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Nonlinear seismic response of soft-first-storey buildings subjected to narrow-band accelerograms

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ABSTRACT: The nonlinear dynamic response of shear systems representative of buildings with excess stiffness and strength at all stories above the first one is studied. Variables covered were number of stories, fundamental period, along-height form of variation of story stiffness, ratio of post-yield to initial stiffness, in addition to the variable of primary interest: the factor r, expressing the ratio of the average value of the safety factor for lateral shear at the upper stories to the at the bottom story. It is concluded that the nonlinear seismic response of shear buildings whose upper stories have lateral strengths and stiffnesses which - correspond to safety factors larger than those applied to the first story is very sensitive to the relation between the average of the safety factors at the upper stories and that at the first one, as well as to the ratio of post-yield to initial stiffnesses.

1 INTRODUCTION

An important number of the buildings which suffered collapse or extreme damage during the Mexico City earthquake of September 19, 1985 belonged to the type herein designated as "soft-first-story" (SFS), characterized by a significantly lower intensity of infill walls (either designed as structural elements or not) in anyone of two orthogonal directions in the first story, as compared to that of the upper stories. As a consequence of this *irregular* distribution of diaphragms, the strengths of the stories above the first one are significantly greater than that of the latter, both in absolute terms and in proportion to that required to keep the response of the system within the linear range. The high rates of damage suffered by constructions of this type may be largely ascribed to the peculiarities of their nonlinear response and to the uncertainties tied to their prediction, enhanced as a result of the drastic variations of safety factors, but probably in many cases the high damage rates are also due to the plain fact that the first-story lateral strength was too low, regardless of its relation to the strengths of the stories above. On the other hand, the high proportion in which these constructions participate in the total number of cases of collapse or severe damage largely reflects the high percentage of these constructions as related to the total number of tall buildings in the city. The above comments point at the necessity of understanding a) the extent to which the behavior of SFS buildings may be more unfavorable than that of buildings with along-height uniform or slowly varying stiffnesses and safety factors, designed for the same seismic coefficients and spectra, and b) how the design criteria applicable to the former should be adjusted, in order to obtain safety levels comparable to those of the latter.

In some cases studied, the degree of irregularity of the system was represented by the ratio of the mean of the safety factors at the upper stories to its value at the first story, while in others the basic independent variable was the ratio of the strength increment applied to all the stories above the first one and the strength of the latter. Lateral stiffnesses were incremented in quantities proportional to the increments of strength. In all cases it was concluded that the sensitivity of the first story's lateral deformations to the degree of irregularity grows with the yield ratio, that is, the quotient between the maximum linear-response seismic shear at the first story and the lateral strength of the latter, and that for values of the yield ratio of the order of those to be found in conventional structures subjected to moderate- or high-intensity earthquake ground motion the degree of irregularity may show a considerable influence on the mentioned lateral deformations. In addition, it was observed that the influence of the irregularities under study may in some instances lead to reductions of the response of the first story, and in others to increments.

This paper presents a summary of previous results, followed by a parametric study or the influence of the presence of a soft first story on the nonlinear dynamic response of shear-beam systems representative of buildings characterized by different numbers of stories and natural periods. For the latter, the ranges of values considered were restricted to those corresponding to the story-stiffnesses that comply with the upper bound to the acceptable deformation established by the last edition of the Mexico City seismic design code (Normas Técnicas Complementarias para Diseño Sísmico del Reglamento de Construcciones del Distrito Federal, 1987). The study includes cases of stories with hysteretic bilinear behavior, both including and neglecting P-delta effects.

2 PREVIOUS RESULTS

The shear systems described by Esteva (1987) were designed in accordance with the Emergency Seismic Design Code of 1985 for the Federal District (Mexico City) with a safety factor equal to unity, and were subjected to the EW component of the record obtained at the parking lot of the Ministry of Communications and Transport (Secretaría de Comunicaciones y Transportes) on September 19, 1985 (record SCT850919EW). Three families of 2 d.o.f. systems were selected, equivalent to buildings with 7, 12 and 25 stories and natural periods of 0.7, 1.4 and 2.0 sec., respectively. The equivalence criteria implied that the linear dynamic response of the first story of each 2 d.o.f. system equals that of the fundamental mode of its multistory counterpart.

