

**EFFECTS OF DURATION ON STRUCTURAL RESPONSE FACTORS AND
ON GROUND-MOTION DAMAGEABILITY**

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ABSTRACT

Ground-motion records from the California Strong Motion Instrumentation Program (CSMIP) and from other sources are used to examine relationships between strong-motion duration, elastic strength demands, structural response factors, and inelastic strength demands, as derived from analytical study.

Structural response factors R are found to have generally slight systematic dependence on strong-motion duration, but they do have a more direct, if not fundamental, relationship to characteristics of elastic response spectra. In addition to the general lack of correlation between R and duration, both elastic and inelastic strength demands (and hence, ground-motion damageability also) show little apparent consistent systematic correlations with duration.

Results of this study imply that seismic load specifications, for safety analysis or design of buildings, can generally be adequately described by appropriate ground-motion spectra without the need to explicitly specify an associated duration.

INTRODUCTION

Intuition leads one to believe that duration plays a key role in the damage effectiveness of strong ground motion. Clearly, if a motion has insignificant duration with respect to the periods of dominant participating modes of vibration for a particular building, it should generally possess little potential to affect response, much less damage, in that building. In addition, short-duration motions do not have the potential to induce several hysteretic cycles of response which are associated with the type of non-linear "ratcheting" often thought to be necessary to damage ductile structures.

Structural response factors, R , describe allowable yield-force reduction factors associated with a given (tolerable) state of damage (as may be characterized, for example, by ductility, normalized hysteretic energy, cumulative damage measures, etc.). Expecting that duration is relevant to motion damageability, therefore, one might logically expect that values of R should depend on duration. In particular, if long-duration motions are more damaging, lower values of R (i.e., lower allowable yield-force reductions for a given damage state) would be expected (and accepted) for such long-duration motions, whereas higher values of R would be acceptable for short-duration records. Stated alternatively, if two motions (one of long-duration and one of

short-duration) produce the same elastic force in a given structure, and the structure is designed to yield at a force level equal to that elastic force divided by a given factor R , then a greater level of damage would generally be expected for the long-duration record, assuming that damage is relevant to duration.

A significant objective of this study has been to test this hypothesis, and to clarify the role of duration by investigating the dependence of R factors, elastic strength demands, and inelastic strength demands on duration. A key question to be addressed is: Given the common engineering intuition and observations that duration has an important influence on motion damageability, should R factors be specified explicitly on the basis of design-motion durations? If not, then how do we insure that the impacts of duration have been adequately considered in design?

The variety and significance of ground-motion records obtained by the CSMIP lead to a productive basis for conducting this investigation.

BACKGROUND

Results of previous research [1-4], not directly aimed at evaluating the effects of strong-motion duration, strongly imply that structural response factors do not have a clear systematic dependence on duration. Rather, these studies suggest that values of R may be only indirectly related to strong-motion duration through the intrinsic effects that duration has on the characteristics (namely, amplitude and breadth of frequency content) of the elastic response spectrum, and through systematic effects that the elastic response spectrum has on R factors.

To illustrate this point, we compare the seismic demands imposed by two motions, of differing durations, which were obtained by CSMIP following the 10/17/89 Loma Prieta, California earthquake. Figure 1 shows 5%-damped linear response spectra for the 0-deg component of the UCSC/Lick Lab., Santa Cruz recording and the 0-deg component of Aloha Ave., Saratoga recording, both scaled to a PGA of 0.5g. These two records are selected because the UCSC recording has a substantially (about 60%) longer duration than the Saratoga recording (see Figures 2 and 3). Using a duration measure T'_D proposed by Kennedy *et al.*[4], for instance, the strong motion duration of the UCSC and Saratoga records are, respectively, 5.96 and 3.78 seconds. Note also that at 2.0 Hertz, the spectral accelerations are equal for the two records. Hence, if ground-motion damageability is strongly dependent on duration, one would expect the 2.18-second-longer UCSC record to be more damaging to a 2.0-Hz structure designed for a given spectral reduction (R) factor. Table 1 shows, however, that this is not the case; for identical design yield forces associated with an R factor of 4.0, all damage parameters computed for the Saratoga record exceed quite substantially those computed for the UCSC record. In addition, the computed R factors for a constant level of normalized hysteretic energy (NHE) equal to 10.0 are 4.3 and 2.9, respectively, for the UCSC and Saratoga records; hence, the 2.0-Hz structure, would have to be designed to have a yield force 50% greater in the case of the Saratoga record (*vis-à-vis* the UCSC record) to limit the NHE damage parameter to 10.0, despite the facts that the duration of the UCSC record is substantially greater and the spectral amplitudes at 2.0 Hz for the

two records are the same.

