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Probabilistic Response of Seismically Isolated Structures

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ABSTRACT

This paper presents a probabilistic study of the seismic response of base isolated buildings. On the basis that the statistical variation of peak seismic response follows a Gumbel Type I extreme value distribution of largest values, the paper develops exceedance probabilities of peak displacements and accelerations, for given seismic intensity and characteristics of the isolation system. These are presented in a graphical format which can be used to determine the parameters of the base-isolation system required to meet target exceedance probabilities. The study includes the variability in seismic ground motion by using 50 randomly generated synthetic records with spectral characteristics representative of earthquakes of firm to medium stiff sites. The isolated structure is considered to displace as a rigid body on the base-isolation system, which is represented by a softening bilinear force-displacement relationship.

1 INTRODUCTION AND SCOPE

Seismic Isolation incorporated into the foundations of buildings is increasingly accepted as a practical, viable option in the seismic design of structures. In anticipation of its use, recommended guidelines for the design of seismically isolated buildings are being promulgated in various countries, e.g. the SEAOC in the United States (SEAOC, 1990). Worldwide, the number of isolated structures, built or under construction, is currently reported to be well over one hundred.

Seismic isolation reduces the acceleration response in the supported structure at the expense of relatively large displacement across the isolation interface. For the most part, these response quantities control the design of the isolation system. It is therefore, particularly important to have good estimates of both early on as they potentially affect the structural and perhaps even the layout and architectural concept of the building. The currently prominent base-isolation systems use reinforced elastomer bearings to support the isolated structure. Most systems also incorporate some means of energy absorption either externally (lead plug, friction surface) or by specially compounding the elastomer to improve its damping properties. Figure 1 presents a load displacement model which captures experimentally recorded nonlinear behavior of isolation bearings. The parameters "k", the initial slope, "p", the second slope, and "b", the ordinate intercept define the bilinear load displacement relationship. Important properties reflected in the bilinear curve are its nonproportionality and non-conservative characteristics.

Since the seismic isolation system is relatively flexible in the horizontal direction, higher frequency horizontal ground motions are significantly attenuated. The resulting response derives only a small participation from the superstructure and the nonstructural components. Consequently, the isolated structure responds predominantly as a rigid body and, $M\ddot{x} + C\dot{x} + f(x) = -M\ddot{s}$, defines its gross seismic response, where M is the mass of the isolated structure above the isolation system, s denotes the ground acceleration, and x is the displacement of M, relative to the ground. The function f(x) is the bilinear force-displacement relationship of

SMiRT 11 Transactions Vol. K (August 1991) Tokyo, Japan, © 1991

the base isolation system. It automatically incorporates the system's hysteretic damping. The coefficient C, represents the damping resulting from the visco-elastic nature of the elastomers. In general, this damping decreases with frequency and for the low frequency response of base-isolated structures, the visco-elastic damping is expected to be relatively small. The study reported here assumes a viscous damping of 2 percent of critical defined in terms of the second slope. The equation of motion illustrates that three parameters control the seismic response of an isolated structure namely, the tangent frequency, f, based on the second slope, the ratio of b/M or, equivalently, the dimensionless ratio b/W, where W is the weight of the structure, and the ratio, r, of the second to initial stiffnesses.

2 PROBABILISTIC APPROACH

In general, factors of safety incorporated into design, account for the uncertainty in load and the strength of structural components. Seismic design recognizes that due to their random nature, future seismic events can be described only in terms of some probabilistic model. Accordingly, it assigns an acceptable risk in the design process in terms of an allowable response. Consistent with this philosophy, the study reported here addresses the isolated structure response in terms of exceedance probabilities which quantify risk and provide a means for acceptance criteria for safety in the design of isolation systems. Since the elements of the isolation systems are generally subjected to stringent quality control requirements, testing programs, and inservice inspections, the variations their mechanical properties are expected to be small and this study assumes that the load deformation characteristics of the seismic isolation system are deterministic. Various isolation types are included by systematically varying the parameters of the bilinear models representing them.

The paucity of actual records available for given site characteristics (topographical, soil, and geotectonic conditions) and with the required intensity is too small to be statistically significant. Consequently, this study uses the stochastic model developed by Ruiz and Penzien (1969) to generate 50 synthetic acceleration records for use in the analysis as seismic input. The overall characteristics of the records were selected to represent medium stiff site conditions. The records were 30 seconds duration and normalized to have a peak ground acceleration of 0.3g. Admittedly, the coefficients of variation inherent in real earthquakes are generally larger than in simulated records with a given spectral density. On the other hand, the variability of synthetic accelerograms might be more representative of a fixed site, since the stratigraphy and other relevant geotechnical characteristics are constant, and epicentral distance and source mechanisms of controlling events are often similar for a site.

