INFLUENCE OF BIDIRECTIONAL SEISMIC MOTION ON THE RESPONSE OF ASYMMETRIC BUILDINGS

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SUMMARY

The influence of bi-directional action of serviceability design earthquakes in the elastic response of one-story asymmetric buildings is investigated in this paper. Global response parameters are examined but the emphasis is directed to the displacement response of the resisting elements of the building plan. It is shown that the simultaneous application of two horizontal seismic components is very important for an accurate determination of the response, mainly for certain relations of the lateral stiffness in the two orthogonal directions of the plan. It is recommended that seismic codes impose the simultaneous application of the two horizontal components of seismic motion, in order to reach an adequate design for serviceability earthquakes and avoiding premature incursions in the inelastic range.

INTRODUCTION

Even though modern studies have emphasized the inelastic torsional response of buildings, the elastic response to minor seismic motions is also a matter of concern in order to satisfy serviceability design conditions [SEAOC, 1995; Goel and Chopra, 1994; Chandler and Duan, 1997]. It is known that some conditions which increase the elastic response can as well increase the inelastic one [Wong and Tso, 1994; De la Llera and Chopra, 1994; De Stefano et al, 1998]. Therefore, the identification of parameters that influence the torsional elastic response can at least accomplish two objectives: a) to improve accuracy in the design for serviceability earthquakes, and b) to direct further research about the torsional inelastic response under major seismic motions. The global elastic response of one-way asymmetric systems has been widely studied for translational seismic motions. Although some references can be mentioned, the elastic response of resisting elements [Dempsey and Tso, 1982; Hegal and Chopra, 1987; Hernandez and López, 1977] and two-way asymmetric buildings [Boroschek and Mahin, 1991; Ozaki et al, 1994; Hernández, 1997] have received less attention. However, it must be pointed out that maximum displacements of the resisting elements are the fundamental variable which support the design of common structural subsystems. Furthermore, buildings will be subjected to multidirectional seismic motion and in some way its plan may have asymmetry, nominal or accidental, in both principal directions. The objective of this paper is to investigate the influence of the simultaneous action of two horizontal seismic motions on the response of one-story asymmetric buildings, with an emphasis on the response of the resisting elements. Detailed results are given by Hernández, 1997.

SYSTEMS, GROUND MOTIONS AND METHOD OF ANALYSIS

The one-story elastic building (Figure 1) has an in-plane rigid diaphragm with mass m and rotational mass j=mr2. The main axes {X,Y}, the center of rigidity {C.R.} and the center of mass (C.M.) are indicated in the figure. The system may have one or two eccentricities {ex,ey}, which lead to one-way asymmetric or two-way asymmetric plans, respectively. We only admit mass movements in the horizontal plane: Two translations and a rotation about a vertical axis. This model may be considered representative of the response of certain class of

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multi-story buildings [Kan and Chopra, 1976]. The system parameters are expressed in a dimensionless form by means of the normalized eccentricities $\varepsilon_x=e_x/r$, $\varepsilon_y=e_y/r$, and the frequency ratios $\Omega_\theta=\omega_\theta/\omega_y$ and $\Omega_x=\omega_x/\omega_y$, being ω_θ,ω_y and ω_x the uncoupled frequencies of the ideal system in which the C.R. and the C.M. coincides, but keeping the rest of the calculated properties with respect to the C.M. A damping ratio of 2% is considered. The radius of gyration of the floor about a vertical axis at the C.M. is denoted by r. The dimensionless parameters $\delta_1=-1.6$ and $\delta_2=1.6$ (Figure 1) represent approximately the extremes planes in direction Y of a plan having the C.M. located in the geometric center and an aspect ratio b/a=2.4. For each seismic excitation the maximum modal responses are combined by the complete quadratic combination rule, adopting the RE correlation coefficient [Rosenblueth and Elorduy, 1969], simplifying it for the case of equal damping in each mode and long duration seismic motions [Kan and Chopra, 1976). The alternative of using the DK correlation coefficient [Der Kiureghian, 1981; Wilson et al, 1981] practically leads to the same results as was numerically verified for the series of results given in this paper. Furthermore, it can be demonstrated {Hernández, 1997] that the quotient between both coefficients is given by:

