IMPORTANT FEATURES OF THE RESPONSE OF INELASTIC STRUCTURES TO NEAR-FIELD GROUND MOTION

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SUMMARY

Idealized structural models are employed to reveal important features of the response of inelastic structures to near-field ground motions, and to illustrate how the response to near-field ground motions differs from that to far-field motions. The effects of near-field ground motions on both strength reduction and displacement amplification are discussed. The applicability of the Capacity Spectrum Method of analysis for cases of near-field ground motions is also examined. A novel representation of the results provides the locus of performance points for structural response as a function of nominal structural period and ductility.

INTRODUCTION

Near-field ground motions can contain distinct, large amplitude pulses in both velocity and displacement. These pulses can cause high levels of inter-story drift ratio in structural systems. Such ground motions were recorded in both the Northridge and Kobe earthquakes. These ground motions resulted in largely unanticipated damage to engineered structures. Recent concern about the damage potential of near-field ground motions has led to considerable interest in the nature of these motions and their impact on structural performance. This paper discusses the response of inelastic structures to near-field ground motion using simplified SDOF and MDOF structural models. The recently proposed ATC-40 Capacity Spectrum Method is examined, and the results of this analysis procedure are compared with results of full inelastic time history analysis.

STRENGTH REDUCTION AND DISPLACEMENT AMPLIFICATION FACTORS

The response spectrum has long been used by earthquake engineers to characterize earthquake ground motion and its effect on structural systems. It provides a simple graphical means by which the effects on response of structural period, structural damping, and, in the case of hysteretic systems, ductility can be assessed. Design spectra are derived from actual earthquake response spectra, but may also incorporate assumptions about the performance of the structural system to which the spectrum applies.

When a structure can sustain inelastic action, the design spectrum is often modified by the use of a force or strength reduction factor (the “R” factor in the 1997 UBC). This factor reduces the design base shear and subsequently the internal design loads in the structure. It is intended to account for the fact that a yielding system will transmit lower loads than a purely linear system with the same initial stiffness. While the design loads are reduced by the use of a reduction factor to account for inelastic action, the design displacements are often assumed to be essentially unchanged by inelastic action. This is the so-called equal displacement rule. These design assumptions have produced buildings that generally perform as intended in far-field ground shaking. However, the use of simple strength reduction factors and displacement rules has been questioned for near-field type earthquake ground motions due to the presence of distinct pulses in these motions.

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As an indication of the effects of near-field ground motions on the spectral properties of inelastic response, consider a SDOF bilinear hysteretic system with a post-yielding stiffness of 10% of the elastic stiffness, and a viscous damping of 5% of critical. Let the system be excited by the S33W component of the Rinaldi Receiving Station (RRS) ground motion that was recorded during the Northridge earthquake [Wang et al., 1996]. This ground motion is shown in Fig. 1. The pulse-like nature of the motion is clearly evident.

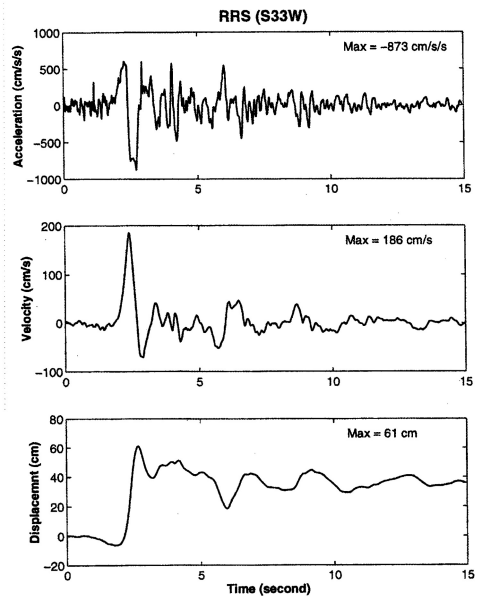

Figure 1: Rinaldi Receiving Station ground motion, Northridge earthquake (S33W)

The strength reduction factor (SRF) is defined as the ratio of the spectral acceleration of an elastic system divided by the spectral acceleration of the corresponding inelastic system. The displacement amplification factor (DAF) is defined as the spectral displacement of an inelastic system divided by the corresponding elastic spectral displacement. The SRF and DAF are computed for the five levels of ductility: μ = 1, 2, 4, 6, and 8. Results are shown in Figs. 2 and 3.

