Influence of Earthquake Direction on Nonlinear Seismic Response of Plan-Asymmetric Structure

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Abstract

This research presents the influence of varying orientations of ground motions on the global seismic demands of a mono-symmetric structural model using a validated numerical model. The considered structure is a ¼-scaled frame shear-wall model. The numerical model was established based on the response validation with the experimental findings. Based on the validated numerical model, seismic response variation at the flexible and stiff edges were compared to present the influence of stiffness eccentricity. It has been concluded in this research that such kind of structures are more sensitive towards rotational response variability compared with the translational response variability. Finally, a conclusion pertaining to the non-conservatism of the principal axis excitation is established from statistical viewpoint.

Keywords: Varying seismic orientation; Asymmetric structure; Seismic response; statistical evaluation

1. INTRODUCTION

The seismic motion is recorded in the form of two horizontal and one vertical direction. In general, these seismic components are correlated, but according to Penzien and Watabe (1974) there exist uncorrelated seismic components which could be used to determine the critical orientation of an earthquake. The determination of critical seismic response can be obtained using response spectrum method. Numerous researchers have demonstrated the influence of varying orientations of ground motion on elastic and inelastic seismic responses. For elastic seismic response, various analytical formulae have already been established (Athanatopoulou 2005) to investigate the critical seismic response of three correlated seismic components. The research concluded that critical direction of a ground motion changes with the response quantity of interest and characteristics of seismic excitation. These conclusions have also been presented in literature (Kalkan and Kwong 2013 and Alam et al. 2016) where the influence of orientation of seismic excitation on various response quantities have been illustrated based on a linear 3-D structure. Kostinakis et al. (2008), examined the critical orientation of seismic excitation and the corresponding peak response quantity on the basis of the formulae (Athanatopoulou, 2005) for special classes of buildings subjected to isotropic bidirectional ground motion (Kalkan and Kwong, 2013).

This research however, emphasizes the assessment of seismic response uncertainty from statistical viewpoint to simplify the directionality problem. In this regards, this research demonstrates seismic response variability at both flexible and stiff edges of a plan-asymmetric structure. The research findings conclude that in torsionally-stiff plan-asymmetric structures, rotational response variability is more sensitive compared with the translational response variability at both flexible and stiff edges when the issue of seismic directionality is considered.

This research highlights a basic design problem as the conventional design practice of considering seismic excitations along the reference axes of the structure may potentially lead towards a non-conservative design estimate. Based on the statistical evaluation presented in this work, the significance of variation in seismic orientation for peak seismic response estimate is highly evident. The presented work is useful mainly for the design engineer in decision making during the design process of critical asymmetric structures.

2. TORSIONAL VIBRATION UNDER VARYING SEISMIC ORIENTATIONS

Figure 1 below shows a schematic representation of the multi-storey plan-asymmetric structure tested on a shake table along transverse direction for El Centro 1940 seismic motion. The details on the experimental setup is already available in a companion paper (Zhang et al. 2018). The structure's equation of motion (Chopra, 2001) can be expressed as follows:

$$\mathrm{M}\ddot{\mathrm{u}}\,(\mathrm{t}) + \mathrm{C}\dot{\mathrm{u}}\,(\mathrm{t}) + \mathrm{K}\mathrm{u}\,(\mathrm{t}) = \mathrm{F}_{\mathrm{eff}} \qquad (1)$$

where,

$$\mathrm{F}_{\mathrm{eff}} = -\mathrm{M}\mathrm{I}\ddot{\mathrm{U}}_{\mathrm{g}} \qquad (2)$$

M, C and K represent the global mass, damping and stiffness matrices of dimensions 3ψ where ψ is the degree of freedom. Each floor has been considered to have three degrees of freedom. After decomposing the external force component of equation 1, the final undamped general equation of vibration of the considered plan-asymmetric structure is expressed in equation 3.

