Transactions of the **14th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 14), Lyon, France, August 17-22, 1997

K02/3

Damage potential characteristics of near-field earthquake motions

Park Y.J.[(1)], **Chokshi N.C.**[(2)]
(1) Brookhaven National Laboratory, USA
(2) U.S. Nuclear Regulatory Commission, USA

ABSTRACT

In recent major earthquakes; i.e., 1994 Northridge earthquake in the U.S. and 1995 Great Kansai earthquake in Japan, several close-distance strong ground motions have been obtained, which may be of a significant interest to earthquake/structural engineers. The damage potential of those recently obtained ground motions is examined based on the nonlinear response analyses of various SDOF systems. For comparison purposes, the El Centro records from the 1940 Imperial Valley earthquake, as well as a set of artificial motions consistent with the R.G. 1.60 spectrum were also used. The engineering insights regarding the seismic design of structures are discussed based on a series of parametric studies.

1 INTRODUCTION

In the recent 1994 Northridge and 1995 Great Kansai earthquakes, several close-distance strong motions records have been obtained. These ground motions are characterized by unusually high acceleration and velocity peak values, relatively strong vertical components, and a relatively short duration. Figures 1 and 2 show the velocity time histories of the N-S components recorded at JMA (Japan Meteorological Agency) Kobe station and at the Sylmar County Hospital station, respectively. The large velocity impulses of 92.2 and 129.1 kine (cm/second) are at least 2 ~ 3 times higher than those implicitly assumed in any existing seismic design codes in the world. Obviously, it is not economically plausible to design all types of structures within the elastic or even moderately inelastic range against such extreme ground shakings. The damage potential of those close-distance ground motions are evaluated in this paper based on a series of parametric studies of various SDOF systems. As a measure of the damage potential, both the ductility demand and the strength demand (for a given ductility level) are calculated and evaluated in the following discussions.

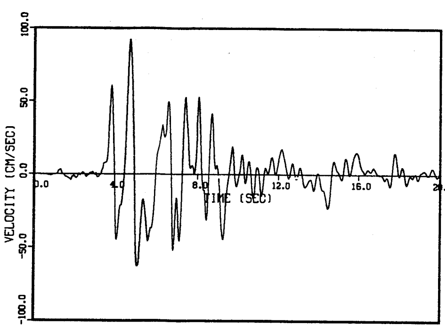


Figure 1 Velocity of N-S Component of Kobe Station Record (Peak = 92.34 cm/sec.)

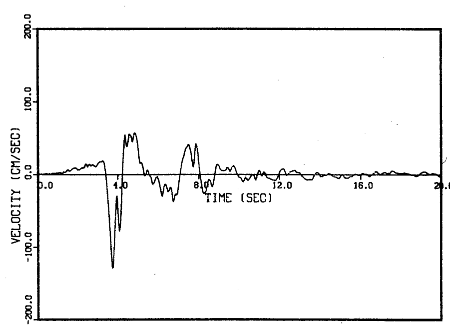


Figure 2 Velocity of N-S Component of Sylmar Hospital Record (Peak = 129.13 cm/sec.)

2 GROUND MOTIONS AND EVALUATION METHODS

As the close-distance strong motion, the JMA Kobe station records from the 1995 Great Kansai earthquake and the Sylmar County Hospital records from the 1994 Northridge earthquake were selected. For comparison purposes, the El Centro records from the 1940 Imperial Valley earthquake were also included. The peak ground motion values are listed in Table 1 and the calculated acceleration response spectra for the N-S components are shown in Figure 3. In addition, to represent the seismic design ground motions, a total of ten (10) artificial motions to fit the R.G. 1.60 spectrum (U.S. NRC, 1973) are also included in the following parametric studies. An example of spectra for the generated motions is shown in Figure 4 (duration of the generated motions in 30 sec.).

The structures are represented by simple SDOF systems with the following hysteretic properties:

- Bilinear model to represent a typical steel structure;
- Degrading tri-linear model to represent a typical R.C. structure; and
- Biaxial hysteretic model to study the effects of biaxial interaction.