Consistent with reported studies on the probabilistic seismic response of nonlinear structures (e.g., Penzien and Liu, 1969, Vaidya and Eggenberger, 1984) the peak response to single events follows the Gumbel Type I distribution whose cumulative probability function is given by $F(x) = \exp[-\exp(-y)]$, and $y = v(x-u)$, where, x is the response of interest, y is the reduced extreme value, and v and u are the parameters of the distribution. For a sample of 50 values of x, $v = 1.1607/S$ and $u = m - 0.5485/v$ (Gumbel, 1958), where m and S are the mean and the standard deviation of the sample.

3 PARAMETRIC STUDY

This study systematically analyses the influence the three parameters that control the seismic response of the isolated structure. The choice of the values and combinations of the parameters was directed by the need to cover different types of isolation systems and force-displacement characteristics. Tangent frequency, f, ranged from 0.25 to 0.60 Hz. resulting in effective frequencies (calculated with the effective secant stiffness on Figure 1) between 0.3 and 1.0 Hz. Most cases of interest in design practice use effective frequencies in this range. Based on reported experimental and analytical studies, the ratio r was varied with f according to the equation $r = 0.5\,f - 0.05$. Additionally, presumptive upper and lower bounds of r were also considered to examine the sensitivity of the response to this parameter. For each combination of f and r, the ratio b/W varied in the range between 0.02 and 0.15, resulting in a total of 198 triplets of the parameters. For each triplet nonlinear dynamic analyses using the 50 synthetic records provided the statistical sample of the response quantities of interest.

4 PEAK RESPONSE OF ISOLATED STRUCTURE

Figure 2 presents the cumulative probability distribution of typical peak relative displacements, D, and total acceleration, A, plotted on a Type I Gumbel paper and illustrate that the response conforms to a straight line theoretical probability distribution. Figure 2 reveals that the cumulative distribution of peak acceleration is strikingly similar to that of peak displacements. This is due to the relatively small viscous damping used in the analysis in which case the equation of motion predicts that A is approximately equal to the maximum of $f(x)/M$, or $f(D)/M$. Thus, the calculated pair "D, A" defines a point on the bilinear force-displacement function used.

5 RESPONSE EXCEEDANCE PROBABILITIES

Based on the above discussion, the study uses the parameters u and v of the theoretical Gumbel Type I distribution to calculate the response "D,A" pairs corresponding to exceedance probabilities of 50, 25, 15, 10, 5, 2, and 1 percent. Contours of "D,A" pairs corresponding to constant exceedance probability were developed onto the load-displacement space capable of also representing the normalized bilinear force-displacement functions as illustrated in Figure 3. This Figure incorporates the results for a particular category of isolation characteristics defined by the tangent frequency f, and the ratio r. A complete set of such plots for all (f,r) combinations representing various isolation system characteristics is provided in a research report by the authors (Bazan and Vaidya, 1991).

Figure 3 can be used in a variety of ways. First, it provides a simple means to estimate peak response values for a given structure weight, exceedance probability, and a prescribed bilinear force displacement relationship. A specific value of b/W and the exceedance probability determine a unique point defining the shear force and displacement of the chosen isolation system category. Due to the manner in which the force-displacement relationship have been normalized this point also defines the peak response displacement and acceleration. If the three parameters defining the bilinear force-displacement relationship are known, Figure 3 provides the exceedance probabilities for different values of peak relative displacements. The corresponding peak accelerations are automatically defined on the vertical axis. Conversely, Figure 3 can be used to determine the required force-displacement characteristic of the isolation system that will lead to pre-established peak displacements and accelerations for any given exceedance probability. For example, assume that the target peak responses is 6 inches of displacement and 0.12g acceleration, with an exceedance probability of 10 percent. Entering in Figure 3, 6 inches of displacement and the intermediate (10 percent) probability curve results in an acceptable peak response acceleration equal to 0.10g for f = 0.25 Hz. r = 0.05 and b/W = 0.06. Other similar plots can be examined to obtain an optimum set of values of f, r and b/W.

The effective frequency in hertz (calculated with the secant stiffness defined on Figure 1) of the isolated structure can be estimated as $3.13\sqrt{A/D}$, where A is the normalized bearing shear force and D is the peak relative displacement, as they are read on the vertical and horizontal axes of Figure 3. For instance, if we read $A = 0.10g$ and $D = 6$ inches, the effective frequency is $3.13\sqrt{0.10/6} = 0.4$ Hz.

