SEISMIC DESIGN CRITERIA FOR RETROFITTING OF BUILDINGS WITH HYSTERETIC ENERGY DISSIPATORS

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SUMMARY

An efficient iterative design method for retrofitting of buildings with hysteretic energy-dissipating devices (EDD's) is presented. Each iterative cycle is a two-step process. The first step makes use of a single-degree-of-freedom model of the system to be retrofitted. It serves to make a decision about the optimum values of the strength and the stiffness of the EDD's that will be added to the system. The decision is based on the values of the global displacement and ductility demands of that model when subjected to a series of ground motion time histories. In the second step, the contributions of the EDD's to the strength and the stiffness of the simplified model are transformed into the contribution of those elements to the strength and the stiffness at each story. An illustrative example is presented of the application of the method proposed to the retrofitting of a multistory building frame. The paper also includes some comments about the conditions that make the use of hysteretic energy-dissipating devices advantageous for retrofitting of buildings, in comparison with other alternatives, such as cross bracing.

INTRODUCTION

The use of energy-dissipating devices (EDD's) for the control of damage in buildings exposed to earthquake ground motion is becoming more frequent everyday. For this reason, significant efforts are being devoted to the development of new types of devices, as well as to the study of their influence on the dynamic response of the structural systems where they are installed. The final aim is to develop criteria and methods applicable to the practice of structural analysis and design that will lead to the optimum use of these devices, both for the construction of new structures and for the retrofitting of previously existing ones.

The criteria and methods mentioned above should be formulated under the framework of performance-based design. For systems with innovative devices (such as energy-dissipating and base-isolation devices) the basic principles, the variables to be used as performance indicators and the corresponding acceptance criteria must be clearly stated, in order to update design criteria in accordance with the increase in knowledge.

This paper starts with a bird's eye view of the decision to be made by a structural designer concerning the possible use of EDD's for the retrofitting of a building, or the alternative of using another type of reinforcing elements (cross braces, for instance). In the second part of the paper, a method for the retrofitting design of buildings is proposed, based on the step-by-step analysis of the response of a single-degree-of-freedom "equivalent system".

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ABOUT THE CONVENIENCE OF USING ENERGY-DISSIPATORS FOR STRUCTURAL RETROFITTING

An important function of EDD's is to contribute to increase the effective damping that can help a structural system to control its seismic dynamic response. An important property of these devices is their low sensitivity to damage accumulation and, therefore, to the processes of strength and stiffness degrading. In addition to augmenting the effective damping of a system, hysteretic EDD's contribute to increase both its strength and its stiffness.

Hysteretic EDD's have been applied to the retrofitting of several buildings in Mexico. ADAS- type devices were employed in three of them; friction devices were used in another case.

Decisions concerning the convenience of using EDD's for retrofitting purposes must be based on cost-benefit studies that account for both, the expected response and performance of the system and the economic expenditures to be made (repair and maintenance cost, etc).

The authors have made analyses of the structural response of several multi-story multi-bay structural frames. They included ten-, twenty- and thirty-three- story buildings with natural periods equal to 1.0, 2.0 and 3.0, respectively [Ruiz *et al*, 1995; Limon and Ruiz, 1997]. Two retrofitting alternatives were considered: cross braces and energy dissipating devices. The seismic excitation considered for design is represented by the EW component of the ground motion acceleration record obtained on soft soil at the SCT site in Mexico City during the 19 September 1985 earthquake (SCT850919EW). The pseudo-acceleration linear-response spectrum derived from the SCT record is shown in Fig.1. The results of those studies show that, for systems with natural periods equal to 1s and 3s, the use of hysteretic EDD's provided a better alternative than the use of cross braces. However, the opposite was observed for the system with natural period equal to 2s. The reason for this can be very easily grasped according to the paragraphs that follow.

The response of the system with initial fundamental period of 2s, strengthened reinforced with cross braces, was first determined. Its resulting fundamental period was equal to 1.33s, and its behavior was almost linear. It was also observed that, under the action of the ground acceleration time history mentioned above, the system developed a lateral force capacity corresponding to a base-shear ratio of 0.24. These values can be easily observed in Fig.1a.