One important reason the Saratoga record is more damaging than the UCSC record, despite its shorter duration, is that its energy content (linear spectral amplitudes) at all frequencies less than 2.0 Hz is substantially greater than that for the UCSC record (as can be seen in Figure 1). Hence, when the structure yields, and its predominant frequency decreases (due to stiffness-reduction softening), it becomes more desensitized to the UCSC input than the Saratoga input, because the Saratoga input has substantially greater energy at frequencies lower than 2.0 Hz.

In this case (and most cases), this spectral effect is much more significant than any direct effect of duration; although duration can have a significant effect for certain cases. Clearly, there are simple academic cases where, given a fixed elastic spectral demand, duration can be found to have an important impact on damage. Real-earthquake motions, however, typically exhibit a characteristic pattern of nonstationarity (i.e., build-up phase, single strong-motion phase, and decay phase) that acts to de-sensitize damage models to duration (i.e., because the response is constrained such that most of the damage accumulates in a few characteristic peak cycles in the strong-motion phase). The use of real earthquake records is therefore essential in studying the impact of duration on R factors, both in analytical studies, as well as in laboratory tests. Certain real ground motions can be expected to reveal an explicit dependence of R on duration--for instance, a so-called "double-event" recording; however, it is anticipated that the number of such records in the ground-motion database may be comparatively few.

STUDY APPROACH

With this background, the approach in this study has been to undertake a direct investigation of the relationship of strong-motion duration, elastic and inelastic strength demands, and structural response factors, based on analytical results pertaining to a comprehensive set of ground-motion records.

Whereas R factors are conventionally thought to be inherent properties of structural systems, this study assesses and treats R factors as characteristics of ground motions (for given structures), just as peak ground accelerations, velocities, displacements, and elastic response spectra are routinely assessed and reported as characteristics of ground motions. For any given ground motion, R depends on the structural vibration frequency, the value of damping, the type of structural system, and the damage parameter of interest.

Here, we examine a set of 262 ground-motion records. For each ground motion, we considered 91 structural vibration frequencies, ranging from .067 to 25.0 Hz. Hysteretic models characterizing bilinear behavior and shear-wall type behavior were both used for nonlinear analyses in each case. A damping ratio of 5% (proportional to elastic stiffness) has been used for all analysis. For a given type of hysteretic behavior, four levels of damage for each of six damage measures were considered in evaluating R factors. These damage indices include, for instance, four values of ductility (e.g., 2,4,6,8), normalized hysteretic energy, cumulative damage measures, and state variables based on ductility and hysteretic-energy demand parameters. These

damage models are representative of modern methods for measuring or characterizing damage, and they include both what may be categorized as duration-sensitive (e.g., normalized hysteretic energy) and duration-insensitive (e.g., ductility) models. Conventionally, analytically derived R factors are computed based on ductility response. Because, however, ductility does not increase directly with numbers of nonlinear cycles (and hence, duration) it, by itself, does not provide a suitable basis for examining the effects of duration on R factors.

Two methods are used for assessing strong-motion duration in this study. The first measure of duration, T'_D , is defined as [4]:

$$T'_D = \text{Max} \left[\begin{array}{l} T_{75\%} \\ T_{pga} \end{array} \right] - T_{5\%}$$

where $T_{x\%}$ is the time at which x% of the input energy is achieved. Input energy at time T is given by [5,6]:

$$E_T = \int_0^T a^2(t) dt$$

where $a(t)$ is the ground acceleration at time t. T_{pga} is the time of occurrence of the peak ground acceleration. The second duration measure, T_D , is given as:

