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THE DRIFT DEMAND SPECTRUM AND ITS APPLICATION TO STRUCTURAL DESIGN AND ANALYSIS

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ABSTRACT

A new measure of the demand of strong earthquake ground motion on structures is described. This measure gives the maximum inter-story drift ratio demand associated with a given earthquake ground motion. A uniform linear shear-beam model is employed to calculate the maximum inter-story drift. The drift demand can be computed algebraically using wave propagation techniques and no differential equations need be solved. The drift demand may be graphed as a function of structural period and damping, just as in the case of the Response Spectrum. This new spectrum is referred to as the Drift Spectrum. The Drift Spectrum and Response Spectrum contain different but complementary information. Examples of Drift Spectra for near-field recorded ground motions from the Northridge and Hyogo-ken Nanbu earthquakes are presented. The concept of the linear Drift Spectrum is extended to account approximately for effects of localized yielding associated with high inter-story drift. It is shown that the drift demand arising from recently recorded near-field ground motions, as indicated by the Drift Spectrum, exceeds the capacity of many current steel frame beam-column connections

KEY WORDS

demand, Drift Spectrum, inelastic response, inter-story drift, near-field ground motion, Response Spectrum

INTRODUCTION

The Response Spectrum was first employed for the analysis of building structures by G. W. Housner in the 1950's. Since then, it has become a standard means of describing earthquake ground motions for analysis and design. A major appeal of the Response Spectrum is its relative simplicity as a direct measure of the effects of strong earthquake ground shaking on a range of structures. The basic concept of the Response Spectrum has been extended to treat non-linear structural behavior as well as the analysis of non-structural attachments to structures.

The Response Spectrum provides useful information regarding the maximum deformation or total drift of a structure, as well as its maximum acceleration. However, in its basic form, it may not give totally reliable information about the internal deformation, or inter-story drift. This is especially true when the internal deformations are associated with higher modes of response. In this case, the nature of the response may more resemble a wave traveling through the structure than a single harmonically oscillating mode. One type of ground motion for which higher modes of response can be particularly important is ground motion within the near-field region of an earthquake.

The near-field region of an earthquake can be defined as the region within a few kilometers of either the surface rupture or the projection on the ground surface of the fault rupture zone and its extension to the surface. This region is also referred to as the near-*source* region. In the near-field region of an earthquake, the ground motion will generally have a distinctive pulse-like character.

Figure 1 shows a representative near-field ground motion record from the Northridge earthquake of January 17, 1994. This ground motion was recorded in the N-S direction at the Sylmar Converter Station (SCS). The station was approximately 12 km from the epicenter of the earthquake, but well within the near-field region as defined above. Other near-field records from the Northridge earthquake have similar character (Iwan, 1995). Figure 2 shows a representative near-field ground motion from the Hyogo-ken Nanbu earthquake of January 17, 1995. This ground motion was recorded in the N-S direction at the Japan Meteorological Agency station in Kobe (JMA-K).

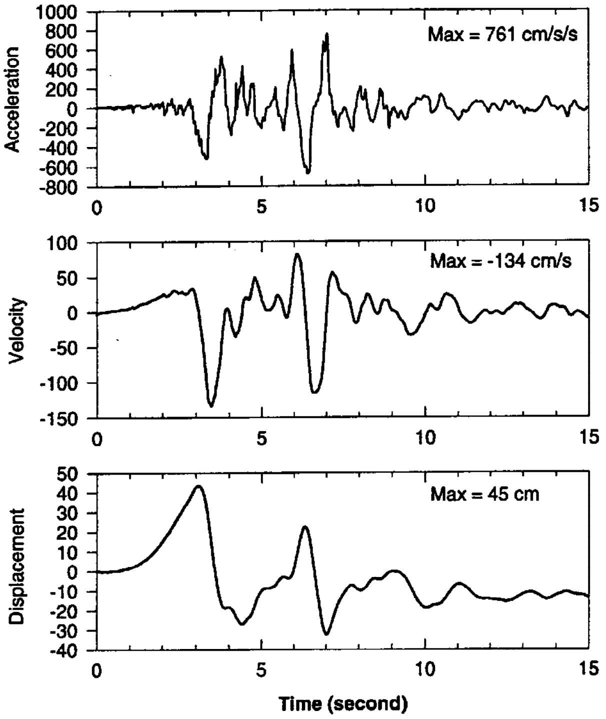

Figure 1. Time history of ground motion. Sylmar Converter Station, N-S, Northridge earthquake.

