reductions in expected costs of damage, thus leading to the conclusion that the use of those devices may not be economically advantageous.

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