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Seismic behavior of Horizontally Irregular Structures: Consequence of Relative Orientation of Acclerogram

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Abstract—*The present study investigates regarding seismic response of plan and vertically asymmetric building structures. The geometric mean of the response spectra for two orthogonal horizontal components of motion, commonly used as the response variable in predictions of strong ground motion. Measurement of ground motion depends on the orientation of the sensors installed in the field which illustrates that ground-motion intensity could differ for the same actual ground motion on different oriented structure as respect to measured orientation. The drift is examined on models of single-storey structures having symmetric and asymmetric (torsional-stiff, torsional-flexible) layouts subjected to an ensemble of bi-directional near-fault strong ground motions with and without distinct velocity pulses over different orientation. The representative structure is analysed under all earthquakes rotated to different orientations (0^0 to 90^0) at an interval of 15^0 under bi-directional excitations. The records are again applied on different type of structures which is adequately modelled using distributed plasticity approach to capture the bi-directional interactions.*
Analyzed results demonstrates that torsional amplification factor which depicts the variation of peak response ($\Delta_{asym}/\Delta_{sym}$) for both 'flexible side' and 'stiff side' over different orientations in the range of 0^0 to 90^0computed at an interval of 15^0. That maximum normalize element displacement which may called torsional amplification factor are vary more or less 10%, 20% and 30% for e_{rr}/D 0.06, 0.14 and 0.22 respectively for T= 0.2sec, 1sec and 3 sec; τ 0.5, 1 and 1.5 and $e_{r\theta}$ 45° and 90° between minimum and maximum values over all orientation taken here. It implies the orientation should take into consideration Relative amplification in response are calculated by taking averages of all five event which reveals that critical orientation, θ_c may or may not follow systematic trend in the neighbourhood of θ_c ($\pm 45^0$).

Keywords*: Bi-directional, asymmetry; seismic; strength dependent stiffness; design chart*

1. INTRODUCTION

Ground motions are often scaled to certain convenient target spectra in the response assessment of structures. The geometric mean of the response spectra for two orthogonal horizontal components of motion, commonly used as the response variable in predictions of strong ground motion, depends on the orientation of the sensors as installed in the field. This means that the measure of ground-motion intensity could differ for the same actual ground motion. This depends on sensor orientation.

Structures are often constrained to be horizontally irregular for architectural and functional reasons. The seismic vulnerability of these systems has been observed during past earthquakes [2], [4], [5], [6] and [15]. Numerous investigations (e.g., [3], [7], [9], [10] and [17]) have been carried out to achieve insight into the basic trend in both elastic and inelastic seismic behavior of symmetric and asymmetric systems. These studies, which use a parametrically defined equivalent single-storey model, are well-documented elsewhere [15], and generally employ a force-based design approach. In traditional approaches, the period of a structure is estimated and changes in its lateral strength (achieved by changing the strengths of components) are assumed to have a negligible effect on its stiffness and period (i.e., constant stiffness model). Two useful design philosophies are conceptualized that recognize the significance of strength dependent stiffness. In the post elastic range of shaking, during severe earthquake, the resulting resistive forces may be envisioned to pass through the center of strength (CV) of the system. If the CV is close to center of mass (CM), i.e., for a small value of strength eccentricity (ev), only minor torque will be generated. In this circumstance, it has been shown [1], [14], based on plastic mechanism analyses of a number of systems, that displacement ductility demand may be minimized by minimizing the strength eccentricity, in the limit through 'CV-CM coinciding' design. On the other hand, it is proposed and verified elsewhere [11], [12], [13] and [18] that an efficient strength design strategy is to ensure a 'Balanced-CV-CR' criterion, i.e., strength should be distributed among the load-resisting elements so that the center of strength (CV) and center of resistance (CR) is located on either side of the center of mass (CM). However, the distance of CV and CR with respect to CM depends on the performance states. Physically, such a strength design may tend to balance the elastic torque and plastic torque up to a given threshold. The state-of-the-art review also reveals that there is latitude to explore the seismic response of a plan asymmetric system by categorizing it into two classes depending upon the nature of prevailing stiffness eccentricity. Systems with eccentricity along one principal direction, parallel to any one side of the rigid deck, are designated as uni-directionally eccentric or mono-symmetric; whereas systems with eccentricities in two principal directions are referred to as bi- directionally eccentric [16].

