CRITICAL ASSESSMENT OF CODE TORSIONAL PROVISIONS FOR LOW-RISE BUILDINGS WITH SEMI-RIGID DIAPHRAGMS DATA

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Abstract

Our research puts the accidental torsion provisions in ASCE-7 for low-rise buildings in perspective; various combinations of plan aspect ratios, irregularity, and diaphragms rigidity are investigated. The presented work is based on simulations; however, the building models used in the study are proportioned to represent a wide range of code conforming buildings. 4-story building prototypes with a 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. Type 1a (Torsional Irregularity) and Type 1b (Extreme Torsional Irregularity) – according to ASCE 7 – is considered as the measure of floor plan irregularity. Uncertainty in stiffness is treated as the source of accidental eccentricity. Results are compared with corresponding MDOF models having regular plans (i.e., symmetric) and rigid diaphragms. We conclude that the magnification in deformation demands due to accidental torsion in buildings with a semirigid diaphragm, or inherent plan irregularity, is smaller than building with regular floor plan and rigid diaphragm. Equivalent design eccentricities obtained from this body of work indicate that the 5% equivalent eccentricity rule is conservative to capture the deformation's magnification due to accidental torsion in low-rise buildings possessing floor plan irregularity or semirigid diaphragms if median estimates of all stories are the basis of code calibration.

Introduction

ASCE 7 (ASCE, 2010, 2017) traditionally requires an increase in the inherent torsional moment by applying a 5% offset (perpendicular to ground motion direction) to the location of the center of mass on each floor. Accidental torsion is intended to account for the randomness in the distribution of floor mass and stiffness of Vertical Lateral Load Resisting systems (VLLRs). These design provisions require a magnification of accidental torsional moment for structures with torsional irregularity Type 1a and Type 1b and designed with Seismic Design Category (SDC) C to F assignment. Meanwhile, ASCE 7 does not distinguish any difference between rigid and semirigid floor diaphragms when it comes to the issue of accidental torsion. These requirements seem counterintuitive; one may expect that accidental torsional effects in semirigid diaphragms are less severe than rigid diaphragms due to the floor system's in-plane deformations. Moreover, the inherent torsional moment of torsionally irregular floor plans dwarfs the effect of accidental torsion, rendering their magnification less plausible.

One of the earliest research endeavors for characterizing accidental torsional moment in symmetric-in-plan structures originated by De la Llera and Chopra (1992); they used instrument data from three low-rise buildings (by California Strong Motion Instrumentation Program, CSMIP) and concluded that the 5% accidental torsional rule is adequate. They employed linear response spectrum analysis (De la Llera & Chopra, 1994;1995) to show 5% eccentricity is adequate for most steel and concrete special moment-resisting frames. Following a similar approach for reduction of MDOF systems to analytical models with three degrees of freedom (two translational and one rotational), other researchers such as Lin et al. (2001), Hernandez & Lopez (2004), De-la-Colina & Almeida (2004), Basu et al. (2014), have made recommendations on enhanced approaches to include accidental torsion in the response assessment of buildings for seismic design purposes.

The sensitivity of buildings' seismic performance to the inclusion (and exclusion) of accidental torsion provisions in their structural design was tackled by a few researchers to shed light on the issue from another angle. DeBock et al. (2014), and ATC (2018), have used a reduced form of MDOF models for ordinary and special reinforced concrete moment frames and investigated the collapse performance of such models with and without the inclusion of accidental torsional moment in their design. They conclude that ASCE 7 accidental torsion design requirements are only significant for buildings with SDC D assignment if their torsional irregularity is beyond Type 1a (i.e., TIR>1.2). They suggest that the inclusion of accidental torsional moment for structural design in the form suggested by ASCE 7 is typically not needed except for extreme plan irregularities. With a similar focus and performance objective (i.e., collapse), Flores et al. (2018) has focused on steel buildings (9-story with Buckling Restrained Brace Frames). They recommend that accidental torsion should be included in the nonlinear analysis of torsionally irregular buildings. Failure to add accidental torsion in the nonlinear analyses can lead to significant underprediction of deformations.

