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The Effect of Strong Motion Duration on Seismic Demands

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Abstract

In various studies related to inelastic seismic design, it has been recognized that energy demands are important. Energy parameters of interest include input energy as well as damage-related parameters such as hysteretic energy. It has also long been believed that it is of importance to understand the influence of strong motion duration on strength and energy demands. Accordingly, in this paper, we study seismic demands focusing on energy demands for bilinear systems and we systematically investigate the effect of duration with the help of simulation methods. We find that while strength demands are not very sensitive to strong motion duration, input energy and hysteretic energy demands are significantly dependent on duration.

Keywords

Strong motion duration, energy demand, input energy, hysteretic energy, strength demand, ductility.

Introduction

The response of a structure subjected to strong ground motion is a process during which the mechanical properties of the structure (e.g., its stiffness and strength) are modified during inelastic excursions. In inelastic seismic design procedures, consideration of strength demands alone is not sufficient for safe design. This was recognized many years ago by Housner (1956) who proposed an alternative energy-based approach to the traditional design procedures of the time. More recently, the inclusion of input energy demand in the design process has been advocated by Uang and Bertero (1988). Additionally, they recommend that input energy might be useful if employed as the basis for selection of design earthquakes, and state that input energy is one of the most reliable parameters for defining damage potential of ground motion. Others such as Krawinkler and Nassar (1992) and Fajfar and Fischinger (1990) have also studied input energy and other energy demand parameters in depth.

After an estimate of input energy has been obtained, the design process requires that this energy "demand" be checked against "supplies" (see Bertero and Uang, 1992). The input energy imparted to a structure is dissipated through viscous damping and hysteresis. Hysteretic energy is a very important indicator of cumulative damage sustained by a structure. Thus, damage and energy demands are closely related. The amount of hysteretic energy dissipated depends on the number and the amplitude of inelastic excursions experienced. The duration of strong motion has a direct effect on the number of these excursions. If cumulative damage is used as a criterion for weighting ductility capacity in design, it would be useful to establish the effect that duration has directly on the hysteretic energy demand, and indirectly on obtaining such ductility capacities. This would give insights into a modified design process that might result out of such duration considerations.

In the present paper, we study the influence of duration on seismic demands with the help of simulation methods. Others (e.g., see Sewell (1993) for an extensive study) have also investigated the influence of duration on seismic demands in inelastic systems. Our focus will be primarily on energy demand parameters. In order to systematically study the effect of strong motion duration, we employ simulation methods which will permit us to control the duration of the artificial accelerogram. The program SIMQKE (see Gasparini and Vanmarcke, 1976, for theoretical details of the simulation procedure) is used. Because of our interest in energy demands, we should point out at this time that in a recent paper, Naeim and Lew (1995) have demonstrated that design spectrum compatible time histories obtained using simulation methods often cannot accurately capture the input energy of the seed accelerograms. They demonstrate that in some cases, simulated motions yielded input energy values that were more than an order of magnitude higher than those from the recorded motions that were used as their bases. In order to address this finding, although we do not employ design spectra, we will compare input energy spectra from both recorded and simulated motions.

The following studies involve dynamic analyses of bilinear single-degree-of-freedom (SDOF) systems with periods ranging from 0.1 to 4.0 seconds. Only Western US records from rock sites are considered. Strong motion durations values of 5, 10, 15, and 20 seconds are considered. Ductility ratios up to 8 are considered. In studying demands on these SDOF systems, although we will focus on energy-related parameters, we will also discuss strength demands and address issues related to simulation.

Ground Motions

Nineteen records were selected for this study. All of these were from five Western US earthquakes (with magnitudes 6.1 and above) and were recorded at rock sites. The epicentral distances ranged from 7 to 54 km. The Trifunac-Brady definition of duration is used in this paper. Table 1 outlines the details of the records selected.

