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EFFECT OF FLOOR IN PLANE FLEXIBILITY ON THE RESPONSE OF TORSIONALLY UNBALANCED SYSTEMS

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SUMMARY

This work presents the results of an analytical study on the seismic response of simple torsionally-unbalanced systems with in-plane flexible diaphragms. The typical system used consists of a linear-elastic flexible diaphragm supported on four lateral resisting elements (two along each principal direction). The system has eccentricity in one direction only. The initial lateral periods along both principal directions are equal. The study covers systems with four values of diaphragm flexibility, three values of seismic-force reduction factor, and ten initial lateral periods. One eccentricity value is considered only. Systems are subjected to a set of ten firm-soil bidirectional seismic records. Results indicate that increasing in-plane floor flexibility leads to a reduction of frame displacements for systems with initial period of vibration $T > 0.4$ s. For systems with $T \leq 0.4$ s, increasing in-plane floor flexibility can lead to significant frame displacement increments (50% higher). Results show that these displacement variations decrease for increasing values of both the seismic-force reduction factor and the initial lateral period.

INTRODUCTION

Floor in-plane stiffness plays an important role in distributing seismic forces to lateral-resisting elements. In most cases, the assumption of rigid floor allows a significant reduction of computational effort in the structural analysis of buildings. In some cases, however, structural configurations with large spans between lateral-resisting elements can invalidate the use of the rigid-floor assumption. For these cases, diaphragm flexibility must be considered in the analysis. Moreover, in the case of plans with irregular distributions of mass or stiffness, torsional unbalance can exacerbate the effects of floor flexibility.

The dynamics and the seismic response of systems with flexible diaphragms has been studied before. For instance, Goldberg and Herness [1965] studied torsionally-balanced (TB) framed structures with both diaphragm and lateral-resisting elements assumed linear-elastic. The effect of in-plane floor flexibility on the dynamic properties of symmetric TB linear-elastic buildings was also studied by Shepherd and Donald [1967], who concluded that neglecting in-plane floor flexibility does not significantly change the dynamic properties of symmetric buildings. Jain [1984] studied the dynamic properties of narrow symmetric TB linear-elastic buildings. He showed that for long narrow buildings with equal frames and floors, as well as equal masses lumped at the intersections of floors and frames, the vibration modes that include in-plane floor deformations are not excited by the ground motion. Similar results were reported by Jain and Jennings [1985].

Using nonlinear models for the slab and the lateral-resisting elements, Kunnath et al. [1991] studied the effect of in-plane floor flexibility on the seismic response of buildings with end walls. They showed that floor flexibility imposes larger demands (displacements and forces) on flexible frames. Their study, however, did not cover explicitly the in-plane floor flexibility effect on the torsional response of buildings.

Saffarini and Qudaimat [1992] studied the error bounds that result when the assumption of rigid diaphragm is used in linear-elastic buildings with several plan configurations. They concluded that, for framed buildings, a

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rigid-floor assumption leads to almost the same results than those computed with a flexible-floor assumption; however, for buildings with shear walls error can result from using the rigid-floor assumption. They also found that the magnitude of the error resulted to be a function of the ratio of the in-plane floor stiffness to the lateral-resisting system stiffness. A similar study by Ju and Lin [1999] considered linear-elastic TB buildings with shear walls. Their work was focused to obtain statistically a formula to estimate the difference in peak column forces between rigid-floor and flexible-floor systems.

Torsionally-unbalanced (TU) linear-elastic systems with flexible diaphragms were studied by Tena-Colunga and Abrams [1996]. They concluded that torsion effects can be significantly reduced when in-plane floor flexibility increases. They also concluded, however, that diaphragm and shear wall accelerations can increase with diaphragm flexibility in some cases.

It can be observed that most of the previous work assumes linear-elastic lateral-resisting elements and torsionally-balanced systems subjected to unidirectional ground motions. The objective of this paper is to understand the effects of in-plane floor flexibility on torsionally-unbalanced systems subjected to bidirectional earthquake records. In this study, lateral-resisting elements are assumed nonlinear.