For all the above models, a viscous damping value of 5% and a post-yield stiffness ratio of 0.01 (1% of the initial stiffness) are assumed. Therefore, a system can be defined by the elastic vibration frequency, f, and the yield strength in terms of seismic coefficient, C. For the degrading tri-linear model, the so-called 3-parameter model is used (Park, 1987), in which the secant stiffness at yield point is assumed to be 50% of the initial stiffness. An example of the degrading hysteretic model is illustrated in Figure 5. For the tri-linear model, the ductility factor is calculated as the deformation ratio to the elastic deformation at the yield level; therefore, a ductility factor of $\mu = 2.0$ is assigned at the yield point.

Table 1 Peak Values of Ground Motions

EQ/STATION	COMPONENT	ACCELERATION	VELOCITY	DISPLACEMENT
Great Kansai 1995 JMA Kobe Station	Vertical N-S E-W	0.339 g 0.835 g 0.630 g	40.5 cm/sec 92.3 cm/sec 75.7 cm/sec	16.4 cm 25.4 cm 15.8 cm
Northridge 1994 Sylmar Hospital	Vertical N-S E-W	0.536 g 0.844 g 0.605 g	19.2 cm/sec 129.1 cm/sec 77.6 cm/sec	10.5 cm 30.7 cm 20.1 cm
Imperial Valley 1940 El Centro	Vertical N-S E-W	0.211 g 0.349 g 0.214 g	10.8 cm/sec 33.4 cm/sec 36.9 cm/sec	5.6 cm 10.9 cm 19.8 cm

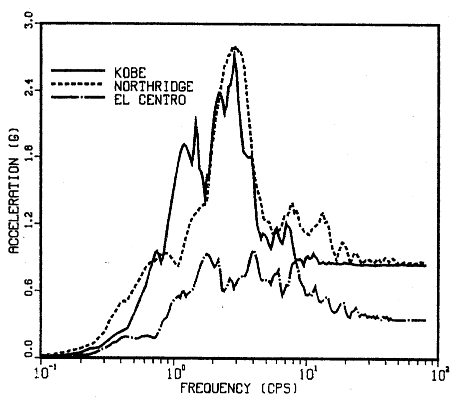


Figure 3 Linear Acceleration Response Spectra of N-S Components

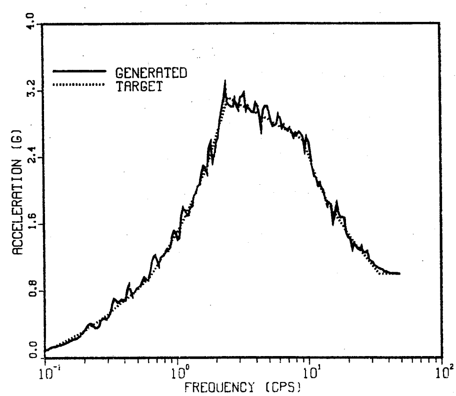


Figure 4 An Example of Generated Motions for REG 1.60 Spectrum

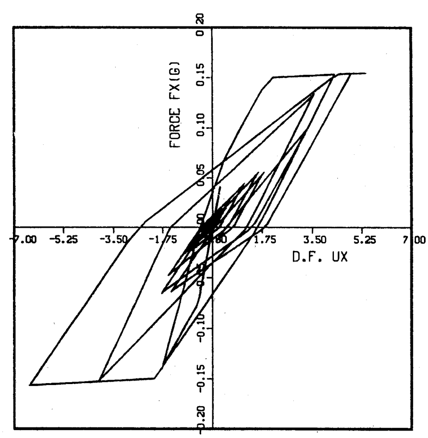


Figure 5 An Example of Hysteretic Response of 3-Parameter Model

3 DUCTILITY AND STRENGTH DEMANDS

Only the N-S components of recorded motions are used in the following parametric studies. Figures 6 and 7 show the ductility demands for bilinear models with yield strength of 0.3g and 0.6g, respectively. The artificial motions are scaled (in terms of mean value) to have ZPA values of 0.3g and 0.8g, and are called REG 1.60-0.3g and REG 1.60-0.8g as indicated in Figures 6 and 7.

For structures with a relatively low yield capacity of 0.3g, the ductility demands for the close-distance motions (i.e., Kobe and Northridge motions) are about twice higher than those for the El-Centro motion at a frequency range lower than, say, 1.5 Hz, as indicated in Figure 6. In the higher frequency range, the ductility demands increase significantly in comparison with those for the El-Centro motion. It can also be observed that the ductility demands of REG 1.60-0.3g are similar to those of El Centro and REG 1.60 - 0.8g for the close-distance motions.

