CRITICAL ASSESSMENT OF ACCIDENTAL TORSION IN BUILDINGS WITH SYMMETRIC PLANS USING CSMIP DATA

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Abstract

This research investigated the validity of accidental torsion provisions in ASCE-7 for buildings that are regular in plan and elevation with rigid diaphragms. MDOF systems of 4-, 8-, 12- and 20-story building prototypes along with plan aspect ratio of 1:1, 1:2, 1:4 and 1:8 are modeled. The building models possess translational to rotational period ratios (Ω) ranging from 1.1 to 2.0. Uncertainty in stiffness is treated as the main source of eccentricity. Equivalent design eccentricity indicates that the 5% equivalent eccentricity rule is adequate to capture the median magnification in deformation due to accidental torsion. 11 buildings selected from CSMIP database are studied to verify the analytical results.

Introduction

Consideration of accidental torsion is required by seismic code provisions such as ASCE 7-10 (ASCE, 2010) and ASCE 7-16 (ASCE, 2017) to account for the randomness in mass location and stiffness of Vertical Lateral Load Resisting systems (VLLRs). Equivalent seismic lateral force needs to be applied at a distance which equals 5% of the plan dimension perpendicular to ground motion direction from the center of mass of floor diaphragm.

A considerable amount of research has been carried out for accidental torsional moments in symmetric-in-plan buildings (De la Llera & Chopra 1992; 1994; 1995; Lin et al., 2001; Hernandez & Lopez, 2004; De-la-Colina & Almeida, 2004; Basu et al., 2014). De la Llera and Chopra (1992) used recorded data from three buildings instrumented by California Strong Motion Instrumentation Program (CSMIP) to conclude that the 5% accidental torsional rule is adequate. They developed single-story linear analytical models in their follow up research (De la Llera & Chopra, 1994; 1995), demonstrating that 5% eccentricity is adequate for most steel and concrete special moment-resisting frames based on response spectrum analysis (RSA).

In order to quantify the level of uncertainty in stiffness of VLLRs, the variability of element cross section dimensions, second moment of inertia, and material strength is studied through literature review. For reinforced concrete material, Ramsay, Mirza and MacGregor (1979) concluded that deformation of reinforced concrete beams has a coefficient of variation (CoV) of 0.14, and the same value is applied in De la Llera and Chopra (1994) to model reinforced concrete frames. While for steel, Ellingwood and Galambos (1980) and Melechers (1987) showed that the coefficient of variation of Young's modulus is approximately 0.06. ASTM A6-05 and ASTM A992-04 provide variability of structural element dimensions and material strength, respectively. Bournonville et al. (2004) concluded that coefficient of variation of reinforcement yield strength ranges from 0.03 to 0.09. In this research, section dimension is assumed to have a coefficient of variation ranging from 0.01 to 0.04, and material yield stress is assumed to have a coefficient of variation of 0.05. To keep consistency with reinforced concrete material, a CoV of 0.14 is set for steel material with a slight overestimate and therefore leads to slightly conservative results.

Methodology

This study aims at quantifying building torsional characteristics such as deformation magnification factors α_1 and α_2 (will be explained in the following) and the equivalent design eccentricity (represented by e(%) shown in the following) which is used to account for effect of accidental torsion during design procedures. Statistics measures of these parameters (e.g. median and 84%) are obtained through building models subject to ground motion excitations of different hazard levels.

Translational and torsional modes of vibrations simultaneously affect the general response of a building. In a parametric form, a factor denoted with Ω, that is the ratio of dominant translational period (T_{tran}) to dominant rotational period (T_{rot}), is introduced (Eq. 1). Large Ω values associated with perimeter frame buildings and small Ω values represent core-wall systems with low torsional stiffness. Building models of Ω ranging from 1.1 to 2.0 are developed, which covers most of the building cases.