No.	Station	Component	Dist. (km)	PGA (g)	Duration (sec)
Northridge Earthquake 01-17-94 (M_l = 6.4)					
1	Castaic - Old Ridge Route	(90°)	41	0.57	9.1
2	Lake Hughes #9	(90°)	44	0.23	8.1
3	Los Angeles - City Terrace	(180°)	38	0.32	13.0
4	Los Angeles - Temple & Hope	(180°)	32	0.18	14.2
5	Mt. Wilson - Caltech Seismic Sta.	(360°)	45	0.23	8.9
6	Pacoima - Kagel Canyon	(360°)	18	0.43	9.9
7	Point Mugu - Naval Air Sta.	(360°)	50	0.18	14.2
8	Rolling Hill Ests. - Rancho Vista	(90°)	50	0.12	18.8
Loma Prieta Earthquake 10-17-89 (M_l = 7.1)					
9	Gilroy#1 - Gavilan Coll., Water Tank (USGS No. 1408)	(90°)	29	0.44	3.7
10	Gilroy#6 - San Ysidro (USGS No. 1413)	(90°)	35	0.17	12.7
11	Gilroy#7 - Mantelli Ranch	(90°)	40	0.32	9.1
12	Monterey City Hall	(0°)	49	0.07	13.3
13	Santa Cruz - Lick Obs. Elec. Lab	(0°)	16	0.44	9.5
14	Corralitos - Eureka Canyon Rd	(0°)	7	0.63	6.9
15	Sago South - Hollister, Cinega Road	(261°)	54	0.07	14.8
Big Bear Earthquake 06-28-92 (M_l = 6.5)					
16	Big Bear Lake - Civic Center Grds	(360°)	11	0.55	10.4

No.	Station	Component	Dist. (km)	PGA (g)	Duration (sec)
Landers Earthquake 06-28-92 (M_s = 7.5)					
17	Twenty-nine Palms - Park Maint. Bldg	(0°)	44	0.08	31.7
Whittier Earthquake 10-01-87 (M_l = 6.1)					
18	Mt. Wilson - Caltech Seismic Sta.	(90°)	19	0.18	8.4
19	Pacoima - Kagel Canyon	(90°)	38	0.16	9.9

Table 1. Description of the Nineteen Western U.S. records used in the analysis.

Based on the "absolute" input energy (E_i) spectrum (see Uang and Bertero, 1990 for an explanation of the differences between "relative" and "absolute" input energy) for each record, the input energy-based equivalent velocity, $v_{eq} = (2E_i/m)^{½}$, was computed for all periods. (For the sake of brevity, we will refer to this velocity simply as "equivalent velocity" in the rest of this paper.) The value of v_{eq} averaged over the range of periods from 0.1 to 1.5 seconds was computed for each record. Then, each record was scaled so that its v_{eq} value was made equal to that of the mean from all the nineteen records. This approach was adopted in order to ensure that all the earthquakes would have a common basis for subsequent comparisons. If one studies only dimensionless demand, scaling to a common severity level is not important. However, we employ the above scaling method because (1) we are interested in input energy and hysteretic energy demands (which are not dimensionless), and (2) we wish to compare input energy spectra from original motions with those from simulated motions to address simulation-related problems raised by Naeim and Lew (1995) and determine errors in estimating input energy per unit mass expressed in physical units (e.g., cm^2/sec^2).

In order to investigate the influence of duration on seismic demands, we chose to generate artificial accelerograms where the duration of the simulated motions could be controlled. Accordingly, using target velocity spectra and peak ground acceleration (pga) values from the original scaled recorded motions, simulations for controlled durations of 5, 10, 15, and 20 seconds were performed using SIMQKE (Gasparini and Vanmarcke, 1976). Additionally, in order to test the reliability of the simulation procedure, the durations of the actual recorded strong motions for each of the nineteen records was used to generate a separate set of motions. In the results that follow, therefore, we will discuss the analyses from six different sets of earthquake motions; namely, the original (scaled) motions, the simulated motions (with durations same as the original ones), and the simulated motions with the four controlled durations of 5, 10, 15, and 20 seconds.

In Figure 1, the nineteen acceleration spectra (equivalently, elastic strength demand spectra) are shown along with the mean spectrum. The scaling procedure has been incorporated in the figure. Figure 2 shows a plot of the equivalent velocity spectra for the nineteen records. The range of periods used in the scaling procedure is also indicated in this figure and it can be confirmed that when the scale factors are applied, the equivalent velocity ordinates for all the records have the same average value in that range. As indicated above, since the equivalent velocity is derived from the input energy, all the records at the outset, thus, have comparable input energy over the specified period range. This is in contrast to other studies where records are generally anchored to a single-valued quantity such as peak ground acceleration or velocity.

