Energy Based Approach to Earthquake Response of Asymmetric Systems

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Abstract

An energy based approach has been used to investigate the seismic behavior of code-designed, asymmetric-plan systems. The presented results demonstrate that the total input energy is about the same whether the system plan is symmetric or asymmetric. Furthermore, elements on the flexible-side in asymmetric-plan systems are more vulnerable compared to the same elements in symmetric-plan systems. The stiff-side elements, on the other hand, are expected to suffer no more damage in asymmetric-plan systems. This observation correlates well with the damage observed during several earthquakes.

Introduction

It has been well recognized that asymmetric-plan buildings are especially vulnerable to earthquake damage due to coupled lateral and torsional motions. The effects of such coupling and how well these effects are represented in seismic codes have been the subject of many investigations (e.g., Goel and Chopra, 1990; Tso and Wong, 1993). Most of these studies were based on the inelastic earthquake response of simple one-story systems and examined ductility demand on various resisting elements. These studies concluded that elements on the stiff-side in code-designed asymmetric-plan systems are likely to suffer more damage compared to the same element in the corresponding symmetric-plan system during earthquakes. The elements on the flexible-side, on the other hand, are expected to suffer no more damage. The observations of damage during the 1985 Mexico earthquake and 1995 Kobe earthquake, however, indicated otherwise. During these earthquakes, the flexible-side elements of many street-corner buildings suffered damage whereas the stiff-side elements remained intact. The contradictory observation clearly indicates that earthquake behavior of asymmetric-plan buildings is not yet well understood.

With the aim of improving our understanding of the earthquake behavior of asymmetric-plan buildings and with the goal of explaining the apparent contradiction between observations during earthquakes and findings of analytical studies, this study investigated how various energy quantities differ between the code-designed asymmetric- and symmetric-plan systems. It was found that hysteretic energy demands are much higher

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on the flexible-side elements whereas they are about the same on the stiff-side elements in code-designed, asymmetric-plan compared to symmetric-plan systems.

System Considered

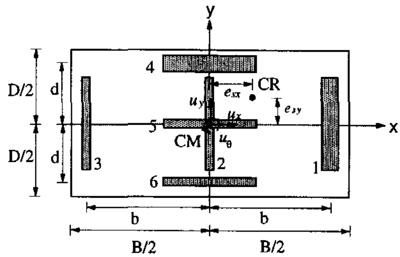


Fig. 1. Idealized one-story system.

The system considered was the idealized one-story building of Fig. 1. This system consisted of a rigid deck supported on three structural elements in each of the two orthogonal directions. The structural elements were frames or walls having strength and stiffness in their planes only. The mass properties of the system were assumed to be symmetric about both the x- and y-axes. As a result, the center of mass (CM) of the system coincided with its geometric center. The stiffness properties of the system were, however, not symmetric about the geometric center. This lack of symmetry was characterized by the stiffness eccentricities, e_{sx} and e_{sy}, defined as x- and y- components of the distance between the CM and the center of rigidity (CR), respectively.

Ground Motions

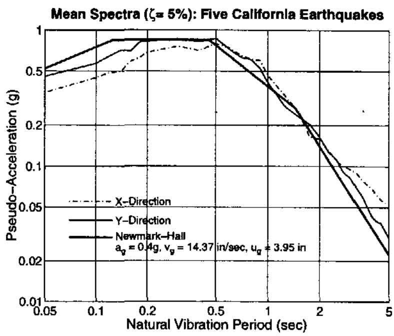


Fig. 2. Mean 5% damped spectra of recorded motions and Newmark-Hall design spectrum.

Five pairs of earthquake records, obtained from rock sites in California, were considered in this investigation as input ground motion for the inelastic response analysis. These records were selected because their elastic response spectra were similar to each other and to the Newmark-Hall design spectrum. All the records were scaled to 0.4g peak acceleration, which was also the peak acceleration used for design of the system considered.