Predictably, two translational components of a real accelerogram are applied along two principal axes of the structures conceited thereby that the orientation of the recoding sensors are aligned with the principal axes of the structure. This may hardly represent the reality. Many studies in the past have recognized the strong dependency of the response on angle of incidence. Studies by [10] have confirmed that the identification of the angle leading to the worst inelastic response may not appear possible.

The authors, in this background, aim to examine the influence of angle of incidence on seismic demand of plan-asymmetric systems. Systems are idealized with equivalent single storey model, where load-resisting elements follow strength-dependent stiffness behaviour. The study appears to offer useful impression on the influence of angle of incidence in plan-asymmetric systems and hence may be important for practical purpose.

2. IDEALIZATION OF STRUCTURE AND METHODOLOGY

Structure have been idealized as rigid diaphragm model with three degrees of freedom at each floor level, two translations in two mutually orthogonal horizontal directions and one in-plane rotation. Masses are assumed to be lumped at the floor levels. The total storey stiffness can be evaluated from standard Eigen value problem knowing the lateral period and mass matrix of the system. Generally, in office buildings, lateral load-resisting structural members are found to be uniformly distributed over its plan. To represent such plan-wise distribution of the load-resisting elements (say, columns); in the present investigation, the structure is modeled to consist of six such elements, three in each orthogonal direction. The locations of the outer edge elements and subsequently the intermediate distance D may vary depending on the various characterizing parameters unlike several previous studies. Fifty per cent of the total lateral stiffness is attributed to the middle element and the rest 50% is equally distributed between two edge elements.

Standard system parameters such as mass, mass moment of inertia; stiffness, strength of the elements etc.are given as basic input to the program. The entire time domain is divided into a large number of time steps. In the parametric simulation, mass of the system is adjusted to achieve a target lateral uncoupled period, while different torsional periods are set to regulate the distribution of the mass by varying the radius of gyration. A simple elasto-plastic hysteresis model is used as constitutive characteristics of the load-resisting elements. Under specified ground acceleration histories, standard equations of motion are solved in the time domain using Newmark'sβ-γ scheme, which considers constant average acceleration over each incremental time step. While Newmark's parameters γ and β are chosen, respectively, as 0.5 and 0.25, iterations are performed in each incremental time step using the modified Newton-Raphson technique. The time step of integration is taken as less than T/1000 second to ensure convergence (T is the lateral natural period of the system). 2% of critical damping in each mode of vibration is considered to constitute the damping matrix. The response of asymmetric structures normalized due to dynamically equivalent reference symmetric systems is presented to identify the impact of asymmetry alone. The normalization is done by dividing asymmetric system response by symmetric system response. Response are taken for every 15º interval from 0º to 90º because after 90º the values repeated itself in same presiding manner. Peak response under bi-directional excitation is marked.

Seismic response of structures is often evaluated by applying one (or two) horizontal component(s) of a recorded accelerogram along one (or two) principal axis(es) of the structure. This clearly ignores the possible influence of angle of incidence and should be prohibitive in practice. Ground motion components with reference to a new orientation defined by an angle ψ relative to the recorded component (refer to Fig. 2a) may be easily computed by the following simple transformation.

$$\begin{Bmatrix} a_{x(\psi)}(t) \\ a_{y(\psi)}(t) \end{Bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{bmatrix} \begin{Bmatrix} a_x(t) \\ a_y(t) \end{Bmatrix} \qquad (1)$$

in which $a_x(t)$, $a_y(t)$ are horizontal components of original record and $a_{x\psi}(t)$, $a_{y\psi}(t)$ the components of the record when rotated anti-clockwise by an angle ψ. We use 'orientation' (denoted by ψ) to refer to the issues related to ground motion alone, while 'angle of incidence' (denoted by θ) is used while response of structures is evaluated. Accelerogram at an angle of incidence θ with respect to principal axis of structure is equivalent to the accelerogram acting along the principal axis, but with orientation ψ = θ (illustrated in Fig. 2b). Thus to account for the different angles of incidences, ground motion components are rotated and applied along the principal axis of the structure.