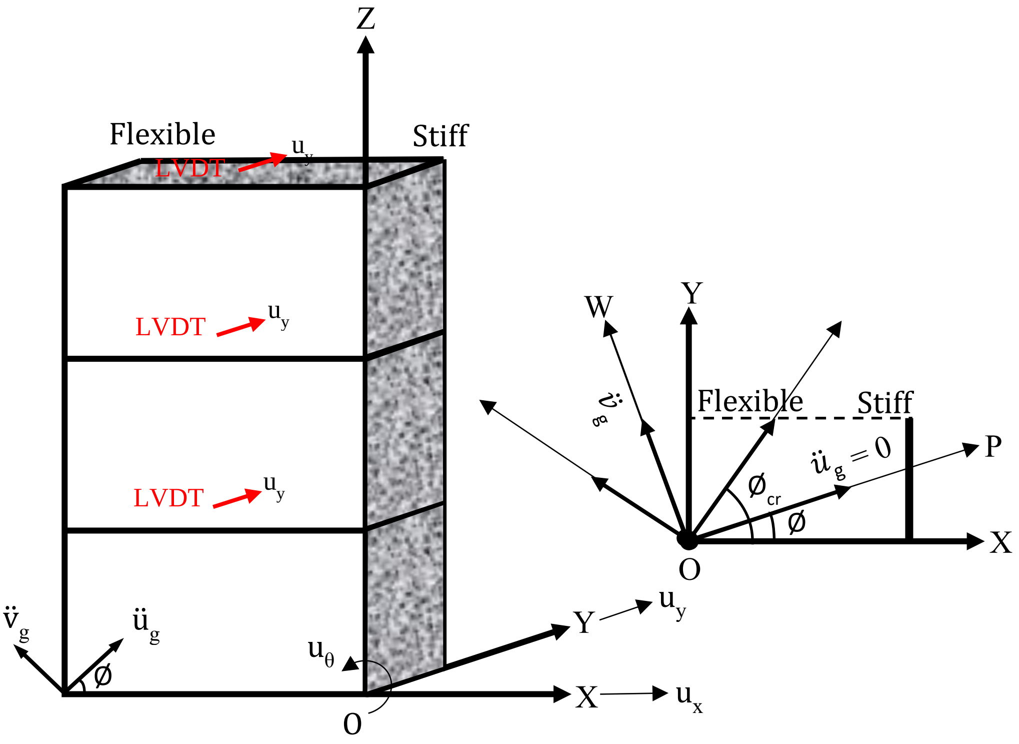


Figure 1: Schematic representation of the experimental model in perspective of varying seismic orientations

$$\begin{bmatrix} [m] & [0] & -[m][\alpha_{ym}] \\ [0] & [m] & [m][\alpha_{xm}] \\ -[m][\alpha_{ym}] & [m][\alpha_{xm}] & [\Omega_{cm}] \end{bmatrix} \begin{bmatrix} [\ddot{u}_x] \\ [\ddot{u}_y] \\ [\ddot{u}_\theta] \end{bmatrix} + \begin{bmatrix} [K]_x & [K]_{xy} & [K]_{x\theta} \\ [K]_{yx} & [K]_y & [K]_{y\theta} \\ [K]_{\theta x} & [K]_{\theta y} & [K]_\theta \end{bmatrix} \begin{bmatrix} [u_x] \\ [u_y] \\ [u_\theta] \end{bmatrix} = \left[-\left(\begin{bmatrix} [m] & [0] & -[m][\alpha_{ym}] \\ [0] & [m] & [m][\alpha_{xm}] \\ -[m][\alpha_{ym}] & [m][\alpha_{xm}] & [\Omega_{cm}] \end{bmatrix} \left(\begin{bmatrix} I_X\ddot{u}_g \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ I_Y\ddot{v}_g \\ 0 \end{bmatrix} \right) \right) \cos\theta + \left(- \begin{bmatrix} [m] & [0] & -[m][\alpha_{ym}] \\ [0] & [m] & [m][\alpha_{xm}] \\ -[m][\alpha_{ym}] & [m][\alpha_{xm}] & [\Omega_{cm}] \end{bmatrix} \left(\begin{bmatrix} -I_X\ddot{v}_g \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ I_Y\ddot{u}_g \\ 0 \end{bmatrix} \right) \right) \sin\theta - \left(\begin{bmatrix} [m] & [0] & -[m][\alpha_{ym}] \\ [0] & [m] & [m][\alpha_{xm}] \\ -[m][\alpha_{ym}] & [m][\alpha_{xm}] & [\Omega_{cm}] \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ I_Z\ddot{\varphi}_{gz} \end{bmatrix} \right) \right] \quad (3)$$

