EFFECTS OF DURATION AND AFTERSHOCKS ON INELASTIC DESIGN EARTHQUAKES

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SUMMARY

Some basic problems in defining design earthquakes for structures that can be allowed to yield during severe, long duration ground shaking are examined. Results of inelastic dynamic analyses of systems with different mechanical characteristics are presented for ensembles of synthetic accelerograms with durations ranging up to 60 sec., for recorded aftershock sequences and for other commonly used records. It is shown that duration effects must be considered in certain cases to limit lateral displacements and energy dissipation demands.

INTRODUCTION

Field surveys following recent major earthquakes indicate that aftershocks can substantially increase structural damage and that it is not unusual for this accumulation of damage to lead to collapse during aftershocks. Damage may also accumulate during severe, long duration ground motions associated with a great earthquake as well as during several severe earthquake sequences which may occur during the service life of a structure. Since cumulative damage from such seismic events may exceed that predicted using records commonly employed in seismic response analyses, more stringent design criteria may be necessitated where long duration motions can occur. As part of an overall evaluation of current seismic-resistant design methods [1,2] analytical studies have been performed to assess the effect of duration of shaking and some results for single degree-of-freedom (SDOF) systems are reported herein.

RESPONSE OF INELASTIC SDOF SYSTEMS

Several analytical studies indicate that the maximum displacement ductility, μ, does not substantially increase with increasing duration of ground shaking, e.g. [3]. However, cycles of reversed inelastic deformations may result in large energy dissipation demands in such cases. To study this possibility, it is convenient to define an equivalent energy dissipation ductility factor, μ_E, equal to the maximum displacement ductility of a monotonically loaded elasto-perfectly plastic (EPP) system that dissipates the same hysteretic energy as the actual system. As indicated in Fig. 1, EPP SDOF systems, designed according to [4] and subjected to 10 standard accelerograms, develop values of μ_E significantly larger on average than can be inferred from μ alone [1].

A number of other studies indicate that displacements can significantly increase with duration of shaking, e.g. [2,5], resulting in an incremental-type failure (Fig. 2). Following an initial seismic excitation a structure may retain a permanent deflection. For systems considered in Fig. 1, permanent deformations averaged more than 40% of the maximum displacements [1]. As discussed in Ref. 2, repetition of severe, long duration acceleration pulses and deformation softening tendencies of the system (representative

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of P-Δ effects or strength deterioration) may preferentially orient further inelastic deformations in the direction of the initial offset. For example, P-Δ effects reduce the effective stiffness of a SDOF system by an amount equal to its weight divided by its effective height. Because of this reduction (expressed herein as a fraction of the initial stiffness), the yield strength of the system will decrease for loads in the direction of the offset (Fig. 2) and will correspondingly increase for loads in the opposite direction. The sensitivity of inelastic response to post-yield stiffness can be seen in the nondimensional maximum displacement ductility spectra shown in Fig. 3 for the derived Pacoima Dam base rock (DPD) record. In this figure, parameter η equals the system's yield resistance divided by the product of its mass and the peak ground acceleration. While moderate amounts of deformation hardening have minor effects, moderate deformation softening results in significant increases in ductility demands in all but the most flexible systems. For example, according to Fig. 3, deformation softening systems with strengths corresponding to an η value of 0.5 and an initial period less than 0.8 would collapse (while EPP systems would not).

EFFECT OF LONG DURATION GROUND MOTIONS

To assess the effect of long duration ground motions, average ductility spectra were constructed based on the response of bilinear hysteretic SDOF systems to five, 60 sec. long, synthetic accelerograms. These records were generated to be representative of severe ground motions recorded at moderate epicentral distances on firm ground [6].

Displacement Ductilities. Average displacement ductility spectra for systems with η equal to 0.2 are plotted at 10 sec. intervals in Fig. 4. Average ductility demands generally decrease with increasing period for systems with constant strength. The maximum displacement ductility demands of EPP systems tend to increase only slightly in the last half of the records, and the greatest increase occurs within the first 10 sec. (Figs. 4 and 5(a)). This trend is maintained for all η values (Fig. 5 (b)). Deformation softening substantially increases ductility demands in general (Fig. 4). The increase is usually small during the initial portion of the excitation, but becomes larger as time progresses. This is particularly true for systems in which μ values exceed 4-6. Small amounts of deformation softening have catastrophic effects on weak structures with low initial periods. Coefficients of variation for μ are generally much larger for softening systems.

Energy Dissipation Demands. Although μ values for EPP SDOF systems tend to remain constant with time, μ_E tends to increase with continued shaking (Figs. 4 and 5). Thus, the duration of potential ground shaking must be carefully considered in the design of systems with limited energy dissipation capacities.