$$T_D = T_{95\%} - T_{5\%}$$

SAMPLE STUDY RESULTS

An extensive database of results on inelastic demands, structural response factors, and ground-motion durations have been obtained from this project, both for use in this study as well as for use by the research community. Figures 4 to 11 illustrate one use of this data--in investigating potential relationships between strong-motion duration and structural response factors R for the present study. Figures 4 to 7 show (respectively, for vibration frequencies of 0.1, 1.0, 10 and 25 Hz) plots of structural response factors versus strong-motion duration T_D , based on an inelastic-response/damage measure of NHE = 16.4 and bilinear hysteretic behavior. Similar results have been obtained for other damage measures and for the duration measure T'_D . Figures 8 to 11 show corresponding results for shear-wall hysteretic behavior (with NHE=11.1). In Figures 4 and 8 (for 10 Hz), the only dependence of R on duration is that low values of R occur systematically in instances where the duration is lower than the predominant period of vibration; otherwise no meaningful correlation between R and T_D can be observed. However, for higher frequencies, a generally increasing (inverse) correlation, although slight, is observed between R and T_D . These results reveal that nonlinear-response based factors have surprisingly little dependence on strong motion duration. Based on numerous other results obtained in this

study, this observation appears to be robust with respect to damage model, hysteretic behavior, duration measure, and all other parameters of importance in assessing ground-motion damageability based on analysis.

Whereas, values of R cannot be shown to have a clear relationship to duration, a fundamental dependence of R on elastic demand spectra can be clearly demonstrated. Figure 12, for instance, shows how R may be accurately predicted based on a simple function of elastic response spectral ordinates alone, without regard to duration. In this case, the equation used to predict R is given by Kennedy, *et. al* [4] as:

$$R_{\mu} = \mu \left(\frac{f_e}{f} \right)^2 \left[\frac{S_a(f, \xi)}{S_a(f_e, \xi_e)} \right]$$

where f and f_e are, respectively, the initial frequency and effective frequency; ξ and ξ_e are values of initial and effective damping; and S_a denotes the elastic demand (i.e., spectral acceleration). For shear-wall type behavior, a ductility factor of 4.0, and initial damping of $\xi=5\%$, values of $(f_e/f)=0.6$ and an effective damping of $\xi_e=10\%$ of critical, describe appropriate values of effective frequency and damping. Hence, values of R for ductility response in a shear-wall type structure may be simply estimated from the following equation:

$$R_{\mu=4} = 1.44 \left[\frac{S_a(f, .05)}{S_a(0.6f, 0.1)} \right]$$

The results in Figure 12 show very good correlation using this formula. Similar formulas are expected to produce good correlations for other damage models. Hence, values of R are predominately effected by the spectral effect discussed earlier, and are related to a simple ratio of elastic demands factored by a constant, without explicit consideration of duration effects.

Figures 13 and 14 illustrate that elastic and inelastic spectral demands also have little consistent relationship to strong-motion duration. These figures show a marked lack of correlation with duration, whereas some cases that produce a slight correlation may be found. Because inelastic demand spectra characterize the damage potential of ground motion [1,8], it is difficult to conclude (based on analysis) that ground-motion damageability has a clear, or even meaningful, dependence on strong-motion duration.

Following the 10/17/89 Loma Prieta earthquake, a number of experts were quoted as saying that the damage from the earthquake would have been much greater if the duration had been significantly longer. While such a statement may be conditionally true (for instance, a greater earthquake magnitude may be needed for a greater duration) it encourages the public to

doubt that duration has been meaningfully factored into the seismic design process by structural engineering professionals.

As the results here confirm, however, the meaningful effects of duration are factored into the design process through the selection of appropriate design spectra. This confirmation, however, is conditional on the applicability of modern analytical models and procedures.

CONCLUSIONS

Structural response factors R have a fundamental relationship with elastic spectral demands. Elastic and inelastic spectral demands show inconsistent correlation with strong-motion duration. Additionally, values of R , themselves, show only slight correlation with duration.

In the SMIP91 proceedings, a paper by Miranda and Bertero [7] concluded that structural response factors are strongly affected by natural period of vibration, the level of inelastic deformation, and local site conditions. The results of this study and previous studies [1,4,8] echo these conclusions. Because of correlation between elastic demands and R factors, for design, it is best to specify site-dependent inelastic spectra directly for a particular state of damage (inelastic response) of interest. (Methods for obtaining probabilistic-based inelastic spectra for limit-state design based on probabilities of tolerable damage levels may be found in Reference [1]).

This study demonstrates that the effects of duration which are important for design are intrinsic to elastic (or inelastic) spectral demands. Therefore, seismic load specification can in most cases, be adequately described by appropriate inelastic ground-motion spectra, without the need to explicitly specify (or separately account for) an associated duration.