STRUCTURAL MODELS

For the present study, simple models consisting of a rectangular floor or diaphragm supported on four frames is used (Figure 1). The diaphragm has plan dimensions a and b, with b = 2a. The Y-direction frame 1 is assumed stiffer than frame 2 and, therefore, the center of stiffness (CS) is located to the left of the diaphragm geometric center. Frame 3 is assumed identical to frame 4. For a mass uniformly distributed on the floor, the system is torsionally unbalanced along the Y-direction. Total initial stiffnesses and periods along both principal directions are equal.

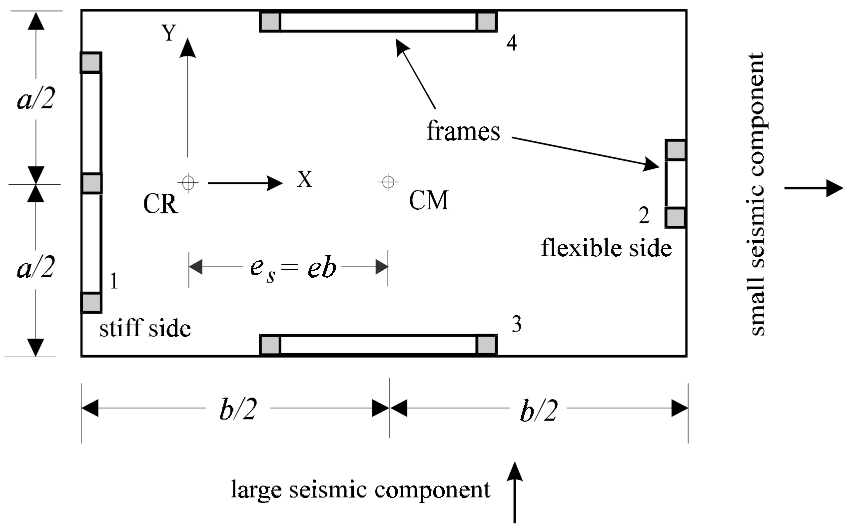

Figure 1. Structural model and earthquake components

As for the diaphragm, it is idealized with 16 four-node plane-stress finite elements (Figure 2). Four values of in-plane floor flexibility are considered by using the parameter rax = 100Et/(E0b), where E = modulus of elasticity, t = thickness, E0 = reference modulus of elasticity, and b = largest diaphragm side. Assuming t = b/100 for all cases, the diaphragm flexibility is controlled in the analysis with the value of the modulus of elasticity, i.e, E = E0 rax. For the present study, the following values are selected: E0 = 200,000 Kg/cm2 and rax = 1.0, 0.1, 0.01, and 0.001. The value rax = 1.0 is used here as the rigid-diaphragm case. As a reference, b = 10 m and rax = 1.0 could correspond to a 10 cm-thick reinforced concrete floor. By comparison, rax = 0.01 could correspond to a 3/4”-thick wooden floor.

Lateral-resisting elements (frames) are assumed to have a hysteretic behavior defined by the Clough-Otani model [Otani, 1981] with a stiffness-degradation coefficient αc = 0.4. The yield force of each frame was determined using the typical static design process based on the application of seismic forces at design eccentricities, relative to the center of stiffness. Design eccentricities ed are usually defined with the following formulas [Goel and Chopra, 1990]

$$ed1 = \alpha es + \beta b = \alpha es + ea \quad [1]$$

$$ed2 = \delta es - \beta b = \delta es - ea \quad [2]$$

where ea is the accidental eccentricity and α, β, and δ are torsion design factors. Here, $\alpha = 1.5$, $\beta = 0.0$, and $\delta = 0.0$ were selected. The post-yield stiffness in the hysteretic model was assumed equal to 5% of the initial stiffness for all frames.