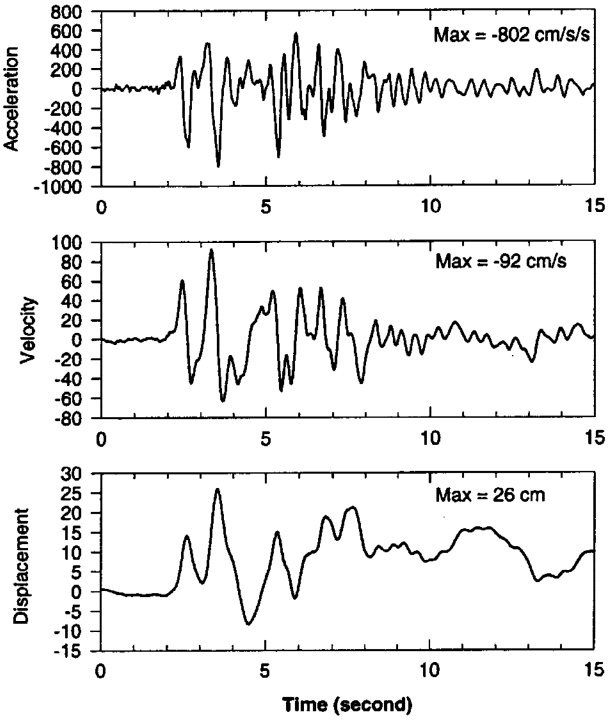

Figure 2. Time history of ground motion. JMA-Kobe Station, N-S, Hyogo-ken Nanbu earthquake.

Neither of the near-field records shown in Figures 1 and 2 resembles a modulated band-limited random process as is often assumed to be the case for far-field earthquake ground motions. Instead, there are rather distinct pulses in the acceleration time histories that translate into even more pronounced pulses in the velocity and displacement time histories. This observation is true for all of the near-field records that have been studied by the author. When a structure is subjected to such ground motion, the distinct pulses will propagate through the structure as waves, possibly leading to large localized internal deformations (inter-story drifts). These localized deformations may not be well characterized by the shape of any one mode of the structure, especially for longer period structures.

A Response Spectrum generally provides a reasonable estimate of the maximum global amplitude of response of a structure subjected an earthquake ground motion. However, this response measure may not provide accurate information about the local shape of the response of the system. The local shape involves the sum of possibly many modes with specific phase relationships. Determining the local shape of the response from a Response Spectrum is made more complicated by the fact that the maximum inter-story drift of a system may not occur at precisely the same instant of time as the maximum global displacement.

For ground motions that resemble a random process, the maximum response usually develops gradually in the form of a resonance buildup and is dominated by one, or at most a small number, of modes. For near-field pulse-like ground motions, the maximum internal deformations are likely to develop more from wave propagation type response behavior than from resonance buildup. Therefore, a Response Spectrum may not provide an adequate measure of the severity of the inter-story drift demand for near-field ground motions.

SHEAR-BEAM MODEL

By analogy to the simple SDOF structural model that provides the basis for the Response Spectrum, an equally simple uniform shear-beam structural model is appropriate as a basis for specifying the inter-story drift demand of earthquake ground motions. Such a model has recently been proposed by the author (Iwan, 1994)

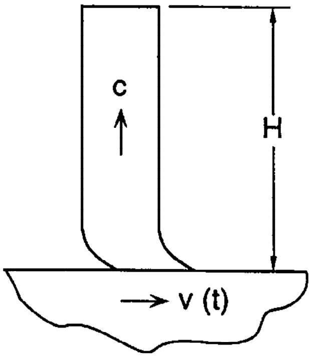

Figure 3. Uniform shear-beam building model.

Consider the idealized uniform shear-beam model shown in Figure 3. Let the height of the structure be denoted by H, the fundamental period by T, and the fraction of critical damping in the first mode by ζ. Let the base of the shear-beam be subjected to a horizontal ground displacement, $z(t)$, and velocity, $v(t)$, and let the displacement of the structure relative to the base be $u(t)$. For this continuous model, the inter-story drift ratio will correspond to the shear-strain, $\partial u / \partial y$. For non-dispersive damped waves in the shear-beam, the shear-strain at the base level will be given by

$$\frac{\partial u}{\partial y}(t) = \frac{1}{c}\left| v(t) + \frac{2\pi\zeta}{T} z(t) + 2\sum_{n=1}^{N \le 2t/T} (-1)^n e^{-n\pi\zeta}\left[v(t - nT/2) + \frac{2\pi\zeta}{T} z(t - nT/2)\right]\right| \tag{1}$$

where c is the shear wave speed in the structure.

