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A RE-EVALUATION OF DESIGN SPECTRA FOR SEISMIC DAMAGE CONTROL

by

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This study investigates the use of simple, non stationary ARMA models to represent underlying earthquake events. Measured earthquake records are considered to be random samples. Models are developed and samples of acceleration records are generated for 4 major events. Maximum displacement ductility demand, normalized hysteretic energy demand and a simple damage index spectra for bi-linear and stiffness softening SDOF systems are computed for these samples of accelerograms. The sensitivity of demand spectra to ARMA model characteristics are also examined.

It is concluded that, for the events studied, simple ARMA models may be considered to capture most of the information contained in earthquake acceleration records insofar as non linear response spectra are concerned. It was found that, for each event, the average of the logarithms of displacement ductility and hysteretic energy demand for bi-linear systems are very nearly linearly related to the logarithm of system period for SDOF systems.

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PREFACE

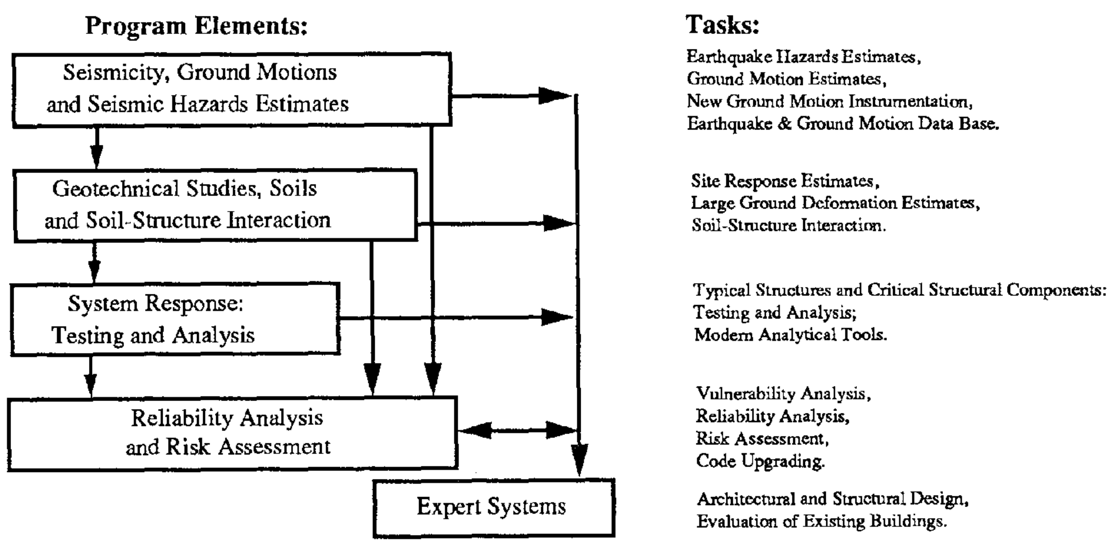
The National Center for Earthquake Engineering Research (NCEER) is devoted to the expansion and dissemination of knowledge about earthquakes, the improvement of earthquake-resistant design, and the implementation of seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures and lifelines that are found in zones of moderate to high seismicity throughout the United States.

NCEER's research is being carried out in an integrated and coordinated manner following a structured program. The current research program comprises four main areas:

- Existing and New Structures
- Secondary and Protective Systems
- Lifeline Systems
- Disaster Research and Planning

This technical report pertains to Program 1, Existing and New Structures, and more specifically to Reliability Analysis and Risk Assessment.

The long term goal of research in Existing and New Structures is to develop seismic hazard mitigation procedures through rational probabilistic risk assessment for damage or collapse of structures, mainly existing buildings, in regions of moderate to high seismicity. This work relies on improved definitions of seismicity and site response, experimental and analytical evaluations of systems response, and more accurate assessment of risk factors. This technology will be incorporated in expert systems tools and improved code formats for existing and new structures. Methods of retrofit will also be developed. When this work is completed, it should be possible to characterize and quantify societal impact of seismic risk in various geographical regions and large municipalities. Toward this goal, the program has been divided into five components, as shown in the figure below:



Reliability Analysis and Risk Assessment research constitutes one of the important areas of Existing and New Structures. Current research addresses, among others, the following issues:

1. Code issues - Development of a probabilistic procedure to determine load and resistance factors. Load Resistance Factor Design (LRFD) includes the investigation of wind vs. seismic issues, and of estimating design seismic loads for areas of moderate to high seismicity.
2. Response modification factors - Evaluation of RMFs for buildings and bridges which combine the effect of shear and bending.
3. Seismic damage - Development of damage estimation procedures which include a global and local damage index, and damage control by design; and development of computer codes for identification of the degree of building damage and automated damage-based design procedures.
4. Seismic reliability analysis of building structures - Development of procedures to evaluate the seismic safety of buildings which includes limit states corresponding to serviceability and collapse.
5. Retrofit procedures and restoration strategies.
6. Risk assessment and societal impact.

Research projects concerned with Reliability Analysis and Risk Assessment are carried out to provide practical tools for engineers to assess seismic risk to structures for the ultimate purpose of mitigating societal impact.

This technical report develops a practical method for modeling earthquake ground motion by means of ARMA models utilizing observed ground motion records. The report then re-evaluates the adequacy of nonlinear response spectra for the eventual purpose of structural design, taking damage control into consideration.

ABSTRACT

Seismic risk analysis for structural engineering purposes is primarily based on peak ground accelerations taken from earthquake records. Such an approach has a number of logical flaws and ignores a great deal of the information in measured data.

This study investigates the use of simple, non stationary ARMA models to represent underlying earthquake events. Measured earthquake records are considered to be random samples. Models are developed and samples of acceleration records are generated for 4 major events. Maximum displacement ductility demand, normalized hysteretic energy demand and a simple damage index spectra for bi-linear and stiffness softening SDOF systems are computed for these samples of accelerograms. The sensitivity of demand spectra to ARMA model characteristics are also examined.

It is concluded that, for the events studied, simple ARMA models may be considered to capture most of the information contained in earthquake acceleration records insofar as non linear response spectra are concerned. It was found that, for each event, the average of the logarithms of displacement ductility and hysteretic energy demand for bi-linear systems are very nearly linearly related to the logarithm of system period for SDOF systems.

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A great deal of the analysis described in this report is due to Mr. Malek Brahimi and Mr. Hee-Joong Kim. Mr Brahimi had primary responsibility for the development of ARMA models and the samples of acceleration records while Mr. Kim was responsible for the analytical models and the generation of response spectra.

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SECTION 1

BACKGROUND AND OBJECTIVES

Current structural design practice for earthquake excitations is based on peak values of historical acceleration records - an approach that is seriously flawed for several reasons.

1. The damage potential in any earthquake record is dependent on other characteristics of the excitation including, for example, frequency content, duration, rms or Arias intensity and duration.
2. Each acceleration record is one realization of a non-stationary random process. The peak value of each realization is a random variable. The measured peak from a single record is just one sample of that random variable.

   The use of such a statistic to scale or otherwise characterize an earthquake process is not a statistically valid procedure.

Calculated structural response spectra for measured acceleration records tend to be highly sensitive to system frequency. It is not surprising that attempts to combine several recorded earthquakes from different sources to form a composite sample of response spectra by normalizing records on the basis of their peak values leads to large coefficients of variation.

In this study, a measured record is assumed to be a sample from an underlying population which is characteristic of the earthquake process involved. Measured records are used to estimate the parameters of the underlying population using maximum likelihood techniques. Simulated records from this population are then used to obtain average response spectra for each historical event along with an estimate of the variance of response.

The major long term objective of this study was to establish minimal stochastic earthquake models which satisfy two primary criteria.

1. The set of parameters for an historical event must be small enough to permit seismic hazard mapping but large enough to effectively summarize the damage potential in seismic events.
2. The parameters for historical events must be estimated using accepted statistical reasoning.

Other long term objectives are to examine the relationship between response and the parameters of earthquake process models and to assess the sensitivity of structural response to model simplification. This report describes the results of the first stage of the study.

After preliminary review, the class of ARMA models was chosen as a basis for analysis. Simple ARMA models were established for four major historical earthquakes and samples of accelerograms for each event were generated.

To assess damage potential, response spectra for damped, single degree of freedom systems were used. Spectra for samples of simulated acceleration records for linear, bi-linear and stiffness softening systems with and without $P - \Delta$ effects were examined. Damage predictors include ductility demand, normalized hysteretic energy demand and various damage indices. Programs have been prepared and used for a preliminary sensitivity study.

SECTION 2

SEISMIC PROCESS MODELS

2.1 GENERAL

The concept underlying this analysis is that any measured acceleration record is a sample from a population of such records. For design purposes, the properties of the population characterize the damage potential of the event.

Previous studies have modeled acceleration records in either the time domain or the frequency domain. Excellent reviews of progress to date have been made by Kozin (1987) and Shinozuka et al (1987). Recent work involving ARMA models includes an extension of the univariate, one-dimensional model to the bi-variate, one-dimensional case by Naganuma, Deodatis and Shinozuka (1987). An analysis of the relationship betweeen non stationary AR models and spectral representations with evolutionary power is given by Deodatis and Shinozuka (1987).

The choice of the domain of analysis for non-stationary processes such as earthquake acceleration is rather arbitrary. Both approaches involve modulation of the amplitude of a stationary white noise process and both approaches can lead to problems in certain ranges of response spectra. In this study, analysis in the time domain by means of ARMA models (Box and Jenkins 1976) was adopted primarily because rather grossly simplified models were to be developed. Interpretation of model parameters for structural design purposes was felt to be intuitively more straight-forward if the models are in physical dimensions rather than derived dimensions.

The techniques of ARMA analysis are well known (Box and Jenkins, 1976, Kozin, 1987). Early applications to seismic analysis (Chang et al 1979, Kozin, 1977, Kozin and Nakajimi, 1978) attempted to reproduce the details of historical acceleration records using multi-variate spline functions or analysis in sequential time segments. The resulting models involve far too many parameters for design purposes or even for the calibration of design procedures.

Most recently, an extensive study of ARMA models was completed by Ellis and Cakmak (1987) who employed a similar model to that used in the present study with additional corrections to account for zero crossing rates and distortions in Fourier spectra at low frequencies. Regression analysis for model parameters were completed for several sets of records.

An ARMA model at any time step "k" may be represented as follows:

$$A_k - \Phi_1 * A_{k-1} \ \ldots \ - \Phi_p * A_{k-p} = W_k - \Theta_1 * W_{k-1} \ \ldots \ - \Theta_q * W_{k-q} \qquad [2\text{-}1]$$

where Φ_i, Θ_j are constant coefficients.

The left side of Eq. 2-1 is known as the auto regressive (AR) part of order "p". The time series $[A_k]$ is the sequence of measured data. The right side of Eq.2-1 is known as the moving average (MA) part of order "q". The sequence $[W_k]$ is a set of independent, identically distributed Gaussian random variables.

In the present study, the digitized data is first normalized. For a moving window of 100 time steps centered on time step "k", the root mean square of acceleration $[S_k]$ is calculated. A record $[Z_k] = [A_k] / [S_k]$ which has zero mean and unit variance is then constructed and modeled as a 2nd order stationary process of the form of Eq. 2-1.

The steps involved in fitting an ARMA model to an acceleration record are the following.

1. Calculate the experimental envelope function S_k and normalize the measured record.
2. Assume a simple general analytical form for S_k and estimate its parameters from a least squares analysis.
3. Stabilize the original record.
4. Calculate the autocorrelation and partial correlation functions.
5. Select an order "p" for the AR part and an order "q" for the MA part of Eq. 2-1.
6. Estimate the coefficients Φ_i, $i = 1,2..p$ and Θ_j, $j = 1,2..q$ on the basis of a maximum likelihood analysis. Calculate the auto-correlation and partial correlation functions to check the orders used and to ensure stationary of the data.
7. Evaluate alternative sets of model orders (p,q) on the basis of the AIC criteria and select the model with minimum AIC (p,q).

Steps 4 and 6 of the preceding analysis were performed using the STATGRAPHICS software package.

2.2 APPLICATIONS

In this study, ARMA models were developed for four major earthquakes - El Centro 1940 (M = 6.7), Parkfield 1966 (M = 5.6), Mexico City 1985 (M = 8.1) and Nahanni 1985 (M = 6.9) in northern Canada (Figs 2-1 a-d). These records were chosen for historical reasons (El Centro and Parkfield), exceptional duration and frequency content (Mexico) and as a major recorded eastern event (Nahanni). Measured acceleration records are shown in Figs 2-1 a-d.

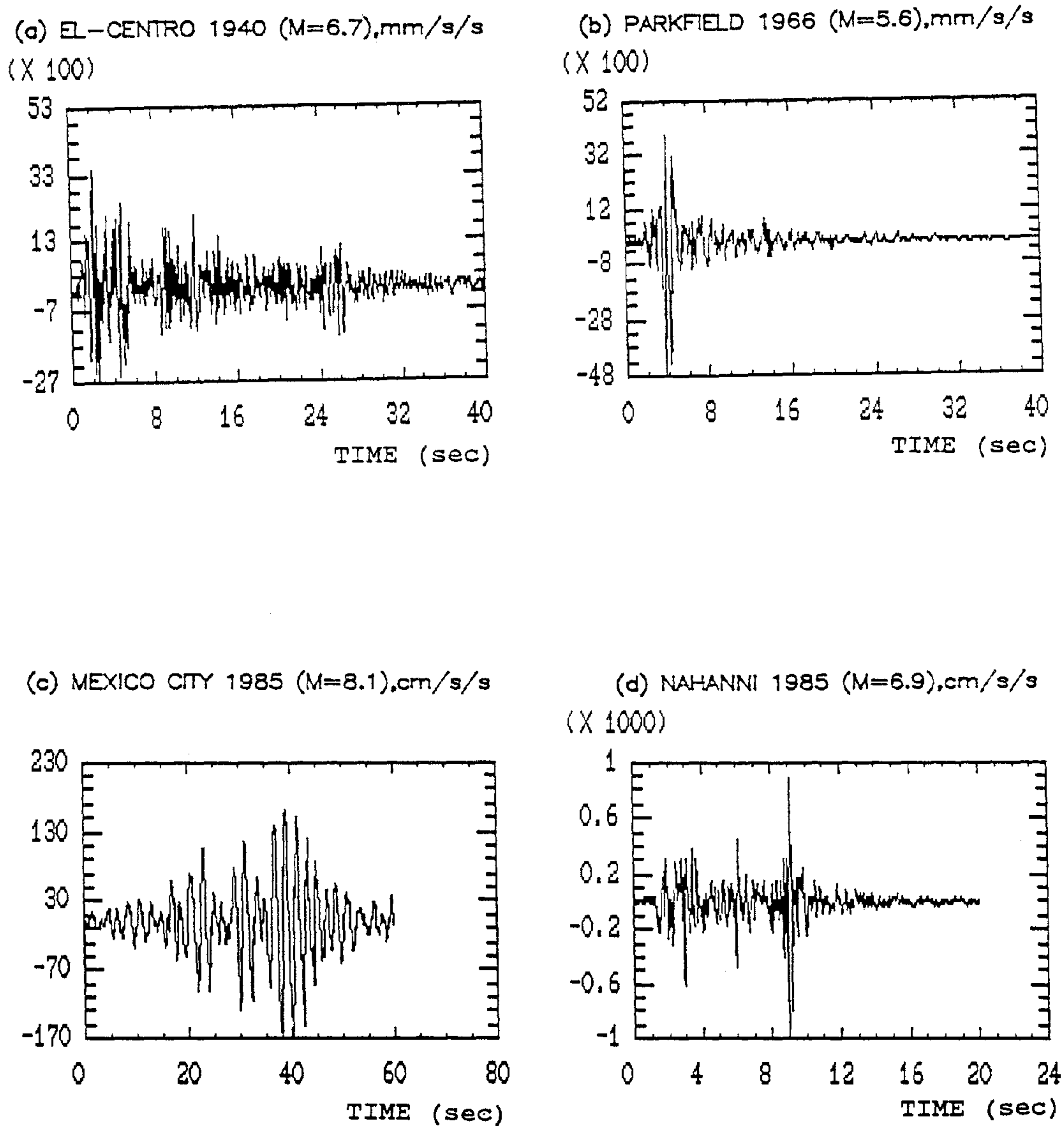


FIGURE 2-1 MEASURED ACCELEROGRAMS

To obtain a practical number of parameters, the envelope function was generally assumed to have a single peak at time T_p and a very simple form:

$$S(t) = \begin{cases} \alpha * [t/T_p]^2 & t \le T_p \\ \alpha * \exp(-\beta(t-T_p) & t \ge T_p \end{cases} \qquad [2\text{-}2]$$

The constants α and β and the peak time T_p were found through an iterative least squares procedure.

The maximum variance $(S_{max})^{2.0} = \alpha^{2.0}$ and its time of occurrence T_p are very important since they are correlated to peak ground acceleration.

To examine the sensitivity of structural response to the shape of the envelope function, a more general form involving peaks at times $T_{p,1}$, $T_{p,2}$ .... $T_{p,m}$ was considered. The records were partitioned into a series of intervals T_1 ,.. T_m by the recursive relationship

$$T_i = T_{p,i} + 0.66[T_{p,i+1} - T_{p,i}] \qquad [2\text{-}3]$$

Algebraic expressions in an interval $T_{i-1} \le t \le T_i$, $T_0 = 0$, were taken in the form

$$S(t) = \begin{cases} \alpha_i * \{[t-T_{i-1}] / [T_{p,i-1} - T_{i-1}]\}^2 + \gamma_i & T_{i-1} \le t \le T_{p,i} \\ \alpha_i * \exp[-\beta_i * (t-T_{p,i})] & T_{p,i} < t < T_i \end{cases} \qquad [2\text{-}4]$$

where the parameters α_i, γ_i and β_i are obtained in any time segment by least squares.