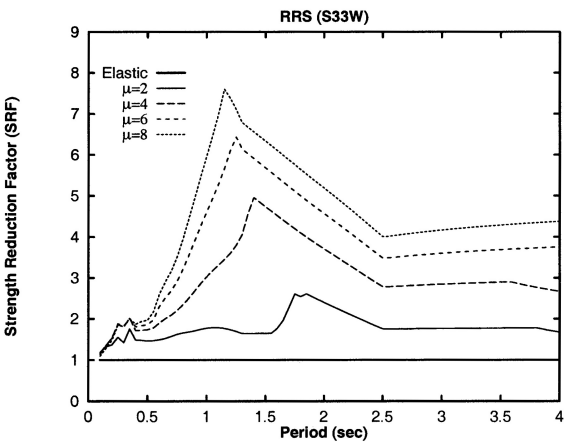

Figure 2: Strength Reduction Factor, RRS

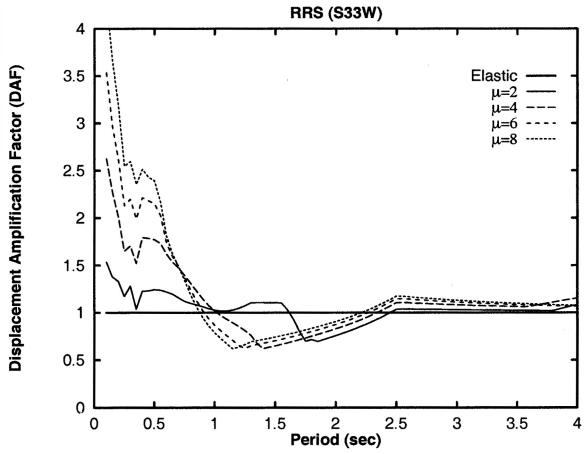

Figure 3: Displacement Amplification Factor, RRS

From Figs. 2 and 3 it is observed that:

- The SRF is generally low (<2) for the structural periods significantly less than the predominant pulse period of the ground motion (in this case about 1.2 seconds), independent of ductility.

- The SRF has a peak near the predominant pulse period of the ground motion.

- For structural periods both near and greater than the predominant ground pulse period, higher ductilities generally produce a higher SRF.

- For structural periods less than the predominant period of the ground motion, the DAF is extremely sensitive to ductility. There is significant displacement amplification for short period inelastic structures, and the amount of this amplification increases with increasing ductility.

- For periods exceeding the predominant pulse period of the ground motion, the DAF generally has a value at or below unity regardless of ductility. This implies that there is little amplification of inelastic deformation for SDOF systems in this period range.

Examining a suite of near-field ground motions [Iwan et al., 1999], it is observed that the peak in the elastic response spectrum generally occurs at nearly the same period at which the DAF first approaches unity with increasing period. For the RRS ground motion this occurs around 1.0 second. However, for the Lucerne Valley ground motion recorded during the Landers earthquake, this occurs at a period slightly larger than 4 seconds.

IMPLICATIONS FOR THE CAPACITY SPECTRUM METHOD OF ANALYSIS

The Applied Technology Council has recently proposed a design/analysis methodology [ATC-40, 1997] in which the traditional design spectrum is reduced to an inelastic demand spectrum and combined with a static push-over curve in what is usually referred to as a Capacity Spectrum Method (CSM). This produces a performance point, which predicts the maximum building response during an earthquake. In the CSM, the inelastic demand spectrum is derived from an elastic design spectrum using the concept of equivalent viscous damping. This results in a overall reduction in both acceleration and displacement demand. The effective viscous damping coefficient is generally based on an equal energy dissipation rule in which the energy dissipated during one complete hysteretic cycle is equated to that from one complete cycle of elastic response with equivalent viscous damping.