$$\Omega = \frac{T_{tran}}{T_{rot}} \qquad \text{Eq. (1)}$$

Parameters that characterize building torsional response

Torsional vibration in a nominally symmetric system is caused by asymmetric stiffness distribution with randomness in stiffness of VLLRs. Measurements are taken for the largest displacement amplification among four corners of each floor based on the rigid diaphragm assumption. Given this background, two torsional vibration parameters are introduced (Eq.2, and Eq.3) to study the contribution of displacement response to building torsional effects at each floor. In these equations, δ_{tran} denotes the maximum displacement of the floor due to translational vibration; δ_{rot} denotes the maximum rotated angle of the floor due to translational vibration. δ_b denotes the displacement of a symmetric base system (with no randomness in VLLRs). α_1 is the ratio of peak total displacement of an asymmetric system to peak translational response of the base system. It estimates the total displacement amplification considering stiffness eccentricity and compares it to a non-eccentric base system. α_2 is the ratio of peak total displacement to peak translational displacement within the same asymmetric system. It stands for the contribution of rotational response to the total response.

$$\alpha_1 = \frac{max(\delta_{trans} + \delta_{rot})}{max(\delta_b)} \qquad \text{Eq. (2)}$$

$$\alpha_2 = \frac{max(\delta_{trans} + \delta_{rot})}{max(\delta_{trans})} \qquad \text{Eq. (3)}$$

Equivalent eccentricity from static pushover

Torsional vibration characteristics represent the amplification in displacement due to stiffness uncertainty in asymmetric buildings, and those characteristics need to be transferred to a measure of a distance representing how far away the equivalent lateral force should be applied to the center of mass to capture the same amount of torsional displacement amplification during the design of the building. To analyze the displacement amplification caused by eccentric static loading, an eccentric equivalent lateral force is applied to the base system. In comparison, a non-eccentric equivalent lateral force is also applied to the base system at the center of mass. The ratio between two displacements in these two scenarios demonstrates the amplification due to eccentric push over (see Eq. 4). It can be shown that aside from Ω, the plan aspect ratio *n* affects pushover displacement amplification as well. The *n* term in Eq. 4 represents displacements measured at the edge of the diaphragm and the $(1+n^2)$ term represent amount of rotational inertia. Given time history displacement data, median and 84% of equivalent eccentricity (denoted as $e^{50\%}$ and $e^{84\%}$)can be obtained by equating median and 84% of α_1 (denoted with $\alpha_1^{50\%}$ and $\alpha_1^{84\%}$) with α_p as shown in Eq. 5 and Eq. 6, with *n* values of 1, 2, 4 and 8 applied.

$$\alpha_p = \frac{\delta_p}{\delta_{np}} = 1 + \frac{6ne}{\Omega^2(1+n^2)} \qquad \text{Eq. (4)}$$

$$e^{50\%} = \frac{\left(\alpha_1^{50\%} - 1\right)\Omega^2(1+n^2)}{6n} \qquad \text{Eq. (5)}$$

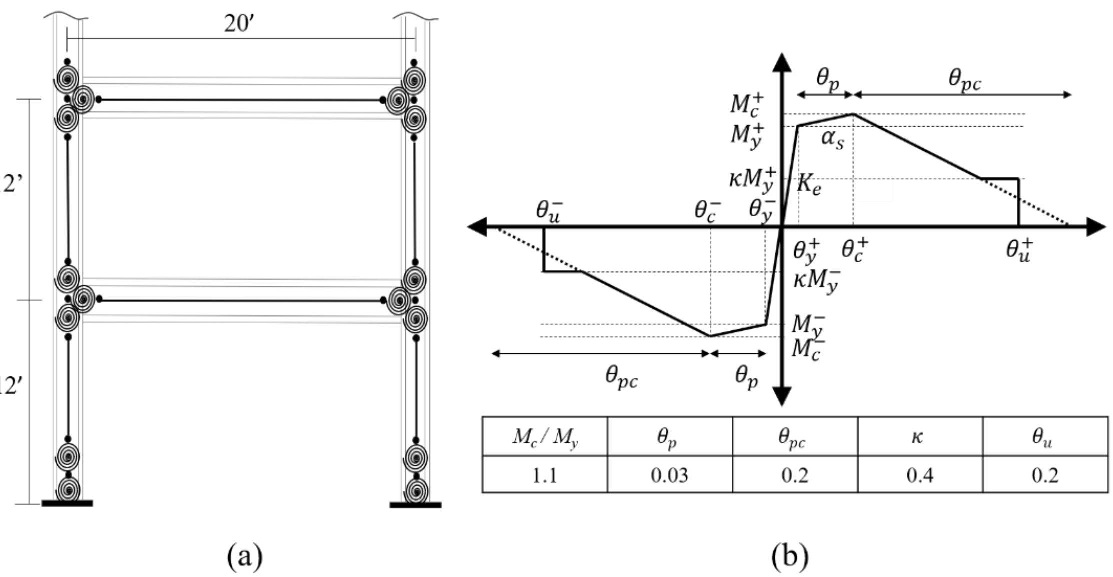
$$e^{84\%} = \frac{\left(\alpha_1^{84\%} - 1\right)\Omega^2(1+n^2)}{6n} \qquad \text{Eq. (6)}$$