ACKNOWLEDGEMENTS

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Table 1. Damage Measures and R Values for the UCSC and Saratoga, Loma Prieta Records

<u>Record</u>	<u>Ductility</u>	<u>NHE</u>
UCSC, Santa Cruz	3.27	8.54
Saratoga, Aloha Ave.	7.83	22.38

<u>Record</u>	<u>R Factors for NHE=10</u>
UCSC, Santa Cruz	4.32
Saratoga, Aloha Ave.	2.86

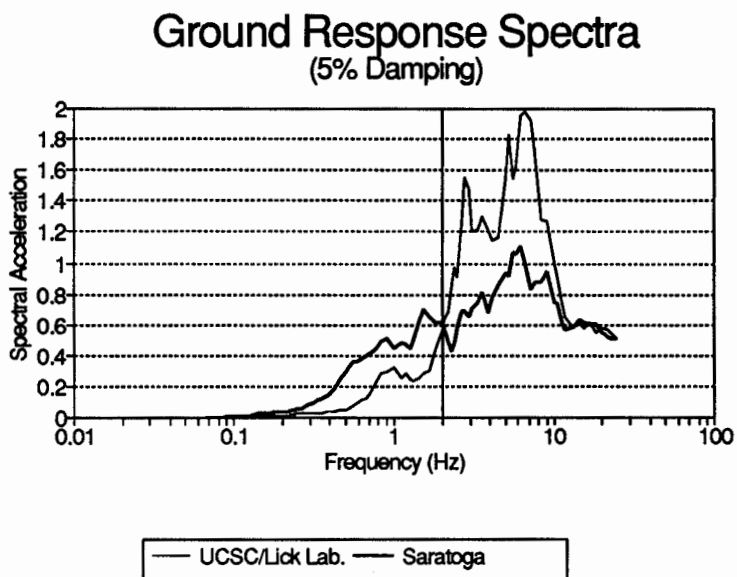


Figure 1. Ground response spectra for the UCSC/Lick Lab, Santa Cruz (0°) and Aloha Ave., Saratoga (0°) recordings from the Loma Prieta earthquake. (Each record has been scaled to have 0.5g PGA).

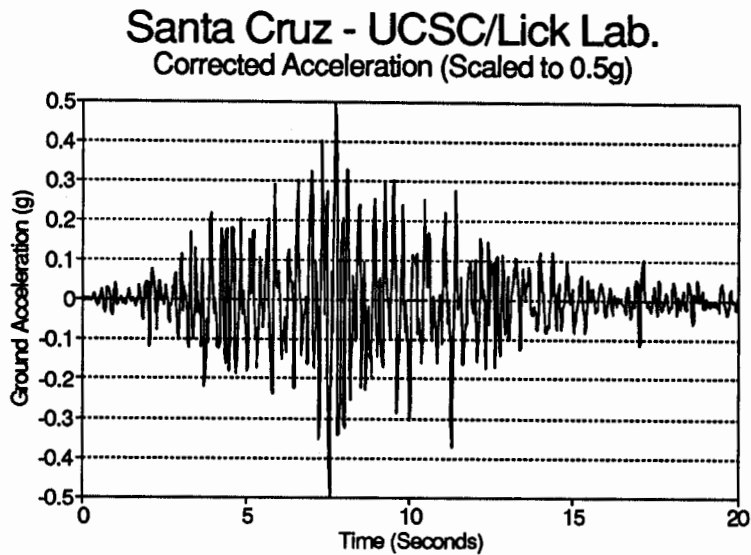


Figure 2. Acceleration time history of the UCSC/Lick Lab, Santa Cruz, (0°) ground motion recording from the Loma Prieta earthquake, scaled to 0.5g PGA.