In what follows, the results of the CSM are compared with the results of a nonlinear time history analysis for both SDOF and MDOF bilinear hysteretic systems subjected to near-field earthquake excitation. This study uses the Newmark-Hall spectral reduction factors SR_A and SR_V to perform global spectral reduction on the damped elastic response spectrum. Whether SR_A or SR_V is used is based upon a comparison of the control period and elastic period of the SDOF analytical model.

Loci of Performance Points for SDOF Systems

For a SDOF system, a uniquely defined capacity spectrum curve is obtained using the CSM because the push-over load profile is unambiguous. Consider a bilinear hysteretic system with a 5% linear viscous damping coefficient. The system is then completely defined by its natural period, T, and the ratio of the post-yielding stiffness to the initial stiffness, α.

The Locus of Performance Points (LPP) is defined as the continuous trace of performance points with a prescribed elastic period and varying ductility plotted in ADRS format. The LPP given by the equivalent viscous damping approach employed in the usual CSM formulation is compared to the Locus of Inelastic Response (LIR) generated by time history analysis. The results for the case of a bilinear hysteretic system with α = 10% subjected to the RRS ground motion are shown in Figs. 4 and 5.

In these figures, the elastic and the μ = 8 inelastic response spectra are both plotted to illustrate the global shape of the demand spectrum. The detailed shape of the demand spectrum and locus of performance points differ somewhat for different earthquake ground motions. However, the following general observations may be made which are illustrated by the example results shown herein:

- The equivalent viscous damping approach yields satisfactory results only for the limited period ranges where a resonance build-up type of response occurs. For such cases, the equivalent viscous damping LPP generally resembles the LIR and is therefore useful in predicting the inelastic response of the hysteretic system.

- For near-field ground motions, the LPP generally underestimates the true LIR of SDOF systems with periods shorter than the predominant period of the ground motion pulse.

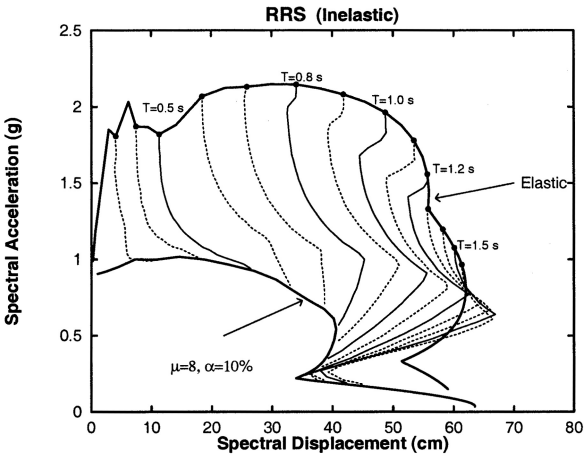

Figure 4: Loci of Inelastic Response, time history analysis, RRS

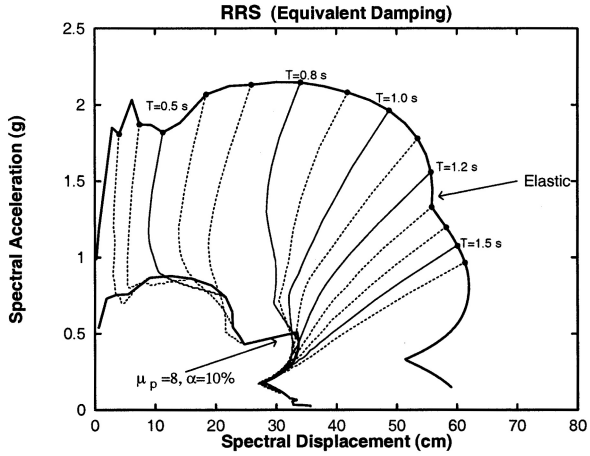

Figure 5: Loci of Performance Points, equivalent viscous damping analysis, RRS

For structures with periods that are considerably shorter than the ground motion pulse duration, it is observed that the post-yield response is highly sensitive to the post-yield ground displacement history. Once inelastic response has been initiated, displacements will increase rapidly due to the reduced stiffness unless the ground motion rebounds in the opposite direction.