For structures with a higher yield strength capacity of 0.6g, only moderate (ductility factor less than 2.0) ductility demands are found in Figure 7 for El Centro and REG 1.60-0.3g motions. The ductility demands for REG 1.60-0.8g tend to increase rather smoothly at higher frequencies, but those from the close-distance motions have a distinct peak, at 2.5 Hz for the Kobe record and at 4 Hz for the Northridge record.

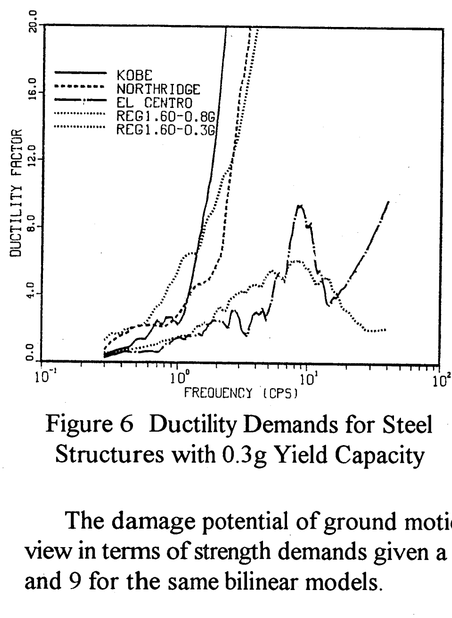


Figure 6 Ductility Demands for Steel Structures with 0.3g Yield Capacity

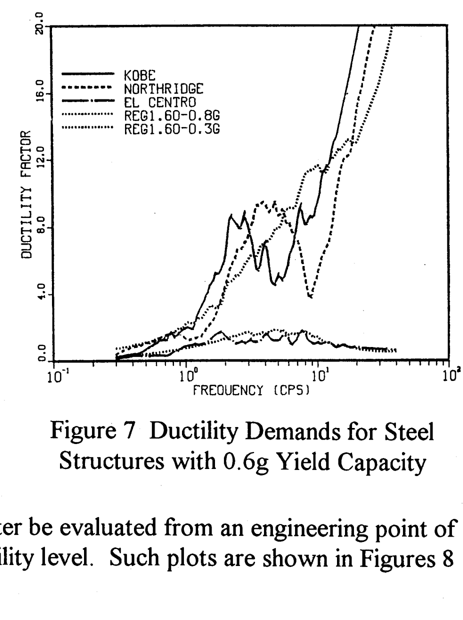


Figure 7 Ductility Demands for Steel Structures with 0.6g Yield Capacity

The damage potential of ground motions may better be evaluated from an engineering point of view in terms of strength demands given a certain ductility level. Such plots are shown in Figures 8 and 9 for the same bilinear models.

At a moderate ductility level of $\mu = 2.0$ shown in Figure 8, the shapes of the nonlinear spectra are somehow similar to those of linear spectra shown in Figure 3, but the spectral peaks are shifted to higher frequencies, and the magnitude of the spectral values is reduced. In general, the strength demands for the close-distance motions are 2 to 3 times higher than those for the El Centro motion. Particularly, at a frequency range of 1.5 to 5 Hz, where most low and medium-rise buildings belong, the calculated strength demands far exceeds the seismic code requirements. This may be consistent with the observed heavy damage in older buildings with relatively poor deformation capabilities in both the Northridge and Great Kansai earthquakes.

The nonlinear spectra for a higher ductility of $\mu = 10$ shown in Figure 9 are quite dissimilar to the linear spectra. The reduction in strength demands becomes more significant for structures with lower frequencies, and spectral peaks become less visible. In general, the strength demands for the close-distance motions are about two times larger than those of El Centro motions, which are quite consistent with REG 1.60-03.g. It can be observed that at a frequency range higher than 2 Hz, the strength demands are still higher than 0.5g for both Kobe and Northridge records although a large ductility of $\mu = 10$ is considered.