In contrast with Debock et al. (2014) and Flores et al. (2018), who used a rigid diaphragm assumption in their analytical building models, Fang and Leon (2018) investigated the difference between the response of low-rise steel buildings with rigid and semirigid diaphragms. Accidental eccentricity was created by shifting the center of mass as much as 5% of the diaphragm dimension. They observe that the drift demands in the asymmetric structures are higher for those with semirigid diaphragms than those with rigid diaphragms. This observation is argued to be due to the diaphragm's finite in-plane rigidity, leading to significant higher-mode effects and larger lateral deformation.

Compared with other studies summarized above, our study aims to quantify the needed amount of accidental torsional moment that can represent uncertainty in stiffness of VLLRs in response assessment at the design level seismic excitation. The intention is to put the seismic design provisions of ASCE 7 in perspective. To this end, our study is aligned with De la Llera and Chopra (1994) because both studies aim to find an equivalent eccentricity to account for the accidental torsional moment. This study, however, is in contrast with DeBock et al. (2014) in which the impact of including (and excluding) accidental torsional moment suggested by ASCE 7 in the design process is evaluated. The research work presented here is complementary to Xiang et al. (2018), where the accidental torsional moments in symmetric buildings with rigid diaphragms were investigated. We have expanded our previous research to address asymmetric floor plans and peculiarities that arise from including the diaphragm's finite stiffness (i.e., semirigid diaphragm) in the context of accidental torsion. The focus here is on low-rise buildings.

Methodology

In this study, uncertainty in VLLR stiffness is the only source of accidental torsion in buildings. This uncertainty is assumed to arise from the variability of element cross-section dimensions, second moment of inertia, and material strength. Using the information suggested in Xiang et al. (2018), a coefficient of variation (CoV) of 0.14 is set for the stiffness of VLLRs.

Three-dimensional (3-D) models of 4-story buildings with a combination of three different plan aspect ratios (1:2, 1:4 and 1:8), three levels of diaphragm rigidity (rigid, and two levels of semirigid, denoted as RI, S1, and S2, respectively), and three levels horizontal irregularity (i.e., TIR = 1.0, 1.2, 1.4) are created. Given that translational and torsional mode of vibrations simultaneously affect a building's general response, the factor Ω is defined as the ratio of the dominant translational period (T_{tran}) to the dominant rotational period (T_{rot}). Large Ω values associated with perimeter frame buildings and small Ω values represent core-wall systems with low torsional stiffness. Building models with Ω ranging from 1.1 to 2.0 are developed, which covers most of the building cases. These models are denoted as *base* models.

The 3-D analytical models' realizations are created by randomizing beam and column stiffness and strength properties using CoV = 0.14. We assume accidental torsional moments are caused by the asymmetric stiffness introduced through randomness in stiffness of VLLRs. Such phenomena lead to a torsional moment at any horizontal irregularity (i.e., TIR = 1.0, 1.2, 1.4). Nonlinear Time History Analysis (NLTHA) is conducted using the Opensees platform and 60 single component ground motion excitations at 475 year return period for San Francisco (37.7749°, -122.4194°). Disaggregation using OpenSHA is first employed to obtain magnitude, distance, and epsilon for each dominant scenario. Conditional spectrum (Baker, 2011) covering a period range from 0.2 times the smallest first translational period to 1.5 times the largest first translational period is then used to select 30 pairs of ground motion with scaling factor larger than 0.5 and lesser than 2.0. For each *base* model, two random realizations are created, leading to 180 (= 3 × 60) models for each combination of plan aspect ratio, diaphragm rigidity, horizontal irregularity, and Ω. Measurements are taken for the largest displacement amplification among four corners of each floor based on the rigid and semirigid diaphragm assumption. Deformation demands are recorded and transformed into two deformation magnification factors α_1 and α_2 (will be explained in the following) to quantify accidental torsion's impact on building response. Statistical measures (e.g., median and 84%) of α_1 are used to estimate the equivalent design eccentricity (represented by e(%) shown in the following), which is used to account for the effect of accidental torsion during design procedures.