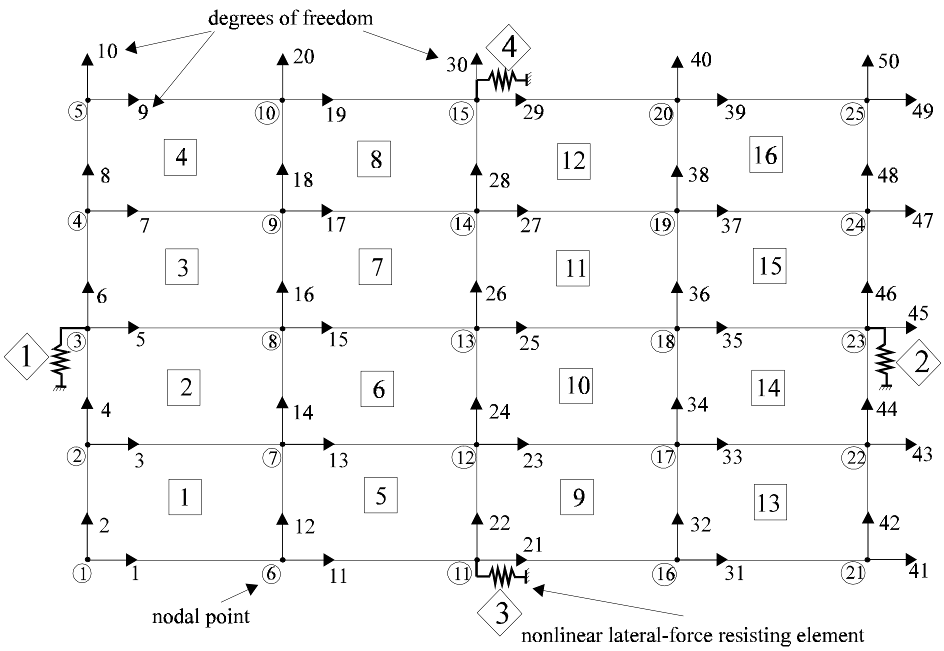

Figure 2. Model idealization using linear-elastic finite elements and nonlinear springs

Seismic design forces along each direction were obtained with a design spectrum like that presented by Newmark and Hall [1982]. For the Y-direction, the design spectrum was scaled to a peak ground acceleration (PGA) of 1g. For the X-direction, the design spectrum was scaled to a PGA of 0.64g. This value corresponds to the average of the PGAs of the scaled X-direction earthquake records used in this study. Both design spectra are shown in Figure 3.

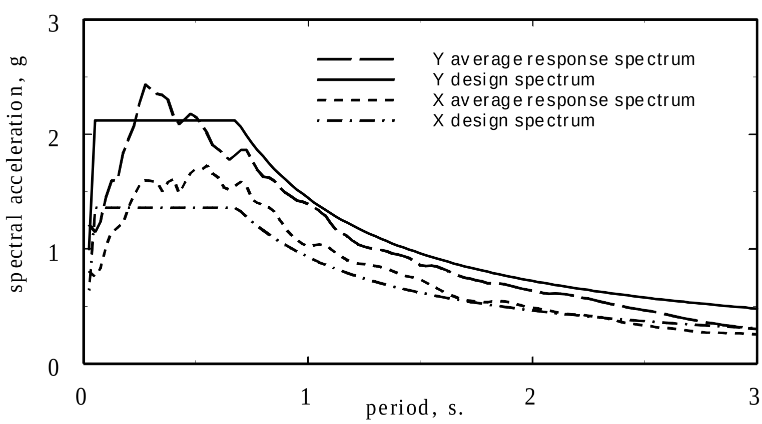

Figure 3. Design and average response spectra

In order to simplify the analysis, the consistent mass matrix of the floor was diagonalized according to the scheme recommended by Hinton et al. [1976]. A mass per unit volume of 1 t-s2/m4 was used in all cases and a Rayleigh damping of 5% was included using two selected frequencies (π and 60π). In this paper, results are reported for systems designed with three values of seismic-force reduction factor (R = 1,3, and 6) and ten initial lateral periods (T = 0.2, 0.4, ..., and 2.0 s). All initial lateral periods are computed with a rigid-floor assumption. A normalized eccentricity e = 0.20 is used for all systems.