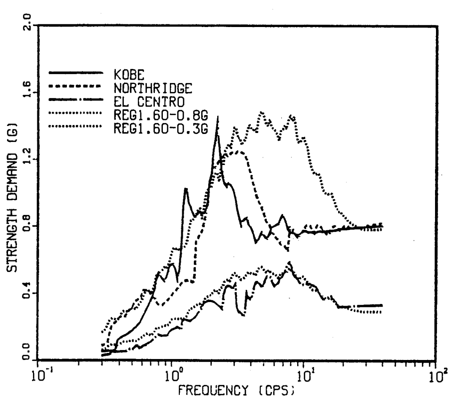


Figure 8 Strength Demands for Steel Structures at Ductility Level of $\mu = 2$

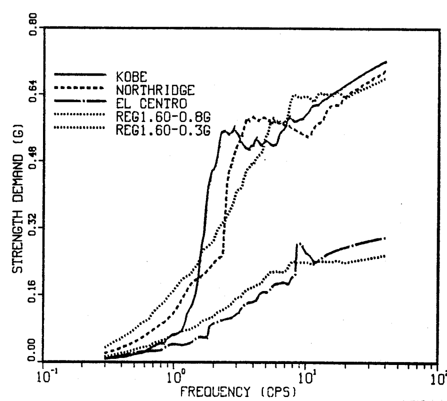


Figure 9 Strength Demands for Steel Structures at Ductility Level of $\mu = 10$

Similar plots are shown in Figures 10 and 11 for trilinear models to represent typical reinforced concrete structures. As mentioned above, a ductility factor of 2.0 for trilinear models corresponds to the yield deformation. Therefore, the nonlinear spectra in Figure 10 are for brittle R.C. structures with no deformation capabilities beyond the yield points. In comparison with the foregoing cases for bilinear models in Figure 8, spectral peaks are smoother, but otherwise no significant differences are observed.

When a ductility factor of $\mu = 10$ (5 times yield deformation) is considered for trilinear models in Figure 11, the calculated strength demands are higher than the foregoing Figure 9, particularly at the higher frequency range. This may be due to a lower energy absorbing capability of R.C. structures in comparison with ductile steel structures.

Although the above analysis results are rather striking, the damage potential on actual building structures should be evaluated based on more detailed component-based nonlinear analyses. The above analysis results may be more applicable to weak-column type buildings. The energy absorbing capability of weak-beam type buildings with a minimum code-defined yield strength may still be sufficient depending on the structural design details of components and joints.

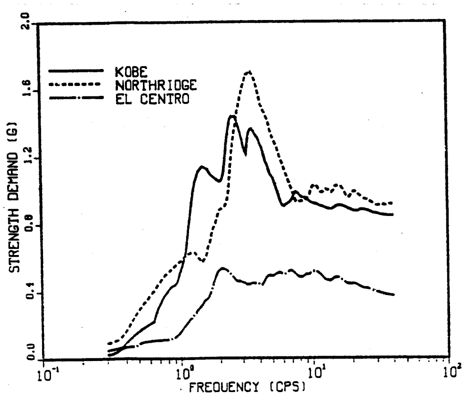


Figure 10 Strength Demands for R.C. Structures at Ductility Level of $\mu = 2$

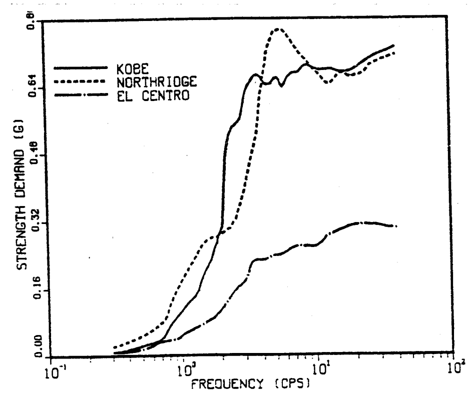


Figure 11 Strength Demands for R.C. Structures at Ductility Level of $\mu = 10$

4 EFFECTS OF BIAXIAL GROUND MOTIONS

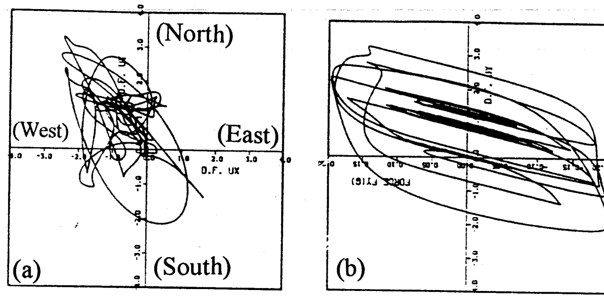
While all the above analyses are based on the uniaxial input assumption, actual structures were subjected to three components of ground motion. The effects of the simultaneous shaking in the two orthogonal horizontal directions are examined using a simple SDOF system with a smoothed biaxial hysteretic model (Park, 1992). The system is assumed to be isotropic, i.e., the hysteretic characteristics are identical in all the horizontal directions. A viscous damping of 5% and a post-yield stiffness ratio of 0.01 were assumed in all the directions; therefore, the system can be defined again by the elastic frequency, f, and the yield strength in terms of seismic coefficient, C.