Among others, a set of elastoplastic shear structures was defined so that in each case the story stiffnesses were proportional to their corresponding safety factors for shear. The absolute values of the required stifnesses were determined by consistency with the specified natural periods, but a few of the structures defined in this manner do not comply with the requirement relative to maximum allowable story sways for the design lateral forces. It was is concluded that the ductility demands on the first story are very sensitive to the ratio of the safety factors in the upper and bottom portions of each structure, as well as to its low-strain natural period. It was also observed that the most unfavorable effects occur for intermediate values of the ratio of safety factors.

Other studies considered a set of 2 d.o.f. shear systems, representative of buildings with their first story free of structural diaphragms, designed as rigid frame systems with homogeneous safety factors along their height, but built in such a way that the infill walls placed at the upper stories are not properly isolated from the structure, thus violating the project specifications. Under these circumstances the strength and stiffness of the first-story coincide with those foreseen in the project, but in the upper stories the values of those properties may be significantly greater than specified. In order to study these cases, two basic systems with uniform safety factors were adopted, each having a different form of variation of story stiffnesses along its height. A new set of systems was generated from each basic system by increasing its strengths and stiffnesses. For each case the increments were constant; they were applied to every story, with the exception of the first one. The ratio $\delta = \Delta K/K_1$ of the stiffness increment to the first-story stiffness was taken equal to the ratio $\Delta R/R_1$ of the strength increment to the first-story strength. As a consequence of the increment on stiffnesses, for the case of constant-along-height initial stiffness the fundamental periods of the systems studied dropped to 0.54, 0.58 and 0.68 of those corresponding to the basic, unmodified systems for 25, 14 and 7 stories, respectively. The design values of the first-story lateral displacement suffered slight changes. For each system, a companion 2 d.o.f. elastoplastic equivalent (in the sense defined above) system was defined and its nonlinear dynamic response was computed neglecting P-delta effects. The results are qualitatively similar to those decribed earlier.

The results presented by Esteva (1987) show also the sensitivity of the response to P-delta and stiffness-degrading effects represented by means of Takeda's model. This phenomenon can be a determining factor to control the response of some systems with significant P-delta effects. These results contribute to make evident the wide uncertainties which affect the prediction of the dynamic response of real structures, arising from our imperfect knowledge of the forms and parameters of the load deformation curves under the action of high-intensity alternating loads.

Ruiz and Diederich (1989) present some results that may help to understand the interaction between the various relevant variables. They study the responses of multistory rigid frames with infill walls in their upper stories, subjected to narrow band ground motion. The presence of the infill walls becomes apparent in the value adopted by the effective vibration period of the system when its response incursions significantly into the range of nonlinear behavior. If the linear fundamental period of the system as stiffened by the infill walls is not too short as compared to the dominant period of the excitation, the effective period of the nonlinear response will reach a value equal to that of the excitation, thus leading to a quasi-resonance condition. The lateral deformation that has to occur at the first story in order for the system's effective period to equal that of the excitation is larger for the building stiffened at the upper stories than for that where those stories do not possess infill elements. This is consistent with the results of the response analyses, which show larger deflections at the bottom story for the case of the stiffened-up building. However, those structures which even before the addition of infilling elements at their upper stories have very short natural periods show an opposite trend. For these cases, the effective vibration periods of unstiffened buildings remain longer than those of their stiffened-up counterparts, and therefore closer to those of the excitation. The net result is that the bottom story deformations of the former exceed in general those of the latter.

The next sections contain a summary of new results. Due to space limitations, only a few of the results are presented in graphical forms. A wider collection of results is presented by Esteva (1992 a, b).

3 ELASTOPLASTIC SYSTEMS WITHOUT P-DELTA EFFECTS

This section presents some results derived from the nonlinear dynamic response analysis of systems representative of buildings with 7, 14 and 20 stories. The behavior of each story is represented by an elastoplastic shear element. All masses were assumed concentrated at the floor levels. Each floor mass was taken as 400 x 10^3 kg (corresponding to a weight of 400 metric tons). On the basis of information derived from the properties of some actual buildings, the story stiffnesses of the basic systems (that is, excluding any stiffening element) were assumed to vary linearly along the height of each building, so that the stiffness at the top story was equal to that at the lowest story divided by $n^{2/3}$, where n is the number of stories. The absolute values of the stiffnesses adopted for each system were those required to produce the specified natural period, in accordance with the following table.