Building Models and Ground Motions

4-story, 8-story, 12-story and 20-story building models are generated in OpenSees. For a 2D building model, each frame is designed as a single bay generic frame with 20’ bay width and 12’ story height. (see Figure 1). The ratio of the second moment of inertia of beams and columns in this idealized model is set to be 1.0, which leads to reasonable beam to column stiffness ratio (ρ) and strong column weak beam ratio (assuming proportional strength and stiffness).

Distribution of second moment of inertia along the building height follows the distribution of story shear using ASCE-7 Equivalent Lateral Force (ELF) method. Moment of inertia of beams and columns are computed through optimization method targeting periods of 1.6s, 2.4s, 3.0s and 4.0s for 4-story, 8-story, 12-story and 20 story building, respectively. Assuming each story yields at a drift ratio of 0.01, rotation of beams and columns are computed at story yield point, from which moment capacity of beams and columns can be obtained based on double curvature assumption. Springs with bilinear hysteretic (Ibarra et al., 2005) characteristics are placed at beam as illustrated in Figure 1. Parameters for the bilinear hysteretic springs are shown in Figure 1b. To show the validity of 2D generic model, pushover analysis is carried out, Figure 2 shows the pushover curve of the generic frames subject to ELF lateral load from ASCE-7.

Three dimensional (3-D) systems with plan aspect ratio of 1:1, 1:2, 1:4 and 1:8 are modeled using 2-D generic frames in both directions. Figure 3 shows the plan view the 3-D models used in this study. A 3-D model with plan aspect ratio of 1:*n* is modeled as *n* numbers of 1:1 square buildings being placed in a row. This model is further simplified using four VLLRs, with each VLLR being *n* times stiffer and stronger, and with rotational stiffness K_θ, period ratio Ω. The dimension of the slab is unchanged. Each building model represents a certain case with fixed Ω and plan aspect ratio, and only those cases with two translational period (in two orthogonal directions) ratio larger than 0.5 and less than 2 are kept for ground motion time history analysis.



M_c/M_y	θ_p	θ_{pc}	κ	θ_u
1.1	0.03	0.2	0.4	0.2

Figure 1. Generic frame used in this study: (a) geometry, (b) spring backbone curve

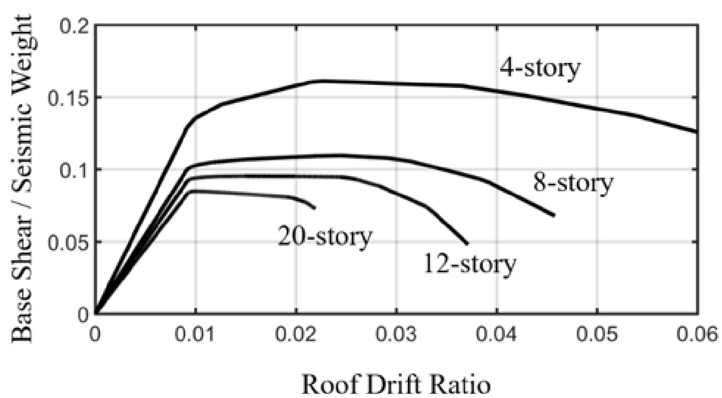


Figure 2. Pushover curves of the generic frames used in this study, (b) Modeling approach to capture plan aspect ratio