Where

$$F^{gx}{}_{eff} = -\begin{bmatrix} [m] & [0] & -[m][\alpha_{ym}] \\ [0] & [m] & [m][\alpha_{xm}] \\ -[m][\alpha_{ym}] & [m][\alpha_{xm}] & [\Omega_{cm}] \end{bmatrix} \left(\begin{bmatrix} I_X\ddot{u}_g \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ I_Y\ddot{v}_g \\ 0 \end{bmatrix} \right) \quad (4)$$

$$F^{gy}{}_{eff} = -\begin{bmatrix} [m] & [0] & -[m][\alpha_{ym}] \\ [0] & [m] & [m][\alpha_{xm}] \\ -[m][\alpha_{ym}] & [m][\alpha_{xm}] & [\Omega_{cm}] \end{bmatrix} \left(\begin{bmatrix} -I_X\ddot{v}_g \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ I_Y\ddot{u}_g \\ 0 \end{bmatrix} \right) \quad (5)$$

$$F^{gz}{}_{eff} = -\begin{bmatrix} [m] & [0] & -[m][\alpha_{ym}] \\ [0] & [m] & [m][\alpha_{xm}] \\ -[m][\alpha_{ym}] & [m][\alpha_{xm}] & [\Omega_{cm}] \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ I_Z\ddot{\varphi}_{gz} \end{bmatrix} \quad (6)$$

After simplification, the general equation of motion of the structure would become:

$$M\ddot{u}\,(t) + C\dot{u}\,(t) + Ku\,(t) = (F^{gx}{}_{eff})\cos\theta + (F^{gy}{}_{eff})\sin\theta + F^{gz}{}_{eff} \quad (7)$$

For a response quantity Θ, utilizing the principle of superposition, the response-history for any arbitrary seismic orientation ∅ may be reflected as a linear combination of three-response histories. Since in this research the uni-directional seismic excitation is in the translation direction is considered, seismic component along the longitudinal direction is ignored ($\ddot{u}_g$ (t) = 0), therefore, the seismic responses $\Theta_{,1X}$ (t) and $\Theta_{,1Y}$ (t) can be reduced using the formulation presented by Song et al., 2007. Thus, the typical response quantities for the case considered in this research can be expressed as follows:

$$\Theta_{,X}\,(\emptyset, t) = \Theta_{,1X}\,(\emptyset, t) \quad (8)$$

$$\Theta_{,Y}\,(\emptyset, t) = \Theta_{,1Y}\,(\emptyset, t) \quad (9)$$

3. VALIDATION OF NUMERICAL MODEL WITH EXPERIMENTAL RESULTS

The numerical structure was exposed to the same El-Centro 1940 earthquake record. The achieved displacement response in the time domain are illustrated as sum square amplitude in Figure 2 for comparison between the numerical and experimental response. Numerical findings demonstrate fairly good agreement with the experimental results.

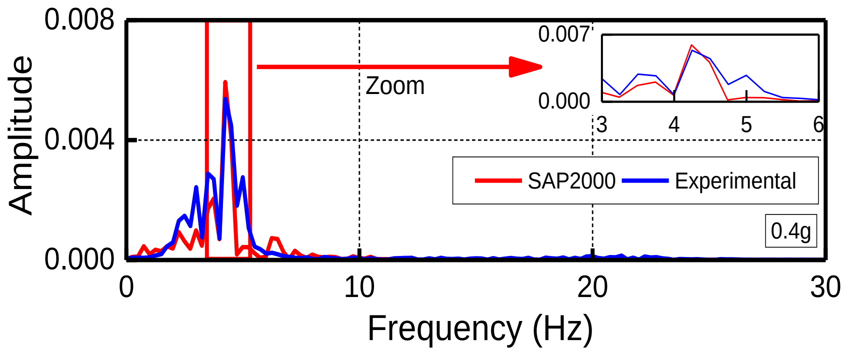
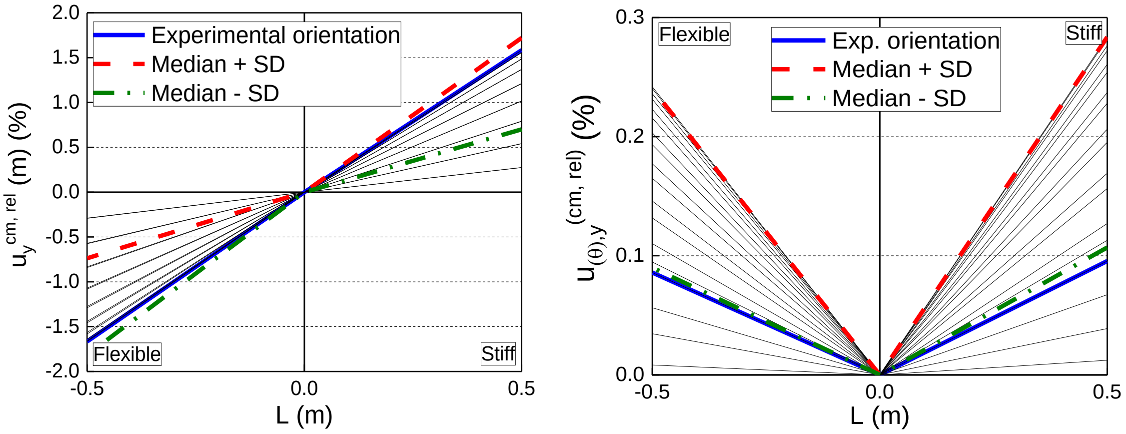