Parameters that characterize building torsional response

Parameters α_1 and α_2 are introduced, Eq. (1) and Eq. (2), to quantify the magnification in displacement response due to uncertainty in VLLR stiffness. α_1 and α_2 are defined for each floor; for a 4-story building, four distinct values of α_1 and α_2 is computed for each random case. Similar factors are computed for drift demands for each story; however, to keep notations simple, we rely on α_1 and α_2 to represent floor displacement and story drift. In these equations, δ_{tot}^{base} denotes the maximum displacement of a floor (or drift of a story) for the *base* model. Conversely, δ_{tot}^{rand} denotes the maximum displacement of a floor (or drift of a story) for a random model. There are two random models for each *base* model; therefore, one can compute two distinct values for α_1, and α_2 for each floor (or story) given a ground motion record. δ_{Tran}^{base} and δ_{Tran}^{rand} denotes the maximum translation of the middle of the floor (or middle of the story) of a *base* model and a random model, respectively. α_1 is formulated to quantify the magnification in deformation demands due to uncertainty in VLLR stiffness compared to the *base* model. α_2 is suggested to quantify the magnification of deformation compared to the middle of the floor (in the spirit of calculating TIR), or story, compared with the same magnification for the *base* model. The denominator of Eq. (2) for symmetric buildings is unity.

$$\alpha_1 = \left(\frac{\delta_{tot}^{rand}}{\delta_{tot}^{base}}\right) \qquad \text{Eq. (1)}$$

$$\alpha_2 = \frac{\left(\frac{\delta_{tot}^{rand}}{\delta_{Tran}^{rand}}\right)}{\left(\frac{\delta_{tot}^{base}}{\delta_{Tran}^{base}}\right)} \qquad \text{Eq. (2)}$$

We suggest equivalent eccentricity be calculated in a manner that maximum deformation obtained by application of lateral loads (from ASCE 7) with a distance from the center of mass result in a similar statistical measure of α_1. One can use median, or 84%, of α_1 for the calculation of equivalent eccentricity.

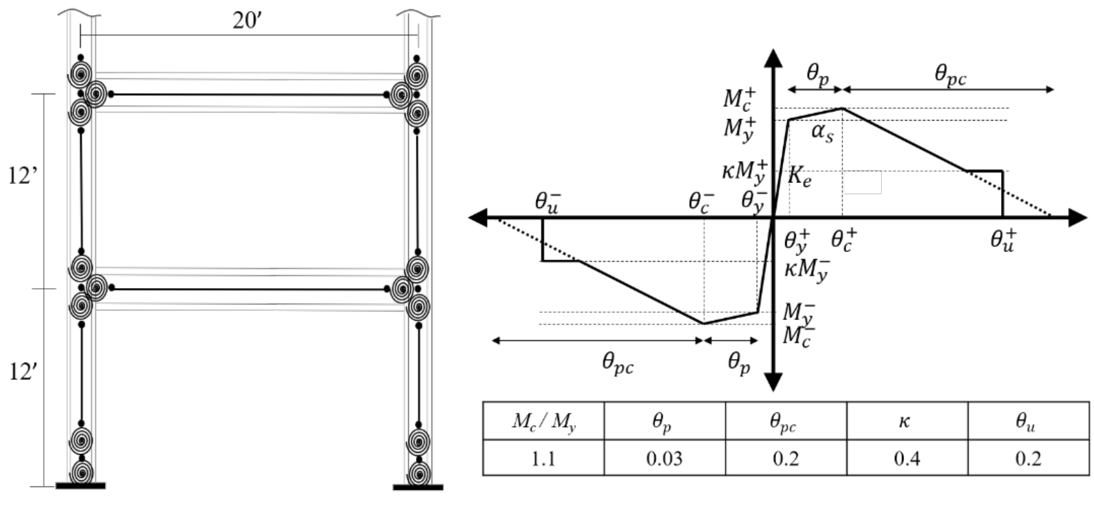
Building Models and Ground Motions

4-story building models are generated in the OpenSees platform. The 3-D building models comprise four 2D frames. 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 moment of inertia of beams and columns in this idealized model is set to be 1.0, which leads to a reasonable beam to column stiffness ratio and strong column weak beam ratio (assuming proportional strength and stiffness).

Distribution of moment of inertia along the building height follows story shear distribution according to the ASCE 7 Equivalent Lateral Force (ELF) method. Moment of inertia of beams and columns of *base* models with symmetric floors are computed through an optimization method targeting a period of 1.6s for the *base* model with symmetric floor plans and rigid diaphragms. Asymmetric *base* models are created by moving the center of mass laterally and perpendicular to the direction of ground motion application to achieve TIR = 1.2 and 1.4. Rotation of beams and columns are computed at story yield point (i.e., 0.01 drift ratio) from which moment capacity of beams and columns is obtained. Springs with bilinear hysteretic (Ibarra et al., 2005) characteristics are placed at the beam, as illustrated in Figure 1. Parameters for the bilinear hysteretic springs are shown in Figure 1b.