A second alternative consisted in strengthening the building with EDD’s. For a global ductility demand μ equal to 2, the required base-shear capacity was equal to 0.22. The effective value of the fundamental period T lies between 1.33 and 2s (an approximate value of 1.5s is considered in the following paragraphs). According to Fig.2a, the ordinate of the nonlinear-response pseudo-acceleration spectrum for a damping ratio ζ of 0.05 is approximately equal to 0.22.

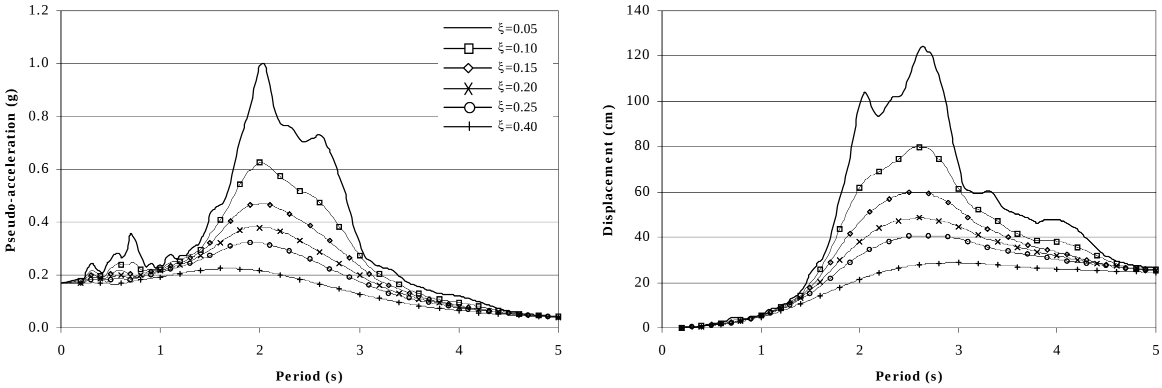
The results show similar values of the base-shear ratio (0.24 and 0.22) for the two retrofitting alternatives. However, the economic analysis performed was clearly in favor of the alternative based on the use of cross braces. On the other hand, it can be seen in Fig.1b that the displacements for a system with $T = 1.33$ and $\mu = 1$ are smaller than those corresponding to a structure with $1.33\text{s} < T < 2\text{s}$ and $\mu = 2$ (Fig.2b), both for $\zeta = 0.05$. This is consistent with the displacements obtained for the detailed multi-degree-of-freedom model of the system.

A similar analysis can be used to show that for the case of a building with a longer natural period ($T = 3$s), the base-shear forces produced on the frame with cross braces are larger than those that are generated on the structure strengthened with energy-dissipating elements. The end result is that the latter system responds with smaller overturning moments and, consequently, the foundation is subjected to smaller forces. This makes the use of EDD’s a better alternative in this case.

The foregoing paragraphs illustrate the fact that the use of energy-dissipating devices is not necessarily a convenient alternative, and that the decisions concerning the best choice must be based on both, the expected system performance and the long term costs of the complete system.

