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Inelastic Response Spectra of Simple Degrading Systems

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Abstract

Ductility was first stated, for single-degree-of-freedom elastic-perfectly plastic systems as the ratio of maximum to yield displacements.

An alternative approach, aimed to reduce design forces for ductile structures and based on the energy dissipated during earthquake allows to obtain more reliable ductility factors even when system restoring characteristics are affected by deterioration during loading history.

Inelastic response of SDOF systems has been investigated under seismic excitation, assuming stable and degrading constitutive laws to model their structural behaviour.

Energy spectra and ductility requirent diagrams are generated and compared with those ones of the corresponding elastic-perfectly plastic systems.

1. Introduction

The importance of the role played by ductility in anti-seismic design of structures is unceasingly growing. Ductility was first defined by Newmark and Veletsos, [1], for single-degree-of-freedom elastic-perfectly plastic systems as the ratio of maximum to yield displacements: $\mu = u_{max}/u_y$.

Based on analytical studies, Newmark and Hall, [2], concluded that: 1) for short period structures, any significant reduction in design forces required for elastic response would result in unacceptably large ductilities; 2) for moderate period structures, the energy absorbed by an inelastic structure at its maximum displacements approximates that absorbed by an elastic system resulting in a strength modification factor of $(2\mu - 1)^{1/2}$ (this is a somewhat more conservative approach); and 3) for relatively long period structures, the maximum displacements of elastic and inelastic systems are nearly equal, so a strength modification factor of μ^{-1} would be appropriate.

An alternative approach to the problem of reducing design seismic forces for ductile structures, based on the energy dissipated during earthquake, has been first proposed by Housner [3], and then developed by Mahin and Bertero [4], Jennings [5] et al. [6,7,8]; this approach allows to obtain more reliable ductility factors even when system restoring characteristics are affected by deterioration during seismic excitation.

Aim of this paper is to present the results of a numerical investigation about the seismic response of a SDOF system and to make a comparison among different constitutive laws governing the restoring characteristics.

2. Damage effects

In the last years large scale investigations based on experimental tests at low cycle fatigue demonstrated that local and global behaviour of materials and structures significantly differs from that one deduced on the basis of the classical assumptions of elastic or ideal plastic constitutive law.

The above mentioned experimental investigations have shown the importance of structural deterioration phenomena affecting strength, stiffness and shape of hysteretic loops,and consequently reducing cyclic dissipated energy. Damage effects are admitting of a unified formulation for wide groups of structural systems, even if they exhibit distinctive features(e. g., clearance enlargements and local buckling in steel connections, crushing, cracking and lack of bond in reinforced concrete elements). Thus, damage modelling requires to adopt constitutive laws governed by mechanical parameters variable according to cycle number and strain amplitude, [9, 10, 11, 12, 13].

In the present paper two stable models and one degrading model have been considered. The former ones are : i) the elastic-perfectly plastic model (dashed line in Fig. 1); ii) the "slip" model (solid line in Fig. 1), which represents a limit loop shape at low cycle fatigue.

The degrading model is described in Fig. 2. The energy Ω (t) dissipated during the loading history up to the present time t has been assumed to govern the deterioration of the single parameter "p" (Fig. 3):

$$p\ (t) = p_o - \Delta p\ \frac{\Omega}{\Omega_{lim}}, \tag{1}$$

where "p_o" is the initial value of the parameter ; "Δp" is the maximum admissible decrement of the parameter at the end of the loading history; and "Ω_{lim}" is the total amount of energy which can be dissipated by the system up to the attainment of the limit state. The values of "p_o, Δp, Ω_{lim}" should be identified on the basis of experimental tests.

3. Numerical investigation program

Spectrum. - The design acceleration spectrum of Italian Seismic Code has been used to design the initial values of system mechanical characteristics and has been depicted in Fig. 4; the considered spectrum is similar to one of the three spectra proposed by U.S. Seismic Code, [14].

Mechanical characteristics. - Initial periods of the SDOF systems range from 0. 1 to 2. 0 sec., with step of 0.1 sec. Mass has been kept constant (mg = 20 t.); initial stiffness "k" depends on the initial period "T" and on the constant mass "m" as

$$k = 4\ \pi^2\ \frac{m}{T^2}\ ; \tag{2}$$

yield strength "f_y" has been designed according to

$$f_y = 1.5\ S_a\ mg, \tag{3}$$

where the multiplier 1.5 is the structural safety factor.

Viscous damping has been neglected in order to stress the influence of the hysteretic effects.