Measured and fitted one peak envelope functions are shown for the four earthquakes in Figs 2-2 a-d. It is important to realize that the peaks occur

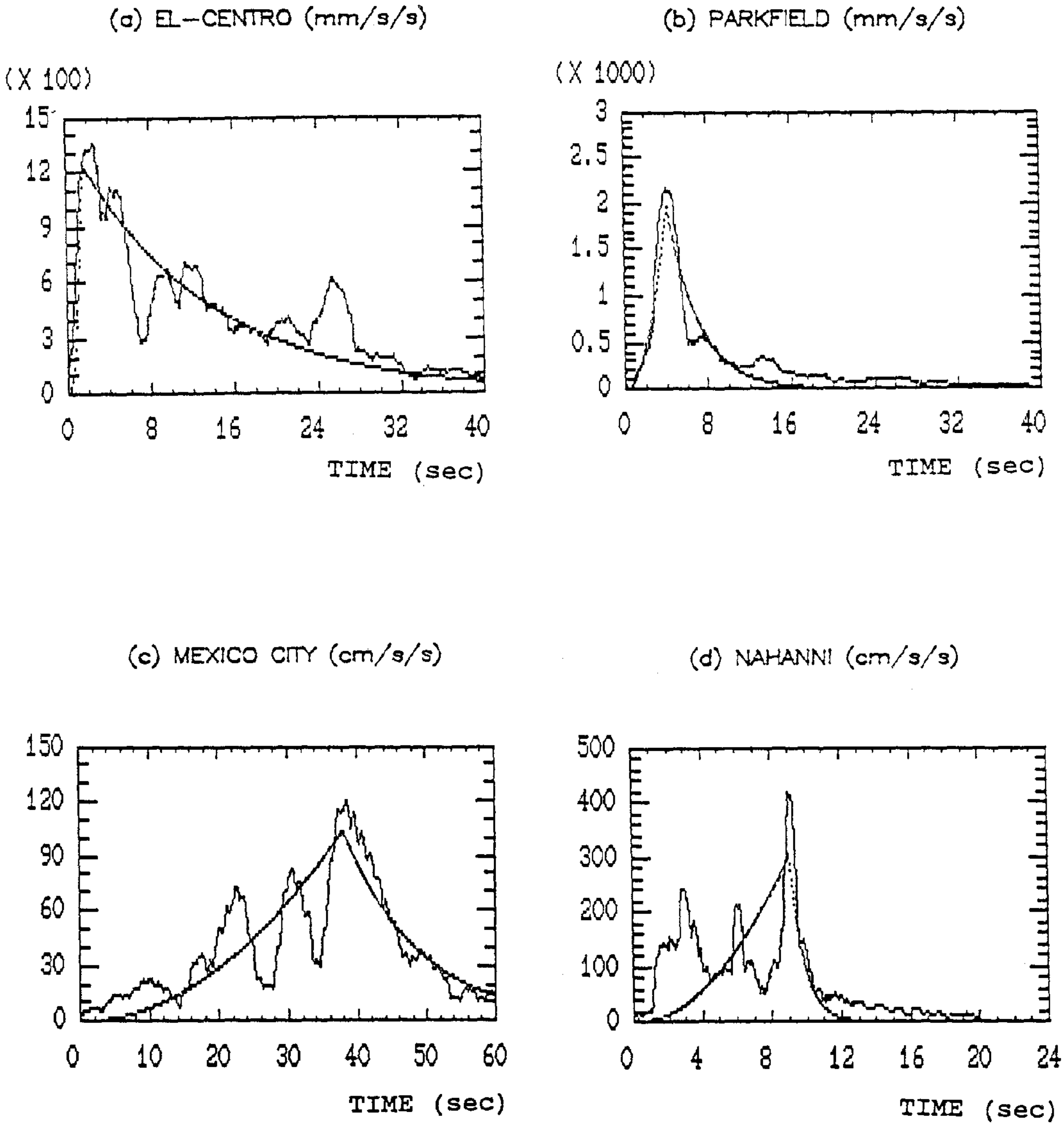


FIGURE 2-2 MEASURED AND ONE-PEAK ENVELOPE FUNCTION

at different times T_p relative to the total duration of the events. A number of possible sets of coefficients Φ_i and Θ_j were examined for each of the four earthquakes.

SECTION 3

RESPONSE ANALYSIS

3.1 GENERAL

As a basis for comparison of alternative earthquake process models, the response of single degree of freedom systems with viscous damping was adopted (Fig.3-1-a). Linear, bilinear and stiffness softening systems were used with consideration of P - Δ effects.

Response spectra were obtained by numerical integration of the general equation assuming linear acceleration in each time step (Clough & Penzien,1975)

$$M*u(t) + C*u(t) + R(u,t) = -M*u_g(t) \qquad [3\text{-}1]$$

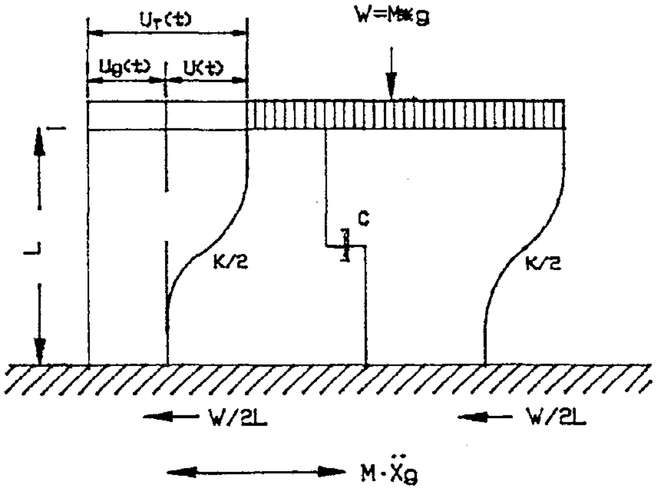
where u(t) is the relative displacement of the mass with respect to the ground, M is the mass, C is the damping coefficient, $u_g(t)$ is the ground acceleration and R(u,t) is the restoring force.

For a system which behaves linearly in at least the initial stages of motion, Eq.[3-1] can be rewritten as

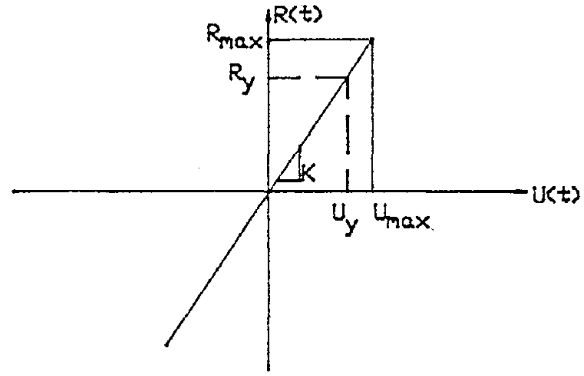
$$u(t) + 2 * \xi * \omega * u(t) + R(u,t)/M = -u_g\ (t) \qquad [3\text{-}2]$$

where R(u,t)/M is the restoring force per unit mass, ω is the initial natural frequency and ξ is the fraction of critical damping of the structure.

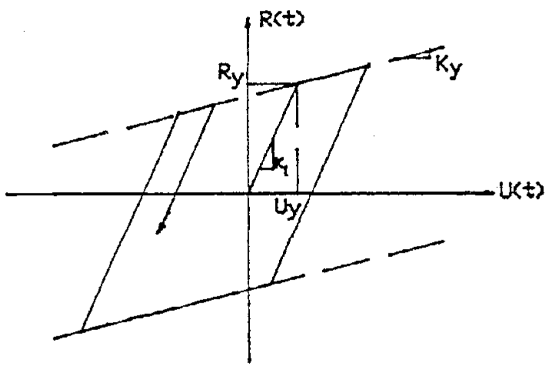
3.2 STIFFNESS MODELS



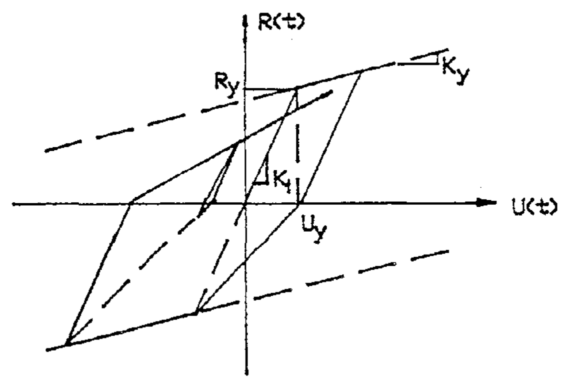
(a) SINGLE DEGREE OF FREEDOM SYSTEM



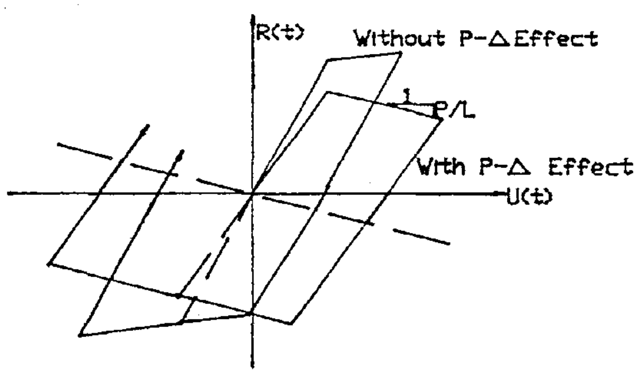
(b) LINEAR SYSTEM



(c) BILINEAR SYSTEM



(d) STIFFNESS DEGRADING SYSTEM



(e) P-Δ EFFECT ON BILINEAR SYSTEM

FIGURE 3-1 MECHANICAL MODELS

3.2.1 LINEAR RESPONSE

The simplest model used in analysis is the linear oscillator (Fig.3-1-b) where the restoring force is given by $R(u,t) = K * u(t)$, K = constant. The natural frequency is then given by $\omega = (K/M)^{0.5}$. Such a system fails suddenly with no indication of distress until the maximum displacement u_{max} is reached. Linear analysis was only used to check analytical programs against published spectra.

3.2.2 BILINEAR RESPONSE

Most real structures behave inelastically before failure. A relatively simple basis for analysis is the bilinear model shown in Fig.3-1-c (Veletsos & Newmark, 1960). Riddell and Newmark(1979) compared the results from several load-deformation models and pointed out that the ordinates of "average" spectra obtained are not significantly different. Iwan and Gates (1979) suggested that the precise details of load-deformation relationships may not be required to make reasonably accurate estimates of maximum response. For these reasons, elastoplastic and bilinear hysteretic load-deformation models have been adopted in recent studies (Nau and Hall 1984, Zahrah 1982, Lin and Mahin 1983).

A bilinear stiffness system is characterized by three parameters; the initial yield displacement u_Y, the initial elastic stiffness K_I and the post-yielding stiffness K_Y. While the absolute value of the displacement is increasing, the restoring force is given by

$$R(u,t) = K_I * u(t) \qquad u(t) \leq u_Y \tag{3-3}$$

$$R(u,t) = K_Y * (u(t) - u_Z) \qquad u(t) > u_Y$$

where u_Z is the displacement at which the yield envelope crosses the displacement axis. When the system is unloading, the stiffness is taken to be the initial stiffness until displacement reaches a yield envelope.

The response of an elasto-plastic system can be evaluated by setting $K_Y = 0.0$ and $R(u,t) = K_I * u_Y$ for $u(t) \geq u_Y$. The response of an elastic system can be evaluated by setting $u_Y = \infty$.

3.2.3 STIFFNESS DEGRADING RESPONSE

Stiffness softening under repeated dynamic loading is generally observed for concrete structures. An early model proposed by Clough & Johnston (1966) and modified by Riddel and Newmark (1979) is used in this study. A comparison of response for elastoplastic and stiffness degrading systems has been made by Mahin and Bertero (1981).

As shown in Fig.3-1d, the stiffness degrading model is defined by three parameters; the initial elastic stiffness, the initial yield displacement and the post-yielding stiffness. Yielding occurs when the displacement of the system reaches one of the envelope lines.

Although the unloading stiffness after yielding decreases with cycling and maximum peak displacement (Fenwick 1983, Park & Paulay 1975), the unloading stiffness in the model is taken to be the initial elastic stiffness. Thus, pinching effects and deterioration are ignored for simplicity. It has been suggested by Lin & Mahin (1983) that consideration of degrading of unloading stiffness does not in general have a significant effect on seismic response.

When, after first loading, the load path crosses the displacement axis and begins loading in the opposite direction, the stiffness is reduced. In this case the load-deformation curve is linear from the zero loading point to the last yielding point.

3.2.4 P-Δ EFFECTS

The axial load effect in reinforced concrete members has been examined analytically and experimentally (e.g. Atalay and Penzien 1975, MacGregor and Hage 1977, Bertero 1987). The effects of axial loads were clearly evident in field observations after the 1985 Mexico City earthquake .

An accurate computation of member response considering axial force is difficult because of variations in axial forces due partly to vertical accelerations. To simplify analysis, it is assumed that the axial load is constant and equal to the system weight.

For the system shown in Fig.3-1-a, the restoring force in Eq. 3-2 is given by

$$R^{*}(u,t) = R(u,t) - (g/L) * u(t) \qquad [3\text{-}4]$$

where g is the acceleration due to gravity, L is the system height and R(u,t) is as before.

When p-Δ effects occur, the load deformation relationship may be modified as shown in Fig.3-1-e. Response is calculated numerically using the same procedures as before. The major effect is that post-yielding stiffness is negative.

3.3 DAMAGE MEASURES

A number of damage measures have been used to summarize the impact of an earthquake on linear and nonlinear structures. Applications of some of these response measures have been made by Zarah and Hall (1984), Lin and Mahin (1985), Park, Ang and Wen (1984), Baron and Veneziano (1982) and Casciatti and Faravelli (1982). A comparison of alternative measures has been made by Grigoriu (1987).

A detailed study of several alternative damage measures was completed by DiPasquale and Cakmak (1987). Non linear response to simulated earthquakes was evaluated with the conclusion that existing damage predictors hold considerable promise for engineering applications.

Many proposed damage models for reinforced concrete structures were investigated analytically by Chung, Meyer and Shinozuka (1987). A new model was proposed and a number of parameters were calibrated against available test data. It was noted that an absence of reliable data limits the evaluation of all damage models.

A convenient way to present the results of response analysis is a frequency spectrum where a response or damage measure is plotted against system frequency or period. At best, any single measure of response to an earthquake can be a relatively weak predictor of damage because dynamic response may involve a variety of failure modes. For example, a structure might fail due to very large displacements in a mode similar to monotonic static failure or it could fail after relatively small displacements due to a large number of cycles with cracking and reduced stiffness.

Such details of response are beyond the scope of this study where the emphasis is on the damage potential of seismic records and general criteria are required. For comparison purposes, damage spectra were obtained for the following damage measures.

3.3.1 MAXIMUM DISPLACEMENT (u_{max})

During response, the absolute maximum displacement is recorded. Under cyclic loading, this measure is useful only for linear systems without fatigue. In this study, linear spectra were only used to check computer programs against published data.

3.3.2 MAXIMUM DISPLACEMENT DUCTILITY (ν)

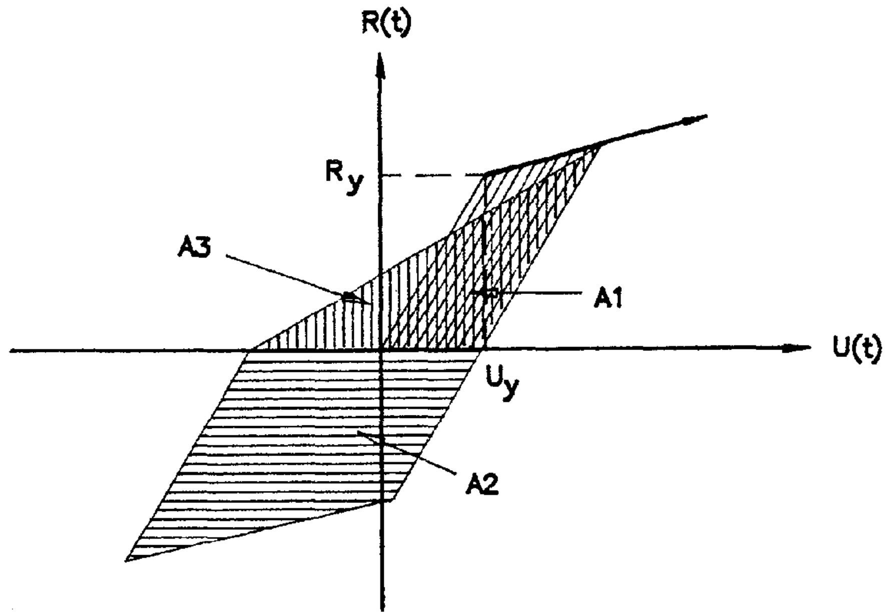
This conventional design measure is defined as the ratio of the absolute maximum displacement during ground motion to the yield displacement. For bilinear systems, it is correlated to the energy absorbed during inelastic response and is a useful measure of the deformation capacity required to avoid collapse.