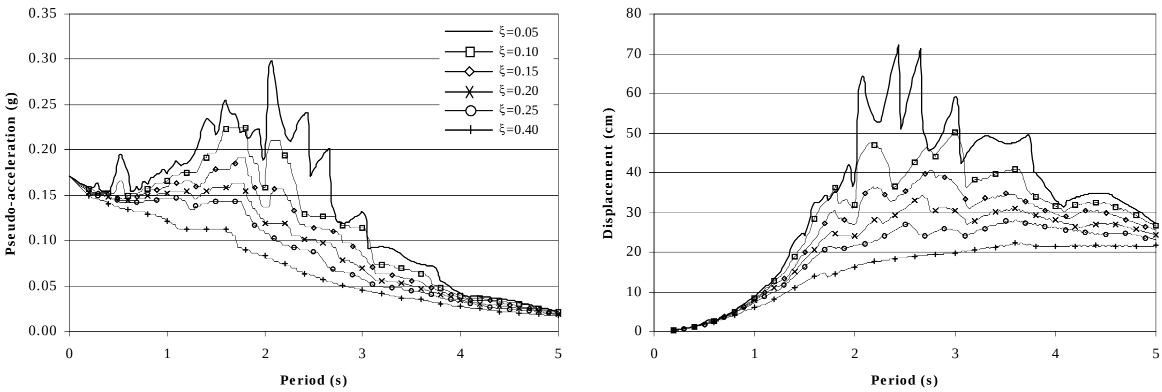
DESIGN CRITERIA

The detailed solution for the retrofitting of the three frames with EDD's mentioned above was reached following an iterative procedure. A criterion based on a capacity design spectrum was first applied, followed by a



a) Pseudo-acceleration spectra   b)Displacement spectra

Figure 1. Linear response spectra, record SCT850919EW



a) Pseudo-acceleration spectra   b)Displacement spectra

Figure 2. Elastoplastic response spectra for μ=2, record SCT850919EW

verification that the story drifts complied with the regulations contained in Mexico City Building Code. In addition, the peak values of the ductility demands on the EDD's were forced to be smaller than their expected capacities as determined in laboratory tests.

The computational effort required by the process described in the foregoing paragraph is excessive, unless it starts from a preliminary design that is sufficiently close to the final solution, which should satisfy an adequate optimization criterion. A more efficient approach, which is also iterative, is formulated in the following paragraphs. According to it, the system to be designed is represented by an "equivalent" single-degree-of-freedom (SDOF) system. Thus, the computational effort is significantly reduced with respect to that needed for dealing directly with a detailed multi-degree-of freedom (MDOF) model of the system.

The method proposed might be seen as an extension of methods already available in the literature for the design of conventional structural systems [Fajfar, 1998]. However, here a step-by-step analysis of structural response is applied to a SDOF model of a combined system formed by a combination of a strength- and stiffness-degrading conventional frame and a non-degrading element that represents the contribution of the EDD's. On the other hand, the performance indicators and acceptance criteria for a system with EDD's are not identical with those that apply to conventional structures.

PROBLEM FORMULATION

Suppose that it is necessary to raise the earthquake resistant capacity of a building in order to make it comply with the requirements specified in a given normative document. Suppose also that the local soil conditions and the expected characteristics (intensity, frequency content, duration) of the design earthquake are known. In the illustrative example presented here, soft soil conditions similar to those found in the downtown area of Mexico City will be considered.

The viable upgrading alternatives include both, the addition of hysteretic energy-dissipating elements and the reinforcement with cross braces. The application of the method described above led to the conclusion that the best alternative was provided by the use of EDD's.

PROPOSED METHOD OF ANALYSIS

For a typical frame of the system to be designed, the proposed method includes the following steps:

a) An equivalent SDOF model of the system to be retrofitted is determined (Fig. 3). In this case, the application of conventional "push-over" models is not considered to permit an adequate representation of the structural behavior of the conventional system subject to cyclic load excitation. Therefore, an improved method for the determination of the equivalent SDOF model is proposed, based on the application of a small number of cyclic deformations, simulating a typical pseudo-dynamic laboratory test with controlled displacements.

   The SDOF equivalent system representative of the conventional frame will be characterized by its mass M^*, as well as by the initial (undamaged) values K_c^* and R_c^* of its lateral stiffness and strength, respectively. The degradation of these properties for cyclic load excitation will be taken into account by the adoption of an adequate constitutive function for this SDOF system.