Limit energy. - A reasonable comparison between responses of degrading and stable systems requires to evaluate the amount of energy which can be dissipated up to the attainment of the limit state by each degrading system. For this end it seemed suitable to provide each degrading system with the amount of dissipable energy which is actually dissipated by the stable elastic-perfectly plastic system having the same initial (elastic) period, during the same earthquake.

Earthquake. -System seismic response has been analysed under the accelerograms of the El Centro NS 19/5/1940 and Tolmezzo EW 6/5/1976 earthquake components.

4. Numerical results

Figure 5 shows the response spectra in terms of dissipated energy for the two considered earthquakes (the T-axis represents the "initial" elastic periods of the SDOF systems).

It is worth noting that the diagrams are confined within a rather restricted band for each earthquake and that the two earthquake responses significantly differ, as it could be obviously expected, according to their different frequency content and intensity. Moreover, both stable and degrading systems having T = 1.7 ÷ 2.0 sec. remain within the elastic range under

Tolmezzo earthquake.

Figure 6 shows the "time histories" of the energy dissipated by the three considered models, having T = 1.0 sec., under the considered earthquakes.

Furthermore, diagrams of ductility requirements in terms of energy, defined as ratio of total dissipated energy to yield elastic energy, are shown in Fig. 7. Figure 8 presents the diagrams of relative ductility requirements, calculated by normalizing the values of energy ductility requirements of the different models with respect to those relevant to the elastic-perfectly plastic models having the same initial elastic period.

5. Conclusions

Numerical results suggest the following remarks:

1) The behaviour of the "slip" model does not significantly differ from that one of the corresponding elastic-perfectly plastic model having the same yield strength and the same elastic stiffness.
2) Providing the single degrading systems with as much dissipable energy as that one dissipated by the corresponding (stable) elastic-ideal plastic systems has allowed only 7 out of 20 systems to survive El Centro earthquake, while 17 out of 20 systems survived Tolmezzo earthquake.
3) Further numerical investigations, based on the preceding remarks, are required in order to assess the amount of limit energy which degrading systems need to survive earthquakes.

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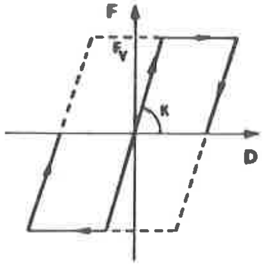

Fig. 1. Stable models.

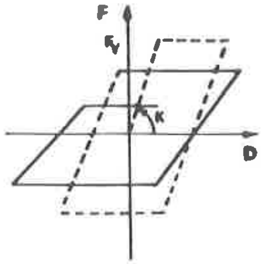

Fig. 2. Degrading model.

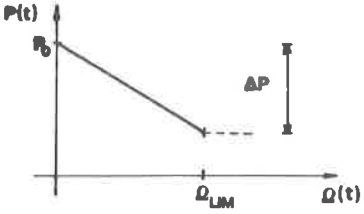

Fig. 3. Deterioration law.

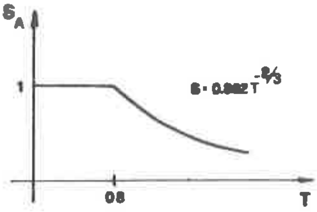

Fig. 4. Design response spectrum.

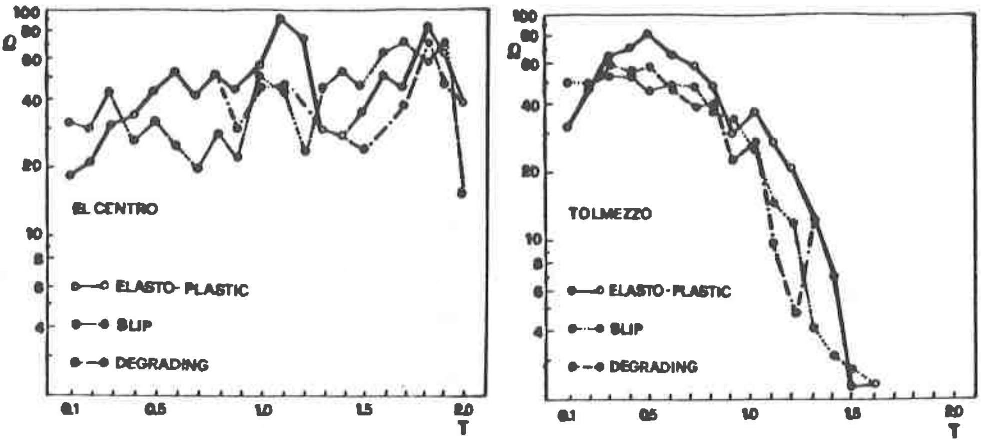

Fig. 5. Total dissipated energy.