$$C_{ij,DK}/C_{ij,RE}=\left(\frac{2\sqrt{a_{ij}}}{1+a_{ij}}\right)^3\leq 1 \qquad (1)$$

where $a_{ij}=\omega_i/\omega_j$ being ω_i and ω_j the vibration frequencies of the i and j modes. It can be observed that the ratio given by Eq. 1 is independent of damping and differs very little from 1 for the a_{ij} values near 1 that are the important ones. Traslational seismic motions of the base are idealized by a flat elastic response spectra. Excitation in one direction as well as simultaneous excitation in two orthogonal directions are considered; they are assumed to be of equal intensity and uncorrelated.. Since both ground components have identical spectrum, then the response is independent of the angle of incidence [Lopez and Torres, 1997]. Hence the reference directions X and Y of the plan are appropriate for design under bidirectional seismic motions of equal intensity. The maximum responses obtained for the seismic excitation in each direction are combined by the SRSS rule.

RESPONSE OF RESISTING ELEMENTS IN ONE-WAY ASYMMETRIC SYSTEMS

The response of a resisting element at $d_p=\pm1.225r$ of one-way asymmetric systems (Figure 1) is examined next. The normalized displacement μ_P is defined as the quotient between the maximum displacement of the perpendicular (X) elements located at a distance d_p from the C.M. and the corresponding displacement of the ideal symmetric plan due to earthquake in direction Y (Figure 1). The results shown in Figure 2 point out that the displacements μ_P can be very large for large eccentricities and/or small torsional stiffness, getting to overcome the displacements of the ideal symmetric plan. For evaluating the significance of the action of simultaneous earthquakes (X,Y), we adopt equal values for the lateral stiffness k_x and k_y. The response values for the resisting elements located at $d_p=\pm1.225r$, are shown in Figure 3. Values of $\mu_P=1$ represent the practical case of design when only a single seismic component in the direction of the resisting elements is considered; values of $\mu_P>1$ measure the importance of the simultaneous application of seismic motions X and Y. It can be observed in Figure 3 that even for moderate eccentricities like e/r=0.2 we may have increments of about 40% when the frequency ratio Ω_θ is near 1 which is a relatively common situation in design. Even for small eccentricities the increments are significant when Ω_θ is close to 1. Evidently, if Ω_θ gets near ε the increments can be considerably greater; for example if $\varepsilon=0.4$, the condition $\Omega_\theta=0.8$ duplicates the unitary displacement and $\Omega_\theta=0.6$ triplicates it. It can be concluded that the design practice should incorporate in the analysis the action of two perpendicular simultaneous seismic motions in order to avoid premature incursions into the inelastic range for serviviability seismic motions.