6 INFLUENCE OF THE ISOLATION SYSTEM CHARACTERISTICS ON RESPONSE

Sensitivity analysis provides insights into the variations that can be expected from changes in the isolation system characteristics. The study examined the mean peak response quantities as a function of b/W , f and r. We found that in general, for constant f and r peak displacements decrease and peak accelerations increase with increasing b/W. In the lower range of b/W, the displacements are more sensitive than accelerations to changes in b/W;and the reverse is true in the upper range. Displacements are relatively less sensitive to f than accelerations, especially in the upper ranges of b/W. On the other hand, displacements are relatively more sensitive to the ratio r than accelerations. The systematic variation of the peak response with both r and b/W allows approximating the mean peak displacement, D', for any value r' of the ratio r, in terms of the result, D, obtained for the basic value, r, as $D' = cD$, where $c = 1 + 8(b/W)(\sqrt{q} - 1)$ and $q = r'/r$. For b/W less than 0.10, the errors in this approximation are less than 5 percent, and are within acceptable range for preliminary design.

We also examined the coefficients of variation (COV) of displacements and accelerations as function of the ratios r and b/W. The COV's for displacements are relatively unaffected by variations in the ratio r while those for accelerations are affected somewhat more, but the differences in the COV's are less than 10 percent for b/W lower than 0.12. We conclude that the COV's for the base value of r are sufficient to provide a "measure" of the statistical variability of the response.

7 EQUIVALENT ELASTIC ANALYSIS

For bilinear softening systems the effective stiffness and the effective viscous damping ratio corresponding to the peak bearing displacements are given in Figure 1. We calculated the linear elastic response using these effective stiffness and damping ratios. Figure 4 presents the ratios of equivalent elastic to inelastic displacements and acceleration as a function of the effective damping ratio, for values of f and b/W up to 0.5 Hz and 0.1, respectively. The figures indicates that the linearization results in significant error for larger damping ratios. Indeed, this is to be expected because larger effective damping represents a stronger system non-linearity. If the damping ratio is smaller than 20 percent, the equivalent elastic analysis underestimates displacements by less than 4 percent and always overestimates accelerations. For higher damping values, which are not uncommon in seismic isolation systems, the errors are as high as 25 percent in displacements and 10 percent in accelerations.

We conclude that when the seismic isolation system is expected to account for relatively significant energy dissipation, equivalent elastic analysis is acceptable to predict peak accelerations, but it could potentially underestimate peak displacements by as much as 25 percent. SEAOC requirements offset this by recommending response reduction factors associated with effective damping which are smaller than theoretically calculated for a linear structure.

8 CONCLUDING REMARKS

This paper has addressed the probabilistic seismic response of base isolated buildings. Variations in the seismic ground motions have been represented by considering 50 synthetic records, randomly generated but with spectral characteristics representative of earthquakes recorded on firm to medium stiff sites. Upon verification that the statistical variation of peak response can be represented by Gumbel Type I extreme value distribution, the study has evaluated exceedance probabilities of the response quantities. Only horizontal seismic isolation is considered and the influence of the isolation characteristics on the parameters of the probability distribution of seismic response has been examined. Exceedance probabilities are presented in a convenient graphical format for various levels of response and force displacement relationships on which the response is based. The results correspond to a peak ground acceleration (PGA) of 0.3g. However, by scaling both axes of the graphical format, the constant probability response presented herein can be easily adopted for other PGA's (Bazan and Vaidya, 1991).

The data presented here is expected to be useful to determine the essential features of the isolation system in the early stages of seismic design, and also to verify the results of subsequent final analyses which, among other issues, use specific structure and site data and include effects of vertical ground motions and torsional response. The results are limited to rigid structures and isolation systems whose lateral force displacement characteristics can be appropriately represented by softening bilinear hysteretic curves. Additional work planned will develop similar information including effects of structure flexibility and for other isolation systems, for example, those that exhibit stiffening at larger displacements.

8 ACKNOWLEDGEMENTS

The support of the National Science Foundation under Grant No. BSC-8818258 is gratefully acknowledged. The cognizant NSF official is Dr. John Scalzi. Any findings, opinions, and conclusions or recommendations are those of the authors and do not necessarily reflect the views of the sponsor.