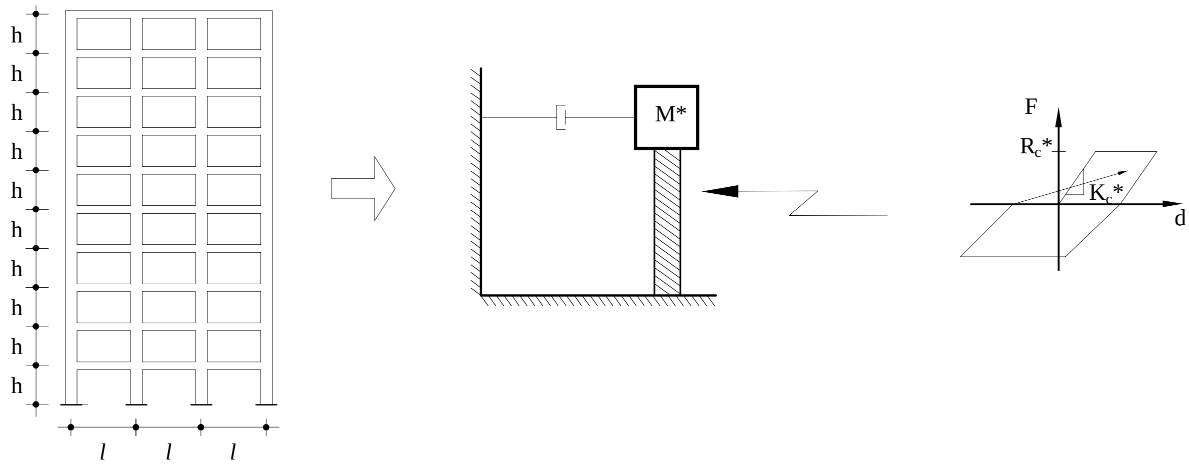


Figure 3. Equivalent system for frame to be retroffitted

b) An energy-dissipating element with lateral stiffness K_d and strength R_d will be added to the SDOF that represents the conventional system (Fig.4). The relations between the corresponding mechanical properties of the components of the combined system will be represented by the non-dimensional ratios $a_0 = K_d/K_c^*$ and $b_0 = R_d/R_c^*$. This element does not show any strength- or stiffness degradation.

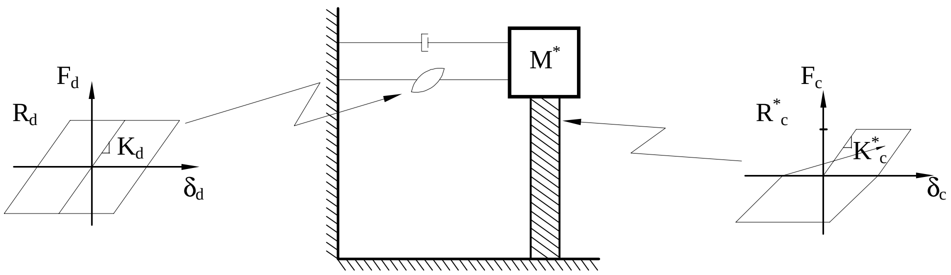


Figure 4. Equivalent system with energy-dissipating element

c) The resulting system is excited with a family of earthquakes with statistical properties similar to those of the design earthquake. The dynamic response is determined by means of a step-by-step analysis. The peak values of the following variables are of interest: 1) parameter that indicates the structural damage of the main frame (this could be: damage index (D_I), ductility demand of the system (μ), etc), 2) ductility demand on energy-dissipating element (μ_d), and 3) relative displacement corresponding to these values of the ductility demands (δ_μ).

d) A number of trial values of a_0 and b_0 are assumed. These values are related as follows:

$$a_0 = b_0(\delta_{yc} / \delta_{yd}) \quad [1]$$

In this equation, δ_{yc} and δ_{yd} are the yield deflections of the elements that represent the conventional frame and the energy dissipating systems, respectively. The ratio R_d/K_d is assumed to remain constant during the design process, because its value is determined by the dimensions of the components of the energy-dissipating system and by the mechanical properties of the materials with which they are built. In the particular case studied here, it was decided to select that ratio in such a manner that δ_{yc} = 0.9δ_{yd}. As a consequence, the choice of a value of a_0 determines that of b_0 (for our particular case a_0=0.9b_0). Therefore, the preliminary design of the system will be a function of only one independent parameter, that is, a_0. Each value of this parameter will determine a SDOF model of the combined system to be studied. The results of the step-by-step dynamic response analysis mentioned above can be represented by a graph similar to Fig.5. The vertical axis at the left of this figure shows values of the relative displacement δ_μ, while values of D_I or of μ, as well as μ_d can be read at the two vertical axes at the right. The scales in these two axes are proportional to each other, as well as to the left-side axis.