Symmetric *base* models with a plan aspect ratio of 1:1, 1:2, 1:4, and 1:8 are generated with rigid diaphragms. These *base* models are later modified to develop *base* models with a semirigid diaphragm. Figure 2 shows the plan view of the 3-D models used in this study. A 3-D model with a plan aspect ratio of 1:*n* is modeled as *n* number 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 periods (in two orthogonal directions) ratio larger than 0.5 and less than 2 are retained for NLTHA.



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

(a) (b)

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

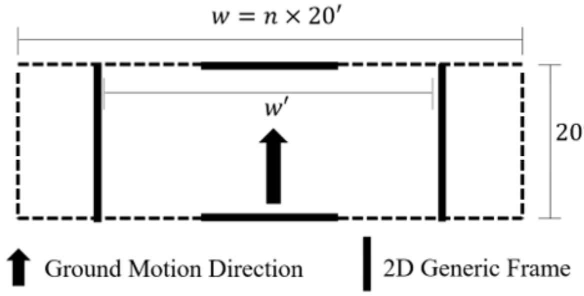


Figure 2. Floor plan to achieve various plan aspect ratios

The semirigid diaphragm is modeled as a beam in the middle of the floor, from one end to another. This beam's in-plane stiffness is uniform for all floors and is calibrated for the most critical level (i.e., roof). Two levels of finite diaphragm stiffness are defined, inspired by ASCE 7, Section 12.3.1.3, denoted with the variable β. $\beta = 1$ represents the case in which the floor's in-plane stiffness leads to an extra amount of lateral drift (in the middle) equal to the story drift if lateral loads are applied as an equivalent tributary lateral load. For $\beta = 2$, the floor's in-plane stiffness is calibrated to two times the lateral drift obtained for $\beta = 1$.

General Observations and Trends

Statistics of torsional characteristics α_2 and equivalent eccentricity (i.e., *e*%) are computed at all floor and story levels. One may focus on statistics of the most critical floor (or story) with the largest value of α_2 and $e\%$, representing the worst-case scenario. On the other hand, utilizing all floors' statistics results in a more refined understanding of accidental torsion's effect on low-rise buildings' deformation response. Both forms are presented in this section, alongside the effect of floor asymmetry and finite in-plane rigidity. We start by investigating the effect of floor asymmetry on α_2 and $e\%$ separately from the effect of finite in-plane rigidity on the same parameters. The intention is to grasp the needed understanding of each of these two building characteristics' impact before studying their combined effect. The combined effect of floor asymmetry and finite in-plane rigidity on α_2 will follow this early discussion.

A short explanation about the format of the presented figures (Figures 3-7) can assist in a better understanding of their intent. Figures are presented in a 3 by 2 mosaic format; the left and right columns show the parameter under study's statistical measures for the critical floor/story and the entire building, respectively. Black and red colors, respectively, indicate 50% and 84% statistics of the parameter studied (i.e. α_2 or $e\%$). Markers are presented for different floor plan aspect ratios of 1:1, 1:2, 1:4, and 1:8. Given its lack of viability, there is no structure with a semirigid diaphragm and a 1:1 floor plan aspect ratio. The horizontal of all plots is set to show Ω with values ranging from 1.1 to 2. Xiang et al. (2018) studied the Ω values of CSMIP instrumented buildings using collected instrument data; the range Ω used here covers a wide range of Ω values observed by Xiang et al. (2018).

Figures 3 and 4 show the impact of plan irregularity and finite in-plane rigidity on α_2, respectively. Both figures show a reduction in median amplification of deformations due to accidental torsion compared to the case with a symmetric floor plan and rigid diaphragm. This observation is stable for both the most critical floor and all floors alike, although the median α_2 once all floors are considered is less. The reduction in the median of α_2, however, because of the inclusion of finite in-plane stiffness of diaphragms is much larger than what is observed for considering asymmetric floor plans. It appears that diaphragm rigidity provides the opportunity of transferring floor rotations (due to accidental torsion) to the frames rather than absorbing it in the form of in-plane curvature. The impact of diaphragm finite in-plane rigidity on the reduction of α_2 is stable and has caused a major reduction in the 84% statistics of α_2 indicating there are not a significant number of cases that do not follow the suggested trend.

