DRIFT SPECTRUM: MEASURE OF DEMAND FOR EARTHQUAKE GROUND MOTIONS

By W. D. Iwan,[1] Member, ASCE

ABSTRACT: A new measure of the demand of earthquake ground motions on structures is presented. This measure, called the drift spectrum, is particularly useful for near-field earthquake motions that contain distinct pulses. Like the well-known response spectrum, the drift spectrum is based on a linear system model. However, the new spectrum differs from the response spectrum in that it is based on a continuous shear-beam model rather than a single-degree-of-freedom model. The continuous model more accurately predicts interstory drift than does a single-degree-of-freedom model for pulse-like excitations. The drift spectrum could be used for design in a manner analogous to the use of the response spectrum. Examples of near-field drift spectra for the Landers, Northridge, and Hyogo-ken Nanbu earthquakes records are provided. The nature of these spectra is discussed and conclusions are drawn regarding the specification of drift demand for structural design.

INTRODUCTION

Since its first use in aseismic design by G. W. Housner in the 1950s, the response spectrum has become a standard measure of the demand of earthquake ground motion. The seismic design input for modern structures is frequently specified in terms of a response spectrum, and response spectra of earthquake accelerograms are routinely computed along with corrected time histories. Although it is based on a simple single-degree-of-freedom (SDOF) linear system, the concepts embodied in the response spectrum have been extended to multi-degree-of-freedom systems, nonlinear elastic systems, and inelastic hysteretic systems. The utility of the response spectrum lies in the fact that it gives a simple and direct indication of the overall displacement and acceleration demand of earthquake ground motion on structures having different period and damping characteristics, without needing to perform detailed numerical analyses.

For many types of earthquake ground motion, the response spectrum is an adequate measure of demand. This is generally the case when the ground motion resembles a modulated broad-band random function of time. In such a case, the demand of the ground motion can generally be specified in terms of the maximum response amplitude of the dominant response mode of a structure. However, there are important cases where such a specification may not be adequate.

One such case is for ground motions within the near-field region of an earthquake. The near-field region of an earthquake is herein taken to be the region within several kilometers of the projection on the ground surface of the fault rupture zone and its extension to the ground surface. This region is also sometimes referred to as the near-source region. Of particular importance are ground motions at stations located toward the direction of propagation of the fault rupture.

It has been observed that the character of the time history of the ground motions for these near-field stations is qualitatively quite different from that of usual far-field earthquake ground motions. Figs. 1–3 show ground motions recorded within the near-field of three recent earthquakes. Fig. 1 shows the fault perpendicular component of the ground motion recorded at the Lucerne Valley (LUC) Station during the Landers earthquake of June 28, 1992 (Iwan and Chen 1994). This station was within approximately 1 mi of the surface rupture of the causative strike-slip fault. Fig. 2 shows the time history of the ground motion recorded at the Rinaldi Receiving Station (RRS) during the Northridge earthquake of January 17, 1994 (Iwan 1994). This station was also within the near-field region defined earlier. Finally, Fig. 3 shows preliminary data for the maximum velocity component of ground motion recorded at Takatori (TAK) Station during the Hyogo-ken Nanbu earthquake of January 17, 1995 (Nakamura et al. 1995). This station was located very close to the inferred surface projection of the rupture plane of the earthquake.

None of the near-field records shown in Figs. 1–3 has the appearance of a broad-band random process. Instead, there are rather distinct low-frequency pulses in the acceleration time histories that translate into pronounced coherent pulses in the velocity and displacement time histories. For structures subjected to such ground motion, these coherent pulses will propagate through the structure as waves, possibly causing large localized deformations or interstory drifts.

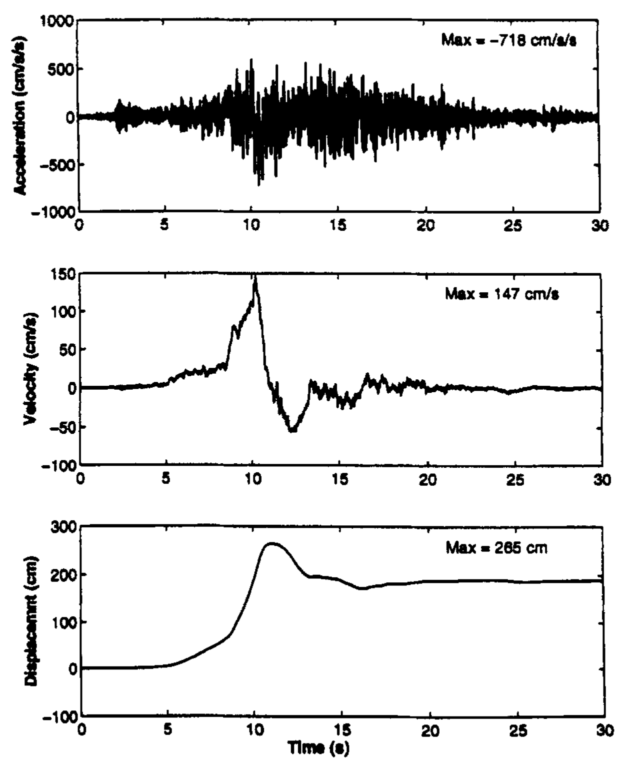

FIG. 1. Time History of Ground Motion [Lucerne Valley Station, Landers Earthquake; Maximum Velocity Direction (N80W); Record Courtesy of Southern California Edison]

[1]Prof. of Appl. Mech., California Inst. of Technol., Pasadena, CA 91125.

Note. Associate Editor: Professor Chia-Ming Uang. Discussion open until September 1, 1997. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on March 11, 1996. This paper is part of the *Journal of Structural Engineering*, Vol. 123, No. 4, April, 1997. ©ASCE, ISSN 0733-9445/97/0004-0397–0404/$4.00 + $.50 per page. Paper No. 12836.