A value of a_0 is selected from Fig.5 in correspondence with each of the three allowable design values, δ_μ* (peak relative displacement), μ*(maximum system ductility demand for the combined system) or D_I* (prescribed damage index) and μ_d* (maximum ductility demand for the dissipating system). Because of the monotonic decreasing of these three variables with a_0, the design value of the latter is equal to the maximum corresponding to the three design conditions. The most efficient design, in the sense that it makes use of the full capacities of both systems, corresponds to the case when the three values of a_0 obtained by the procedure described above coincide.

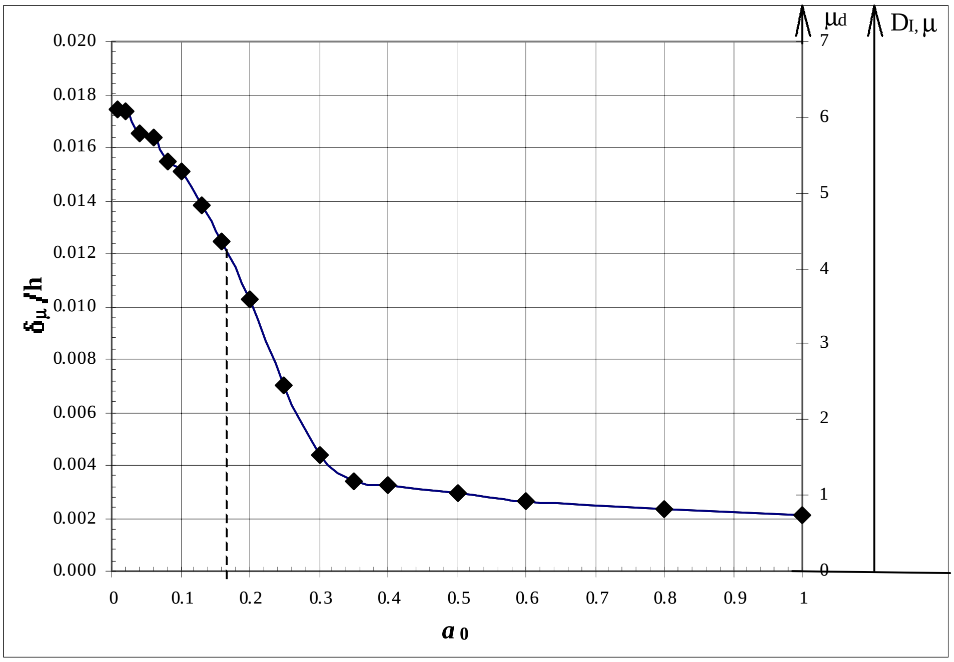


Figure 5. SDOF system response

e) Transform the results obtained by means of the SDOF system into those applicable to the MDOF detailed model. Now some decisions must be made about the spatial variations of the mechanical properties (story strength and stiffness) along the building height (H). In general, it will be convenient to assume that both variables decrease from the bottom to the top of the building. Several alternative forms of variation along the building height can be considered (Fig.6). This transformation may require of a few iterative cycles until a solution is found for which the response predicted with the aid of the SDOF model of the system represents with sufficient accuracy that associated with the detailed MDOF model (Fig.7). This is a subject of study at present at the Institute of Engineering of the National University of Mexico.

f) Verify for the MDOF system that the peak relative displacement, the maximum ductiliy demand for the dissipating system, and the structural damage of the main frame (which could be represented by plastic hinge rotations of the structural members) are within allowable values.