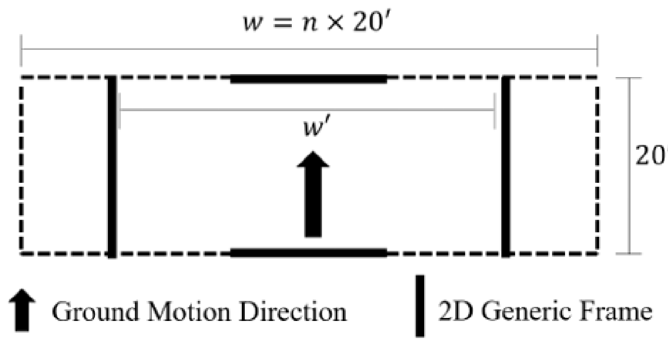


Figure 3. Modeling approach to capture plan aspect ratio

Two building locations are selected: Downtown San Francisco (37.7749°, -122.4194°) and Downtown Los Angeles (37.0416°, -118.2468°) and three design hazard levels are considered: 50% probability of exceedance in 50 years (return period of 72 years), 10% probability of exceedance in 50 years (return period of 475 years) and 2% probability of exceedance in 50 years (return period of 2475 years). Altogether six scenarios are analyzed in this study. Disaggregation using OpenSHA is first employed to obtain magnitude, distance and epsilon for each scenario. Conditional spectrum covering a period range from 0.2 times smallest first translational period to 1.5 times largest first translational period is then used for selection of 30 pairs of ground motion with scaling factor larger than 0.5 and lesser than 2.0.

General Observations and Trends

Results of the downtown Los Angeles site at 475 years average return period are illustrated in this section, similar patterns can be found at other hazard levels, and at the downtown San Francisco site. The authors suggest that the results of a 475 years average return period would be more attractive given that this hazard level is generally closer to the design basis earthquake in ASCE-7. Statistics of torsional characteristics such as α_1, α_2 and equivalent eccentricity are computed at all story levels. One may either focus on statistics of the most critical floor with the largest value of α_1 and α_2, representing the worst-case scenario, or focus on statistics of all floors. Results of *all floors* from 8-story and 12-story building models are illustrated in this section, similar results can be found for 4-story and 20-story buildings.

Figure 4 shows the variation of median and 84% of α_1 (i.e. $\alpha_1^{50\%}$ and $\alpha_1^{84\%}$) for all buildings with combinations of aspect ratio and Ω. Circle, asterisk, triangle, and square markers represent information associated with 1:1, 1:2, 1:4, and 1:8 floor plan aspect ratios, respectively. Similar trend can be observed in both median value and dispersion (difference between 50% and 84%) of α_1 as they decline with Ω becomes larger. In general, 12-story buildings have higher α_1 compared to 8-story buildings: the median of α_1 for 12-story buildings can reach up to 1.16 and the 84 percentiles up to 1.35; the median of α_1 for 8-story buildings can reach up to 1.10 and the 84 percentiles up to 1.30.

Figure 5 shows the variation of median and 84 percentiles of α_2 (i.e. $\alpha_2^{50\%}$ and $\alpha_2^{84\%}$) for all buildings with respect and Ω. It can be observed that although both acting as inversely proportional to Ω, α_2 has a much higher dependency on Ω than α_1. 8-story buildings can have α_2

values as high as 1.15 in median, and 1.37 in 84 percentiles. For tall buildings such as 12-story ones, α_2 goes up to 1.19 in median and 1.37 in 84 percentiles.

Equivalent eccentricity is even less dependent on Ω, because the mapping from α_1 to α_p offsets the Ω dependency. Figure 6 shows that the median value of equivalent eccentricity to capture accidental torsional moment is between 2% to 5% for almost all buildings and floor aspect ratios except for 1:1 floor plan aspect ratio, where median equivalent eccentricity exceeds 9%. Much of this deviation is due to the derivation of α_p (see Eq. 4). A larger equivalent eccentricity is needed for a 1:1 plan to achieve similar displacement magnification to that of a larger floor plan aspect ratio. In the same manner, for the 84 percentiles, equivalent eccentricity is between 6% and 12% for all cases except 1:1 plan aspect ratio, which can reach 28%.