3. RESULTS AND DISCUSSIONS

The response of systems with different orientation is computed under bi-directional ground motion applied along two principal directions of the system. Different eccentricities shows different type of structure. Maximum in-plane deformation of the edge elements due to the coupled effect of translation and torsion over the entire earthquake history is normalized by those of the reference symmetric model. The quantities computed for load-resisting elements orientated in both the principal directions are compared for flexible and stiff sides separately and the greatest ones are referred to herein as maximum normalized element displacement of the respective side. Fig. 3 describes the variation of the maximum normalized element displacement for both flexible and stiff sides as a function of orientation. Combinations of other influential parameters are chosen to cover torsionally flexible to stiff systems with various lateral periods and different degrees of inelastic excitation defined by R. Response histories (variation of top displacement, i.e., drift with time) for each case is also included. Similar set of curves under bi-directional shaking are furnished in parallel for comparison.

During bi-directional seismic shaking in so-called bi-directionally eccentric structures, eccentricities along two principal directions result in two torsional moments. The effect of torsion seems to be amplified if the moments generated due to eccentricities in each direction are additive in nature, while the mutually cancelling nature of such moments tend to lower the impact of torsion. Such addition or cancellation of two torsional moments depends on the relative sense of eccentricities. Interaction between such pair of torsional moments (additive/cancelling) may also depend on the ground motion characteristics (in phase or out of phase). Accounting such issues through comparing responses between $e_{r\theta} = \theta$ and $\pi - \theta$, response for flexible and stiff sides are noted separately under the ground motions rotated to different orientations and then applied along the principal axes of the structure. Fig. 3 presents the maximum normalized element displacement for representative systems for different angle of incidences. Results are presented for five different ground motions for angle of incidence varying over one quadrant. This is because response appears to repeat itself after an incidence angle of $\pi/2$. Limited case studies in Fig. 4 reveals that the angle of incidence may arbitrarily influence the torsion-induced amplification particularly for large e_{rr} regardless of the period of interest.

It is noted from the Fig. 3 and table 1 that maximum normalize element displacement which may called torsional amplification factor are vary more or less 10%, 20% and 30% for e_{rr}/D 0.06, 0.14 and 0.22 respectively for T= 0.2sec, 1sec and 3 sec; τ 0.5, 1 and 1.5 and $e_{r\theta}$ 45º and 90º between minimum and maximum values over all orientation taken here. It implies the orientation should take into consideration.

From Fig. 4 we can see in which orientation the maximum and minimum values of torsional amplification factor, which takes place for flexible and stiff sides. From the results we can make out the critical orientation. It may be noted that the peak torsional amplification factor ($\Delta_{(asym)}/\Delta_{(sym)}$) although does not follow any systematic trend, generally occurs in the neighbourhood of θ_c ($\pm 45^{\circ}$). This observation may be useful to estimate the orientation to build a structure for peak amplification $\Delta_{asym}/\Delta_{sym}$ under NF motions.

4. SUMMARY AND CONCLUSIONS

The results presented in this Chapter leads to the following conclusions.

1. Structural damage is measured in terms of maximum normalized displacement (torsional amplification factor). Such damage under bi-directional shaking may considerably change with orientations. This implies that the rotation of ground motion to different orientations may be important.
2. Appreciating the fact that a fully bi-directional non-linear analysis for a complicated structure is very challenging, attempt is made to find the orientation (critical orientation, θc) where the torsional amplification factor in damage due to bi-directional shaking is considerably changed. It is observed that the θc for peak response corresponds to the orientation and its does follow systematic trend, generally occurs in the neighbourhood of θc ($\pm 45^{\circ}$) for torsional amplification factor.

In parallel, it may also be useful to identify the orientation (θm) that correspond to maximum increase of bi-directional response as per the IS codes are change accordingly this implies that for design performance states such as Life safety or Collapse prevention

actor.