The story strengths (that is, the ordinates of the horizontal branch of the load-deformation curve) were taken equal to the nominal design values (affected in each case by the applicable load factor) obtained by modal dynamic analysis for the seismic design spectrum specified by the Federal District (Mexico City) Building Code of 1987 (RDF-87, according to its Spanish initials).

The acceleration design spectrum for a nonlinear behavior (ductility) factor of 4 has maximum values lying along a plateau between 0.6 and 3.9 sec. In addition, attention was paid to complying with the upper bound of 0.012 imposed by the building code considered on the maximum allowable story angular deformations for the design seismic loads. This restriction is satisfied by the stiffnesses which correspond to the natural periods listed in Table 1.

TABLE 1.

n = number of stories	Natural periods
7	0.4, 0.7, 1.0
14	1.1, 1.4, 1.5
20	1.8, 2.0

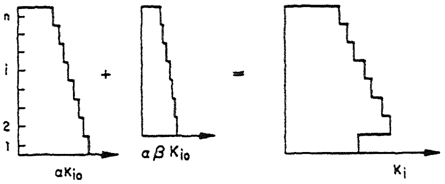

Fig 1 Distribution of lateral stiffnesses in shear buildings with soft first story

Starting from each basic system as described in the foregoing paragraph, a set of modified SFS systems was defined, having the periods listed in Table 1 and story stiffnesses given as follows (Fig. 1):

$$K_1 = \alpha K_{10} \tag{1}$$

$$K_i = \alpha (1 + \beta) K_{io} \quad , i \neq 1 \tag{2}$$

Here, K_{io} is the lateral stiffness of the i-th story of the basic system, K_i that corresponding to a modified SFS system, β the over-stiffness factor at the upper stories, and α a scalar used to adjust the natural period of the modified system to the desired value. It was also assumed that in each modified system the story shear strengths vary in accordance with the following equation.

$$R_i = \frac{K_i}{K_{io}} R_{io} \tag{3}$$

Hence, β may also be defined as an overstrength factor. This variable was assigned values within the interval (0, 2). It was verified that for such values the systems whose properties were defined in accordance with the above paragraphs comply with the codified restrictions relative to allowable story deformations. Then a step-by-step integration procedure was applied to computing the dynamic response of each system to the record SCT850919EW. P-delta effects were neglected in this part of the study. The re-

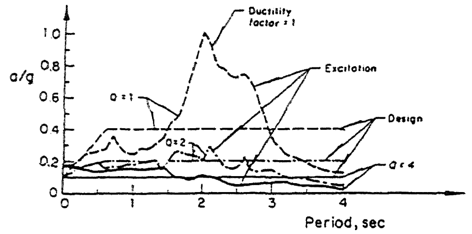

Fig 2 Response spectra for excitation and for nominal design conditions

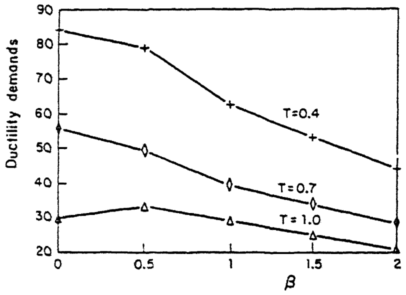

Fig 3 Response of seven-story systems without P-delta effects

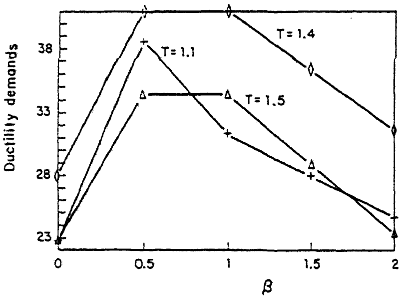

Fig 4 Response of fourteen-story systems whithout P-delta effects

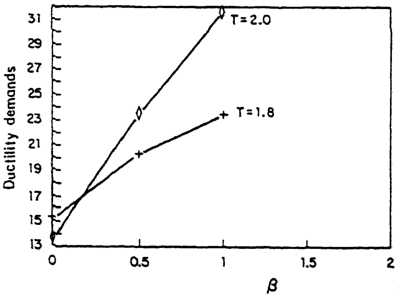

Fig 5 Response of twenty-story systems whithout P-delta effects

sponse was expressed in each case in terms of the maximum ductility demand (ratio between maximum and yield deformations) at the first story.