The wave speed, c, fundamental period, T, and height of the shear-beam, H, are related as

$$c = 4H/T \tag{2}$$

Furthermore, from the Uniform Building Code (1994), the period, T, and building height, H, for steel-frame buildings may be related as

$$T = 0.0853H^{3/4} \tag{3}$$

where H is in meters. A similar expression may be obtained for other types of structures.

INTER-STORY DRIFT DEMAND SPECTRUM

The maximum base-level inter-story drift ratio may be expressed as a function of structural period and damping. Let this be denoted by $\mathcal{D}$, where

$$\mathcal{D}(T,\zeta) = \max_{\forall t} \left|\partial u / \partial y\right| \tag{4}$$

$\mathcal{D}$ may be graphed as a function of period for different damping ratios just as in the case of the Response Spectrum. The resulting spectrum is referred to as the Drift Spectrum.

It may be shown that the maximum value of $\mathcal{D}$ generally occurs at times of maximum v and minimum z. Therefore, for practical purposes, Equation (1) may be simplified by ignoring the $z(t)$ terms. Computation of the Drift Spectrum thus involves only a simple summation over the ground velocity and does not involve the solution of any differential equations. For this reason, the Drift Spectrum is actually much easier to compute than the corresponding Response Spectrum.

EXAMPLES OF DRIFT SPECTRA

The Drift Spectra for the N-S components of the recorded ground motion at the Sylmar Converter Station and the JMA-Kobe Station are shown in Figures 4 and 5. These spectra are representative of the Drift Spectra of other ground motions in the near-field of the Northridge and Hyogo-ken Nanbu earthquakes.

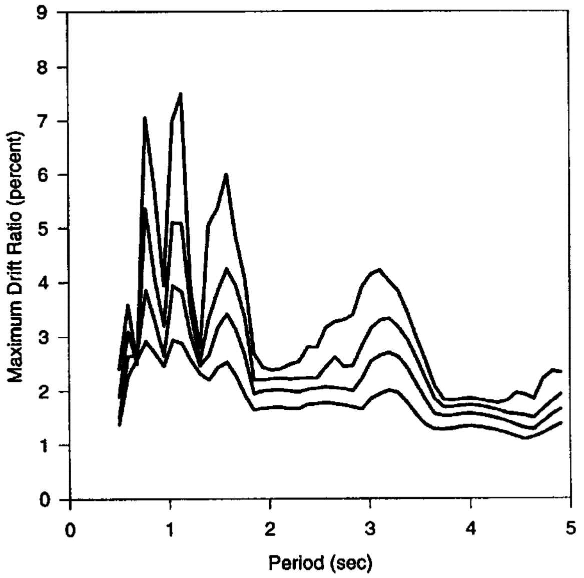

Figure 4. Drift Spectrum. Sylmar Converter Station, N-S, Northridge earthquake. ζ=0, 2, 5, 10%

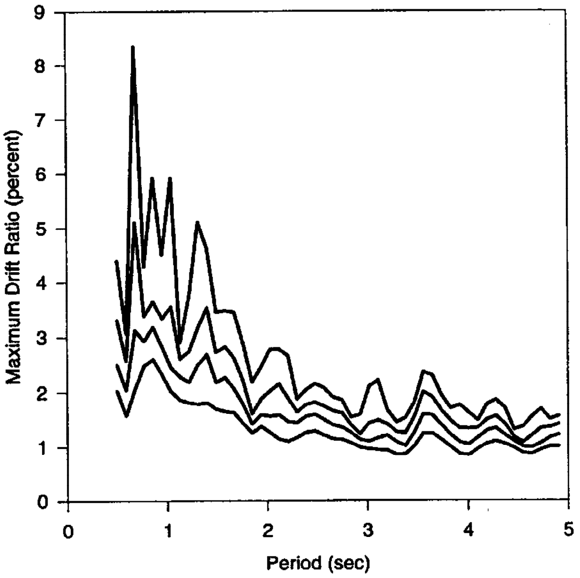

Figure 5. Drift Spectrum. JMA-Kobe Station, N-S, Hyogo-ken Nanbu earthquake.. ζ=0, 2, 5, 10%

The Drift Spectra of Figures 4 and 5 have features that resemble those of a Response Spectrum. They fall off for both short and long periods and have a maximum in some middle range of periods. There are typically one or more distinct period ranges for which the spectra are substantially greater than for other periods. Increasing the damping ratio both decreases and smoothes the Drift Spectrum just as in the case of the Response Spectrum.