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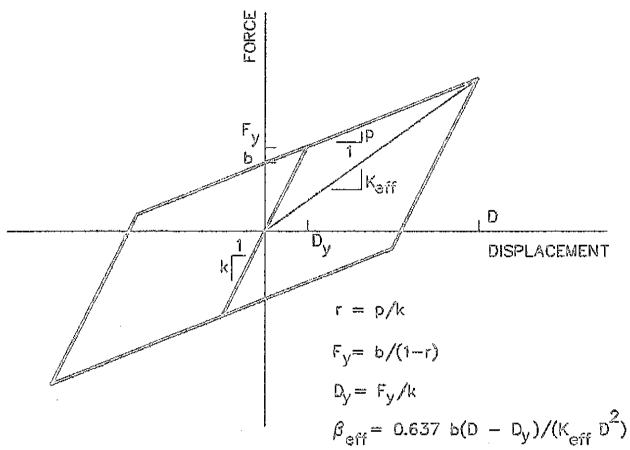

FIG. 1. BILINEAR HYSTERESIS CURVE

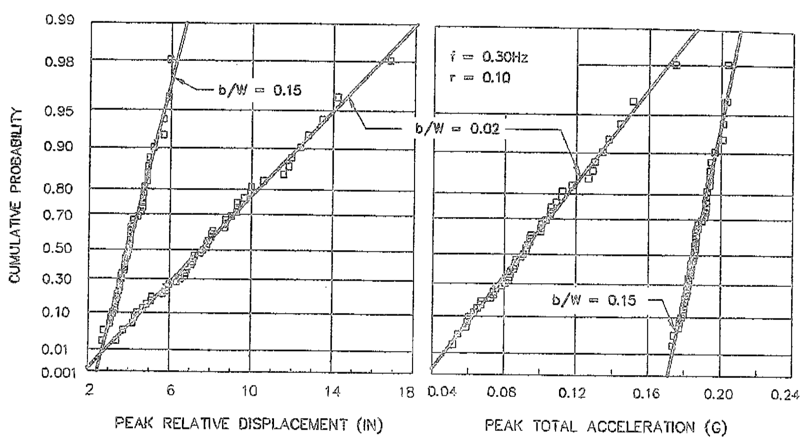

FIG. 2. PROBABILITY DISTRIBUTION OF PEAK RESPONSE

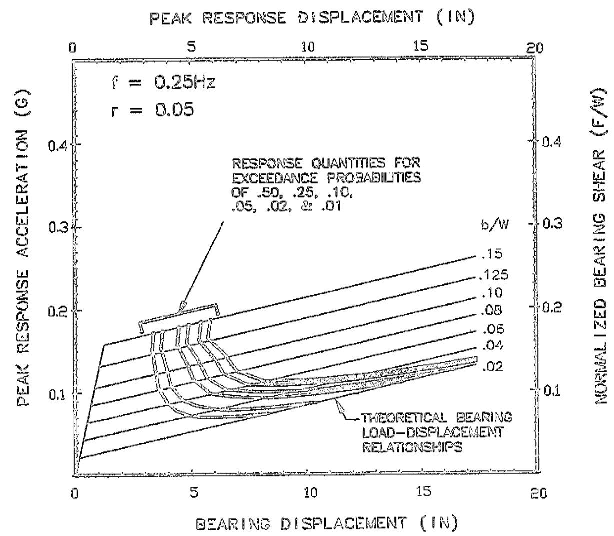

FIG. 3. EXCEEDANCE PROBABILITY FOR BASE-ISOLATED RESPONSE

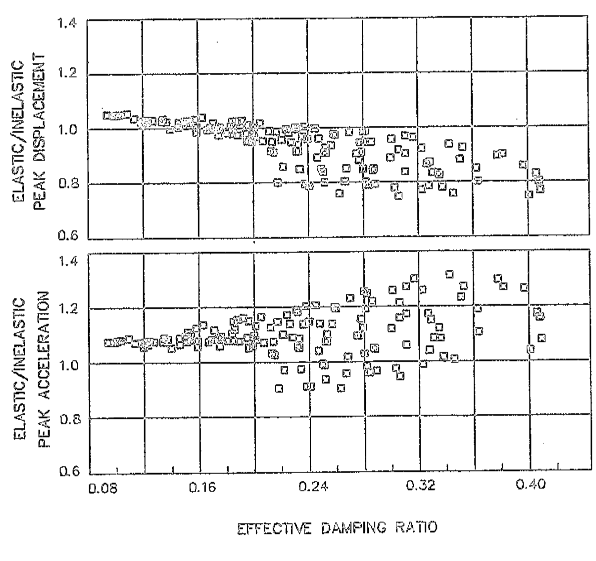

FIG. 4. RATIO OF ELASTIC TO INELASTIC RESPONSE