GLOBAL RESPONSE OF TWO-WAY ASYMMETRIC SYSTEMS

The torsional response (T) is defined in terms of the overall amplification coefficient τ , $T=\tau eV_0$ where τ is the amplification of the total eccentricity $e=(e_x^2+e_y^2)^{1/2}$. The shear force generated in direction X is evaluated by υ_x , being $V_x=\upsilon_xV_0$. Next a parametric variation is presented, considering three different values of the lateral stiffness ratio $K_x/K_y=$ 0.5, 1 and 2, and several values of the frequency ratio Ω_θ and the eccentricity e_x/r. The other eccentricity e_y/r is fixed to 0.2. The systems are analyzed for the simultaneous action of seismic components X and Y. Results are shown in Figure 4. We observe a greater similarity of the τ values for the three cases considered of k_x/k_y , besides the presence of two amplification peaks when the eccentricitiy is small, corresponding to the proximity of the two lateral to the torsional uncoupled frequencies. The maximum values of τ are somewhat greater than 3, for small e/r, in the same order as for one-way asymmetric buildings when e/r=0.2 [Kan and Chopra, 1976]. It is interesting to observe that the value of Ω_θ for the peaks, correspond to the proximity of the uncoupled lateral frequencies with the corresponding torsional frequency and therefore depends on the relations of lateral stiffness. When k_x/k_y =1 the maximum is in the proximity of $\Omega_\theta = 1$, since $\omega_\theta \cong \omega_x \cong \omega_y$ When $k_x/k_y = 0.5$ there is tendency for two local maxima, one about $\Omega_\theta \cong 1$ for the case $\omega_\theta \cong \omega_x$ and other toward $\Omega_\theta \cong 0.7 \cong (0.5)^{1/2}$ since in this case $\omega_\theta \cong \omega_x \cong 0.7\ \omega_y$. Similarly, when k_x/k_y =2, one peak is for $\Omega_\theta \cong 1$ for the case $\omega_\theta \cong \omega_y$, and other towards $\Omega_\theta \cong 1.4 \cong 2^{1/2}$ for the case $\omega_\theta \cong \omega_x \cong 1.4\omega_y$.The values of υ_x express a similar pattern but emphasizing more the implications of the case in which $\omega_\theta \cong \omega_x$. These patterns could not be identified when considering a single seismic component and defining the amplification coefficient τ in terms of the eccentricity perpendicular to the earthquake direction [Kan and Chopra, 1976; Hernandez, 1997].

RESPONSE OF RESISTING ELEMENTS IN TWO-WAY ASYMMETRIC SYSTEMS

The normalized displacement μ is defined as the maximun displacement divided by the corresponding displacement of the ideal symmetrical building. Figure 5 shows the values of μ for the stiff and flexible edges in direction Y (Figure 1) of two-way asymmetric plans with eccentricity $e_y/r=0.2$, for the three relations of lateral stiffness $k_x/k_y=0.5$, 1 and 2, under the action of a single component of seismic excitation Y. Figure 6 presents results in terms of the parametert η defined as the ratio between the μ values obtained under the simultaneous action of both X and Y seismic components, and the μ values corresponding to the Y component given in Figure 5, for the stiff and flexible edges along direction Y. The response parameter η measures the significance of the simultaneous application of two horizontal ground motions. A value of $\eta=1$ means that a single seismic component is enough to quantify the response. In Figure 6 we kept the same value of $e_y/r=0.2$. The results shown in Figure 6 point out significant increments in the displacements even for moderate eccentricities and high torsional stiffness. For example, for $e_x/r=0.2$ and $\Omega_\theta \cong 1.3$ the increments are larger that 50% when k_x/k_y =2. The largest influence occurs for low torsional stiffness, particularly when the orthogonal lateral stiffness is small. The local maximums can be identified in some cases, corresponding to the proximity of modal frequencies; when the eccentricities are small these local peaks are: a) in the proximity of $\Omega_\theta=0.7$ if k_x/k_y =0.5 or $\Omega_\theta = 1.4$ if $k_x/k_y = 2$, corresponding to $\omega_\theta \cong \omega_x$; b) in the proximity of $\Omega_\theta=1$ for all values of k_x/k_y , corresponding to $\omega_\theta \cong \omega_y$.

CONCLUSIONS

a) When the torsional moment is quantified in terms of the total eccentricity of two-way asymmetric buildings subjected to bidirectional seismic motion, the resulting generalized forces allow to identify properly the importance of the system parameters that influence the seismic response. This behavior is not evidenced when considering the action of a single seismic component and using the eccentricity perpendicular to it.

b) The incorporation of simultaneous horizontal seismic components has a significant effect in the displacements of the resisting elements, in relation to the values obtained for a single seismic component. These increments in displacements depend on the eccentricities in both directions and the relation of lateral stiffness. These effects can be significant, even for small orthogonal eccentricities. Increments larger than 50% are observed at the stiff edge for eccentricities $e_x/r=e_y/r=0.2$ and a large value of the torsional stiffness, for a lateral stiffness ratio of 2. These effectes are more significant in the common situation of building plans having similar lateral stiffness in its orthogonal directions. It is concluded that the simultaneous action of the two horizontal seismic components should be considered in the analysis of one-way and two-way asymmetric plans in order to avoid incursions in the inelastic range and hence to reach an adequate design for serviceability conditions..