EFFECT OF AFTERSHOCK SEQUENCES

To assess the effect of the accumulation of damages due to successive ground motions, a number of earthquake aftershock sequences have been investigated. For example, the 1972 Managua earthquake main shock was followed by two large aftershocks. Cumulative ductility spectra for the east component of the Esso Refinery records are presented in Fig. 6. Depending on the initial period and strength, the main shock (351 gal) would have induced significant inelastic deformations in EPP SDOF systems. The first aftershock (120 gal) had relatively little effect. However, inelastic deformations during the second aftershock (277 gal) predominantly occurred in the same direction as in the main shock, more than doubling μ for many systems (especially those with relatively low η values). Energy dissipation demands were similarly increased. As shown in Fig. 7, small amounts of deformation softening again have a significantly adverse effect on ductility demands.

CONCLUSIONS

Duration of severe ground shaking can have a significant effect on inelastic deformational and energy dissipation demands. This is especially true of relatively weak, short period structures which may be expected to develop significant inelastic deformations. Particular attention must be devoted to determination of the total duration of shaking if a structure may exhibit deformation softening or has a limited capacity to dissipate energy. Additional research is needed to devise reliable design methods for such systems and to assess the effect of duration on stiffness and strenth degrading systems.

ACKNOWLEDGEMENTS

The financial support of the NSF is gratefully acknowledged. The numerical computations were performed by M. Williams and A. Ziegler.

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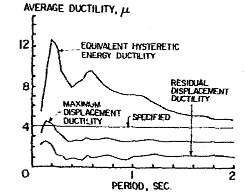


FIG. 1 AVE. RESPONSE FOR TEN RECORDS--EPP SDOF SYSTEMS DESIGNED USING [4]; ξ = 5%

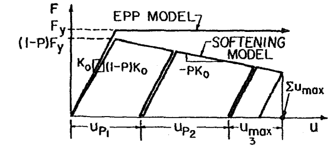


FIG. 2 INCREMENTAL TYPE FAILURE

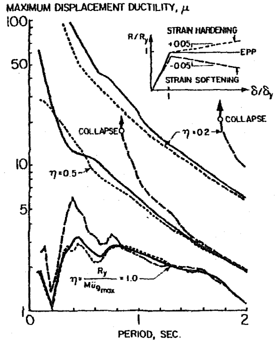


FIG. 3 EFFECT OF HARDENING AND SOFTENING ON μ;DPD RECORD(S16E)

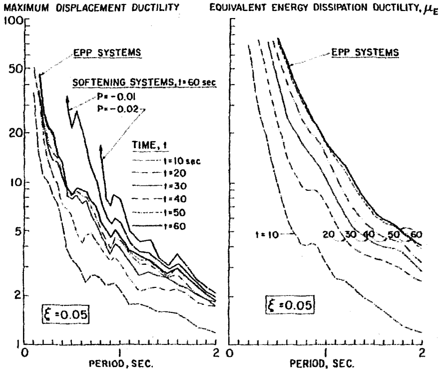
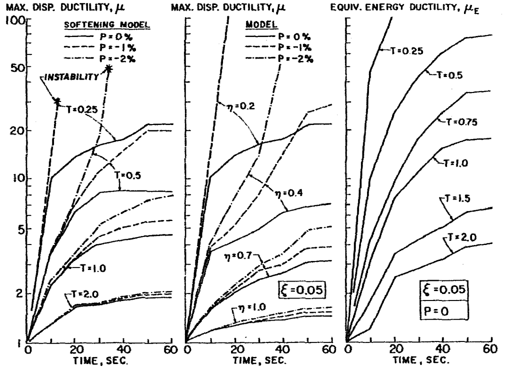


FIG. 4 EFFECT OF DURATION ON DUCTILITY SPECTRA--AVE. FOR 5 SYNTHETIC RECORDS



(a) μ AS FUNCTION OF T; η=0.2 (b) μ AS FUNCTION OF η; T=0.25 (c) μ_E AS FUNCTION OF T; η=0.2

FIG. 5 VARIATION OF μ WITH TIME--AVE. FOR 5 SYNTHETIC RECORDS

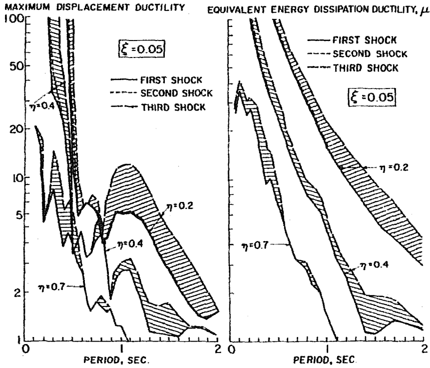


FIG. 6 EFFECT OF ESSO REFINERY AFTERSHOCKS(EW) ON μ; P = 0

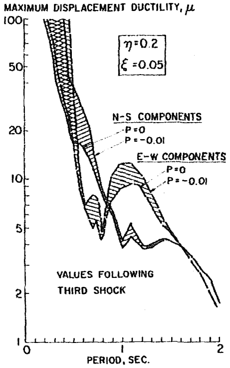


FIG. 7 EFFECT OF SOFTENING ON μ; ESSO REFINERY AFTERSHOCK SEQUENCE (EW)