The design spectra proposed for various "seismic behavior factors" by RDF-87, adopted in this study, are compared in Figure 2 with those computed from the accelerogram SCT850919EW for various ductility factors. From the comparison it is concluded that for values of the seismic behavior factor between 2 and 4 the ordinates of the design spectrum generally coincide with those corresponding to the mentioned accelerogram for a ductility factor numerically equal to the seismic behavior factor. However, for short vibration periods the ordinates of the spectra derived from the recorded ground motion are slightly greater than those specified by the design spectra.

The results of the response analyses are shown in Figures 3-5. There it may be observed that the computed first-story ductility demands are very large for short natural periods. This may be ascribed to the discrepancies between the design-spectrum ordinates and those obtained from the recorded accelerogram for a ductility factor of 4. Another concept which contributes to the large values of the first-story nonlinear response is the difference between the nominal seismic design coefficient (0.10) and the ratio of the first-story lateral strength and the weight of the building. In those cases whose results are shown in Figure 4 *for β=0 and periods between 1.1 and* 1.5 sec, this ratio equals 0.0758. Its discrepancy with the nominal seismic design coefficient is due to the introduction of modal participation factors in conventional linear dynamic analysis. Differences like these are often associated to excessive ductility demands at the bottom stories of multi-degree-of-freedom shear systems (Esteva, 1980).

Figures 3-5 also show that for short-period systems ductility demands decrease while β grows, while for moderate and long periods those demands show an initial increase up to a maximum and then start decreasing for large values of β. These results are consistent with those derived from the previous studies described above.

4 BILINEAR SYSTEMS WITH P-DELTA EFFECTS

Two series of studies were undertaken. The first one was devoted to obtaining the responses of the structures described in the preceding section subjected to the same accelerogram, that is SCT850919EW. Because for some structures collapse by instability was reached before the end of the ground motion, it was decided to present the results as in Figures 6 and 7, in terms of the safety factors (ratios of story strengths to acting shear forces) applied in the design of the shear systems, as well as of the coefficient β of over-strength of the upper stories. The figures show that, for the chosen design and excitations, safety factors as high as 2.0 or more are required to keep ductility demands of short period structures within reasonable limits. For structures with long natural periods the required safety factors may lie around 5.0. On the other hand, it was concluded that for short period structures ductility demands at the first story decrease when β grows, while for long period structures the inverse effect takes place.

The second series of studies dealt with structures having stories with initial stiffnesses and yield capacities equal to those of the first series. However, three different values of the ratio k_2/k_1 were now considered, where k_1 is the initial tangent stiffness and k_2 the post/yield stiffness. The response of each system was computed for a set of artificial accelerograms having statistical properties equal to those of SCT850919EW (Grigoriu et at, 1988). The results were represented in terms of the minimum safety factors required to avoid in each case the collapse by dynamic instability.

Figures 8 and 9 are typical of those showing the response to each accelerogram of some of the systems studied, as well as the points joining the mean values of the responses with respect to the set of accelerograms. Besides the considerable dispersion of the results, other trends become evident. They are studied in detail by means of figures similar to Fig. 10, showing the mean values obtained for all the cases studied. From those figures it was concluded that for the design and excitation conditions described above (RDF-87, artificial accelerograms with statistical properties equal to those of SCT850919EW) the mean values of the required safety factors for elastoplastic systems vary from 1.9 to 1.6 for short period systems (0.4 and 0.7 sec), remain between 1.8 and 2.1 for periods of 1.0 and 1.1 sec, grow with β from 2.5 to 3.4 sec for structures with periods of 1.4 and 1.5 sec and reach values between 4.3 and 6.3 for periods of 1.8 and 2.0 sec. The ratio k_2/k_1 significantly reduces these values, as well as the sensitivity of the required safety factors to β.