Analysis

Inelastic analyses were performed with each of the 19 original (scaled) motions, 19 simulated motions with the same duration as the recorded motions, and 76 (19 times 4 durations) simulated motions, using bilinear systems in which the yield levels were adjusted so that target displacement ductility ratios of 2, 3, 4, 5, 6, and 8 were achieved. Damping of 5-percent of critical was used in all the analyses and a strain hardening ratio of

19 Western US Records scaled to have same equivalent velocity in the 0.1 - 1.5 sec range.

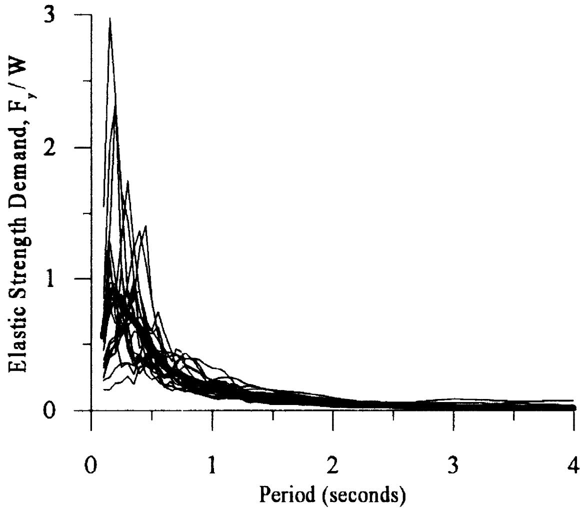


Figure 1: Acceleration spectra for 19 scaled records.

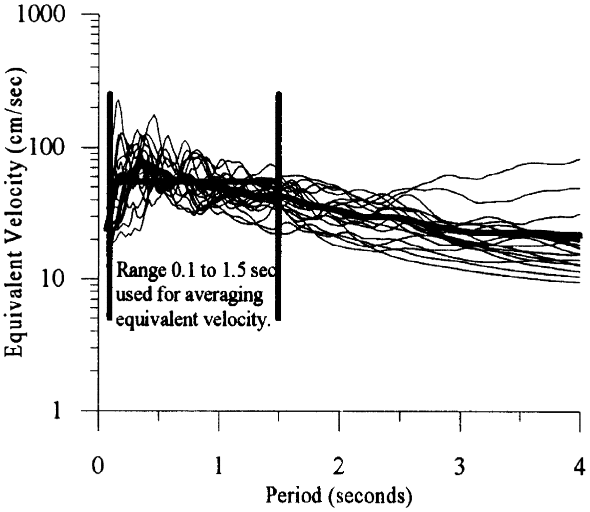


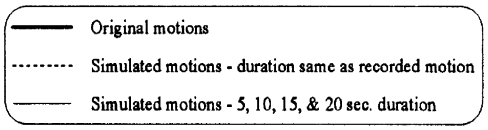
Figure 2: Equivalent velocity spectra for 19 scaled records.

5-percent was employed. For the sake of brevity, only results from the inelastic analyses that involve target ductility ratios of 2 and 6 will be discussed in the paper.

First, we examine the strength demands for two different cases: one, elastic and the other, inelastic with a ductility ratio of 6. Figure 3 shows a plot of the strength demands for these two cases. As can be seen, the strength demands are quite insensitive to duration for both elastic and inelastic systems and for all periods. Also, the simulated motions result in strength demands that are comparable to those from the original motions.

Next, we study strength reduction factors for the ductility ratios of 2 and 6. For the ductility ratio of 2, it is seen in Figure 4 that the strength reduction factor is almost constant over the entire period range and is also not dependent on duration. For the larger ductility ratio of 6, it is difficult to establish a relationship between the strength reduction factor and duration, although it appears that duration does not have a strong influence.