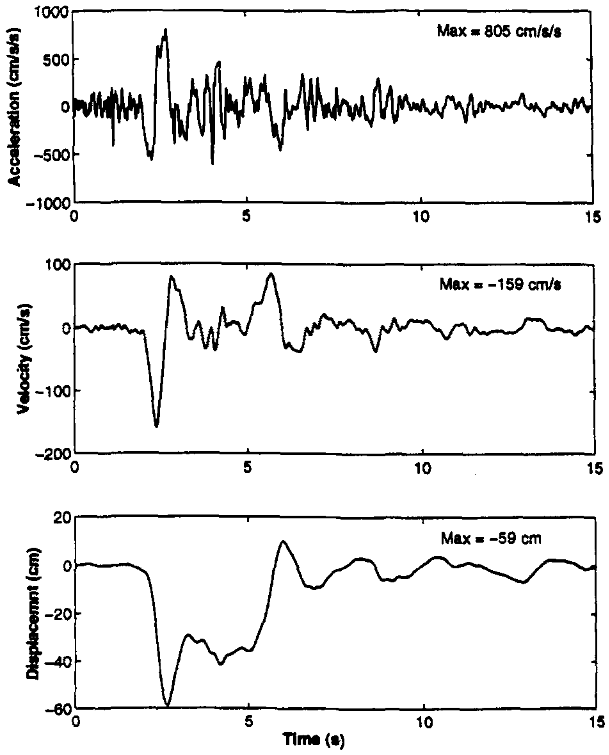

FIG. 2. Time History of Ground Motion (Rinaldi Receiving Station, Northridge Earthquake; N-S Direction; Record Courtesy of Los Angeles Department of Water and Power)

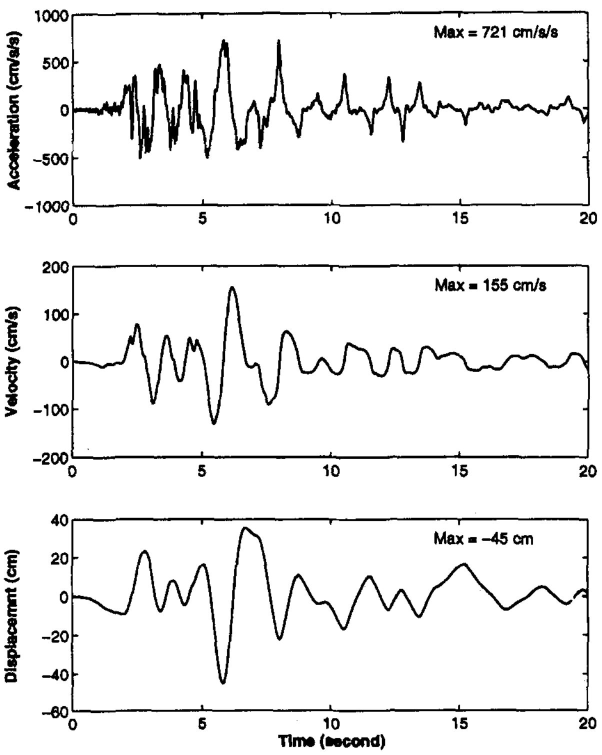

FIG. 3. Time History of Ground Motion [Takatori Station, Hyogo-ken Nanbu Earthquake; Maximum Velocity Direction (N49W); Record Courtesy of Railway Technical Research Institute of Japan]

The response spectrum generally provides a good estimate of the maximum global amplitude of a response of a structure subjected to a particular earthquake excitation. However, it does not always provide accurate information on the local shape or internal deformation of the response of the structure. The latter involves the sum of possibly many modes with specific phases. Determination of the local shape of the response from a response spectrum is further complicated by the fact that the maximum internal deformation (drift ratio) of a system may not even occur at the same instant of time as the maximum global displacement.

For far-field ground motions, these are not serious problems since the maximum response usually develops gradually as a kind of resonance buildup that is dominated by one mode or, at most, a small number of modes. However, for near-field ground motion this is not always the case. The coherent pulse-like nature of the near-field ground motion time history may cause the maximum response of the structure to occur before a resonant mode-like response can build up. Therefore, the SDOF-based response spectrum may not provide an adequate measure of the severity of the interstory drift demand of near-field type ground motions.

This paper discusses a new measure of earthquake demand that is particularly suitable for near-field ground motions. It is based on the response of a continuous shear-beam model. The concept of this new demand measure was first proposed by the writer at the 10th European Conference on Earthquake Engineering (Iwan 1994). In the present paper, the concept is further developed and clarified, and additional examples of its application are presented and discussed.

UNIFORM SHEAR-BEAM STRUCTURAL MODEL

Whereas a simple SDOF system may adequately characterize resonance buildup response associated with far-field ground motions, a different approach is useful in describing wave propagation response behavior associated with near-field ground motions. To be useful, any new model should have a minimum number of parameters, consistent with providing an adequate description of wave propagation type response. It is believed that the linear shear-beam structural model is just such a simple model, capable of providing valuable information about internal structural deformations of structures subjected to earthquake ground motions.

Consider the simple shear-beam model shown in Fig. 4. 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 motion displacement, $z(t)$, and let the displacement of the structure relative to the base be $u(y, t)$. For this continuous structural model, the interstory drift ratio will then correspond to the shear-strain, $\partial u/\partial y$.

