Dual-Level Approach for Seismic Design of Asymmetric-Plan Buildings

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Abstract: Buildings should be designed to resist moderate ground motion without structural damage and resist intense ground motion with controlled damage. However, most codes do not consider both these requirements explicitly and specify a single design earthquake that generally corresponds to intense ground motion. Investigated in this study is the response of one-story, asymmetric-plan systems designed according to torsional provisions of seismic codes to the two levels of ground motions with the objective of evaluating whether such systems satisfy these requirements. The presented results demonstrate that such systems may not remain elastic during moderate ground motion resulting in structural damage and may experience ductility demand in excess of the design ductility, causing excessive damage during intense ground motion. Therefore, the dual-design approach, proposed earlier for symmetric-plan systems, is extended to asymmetric-plan systems. In this approach, the design earthquakes and the design eccentricities corresponding to the moderate and intense ground motions are considered to be different; for the latter ground motion, the values of design eccentricity are considered to depend on the design ductility of the system. It is shown in this exploratory investigation that systems designed by this extended dual-design approach would satisfy the design requirements for both levels of ground motion.

INTRODUCTION

The effects of coupling between lateral and torsional motions on the earthquake response of asymmetric-plan buildings and how well these effects are represented in seismic codes have been the subject of numerous investigations (Chandler and Hutchinson 1987; Chopra and Goel 1991; Esteva 1987; Goel and Chopra 1990, 1991; Humar 1984; Pekau and Rutenberg 1987; Tso and Meng 1982; Tso and Ying 1990, 1992; Tso and Zhu 1992; Zhu and Tso 1992). These studies have often led to contradictory conclusions. Elastic response studies showed that the torsional response is pronounced in systems with close torsional and lateral vibration frequencies, which has led to suggestions to increase the design eccentricity from 1 to 1.5 times the static eccentricity to between three and six times the static eccentricity (Tso and Meng 1982). In contrast, inelastic response studies showed that the torsional motion is reduced significantly by inelastic action of the system, suggesting that the code values of design eccentricity may require a slight modification, if at all, to be consistent with the dynamic response (Chopra and Goel 1991; Tso and Ying 1990; Tso and Zhu 1992).

As is well known, buildings should be designed to resist moderate ground motion without structural damage and resist intense ground motion with controlled damage; the former criteria is known as the serviceability limit state and the latter as the ultimate limit state. Therefore, the code design procedures for asymmetric-plan systems should be evaluated by simulta-

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neously investigating their elastic response to moderate ground motion, and their inelastic response to intense ground motion.

This investigation is a first step towards filling this need. The response of one-story, asymmetric-plan buildings, designed according to torsional provisions of the U.S. seismic codes (*Recommended* 1990; *Uniform* 1991; *Tentative* 1978) to moderate and intense ground motions is investigated. The response of systems designed for the ultimate limit state or serviceability limit state to both ground motions is investigated. Subsequently, the response of buildings designed by the dual design approach, wherein the building is designed for the larger of the forces due to the two limit states, is investigated. Based on these results, shortcomings of the code provisions are identified. In order to alleviate these shortcomings in seismic codes, an extended dual-design approach is proposed, wherein not only the design earthquake but also the values of design eccentricity are defined differently for the two limit states. It is demonstrated that the extended dual-design approach leads to asymmetric-plan systems that satisfy the design requirements for moderate as well as intense ground motion.

EARTHQUAKE-RESISTANT DESIGN APPROACH

The commentary to the earthquake force recommendations of the SEAOC (*Recommended* 1990), which are adopted in the *UBC-91* (*Uniform* 1991), states that "structures designed in conformance with these recommendations should, in general, be able to:

1. Resist minor levels of earthquake ground motion without damage.
2. Resist moderate levels of earthquake ground motion without structural damage, but possibly experience some nonstructural damage.
3. Resist major levels of earthquake ground motion having an intensity equal to the strongest either experienced or forecast at the building site, without collapse, but possibly with some structural as well as nonstructural damage.

The first two criteria are commonly referred to as the serviceability limit state. This limit state may be interpreted as requiring the building to remain elastic during the serviceability-design earthquake, to avoid structural damage, and the largest of the interstory drifts to remain within a prescribed value in order to limit or avoid nonstructural damage. The third criterion is referred to as the ultimate limit state. This limit state requires that the building possess enough strength and ductility to avoid collapse and nonrepairable structural damage during the ultimate design earthquake.

Although *UBC-91* and other seismic codes mention both limit states, most codes do not consider both of the limit states explicitly; in particular, the *UBC-91* is primarily intended to safeguard against major failures and loss of life (*Recommended* 1990). In such codes, the forces specified are associated with the ultimate design earthquake. The design force, V, is generally of the form

$$V = \frac{C}{R} W \qquad (1)$$

in which C = a seismic coefficient, R = a reduction factor, and W = the weight of the building, including the dead load, a portion of the live and snow load, and total weight of the permanent equipment.

The seismic coefficient, C, is given by the smooth elastic design spectrum for the ultimate design earthquake modified in the short and long period regions (*Recommended* 1990). The reduction factor, R, in general depends on the design ductility, and the performance of various structural systems during earthquakes, among other factors. The latter indirectly includes the overstrength of the structure resulting from several sources: structural redundancy, higher material strength than those specified in design, strain hardening, deflection constraints on system performance, member oversize, minimum requirements regarding proportioning and detailing, multiple loading combinations, effects of nonstructural elements, and strain rate effects.

DESIGN OF ASYMMETRIC-PLAN SYSTEMS

Method for Computing Design Forces

In asymmetric-plan systems [Fig. 1(*a*)], the design force V is applied eccentric from the center of rigidity (CR) at a distance equal to design eccentricity, e_d, which is defined in the next section. If the floor diaphragm is rigid, the design force in the jth structural element along the direction of ground motion is

$$V_j = \frac{k_{jy}}{K_y} V + \frac{e_d V}{K_{\theta s}} (-x_j + e_s) k_{jy} \quad \text{(2)}$$

in which K_y = the lateral stiffness of the system along Y-direction; $K_{\theta s}$ = the torsional stiffness of the system about the CR; k_{jy} = the lateral stiffness of the jth structural element in the Y-direction and x_j is its distance from the center of mass (CM); and e_s is the stiffness eccentricity defined as the distance between the CM and the CR [Fig. 1(*a*)].