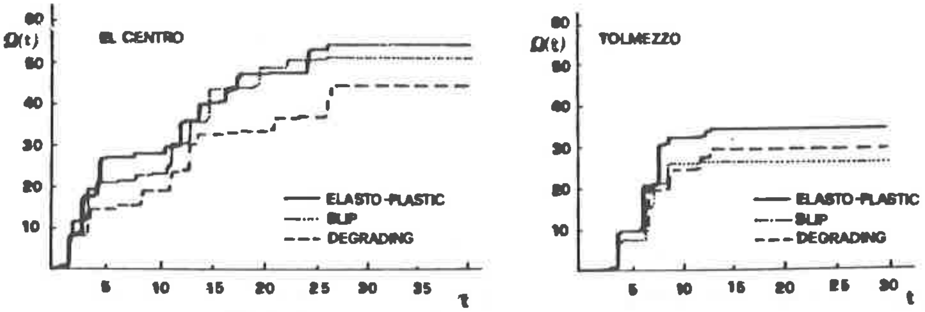

Fig. 6. Dissipated energy history.

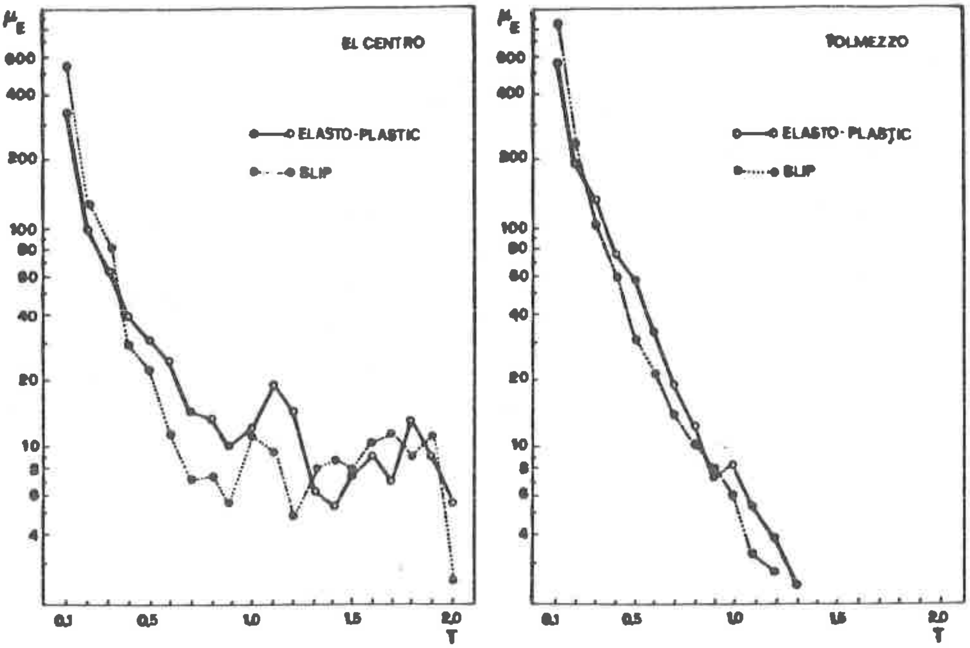

Fig. 7. Energy ductility requirement.

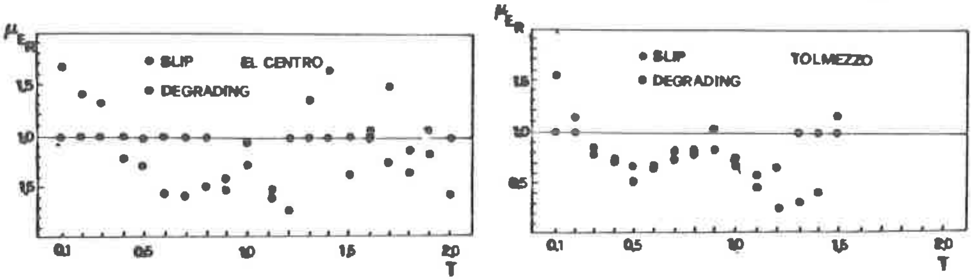

Fig. 8. Relative energy ductility requirement.