Fig. 2 shows the mean 5% spectra in the x- and y-directions of the ensemble of records. Also included in this figure is the mean Newmark-Hall design spectra constructed for 5% damping and peak values of ground acceleration = 0.4g, velocity = 36.5 cm/sec (14.37 in/sec), and displacement = 10 cm (3.75 in). The values of the ground velocity and displacement used for constructing the Newmark-Hall spectrum were the same as the average values for the five y-components (scaled first to peak acceleration on 0.4g) of the earthquake records considered in this study.

System Design

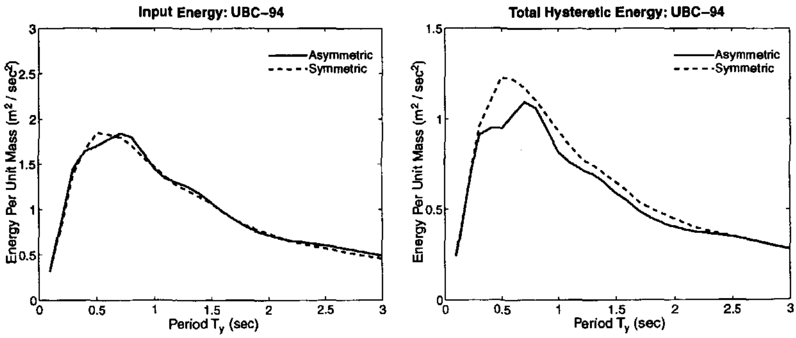
The systems were designed using base shear coefficient from the Newmark-Hall design spectra with a reduction factor of four (to account for the capacity of the system to undergo inelastic deformation due to ductility) in conjunction with the torsional provisions of UBC-94 (*Uniform Building Code*, 1994). Accidental eccentricity was considered for the design of asymmetric-plan system but was excluded for the reference symmetric-plan system. Furthermore, the systems were designed for both components of ground motions acting simultaneously. The combination rule proposed by Wilson et al. (1995) was used for this purpose. Since UBC-94 does not permit reduction of forces due to torsion, the final design force in each resisting element was selected to be equal to at least that in the same element of the reference system.

System Parameters

The parameters of the selected system that were fixed are: uncoupled torsional to lateral frequency ratio, $\Omega_\theta = 1$; ratio of uncoupled translational frequencies in the x- and y-directions, $\Omega_x = 1$; ratio of torsional stiffness provided by x-directional elements to the total torsional stiffness, $\gamma_x = 0.5$; stiffness eccentricities in the two directions normalized by the respective system plan dimensions, $\bar{e}_{sx} = \bar{e}_{sy} = 0.3$; aspect ratio, $\eta = 1$; and damping ratio in each of the first two modes of vibration = 5%. The yield strengths of the resisting elements were computed according to the code torsional provisions. The force-deformation behavior of each resisting element was selected as elasto-plastic with 3% post yield strain hardening.

Energy Spectra

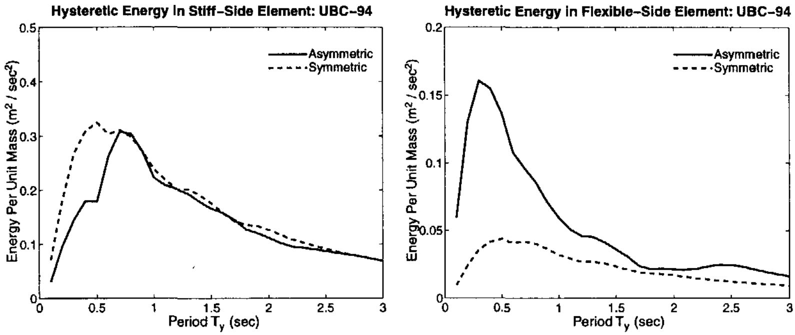
In order to evaluate how plan asymmetry affects the relative seismic input energy and total energy dissipated by all resisting elements, the spectra for these energy quantities are compared for the asymmetric-plan systems with those of the reference system. The mean spectra for the energy quantities are presented in Fig. 3. These results show that total energy input to the asymmetric-plan system is about the same as that to the reference system for the entire period range. The hysteretic energy, however, is slightly smaller for the asymmetric-plan system. This is especially so for systems with period longer than 0.4 sec.