Displacement Demand Ratio for SDOF Systems

The Displacement Demand Ratio (DDR) is defined as the ratio of maximum inelastic spectral displacement resulting from the time history analysis to the spectral displacement calculated from the CSM approach using equivalent viscous damping. This ratio is used as an indicator of the validity of the equivalent viscous damping assumption for near-field ground motions. DDR results for a bilinear hysteretic system with α = 10% subjected to the RRS ground motion are shown in Fig. 6 for μ = 1, 1.5, 2, 4 and 6. From this result, and a suite of other near-field ground motions studied, it is concluded the equivalent viscous damping assumption is significantly unconservative for natural periods less than the predominant pulse period of the ground motion, particularly for higher values of ductility. The equivalent viscous damping approach works fairly well in the period range near the predominant ground pulse period. For longer periods, the equivalent viscous damping assumption again becomes unconservative, but the DDR usually stays below 2.0.

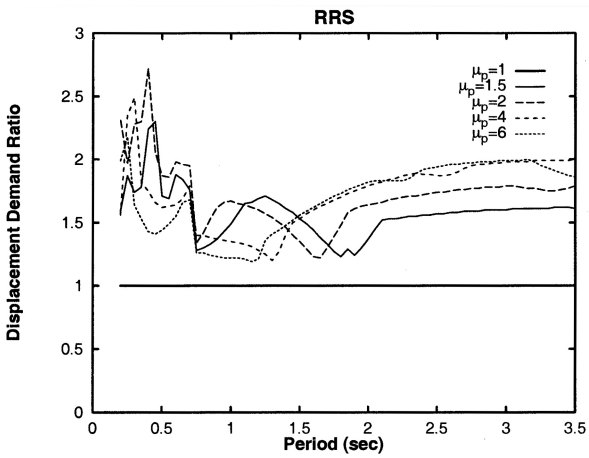

Figure 6: Displacement Demand Ratio for RRS (S33W) 5% damped elastic spectrum

Shear and Drift Demand for MDOF Systems

The predominant response of MDOF systems excited by far-field earthquake ground motions is usually in the fundamental mode. The static push-over technique employed in the CSM approach makes use of this fact by using a lateral load profile resembling the fundamental mode of the structure. Thus, predictions of areas of yielding in the structure are based upon a response shape that is similar to the first mode shape. However, near-field ground motions containing large displacement and velocity pulses cause the response of tall buildings to have greater participation in the higher modes.

A shear-building model is used to analyze building response to near-field earthquake ground motion. An equal mass distribution is assumed except for the top floor, for which the mass is half of the other masses. A bilinear hysteretic model is used to characterize the inter-story shear force-deformation characteristics. The post-yielding ratio, α, is assumed to be 5%. The yielding inter-story shear force is assumed to be proportional to the story shear stiffness. Rayleigh damping of 5% in the first two modes is assumed. Given the fundamental period of the structure, T, the height of the structure, L (in meters), is determined using the UBC formula $T = 0.0863\, L^{3/4}$. The number of stories is estimated using 3 meters per story height. The story shear stiffness distribution (or equivalently the story yielding shear) is chosen to give a straight-line deformation shape under the UBC lateral load distribution.

The focus of the results presented is on the spatial distribution of the story shear and drift demands. The spatial distributions of the shear and drift demands for structures with a fundamental period of 0.7 and 2.5 seconds subjected to the RRS ground motion are shown in Fig. 7 and 8.