The problem of damped waves in a one-dimensional continuous medium, sometimes referred to as the "telegraph"

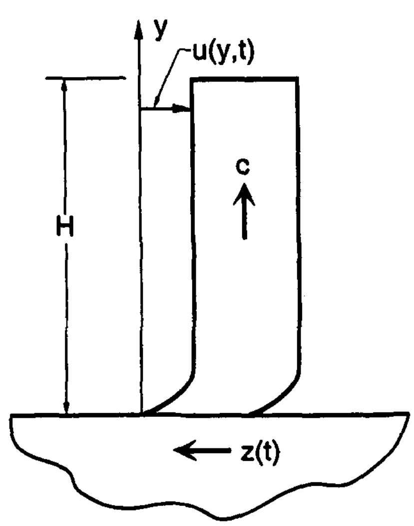

FIG. 4. Continuous Shear-Beam Building Model

problem, was treated by Courant and Hilbert (1962). For nondispersive damped waves, the solution may be shown to be of the form

$$u(t) = e^{-\alpha t}\phi(y \pm ct) \tag{1}$$

where α = constant; $\phi(y \pm ct)$ = wave traveling either up (+) or down (−) shear-beam; and c = wave speed. The wave speed, c, fundamental period, T, and height of the shear-beam, H, are related as

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

By considering the free oscillation of a shear-beam with an initial displacement, and comparing the decaying amplitude of oscillation to that of an SDOF system, the parameter α may be related to ζ as

$$\alpha = 2\pi\zeta/T \tag{3}$$

Let h be some arbitrary height above the base of the shear-beam defined in terms of a dimensionless height variable, β, where

$$h = \beta H; \quad \beta \le 1 \tag{4}$$

Also, let $v(t)$ be the velocity time history of the ground motion. That is

$$v(t) = dz/dt$$

Then, applying $z(t)$ to the base of the shear-beam and summing the contributions of the decaying waves traveling up and down the beam, it is readily shown that the shear-strain at a dimensionless height β is given by

$$\frac{\partial u}{\partial y}(h, t) = \frac{1}{c}\left\{e^{-\pi\beta\zeta/2}\left[v(t - \beta T/4) + \frac{2\pi\zeta}{T} z(t - \beta T/4)\right] + \sum_{n=1}^{N \le 2t/T - \beta/2} (-1)^n e^{-(n\pi+\beta/2)\zeta}\left[v(t - nT/2 - \beta T/4) + \frac{2\pi\zeta}{T} z(t - nT/2 - \beta T/4)\right] + \sum_{n=1}^{N \le 2t/T + \beta/2} (-1)^n e^{-(n\pi+\beta/2)\zeta} \cdot \left[v(t - nT/2 + \beta T/4) + \frac{2\pi\zeta}{T} z(t - nT/2 - \beta T/4)\right]\right\} \tag{5}$$

The terms in the summations represent a superposition of the contributions of upward and downward traveling waves at height, h, and time, t, generated by the base input at some previous time. The greater the interval between the current and previous time, the greater will be the attenuation of these waves due to damping. Therefore, the terms in the summations tend to decrease in magnitude as n increases.

Of course, a different continuous building model could be employed in place of the uniform shear beam. For example, a bending beam model could be used. This would no doubt yield somewhat different drift ratio results. However, it is not clear that the additional insight gained by such an analysis would justify the significant increase in analytical complexity associated with the bending beam problem due to the presence of wave dispersion in the fourth-order system.

INTERSTORY DRIFT DEMAND SPECTRUM

By analogy to the response spectrum, let the maximum value of the shear strain be a new measure of the demand of the excitation $z(t)$. The shear strain is analogous to the interstory drift ratio in the building. Let the maximum shear strain or interstory drift ratio be denoted by $\mathfrak{D}$. Then

$$\mathfrak{D} = \max_{\forall t} |\partial u/\partial y| \tag{6}$$

Due to the existence of finite story heights in a discrete system, the shear strain will yield an approximation of the interstory drift of the discrete system. The shear strain obtained from the continuous model can be averaged over the story height if the variation in shear strain over the story is significant.

For many types of structures, there is an approximate relationship between T and H. For example, from the *Uniform Building Code* (1994), the relationship for steel frame buildings is

$$T = 0.0853H^{3/4} \tag{7}$$

where H is in meters.

In many cases, the maximum interstory drift ratio will occur at the base of the structure ($\beta = 0$). In this case, $\mathfrak{D}$ may be expressed as a function of T and ζ as

$$\mathfrak{D}(T, \zeta) = \max_{\forall t} \frac{T}{4H}\left| v(t) + \frac{2\pi\zeta}{T} z(t) + 2\sum_{n=1}^{N \le 2t/T} (-1)^n e^{-n\pi\zeta}\left[v(t - nT/2) + \frac{2\pi\zeta}{T} z(t - nT/2)\right]\right| \tag{8}$$

This result may be graphed as a function of period for different damping ratios just as in the case of the response spectrum. This new spectrum will be referred to as the interstory drift demand spectrum or simply the drift spectrum.

Note that computation of the drift spectrum involves only a simple summation over the ground motion time history and therefore does not involve the solution of any differential equations. In this regard, the drift spectrum is actually much easier to compute than the response spectrum. However, since ground velocity and displacement are required, accurate processing of the ground motion records is important.

It is also possible to represent the drift spectrum in terms of the number of stories, N, of a structure instead of its height. This would be done by substituting for T in (8) in terms of N using some nominal story height. The drift spectrum can be graphed as a function of both T and N simultaneously using a log scale.