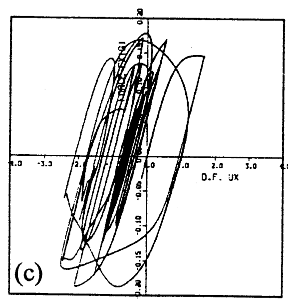
Figures 12 and 13 show examples of the calculated biaxial responses for the Kobe station records. In the example in Figure 12, no significant interaction effects are observed; i.e., the peak displacement responses in the N-S and E-W directions are approximately the same with those obtained by independent uniaxial input. However, in the case of Figure 13 for a higher vibration frequency, the peak biaxial response of $\mu \simeq 12$ is more than twice that of the uniaxial responses ($\mu \simeq 5$). A distinct directionality in the North-West direction is observed in Figure 13, which approximately coincides with the direction some buildings collapsed at a medium-height story (e.g., Kobe City Hall, Ref. 1).

Since only a few cases have been analyzed to study the effects of the biaxial ground motions, it is not possible to draw a general conclusion regarding the biaxial interaction effects associated with the close-distance ground motions. Nevertheless, the results imply that some structures may have been subjected to an inelastic distortion higher than predicted by ordinary uniaxial input response analyses.

5 CONCLUSIONS

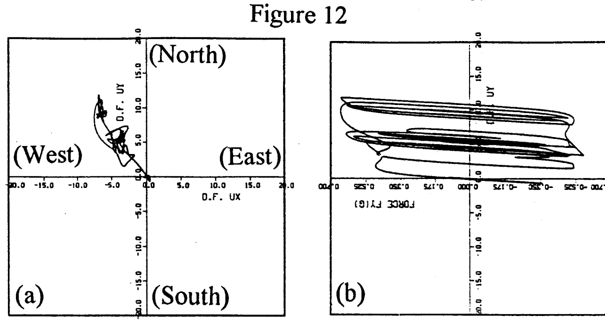
The damage potential of recently obtained close-distance ground motions were evaluated based on nonlinear responses of various SDOF systems. In terms of both strength and ductility demands, the Kobe station and Sylmar Hospital records were considered to be approximately equivalent to the REG 1.60 spectra with a 0.8 ZPA. The calculated strength demands of these close-distance motions are at least twice higher than those of the El Centro record, which was considered to be approximately equivalent to the REG 1.60 spectra with a 0.3 ZPA. However, for structures with an elastic frequency between 2.5 to 5 Hz and with poor deformation capabilities, the calculated strength demands are significantly higher than the seismic load levels considered in most existing design codes. These structures represent older low- to medium-rise buildings, that were heavily damaged during the two earthquakes. The effects of biaxial ground motions were also studied using the Kobe station records. It was concluded that, due to strong directionality of close-distanced ground motions, some structures may have been subjected to an inelastic

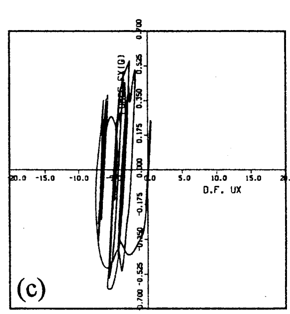




(a) Displacement Trajectory (in terms of ductility factor)
(b) Hysteresis in North-South Direction
(c) Hysteresis in East-West Direction

Figure 12 Biaxial Responses for Kobe Station Records (f = 1 Hz, C = 0.2g)
Figure 12





(a) Displacement Trajectory (in terms of ductility factor)
(b) Hysteresis in North-South Direction
(c) Hysteresis in East-West Direction

Figure 13 Biaxial Responses for Kobe Station Records (f = 5 Hz, C = 0.6g) distortion higher than predicted by ordinary uniaxial input response analyses.

6 DISCLAIMER

This work was performed under the auspices of the U.S. Nuclear Regulatory Commission. The findings and opinions expressed in this paper are those of the authors, and do not necessarily reflect the views of the U.S. Nuclear Regulatory Commission or Brookhaven National Laboratory.

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