The first term in (2) represents the element force associated with its deformation resulting from deck translation and is the same as in the corresponding symmetric-plan system [Fig. 1(*b*)], a system with coincident CM and CR but m, the mass of the rigid deck, K_y and $K_{\theta s}$, the lateral and torsional stiffnesses of the system, and the relative locations of the structural elements same as in the asymmetric-plan system. The second term represents the element force associated with its deformation resulting from deck rotation and thus the change in element force due to plan asymmetry.

Clearly, the second term in (2) results in either increase or decrease in design force of a structural element of the asymmetric-plan system compared to the corresponding symmetric-plan system. Some seismic codes, e.g., *UBC-91*, do not permit decrease in the design forces due to torsion implying that the second term in (2) be ignored if it is subtractive from the first term. As a result, the total design force for the asymmetric-plan system, which is the sum of the design forces for all structural elements, is larger than the corresponding symmetric-plan system.

Design Eccentricity

Most building codes (*Earthquake* 1992) require that the lateral earthquake force at each floor level of an asymmetric-plan building be applied eccentrically relative to the CR. The design eccentricity, e_d, specified in most seismic codes is of the form

$$e_d = \alpha e_s + \beta b \quad \text{(3a)}$$

$$e_d = \delta e_s - \beta b \quad \text{(3b)}$$

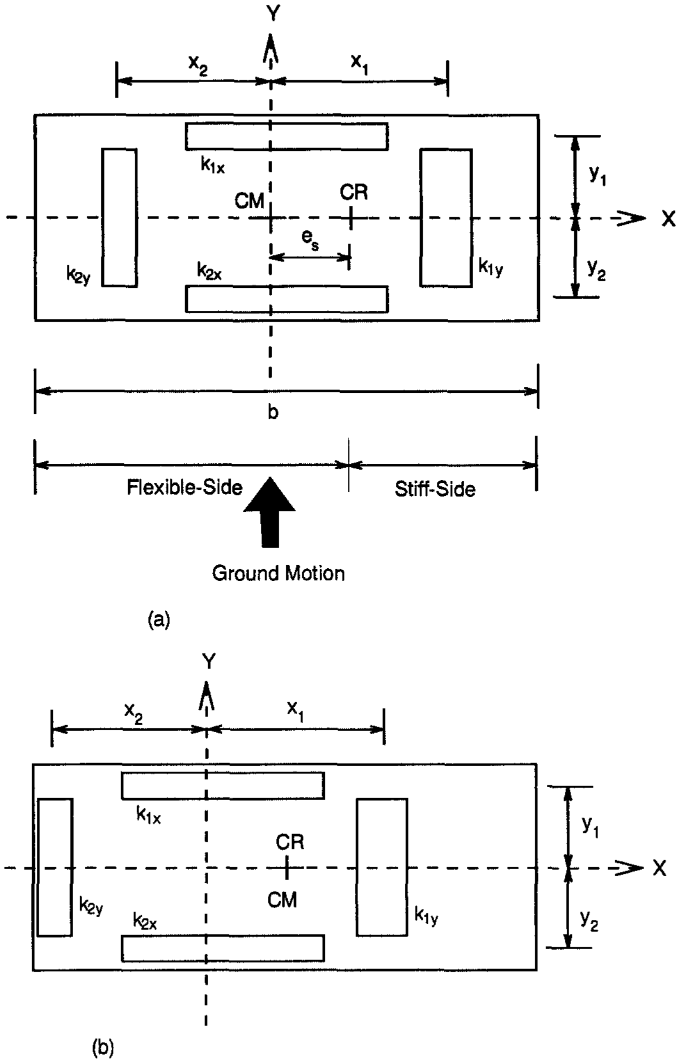

FIG. 1. Systems Considered: (*a*) Asymmetric-Plan System; and (*b*) Corresponding Symmetric-Plan System

where e_s = the stiffness eccentricity; b = the plan dimension of the building transverse to the direction of ground motion [Fig. 1(*a*)]; and α, β, and δ = specified coefficients. For each element the e_d value leading to the larger design force is to be used.

The coefficients, α, β, and δ vary among building codes. For example, the *UBC-91*, 1990 SEAOC recommendations, and Applied Technology Council (ATC-3) provisions (*Tentative* 1978) specify β = 0.05 and α = δ = 1; the latter imply no dynamic amplification of torsional response. The 1987 Mexico Federal District Code (*MFDC-87*) (Gomez and Garcia-Ranz 1988) specifies β = 0.1, δ = 1, and α = 1.5; the latter implies dynamic amplification. The *NBCC-90* (*National* 1990) specifies $\beta = 0.1$, $\alpha = 1.5$, and $\delta = 0.5$; and the *NZC-92* (*New* 1992) specifies $\beta = 0.1$ and $\alpha = \delta = 1$.

The first term in (3) involving e_s is intended to account for the coupled lateral-torsional response of the building arising from lack of symmetry in plan, whereas the second term is included to consider torsional effects due to other factors such as the rotational component of ground motion about a vertical axis; differences between computed and actual values of stiffnesses, yield strengths, and dead-load masses; and unforeseeable unfavorable distribution of live-load masses. This accidental eccentricity, βb, which is a fraction of the plan dimension, b, is considered in design to be on either side of the CR.

SYSTEMS, GROUND MOTIONS AND DESIGN CRITERIA

One-Story System

The system considered is the idealized one-story building of Fig. 1(*a*), consisting of a rigid deck supported on structural elements oriented along the direction of ground motion as well as transverse to the ground motion. Structural elements are frames or walls having strength and stiffness in their planes only. The mass, stiffness, and strength properties of the system are symmetrical about the X-axis, but not about the Y-axis. This lack of symmetry is characterized by the stiffness eccentricity e_s. The system plan is divided into the flexible side and the stiff side as shown in Fig. 1(*a*), and the associated structural elements are referred to as the flexible-side and stiff-side elements, respectively.