Eq. (8) may be simplified by observing that the maximum shear strain will most likely be associated with times in the excitation where $v(t)$ is a maximum. At such instants, $z(t)$ is likely to be small. Hence, (8) can be approximated as

$$\mathfrak{D}(T, \zeta) \approx \max_{\forall t} \frac{T}{4H}\left| v(t) + 2\sum_{n=1}^{N \le 2t/T} (-1)^n e^{-n\pi\zeta} v(t - nT/2)\right| \tag{9}$$

An interesting special case of the drift spectrum is obtained by assuming that the ground motion is an isolated displacement pulse consisting of a positive velocity pulse followed at a time, T_p, by an identical-shaped negative velocity pulse of the same magnitude. That is

$$v_{min} = -v_{max}; \quad t_{min} = t_{max} + T_p \tag{10}$$

This would correspond to a single displacement pulse with a duration of approximately $2T_p$. From (9), the maximum interstory drift for this case will occur when the structural period, T, is equal to T_p, and it will be seen that

$$\mathfrak{D} \approx \frac{T_p}{4H}(1 + 2e^{-\pi\zeta})v_{max} \tag{11}$$

For $\zeta = 0$, this becomes simply

$$\mathfrak{D} \approx \frac{3T_p}{4H} v_{max} = \frac{3v_{max}}{c_p}; \quad \zeta = 0 \tag{12}$$

where c_p = speed of waves in structure having structural period equal to T_p, or about one-half the duration of input displacement pulse. For reinforced concrete and steel buildings, c_p is typically within the range of 100–200 m/s, but could be as low as 75 m/s, depending on the particular type of design.

Eq. (12) clearly illustrates the nature of the basic relationship between the maximum ground velocity, shear wave velocity, and drift demand. This relationship clarifies why near-field ground motions with large coherent velocity pulses are particularly demanding to structures in regard to interstory drift. For the extreme case of an isolated displacement pulse or double velocity pulse of the type considered, an interstory drift ratio demand of 0.005 for an undamped structure would be exceeded for peak ground velocities as low as 17 cm/s. A drift ratio of 0.025 could be exceeded for peak ground velocities of the order of only 85 cm/s. The peak ground velocities of the three near-field records shown in Figs. 1–3 all exceed 100 cm/s. Of course, lack of complete coherence of the ground motion pulses and the presence of structural damping will act to reduce the drift demand.

NATURE OF ELASTIC DRIFT SPECTRUM

The base-level drift spectrum for the north-south (N-S) component of the measured ground motion at the RRS during the Northridge earthquake is shown in Fig. 5. This spectrum is representative of the drift spectra of ground motions in the near-field of the Northridge earthquake.

The drift spectrum of Fig. 5 has features that resemble those of a response spectrum. It tends to fall off at both short and long periods and has a maximum in some middle range of periods. There are typically one or more distinct period ranges for which the spectrum is substantially greater than for other periods. Increasing the damping ratio both decreases and smooths the spectrum.

The spectrum in Fig. 5 was computed using both the complete drift equation, [(8), solid line], and the simplified expression, [(9), dashed line]. There is no significant difference between the two results. This is typical of other cases studied.

Fig. 6 shows the 5% damped drift spectrum of the RRS record as a function of elevation above the base. Four cases are shown, β = 0, 0.25, 0.50, and 0.75. It is observed that for a structure with uniform properties, the interstory drift ratio is generally a maximum at the base of the structure. However, there can be exceptions to this observation depending on building period and the precise nature of the ground motion. When the stiffness of a structure, and therefore the wave speed, is not uniform with height, the maximum interstory drift may readily occur at some higher level in the structure.

In most buildings, the stiffness decreases with height since the design lateral load decreases with height. This implies that the shear wave velocity also decreases with height. This can result in higher interstory drift ratios at higher levels in the structure. When viewed from a wave propagation point of view, it is also seen that the variation of drift demand with height becomes particularly significant when the structural properties of the building are discontinuous at some height. In this case, the maximum interstory drift is likely to occur at the level of stiffness discontinuity due to the abrupt change in wave speed at that level. This concentration of drift demand at levels of structural property discontinuity likely contributed to the failure of some mixed-construction buildings in Kobe during the Hyogo-ken Nanbu earthquake. In the text to follow, attention will be restricted to the base-level interstory drift demand. However, it should be kept in mind that the interstory drift ratio can be larger at higher elevations in special cases.

EXAMPLES OF DRIFT SPECTRA

The base-level drift spectra for three additional near-field earthquake ground motion recordings are presented in Figs.

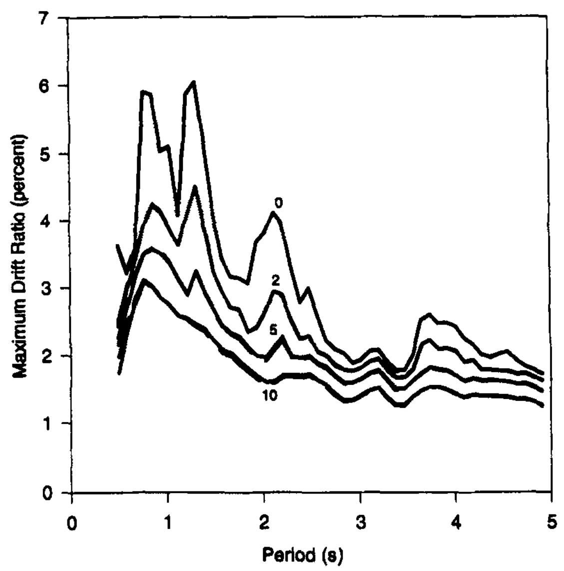

FIG. 5. Base-Level Drift Spectrum [Rinaldi Receiving Station; N-S Direction; Eq. (8), Solid Line; Eq. (9), Dashed Line]

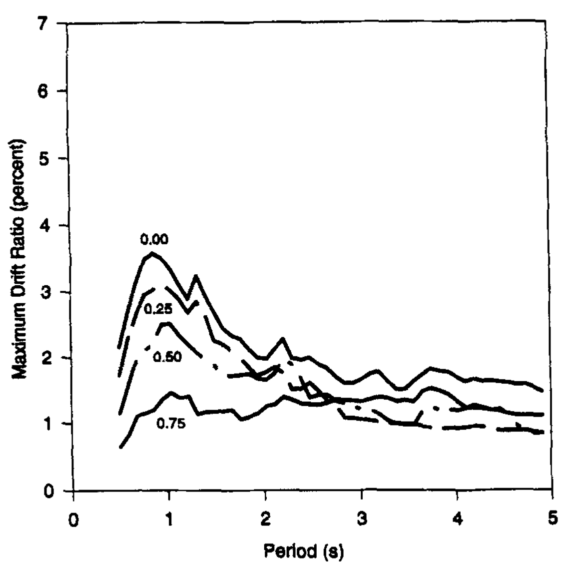

FIG. 6. Drift Demand As Function of Level above Base (Rinaldi Receiving Station, Northridge Earthquake, N-S Direction; 5% Damping; β = 0, 0.25, 0.5, 0.75)