For both of these ground motions, the highest inter-story drift demand occurs for structures with fundamental periods in the range of 0.7-1.5 seconds which corresponds to buildings with heights ranging from about 5-15 stories. For the Sylmar Converter Station record, there is also a region of high inter-story drift in the period range of 2.5-3.5 seconds. The shape of the Drift Spectrum is clearly affected by the nature of the earthquake source, propagation path, and local site topography just as in the case of the Response Spectrum.

For a structure with uniform properties, the inter-story drift ratio is generally observed to be a maximum at the base of the structure. However, there may be exceptions to this depending on building period and the precise nature of the ground motion. When the stiffness of a structure, and therefore its wave speed, is not uniform with height, the maximum inter-story drift may occur at a higher level within the structure. In many buildings the stiffness decreases with height, implying that the shear wave velocity also decreases with height. This can lead to substantially higher inter-story drift ratios at higher levels in the structure.

The variation of drift demand with height can become quite important when the structural properties of a building are discontinuous at some height. Due to the abrupt reduction in wave speed at a level of stiffness reduction discontinuity, the maximum inter-story drift is likely to occur at that level. Such a concentration of drift demand at levels of discontinuity probably contributed to the failure of some mixed-construction buildings in Kobe during the Hyogo-ken Nanbu earthquake.

The Drift Spectrum for the N-S component of the El Centro record is shown in Figure 6 for comparison. This record is frequently used in structural design. Although it was obtained within fairly close proximity to the causative fault, the traditionally processed data shows little of the characteristics of near-field ground motion.

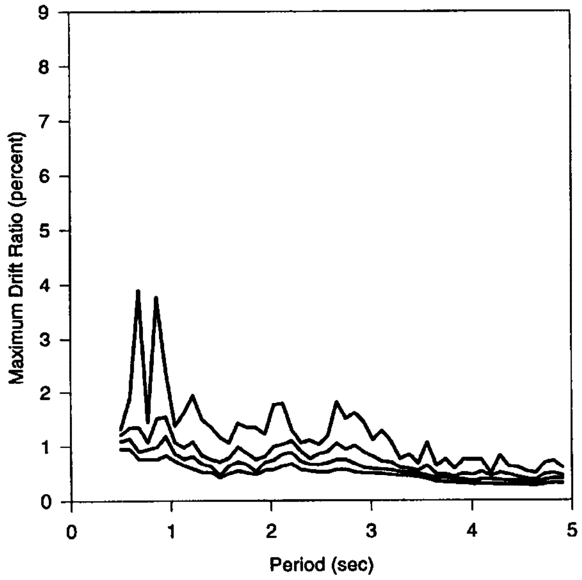

Figure 6. Drift Spectrum. El Centro record, N-S component. . ζ=0,2,5,10%

The difference in the magnitude of the drift demand resulting from the El Centro record and the two near-field stations presented above is clearly apparent. This should raise serious concerns regarding structural designs that have been based solely on El Centro-type ground motions if near-field ground motions are possible.

Table 1 gives the peak value of the 2 percent damped Drift Spectrum for several near-field records obtained from Northridge and Kobe including those of Figures 4 and 5. The structural period for which the peak drift demand occurs is also indicated, as are the corresponding values of peak ground acceleration (PGA) and peak ground velocity (PGV). The corresponding values for the El Centro record are included for reference.

The near-field records included in Table 1 all have very high peak drift demand. The peak drift demand for these records also occurs for fairly short periods ranging from 0.8-1.4 seconds. Based on these high drift demands, it is not surprising that numerous joint failures were observed in moderate height steel-frame buildings as a consequence of both the Northridge and Hyogo-ken Nanbu earthquakes. Design drift in the United States is of the order of 0.5 percent as specified by the Uniform Building Code. Recent testing has indicated that joint capacities much in excess of two percent are very difficult to obtain using current techniques. Yielding will generally cause the drift demand to be further increased over the linear value given by the Drift Spectrum. However, even without consideration of yielding, the drift demand indicated from the Drift Spectra for records from the Northridge and Hyogo-ken Nanbu earthquakes significantly exceeds safe levels for current steel-frame connections.