The cases with asymmetric floor plan and rigid diaphragm (i.e., Figure 3) show a reduction in the median value of α_2 especially for low values of Ω that represent torsionally flexible structures. We postulate that randomness in VLLR stiffness ameliorates the impact of asymmetric plan in increasing α_2. Given the dynamics of such a system, it is likely that the value of α_2 is less than unity; for this reason, the 50% values of α_2 are low once all the floors are included in the statistics. The slope of α_2 to Ω is reduced for larger values of TIR, which mainly shows that the torsional flexibility of the building is less important once the system is inherently asymmetric. 84% of α_2 for asymmetric floor plan and rigid diaphragm does not show the same level of drop that 84% of α_2 for cases with finite in-plane rigidity of diaphragms show. This shows that the reduction of α_2 for asymmetric floor plans with a rigid diaphragm is not as determined as to when the diaphragm is semirigid. The variability of α_2 has increased for torsionally stiff structures (large Ω) with asymmetric floor plans.

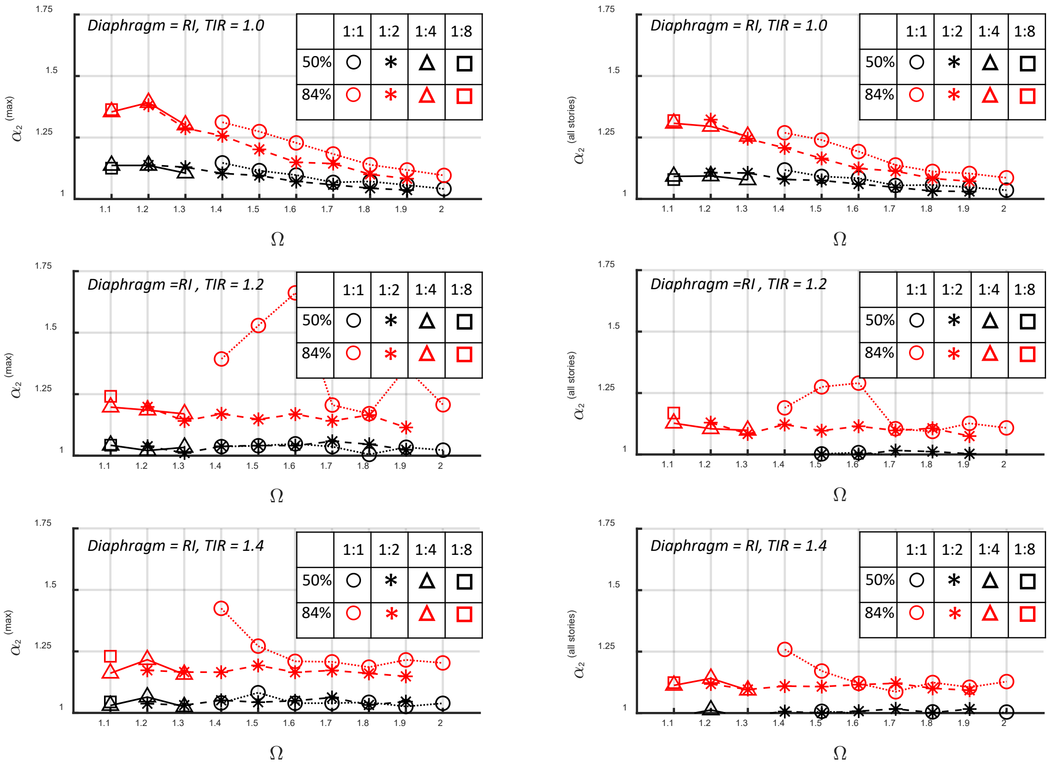


Figure 3. Variation of statistical measures of α_2 concerning Ω, plan aspect ratio, and floor plan irregularity for rigid diaphragm structures: critical story, all stories