The input energy spectra for elastic systems are studied next. Figure 5(a) shows a plot of the mean spectra from the nineteen records of each of the six loading sets. First, we compare the input energy from the original motions (solid line) with that from the simulated motions (dotted line) having the same durations. It can be seen that the input energy spectra in these two cases are considerably different. On studying the time histories of both sets of motions, it was found that the simulated motions displayed a much larger number of strong cycles than the original recorded motions for the same duration. It is not surprising then that the input energy spectra from the simulated motions are larger. Clearly, this is a result of the simulation technique being unable to accurately represent the physics of the earth process that creates the accelerogram signature. Notwithstanding these differences, it is still acceptable to employ the simulation methods to compare seismic demands for the 4 controlled duration simulated motion sets. Note that the differences resulting from the simulation procedures adopted are not large (relative to the original) nor is the frequency content of the input energy spectra grossly different between the original and simulated motions as has been reported recently when design spectrum compatible simulated motions using Northridge records as seed motions have been used (see Naeim, 1995). This suggests that the simulated motions may be used without undue concern about their inability to correctly estimate input energy. In Figure 5(a), the thin lines (the highest is for 20 seconds duration) represent the mean input energy spectra for the four controlled duration cases (5 to 20 seconds).



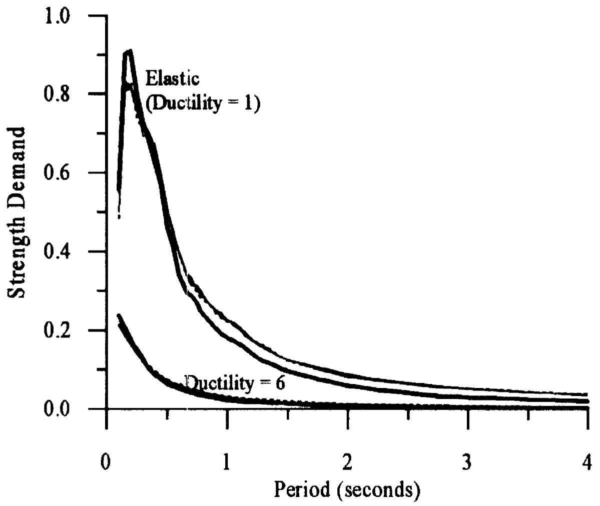


Figure 3: Elastic and Inelastic (ductility = 6)
Strength Demand

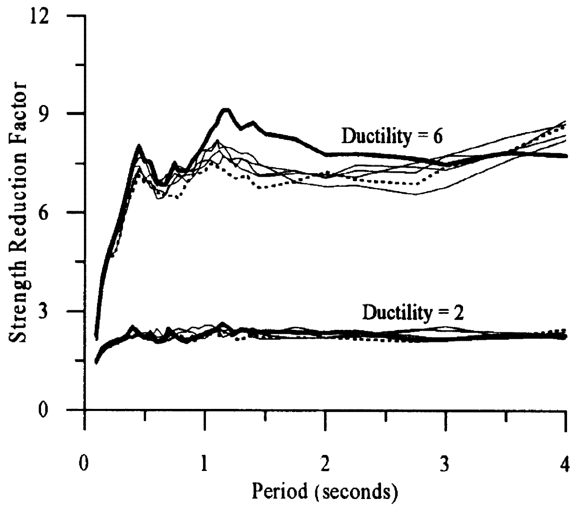


Figure 4: Strength Reduction Factors.

Figure 5(b) shows a plot of the coefficient of variation (COV) of the elastic input energy spectra. The COV represents a measure of the record-to-record variability at each period. Except for the long period range, this variability is seen to be consistent between the recorded motions and the simulated motions. The comparable variability up to about 2.5 seconds suggests that in the short-to-moderate period range, the simulation procedure does not introduce nor remove any intrinsic variability that exists in the actual recorded motions. As is to be expected, the COV is smallest in the period range 0.1 to 1.5 seconds where the records have the same equivalent velocity by virtue of the scaling procedure employed. This will be subsequently seen in COV estimates for other energy demands as well.

Next, we study the energy demands for inelastic systems with ductility ratio equal to 6. Figures 6(a) and 7(a) show mean input energy spectra and hysteretic energy spectra, respectively. The general behavior of these mean spectra is similar to that of the elastic input energy spectra in Figure 5(a) (i.e., energy demands increase with duration) and the spectra are somewhat smoother due to the large inelastic behavior associated with this target ductility. The mean input energy demand for the inelastic system in Figure 6(a) is less than that for the elastic one in Figure 5(a). On examining the COV's for these energy demands (see Figures 6(b) and 7(b)), we again observe that the simulated motions have comparable variability to that of the recorded motions. Hence, the sensitivity of duration to inelastic demand parameters can be studied using simulations with some degree of confidence. We might note that the variability in the simulations for long periods is smaller than that from the original motions for all energy demands. However, energy demands are less important for long periods since only a small number of amplitude cycles of response are involved, and displacement demands are of greater importance then.