5 CONCLUSIONS

From previous studies and those presented in this work the following conclusions are reached, applicable to ground motion histories having durations and frequency contents

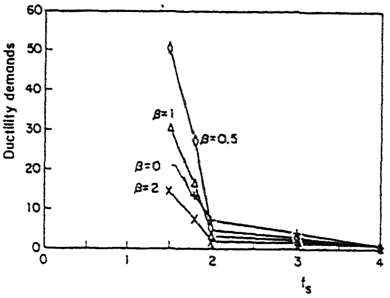

Fig 6 Response of systems with P-delta effects to SCT850919 EW. 7 stories, T=0.7 sec

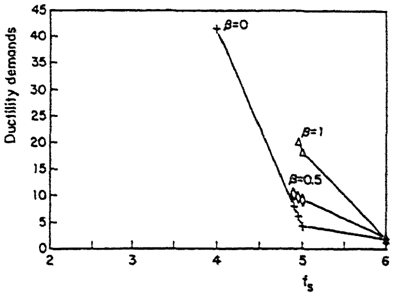

Fig 7 Response of systems with P-delta effects to SCT850919 EW. 20 stories, T= 1.8 sec

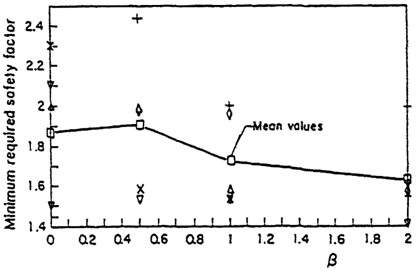

Fig 8 Response of bilinear structures with P-delta effects to artificial accelerograms. 7 stories, T=0.4 sec, k_2/k_1=0

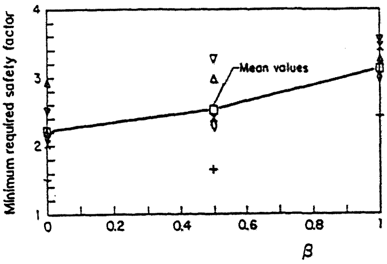

Fig 9 Response of bilinear structures with P-delta effects to artificial accelerograms. 20 stories, T=2.0 sec, k_2/k_1=0.1

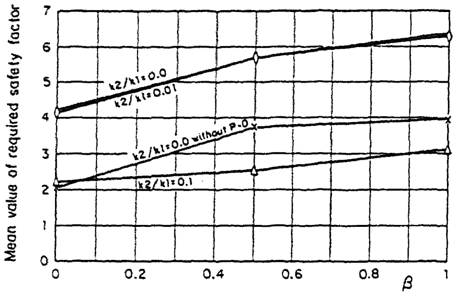

Fig 10 Shear systems with P–delta effects. Artificial accelerograms. 20 stories, T=2.0 sec

similar to those of SCT850919EW.

1. The nonlinear seismic response of shear buildings whose upper stories have lateral strengths and stiffnesses which correspond to safety factors larger than those applied to the first story is very sensitive to the ratios between the safety factors at the upper and bottom stories.
2. The nature and magnitude of the influence of the ratio $r = 1 + \beta$ of the average safety factor at the upper stories to the safety factor at the first story on the maximum ductility demands at the latter depend on the low-strain fundamental natural period of the system. For very short natural periods (0.4 sec) those ductility demands may be reduced in about 30 percent when r grows from 1.0 to 3.0. For intermediate periods (T = 1.0), ductility demands are little sensitive to r, but for longer periods they may reach increments of 50 to 100 percent while r varies within the mentioned interval. For periods between 1.1 and 1.5 sec the maximum amplifications occur for r values between 1.5 and 2.0, while for periods of 1.8 and 2.0 sec ductility demands grow monotonically with r within the interval of values considered (1.0 - 2.0).
3. The ductility demands computed for elastoplastic shear systems with periods ranging from 1.1 to 2.0 sec are extremely large, even in those cases where the amplification due to the sharp variation of safety factors is not present.
4. The influence of r on the response of the first story is strongly enhanced if P-delta effects are taken into account.
5. The above mentioned effects suffer qualitatively similar variations for bilinear hysteretic systems with post-yield stiffness greater than zero. However, those variations are less pronounced than for elastoplastic systems.
6. The results described above are amenable to direct applications by structural designers and code writers. However, it appears convenient to widen the scope of this contribution by means of additional studies, covering the following concepts, among others:
   - a) Accelerograms with various durations and frequency contents,
   - b) Systematic study of the influence of post-yielding stiffness,
   - c) Probabilistic response analyses, incorporating uncertainties tied to mechanical properties of the systems,
   - d) Response of frame systems with infilled panels, and
   - e) Systems whose response may be significantly sensitive to soil-structure interaction.

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