The natural, elastic vibration frequencies, ω and ω_θ, of the corresponding symmetric-plan system [Fig. 1(*b*)] are given as

$$\omega = \sqrt{\frac{K_y}{m}} \qquad (4a)$$

and

$$\omega_\theta = \sqrt{\frac{K_{\theta s}}{mr^2}} \qquad (4b)$$

where r = the radius of gyration of the deck about the CM. The ratio of these uncoupled torsional and lateral frequencies is defined as

$$\Omega_\theta = \frac{\omega_\theta}{\omega} \qquad (5)$$

For the asymmetric-plan selected in this study, the uncoupled lateral to torsional frequency ratio, $\Omega_\theta = 1$; the stiffness eccentricity normalized by the radius of gyration, $e_s/r = 0.5$; half of the total torsional stiffness of the system about the CR is provided by the structural elements oriented transverse to the direction of the ground motion; the uncoupled vibration frequencies in the X and Y translation are equal; and the damping ratio $\zeta = 0.05$. The force-deformation relationship of each structural element is assumed to be elastic-perfectly-plastic. This simple system is appropriate for the purpose of this exploratory investigation. Eventually, several alternative system configurations having different distributions of mass and stiffness (Tso and Ying 1992; Tso and Zhu 1992) and appropriate strengths of structural elements oriented along the direction transverse to the ground motion should be considered.

Ground Motions

The ground motion selected is a simple half-cycle displacement pulse with the half-duration of t_1; the displacement, velocity, and acceleration histories of this ground motion are shown in Fig. 2. The peak acceleration is selected as 0.4g for the ultimate design earthquake and 0.1g for the serviceability design earthquake where g = the acceleration due to gravity. The elastic response spectra for the two ground motions are shown in Fig. 3, plotted against the period ratio, T/t_1, in which $T = 2\pi/\omega$ and t_1 = the half-duration of the ground motion. These two spectra have the same shape but their ordinates differ by a factor of 4. This simple excitation and same spectral shapes for the two earthquakes are appropriate for this exploratory investigation of the extended dual design approach for asymmetric-plan systems. Eventually, actual earthquake ground motion with different spectrum shapes for the two levels of ground motions should be used. The spectral shapes are different for the two design earthquakes because of differences in occurrence probabilities, source mechanisms, and site-to-fault distances. Appropriate design spectra for the two earthquakes should account for all these factors.

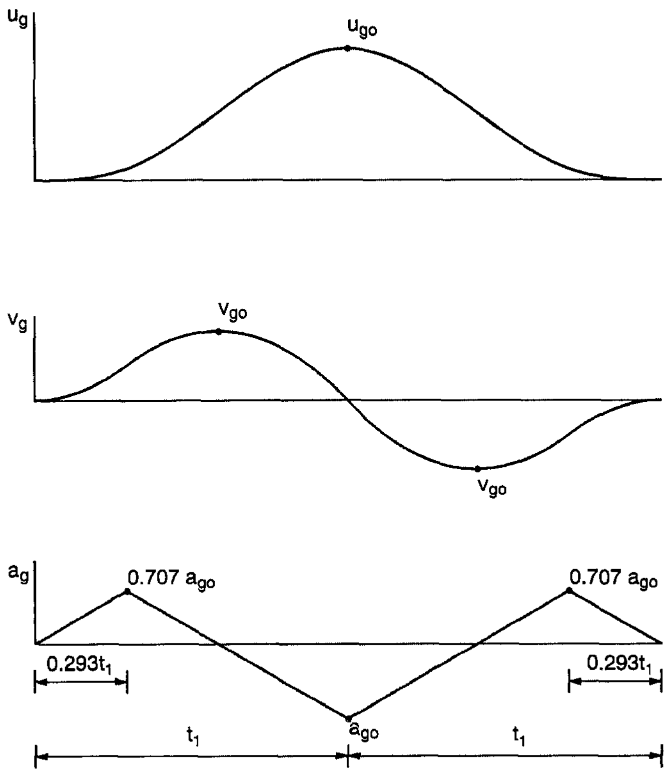

FIG. 2. Time Histories of Deformation, Velocity, and Acceleration for Half-Cycle Displacement Ground Motion (after Veletsos)

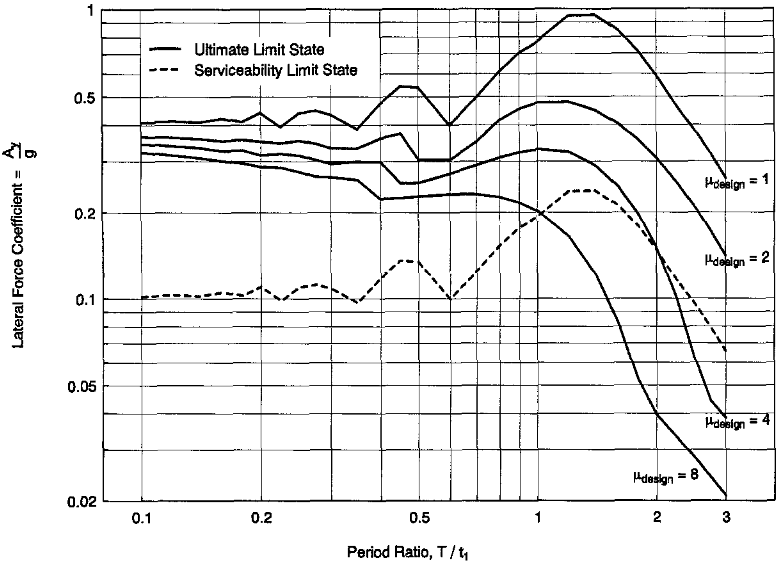

FIG. 3. Design Spectra for Ultimate and Serviceability Limit States

Design Spectra and Forces

The base shear for a one-story, symmetric-plan system is given by:

$$V = \left(\frac{A_y}{g}\right) W \quad (6)$$

where W = the weight of the system and A_y = the ordinate of the pseudo-acceleration spectrum corresponding to the natural vibration period T, damping ratio, and the design ductility ratio μ_{design} of the system. For the serviceability limit state design, A_y is obtained from the elastic design spectrum, i.e., $\mu_{design} = 1$, for the serviceability design earthquake (Fig. 3). For the ultimate limit state design, A_y is obtained from the inelastic design spectrum associated with the selected design ductility μ_{design} for the ultimate design earthquake. These design spectra are shown in Fig. 3 for μ_{design} = 1, 2, 4, and 8. Note that the design spectra for the two limit states are selected as the response spectra for the two design earthquakes, defined in the previous section.

With the base shear, V, determined in this manner, the yield force for each element oriented in the Y-direction is defined as the design force, V_j, computed from (2) with the design eccentricity e_d specified in U.S. seismic codes, which is equivalent to (3) with $\alpha = \delta = 1$ (*Recommended* 1990; *Tentative* 1978; *Uniform* 1991). Since this investigation is primarily concerned with asymmetric-plan systems, the accidental eccentricity is not included in computing the design forces for structural elements, i.e., $\beta = 0$ in (3). Furthermore, consistent with the *UBC-91*, reduction in design forces of structural elements due to torsion is precluded.