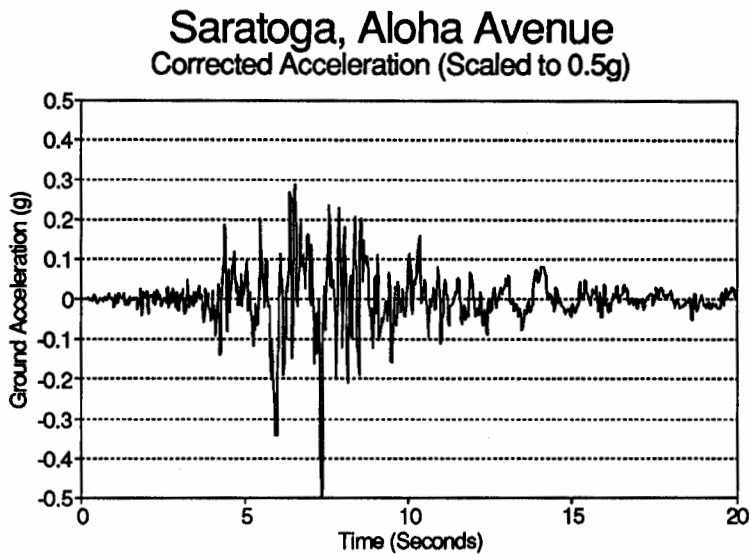


Figure 3. Acceleration time history of the Aloha Ave., Saratoga (0°) ground motion recording from the Loma Prieta earthquake, scaled to 0.5g PGA.

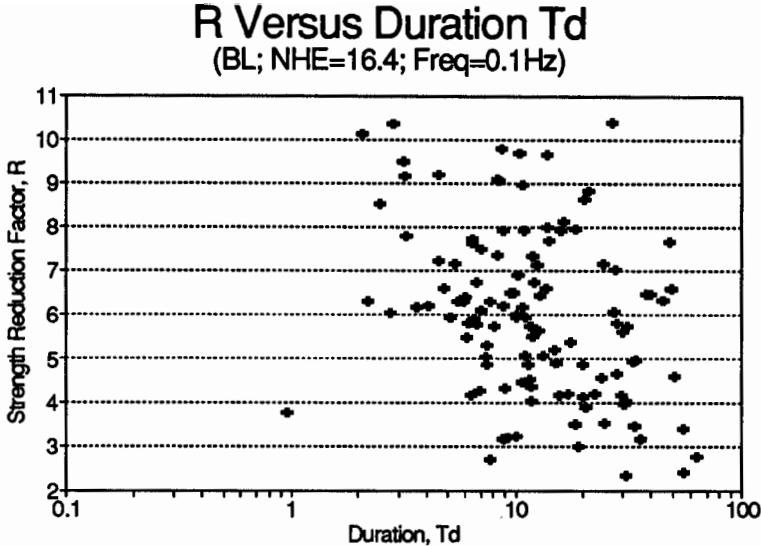


Figure 4. Inelastic strength reduction factor R versus duration T_D based on bilinear behavior and frequency of 0.1 Hz.

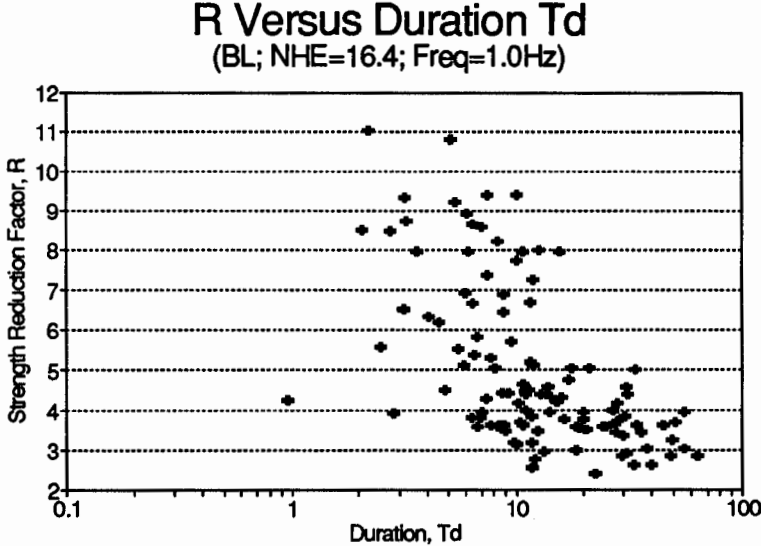


Figure 5. Inelastic strength reduction factor R versus duration T_D based on bilinear behavior and frequency of 1.0 Hz.