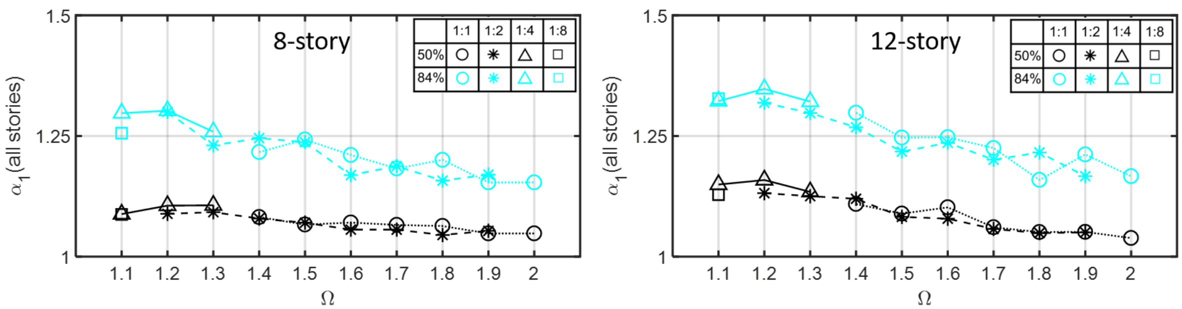


Figure 4. Variation of $\alpha_{1,all}^{50\%}$ and $\alpha_{1,all}^{84\%}$ with respect to Ω and plan aspect ratio for all buildings

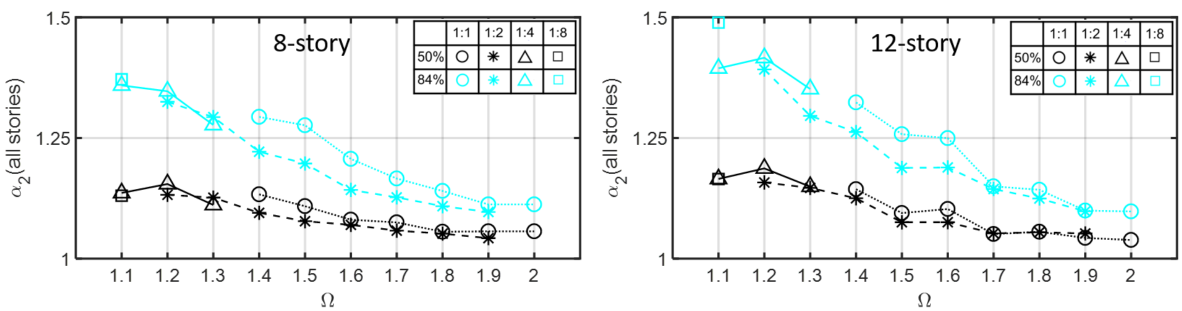


Figure 5. Variation of $\alpha_{2,all}^{50\%}$ and $\alpha_{2,all}^{84\%}$ with respect to Ω and plan aspect ratio for all buildings

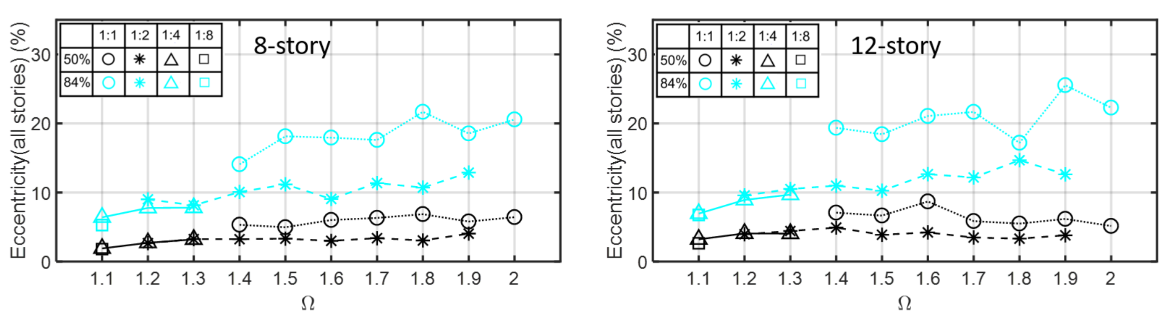


Figure 6. Variation of $e_{all}^{50\%}$ and $e_{all}^{84\%}$ with respect to Ω and plan aspect ratio for all buildings