RESPONSE OF SYSTEMS DESIGNED WITH TRADITIONAL APPROACHES

Presented in this section is the response of asymmetric-plan systems designed as described in the previous section; the response of the corresponding symmetric-plan system is also included for the purpose of comparison. The responses are computed for the ultimate as well as the serviceability design earthquake applied in the Y-direction. The response results are presented first for the systems designed for the ultimate limit state followed by those designed for the serviceability limit state. Subsequently, the response results are presented for systems designed by the dual approach wherein the design forces are selected as the larger of the forces for the two limit states.

Systems Designed for Ultimate Limit State

Response to Ultimate Design Earthquake

Fig. 4 shows the ductility demands imposed by the ultimate design earthquake on structural elements of systems designed for the ultimate limit state. Because the base shear is determined from the constant ductility spectrum, the ductility demand imposed on each element of the corresponding symmetric-plan system is exactly equal to the design ductility over the entire period range. If the system plan is asymmetric, however, the ductility demands imposed on structural elements by the ultimate design earthquake are no longer equal to the design ductility or independent of the vibration period. For many period values, the ductility demands on structural elements are less than the design ductility. For some period values, however, the ductility demand exceeds the design ductility, especially for the smaller values of the design ductility. Therefore, the code torsional provisions should be modified in order to insure that the ductility demands are smaller than the design ductility.

Response to Serviceability Design Earthquake

Fig. 5 shows ductility demands imposed by the serviceability design earthquake on structural elements of the asymmetric-plan and the corresponding symmetric-plan system, both designed for the ultimate limit state. A value

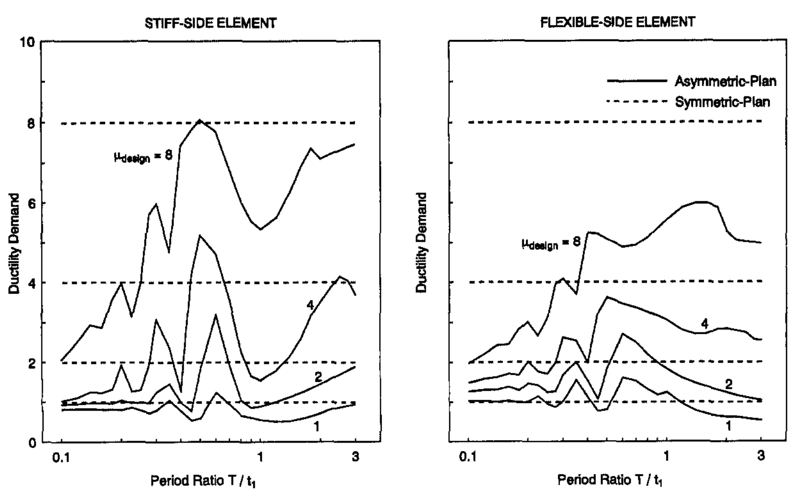

FIG. 4. Ductility Demands due to Ultimate Earthquake on Systems Designed for Ultimate Limit State; μ_{design} = 1, 2, 4, 8

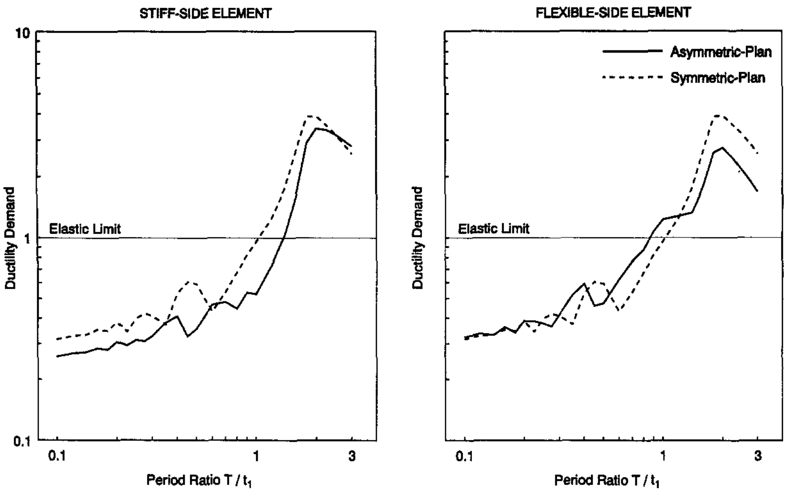

FIG. 5. Ductility Demands due to Serviceability Earthquake on Systems Designed for Ultimate Limit State; $\mu_{design} = 8$

of ductility demand smaller than one indicates elastic behavior, whereas a value larger than one implies inelastic action during the serviceability design earthquake. Whereas short-period, symmetric-plan systems remain elastic during the serviceability design earthquake, long-period ($T/t_1 > 1$) systems may undergo inelastic action. This observation could have been predicted by examining Fig. 3, which shows that the base shear coefficient for long-period systems is larger for the serviceability design earthquake than for the ultimate design earthquake with design ductility of $\mu_{design} = 8$.

The trends for element ductility demands in asymmetric-plan systems are generally similar to the ones noted previously for symmetric-plan systems with a few minor differences. The ductility demand on the stiff-side element of asymmetric-plan system tends to be smaller because, as mentioned previously, the total strength of this system is larger compared to the symmetric-plan system — even though the two are designed for the same nominal base shear — which, in turn, results in smaller ductility demand (Goel and Chopra 1990). However, the trends for the flexible-side elements are not uniform over the period range considered; ductility demand in the asymmetric-plan system may be smaller compared to the symmetric-plan value for some period ratios and larger for the others. This depends on whether the increase in the strength of the flexible-side element due to code torsional provisions is sufficient to offset the increased deformation of this element due to plan asymmetry.

It is clear from these results that a system, whether it is symmetric in plan or asymmetric, designed only for the ultimate limit state, may not necessarily remain elastic during the serviceability design earthquake. Based on similar results for symmetric-plan systems, there have been proposals in the past to modify the seismic code provisions to design for the more critical of the ultimate and serviceability limit states; Building Standard Law of Japan and Tri-Services guidelines for essential buildings already include such provisions (Kato 1986; *Seismic* 1986) and the *NZC-92* has recently adopted similar provisions. Results presented here for asymmetric-plan systems also support the need for such modifications in seismic codes.