SEISMIC RECORDS AND RESPONSE COMPUTATION

Each structural system was analyzed for a set of ten pairs of seismic records corresponding to firm soil (Table 1). For each pair, the component with the largest PGA was scaled to 1g and it was applied along the Y-direction (Figure 1). The perpendicular component was scaled with the same scale factor and it was applied along the X-direction. Figure 3 also shows the average response spectra of the scaled ground motions computed with a viscous damping of 5%. The response was computed with the constant-acceleration step-by-step method and the modified Newton-Raphson algorithm, both described in Chopra [1995].

Table 1. Earthquake ground motions

Earthquake	Station	Components	Duration used (s.)	Peak recorded ground acceleration
Imperial Valley, May/18/1940	El Centro	S90W, S00E	20	0.21g, 0.35g
Kern County, July/21/1952	Santa Barbara	N42E, S48E	20	0.09g, 0.13g
México (Mich.), Sept/19/1985	La Unión	EW, NS	60	0.15g, 0.17g
México (Mich.), Sept/19/1985	Papanoa	EW,NS	60	0.12g, 0.17g
San Salvador, Oct/10/1986	Nat. Inst. of Geo.	NS,EW	20	0.40g, 0.53g
San Salvador, Oct/10/1986	Geo. Res. Center	NS, EW	8	0.42g, 0.69g
Loma Prieta, Oct/17/1989	Corralitos	EW,NS	20	0.48g, 0.63g
Loma Prieta, Oct/17/1989	Presidio	NS, EW	20	0.10g, 0.20g
Northridge, Jan/17/1994	Sylmar/Hospital Park.	EW, NS	20	0.60g, 0.84g
Northridge, Jan/17/1994	S. Mónica/City Hall G.	NS, EW	20	0.37g, 0.88g

RESULTS

In this work, the response parameters used to study the diaphragm flexibility effects are the averages of the peak displacements of frames 1, 2, and 3 (or 4), taken with respect to the ten ground motions. In order to appreciate the effect of floor flexibility, these displacement averages are normalized with respect to the values computed for rax = 1.0 (assumed as the rigid-floor case). Normalized displacements are denoted with the letter v.

The normalized average of the peak displacements for the stiff-side element (v1) is considered first. Figure 4 shows relationships of this displacement in terms of the initial lateral period of systems with e = 0.20. Each one of these graphs corresponds to systems designed with different values of the seismic-force reduction factor R. As indicated before, the most flexible diaphragm considered corresponds to rax = 0.001, while the stiffest one corresponds to rax = 1.0. Plots in these three graphs show that increasing values of the floor flexibility lead to decreasing peak displacement averages (PDAs) of frame 1 for almost all periods considered and for all values of R used. However, significant PDA increments (up to 50%) can be observed for short-period systems (say $T \leq 0.4$ s). These graphs also shows that the effects of in-plane floor flexibility seem to decrease for increasing values of both the seismic force-reduction factor R and the initial lateral period of vibration T. The reduction of in-plane flexibility effects for increasing values of R and T is due to the increment of the ratio of the in-plane floor stiffness to the system lateral stiffness, as noted previously by Saffarini and Qudaimat [1992].

Figures 5 and 6 show the averages of peak displacements, normalized with respect to those obtained for rax = 1.0, for the flexible-side and the X-direction elements. The observed trend is similar to that observed for the stiff-side element, i.e., PDAs decrease for increasing in-plane floor flexibility for almost all periods considered. Again, some significant PDA increments are observed for short periods. The effect of in-plane floor flexibility is reduced with increasing values of R and T.

CONCLUSIONS

This study on simple torsionally-unbalanced systems subjected to bidirectional firm-soil earthquake records leads to the following conclusions. The peak displacement averages (PDAs) of lateral-resisting elements (frames) decrease for increasing in-plane floor flexibilities of systems with medium-to-large initial lateral periods ($T > 0.4$ s). The PDA of these elements increases (up to 50% higher) for systems with short initial periods ($T \leq 0.4$ s). In all cases, the in-plane floor flexibility effect decreases for increasing values of the seismic-force reduction factor R and the initial lateral period of vibration T.

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