Table 1. PGA, PGV, and Maximum Value of Drift Spectrum (DS) for Selected Near-Field Records with Structural Period for Maximum Drift Demand. 2% Damping.

Record	PGA (g)	PGV (cm/sec)	Max DS (%)	Period (sec)
Rinaldi Receiving Station, N-S	0.82	159	4.5	1.3
Sylmar Converter Station, N-S	0.78	134	5.3	0.8
JMA-Kobe Station, N-S	0.82	92	5.1	0.7
JR Takatori Station, Kobe, Max. Vel. Dir.	0.81	176	8.2	1.2
El Centro, N-S	0.35	33	1.6	1.4

COMPARISON WITH RESPONSE SPECTRUM AND NUMERICAL MODELING RESULTS

The Drift Spectrum and Response Spectrum contain different but complimentary information regarding earthquake ground motion. The Response Spectrum primarily contains information about the maximum relative displacement demand, while the Drift Spectrum contains information about the maximum inter-story drift ratio demand. Neither spectrum contains all of the information necessary for good seismic design.

If the maximum inter-story drift as computed directly from the Response Spectrum assuming a single-mode of response, it is observed that the results obtained from the Response Spectrum and those from the Drift Spectrum for near-field Northridge earthquake records are fairly close for structural periods less than about 2 seconds (Iwan, 1995). This implies that a single (first) mode approximation works fairly well in estimating internal deformation or inter-story drift for this type of near-field ground motion when the structural period is short. In this case, the response is fairly accurately characterized by a single mode of response.

However, for longer structural periods (greater than 2 seconds in this case), the results of the Response Spectrum and Drift Spectrum differ substantially; the Drift Spectrum giving values that are as much as a factor of three greater than those implied by the Response Spectrum. This is due to the fact that higher modes are much more important in the response of longer period structures, and the response becomes more wave-like in nature.

The results of the Drift Spectrum have been compared (Iwan, 1995) with the those of detailed numerical analyses (Hall, 1995) of prototypical building structures subjected to different near-field earthquake excitations. Two different prototype buildings were examined by Hall; a six-story building with a linear fundamental period of 1.36 sec, and a twenty-story building with a period of 3.5 sec. The buildings were subjected to a variety of near-field ground motion records. Both linear and plastic structural behavior was considered. In general, the results of the Drift Spectrum agree quite well with those of the detailed numerical modeling for linear structural models. This provides support for the use of the Drift Spectrum in structural design.

EFFECTS OF LOCALIZED YIELDING

High inter-story drift, in excess of code allowables, is almost certain to be accompanied by yielding and resulting softening of the stories affected. This softening, or reduction in stiffness, will be associated with a local reduction in the shear wave velocity in the simple shear-beam structural model. A localized reduction in shear wave velocity will cause an increase in the local shear deformation or drift ratio which, in turn, will lead to further reduction in stiffness. In this way, it is easy to see that localized yielding may lead to substantially larger inter-story drift than would be predicted for a purely linear structure. Once yielding occurs in particular floors, damage will generally tend to concentrate there and make further stiffness reduction even more likely.

As a first approximation to account for the effects of localized yielding, let it be assumed that the yielding is confined to the lower few stories where the linear inter-story drift ratio is generally highest. Then, two new factors must be taken into account. First, and most important, the local shear wave velocity in the lower few stories will be reduced by yielding. Second, the fundamental period of the structure will be increased.

The local shear wave velocity reduction can be related to the local ductility ratio of the response using any of a number of approximate formulas. The following approximate relationship is deduced from Iwan (1980)

$$c / c_o = \left[1 + 0.121(\mu - 1)^{0.94}\right]^{-1} \tag{5}$$

where μ is the local ductility of the response and c_o is the linear wave speed given by equation (2). It remains to relate μ to the local inter-story drift. As an initial estimate, let it be assumed that the code allowable inter-story drift corresponds to a ductility of approximately 1.5. Then,

$$\mu = 300\vartheta . \tag{6}$$

Substituting equation (6) into equation (5) yields an expression for the local shear wave velocity in terms of the calculated maximum inter-story drift. This equation may be solved simultaneously with equation (4) to compute an approximate Drift Spectrum for a structure with localized yielding in the lowest story. If the region of yielding is highly localized, the effect of yielding on period reduction will likely be less than its effect on local shear wave velocity reduction. The effect of overall period reduction can be accounted for by entering the Drift Spectrum with a value for the estimated effective (yielding) structural period.