Some observations based on the results shown in Figs. 7 and 8 and a study of a suite of other near-field ground motions are summarized below:

- For both elastic and inelastic analysis, the story shear force demand generally has its greatest value at the base level and gradually decreases as elevation level increases.

- The maximum story drift generally occurs at the base level except for a few cases where the maximum drift is located in the upper-stories. Such a case is the 2.5 second period building shown, where both the elastic and $\mu = 2$ cases show the greatest drift at $x/L \approx 0.8$. In this case, the maximum drift for the $\mu = 2$ case is greater than 2 times the base drift.

- For structural periods shorter than the ground pulse duration, there is generally good correlation between elastic SDOF analysis and elastic MDOF analysis. For these cases, the MDOF elastic building response exhibits a fundamental mode type of response and higher-mode contributions to the drift and shear demand are negligible.

- For long period structures, the elastic SDOF analysis and the elastic MDOF analysis are very different in both shape and magnitude. Therefore, a single-mode analysis may provide very misleading results for long period structures subjected to pulse-like ground motions. A more detailed discussion of the causes for this difference is given below.

- An increase in ductility generally amplifies the base level drift ratio and often decreases the upper-story drift ratios. For short period structures ($T = 0.7$ seconds), the amplification in base drift can be very large.

As an aid to understanding the above observations, Fig. 9 shows the evolutionary deformation response of the 2.5 second period building subjected to the RSS ground motion. As seen from the figure, the top of the building begins to respond to the ground pulse at about $t = 2.7$ seconds, which is when the ground begins its backward stroke. The response deformation shows that the maximum roof displacement occurs at $t = 2.6$ seconds and the value of maximum roof displacement is roughly equal to the maximum ground displacement for this case.

It is observed that two different stories give high inter-story drift. One high drift demand occurs in the base level at $t = 2.5$ seconds during the forward stroke of the ground motion. The maximum roof displacement correlates well with this high demand. However, another high drift demand occurs in the upper stories at $t = 3.3$ seconds, which is not correlated in time with the maximum roof displacement. The second high drift occurs after the completion of the main ground pulse and is due to the effects of wave propagation within the structure. The

global deformation shape corresponding to the second high drift is not at all similar to the first mode shape. Thus, neither an elastic or inelastic fundamental mode analysis will detect this high drift response.

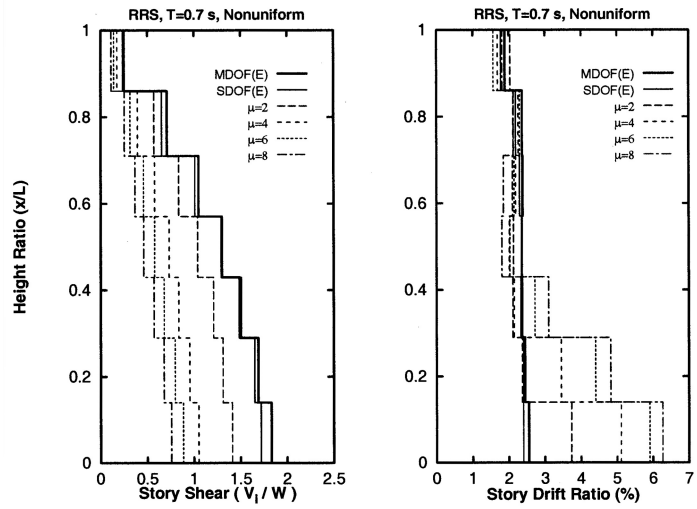

Figure 7: Spatial distribution of story shear and drift demands, *T* = 0.7 second, RRS (S33W)