d) Recently, bidirectional seismic motion has been shown to have a significant influence on the ductility demands of one-way asymmetric plans [De la Llera and Chopra, 1994; De Stefano et al, 1998]. Such results are similar to the ones obtained in this paper for elastic responses. It is expected that further inelastic studies that additionally take into account the condition of two-way asymmetry under bidirectional seismic motion, will confirm the general importance of this condition which is "accidentally" inevitable.

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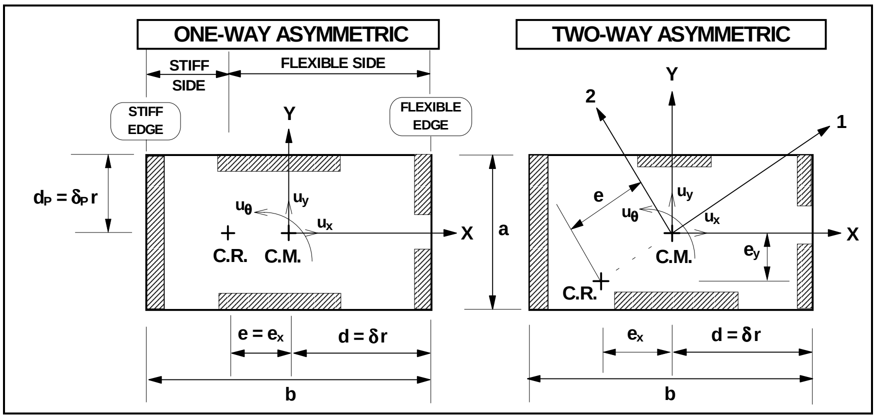

Figure1: One-story building models.

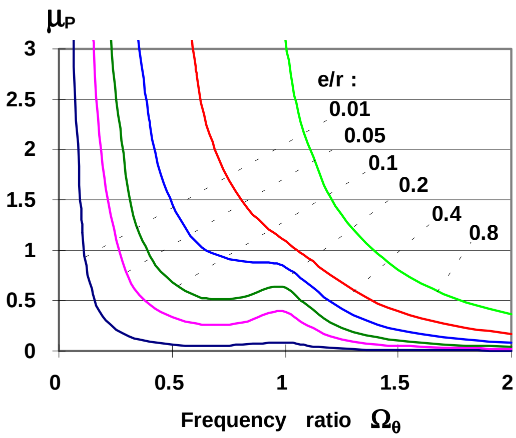

Figure 2: Normalized displacement at the orthogonal resisting element (X) of one-way asymmetric systems subjected to seismic motion in the asymmetric direction (Y).

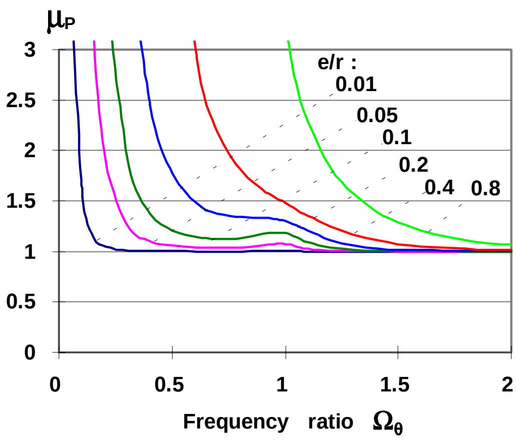

Figure 3: Normalized displacement at the orthogonal resisting element (X) of one-way asymmetric systems subjected to bidirectional seismic motion (X and Y).