Figure 2: Numerical and experimental response validation as sum square amplitude

4. RESPONSE UNDER VARYING ORIENTATIONS

Response variability depends upon both the seismic excitation and the response quantity. This fact has been illustrated in Figure 3 in which flexible and stiff side-wise distribution of response quantities over all possible seismic directions has been presented for the validated numerical model with PGA = 0.4g as shown in Figure 3. The seismic direction that was considered along the transverse direction of the structure to induce excitation during the experimental testing is termed as exp. orientation so that the seismic response from other orientations could easily be distinguished. The distribution of seismic response quantities corresponding to exp. orientation has been highlighted with a dashed blue line whereas the black lines demonstrate the seismic response from varied orientations. It is evident from the presented illustrations that for almost all the seismic response quantities, exp. orientation has not led to the maximum response except. Moreover, rotational response has demonstrated higher seismic response variability compared with the translation response.



(a) (b)

Figure 3: Seismic response quantities under varying seismic orientations (a). Maximum translational displacement (b). Maximum rotational displacement; the blue line corresponds to the response obtained when the seismic excitation was considered along exp. orientation; the red line corresponds to median + standard deviation response; the green line corresponds to the median – standard deviation response; the black lines corresponds to other possible orientations

5. SEISMIC RESPONSE UNCERTAINTY FROM STATISTICAL VIEWPOINT

To quantify this observation, the idea of evaluating the seismic response in terms of probability of exceedance is explored. In Figure 4, the solid red line indicates the response obtained when the seismic excitation was considered along the principal axis of the structure. In the mentioned Figure, there lies approximately 20% probability of observing top roof's rotational displacement response when the seismic excitation was considered along the principal axis of the structure. Eventually, this describes the fact that there is an underestimation of rotational displacement response with approximately 80% probability. Hence, it can be said that there is always a possibility of underestimation of the peak seismic response during conventional design practices as the conventional design practices involve the use of seismic excitations only along the principle directions of a structure.

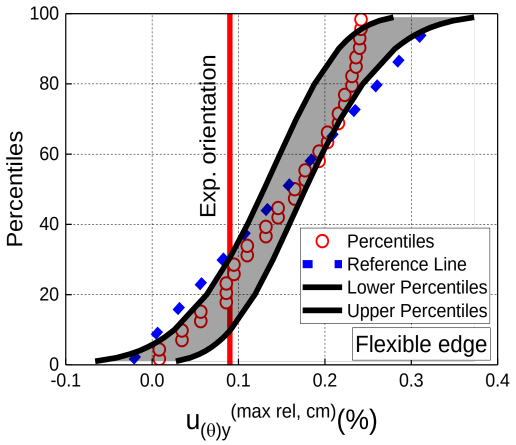


Figure 4: The probability of randomly observing rotational drift at top roof level of the plan-asymmetric structure; the red line corresponds to the response quantity obtained from the seismic excitation along principal axis of the structure

6. CONCLUSION

In this research the influence of varying orientations of ground motion using a validated numerical model was carried out on a mono-symmetric torsionally stiff structure. It has been concluded that the investigated mono-symmetric frame shear-wall structure appears to have more sensitivity towards rotational response variability compared with the translational response variation under varying seismic orientations. Both translational and rotational seismic demands from excitation along the principal axis of the plan-asymmetric structure do not demonstrate peak structural response, which implicates the non-conservatism of the traditional design approach of considering seismic excitation along the principal axis of the structure for design purposes. Treating the structure's principle axis excitation as a randomly selected orientation, there exists approximately 80% probability that for most of the rotational response quantities, the seismic response will exceed the principal axis response.

Since the peak seismic values are underestimated while considering seismic orientation only along reference axes of the structure, conventional design practices may therefore, lead to an unsafe seismic design. Based on the findings of this research, the variation in the seismic orientation is recommended for the determination of peak seismic response during the design process of critical asymmetric structures.

ACKNOWLEDGEMENTS:

The careful review and constructive suggestions by the anonymous reviewers are gratefully acknowledged.

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