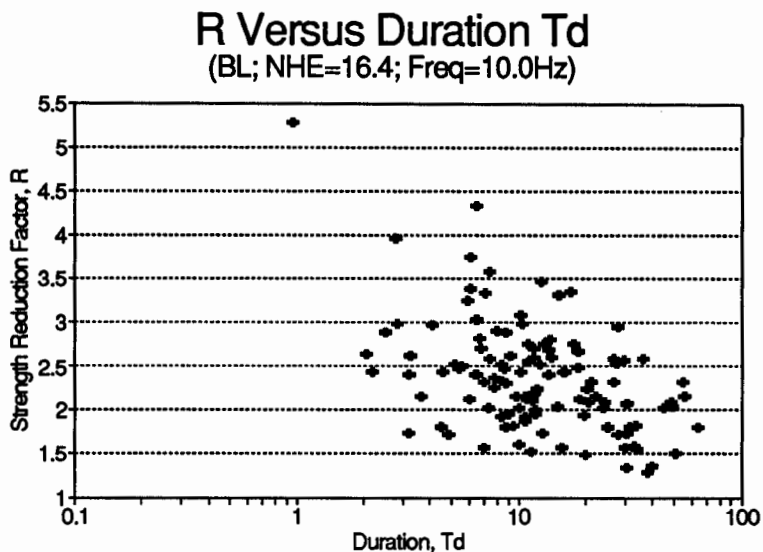


Figure 6. Inelastic strength reduction factor R versus duration T_D based on bilinear behavior and frequency of 10.0 Hz.

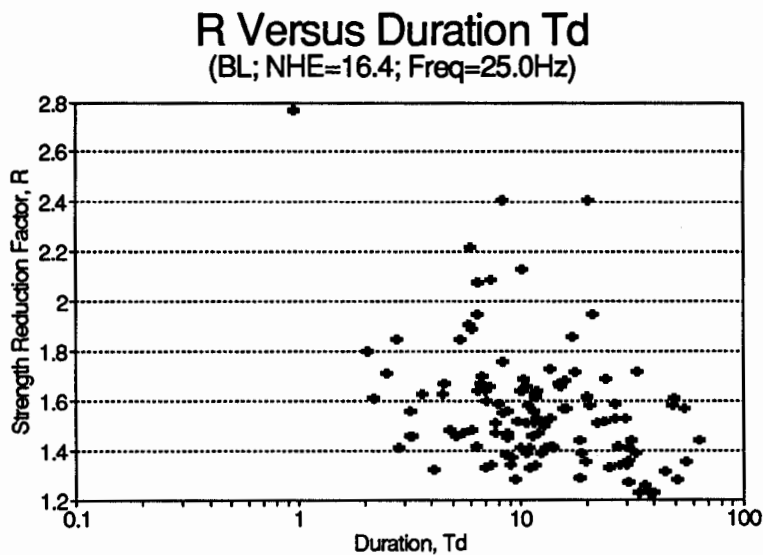


Figure 7. Inelastic strength reduction factor R versus duration T_D based on bilinear behavior and frequency of 25.0 Hz.

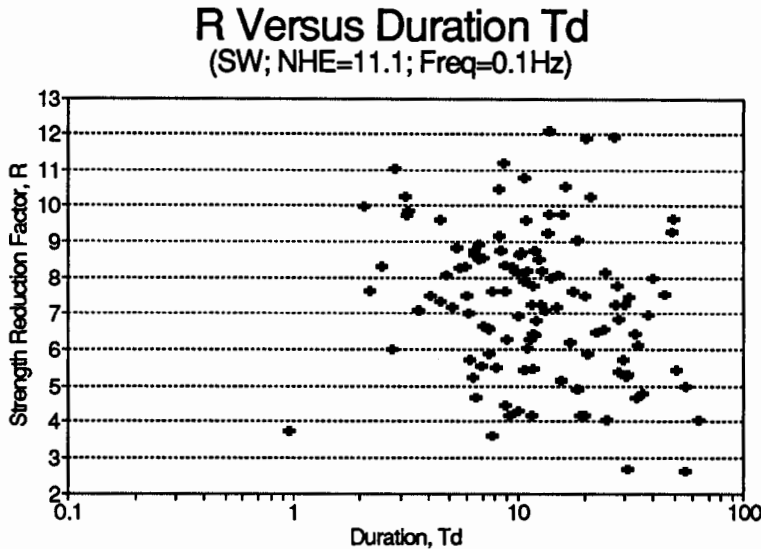


Figure 8. Inelastic strength reduction factor R versus duration T_D based on shear-wall behavior and frequency of 0.1 Hz.