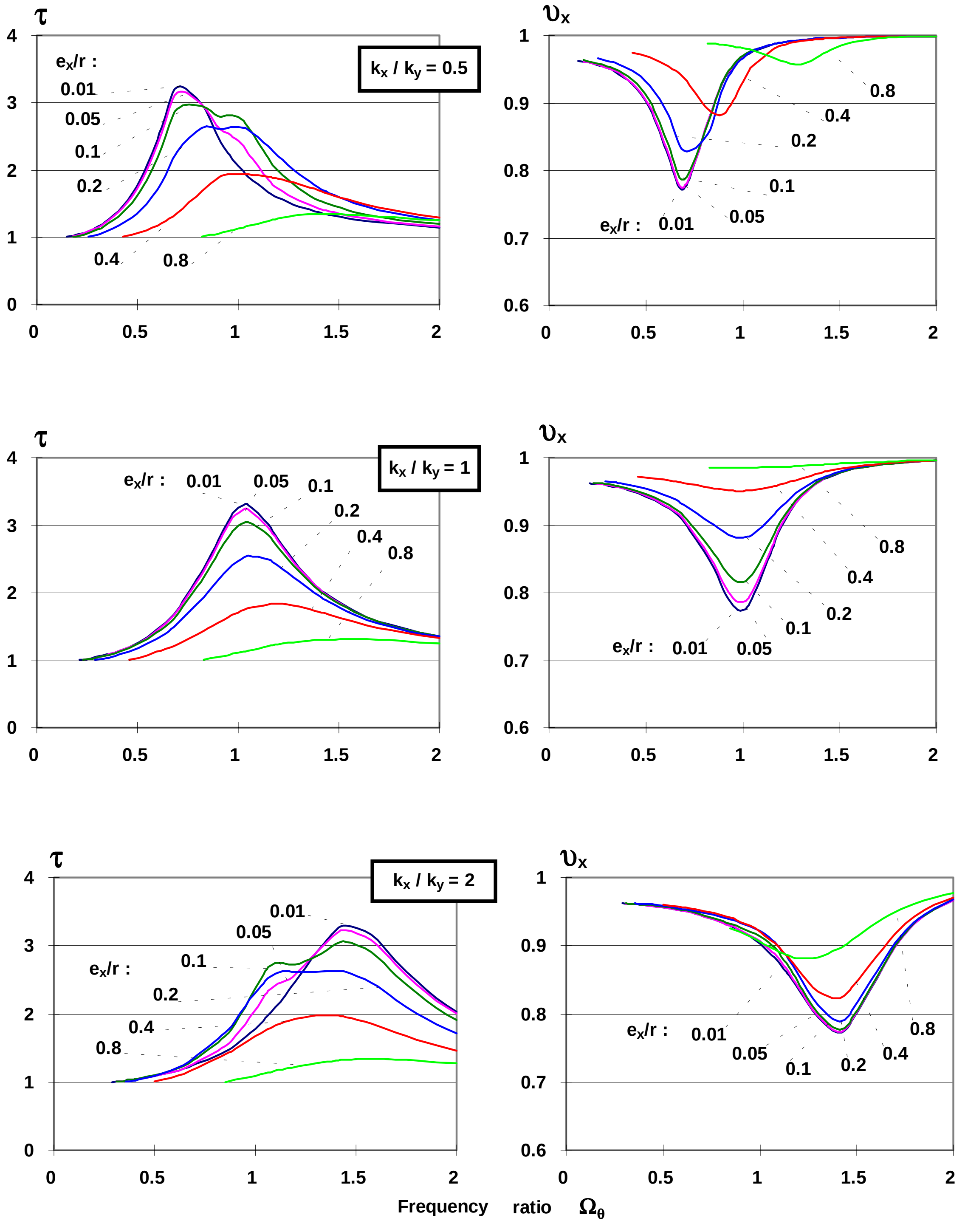

Figure 4: Overall torsional amplification (τ) and shear reduction (υ_x) coefficients of the two-way asymmetric system subjected to bidirectional (X, Y) seismic motion, for e_y /r = 0.2.