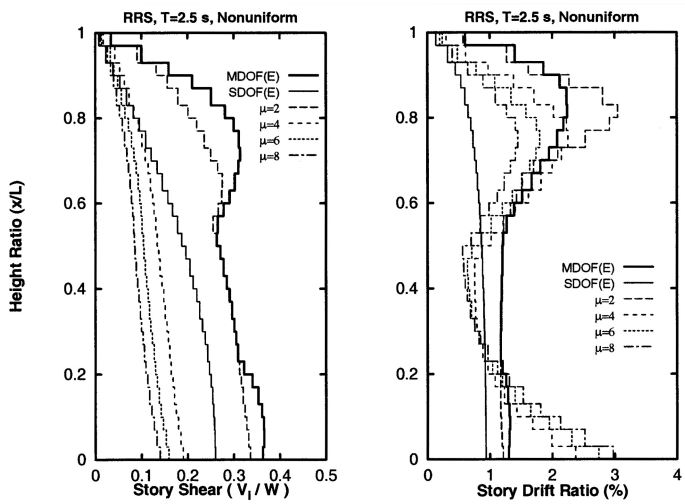

Figure 8: Spatial distribution of story shear and drift demands, *T* = 2.5 second, RRS (S33W)

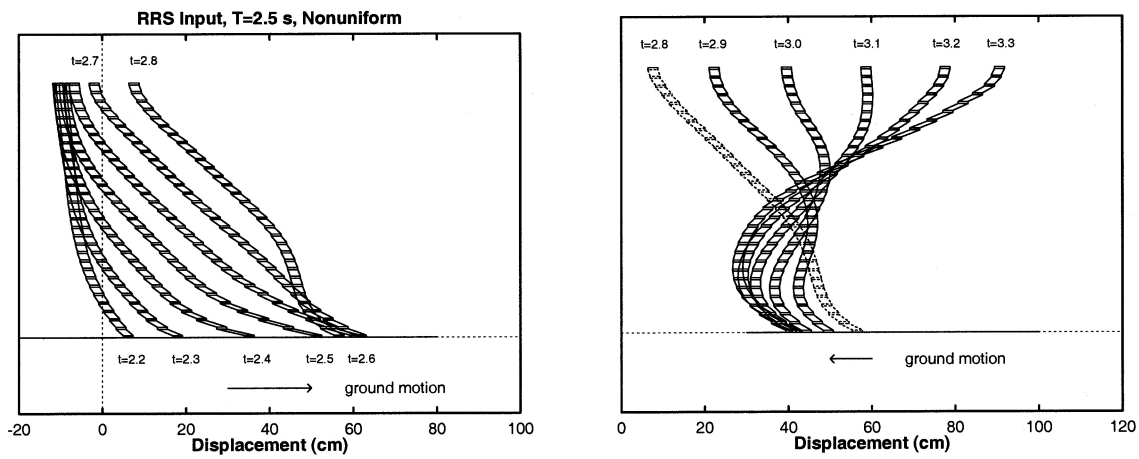

Figure 9: Time response of nonuniform shear building model subjected to RRS (S33W) (not drawn to scale), *T* = 2.5 second, μ = 2

Response Shape Estimation Using the CSM for MDOF Systems

When the push-over procedure is performed on a MDOF system, the response prediction is dependent upon many factors. There is no unique representation for the capacity of the structure, since the capacity becomes dependent upon the load patterns and detailed procedures used in the push-over analysis. A potential source of error is the difference between the inelastic deformation shape resulting from the push-over analysis and that resulting from an actual seismic event. Additionally, the maximum local deformation may not directly correlate in time with the maximum global response, particularly for near-field earthquake motions.

In what follows, errors in response shape estimation are examined. Consideration is restricted to shape estimation in order to avoid possible redundancy in error evaluation. To this end, the CSM approach is implemented in such a manner that any error in demand estimation, is minimized.

The procedure used for determining the nature of shape estimation errors is as follows:

Step 1 – Perform a static push-over analysis. The static push-over analysis is performed in accordance with the Level 4 push-over procedure described in ATC-40.

Step 2 – Construct the capacity spectrum. The capacity spectrum is derived from the static push-over analysis of Step 1.

Step 3 – Construct a SDOF bilinear hysterestic system to represent the MDOF. This system is based on equivalence of the capacity spectrum developed in Step 2.