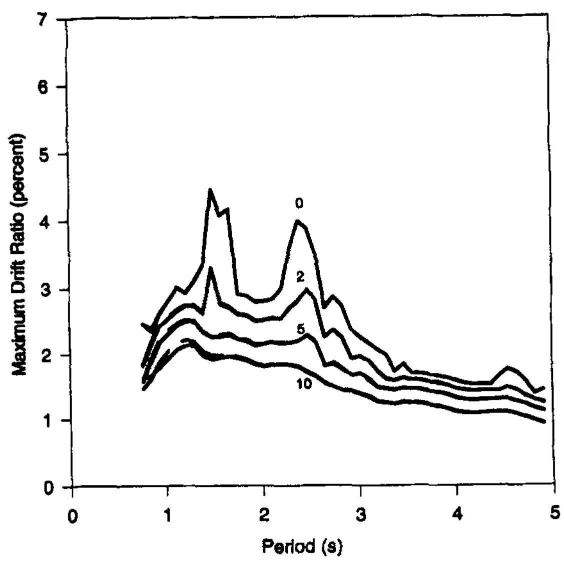

FIG. 7. Base-Level Drift Spectrum (Sylmar County Hospital Parking Lot, Northridge Earthquake; N-S Direction); Eq. (8)—Solid Line; Eq. (9)—Dashed Line

7–9. Fig. 7 shows the drift spectrum for the N-S component of the ground motion recorded in the free field of the parking lot at the Sylmar County Hospital (SCH) during the Northridge earthquake. Fig. 8 gives the drift spectrum for the maximum velocity component direction of the TAK Station record. Finally, Fig. 9 shows the drift spectrum for the fault-perpendicular component of the near-field ground motion recorded at the LIUC Station during the Landers earthquake. Fig. 10 gives the drift spectrum for the El Centro (ELC) N-S direction record from the 1940 Imperial Valley earthquake. This record is frequently used in seismic design.

Distinct differences may be observed between the three near-field drift spectra and that of the ELC record. For damped structures, the drift demand for the ELC record is a relatively insensitive function of period. In contrast to this, the drift demand for the near-field Northridge earthquake records (a buried thrust fault earthquake) has a pronounced peak in the period range of 0.5–2.0 s. The drift demand for the TAK Station record (resulting from a strike-slip fault rupture) is sharply peaked in the period range of 1.0–1.5 s. This drift demand is the highest thus far observed by the writer. The drift demand for the Landers (LUC) earthquake record (another strike-slip earthquake, but with much simpler surface geology than that of the TAK Station site) has a broad peak in the long period range of 3–5 s.

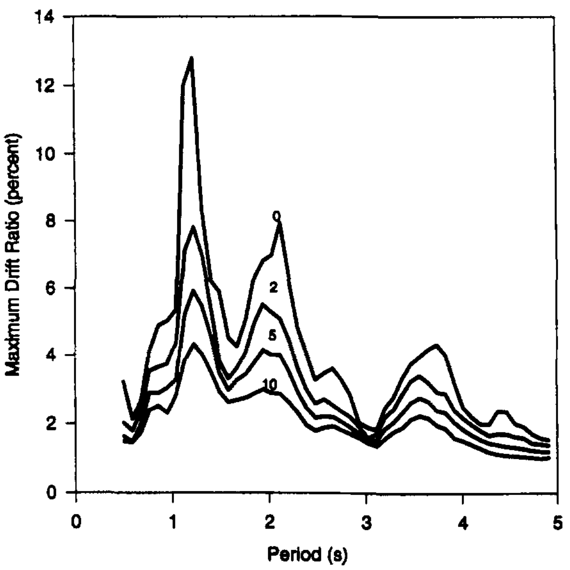

FIG. 8. Base-Level Drift Spectrum (Takatori Station, Hyogo-ken Nanbu Earthquake; Maximum Velocity Direction)

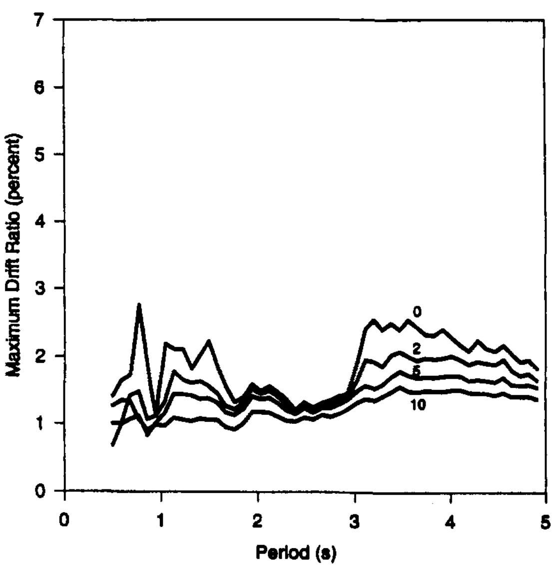

FIG. 9. Base-Level Drift Spectrum (Lucerne Valley Station, Landers Earthquake; Maximum Velocity Direction)

Table 1 shows the peak value of the 2% damped drift spectrum for several important near-field records. The entries are arranged in descending order of peak drift demand. The structural period for which the peak drift demand occurs is indicated, as are the corresponding values of peak ground acceleration (PGA) and peak ground velocity (PGV). The values for the ELC record are included for reference.