Comparison between Analytical and CSMIP data

To validate analytical results, variation of α_2 with respect to Ω and plan aspect ratio of 11 buildings along with 12 sets of translational and rotational responses are selected from CSMIP database (Table 1). The selected buildings are nominally symmetric in plan and have more than one sensor on each floor in at least one direction (#57357 has two sensors in both directions) to enable extraction of rotational response. 4- and 5-story CSMIP buildings are categorized into the 4-story building group, 7-, 8- and 9-story CSMIP buildings are categorized into the 8-story building group and 13-story CSMIP buildings are categorized into the 12-story building group. As shown in Figure 7 and 8, α_2 is computed from every instrumented floor for each seismic event, then compared to the analytical results of $\alpha_{2,all}^{50\%}$ and $\alpha_{2,all}^{84\%}$ under hazard level of 50% probability of exceedance in 50 years (72-year average return period) at downtown Los Angeles site. The authors believe this comparison is relatively accurate since the recorded seismic events have spectral acceleration ranging from 0.0004g to 0.5g, with a median of 0.03g. In order to make comparison with analytical results, plan aspect ratio of CSMIP buildings is manually divided into two categories: larger than 1:1 and less than 1:2, larger than 1:2 and less than 1:4, denoted by red circle and blue cross respectively in Figure 7 and 8. Ω is computed using signal processing and system identification techniques, so that the Ω estimate varies for the same building subject to different ground motion excitations.

Table 1. Selected buildings from CSMIP database

Building ID	*Number of stories*	*Plan Aspect Ratio*	*Category*
12299	4	1.8	4-story
58261	4	1.9	
24463	5	1.4	
12493	4	1.7	
24571	9	2.5	8-story
24386	7	2.8	
23481	7	1.5	
24249	8	2.3	
57357, x-dir	13	1.0	12-story
57357, y-dir	13	1.0	
58354	13	1.0	
24322	13	2.6	

Analytical building models have Ω values ranging from 1.1 to 2; Ω of CSMIP buildings do not necessarily cover the same range and can reach less than 1.1 under certain circumstances. However, a declining trend in α_2 with increasing Ω can be observed both in analytical models and CSMIP buildings. Plan aspect ratio, on the other hand, is not as a significant factor as Ω for both analytical and CSMIP statistics. The 50 percentiles of the analytical results are able to capture the median of α_2 obtained from CSMIP buildings and the dispersion of CSMIP data matches well with that of analytical data: the more torsionally sensitive the system is, the higher the variance of α_2 will be.

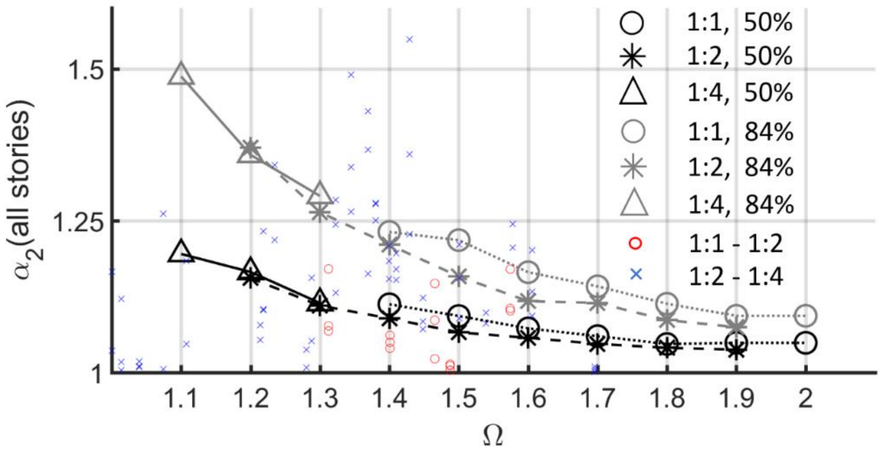


Figure 7. Analytical and CSMIP data of $\alpha_{2,all}^{50\%}$ and $\alpha_{2,all}^{84\%}$ with respect to Ω and plan aspect ratio for 4-story buildings subject to ground motions of 72-year average return period