Systems Designed for Serviceability Limit State

Response to Serviceability Design Earthquake

Fig. 6 shows the ductility demands imposed by the serviceability design earthquake on structural elements of systems designed for the serviceability limit state. Because the base shear is determined from the elastic design spectrum, the corresponding symmetric-plan system remains elastic during the serviceability design earthquake, which is indicated by a ductility demand on structural elements equal to one over the entire period range. In contrast, structural elements of the asymmetric-plan system may not remain elastic during the serviceability design earthquake. In particular, yielding occurs in the flexible-side element over a wide range of period values. Such is the case because the increase in the strength of the flexible-side element due to code torsional provisions is not sufficient to offset the increased deformation of this element due to plan-asymmetry (Goel and Chopra 1990). The ductility demand on the stiff-side element of asymmetric-plan system is generally smaller than one, indicating that these elements remain elastic, with exceptions at a few period values. Therefore, code torsional provisions in current seismic codes should be modified in order to ensure that systems designed for serviceability limit state remain elastic during the serviceability design earthquake.

Response to Ultimate Design Earthquake

Fig. 7 shows the ductility demands imposed by the ultimate design earthquake on structural elements of symmetric-plan and asymmetric-plan systems designed for the serviceability limit state. The ductility demands on structural elements of both systems are seen to be excessively large for short-period systems; these would reduce, however, if the considerable overstrength typical of short-period buildings is recognized. Such is the case because the design strength provided in the serviceability limit state design is much smaller than the strength required for the system to remain elastic during the ultimate design earthquake (Fig. 3). For longer-period systems,

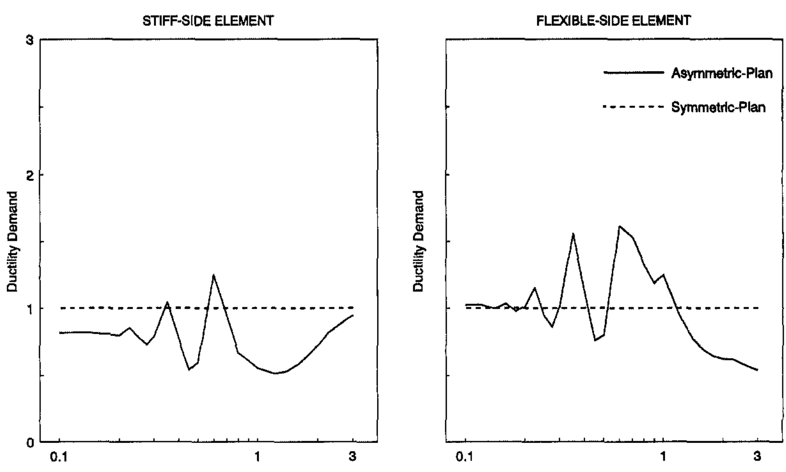

FIG. 6. Ductility Demands due to Serviceability Earthquake on Systems Designed for Serviceability Limit State

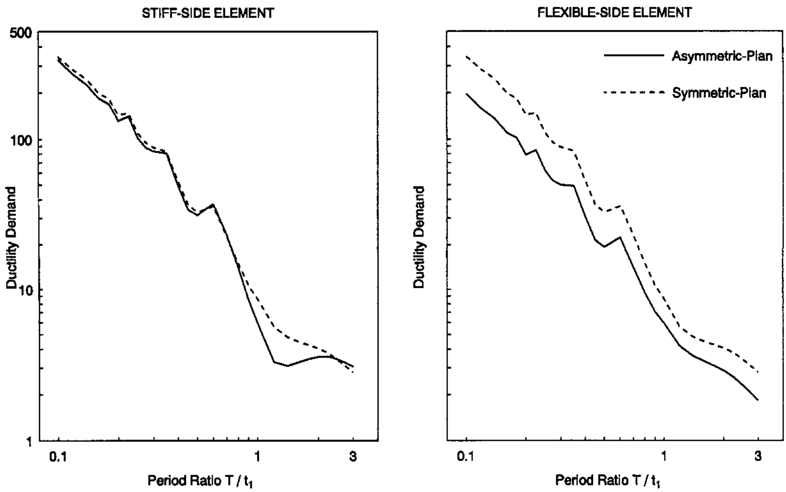

FIG. 7. Ductility Demands due to Ultimate Earthquake on Systems Designed for Serviceability Limit State

however, the ductility demands are much smaller. The ductility demand on asymmetric-plan system tends to be smaller compared to symmetric-plan system because of the higher total strength of the former resulting from code torsional provisions (Goel and Chopra 1990).

It is clear from these results that short-period systems designed for serviceability limit state alone may experience unrealistically high ductility demands during the ultimate design earthquake; this occurs for both symmetric- as well as asymmetric-plan systems. While this conclusion has been deduced earlier for symmetric-plan systems, it also holds for asymmetric-plan systems.

Systems Designed by Dual Approach

It is apparent from the results presented in previous sections that building designed for a single limit state, ultimate or serviceability, may not satisfy the objectives for the other limit state. In particular, a building designed for the ultimate limit state may not remain elastic, i.e., it may experience structural damage, during the serviceability design earthquake; on the other hand, the ultimate design earthquake may impose unrealistically high ductility demands on a building designed for the serviceability limit state causing excessive damage. Therefore, it has been suggested in the past that buildings should be designed for a critical (or two-level) limit state (*Seismic* 1986), wherein the design force is selected as the larger of the forces for the two limit states; such a design approach is often referred to as the dual-design approach. Since this dual-design approach has been proposed based on research studies on symmetric-plan systems, it is not clear if this approach would alleviate any of the aforementioned shortcomings of the single-limit-state design approach for asymmetric-plan systems. This is examined next. In designing asymmetric-plan systems, the base shear for the symmetric-plan system is taken as the larger of the two values associated with the two limit states and the values of design eccentricity are specified by the U.S. seismic codes, i.e., (3) with $\alpha = \delta = 1$. For the ultimate limit state design, four values of the system design ductility $\mu_{design} = 1, 2, 4$, and 8 are considered.