Figure 8(a) shows a plot of the mean ratio of hysteretic energy to input energy for ductility ratios of 2 and 6 in our studies with 5-percent damping. For the lower ductility case, the ratio is fairly constant for periods greater than about 0.2 seconds. Also, this ratio does not appear to depend on the duration of strong motion. The simulated motions all predict higher ratios than the actual recorded motions. For the target ductility of 6, the ratio is larger which indicates that the hysteretic effects are more significant in the higher inelastic regime.

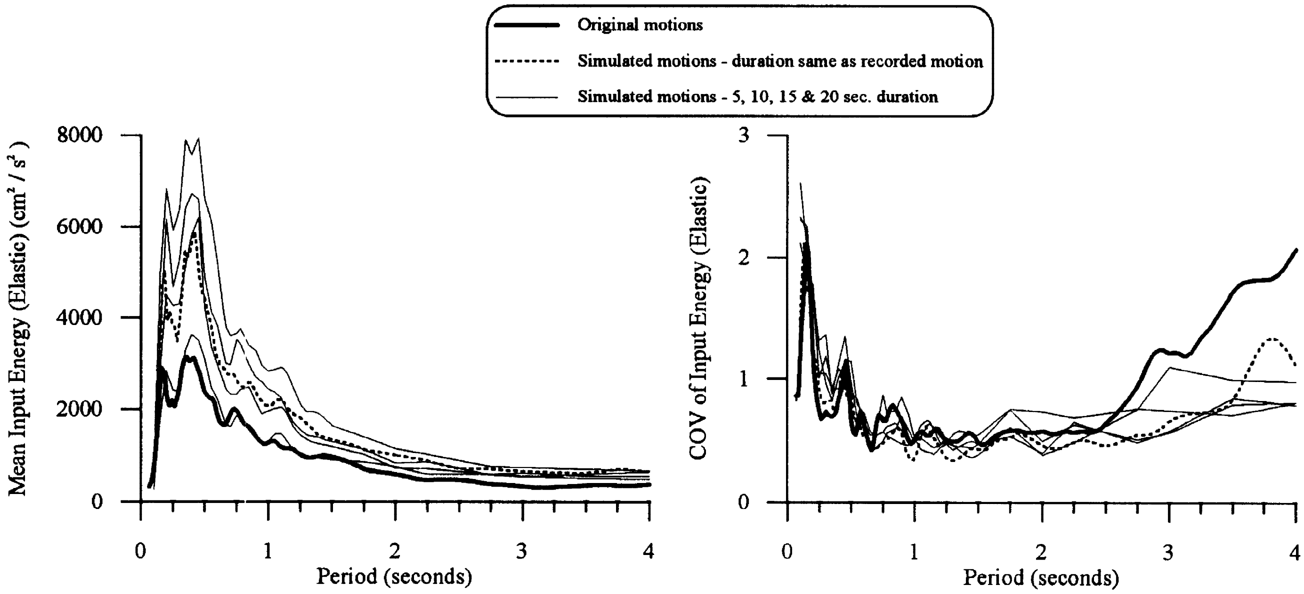


Figure 5: (a) Elastic Input Energy, (b) COV of Elastic Input Energy

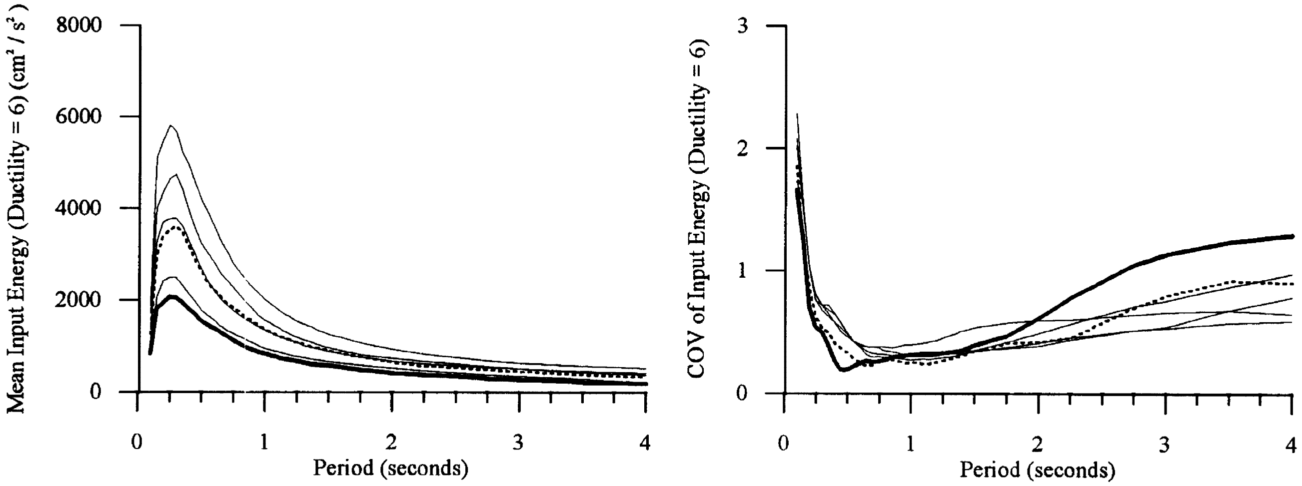


Figure 6: (a) Input Energy (Ductility = 6), (b) COV of Input Energy (Ductility = 6)

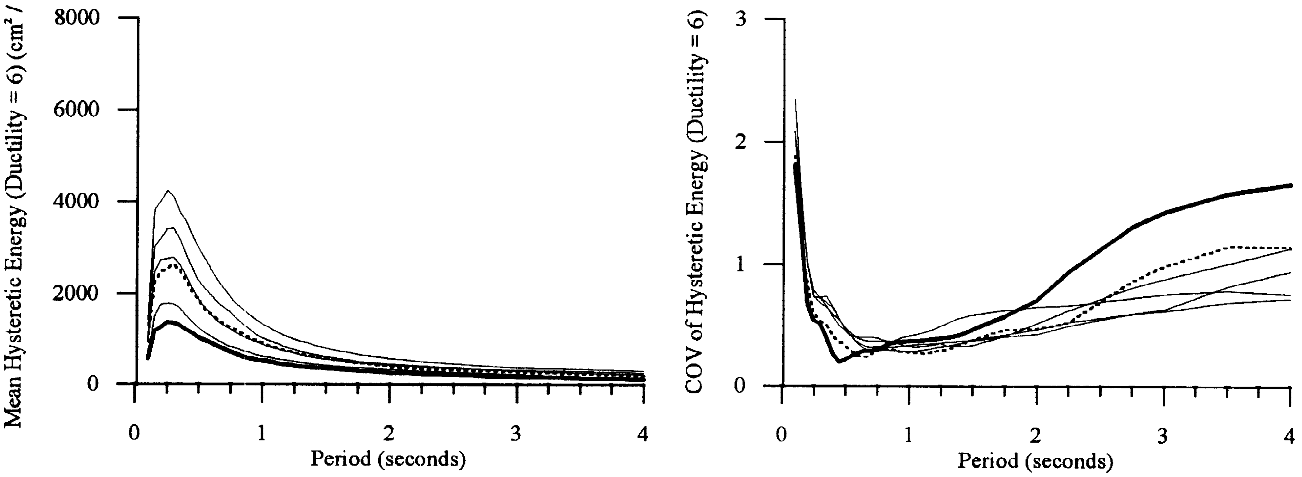


Figure 7: (a) Hysteretic Energy (Ductility = 6), (b) COV of Hysteretic Energy (Ductility = 6)