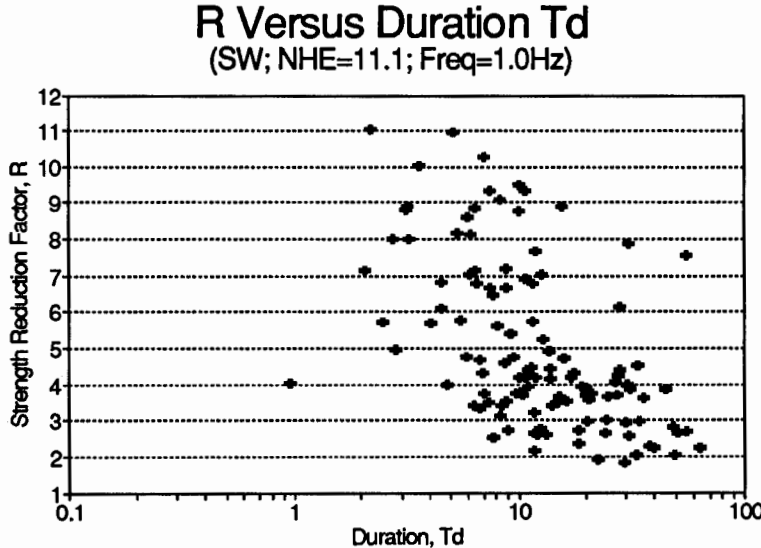


Figure 9. Inelastic strength reduction factor R versus duration T_D based on shear-wall behavior and frequency of 1.0 Hz.

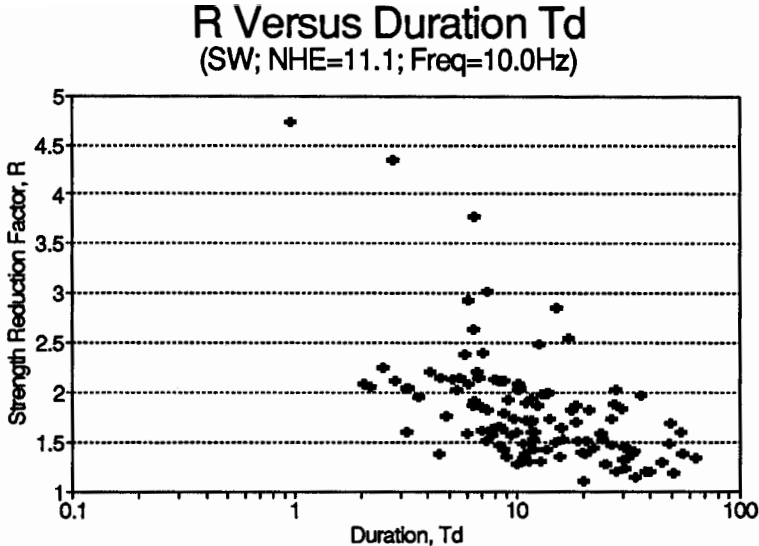


Figure 10. Inelastic strength reduction factor R versus duration T_D based on shear-wall behavior and frequency of 10.0 Hz.

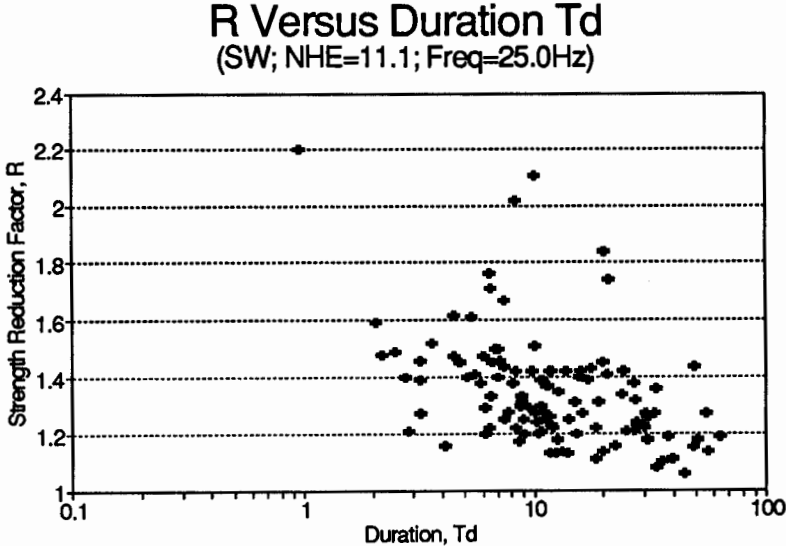


Figure 11. Inelastic strength reduction factor R versus duration T_D based on shear-wall behavior and frequency of 25.0 Hz.