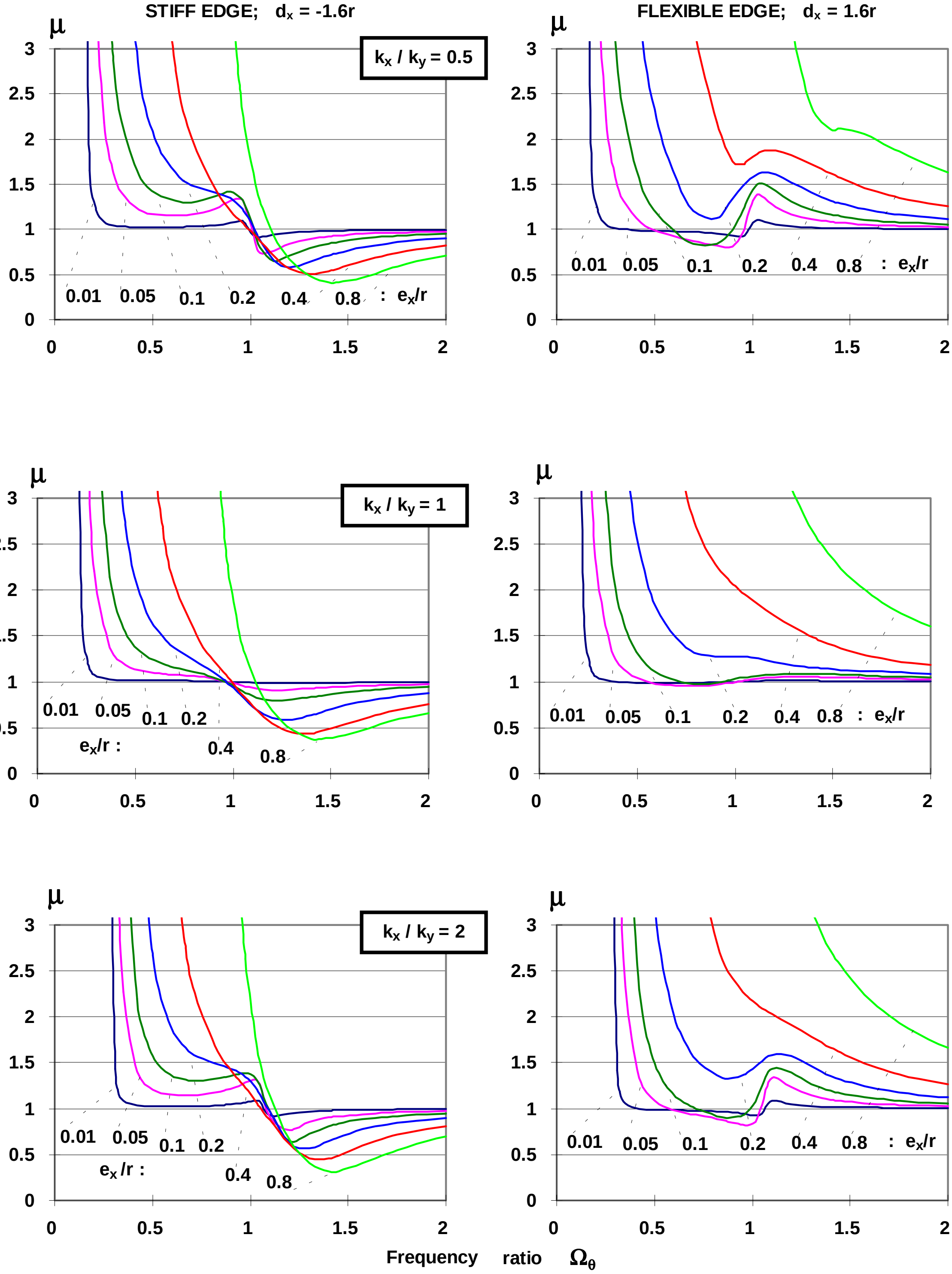

Figure 5: Effects of system parameters on the normalized displacements at the stiff and flexible edges of two-way asymmetric buildings when subjected to unidirectional seismic motion (Y), for e_y /r = 0.2.