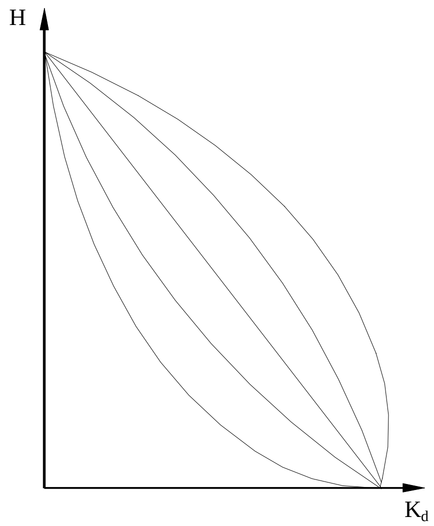


Figure 6. Possible forms of variation of the stiffness of the energy-dissipating system along the building height

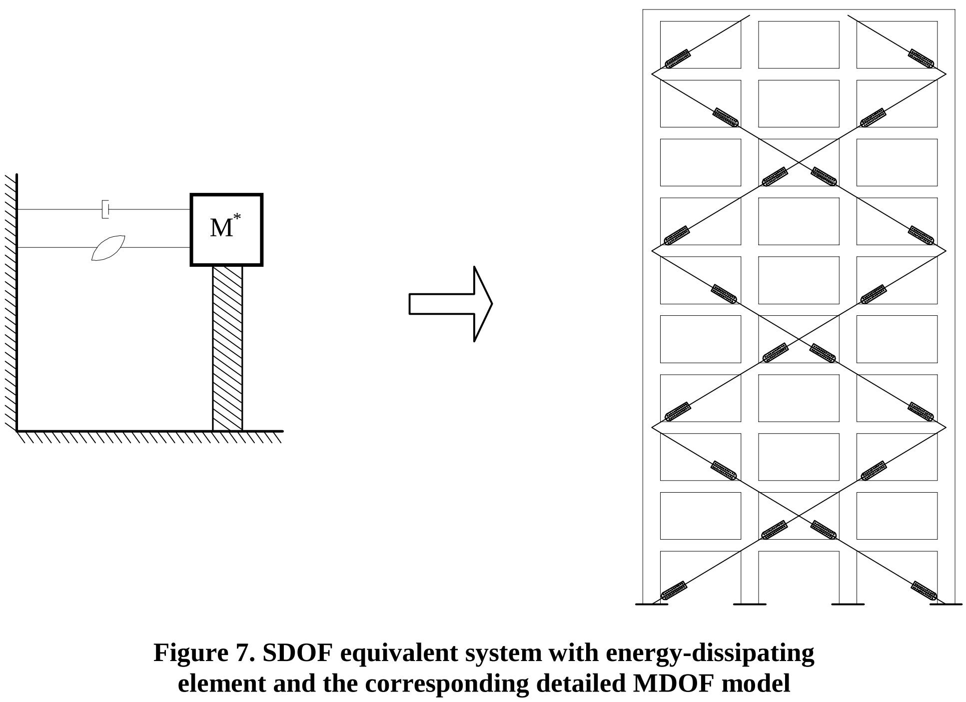


Figure 7. SDOF equivalent system with energy-dissipating element and the corresponding detailed MDOF model

ILLUSTRATIVE EXAMPLE

Suppose that the frame schematically shown in Fig.3 (h = 3m and l = 5m) must be retrofitted in accordance with a set of performance requirements related to its response to an earthquake ground motion characterized by a set of response spectra similar to that shown in Fig. 1 (SCT-850919EW). The main properties of the system, before retrofitting, are summarized in Table 1.