3.3.3 HYSTERETIC ENERGY DEMAND (E_H)

This response measure indicates the total energy dissipated by inelastic deformation in a structure with a hysteretic load-deformation relationship. It is calculated from the relationship

$$E_H = \int R(u,t) * u(t)*dt \quad -E_S \qquad [3-5]$$

where E_S is the elastic strain energy. A "normalized" hysteretic energy demand E_{NH} is defined (Fig. 3-2) as the total energy dissipated by the system during excitation divided by twice the energy absorbed at first yield plus 1.0:



$$\text{Normalized Hyste. Energy} = \frac{(A1 + A2 + A3)}{R_y * U_y} + 1.$$

FIGURE 3–2 NORMALIZED HYSTERETIC ENERGY

$$E_{NH} = 1.0 + \{ E_H / [R_Y * u_Y] \} \qquad [3\text{-}6]$$

where $R_Y = K_Y * u_Y$ is the yield force. Normalized hysteretic energy is used in this analysis to avoid problems dealing with systems that do not yield.

Alternative methods for normalizing the hysteretic energy have been developed (Zahrah and Hall, 1982). For example, the "equivalent number of yield cycles" is defined by the ratio of the total energy dissipated by yielding to the energy corresponding to the system loaded monotonically until maximum displacement ductility is reached.

Hysteretic energy demand is an indirect measure of both the magnitude of displacements and the number of cycles experienced during an excitation. It is related to other measures such as the number of yield events, yield reversals and zero crossings.

For bilinear systems, energy demand depends on the yield force R_Y. In this study, results are shown as a function of the non-dimensional ratio $Y = R_Y/(M*g)$ where the product $M*g$ is the weight of the system.

3.3.4 DAMAGE INDICES (DI)

Theoretically, none of the preceding elementary measures of response are sufficient to predict the effects of an earthquake on a structure. For this reason, several combined measures have been defined as "Damage Indices". (See for example, DiPasquale and Cakmak, 1987, and Chung, Meyer and Shinozuka, 1987.) Banon(1980) developed a stochastic model for damage in reinforced concrete using normalized dissipated energy and normalized cumulative rotation. Park, et al (1984) introduced a very simple damage index defined to be the ratio of demand to capacity of a structure.

In the form proposed by Park, the damage index is expressed as a linear combination of relative maximum deformation and relative energy demand.

$$DI = \frac{u_{max}(t)}{U_{max}} + \frac{\beta}{R_Y * U_{max}} * [\ E_H\ ] \qquad [3\text{-}7]$$

where $u_{max}(t)$ is the maximum deformation under the earthquake loading, U_{max} is the ultimate deformation capacity under monotonic loading, R_Y is the yield force and E_H is the hysteretic energy due to inelastic deformation. The structural property β is a non-negative number reflecting the relative energy absorption capacity of a structure and may not be independent of the excitation.

For calculation purposes, development of a spectrum of damage index requires specification of β as well as the frequency, damping and yield force of a structure. It should be noted that Eq. 3-7 has not been validated for general use.

SECTION 4

NUMERICAL RESULTS

4.1 GENERAL

As mentioned previously, a variety of ARMA models were fitted to the experimental records for four earthquakes. The complete set of orders (p,q) and alternative envelope functions is indicated in TABLE 4-I. The AR coefficients Φ_1,Φ_2, MA coefficient Θ_1, white noise standard deviation WNSD, and single peak envelope parameters α, β, T_p corresponding to maximum likelihood, one peak, order (2,1) estimates for each event are shown in TABLE 4-II. As shown subsequently, the use of one peak envelope functions and one set of orders seems to be sufficient for response analysis. Also shown are the peak accelerations and the durations of recorded events defined as the time between the 1% and 98% fractiles of the integral of the squared amplitude.

Response for other sets of parameters was also obtained for sensitivity studies as explained subsequently.

For each set of model coefficients, a sample of twenty acceleration records was generated. In each case, a standard baseline correction was applied along with a low pass filter. To test the stability of the variance of response spectra, a sample of 50 records was generated for El Centro with a single peak and orders p = 2, q = 1. To generate a sample of twenty records for one set of parameters for one event required approximately one hour of computer time on an ATT 6300 micro computer.

As an indication of the general nature of results, one record from each sample of twenty for the one-peak (2,1) models is shown in Figs 4-1 a-d. Rather

TABLE 4.I SET OF ARMA MODELS

ARMA MODELS	EARTHQUAKES El-Centro	Parkfield	Nahanni	Mexico
ORDERS	ARMA(1,1) ARMA(2,1)* ARMA(3,1) ARMA(4,1)	ARMA(2,1)* ARMA(3,1) ARMA(4,1)	ARMA(1,1) ARMA(2,1) ARMA(3,1) ARMA(4,1)	ARMA(1,1) ARMA(2,1)* ARMA(3,1)
ENVELOPE FUNCTION	1-peak 2-peaks	1-peak	1-peak 2-peaks 3-peaks	1-peak

*:Optimal set by AIC criteria

TABLE 4.II PARAMETERS FOR ONE PEAK ARMA(2,1) MODELS

ARMA PARAMETERS	EARTHQUAKES El-Centro	Parkfield	Nahanni	Mexico
AR(1)	1.383	1.612	0.397	1.894
AR(2)	-0.574	-0.695	0.136	-0.899
MA(1)	0.144	-0.394	-0.587	0.375
WNSD	0.455	0.156	0.610	0.059
α (cm/s^2	124.118	199.461	302.230	103.800
β (sec^{-1}	0.079	0.340	1.275	0.093
T_p (sec)	1.500	4.040	9.020	58.000
DURATION (sec)	27.000	11.680	10.120	42.580
PGA	0.348	0.489	0.981	0.171

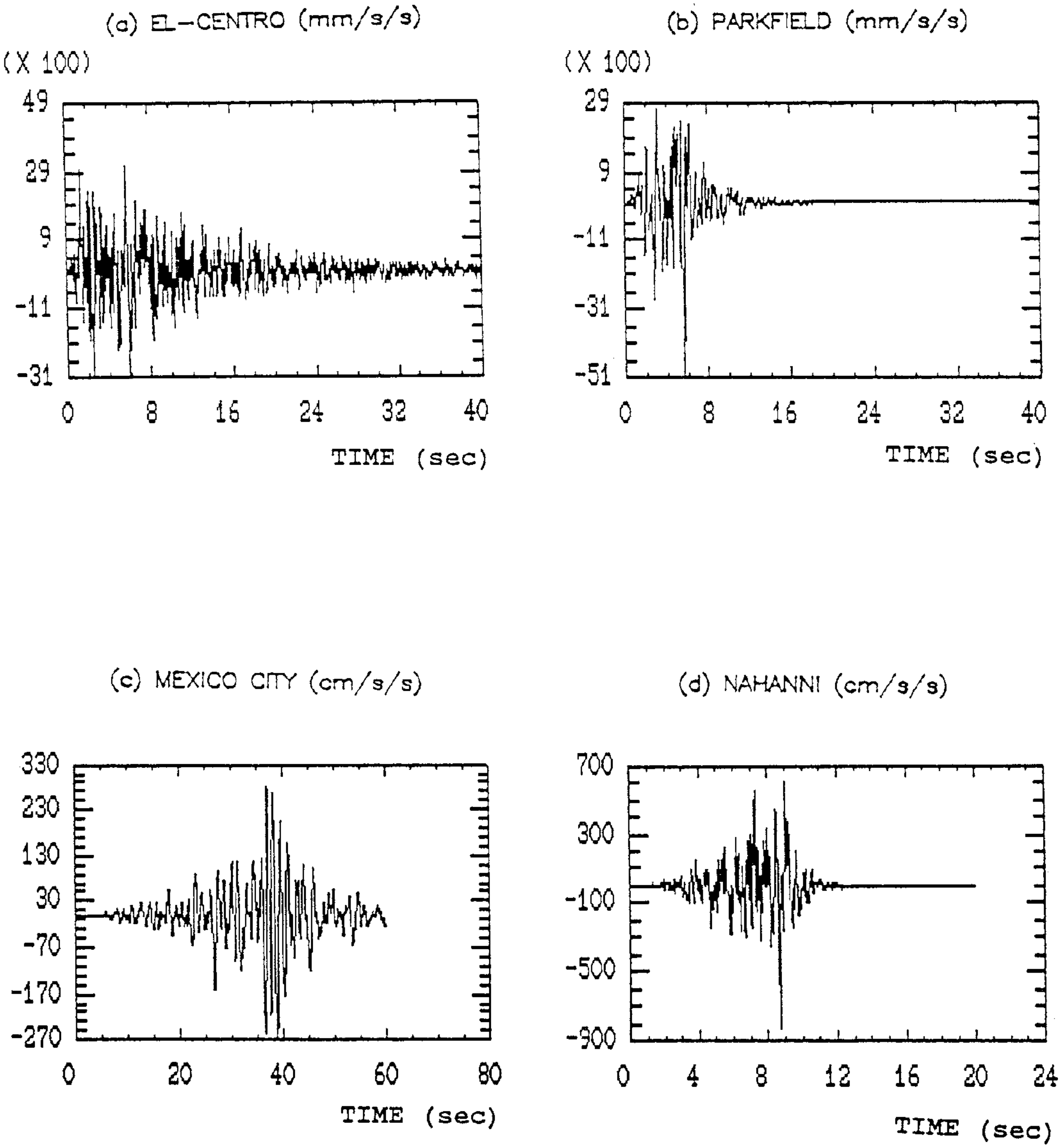


FIGURE 4-1 SINGLE SAMPLES OF SIMULATED RECORDS

unexpectedly, the simple model captured a good deal of the periodicity of the Mexico City event.

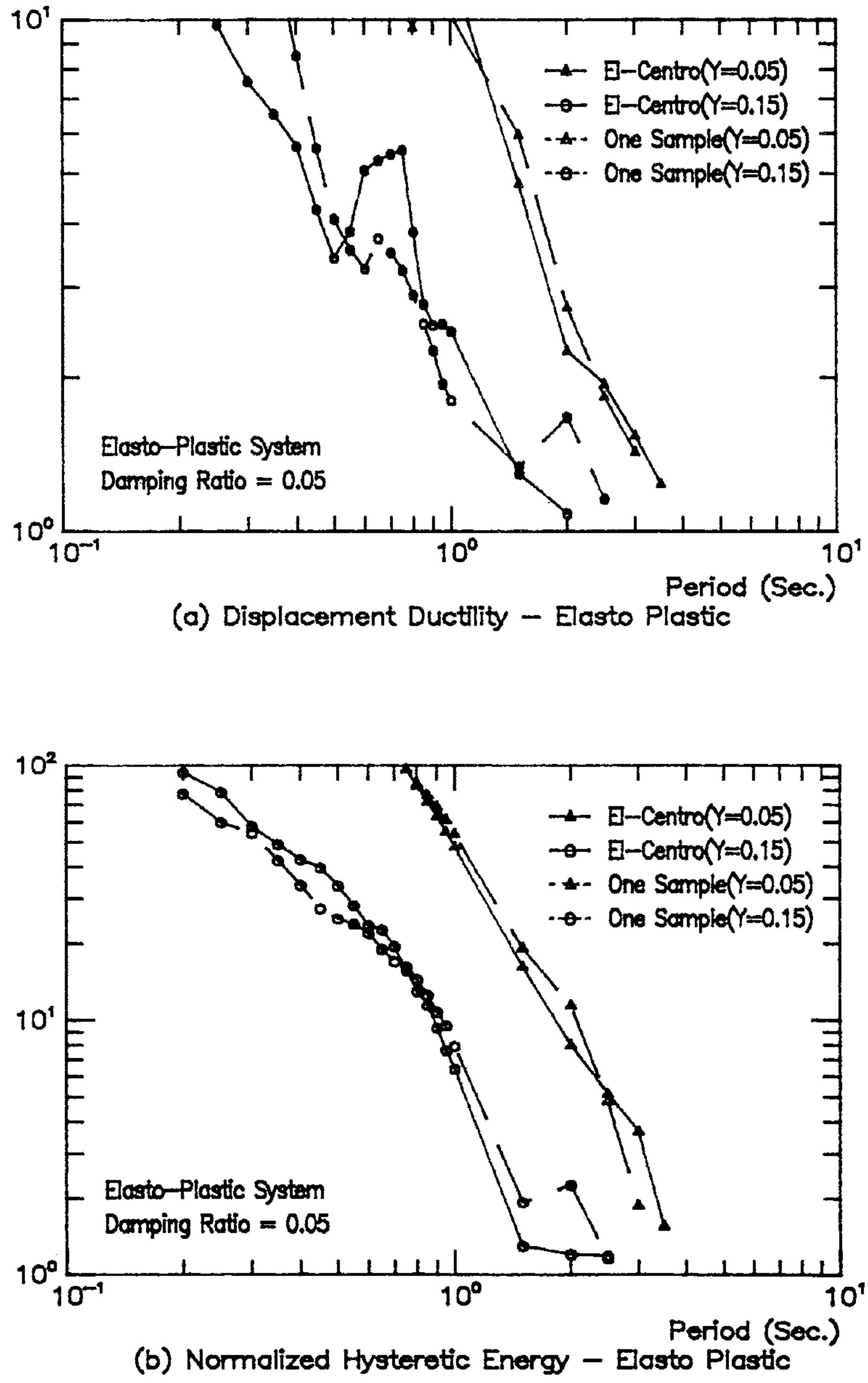
For the response analysis, numerical values of the damping ratio ξ were .02 and .05 with yield ratios $Y = R_Y/M*g$ of 0.05, 0.10 and 0.15. For calculation of P-Δ effects, the column height was taken as 10.0 ft. For spectra of damage indices, it was assumed that U_{MAX} was $3u_Y$ with β in Eq. 11 = .05.

For the original and one sample of El Centro, ductility demand and normalized hysteretic energy demand spectra for an elasto-plastic system are shown in Figs 4-2 a,b. Corresponding demand spectra for a stiffness degrading system are shown in Figs 4-2 c,d.

A major problem in evaluation of results for relatively long periods in some cases was that all earthquake records in a sample of twenty did not cause yielding. As a result, the average hysteretic energy demand, for example, for a sample of twenty is not meaningful. In analysis, only the records causing yielding were used to calculate average demand and demand ratios. The result is an over estimation of average demand.

Shown in Figs 4-3 a-d are selected, average, elasto plastic and stiffness degrading demand spectra with one standard deviation confidence intervals for the samples of twenty and fifty El Centro earthquakes. Other spectra showed similar dependence on sample size. It can be concluded that a sample of twenty records for each event provided a reasonable estimate of average nonlinear demand spectra and their standard deviations.

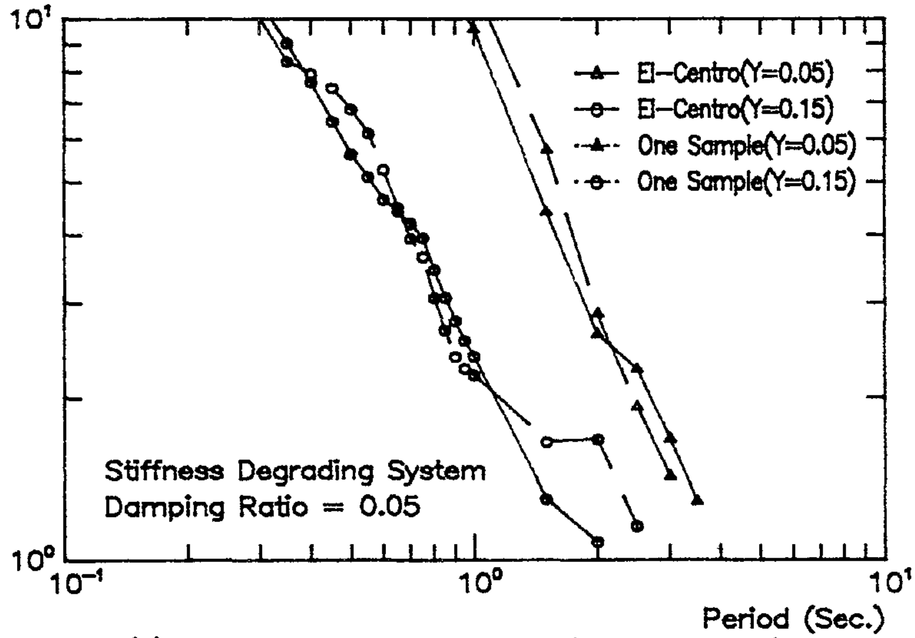
Shown in Figs 4-4 a-d are mean +/- one standard deviation confidence intervals for typical one peak, elasto-plastic demand spectra for the four earthquakes investigated. As expected, the artificial records do not duplicate the



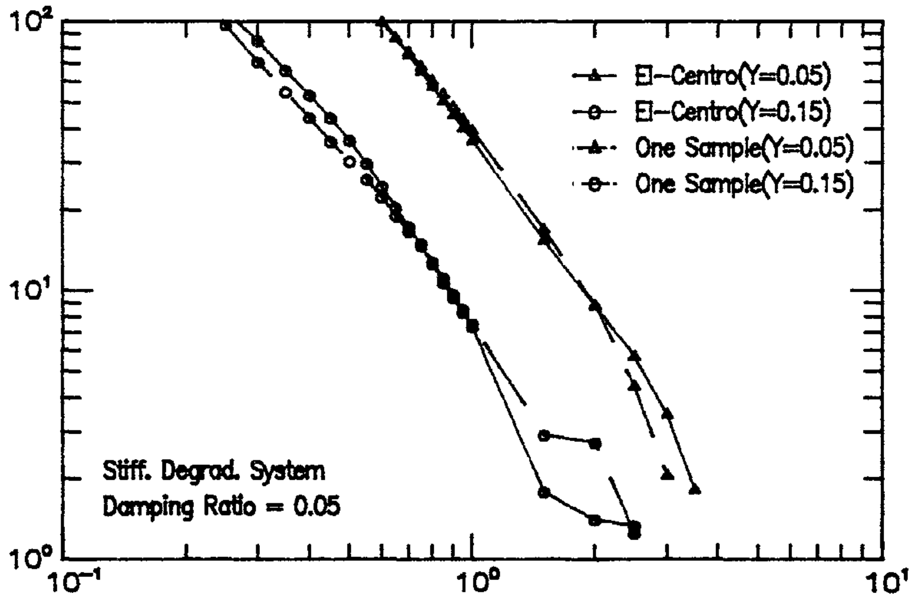
(a) Displacement Ductility – Elasto Plastic