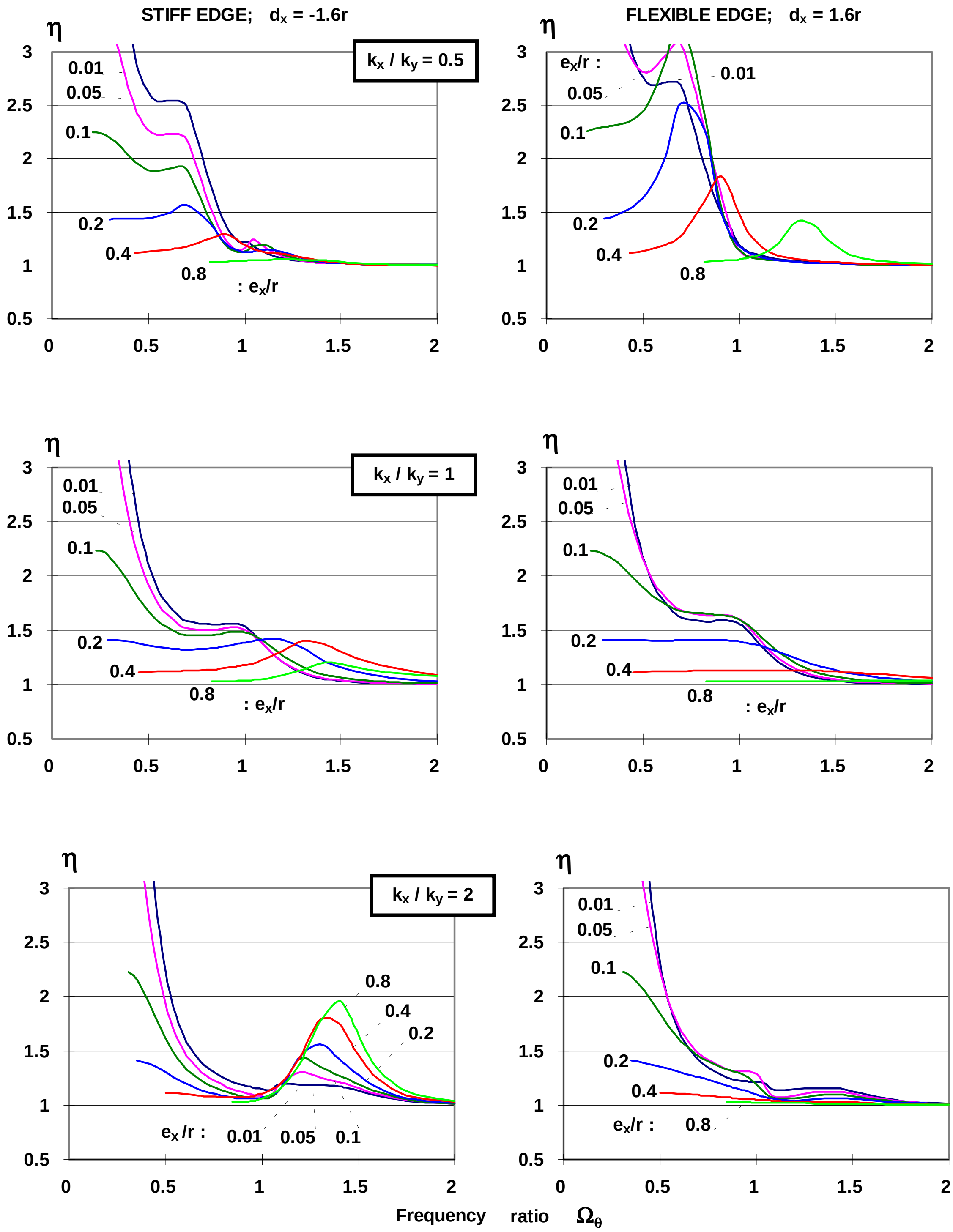

Figure 6: Effects of bidirectional seismic motion on the normalized displacements at the stiff and flexible edges of two-way asymmetric buildings, for e_y /r = 0.2.