Table 1. Properties of the cross sections of the MDOF to be retrofitted

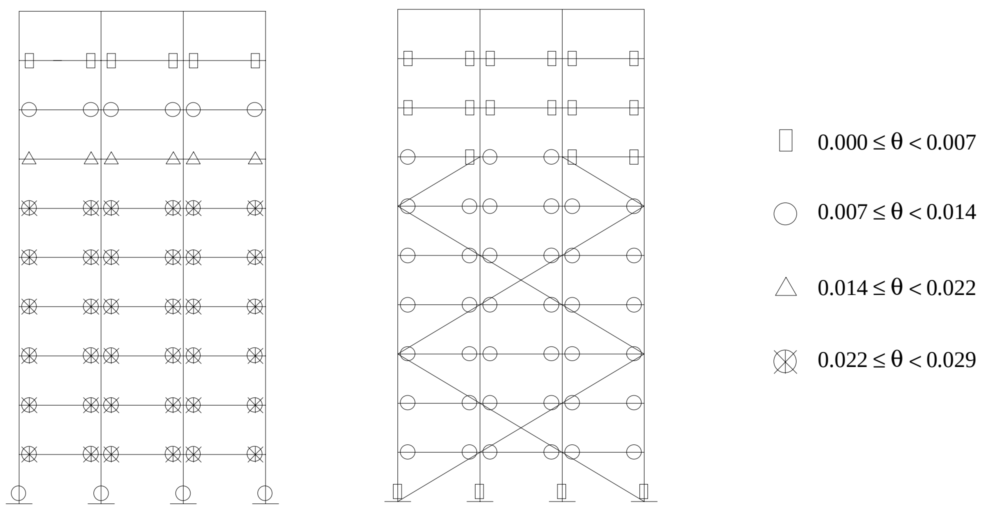
Story	Column section (cm)	Girder section (cm)
1 to 4	56×56	
5 and 6	54×54	
7 and 8	50×50	35×75
9 and 10	42×42	

The properties of the SDOF equivalent system for the frame to be retrofitted are K_c* = 1009.6 T/m, R_c* = 52.5 T, M* = 28.9 T-s^2/m, P* = 1.25 (scale factor for base motion), α = 0.1 and β = 0.4 [Badillo *et al*, 1998]. Here, α and β are the parameters of the extended version of Takeda's constitutive function and the other variables were defined previously.

For the purpose of facilitating the illustration, the excitation was represented by a single time history of ground acceleration. The history selected was that given by the SCT850919 record mentioned above. A plot of values of μ, μ_d andδ_μ, similar to that shown in Fig. 5, was prepared. From this plot it was concluded that the value of a_0 that leads to the best solution that complies with the specified performance requirements is equal to 0.17; that is, $K_d = 0.17K_c$*.

A tentative distribution of values of the story stiffness along the building height is determined on the basis of the results described in the preceding paragraph. In our case, the initial tentative solution consisted in placing eighteen energy-dissipating plate elements at the first story (nine at each diagonal), twelve at stories 2 to 5, ten at stories 6 and 7, and six at the two uppermost stories. The mechanical properties of each of those elements are its initial tangent stiffness K_d = 5681kg/cm and its yield deflection δ_{yd} = 0.366cm. The ratio of the post-yield stiffness to the initial tangent value is equal to 0.03.

Under the assumptions mentioned above, the story distortions obtained by means of a step-by-step dynamic response analysis were very small (ranging from about 0.007 at the bottom of the structure to 0.001 at the top). For this reason, a second assumption was made regarding the distribution of the number of energy-dissipating elements along the building height. The third tentative assumption led to the final design. This consisted in twelve elements at each of the fist two stories, ten at stories 3 and 4, eight at stories 5 and 6, and two at the seventh. No EDD's were required at the three uppermost stories. For the final design the maximum drift δ_μ was 0.011. It corresponded the third story. The accumulated plastic hinge rotations (θ) developed on the original frame and on the retrofitted structure are shown in Fig. 8.



a) MDOF system b)MDOF retrofitted system

Figure 8. Accumulated plastic hinge rotations developed on the frames

CONCLUSIONS

1. A general criterion was presented for deciding about the convenience of using hysteretic energy-dissipating devices or conventional cross braces for the retrofit of building frames exposed to narrow band earthquake ground motion.

2. A performance-based design method was proposed for the selection of the characteristics of the energy-dissipating devices used for the retrofit operations mentioned above. The method is based on an iterative procedure that starts from an approximate prediction of the story displacements and ductility demands. The prediction is achieved by means of a step-by-step dynamic response analysis for a SDOF equivalent system with constitutive functions that account for the degradation of stiffness and strength on the members of the conventional frame system. Three design requirements were established. The method was successfully applied to a ten-story three-bay reinforced concrete frame.

3. Additional efforts must be devoted to the study of the optimum distributions of energy-dissipating devices along the height of the systems where they are used. Closely related with this problem is that of developing efficient and reliable methods to transform the predicted responses of SDOF equivalent systems into those of more detailed models of the systems studied.

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