(b) Normalized Hysteretic Energy – Elasto Plastic

FIGURE 4–2 RESPONSE SPECTRA – ORIGINAL AND ONE SAMPLE

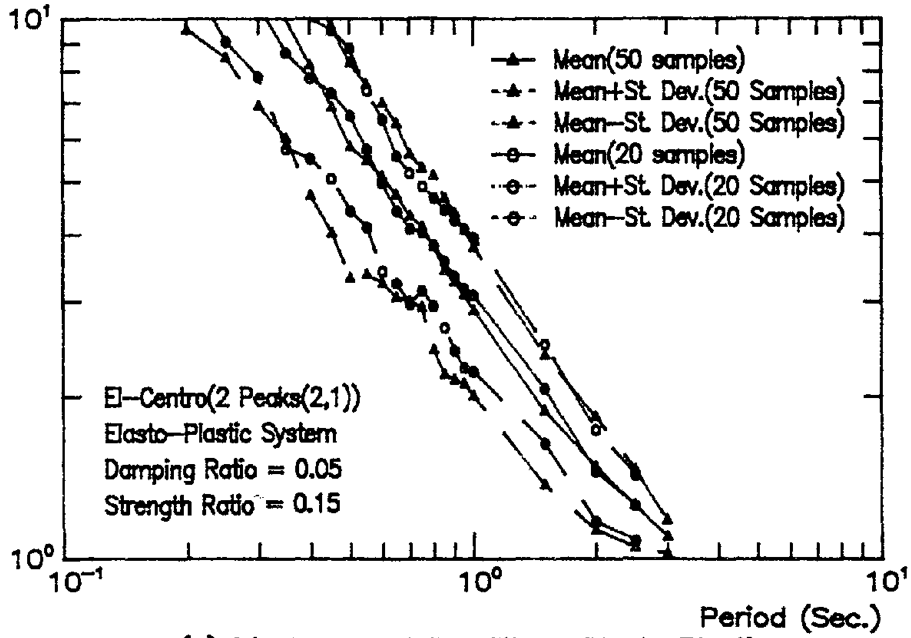


(c) Displacement Ductility — Stiffness Degrading

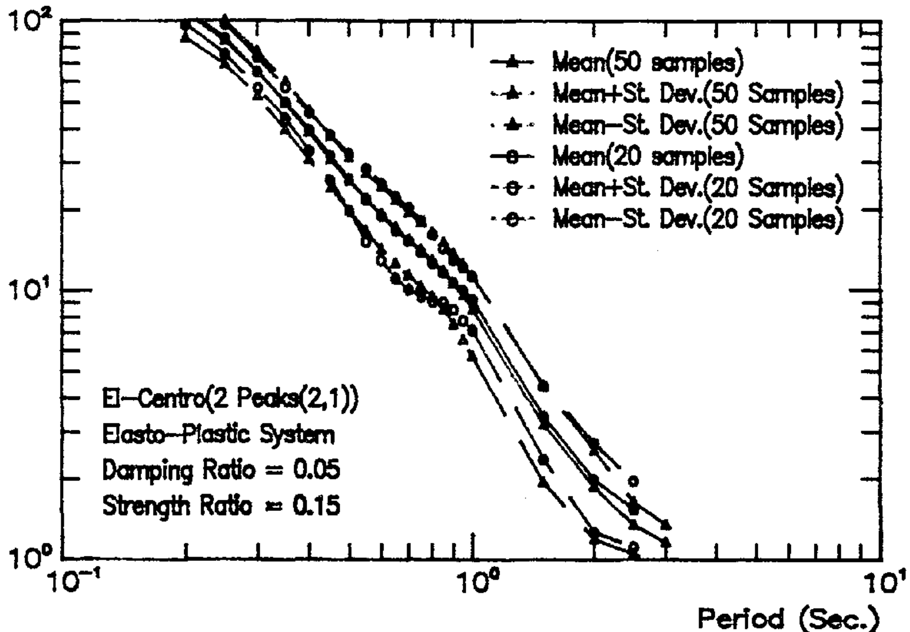


(d) Normalized Hysteretic Energy — Stiffness Degrading

FIGURE 4—2 RESPONSE SPECTRA — ORIGINAL AND ONE SAMPLE (Continued)

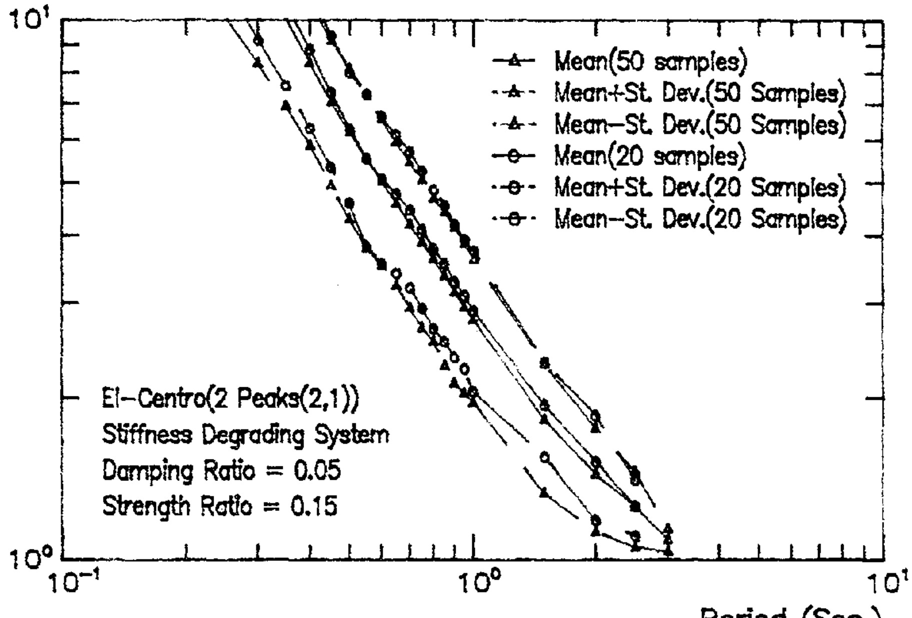


(a) Displacement Ductility – Elasto Plastic

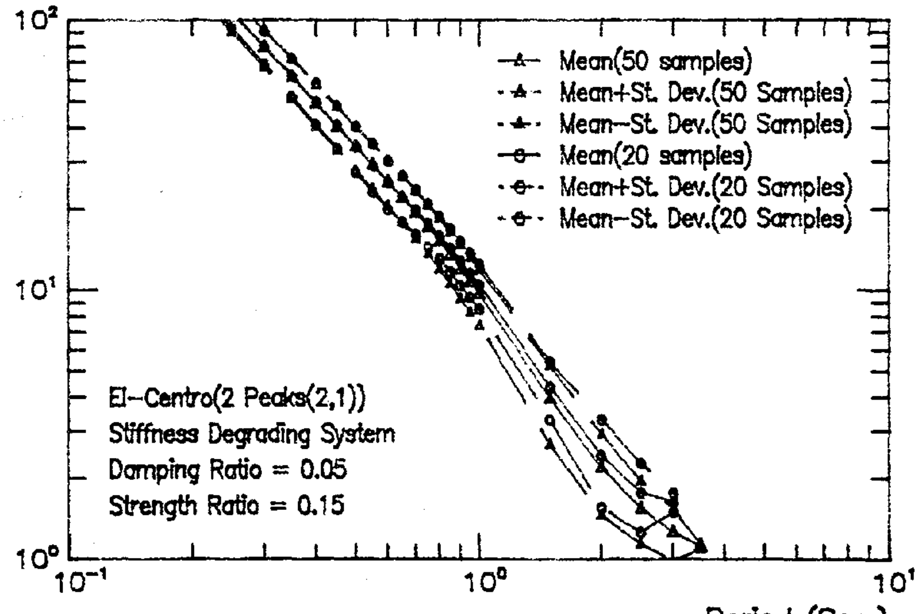


(b) Normalized Hysteretic Energy – Elasto Plastic

FIGURE 4–3 AVERAGE SPECTRA – EFFECT OF SAMPLE SIZE

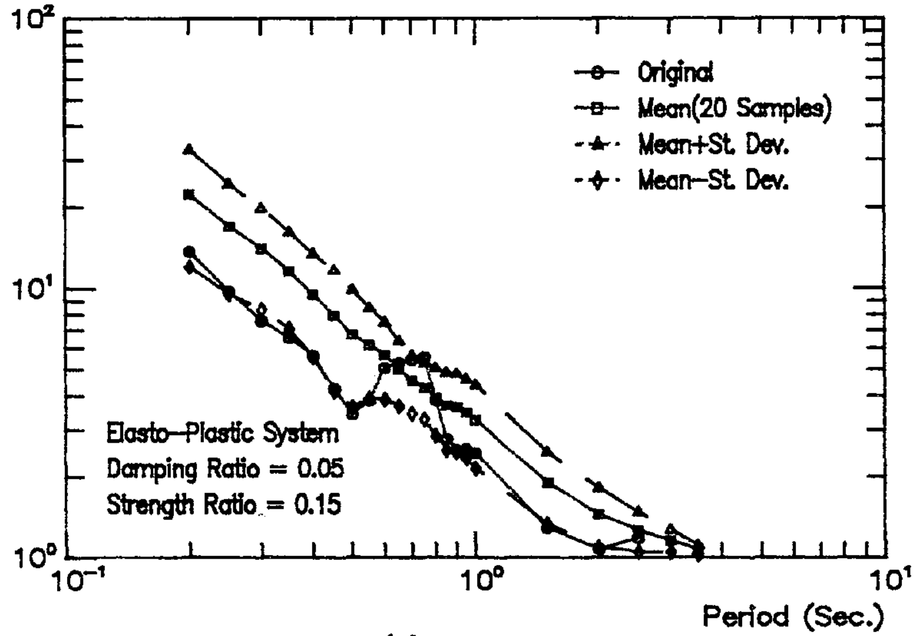


(c) Displacement Ductility – Stiffness Degrading

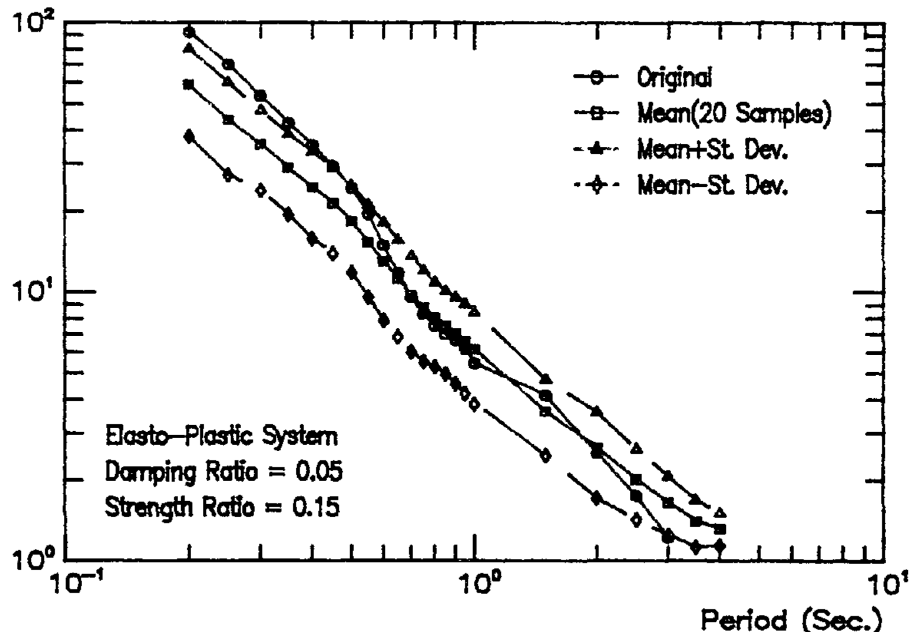


(d) Normalized Hysteretic Energy – Stiffness Degrading

FIGURE 4–3 AVERAGE SPECTRA – EFFECT OF SAMPLE SIZE (Continued)

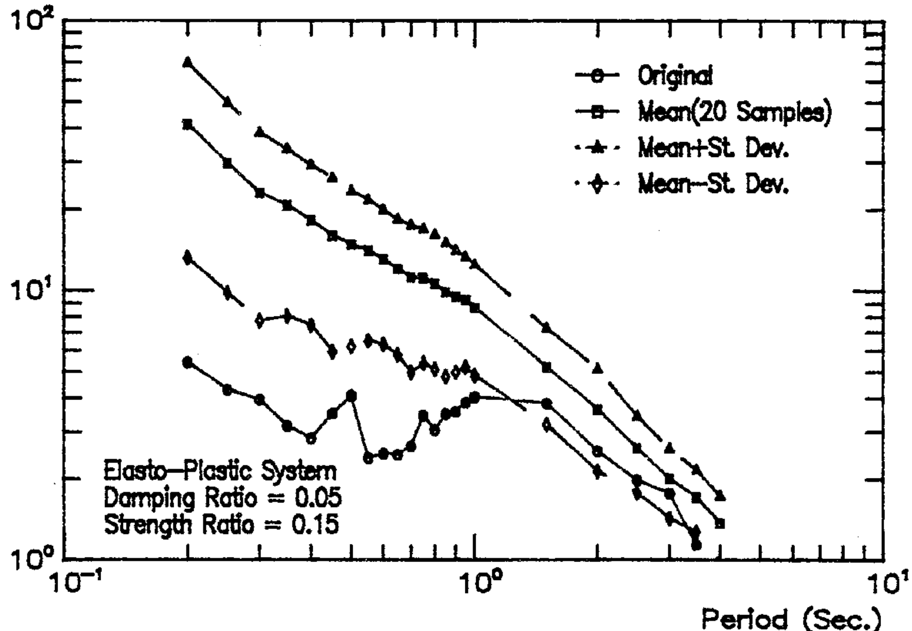


(a) El−Centro

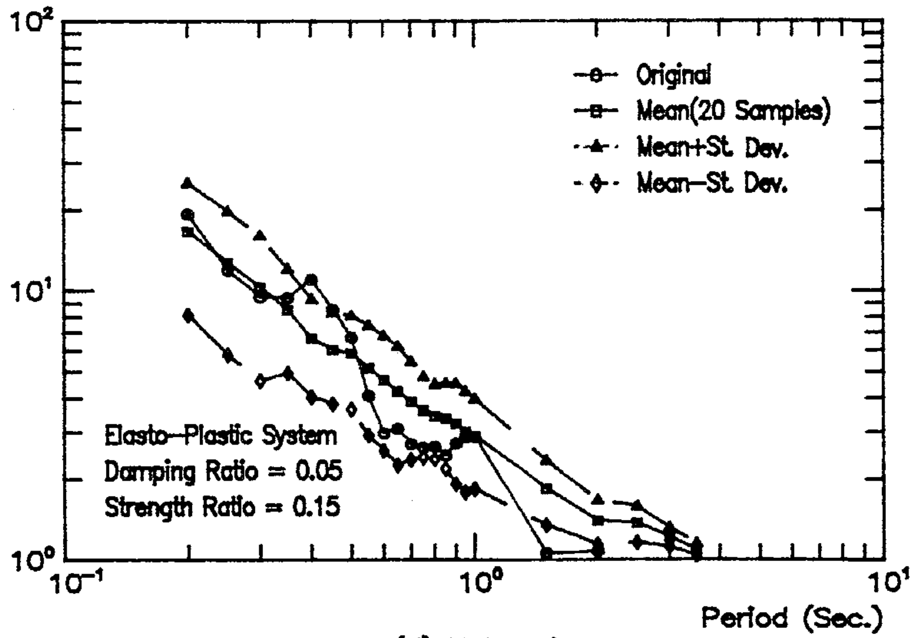


(b) Parkfield

FIGURE 4−4 ONE σ CONFIDENCE INTERVALS FOR DISPLACEMENT DUCTILITY



(c) Mexico City



(d) Nahanni

FIGURE 4–4 ONE σ CONFIDENCE INTERVALS FOR DISPLACEMENT DUCTILITY (Continued) originals. However, for this limited set of data it can be concluded that, assuming conventional criteria for statistical analysis, the hypothesis that the measured record is drawn from the model process may be accepted for at least a limited class of response characteristics.