(a) (b)

Fig. 3. Energy spectra for systems designed according to UBC-94: (a) Input energy and (b) Hysteretic energy.

The results of Fig. 3 provide an important clue to understanding the behavior of asymmetric-plan systems, that is, earthquakes do not necessarily impart more seismic energy or impose higher hysteretic energy dissipation demands on asymmetric-plan systems compared to their symmetric counterparts. Therefore, the higher vulnerability of asymmetric-plan systems during earthquakes, evident either from data collected on building damage during actual earthquakes (Whittaker et al., 1995; Esteva, 1987) or from analytical studies (e.g., Goel and Chopra, 1990) appear to be related to how the total hysteretic energy is dissipated by various resisting elements. In order to further investigate this issue, the spectra of hysteretic energy were also generated for the individual elements and are presented in Fig 4. These results lead to the following conclusions.



(a) (b)

Fig. 4. Hysteretic energy spectra for resisting elements of systems designed according to UBC-94.

In the short-period range, the stiff-side element of an asymmetric-plan system experiences much smaller hysteretic energy demand compared to the reference system. In the mid-period range, however, the demands are comparable for the two systems. The demand on the flexible-side element of an symmetric-plan system is higher than the symmetric-plan system for the entire period range, with the difference being particularly large in the short-period range. These trends indicate that the flexible-side elements in a short-period asymmetric-plan system will experience significantly more damage whereas stiff-side elements may undergo no more damage compared to the same element in the corresponding symmetric-plan system.

The results presented so far indicate that in order to prevent earthquake damage, flexible-side elements should possess larger energy dissipation capacities (to meet higher demands) in asymmetric-plan system compared to the same element in the symmetric-plan system. Therefore, codes should provide detailing guidelines for asymmetric-plan buildings that would ensure enough energy dissipation capacity to meet the demand. Clearly, these guidelines have to be more stringent for asymmetric-plan systems compared to symmetric-plan systems.

The above results lead to the conclusion that elements on the flexible-side of asymmetric-plan buildings are especially vulnerable to earthquakes. This conclusion is in agreement with the observations of damage in street-corner buildings during the 1985 Mexico and the 1995 Kobe earthquakes when significant damage occurred in elements located on the street-side face (that is, flexible-side) of many such buildings (Esteva, 1987; Whittaker et al., 1995). This suggests that failure in street-corner buildings were due to lack of energy dissipation capacity in flexible-side (or street-face) elements.

Conclusions

This investigation on inelastic seismic response of code-designed, asymmetric-plan systems subjected to two components of ground motion has led to the following conclusions.

1. The total energy input to the system is about the same whereas the total hysteretic energy dissipated by all elements is slightly smaller for the asymmetric-plan system compared to the corresponding symmetric-plan system.

2. The flexible-side elements undergo much larger hysteretic energy demand in asymmetric-plan system compared to the corresponding symmetric-plan systems. The stiff-side elements, on the other hand, do not necessarily experience any larger hysteretic demands in asymmetric-plan systems.

3. The damage observed to many street-corner buildings during the 1985 Mexico and 1995 Kobe earthquakes correlates well with the conclusion based on the hysteretic-energy demand which show that that flexible-side elements are more vulnerable due to higher energy dissipation demands.

4. Building codes should provide detailing guidelines for asymmetric-plan buildings that would ensure enough energy dissipation capacity to meet the demand. These guidelines should be more stringent for asymmetric-plan systems compared to symmetric-plan systems.

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