Figs. 8–11 show the ductility demands imposed by both earthquakes on structural elements of symmetric- and asymmetric-plan systems designed by the dual approach. As expected, the ductility demand imposed on symmetric-plan systems by the ultimate design earthquake is either equal to or smaller than the design ductility, and these systems remain elastic under the serviceability design earthquake, as indicated by the ductility demand smaller than or equal to one. If the ultimate design earthquake controls the design force, the ductility demand imposed by this earthquake is equal to

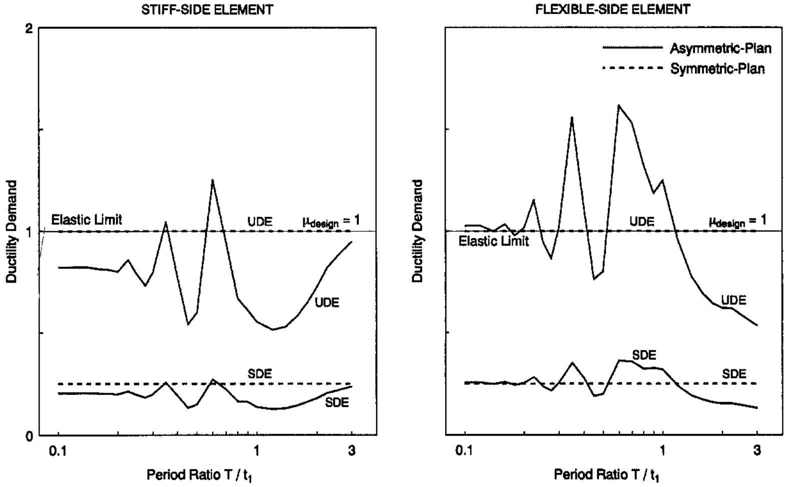

FIG. 8. Ductility Demands due to Ultimate (UDE) and Serviceability Earthquakes (SDE) on Systems Designed by Dual Approach; $\mu_{design} = 1$

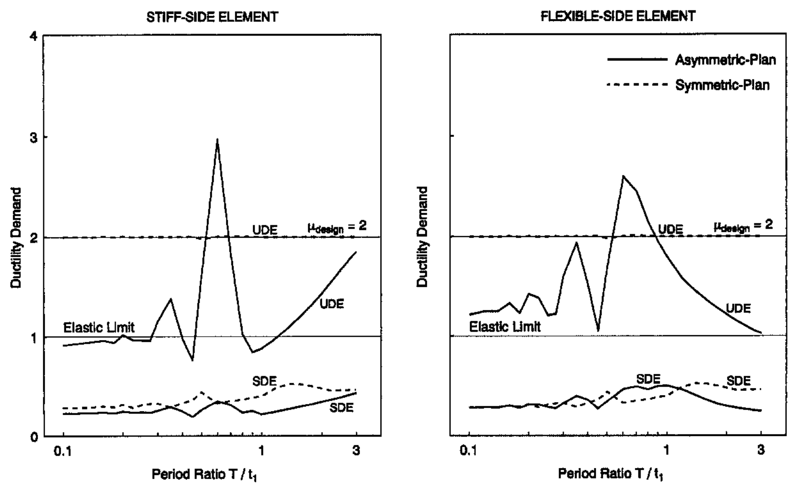

FIG. 9. Ductility Demands due to Ultimate (UDE) and Serviceability Earthquakes (SDE) on Systems Designed by Dual Approach; $\mu_{design} = 2$

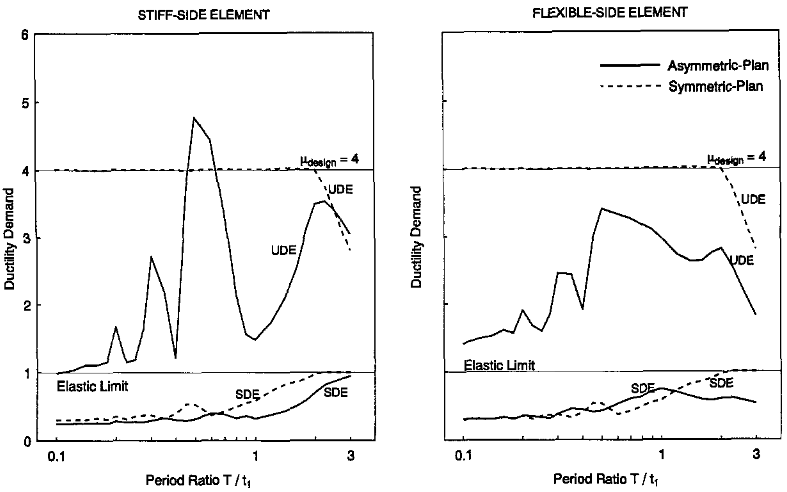

FIG. 10. Ductility Demands due to Ultimate (UDE) and Serviceability Earthquakes (SDE) on Systems Designed by Dual Approach; μ_{design} = 4

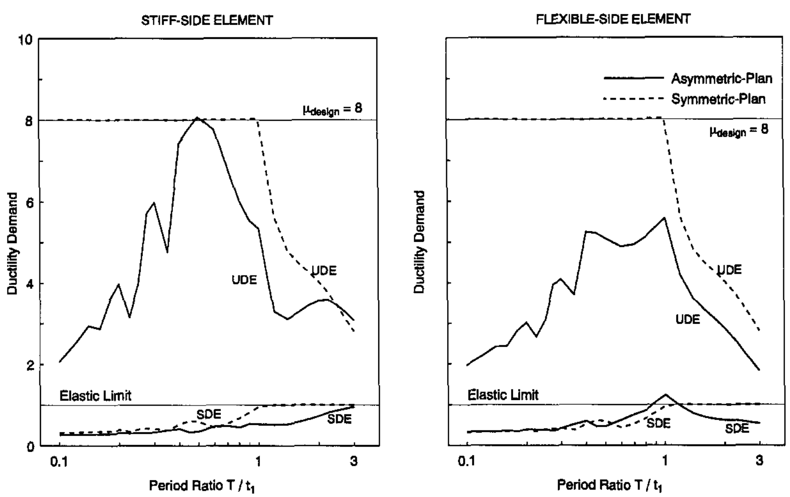

FIG. 11. Ductility Demands due to Ultimate (UDE) and Serviceability Earthquakes (SDE) on Systems Designed by Dual Approach; μ_{design} = 8; These Results Also Apply to Systems Designed by Extended Dual Approach

the design ductility and the demand due to the serviceability design earthquake is smaller than one. If the serviceability design earthquake controls the design force, the ductility demand imposed by this earthquake is equal to one, and the demand due to the ultimate design earthquake is smaller than the design ductility. Consistent with the results of earlier studies, these results indicate that the dual design approach alleviates the shortcomings of the single-limit-state-design approach for symmetric-plan systems.