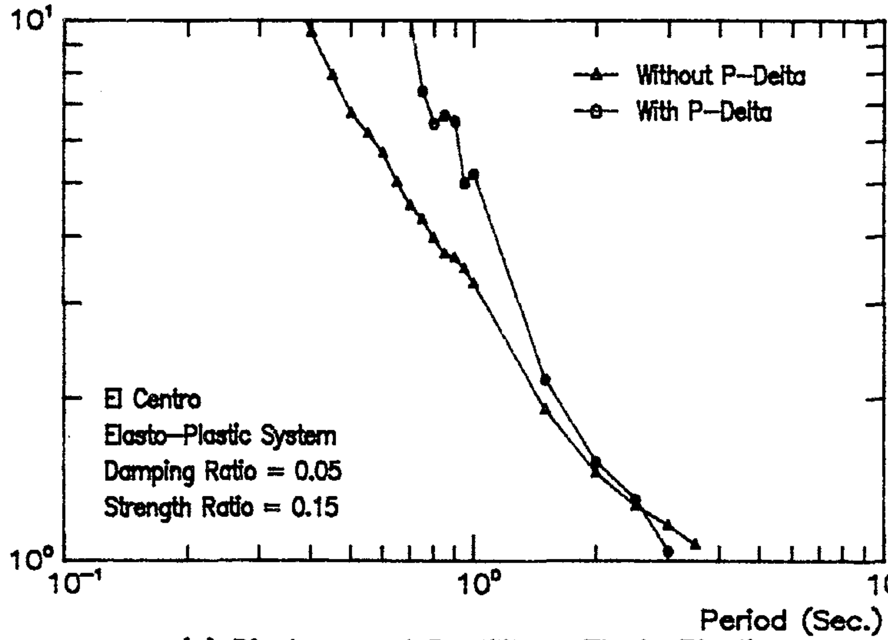
Although the results for Mexico City do not contradict this statistical statement, the systematic variation of the difference between measured and simulated response spectra suggest caution.

Since average response spectra for the earthquake processes are quite smooth, it may also be concluded that irregularities in nonlinear response spectra for individual measured acceleration records may be considered to be random variations which do not represent a reliable property of the process.

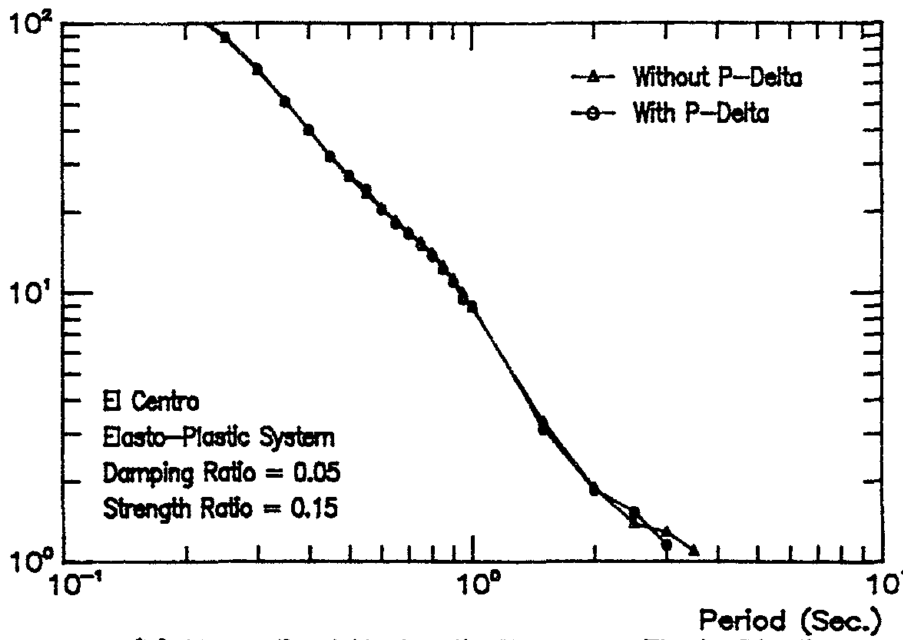
As a preliminary study of the influence of P-Δ effects, selected nonlinear demand spectra were obtained. Results for the average of 20 for El Centro are shown in Figs 4-5 a-d. These suggest that the effects may not be significant in some cases. However, in other cases it was found that all structures in a sample of twenty failed due to P-Δ effects in the sense that displacements began to grow without limit. In fact, the loss of stiffness due to P-Δ effects was the only failure mechanism considered in analysis.

These results are very limited but several observations can be made. In general, as the initial period increases the number of structures in a sample of twenty that collapsed increased significantly. In some cases , long period structures which did not even yield without P-Δ effects collapsed when the effects were considered.

Finally, as a general note concerning all four sets of response data, the coefficients of variation of both ductility demand and normalized hysteretic

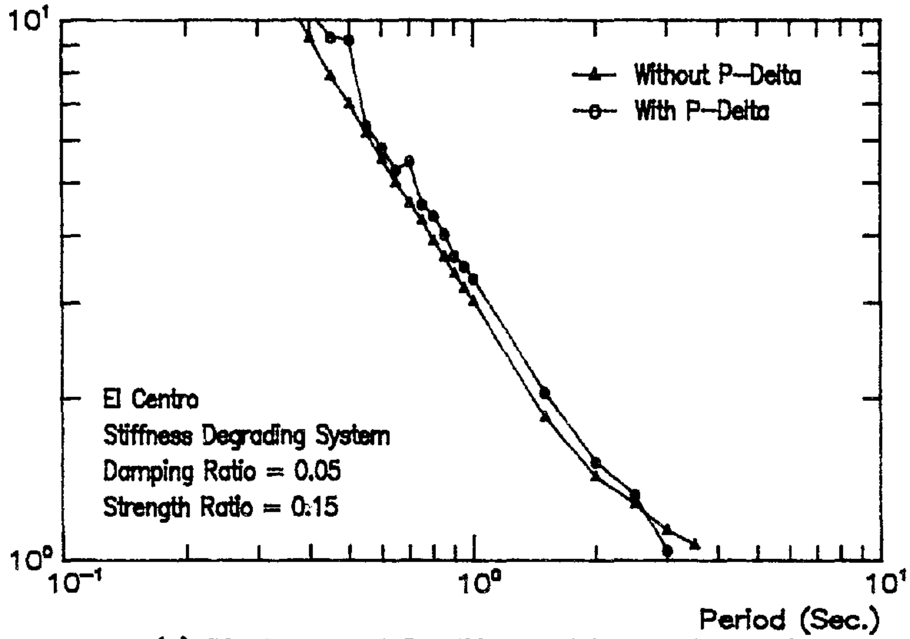


(a) Displacement Ductility – Elasto Plastic

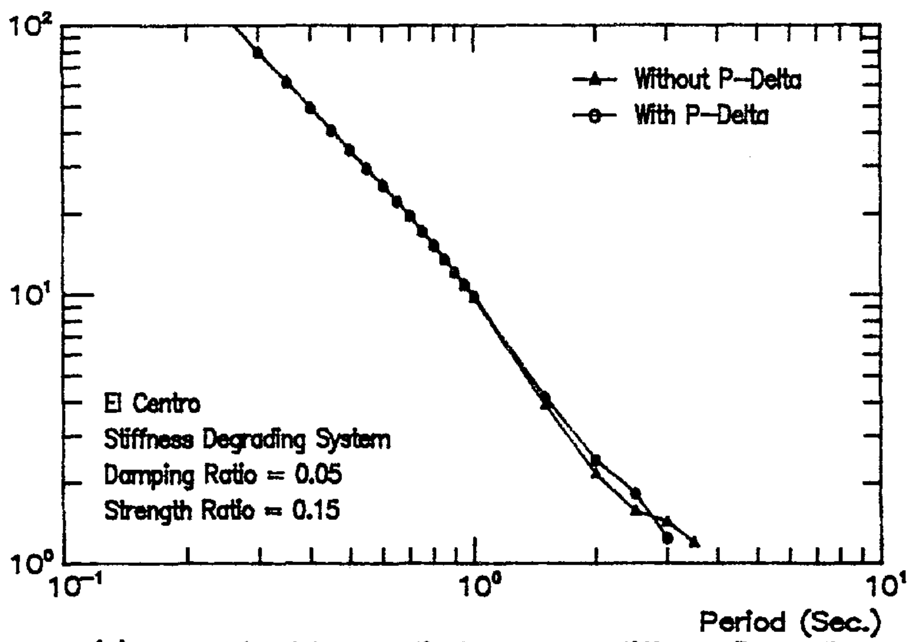


(b) Normalized Hysteretic Energy – Elasto Plastic

FIGURE 4–5 INFLUENCE OF P–Δ EFFECTS



(c) Displacement Ductility — Stiffness Degrading



(d) Normalized Hysteretic Energy — Stiffness Degrading

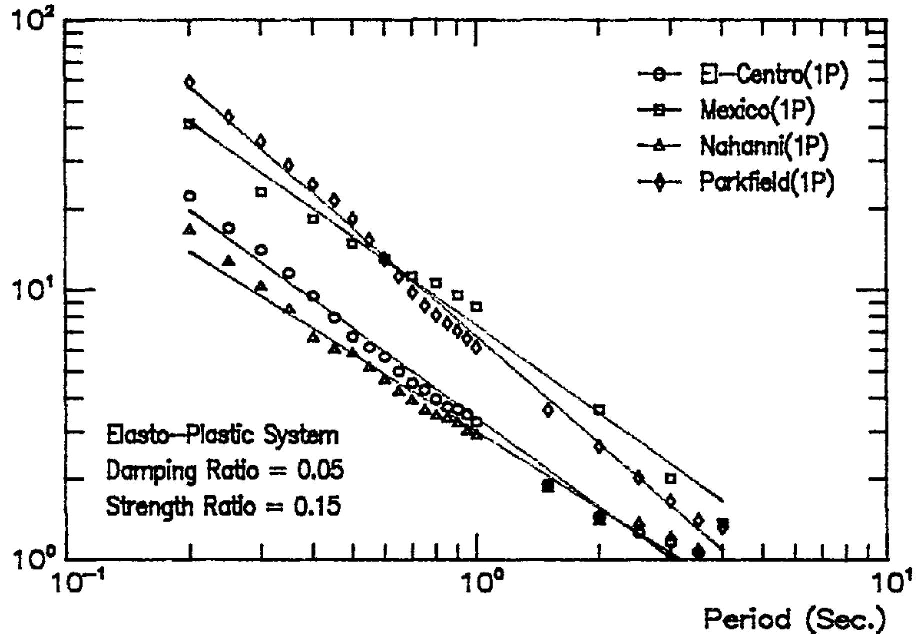
FIGURE 4—5 INFLUENCE OF P—Δ EFFECTS (Continued) energy demand were quite large (20-50%). In the case of an elasto-plastic system under El Centro type excitation, the 20 sample average ductility demand for a structure with an initial period of 0.20 sec., for example, was 22.4. Since, the standard deviation was 10.4, the +/- one standard deviation confidence interval on ductility demand was from 12.0 to 34.8 This represents a significant uncertainty in response.

4.2 COMPARISON OF EVENTS

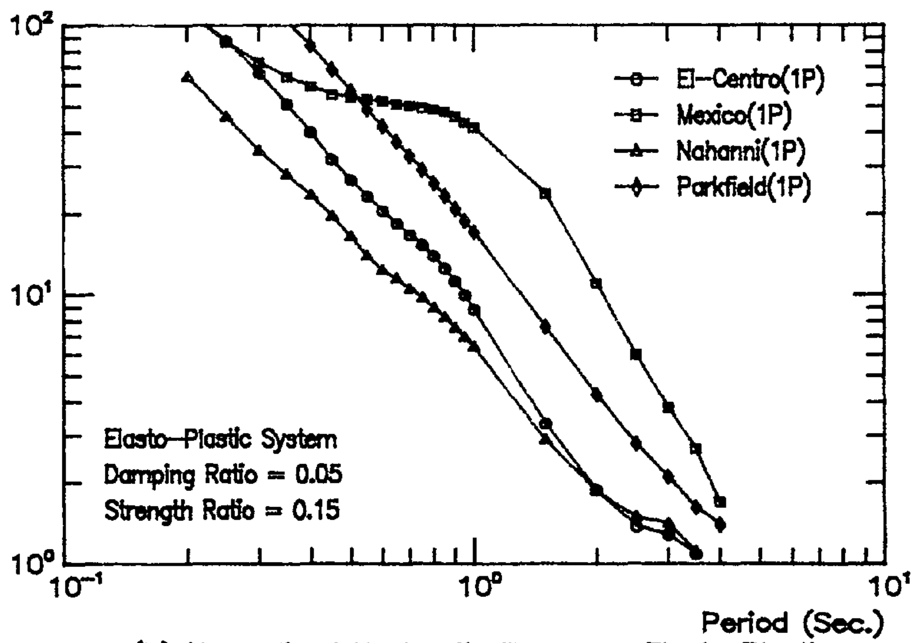
As a first step in the evaluation of alternative models, average nonlinear response spectra for the one-peak process models of order (2,1) were computed for the four earthquakes considered. Elasto-plastic and stiffness softening systems were examined.

Selected ductility demand and hysteretic energy demand spectra for elasto-plastic and stiffness degrading systems are shown in Figs 4-6 a-d. Least squares straight lines were fitted to the ductility demand spectra as shown. It can be seen that except perhaps for the Mexico City event which is known to have pronounced site effects, one can conclude that, for the earthquakes studied, the logarithms of both average ductility and hysteretic energy demand spectral ordinates were very nearly linearly related to the logarithms of initial period.

Although the numerical values of spectral ordinates for elasto-plastic and stiffness softening systems are not identical, both classes of behavioral models display similar spectral shape. For evaluations of earthquake models it seems that simple elasto-plastic behavior could be assumed. Similar conclusions were reached by Lin and Mahin(1983)

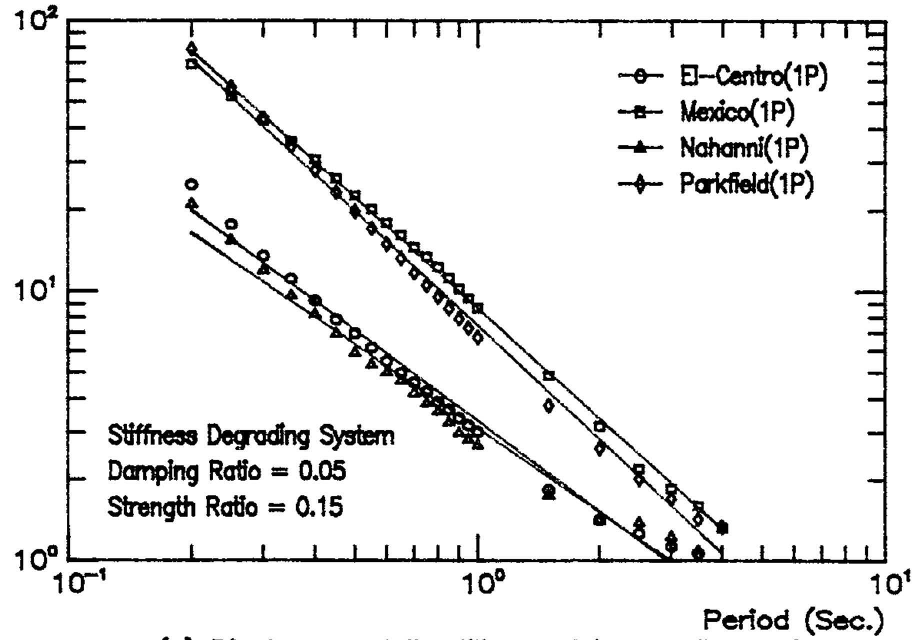


(a) Displacement Ductility – Elasto Plastic

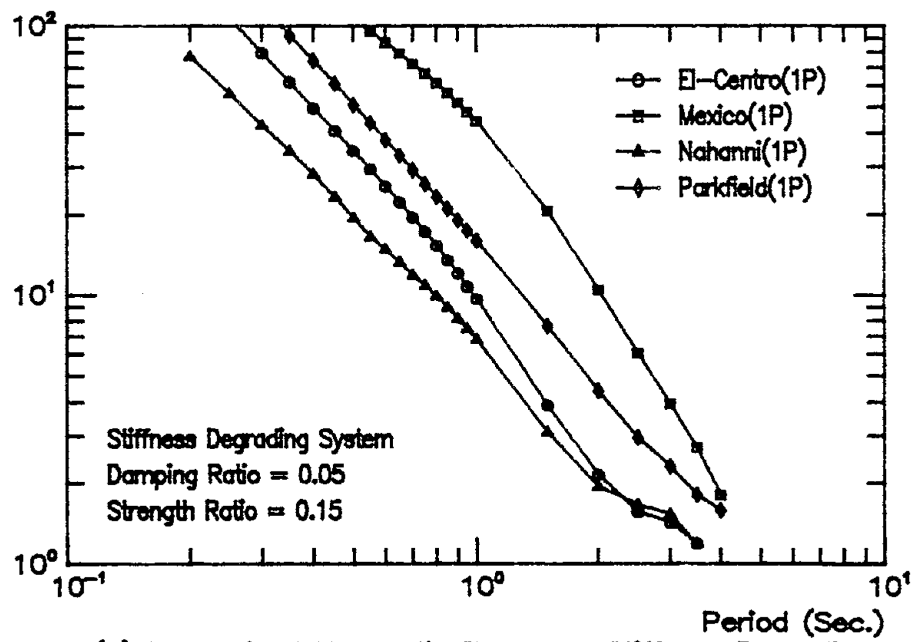


(b) Normalized Hysteretic Energy – Elasto Plastic

FIGURE 4–6 COMPARISION OF RESPONSE SPECTRA FOR FOUR EVENTS



(c) Displacement Ductility — Stiffness Degrading



(d) Normalized Hysteretic Energy — Stiffness Degrading

FIGURE 4–6 COMPARISION OF RESPONSE SPECTRA FOR FOUR EVENTS (Continued)

It should be noted that for long period structures, average response spectra are not very reliable. As the average demand approaches 1.0 (i.e. no yielding) more and more structures in a sample of twenty do not yield.