"Inelastic" Drift Spectra are shown in Figures 7 and 8 for the N-S components of the records at the Sylmar Converter and JMA-Kobe Stations. The linear counterparts of these spectra are given in Figures 4 and 5. The damping values indicated in these spectra are effective damping ratios which include the effects of hysteretic energy loss. Therefore, the range of damping considered is from 10-20 percent. It is apparent that the effect of yielding in the lower floors is to significantly increase the drift demand in these stories.

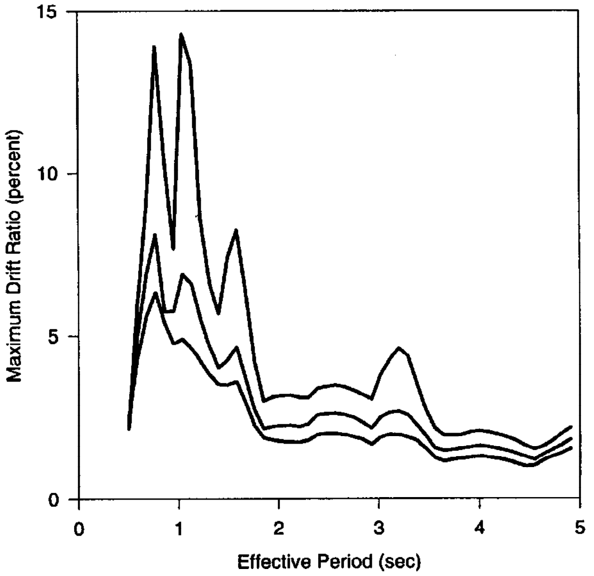

Figure 7. Inelastic Drift Spectrum. Sylmar Converter Station, N-S, Northridge earthquake. Effective damping = 10, 15, and 20%

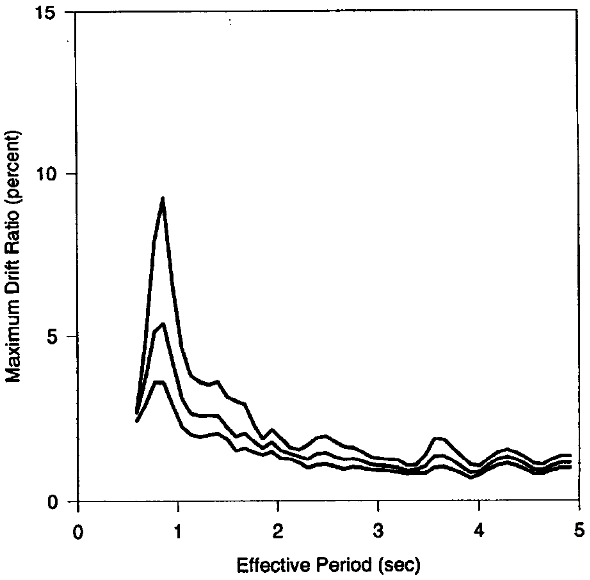

Figure 8. Inelastic Drift Spectrum. JMA-Kobe Station, N-S, Hyogo-ken Nanbu earthquake. Effective damping = 10, 15, and 20%

Assuming an effective elastic plus inelastic damping of 15 percent, the peak drift demand for the Sylmar Converter Station record increases to over 8 percent while that of the JMA-Kobe record is slightly over 5 percent. Both records have comparable peak drift demand for the linear case of 2 percent damping. Therefore, the effects of inelastic behavior, as accounted for by shear wave speed reduction and increased damping, do not scale linearly. For effective damping ratios of less than 15 percent, the inelastic drift demand becomes excessively large for certain period ranges.

A comparison of drift demand results obtained from inelastic Drift Spectra and from detailed numerical modeling performed by Hall (1995) indicates that the two approaches generally give comparable results (Iwan, 1995).

CONCLUSIONS

The Drift Demand Spectrum, used in conjunction with the Response Spectrum, can provide important new insight into the demand of earthquake ground motion on structures. Use of the new spectrum is especially recommended for situations in which a structure may be subjected to near-field ground motions from moderate to large earthquakes. The new demand measure can be applied to both structural design and analysis. The author recommends that measured Drift Demand Spectra be employed to develop *Design Drift Spectra* for structures subjected to near-field earthquake ground motions. Such Design Drift Spectra, used in conjunction with customary Design Response Spectra, would provide a more adequate specification of earthquake demand on structures.

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