Most of the near-field records included in Table 1 have a very high peak drift demand, ranging from 3.5 to 5.3% for the Northridge earthquake, and from 4.5 to 8.0% for the Hyogo-ken Nanbu earthquake. Peak drift demand for the Northridge and Hyogo-ken Nanbu records occurs for fairly short structural periods ranging from 0.7 to 1.5 s, and corresponds to moderate-height buildings.

It is not surprising that all of the high drift demand records in Table 1 also have high PGV. Clearly, there is some connection between drift demand and PGV, as implied by (12). Yet, there is no obvious simple relationship between the PGV and peak drift demand for this sample of earthquakes. The lowest peak drift demand for the near-field records considered herein is exhibited for the LUC record. Although the PGV for this record is high, the period for which the peak drift demand occurs is also large—leading to a fairly modest level of peak drift demand compared to some of the records with greater high-frequency content. However, the peak drift demand of this record at 4.1 s is still a factor of three greater than that of the ELC record at the same period.

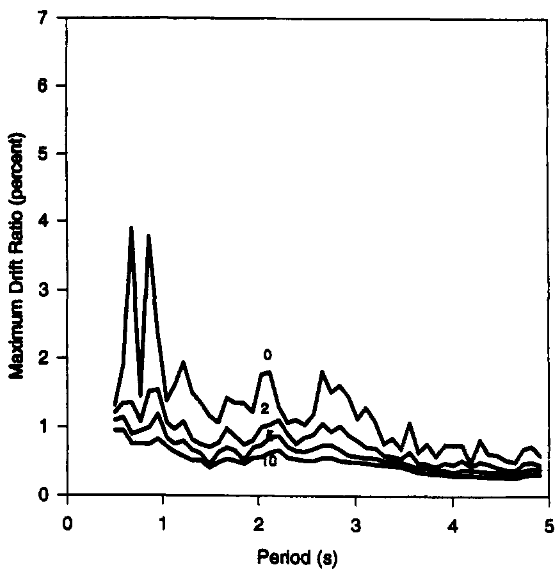

FIG. 10. Base-Level Drift Spectrum (El Centro Station, Imperial Valley Earthquake; N-S Direction)

TABLE 1. Peak Value of Drift Spectrum (DS) for Selected Earthquake Records, Structural Period for Peak Drift Demand, PGV, and PGA (2% Damping)

Record (1)	Max DS (%) (2)	Period (s) (3)	PGV (cm/s) (4)	PGA (g) (5)
Takatori (TAK) Station, Kobe; maximum velocity direction	7.8	1.2	155	0.73
Sylmar Converter Station (SCS); N-S	5.4	0.8	134	0.78
JMA-Kobe (JMA-K) Station; N-S	4.6	0.7	92	0.82
Rinaldi Receiving Station (RRS); N-S	4.5	1.3	159	0.82
Sylmar County Hospital (SCH), Free Field; N-S	3.3	1.5	136	0.88
Lucerne (LUC) Station, Landers; maximum velocity direction	2.1	4.1	147	0.73
El Centro (ELC); N-S	1.4	1.0	33	0.35

Based on the magnitude of the computed drift demand for both the Northridge and Hyogo-ken Nanbu earthquakes, it is not surprising that there were numerous cases of joint failures in moderate-height steel frame buildings during both of these earthquakes. The *Uniform Building Code* design drift is about 0.5%. Furthermore, recent testing has indicated that it is difficult to obtain drift capacities much in excess of 2–3% using present beam-column connection techniques. Even without consideration of yielding, the drift demand associated with the Northridge and Hyogo-ken Nanbu earthquakes significantly exceeds these levels. Yielding will generally cause the effective drift demand to be further increased (Iwan 1995).

COMPARISON OF ELASTIC RESPONSE SPECTRUM AND DRIFT SPECTRUM

The elastic drift spectrum and response spectrum contain different but complementary information about the demand of earthquake ground motion. The response spectrum primarily contains information about the maximum global displacement or acceleration demand, while the drift spectrum contains information about the maximum interstory drift ratio demand. Neither spectrum contains all of the information necessary for good seismic design.

To illustrate the difference between the drift and response spectra, Figs. 11–13 compare the maximum interstory drift computed directly from the response spectrum assuming a single mode of response with that provided by the drift spectrum for three different near-field records. The mode shape assumed for the response spectrum calculation is the true mode shape of the uniform shear beam. If an approximate linear mode shape were assumed, rather than the exact mode shape, the response spectrum-based drift would be 25% lower than that shown.

In each of the cases shown, the peak drift ratio is fairly well represented by the response spectrum result. For the RRS record, the results obtained from the response spectrum using the true mode shape and those from the drift spectrum are close for structural periods less than about 2 s. This implies that a true single-mode approximation gives satisfactory results for internal deformations or interstory drift when the structural period is relatively short.

For longer structural periods, the results of the response spectrum and drift spectrum diverge significantly. The drift spectrum gives values that are as much as a factor of three

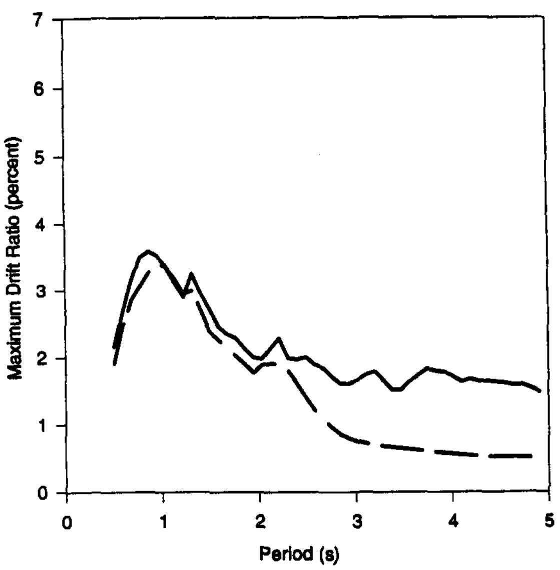

FIG. 11. Comparison of Drift Demand As Computed from Drift Spectrum (Solid Line) and Response Spectrum (Dashed Line), 5% Damping (Rinaldi Receiving Station)