R Versus Predicted Value of R From Elastic Demand Spectra (SW; Duct.=4)

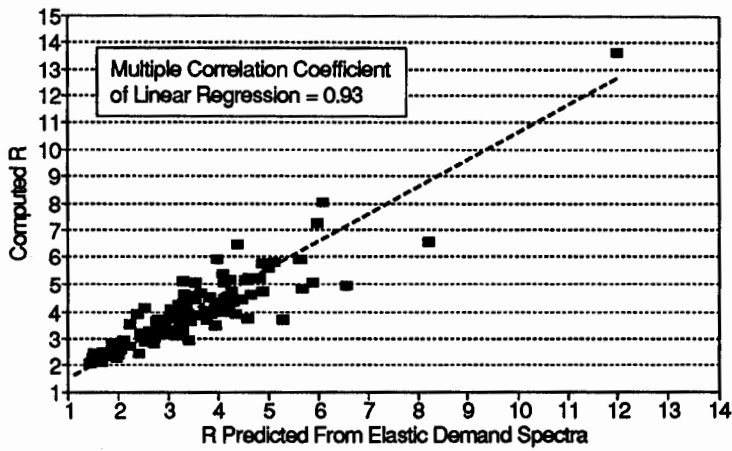


Figure 12. Prediction of R from elastic spectral demand ratios alone, without explicit consideration of motion duration (shear-wall behavior, ductility ratio of 4.0)

Elastic Demand Versus T_d'
(5% Damping; Frequency= 1.0Hz)

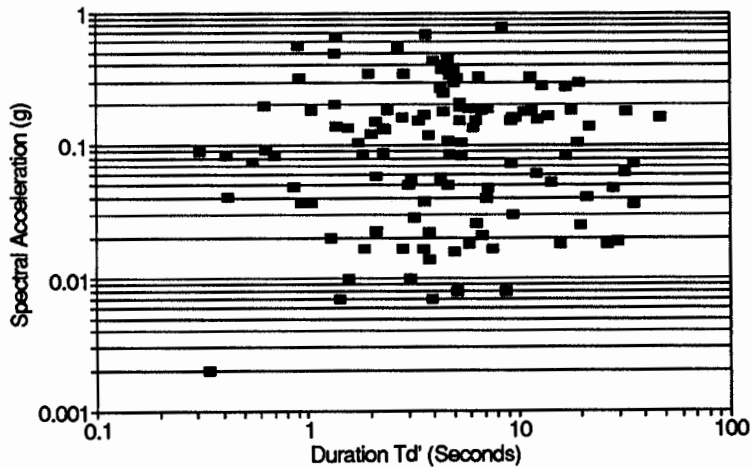


Figure 13. Elastic strength demand versus duration T'_D for frequency of 1.0 Hz.

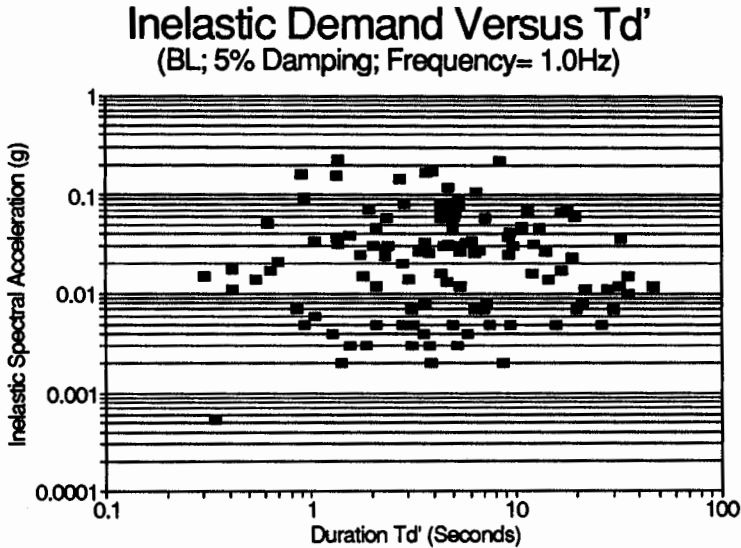


Figure 14. Inelastic strength demand versus duration T'_D , based on bilinear behavior and frequency of 1.0 Hz.