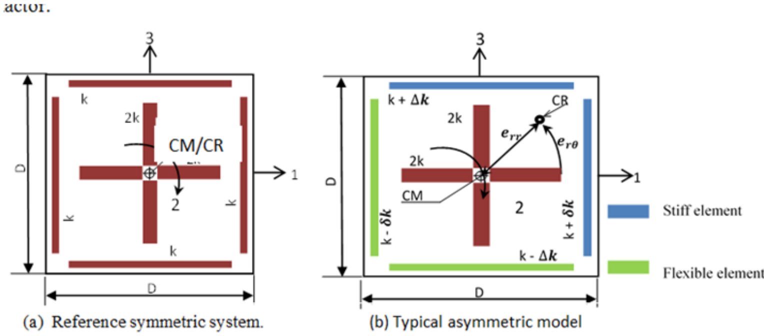

Fig. 1: Schematic representation of equivalent single storey system.

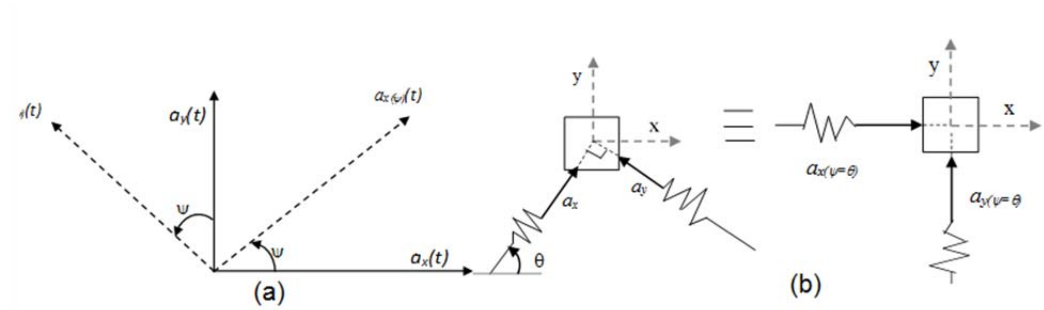

Fig. 2: (a) Transformation of components of motion to arbitrary orientation. (b) Equivalent between angle of incidence and rotation of motion.

Table 1: Torsional amplification factor details of respective asymmetric structures which are shown in Fig. 1

	Torsional amplification factor		Orientation		Torsional amplification factor		Orientation		Torsional amplification factor		Orientation	
	stiff	flexible	stiff	flexible	stiff	flexible	stiff	flexible	stiff	flexible	stiff	flexible
	$\frac{e_{rr}}{D}=0.06$				$\frac{e_{rr}}{D}=0.14$				$\frac{e_{rr}}{D}=0.22$			
	T=0.2s, τ= 0.5											
min	1.042403	1.008391	60	45	1.059784	1.033305	45	45	1.149114	1.105919	45	60
max	1.10296	1.095538	75	0	1.237886	1.211614	90	90	1.516104	1.419231	90	15
	T=1s, τ= 1											
min	1.01278	1.011337	45	15	1.01278	1.011337	45	15	1.01278	1.011337	45	15
max	1.113569	1.114252	60	30	1.113569	1.114252	60	30	1.113569	1.114252	60	30
	T=3s, τ= 1.5											
min	0.995778	0.95614	90	0	1.008474	0.873531	15	0	0.986487	0.871609	30	15
max	1.039031	1.032997	60	90	1.063353	1.029126	75	45	1.061484	1.018447	90	45