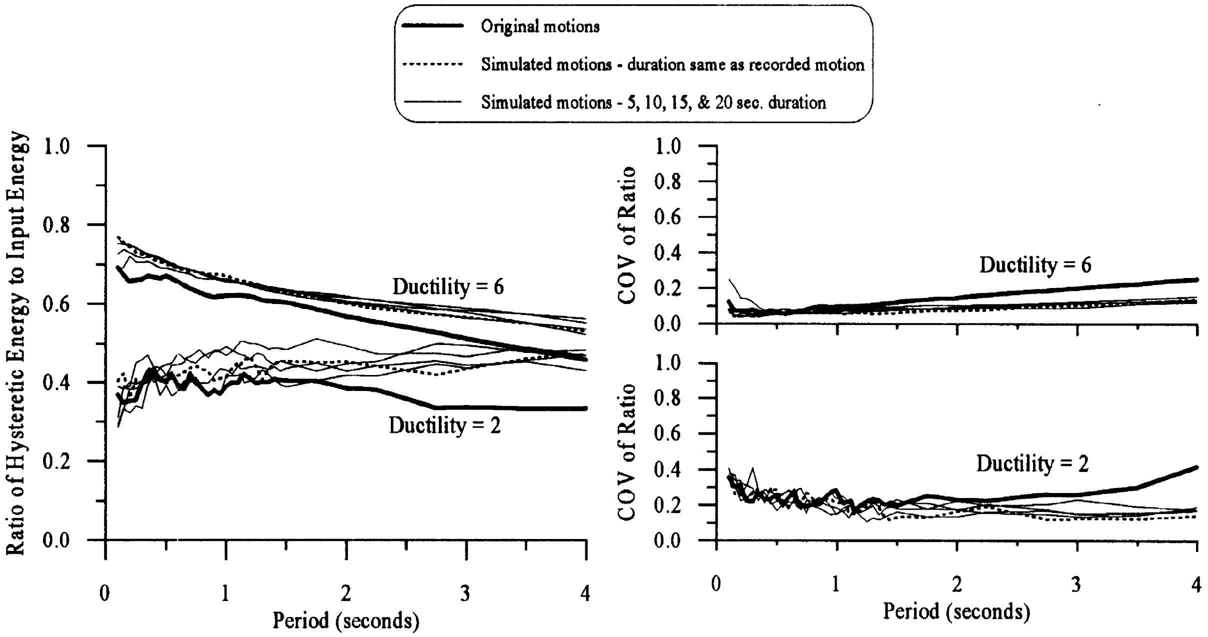


Figure 8: (a) Mean Ratio of Hysteretic Energy to Input Energy, (b) COV of Ratio of Hysteretic Energy to Input Energy.

This ratio is seen to decrease gradually with increasing natural period of the SDOF system. This is similar to the findings of Krawinkler and Nassar (1992). Figure 8(b) shows plots of the COV of the ratio of hysteretic energy to input energy. Here, we see that the COV values are less than about 20 percent for all periods indicating that this energy ratio is a very stable demand measure. Also, these low COV values are consistent with results reported by Fajfar et al. (1992) and this variability is considerably smaller than that of either input energy or hysteretic energy alone (as can be verified by examining Figures 5(b), 6(b), and 7(b)). Moreover, the small variability of the energy ratio is also not dependent on strong motion duration. The recorded motions show only slightly higher variability than the simulated motions.

Conclusions

The influence of strong motion duration on seismic demands has been studied with special emphasis on energy demand parameters. The following general conclusions were reached from the present study:

1. Both elastic and inelastic strength demands as well as strength reduction factors appear to be insensitive to the duration of strong motion for all periods.

2. Strength and energy demands estimated using simulated motions were "qualitatively" consistent in their general behavior with these demands from the original recorded motions. Also, these simulated motions accurately represent the variability of energy demand observed from actual recorded motions. This is true for elastic as well as inelastic behavior, and for systems with all periods.

3. Energy demands increase with strong motion duration and decrease with ductility. This is true for input energy as well as hysteretic energy.

4. The ratio of hysteretic energy to input energy was found to be a very stable demand parameter. It does not appear to depend on the duration of strong motion. Moreover, it decreases gradually with period for high ductility cases, but is almost constant for lower ductilities. The variability of this ratio is also very

small, especially when compared to other energy demand parameters for all ductility ratios, and is not dependent on duration.

In summary, we have found that strong motion duration has almost no influence on strength demands and on strength reduction factors. On the other hand, input energy and hysteretic energy demands were seen to increase with an increase in duration. The ratio of hysteretic energy to input energy was seen, however, to be insensitive to strong motion duration. This suggests that the relative proportion of input energy dissipated in hysteresis is not dependent on duration although the absolute hysteretic energy alone (an indicator of cumulative damage) is dependent on duration. This last finding provides information that might be useful when cumulative damage measures such as hysteretic energy are employed as a criterion in weighting ductility capacity in inelastic design and if consideration of duration is of interest.

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