Step 4 – Perform an inelastic analysis. The displacement response of the equivalent SDOF system is evaluated using a time history analysis.

Step 5 – Estimate the maximum response of the physical MDOF system. This is accomplished using the calculated maximum SDOF displacement response obtained in Step 3.

Typical results are presented in Fig. 10 for the case of a 2.5 second period building subjected to the RRS ground motion. Shown are the spatial distribution of the maximum displacement and maximum inter-story drift ratio based on the simplified CSM approach and a full MDOF inelastic time-history analysis. This figure clearly shows the effects of errors in global and local response shape.

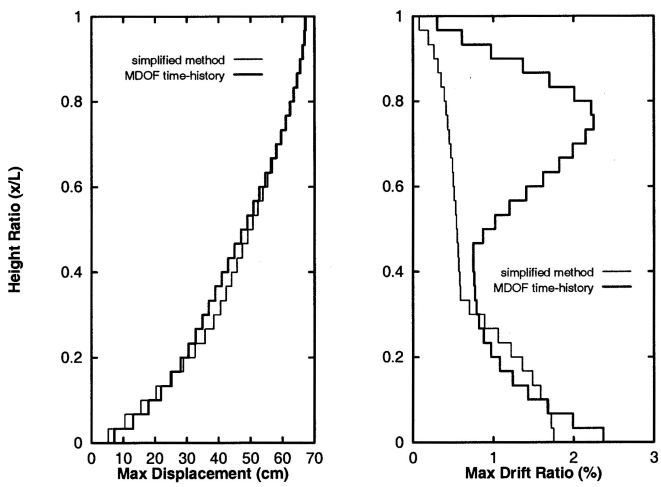

Figure 10: Comparison of solutions obtained by CSM (Simplified Method) and full nonlinear time-history analysis for structure S8 (T = 2.5 second, μ = 4)

Based on the results shown in Fig. 10 and those for a suite of near-field ground motions, the following observations are made:

- The CSM approach provides a reasonable prediction of the maximum roof displacement for all cases considered regardless of building period, level of nonlinearity, or stiffness distribution. Thus, the push-over

analysis is a useful tool for providing global inelastic shape estimations for a building under a pulse-like ground motion. Consequently, the results suggest that a push-over analysis combined with an inelastic SDOF time-history analysis can be a useful method for estimating maximum structural displacement response.

- For tall buildings, the simplified CSM analysis gives unsatisfactory predictions for maximum interstory drift response, particularly in upper stories. In some cases, the actual drift demand is more than four times that predicted by the simplified method.

To help explain these observations, it is useful to again consider the response characteristics shown in Fig. 9. In this case the structural response is dominated by the effects of wave propagation within the structure. This is true when the fundamental period is significantly greater than the ground pulse duration. The maximum upper-story drift response does not occur at the same time as the maximum roof displacement. This explains why the CSM can actually predict the maximum story displacements fairly well, but fails to predict the maximum story drift. It is therefore concluded that any push-over procedure using a single-mode analysis may fail to predict the local deformations for structures with periods significantly greater than the pulse duration.

CONCLUSIONS

Based on the results presented herein and a study of a suite of near-field ground motions, the following conclusions are drawn:

1. The strength reduction factor for inelastic structures with periods less that the predominant period of the near-field ground motion is generally considerably less than that for longer structural periods or for far-field ground motion.

2. The ratio of inelastic displacement to elastic displacement is significantly greater than unity for structural periods less than the predominant period of near-field ground motion. The displacement amplification is also an increasing function of ductility level in this shorter period range.

3. The use of an equivalent viscous damping factor to account for inelastic behavior in a Capacity Spectrum Method of analysis is not generally valid for near-field ground motions.

4. A response deformation shape that is determined from a static pushover or elastic analysis may not accurately predict local structural deformations. Inelastic deformations tend to accumulate at particular levels of a structure and increase with increasing ductility.

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