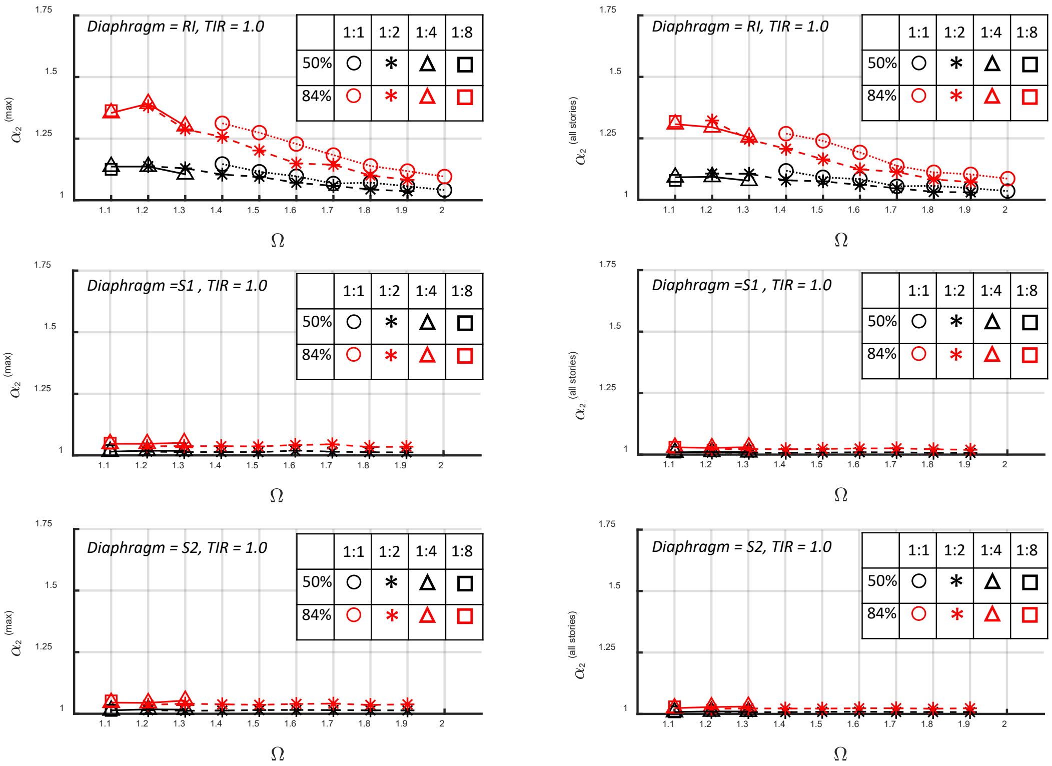


Figure 4. Variation of statistical measures of α_2 concerning Ω, plan aspect ratio, and diaphragm in-plane rigidity for symmetric structures: critical story, all stories

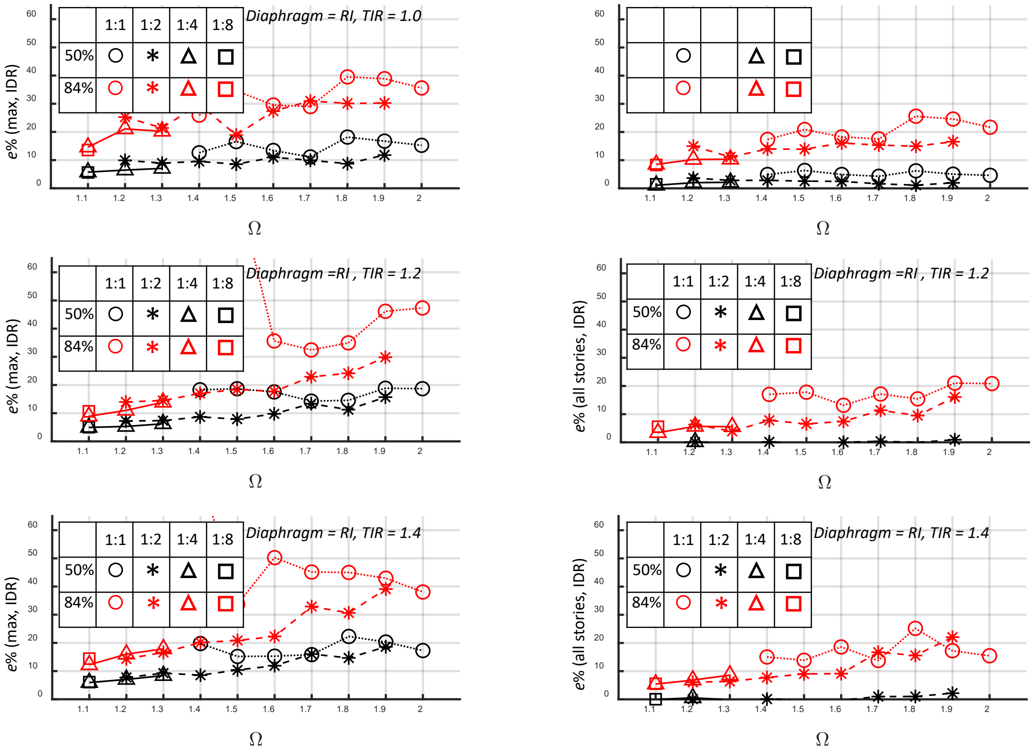


Figure 5. Variation of statistical measures of *e*% concerning Ω, plan aspect ratio, and floor plan irregularity for rigid diaphragm structures: critical story, all stories