Similar effects for the spectra of damage index are shown in Figs 4-7 a-d for elasto-plastic systems with and without P-Δ effects. Results are too limited to suggest conclusions. However, it should be noted that the damage index spectra can be obtained from a combination of the ductility demand and hysteretic energy demand spectra.

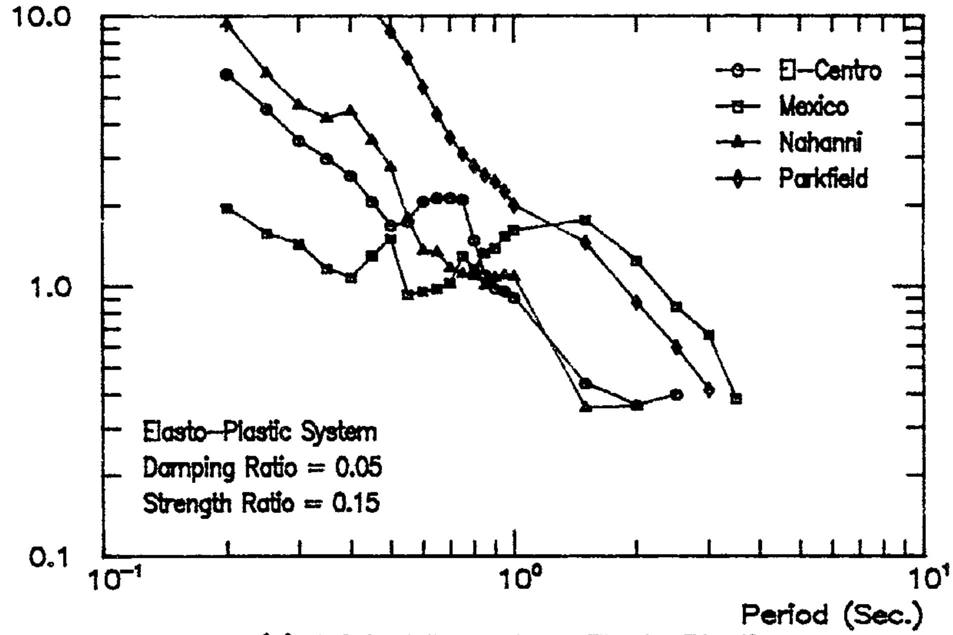
4.3 SENSITIVITY STUDIES

The following results involve two sets of response analysis; one set corresponds to the one peak, order (2,1) maximum likelihood models found using the formal Box and Jenkins approach; the second set involves arbitrary perturbations to the process model parameters in a sensitivity analysis. To normalize data for comparison purposes, spectral ordinates were divided by the corresponding ordinates for the one-peak, (2,1) ARMA models.

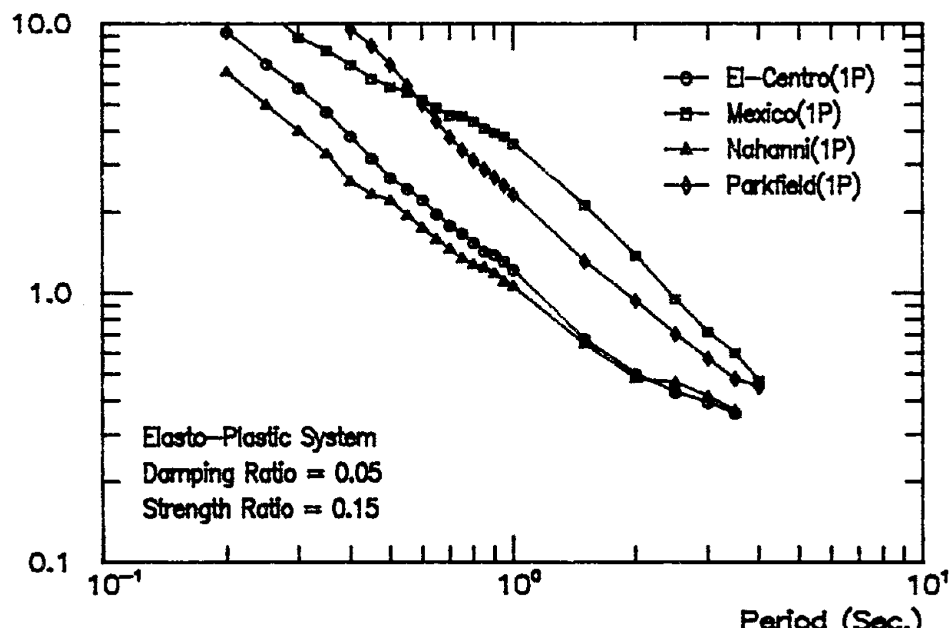
Because of the volume of calculations involved, most spectral ordinates were calculated for only four initial periods of vibration: $2\pi/\omega$ = 0.3 sec., 0.6 sec., 1.0 sec., and 3.0 sec. Damping ratios ν = 0.02, 0.05, and yield force ratios $Y = R_Y/M*G$ = 0.05, 0.15 were used.

4.3.1 PEAKS IN THE ENVELOPE FUNCTION

To evaluate the effects of the number of peaks assumed for the envelope function, average (samples of 20) response spectra for the El Centro (1,2 peaks) and Nahanni (1,2,3 peaks) are shown in TABLE 4-III.

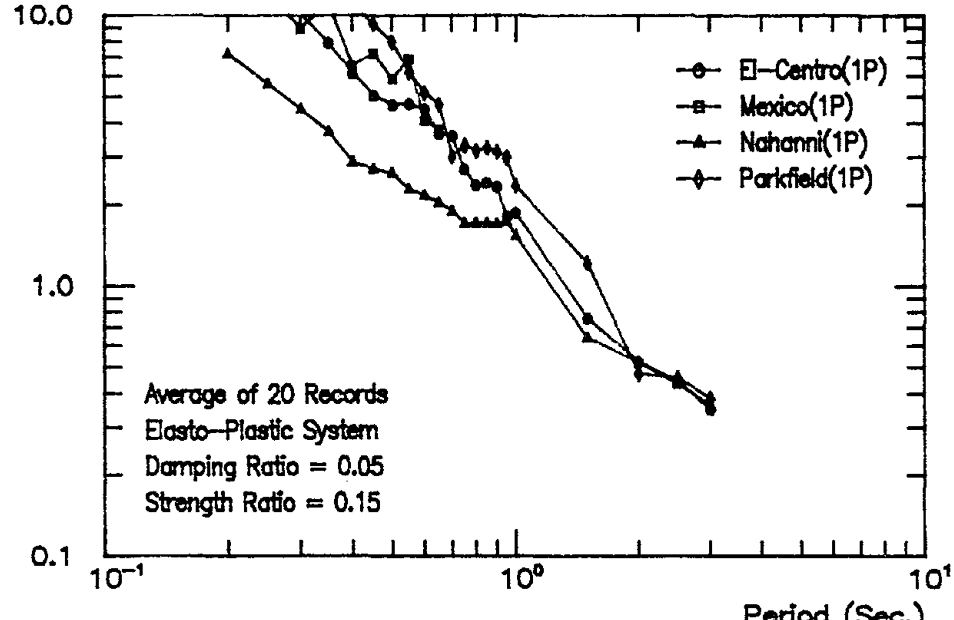


(a) Original Records – Elasto Plastic

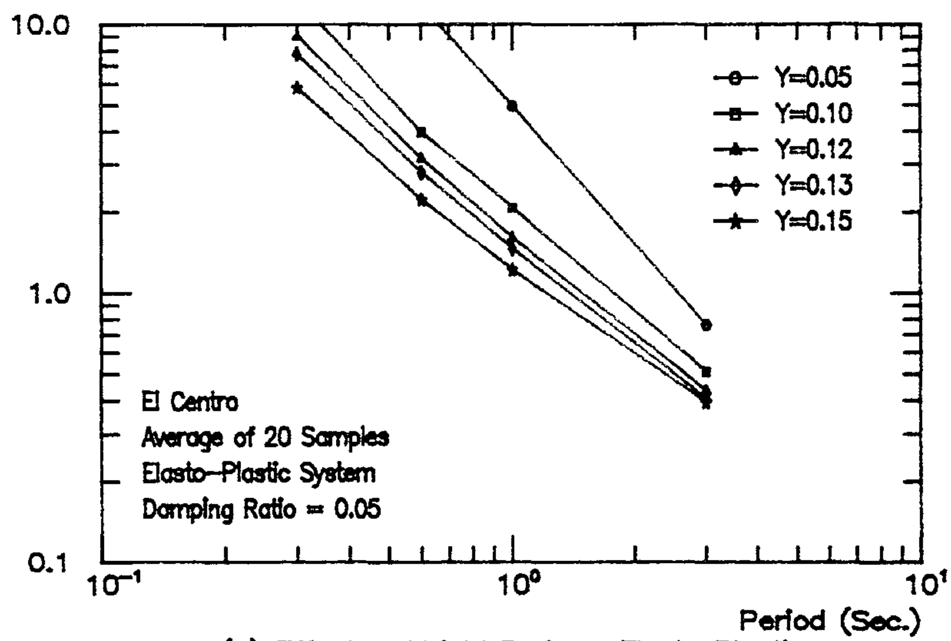


(b) Average of 20 Samples – Elasto Plastic

FIGURE 4–7 SPECTRA OF DAMAGE INDEX



(c) P--Delta Effects -- Elasto Plastic



(d) Effects of Yield Ratio -- Elasto Plastic

FIGURE 4-7 SPECTRA OF DAMAGE INDEX (Continued)

TABLE 4.III EFFECTS OF NUMBER OF ENVELOPE PEAKS

(a): DISPLACEMENT DUCTILITY: ELASTO-PLASTIC SYSTEM

ν	Y	$2\pi/\omega$	EL-CENTRO original	EL-CENTRO 1p (2,1)	EL-CENTRO 2p (2,1)	NAHANNI original	NAHANNI 1p (2,1)	NAHANNI 2p (2,1)	NAHANNI 3p (2,1)
.02	.05	.30	.50	1.00	.93	1.08	1.00	1.75	2.68
		.60	.54	1.00	.97	.91	1.00	1.78	2.46
		1.00	1.26	1.00	1.03	1.10	1.00	1.84	2.53
		3.00	.73	1.00	1.05	1.08	1.00*	1.23	1.61
	.15	.30	.55	1.00	.77	1.05	1.00	1.99	3.59
		.60	.91	1.00	.88	.63	1.00	1.59	2.41
		1.00	.82	1.00	.97	.69	1.00	1.64	1.31
		3.00	.92	1.00*	1.03*	.78	1.00*	1.24*	1.30*
.05	.05	.30	.61	1.00	.91	1.20	1.00	1.66	2.55
		.60	.53	1.00	1.01	.97	1.00	1.68	2.35
		1.00	1.10	1.00	1.02	1.05	1.00	1.72	2.40
		3.00	.72	1.00	1.02	1.10	1.00*	1.20	1.59
	.15	.30	.54	1.00	.75	1.04	1.00	1.92	3.37
		.60	.89	1.00	.87	.67	1.00	1.61	2.46
		1.00	.75	1.00	.94	.65	1.00	1.68	1.93
		3.00	**	1.00*	1.10*	**	1.00*	1.24*	1.27*

*:Some of samples do not yield
**:Original recorcd does not yield

(b): NORMALIZED HYSTERETIC ENERGY: ELASTO-PLASTIC SYSTEM

ν	Y	$2\pi/\omega$	EL-CENTRO original	EL-CENTRO 1p (2,1)	EL-CENTRO 2p (2,1)	NAHANNI original	NAHANNI 1p (2,1)	NAHANNI 2p (2,1)	NAHANNI 3p (2,1)
.02	.05	.30	.96	1.00	1.07	1.55	1.00	2.21	2.53
		.60	.93	1.00	1.10	1.32	1.00	2.09	2.38
		1.00	.77	1.00	1.13	1.11	1.00	2.00	2.26
		3.00	.97	1.00	1.03	1.51	1.00*	1.70	2.06
	.15	.30	.87	1.00	.98	2.49	1.00	2.89	4.07
		.60	1.14	1.00	.95	1.74	1.00	2.74	3.52
		1.00	.72	1.00	1.09	1.18	1.00	2.19	2.72
		3.00	.81	1.00*	1.04*	.68	1.00*	1.37*	1.36*
.05	.05	.30	.97	1.00	1.05	1.67	1.00	2.22	2.59
		.60	.97	1.00	1.09	1.38	1.00	2.14	2.46
		1.00	.76	1.00	1.13	1.12	1.00	2.04	2.32
		3.00	.95	1.00	.98	1.31	1.00*	1.66	2.04
	.15	.30	.87	1.00	.97	2.68	1.00	2.94	4.21
		.60	1.15	1.00	.92	1.79	1.00	2.83	3.76
		1.00	.73	1.00	1.04	1.12	1.00	2.32	2.95
		3.00	**	1.00*	1.05	**	1.00*	1.32*	1.26*

*:Some of samples do not yield
**:Original record does not yield

TABLE 4.III EFFECTS OF NUMBER OF PEAKS (continued)

(c): DISPLACEMENT DUCTILITY: STIFFNESS DEGRADING SYSTEM

			EL-CENTRO			NAHANNI			
ν	Y	$2\pi/\omega$	original	1p (2,1)	2p (2,1)	original	1p (2,1)	2p (2,1)	3p (2,1)
.02	.05	.30	.56	1.00	1.01	.80	1.00	1.54	2.19
		.60	.63	1.00	.98	.71	1.00	1.55	2.16
		1.00	.83	1.00	1.02	.73	1.00	1.41	1.95
		3.00	.80	1.00	.97	.96	1.00*	1.17	1.42
	.15	.30	.83	1.00	.93	.83	1.00	1.96	3.23
		.60	.79	1.00	.93	.71	1.00	1.64	2.52
		1.00	.78	1.00	.97	.72	1.00	1.50	1.97
		3.00	.93	1.00*	1.04*	.78	1.00*	1.22*	1.22*
.05	.05	.30	.57	1.00	.96	.88	1.00	1.50	2.20
		.60	.63	1.00	.99	.78	1.00	1.54	2.17
		1.00	.82	1.00	1.00	.78	1.00	1.47	2.11
		3.00	.80	1.00	.96	.92	1.00*	1.13	1.39
	.15	.30	.80	1.00	.97	.73	1.00	1.89	3.08
		.60	.84	1.00	.92	.79	1.00	1.68	2.54
		1.00	.79	1.00	.96	.72	1.00	1.55	1.99
		3.00	**	1.00*	1.13*	**	1.00*	1.22*	1.18*

*:Some of samples do not yield
**:Original record does not yield

(d): NORMALIZED HYSTERETIC ENERGY: STIFFNESS DEGRADING SYSTEM

			EL-CENTRO			NAHANNI			
ν	Y	$2\pi/\omega$	original	1p (2,1)	2p (2,1)	original	1p (2,1)	2p (2,1)	3p (2,1)
.02	.05	.30	.91	1.00	1.06	1.15	1.00	1.78	2.02
		.60	.87	1.00	1.06	1.16	1.00	1.76	2.02
		1.00	.82	1.00	1.07	1.15	1.00	1.73	2.02
		3.00	.87	1.00	1.06	1.32	1.00*	1.54	1.87
	.15	.30	1.04	1.00	1.01	1.71	1.00	2.51	3.08
		.60	.91	1.00	1.01	1.47	1.00	2.20	2.65
		1.00	.76	1.00	1.11	1.02	1.00	1.87	2.20
		3.00	.81	1.00*	1.11*	.61	1.00*	1.34*	1.31*
.05	.05	.30	.94	1.00	1.06	1.18	1.00	1.78	2.04
		.60	.88	1.00	1.07	1.15	1.00	1.77	2.02
		1.00	.81	1.00	1.08	1.15	1.00	1.77	2.06
		3.00	.90	1.00	1.04	1.28	1.00*	1.50	1.33
	.15	.30	1.06	1.00	1.01	1.83	1.00	2.58	3.26
		.60	.96	1.00	.99	1.61	1.00	2.35	2.88
		1.00	.76	1.00	1.09	1.07	1.00	1.98	2.37
		3.00	**	1.00*	1.15	**	1.00*	1.31*	1.24*

*:Some of samples do not yield
**:Original record does not yield

For both elasto-plastic and stiffness degrading systems, it can be seen that displacement ductility and hysteretic energy demand generally but not always increase with the number of peaks in the envelope function. Except perhaps for several cases of hysteretic energy demand, spectral ordinates for the original record were within reasonable confidence intervals for the one peak samples.

Although the data are limited, they suggest that increasing the number of peaks in the envelope function did not yield improved estimates of non-linear response for the cases studied.

Since many recorded events have only one obvious peak, the use of a single peak in most cases would seem to be justifiable. A single peak was used in all subsequent analysis.

4.3.2 ORDERS (p,q) OF THE ARMA PROCESS

Shown in TABLE 4-IV are average, normalized, nonlinear spectral ordinates for alternative orders (p,q) for El Centro and Nahanni. Comparing these data for each event suggests that models with order (1,1) did not lead to reliable demand spectra. Results for models of order (2,1) seemed to have a random relationship to the spectra for the measured events. Nahanni spectra for the optimal order (3,1) were not significantly closer to the original spectra than results for order (2,1).

Although the data are again quite limited, it was concluded that models of order (2,1) were sufficient for further analysis.