The results for asymmetric-plan systems show that the ductility demands imposed by the ultimate design earthquake on structural elements of systems with large design ductility (μ_{design} = 8) are in general smaller than the design ductility, and all elements remain elastic during the serviceability design earthquake (Fig. 11). However, as the design ductility is reduced, there is an increasing tendency for the ductility demand imposed by the ultimate design earthquake becoming larger than the design ductility, e.g., the ductility demand on the stiff-side element exceeds the design ductility of 4 (Fig. 10). For very small values of design ductility (e.g., μ_{design} = 1 and 2), the ductility demands on the stiff-side as well as flexible-side element exceed the design value (Figs. 8 and 9). All the structural elements of such systems remain elastic during the serviceability-design earthquake.

The results presented so far indicate that the torsional provisions in U.S. seismic codes, used in conjunction with the dual-design approach, would satisfy the serviceability limit state; for ultimate limit state, however, these provisions may not be adequate for systems with lower values of design ductility. In particular, ductility demand may exceed the design ductility for such systems. This excessive ductility demand may be reduced by increasing the strength of the affected elements. The design eccentricity, which influences the strength of the structural elements in asymmetric-plan systems, should therefore be modified to provide additional element strength for the ultimate limit-state design. These modifications should recognize that the design eccentricity for the ultimate limit state should depend on the design ductility of the system, and would be different for the two limit states (Goel and Chopra 1990).

The trends observed in the preceding sections would apply, with minor differences, to systems designed according to *NBCC-90*, *MFDC-87*, and *NZC-92*. The differences would occur due to different strengths of structural elements in systems designed by these seismic codes. For example, the flexible-side element in systems designed by *NBCC-90* and *MFDC-87*, which have higher strength compared to *UBC-91*, would experience smaller ductility demand; the higher strength results from higher value of the coefficient α, controlling the strength of this element, in *NBCC-90* and *MFDC-87* (α = 1.5) compared to in *UBC-91* (α = 1). The ductility demand on the flexible-side element in systems designed by *NZC-92* and *UBC-91* would be similar because α = 1 in both codes. The stiff-side element would, however, undergo higher ductility demand in systems designed according to *NBCC-90*, *MFDC-87*, and *NZC-92* because of the reduction in the strength of this element resulting from nonzero values of the coefficient δ (δ = 0.5 in *NBCC-92* and 1 in *MFDE-87* and *NZC-92*); such reduction is precluded in *UBC-91*.

RESPONSE OF SYSTEMS DESIGNED BY EXTENDED DUAL DESIGN APPROACH

This section examines how the dual-design approach, proposed for symmetric-plan systems, can be extended to asymmetric-plan systems. In this extended approach, the design forces for structural elements are determined from (2) for each of the two limit states. For each limit state the base shear V is taken as the value for the associated symmetric-plan system; this base shear is obviously different for the two limit states. In contrast to the code approach and motivated by the earlier results, the values of design eccentricity e_d are also considered to be different for the serviceability and ultimate limit states, and for the latter it is considered to depend on the design ductility (Goel and Chopra 1990): the coefficients α and δ, which define e_d (3), are specified as α = 1 and δ = 1 for μ_{design} = 8; α = 1 and δ = -0.5

for μ_{design} = 4; α = 1.5 and δ = -0.5 for μ_{design} = 2; and α = 2 and δ = -0.5 for μ_{design} = 1; a value of α greater than 1 results in additional strength of the flexible-side element, whereas a negative value of δ leads to additional strength of the stiff-side element. For the serviceability limit state, the coefficients are specified as α = 1 and δ = 1. The design force for each element is determined for each limit state by (2), using the appropriate values of V and e_d. The yield force for the element is defined as the larger of the two design values, which is not allowed to be smaller than the symmetric-plan value. Since the accidental eccentricity is not included in designing the systems for the two limit states, β = 0 for each of these limit states. Note that the results for the design ductility of μ_{design} = 8 would remain the same as in Fig. 11 because the selected design eccentricities for the two limit state are identical and equal to that selected in Fig. 11; such being the case because no excess ductility demand was observed in Fig. 11. Unlike the results presented in the preceding sections, which are for systems designed by U.S. seismic codes, the results presented in this section are not tied to any particular code because the design eccentricities are selected to satisfy the design requirements of the two limit states and are not taken from any seismic code.

Figs. 11–14 show that ductility demands imposed by both earthquakes on both structural elements, flexible-side and stiff-side, of asymmetric-plan systems designed by the extended dual design approach remain within the design ductility during the ultimate design earthquake; and both the structural elements remain elastic during the serviceability design earthquake. Therefore, asymmetric-plan systems designed by the extended dual approach with the modified design eccentricity satisfy the design requirements for both limit states. The results for the symmetric-plan systems are unaffected (same as Figs. 8–11) because the design eccentricity for such systems is zero.

The results of Figs. 11–14 also show that, although the ductility demands imposed on structural elements of asymmetric-plan systems can be reduced below the demands on the associated symmetric-plan systems by modifying

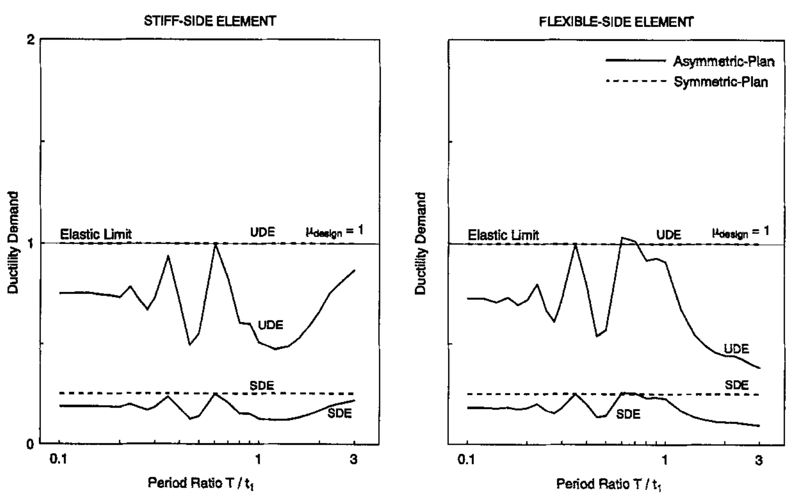

FIG. 12. Ductility Demands due to Ultimate (UDE) and Serviceability Earthquakes (SDE) on Systems Designed by Extended Dual Approach; μ_{design} = 1