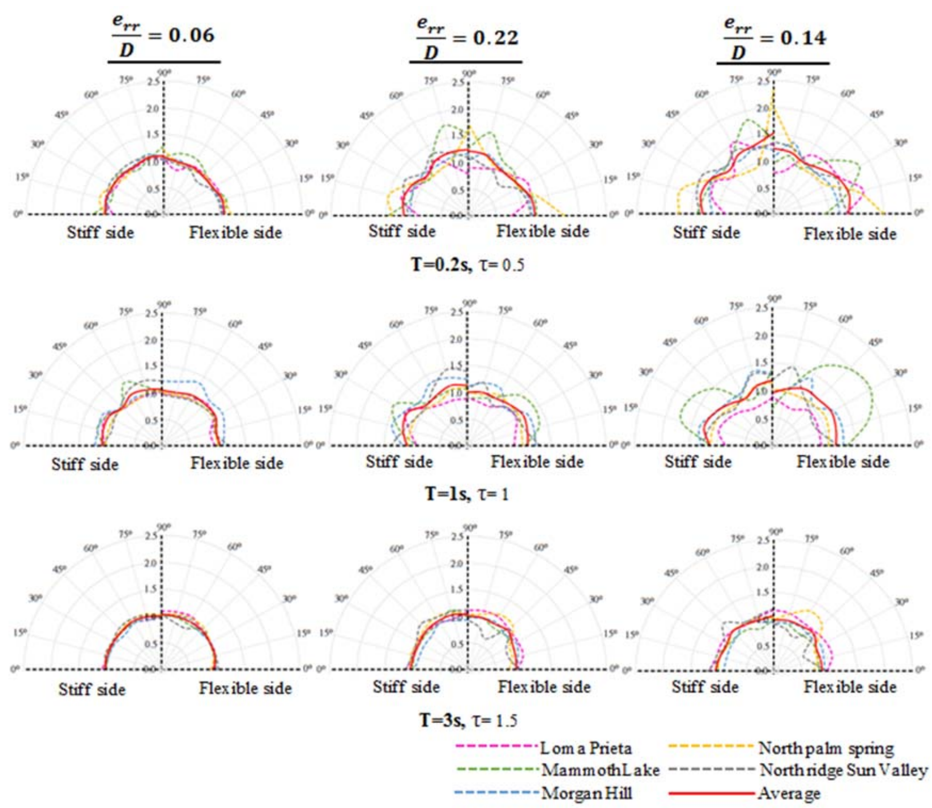

Figure 3: Variation of torsional amplification factor with changes of orientation in respectfully asymmetry system ($e_{r\theta}$= 45º, R= 4)

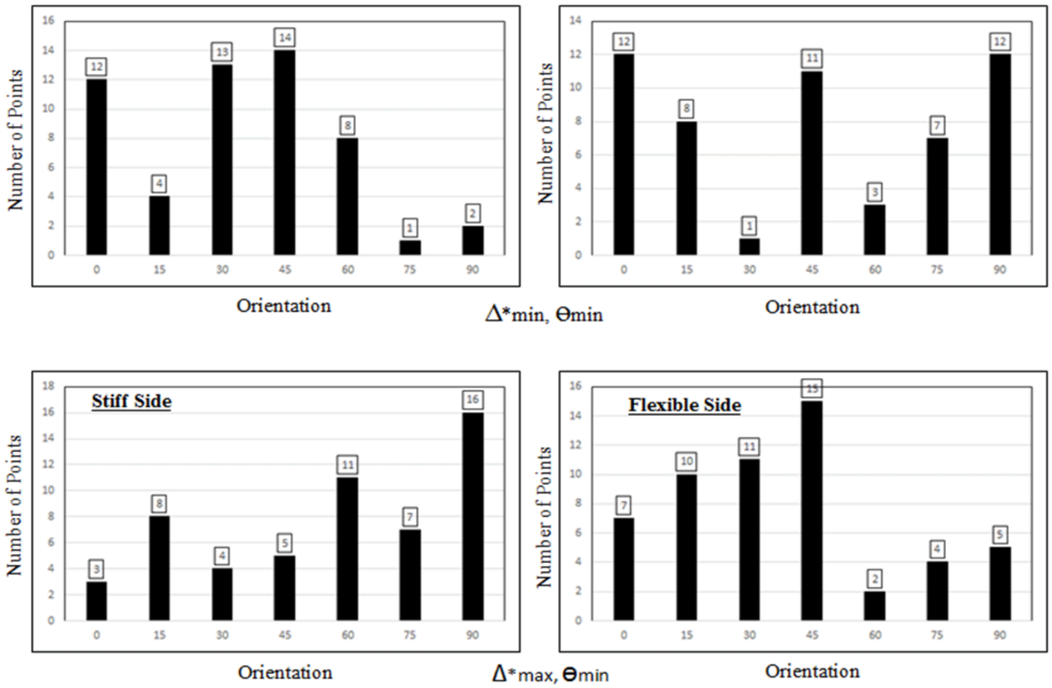

Figure 4: Summary of number of points in respective sides in different orientation at which maximum and minimum values of torsional amplification factor occurs.

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