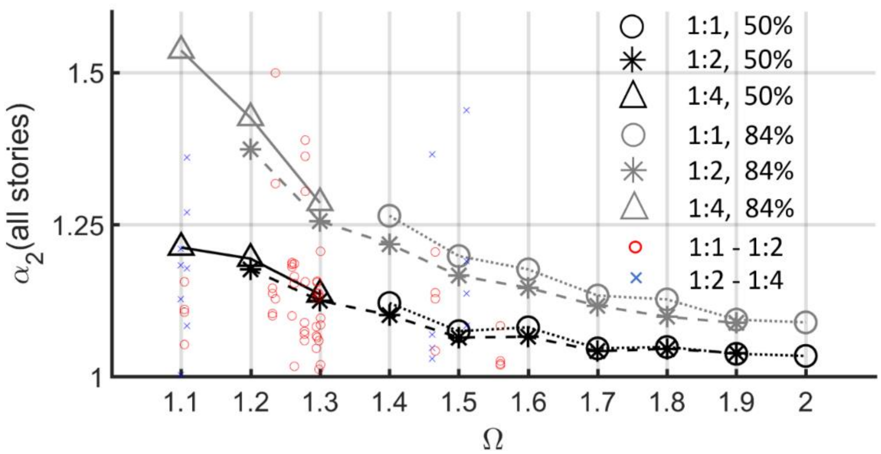


Figure 8. Analytical and CSMIP data of $\alpha_{2,all}^{50\%}$ and $\alpha_{2,all}^{84\%}$ with respect to Ω and plan aspect ratio for 4-story buildings subject to ground motions of 72-year average return period

Conclusions

The research aims at quantification of equivalent eccentricity and other torsional vibration characteristics such as displacement amplifications that captures the effects of accidental torsional moment in building structures. It is assumed that randomness in VLLRs stiffness is the source of accidental torsion. A combination of four build heights with 4, 8, 12, and 20 stories, four floor plan aspect ratios (i.e. 1:1, 1:3, 1:4, and 1:8) and period ratio Ω ranging from 1.1 to 2.0 are considered. For each combination, 3-D models are generated, and each model consists of a single-bay generic frame whose stiffness and strength are well calibrated to meet target dominant periods and reach yield moment at beam ends at 1% inter-story drift ratio.

The coefficient of variation of the stiffness of all structural elements is set to 0.14 following a comprehensive literature survey. By selecting 30 pairs of ground motions that represent seismic hazard with average 475 years return period at Downtown Los Angeles, Monte-Carlo simulation was employed to obtain statistical measures of α_1, α_2 and equivalent eccentricity e% due to randomness in VLLRs stiffness. Similar simulations were conducted for Downtown San Francisco, and at 72 and 2475 years return period at both locations.

The results demonstrate that the 5% equivalent eccentricity rule is adequate to capture the median value of magnification in deformation due to accidental torsion. In all cases this value is conservative other than buildings with 1:1 aspect ratio, where a 10% equivalent eccentricity may be required. This conclusion is based on preforming statistical analysis on all floor displacement magnifications and the reported value would be larger if the most critical is or a higher than median confidence (e.g. 84%) is sought to develop the estimates of equivalent eccentricity.

11 symmetric-in-plan buildings with recorded translational and rotational response are selected from CSMIP database. Selected buildings fall into 3 categories in terms of building heights: 4-, 8- and 12-story, and into 2 categories in terms of plan aspect ratio: 1:1 – 1:2 and 1:2 – 1:4. Results of CSMIP data is compared to analytical data obtained from 72-year average return period at downtown Los Angeles site. A good match in median values and dispersion of α_2 with respect to Ω verifies the validity of analytical results.

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