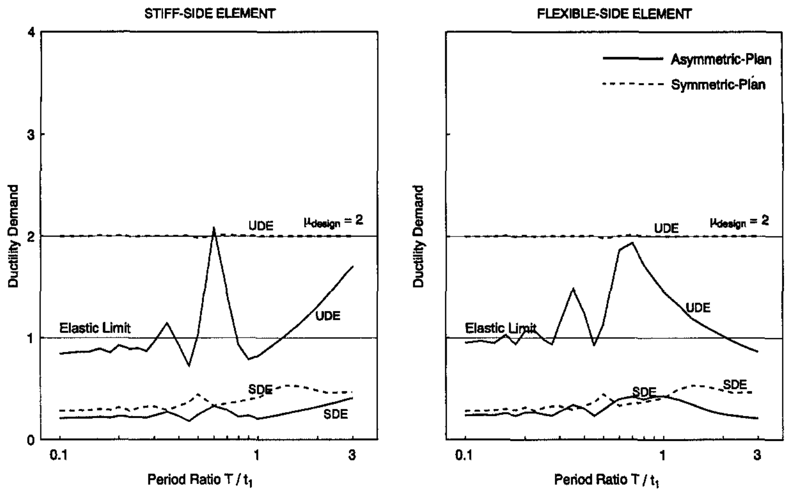

FIG. 13. Ductility Demands due to Ultimate (UDE) and Serviceability Earthquakes (SDE) on Systems Designed by Extended Dual Approach; $\mu_{\text{design}} = 2$

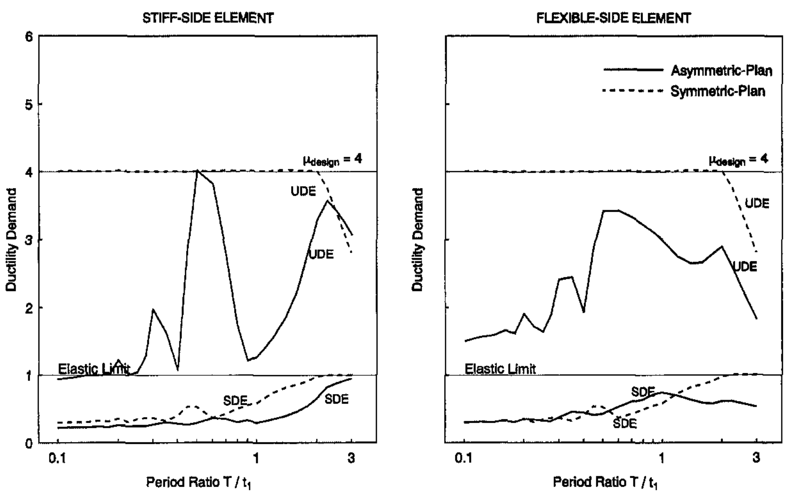

FIG. 14. Ductility Demands due to Ultimate (UDE) and Serviceability Earthquakes (SDE) on Systems Designed by Extended Dual Approach; $\mu_{\text{design}} = 4$

the design eccentricity values in the aforementioned manner, the difference between the ductility demands of the two systems depends on the vibration period of the system. It would seem that asymmetric-plan systems should be designed in such a way that ductility demands should be similar to the corresponding symmetric-plan system. The results of Figs. 12–14 indicate that, in order to achieve this goal, the design eccentricity should not only depend on the design ductility, as considered previously in this section, but also on the system vibration period. Furthermore, as mentioned previously, the design eccentricity may also depend on other system parameters: the stiffness eccentricity e_s, the torsional to lateral frequency ratio, Ω_θ; the system configuration in terms of distribution of strength and stiffness; and the ground motion.

To determine the optimal values of design eccentricity considering all of the aforementioned parameters, it would be necessary to solve an optimization problem for the values of design eccentricity with the objective function (or the constraint) that the ductility demand on structural elements of the asymmetric- and symmetric-plan systems be identical and equal to the design ductility. Clearly, such an optimization problem would involve a large number of variables and would require iterative numerical techniques since relationships between the ductility demands and some of the variables would not be known explicitly. Such an approach seems impractical for design applications.

More appropriate would be a simpler approach, wherein the objectives are relaxed and only require that the ductility demands imposed on structural elements of the asymmetric-plan system should not exceed the design ductility and the ductility demands imposed on the corresponding symmetric-plan system. This is equivalent to the requirement that the performance of the asymmetric-plan system is no worse than that of the symmetric-plan system. Using this simpler approach, as demonstrated in this section, the values of design eccentricity can be specified as a function of only the design ductility. However, for the purpose of generating generally applicable values of design eccentricity, it would still be necessary to vary the system parameters over a wide range and consider several earthquake ground motions.

CONCLUSIONS

This study on response of one-story, asymmetric-plan systems to moderate and intense ground motion indicates that the practice of specifying a single design earthquake and a single set of values for design eccentricity in most seismic codes does not satisfy the requirements of both, serviceability and ultimate, limit states. In particular, asymmetric-plan buildings designed for the ultimate limit state may not remain elastic during moderate ground motion resulting in structural damage and intense ground motion may impose ductility demand in excess of the design value causing excessive damage. On the other hand, buildings designed for the serviceability limit state may experience unrealistically high ductility demand during intense ground motion causing excessive damage, and may not remain elastic during moderate ground motion resulting in structural damage.

In order to alleviate these shortcomings of current seismic codes, the dual-design approach, proposed earlier for symmetric-plan systems, is extended to asymmetric-plan systems. In this extended dual-design approach, the design earthquake and the values of design eccentricity are considered to be different for the serviceability and ultimate limit states; for the latter, the values of design eccentricity depend on the design ductility. The results of this exploratory study show that asymmetric-plan systems designed by this extended dual design approach satisfy the requirements of both the limit states, i.e., they remain elastic during moderate ground motion and do not experience ductility demands in excess of the design value during intense ground motion.

The recommended values of design eccentricity for the two limit states were determined by a trial-and-error process for the purpose of demonstrating the concept of the extended dual design approach. These recommendations may not necessarily be applicable for other system parameters and other ground motions. For the purpose of generating generally applicable design recommendations, the system parameters should be varied over a wide range and several earthquake ground motions should be considered. Furthermore, the extended dual design concept presented here for one-story systems should be extended to multistory buildings.

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