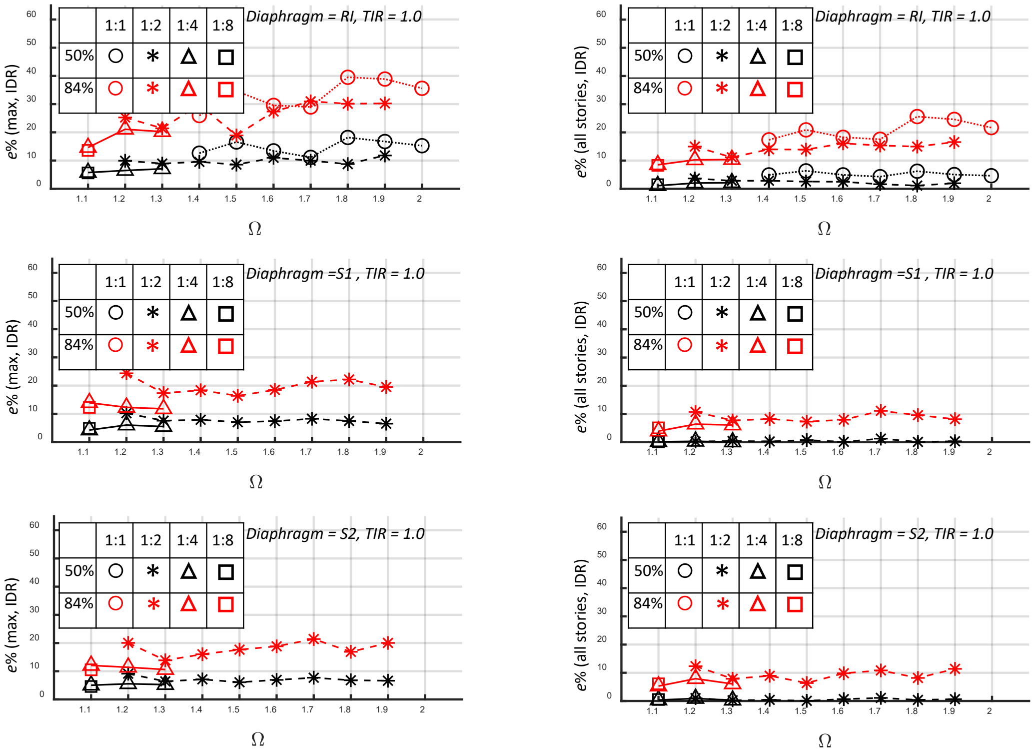


Figure 6. Variation of statistical measures of *e*% concerning Ω, plan aspect ratio, and diaphragm in-plane rigidity for symmetric structures: critical story, all stories