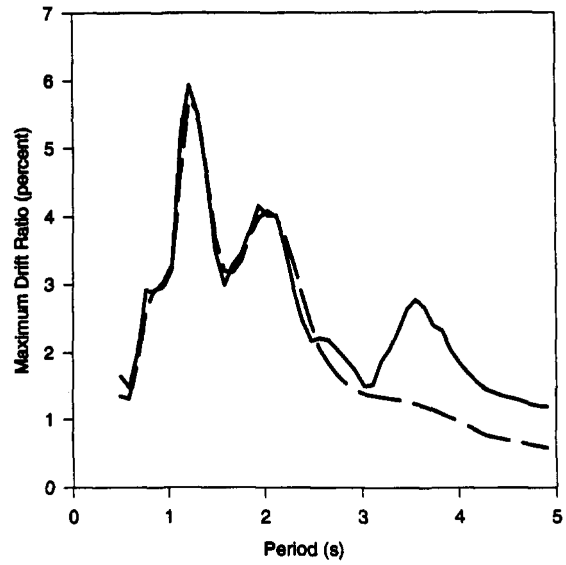

FIG. 12. Comparison of Drift Demand As Computed from Drift Spectrum (Solid Line) and Response Spectrum (Dashed Line), 5% Damping (Takatori Station)

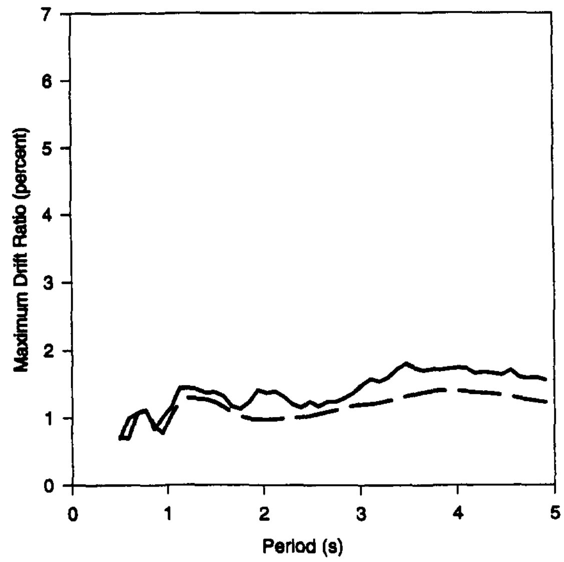

FIG. 13. Comparison of Drift Demand As Computed from Drift Spectrum (Solid Line) and Response Spectrum (Dashed Line), 5% Damping (Lucerne Station)

greater than those based on the response spectrum using the true single-mode shape assumption. If an approximate linear mode shape were used, the difference would be a factor of four. For the TAK Station record, the two results diverge for structural periods greater than about 3 s with the difference exceeding a factor of two. For the LUC record, the two results are fairly close, at least up to structural periods of 5 s.

The discrepancy between the response spectrum and drift spectrum for records from the Northridge and Hyogo-ken Nanbu earthquakes is a consequence of (1) the fact that the response of structures becomes more wave-like in nature for longer periods; and (2) the presence of distinct pulses in the time history of the ground motion. The period at which the two spectra diverge will vary somewhat, but the trend is the same. The single-mode response spectrum significantly underestimates the drift demand for longer period structures. The very long period content of the LUC record minimizes the differences for ordinary structural periods.

From Figs. 11 and 12, it may be concluded that no simple linear scaling of the response spectrum can adequately account for the interstory drift demand associated with near-field earthquakes. If the response spectrum is adjusted to account for the interstory drift demand of short- to moderate-period structures (less than 2–3 s), it will severely underestimate the drift demand for longer-period structures. Conversely, if it is adjusted for longer-period structures (greater than 2–3 s), it will significantly overestimate the drift demand for short- to moderate-period structures. This would indicate that additional steps are needed to account for near-field effects in design beyond merely multiplying the code base shear coefficient by a near-field factor that is constant for periods greater than some very small value such as 0.5 s.

The writer belies that both a design response spectrum and a design drift spectrum should be specified for near-field structural design purposes. This could be done rather easily for significant engineered structures on a site-specific basis. For structures designed on a seismic zone basis, a generic design drift spectrum could be specified in the same manner that a design response spectrum is effectively specified by the code.

COMPARISON WITH RESULTS OF DETAILED NUMERICAL MODELING

As a means of demonstrating the applicability of the drift spectrum to actual structures, the results of the drift spectrum are compared with those of detailed numerical analyses of the response of prototypical building structures subjected to a sample of different near-field earthquake excitations. The detailed modeling was performed by Hall (1995) as part of the SAC Joint Venture study of the failure of steel frame buildings during the Northridge earthquake.

Hall modeled two different prototype buildings: a six-story building with a linear fundamental period of 1.36 s, and a 20-story building with a period of 3.5 s. The prototype buildings were subjected to a variety of ground motion records including the SCH parking lot record as well as several synthetic near-field accelerograms. One synthetic accelerogram, NR11, was generated by Somerville (1995) as part of a study to simulate the ground motion that occurred along a benchmark profile during the Northridge earthquake. Another synthetic earthquake, C05, was generated by Heaton and Wald (Heaton et al. 1995) as a part of a study to simulate ground motions for a possible large (M_W = 7.0) blind thrust fault earthquake below downtown Los Angeles.