4.3.3 ENVELOPE PARAMETERS

TABLE 4.IV INFLUENCE OF MODEL ORDER (p,q)

(a): **DISPLACEMENT DUCTILITY: ELASTO-PLASTIC SYSTEM**

			EL-CENTRO				NAHANNI			
ν	Y	$2\pi/\omega$	original	(1,1)	(2,1)	(3,1)	original	(1,1)	(2,1)	(3,1)
.02	.05	.30	.50	1.57	1.00	1.07	1.08	1.08	1.00	1.25
		.60	.54	1.56	1.00	1.07	.91	1.01	1.00	1.16
		1.00	1.26	1.57	1.00	1.07	1.10	1.07	1.00	1.29
		3.00	.78	1.48	1.00	1.05	1.08	.84*	1.00*	.96
	.15	.30	.55	1.36	1.00	1.06	1.05	1.07	1.00	1.10
		.60	.91	1.29	1.00	1.04	.63	1.14	1.00	1.19
		1.00	.82	1.47	1.00	1.06	.69	1.02	1.00	1.10
		3.00	.92	1.30*	1.00*	1.03*	.78	.97*	1.00*	.99*
.05	.05	.30	.61	1.45	1.00	1.06	1.20	1.10	1.00	1.21
		.60	.53	1.52	1.00	1.08	.97	1.02	1.00	1.14
		1.00	1.10	1.51	1.00	1.06	1.05	1.05	1.00	1.23
		3.00	.72	1.45	1.00	1.05	1.10	.82*	1.00*	.93
	.15	.30	.54	1.32	1.00	1.05	1.04	1.02	1.00	1.05
		.60	.89	1.31	1.00	1.04	.67	1.11	1.00	1.20
		1.00	.75	1.46	1.00	1.05	.65	1.02	1.00	1.13
		3.00	**	1.25*	1.00*	1.00	**	.94*	1.00*	.96*

*:Some of samples do not yield
**:Original record does not yield

(b): **NORMALIZED HYSTERETIC ENERGY: ELASTO-PLASTIC SYSTEM**

			EL-CENTRO				NAHANNI			
ν	Y	$2\pi/\omega$	original	(1,1)	(2,1)	(3,1)	original	(1,1)	(2,1)	(3,1)
.02	.05	.30	.96	1.37	1.00	1.04	1.55	.95	1.00	1.10
		.60	.93	1.50	1.00	1.06	1.32	.92	1.00	1.10
		1.00	.77	1.59	1.00	1.08	1.11	.90	1.00	1.07
		3.00	.97	1.75	1.00	1.09	1.51	.93*	1.00*	1.05
	.15	.30	.87	1.07	1.00	1.00	2.49	1.11	1.00	1.16
		.60	1.14	1.55	1.00	1.07	1.74	1.13	1.00	1.27
		1.00	.72	1.68	1.00	1.09	1.18	.98	1.00	1.07
		3.00	.81*	1.49*	1.00*	1.05*	.68	.94*	1.00*	.88*
.05	.05	.30	.97	1.32	1.00	1.04	1.67	.96	1.00	1.09
		.60	.97	1.49	1.00	1.06	1.38	.93	1.00	1.11
		1.00	.76	1.60	1.00	1.08	1.12	.91	1.00	1.06
		3.00	.95	1.80	1.00	1.09	1.31	.89*	1.00*	1.02
	0.15	.30	.87	1.04	1.00	.99	2.68	1.09	1.00	1.16
		.60	1.15	1.57	1.00	1.07	1.79	1.14	1.00	1.26
		1.00	.73	1.74	1.00	1.10	1.12	.98	1.00	1.09
		3.00	**	1.29*	1.00*	1.00*	**	.87*	1.00*	.83*

*:Some of samples do not yield
**:Original record does not yield

TABLE 4.IV INFLUENCE OF MODEL ORDER (p,q) (continued)

(c): **DISPLACEMENT DUCTILITY: STIFFNESS DEGRADING SYSTEM**

			EL-CENTRO				NAHANNI			
ν	Y	$2\pi/\omega$	original	(1,1)	(2,1)	(3,1)	original	(1,1)	(2,1)	(3,1) @
.02	.05	.30	.56	1.62	1.00	1.08	.80	1.05	1.00	1.15
		.60	.63	1.53	1.00	1.07	.71	1.05	1.00	1.17
		1.00	.83	1.50	1.00	1.06	.73	.99	1.00	1.09
		3.00	.80	1.37	1.00	1.04	.96	.89*	1.00*	.98
	.15	.30	.83	1.67	1.00	1.09	.83	1.15	1.00	1.24
		.60	.79	1.56	1.00	1.08	.71	1.07	1.00	1.10
		1.00	.78	1.58	1.00	1.07	.72	1.06	1.00	1.22
		3.00	.93	1.30*	1.00*	1.03*	.78	.98*	1.00*	1.00*
.05	.05	.30	.57	1.51	1.00	1.07	.88	1.09	1.00	1.17
		.60	.63	1.53	1.00	1.07	.78	1.07	1.00	1.16
		1.00	.82	1.44	1.00	1.06	.78	1.03	1.00	1.14
		3.00	.80	1.37	1.00	1.04	.92	.88*	1.00*	.94
	.15	.30	.80	1.62	1.00	1.08	.73	1.12	1.00	1.19
		.60	.84	1.54	1.00	1.07	.79	1.07	1.00	1.14
		1.00	.79	1.51	1.00	1.07	.72	1.09	1.00	1.22
		3.00	**	1.26*	1.00*	1.02*	**	.93*	1.00*	.95*

*:Some of samples do not yield
**:Original record does not yield

(d): **NORMALIZED HYSTERETIC ENERGY: STIFFNESS DEGRADING SYSTEM**

			EL-CENTRO				NAHANNI			
ν	Y	$2\pi/\omega$	original	(1,1)	(2,1)	(3,1)	original	(1,1)	(2,1)	(3,1)
.02	.05	.30	.91	1.44	1.00	1.06	1.15	.94	1.00	1.10
		.60	.87	1.47	1.00	1.06	1.16	.93	1.00	1.13
		1.00	.82	1.49	1.00	1.06	1.15	.92	1.00	1.13
		3.00	.87	1.62	1.00	1.08	1.32	.95*	1.00*	1.06
	.15	.30	1.04	1.51	1.00	1.06	1.71	1.01	1.00	1.07
		.60	.91	1.50	1.00	1.07	1.47	.96	1.00	1.09
		1.00	.76	1.60	1.00	1.07	1.02	.93	1.00	1.06
		3.00	.81	1.46*	1.00*	1.05*	.61	.95*	1.00*	.89*
.05	.05	.30	.94	1.40	1.00	1.05	1.18	.93	1.00	1.07
		.60	.88	1.45	1.00	1.06	1.15	.94	1.00	1.10
		1.00	.81	1.49	1.00	1.06	1.15	.93	1.00	1.12
		3.00	.90	1.65	1.00	1.08	1.28	.91*	1.00*	1.00
	0.15	.30	1.06	1.44	1.00	1.05	1.83	1.04	1.00	1.08
		.60	.96	1.52	1.00	1.07	1.61	.98	1.00	1.13
		1.00	.76	1.60	1.00	1.08	1.07	.95	1.00	1.07
		3.00	**	1.32*	1.00*	1.00*	**	.86*	1.00*	.81*

*:Some of samples do not yield
**:Original record does not yield

Shown in TABLES 4-V are normalized average nonlinear demand spectra for one-peak (2,1) models of selected events where the decay constant β has been increased by +/- 25% relative to the least squares values.

As expected, decreasing the rate of decay (increasing duration) increases spectral ordinates while increasing the rate of decay (decreasing duration) decreases demand. In general however, it may be observed that nonlinear ductility and hysteretic energy demand spectra were not highly sensitive to the envelope decay rate. The effects of decay rate did not significantly depend on the initial structural period.

Similar results involving +/- 25% changes in the time to the peak of the envelope function are shown in TABLES 4-VI. After analysis it was concluded that these results were not meaningful since the effects on non-linear response spectra depend on the original duration of motion.

For El Centro, for example, the peak time T_P = 1.5 sec. so the range of peak times in TABLES 4-VI are +/- .375 sec. which corresponds to a total variation of about +/- 1.5% of the total duration. As expected, the effects are small. For Nahanni with T_P = 9.9 sec, the range is +/- 2.3 sec which corresponds to about +/- 23.0% of the total duration. Since the peak for Nahanni occurs very near the end of the record, increasing T_P significantly increased the duration of the event. As a result, the effects were significant.

TABLES 4-VII provide similar data for a +/- 25% change in the height of the peak α of the envelope function. This factor is in fact a scaling factor for the whole envelope function and, as such, it has an implicit effect on duration..

TABLE 4.V SENSITIVITY TO ENVELOPE DECAY FACTOR β

(a): DISPLACEMENT DUCTILITY: ELASTO-PLASTIC SYSTEM

			ELCENTRO		NAHANNI	
ν	Y	$2\pi/\omega$	+25%	-25%	+25%	-25%
.02	.05	.30	.94	1.09	.96	1.07
		.60	.92	1.12	.95	1.07
		1.00	.90	1.14	.95	1.07
		3.00	.95*	1.13	.97*	1.04*
	.15	.30	.89	1.14	.96	1.05
		.60	.91	1.10	.97	1.06
		1.00	.93	1.13	.98	1.02
		3.00	.97*	1.05*	1.09*	1.00*
.05	.05	.30	.93	1.08	.96	1.07
		.60	.93	1.10	.95	1.07
		1.00	.92	1.12	.96	1.06
		3.00	.96*	1.11	1.00*	1.05*
	.15	.30	.89	1.16	.97	1.06
		.60	.90	1.11	.97	1.05
		1.00	.93	1.11	.98	1.03
		3.00	.95*	1.01*	1.00*	1.00*

*:Some of samples do not yield

(b): NORMALIZED HYSTERETIC ENERGY: ELASTO-PLASTIC SYSTEM

			EL-CENTRO		NAHANNI	
ν	Y	$2\pi/\omega$	+25%	-25%	+25%	-25%
.02	.05	.30	.82	1.29	.93	1.12
		.60	.82	1.29	.93	1.12
		1.00	.82	1.30	.93	1.11
		3.00	.90*	1.23	.94*	1.09*
	.15	.30	.81	1.31	.94	1.10
		.60	.82	1.27	.94	1.10
		1.00	.83	1.29	.93	1.12
		3.00	.96*	1.10*	1.14*	.99*
.05	.05	.30	.82	1.29	.93	1.11
		.60	.82	1.29	.93	1.12
		1.00	.82	1.29	.93	1.11
		3.00	.91*	1.20	.98*	1.09*
	.15	.30	.81	1.31	.93	1.10
		.60	.83	1.28	.94	1.10
		1.00	.85	1.27	.93	1.11
		3.00	.92*	1.00*	.97*	.99*

*:Some of samples do not yield

TABLE 4.V SENSITIVITY TO ENVELOPE DECAY FACTOR β (continued)

(c): DISPLACEMENT DUCTILITY: STIFFNESS DEGRADING SYSTEM

			EL-CENTRO		NAHANNI	
ν	Y	$2\pi/\omega$	+25%	-25%	+25%	-25%
.02	.05	.30	.94	1.10	.95	1.07
		.60	.94	1.07	.95	1.08
		1.00	.94	1.06	.95	1.08
		3.00	.97*	1.09	.98*	1.03*
	.15	.30	.89	1.14	.94	1.11
		.60	.92	1.11	.96	1.07
		1.00	.95	1.07	.96	1.06
		3.00	.97*	1.05*	1.10*	.99*
.05	.05	.30	.95	1.08	.96	1.07
		.60	.94	1.08	.95	1.07
		1.00	.94	1.06	.96	1.08
		3.00	.97*	1.08	1.01*	1.04*
	.15	.30	.92	1.12	.95	1.08
		.60	.93	1.11	.96	1.05
		1.00	.95	1.07	.96	1.06
		3.00	.95*	1.02*	.99*	1.00*

*:Some of samples do not yield

(d): NORMALIZED HYSTERETIC ENERGY: STIFFNESS DEGRADING SYSTEM

				EL-CENTRO		NAHANNI
ν	Y	$2\pi/\omega$	+25%	-25%	+25%	-25%
.02	.05	.30	.85	1.22	.94	1.10
		.60	.85	1.23	.94	1.09
		1.00	.85	1.22	.94	1.09
		3.00	.91*	1.19	.96*	1.07*
	.15	.30	.82	1.29	.92	1.13
		.60	.83	1.26	.92	1.13
		1.00	.85	1.24	.93	1.12
		3.00	.94*	1.13*	1.16*	.99*
		.30	.85	1.23	.94	1.09
		.60	.85	1.23	.94	1.10
		1.00	.85	1.23	.94	1.09
		3.00	.91*	1.19	.99*	1.07*
	.15	.30	.82	1.28	.93	1.12
		.60	.83	1.27	.92	1.13
		1.00	.85	1.24	.93	1.12
		3.00	.90*	1.01*	.98*	.99*

*:Some of samples do not yield

TABLE 4.VI SENSITIVITY TO PEAK TIME FACTOR T_p

(a): DISPLACEMENT DUCTILITY: ELASTO-PLASTIC SYSTEM

			EL-CENTRO		NAHANNI	
ν	Y	$2\pi/\omega$	+25%	-25%	+25%	-25%
.02	.05	.30	.94	.94	1.30	1.52
		.60	.94	.97	1.21	1.43
		1.00	1.04	.98	1.23	1.47
		3.00	1.00	1.00	1.09	1.04*
	.15	.30	.95	1.00	1.21	1.71
		.60	1.01	.99	1.03	1.57
		1.00	1.05	.95	1.07	1.21
		3.00	.99*	1.00*	1.04*	1.05*
.05	.05	.30	.95	.96	1.23	1.42
		.60	.95	.97	1.21	1.35
		1.00	1.03	.98	1.19	1.38
		3.00	.98	.99	1.05	1.01*
	.15	.30	.96	.99	1.16	1.47
		.60	1.01	.99	1.01	1.45
		1.00	1.05	.94	1.13	1.24
		3.00	1.01*	.99*	.99*	1.00*

*:Some of samples do not yield

(b): NORMALIZED HYSTERITIC ENERGY: ELASTO-PLASTIC SYSTEM

			EL-CENTRO		NAHANNI	
ν	Y	$2\pi/\omega$	+25%	-25%	+25%	-25%
.02	.05	.30	1.01	.98	1.29	1.06
		.60	1.01	.98	1.25	1.01
		1.00	1.01	.98	1.23	.97
		3.00	1.00	.98	1.16	1.15*
	.15	.30	1.00	.98	1.27	1.66
		.60	1.02	.97	1.29	1.56
		1.00	1.02	.96	1.31	1.38
		3.00	.99*	.99*	.98*	1.10*
.05	.05	.30	1.01	.98	1.27	1.00
		.60	1.01	.98	1.27	1.00
		1.00	1.01	.98	1.24	.96
		3.00	1.00	.98	1.13	1.12*
	.15	.30	1.00	.98	1.28	1.53
		.60	1.02	.97	1.27	1.54
		1.00	1.02	.96	1.31	1.41
		3.00	1.03*	.98*	.89*	.95*

*:Some of samples do not yield

TABLE 4.VI SENSITIVITY TO PEAK TIME FACTOR T_p (continued)

(c): DISPLACEMENT DUCTILITY: STIFFNESS DEGRADING SYSTEM

			EL-CENTRO		NAHANNI	
ν	Y	$2\pi/\omega$	+25%	-25%	+25%	-25%
.02	.05	.30	.97	.96	1.22	1.06
		.60	.96	.96	1.27	1.06
		1.00	.99	.97	1.21	.98
		3.00	.99	.98	1.07	.97*
	.15	.30	1.00	.96	1.36	1.28
		.60	1.02	.94	1.38	1.09
		1.00	1.05	.97	1.30	1.14
		3.00	1.00*	.99*	1.05*	1.11*
.05	.05	.30	.98	.97	1.23	1.09
		.60	.98	.96	1.23	1.07
		1.00	1.00	.96	1.26	1.04
		3.00	.98	.98	1.04	.94*
	.15	.30	.99	1.01	1.27	1.23
		.60	1.03	.95	1.35	1.14
		1.00	1.04	.97	1.34	1.16
		3.00	1.02*	.99*	.99*	1.10*

*:Some of samples do not yield

(d): NORMALIZED HYSTERETIC ENERGY: STIFFNESS DEGRADING SYSTEM

			EL-CENTRO		NAHANNI	
ν	Y	$2\pi/\omega$	+25%	-25%	+25%	-25%
.02	0.05	.30	1.01	.99	1.23	.89
		.60	1.01	.99	1.22	.91
		1.00	1.01	.98	1.20	.92
		3.00	1.00	.99	1.16	.98*
	.15	.30	1.00	.99	1.24	.93
		.60	1.01	.98	1.27	.92
		1.00	1.02	.97	1.31	.88
		3.00	.98*	.99*	.99*	1.13*
.05	.05	.30	1.01	.99	1.23	.88
		.60	1.01	.98	1.23	.89
		1.00	1.01	.98	1.22	.92
		3.00	1.00	.99	1.12	.96
	.15	.30	1.00	.99	1.23	.95
		.60	1.01	.98	1.29	.94
		1.00	1.01	.96	1.33	.90
		3.00	1.03*	.97*	.88*	1.03*