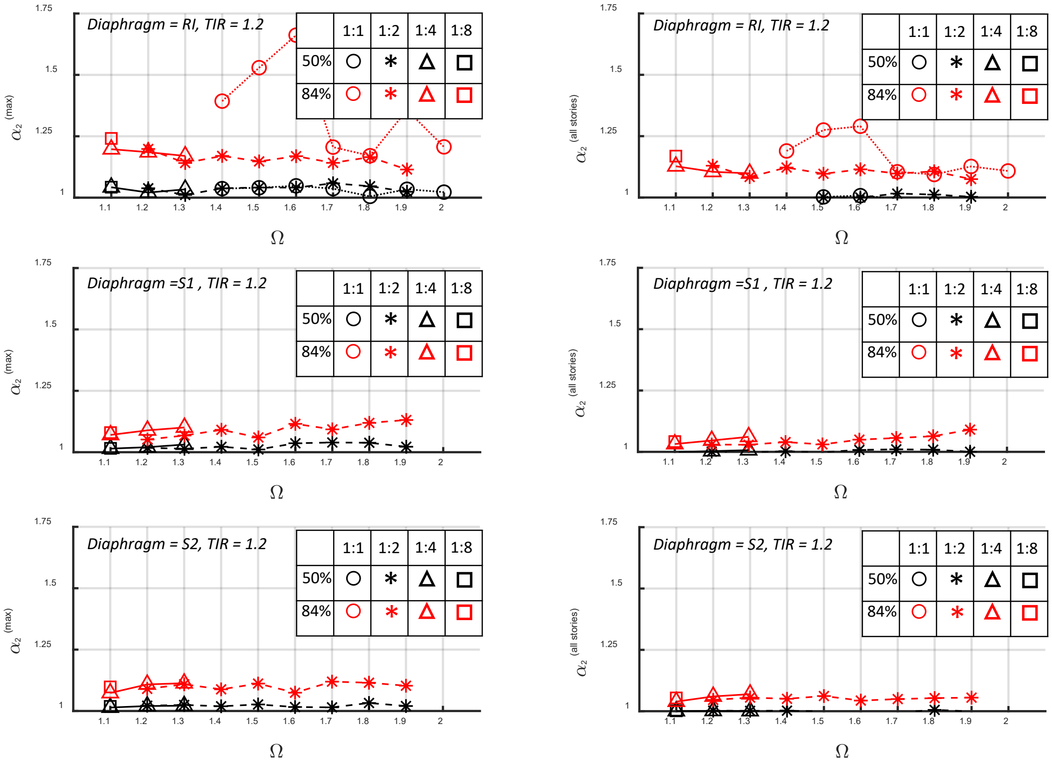


Figure 7. Variation of statistical measures of α_2 concerning Ω, plan aspect ratio, and diaphragm in-plane rigidity for TIR = 1.2 structures: critical story, all stories

The sensitivity of statistical measures of equivalent eccentricity due to plan irregularity and finite in-plane rigidity, respectively, is illustrated in Figures 5 and 6. The estimated equivalent eccentricity is based on the similarity of story drifts for pushover and NLTHA results. The observations and discussion presented for the median of α_2 is applicable for $e\%$; the median of $e\%$ is reduced compared to the case with a symmetric floor plan and rigid diaphragm. The reduction is mostly observed for the median of $e\%$ of all stories. The statistics for the most critical story was relatively unchanged when floor asymmetry was introduced. For cases with a semirigid diaphragm, the reduction in $e\%$ is not as severe as it is for α_2; this is mainly because both pushover and NLTHA estimates of drift are reduced and their ratio (which is how $e\%$ is calculated) remains unchanged. Based on the presented results, it is plausible to declare that the 5% accidental torsion provisions of ASCE 7 is relatively conservative for low-rise buildings with semirigid diaphragms or with plan asymmetry if median estimates of $e\%$ for all stories are the basis of such code calibration.

The combined effects of plan irregularity and finite in-plane rigidity on α_2 is illustrated in Figures 7. A comparison between Figure 7 and Figure 4 shows that the combination of plan asymmetry and finite in-plane rigidity does not affect the trends observed earlier. Still, the median of α_2 is reduced as finite in-plane rigidity is considered. The increase in observed variations (i.e., 84% estimate of α_2) compared to the case of a symmetric floor plan is an expected phenomenon, as observed in Figure 3.

Concluding Remarks and Future Work

We quantified the equivalent eccentricity and displacement amplifications that capture the accidental torsional moment's effects in low-rise building structures. It is assumed that randomness in VLLRs stiffness is the source of accidental torsion. 4-story buildings with plan aspect ratios of 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 calibrated to meet target dominant periods. Models with various plan asymmetry and diaphragms in-plane rigidity were developed. The coefficient of variation of the stiffness of all structural elements is set to 0.14. By selecting 30 pairs of ground motions representing seismic hazard with average 475 years return period at San Francisco, Monte-Carlo simulation was employed to obtain statistical measures of α_2 and $e\%$ due to randomness in VLLRs stiffness.

The results demonstrate that the 5% equivalent eccentricity rule is conservative to capture the effect of accidental torsion in low-rise buildings; in all cases, this value is conservative unless statistics other than the median of all stories are planned to be used as the basis of code calibration. We plan to use instrumented buildings data with recorded translational and rotational responses to validate the presented simulation results.

Acknowledgments

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