Hall performed analyses of the buildings assuming linear structural behavior and also conducted studies of models exhibiting plastic behavior and models with failed joints. Only the results of linear model studies are described herein. Further results may be found in the SAC Project report by the writer (Iwan 1995). The synthetic accelerograms are each rotated to the direction of maximum ground velocity. The linear viscous damping assumed by Hall was 5% in all modes of response.

Table 2 shows the base-level interstory drift ratio as computed by Hall and as determined from the drift spectrum. Also shown for comparison are the results obtained from the response spectrum assuming a single mode of response. With the exception of the case of the 20-story building subjected to the SCH ground motion, which will be discussed later, the results of the drift spectrum agree quite well with the results of the detailed numerical studies. The difference between the drift spectrum estimate of the drift ratio and the numerically calculated drift ratio ranges from 5 to 13%. The greatest value of drift ratio occurs for the six-story building subjected to the NR11 ground motion. The natural period of the building for this case is in a region in which the drift spectrum is very sensitive to period. This may explain the slight underestimate of the drift ratio. A more conservative estimate of the drift ratio based on the drift spectrum would have been obtained by using the value of 4.5%, which is the value of drift ratio at a local peak in the spectrum that occurs at about a 1.5 s period.

For the same cases, the response spectrum gives drift ratio results that are comparable to the drift spectrum results, except for the six-story building subjected to the SCH ground motion. For this case, the drift ratio inferred from the response spectrum is more than 20% low. For the NR11 ground motion, the drift ratio obtained from the response spectrum is also very sensitive to period near 1.36 s. The peak drift in this region has the same value (4.5%) as the drift spectrum.

For most of the cases described previously, the value of the drift ratio obtained from the drift spectrum is quite close to that obtained from the response spectrum. This indicates that the structural response for these cases is more mode-like than wave-like in nature. Therefore, these results indicate only the general accuracy of the drift spectrum results, and may not be used to infer superiority of the drift spectrum over the response spectrum or vice versa.

The results for the 20-story building subjected to the SCH ground motion warrant further comment. The drift ratio predicted by the drift spectrum is greater than that predicted by the response spectrum for the SCH ground motion for all periods greater than 3 s. For example, at a period of 4 s, the drift spectrum value of drift ratio is approximately twice the response spectrum value. This implies that the response of structures with longer periods subject to the SCH ground motion case is more wave-like in nature than for the other cases considered.

For wave-type response, the shear deformation depends strongly on the local wave speed, as discussed earlier. For the 20-story building studied by Hall, the base level shear wave velocity is 27% greater than the average shear wave velocity that would be deduced from the structural period. This is due to the nonuniform stiffness properties of the structure with height. Hence, the drift ratio value obtained from the drift spectrum for the uniform shear beam model should in this case be reduced by a factor of 0.79 to account for variable stiffness.

In addition, the effect of finite story height in the numerical model can be accounted for by averaging the strain of the continuous shear beam over the height of the first story. This results in a 7% reduction in the drift ratio from that obtained at the base of the continuous model for this case. Combining these two corrections, the value predicted by the drift spectrum would be 1.1%, as indicated in the table.

Overall, it is believed that the results of the drift spectrum

TABLE 2. Maximum Base-Level Interstory Drift Ratio in Percent As Computed from Detailed Numerical Modeling of Prototype Buildings (Hall) and from Drift Spectrum (5% Damping)

	Six-Story Building (1.36 s)			20-Story Building (3.5 s)		
Record (1)	Numerical modeling (2)	Drift spectrum (3)	Response spectrum (4)	Numerical modeling (5)	Drift spectrum (6)	Response spectrum (7)
SCH (N-S)	2.6	2.4	2.0	1.0	1.5 (1.1)[a]	0.9
C05 (max)	1.8	1.7	1.5	2.1	1.9	2.0
NR11 (max)	4.6	4.0	4.2	1.5	1.6	1.4

[a]Adjusted for stiffness variation with height and finite story height.

are in good agreement with the results of Hall's detailed numerical studies. However, further studies of buildings with periods in the range where there is substantial difference between the drift spectrum and response spectrum results (usually the longer period range) would be very useful.

SUMMARY AND CONCLUSIONS

The drift demand spectrum is proposed as a simple measure of the drift demand associated with strong earthquake ground motion. As such, it is a useful adjunct to the customary response spectrum. It has been shown that the drift spectrum provides information not directly obtainable from the response spectrum. It has further been shown that drift demand cannot be adequately accounted for by merely scaling the code base shear coefficient.

Drift spectra for near-field Northridge and Hyogo-ken Nanbu accelerograms exhibit high values consistent with observations of failures in structural frame members resulting from these earthquakes. It has been shown that the results of the drift spectrum are in general agreement with results of detailed numerical analyses of prototype building structures. The use of the drift spectrum in structural design is strongly recommended.

The writer hopes that the present paper will generate increased interest in the interstory drift demand associated with near-field earthquake ground motions and promote further discussion and investigation of the drift spectrum as a measure of this demand.

ACKNOWLEDGMENTS

The writer wishes to thank Qun Gu and Luo-Jia Wang for their assistance with the numerical studies reported in this paper. The writer is indebted to the Los Angeles Department of Water and Power, Lee Benuska of Lindvall Richter Benuska Associates, Robert Nigbor of Agbabian Associates for supplying uncorrected data for the RRS and SCS records, and to Tony Shakal of the California Division of Mines and Geology for supplying uncorrected data for the SCH record. The writer is also grateful to Yutaka Nakamura of the Railway Technical Research Institute of Japan for supplying the Takatori Station data and H.-N. Tong of the Institute for Industrial Science, University of Tokyo, for supplying the JAM-Kobe data. The study reported in this paper was supported in part by grants from the National Science Foundation and the SAC Joint Venture Project on the failure of steel frame joints in the Northridge earthquake. The opinions expressed are those of the writer and do not necessarily reflect those of any sponsor.

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