*:Some of samples do not yield

TABLE 4.VII SENSITIVITY TO ENVELOPE SCALE FACTOR α

(a): DISPLACEMENT DUCTILITY: ELASTO-PLASTIC SYSTEM

			EL-CENTRO		NAHANNI	
ν	Y	$2\pi/\omega$	+25%	-25%	+25%	-25%
.02	.05	.30	1.34	.16	1.39	.65
		.60	1.35	.19	1.31	.65
		1.00	1.36	.26	1.39	.69
		3.00	1.26	.52*	1.13*	.85*
	.15	.30	1.55	.14	1.59	.57
		.60	1.33	.22*	1.45	.65
		1.00	1.29	.38*	1.25	.70
		3.00	1.22	**	1.10*	.86*
.05	.05	.30	1.32	.17	1.38	.66
		.60	1.35	.21	1.34	.67
		1.00	1.33	.27	1.31	.71
		3.00	1.25	.54*	1.13*	.79*
	.15	.30	1.54	.14	1.57	.58
		.60	1.38	.22	1.42	.65
		1.00	1.28	.39	1.31	.73
		3.00	1.10*	**	1.13*	.91*

*:Some of samples do not yield
**:All samples do not yield

(b): NORMALIZED HYSTERETIC ENERGY: ELASTO-PLASTIC SYSTEM

			EL-CENTRO		NAHANNI	
ν	Y	$2\pi/\omega$	+25%	-25%	+25%	-25%
.02	.05	.30	1.42	.12	1.43	.61
		.60	1.40	.13	1.40	.62
		1.00	1.40	.16	1.37	.65
		3.00	1.40	.30*	1.33*	.78*
	.15	.30	1.62	.07	1.71	.50
		.60	1.58	.07*	1.62	.53
		1.00	1.50	.18*	1.49	.59
		3.00	1.30	**	1.07*	.89*
.05	.05	.30	1.43	.11	1.43	.61
		.60	1.42	.12	1.41	.62
		1.00	1.41	.14	1.38	.64
		3.00	1.42	.33*	1.30*	.74*
	.15	.30	1.67	.05	1.72	.48
		.60	1.64	.06*	1.65	.52
		1.00	1.55	.16*	1.52	.58
		3.00	1.11	**	1.07*	.81*

*:Some of samples do not yield
**:All samples do not yield

TABLE 4.VII SENSITIVITY TO ENVELOPE SCALE FACTOR α (continued)

(c): DISPLACEMENT DUCTILITY: STIFFNESS DEGRADING SYSTEM

			EL-CENTRO		NAHANNI	
ν	γ	$2\pi/\omega$	+5%	-25%	+25%	-25%
.02	.05	.30	1.38	.16	1.35	.65
		.60	1.33	.19	1.36	.66
		1.00	1.27	.24	1.30	.63
		3.00	1.19	.52*	1.19*	.85*
	.15	.30	1.56	.12	1.61	.53
		.60	1.40	.21*	1.44	.60
		1.00	1.35	.42*	1.33	.70
		3.00	1.20	**	1.11*	.89*
.05	.05	.30	1.32	.17	1.36	.67
		.60	1.32	.20	1.34	.67
		1.00	1.28	.25	1.33	.67
		3.00	1.19	.53*	1.17*	.81*
	.15	.30	1.57	.13	1.51	.55
		.60	1.38	.22*	1.46	.61
		1.00	1.31	.42*	1.32	.73
		3.00	1.11	**	1.11*	.90*

*:Some of samples do not yield
**:All samples do not yield

(d): NORMALIZED HYSTERETIC ENERGY: STIFFNESS DEGRADING SYSTEM

			EL-CENTRO		NAHANNI	
ν	γ	$2\pi/\omega$	+25%	-25%	+25%	-25%
.02	.05	.30	1.29	.21	1.33	.68
		.60	1.30	.22	1.33	.69
		1.00	1.30	.22	1.32	.68
		3.00	1.34	.36*	1.27*	.83*
	.15	.30	1.47	.09	1.59	.49
		.60	1.39	.09*	1.48	.54
		1.00	1.39	.22*	1.38	.64
		3.00	1.31*	**	1.10*	.90*
.05	.05	.30	1.30	.20	1.32	.67
		.60	1.30	.22	1.32	.68
		1.00	1.31	.21	1.33	.68
		3.00	1.35	.36*	1.25*	.79*
		.30	1.48	.08	1.60	.48
		.60	1.42	.07*	1.52	.52
		1.00	1.40	.19*	1.43	.62
		3.00	1.12*	**	1.08*	.81*

*:Some of samples do not yield
**:All samples do not yield

In this case, the effects of variations in the parameter are nonlinear and significant. When the peak is increased, spectral ordinates for all cases are increased on average rather more than the increase in the factor. When the peak is decreased, demand ordinates are decreased significantly. For longer periods, ductility demand approaches zero as more samples do not result in yielding of the systems. These results support the observation that the peak value of the envelope function has a primary influence on response spectra.

After completion of this analysis, when it was concluded that an assumption of a single peak was reasonable, it was decided that a continuous one-peak envelope function should have been used to cover the entire duration of motion. Use of a two parameter Gamma function with unit area multiplied by a scaling factor would have permitted a sensitivity study in which the average total energy in a sample of an event was held constant.

4.4 FREQUENCY DEPENDENCE AND SCALING

To investigate possible differences in the response-period relationship for different earthquakes, average response ordinates after scaling by the corresponding ordinate for El Centro are shown in Figs 4-8 a-d. These data suggest that, relative to El Centro, ductility demand increased slightly with period for Nahanni and decreased with frequency for Parkfield. Trends for hysteretic energy demand are not as clear. Results for Mexico City are not conclusive because of site effects.

Given the large coefficient of variation of spectral ordinates and the fact that for longer periods a significant number of structures in a sample may not yield, it may be concluded that this study does NOT provide strong evidence

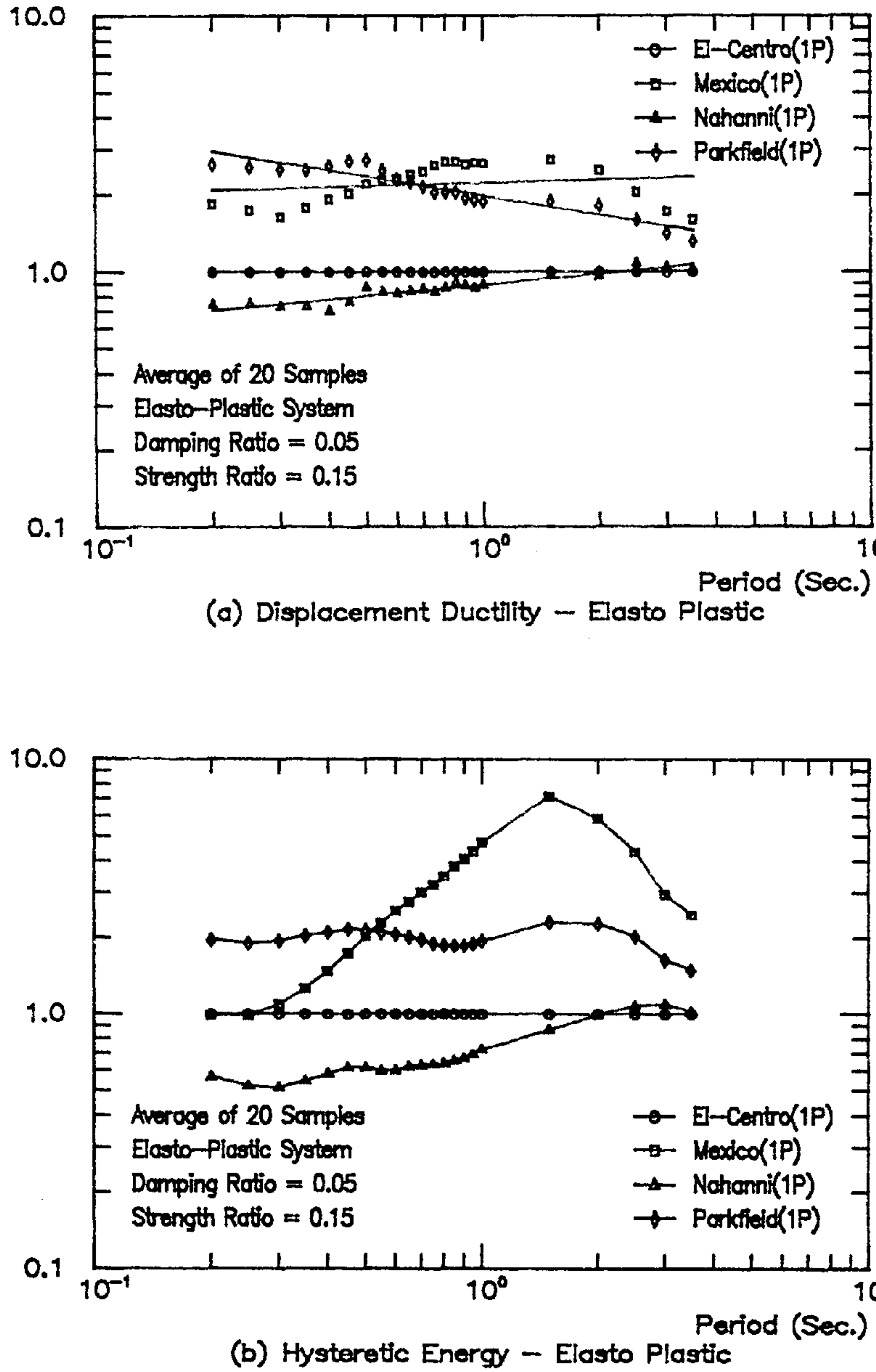
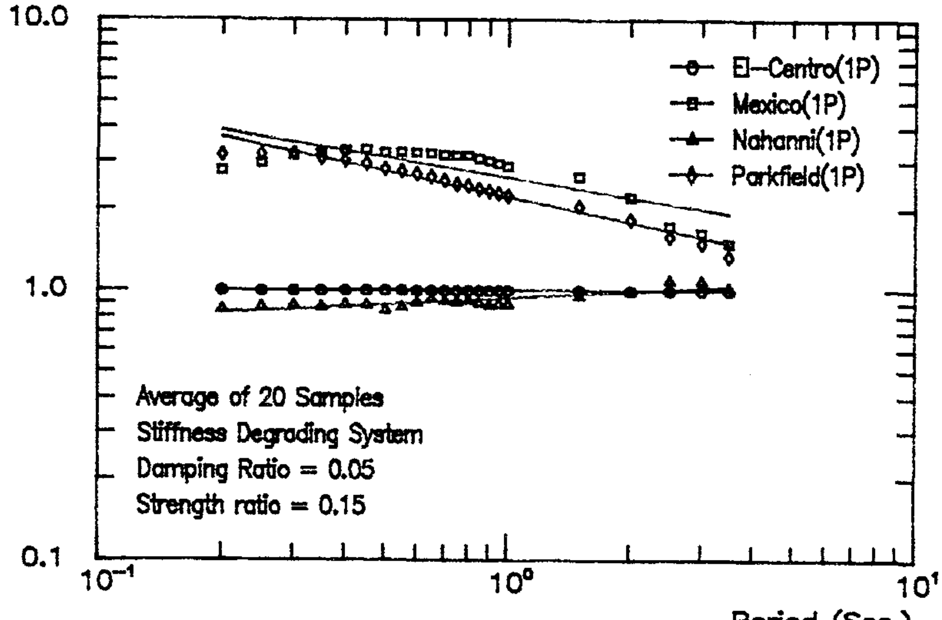
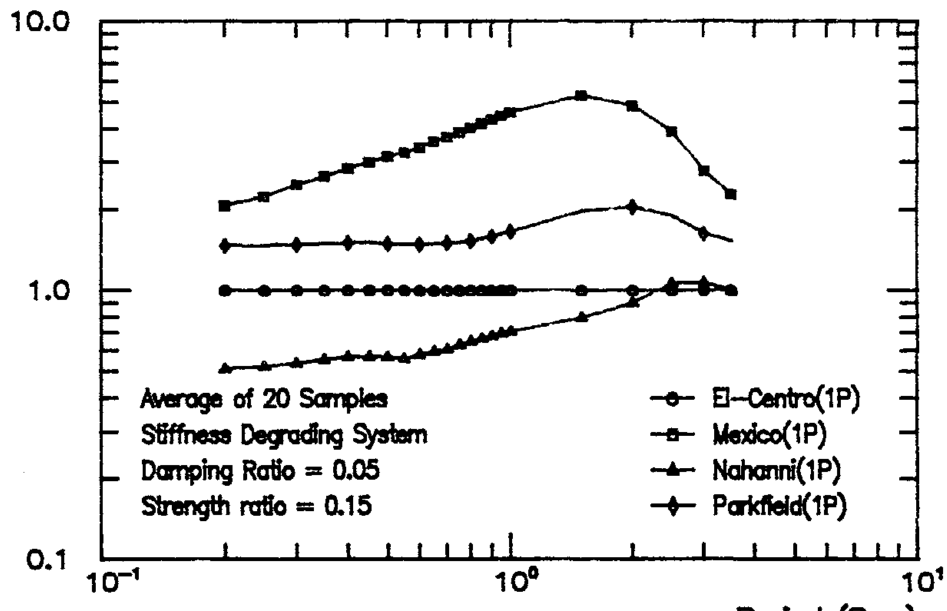


FIGURE 4-8 RESPONSE SPECTRA SCALED BY EL-CENTRO



(c) Displacement Ductility – Stiffness Degrading



(d) Hysteretic Energy – Stiffness Degrading

FIGURE 4–8 RESPONSE SPECTRA SCALED BY EL-CENTRO (Continued) for the hypothesis that the dependence of nonlinear response spectra on period varies between earthquakes.

From Fig 4-8 a, it can be observed that the ratio of ductility demand for Parkfield, Nahanni and Mexico City relative to El Centro were on average about (0.9, 2.0 and 2.0) respectively. In contrast, the corresponding peak ground accelerations relative to El Centro were (1.4, 3.86 and 0.49). Clearly, the damage spectra can not be scaled by peak ground acceleration.

The ratio of the magnitudes of Parkfield, Nahanni and Mexico City were (.85, 1.0 and 1.25) respectively. Thus, nonlinear demand spectra can not be scaled by magnitude either.

SECTION 5

SUMMARY AND CONCLUSIONS

5.1 ARMA MODELING

The purpose of this study was to develop non stationary process models which can be considered to be characteristic of specific historical earthquakes. Measured records are considered to be one realization of the underlying process. Process parameters are estimated from measured accelerograms.

This study suggests that the development of simple ARMA models with a limited number of parameters is a straight forward operation. A sample of twenty records generated for each event provided reasonable estimates of average nonlinear demand spectra and their standard deviations

Since only four earthquakes were modeled, general conclusions can not be drawn. However, an evaluation of elasto-plastic and stiffness degrading spectra coupled with an extensive sensitivity study of the effects of the parameters of the ARMA processes supports a number of observations which seem likely to have general validity. In particular, the use of only one peak in the envelope function and models of order (2,1) seem to be sufficient for analysis.

Nonlinear ductility and hysteretic energy demand spectra were not highly sensitive to the envelope decay rate. The effects of decay rate did not significantly depend on the initial structural period. The peak value of the envelope functions had a major (nonlinear) influence on response spectra. Since results did not suggest that the effects of variations in the peak value were frequency dependent, the peak of the envelope function has great potential as an overall scale factor for the effects of earthquakes.

5.2 GENERAL CONCLUSIONS

Although this study dealt with only four earthquakes, the following conclusions seem to be justified.

1. The hypothesis that the measured records were drawn from populations corresponding to the process models was statistically acceptable for the limited class of response characteristics studied.
2. Irregularities in nonlinear response spectra for individual measured acceleration records can be considered to be random variations which do not represent a reliable property of the earthquake processes.
3. With the exception of the Mexico City event, the logarithms of average nonlinear spectral ordinates were very nearly linearly related to the logarithms of initial period.
4. This study does not provide strong evidence for the hypothesis that the dependence of response spectra on period varies between earthquakes.
5. Response spectra for elasto-plastic and stiffness degrading single degree of freedom systems were similar in nature. To compare the effects of two events or the effects of variations in model parameters, either response model was sufficient.
6. Nonlinear response spectra can not be scaled by either peak measured accelerations or magnitudes.

5.3 REMAINING QUESTIONS

This study provides a good deal of support for the conclusion that reasonable average nonlinear demand spectra can be obtained from one-peak, order (2,1) ARMA models. To confirm this observation, a number of other events should be modeled and mean +/- one standard deviation response spectra should be compared to original records such as those in Figs. 4-4.

In future studies, it would be preferable to use a continuous envelope function over the entire duration of an event. The parameters of the envelope function could be found from least squares analysis subject to constraints on total energy and duration. Members of the Gamma family of probability density functions multiplied by a global scaling factor would be likely candidates for such an approach.

This study did not consider the sensitivity of average response ordinates to numerical values of the AR and MA coefficients or the magnitude of the white noise variance. It seems possible that adequate models might be developed in which only the envelope functions were chosen from data.

A limited number of response spectra including P-Δ effects were obtained with interesting results. In particular, it was found that as period increased and hence ductility and hysteretic energy demand decreased, the number of structures that collapsed increased significantly. Some structures which did not yield without P-Δ effects collapsed under the same acceleration input when the effects were considered. The entire question of P-Δ effects deserves careful study.

The approach to nonlinear spectra for long periods where not all accelerograms in a sample cause yielding should be reviewed. The probability distribution of ductility demand in such cases is of the mixed type and should be treated separately.

Finally, the conclusion that the logarithm of nonlinear demand ordinates are linearly related to the logarithm of period should be investigated in greater depth. If the linearity conclusion can be confirmed, a significant improvement in structural hazard mapping will be possible.

If, as seems likely, the spectra for ductility and hysteretic energy demand for different classes of stiffness models and strength ratios R_Y/M^*g can be correlated to the ductility spectra for a basic elasto-plastic case (e.g. $\xi=.05$, $Y=.15$), the two parameters of the basic linear log-log spectra can be used for mapping purposes.

SECTION 6

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