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TORSIONAL BEHAVIOR OF STEEL BRACED FRAMES

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Abstract

In this study, torsional response of steel braced frame structures is evaluated. Three dimensional model of a three story braced frame with various levels of eccentricity is created and effects of torsion on the seismic response is assessed for three hazard levels. The response history analysis results indicate that, unlike frame structures, the torsional amplifications in the inelastic systems exceed those in the elastic systems and tend to increase with an increase in the level of inelasticity. The ability of two simplified procedures, elastic response spectrum analysis and pushover analysis, in capturing the torsional amplifications in steel braced frames is evaluated.

Introduction

Torsional irregularities in the plan of a building caused by the actual distance between the centers of rigidity and mass result in non-uniform demands among the structural members of the building. Post-earthquake surveys show that this non-uniform demand distribution leads to increased vulnerability compared to torsionally regular buildings (Seong-Hoon and Elnashai 1993). Torsional effects were also reported to be the major cause of severe damage and collapse of several buildings during the 1985 earthquakes in Mexico and Chile (e.g.(Meli 1985)). As such, understanding the behavior of torsionally irregular buildings is of significant importance and has been a subject of interest for several decades.

Early studies of the seismic behavior of torsionally irregular buildings focused on buildings responding in the elastic range (Kan and Chopra 1977). Later research efforts focused on the inelastic response of single story (e.g.(Goel and Chopra Goel and Chopra, Peruš and Fajfar 2005)) and multi-story (Kosmopoulos and Fardis 2007, Marušić and Fajfar 2005) buildings. A common conclusion was that the normalized story drifts (story drifts on the flexible edge normalized by those at the center of mass) in inelastic systems do not exceed the comparable normalized drifts in elastic systems, and that the relative torsional component of deformation decreases as the ground motion intensity, and hence, ductility demands increase (Kosmopoulos and Fardis 2007, Marušić and Fajfar 2005, Peruš and Fajfar 2005).

The majority of the prominent studies on torsionally irregular buildings have been performed on shear structures (rigid beam assumption) or moment resisting frames, where

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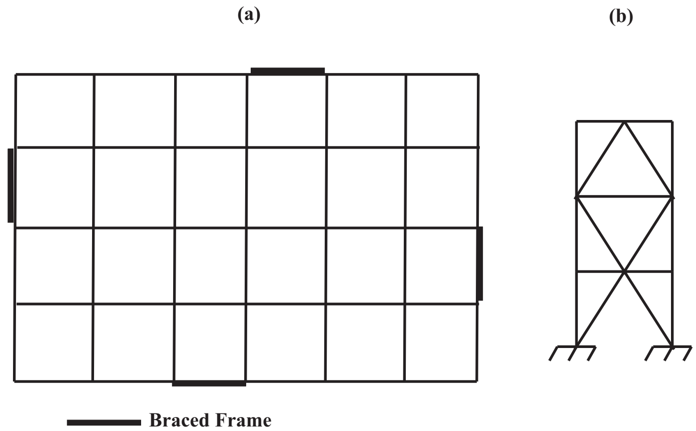

Figure 1: (a) Plan view of the building and (b) elevation view of a braced bay

the lateral resisting elements were modeled using elasto-plastic or bilinear models. Two unique features of steel braced frames elicit the expectation that their torsional behavior may not be similar to typical frame structures: (1) the (axial) force-deformation relation of the braces, which are the main lateral load carrying elements, is substantially different than the force-deformation (moment-rotation) relation of moment resisting elements; (2) moment resisting frames are generally much more redundant compared to the steel braced frames. Recently, Ding (Ding 2006) investigated the torsional behavior and redundancy of steel braced frames and reported that the fracture of a brace on one side of the building resulted in significant additional torsional rotations, which quickly led to the fracture of the "mate" brace.

The objectives of this study are (1) to evaluate the torsional amplification in a code-designed, mass-eccentric, 3-story steel braced-frame building analyzed by nonlinear response history analysis under various earthquake intensities; and (2) to highlight the significance of several key modeling assumptions such as inelastic response, level of mass eccentricity, and biaxial excitation.

Design and Modeling Assumptions for the Buildings

Design Assumptions

A hypothetical 3-story steel braced frame office building, designed by Forell/Elsesser Engineers, Inc. of San Francisco was used in this study. The building has been designed according to the provisions of ASCE 7-05 (ASCE 2005) and AISC 341-05 (AISC 2005) using *Equivalent Lateral Force Method*. The characteristic yield strength of steel was assumed to be 345 MPa (50 ksi) for frame members and 318 MPa (46 ksi) for brace members.

The building is 55 m x 36.6 m (180 ft x 120 ft) in plan, with story heights of 4.57 m (15 ft) and column spacing of 9.15 m (30 ft) in each direction. The lateral loads are carried by a single braced bay on each side of the building perimeter, while the remaining elements

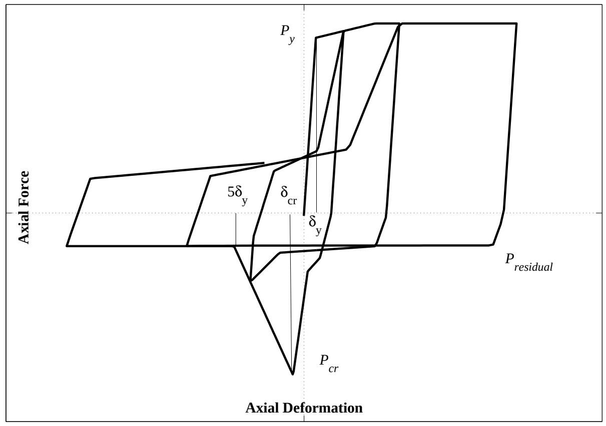

Figure 2: Cyclic constitutive force deformation relationship for axial behavior of braces

were designed to resist gravity loads only (Figure 1).

Modeling Assumptions and Details

A detailed three dimensional (3D) model of the building was developed in the *OpenSees* computational environment. Various levels of mass eccentricity were considered by changing the location of applied mass and rotational inertia at each level. An eccentricity of 5% of the longest plan dimension in both directions, which is consistent with the code mandated accidental eccentricity for dynamic analysis (ASCE 2005), was applied as the benchmark to evaluate the effects of torsion in the building.

Assigned member capacities reflected the expected yield strength of structural steel, 379 MPa (55 ksi) for frame members and 345 MPa (50 ksi) for braces. Columns and moment resisting (braced bay) beams were modeled using force-based beam-column elements that combine finite length "plastic hinge" regions at the element ends with an interior elastic region (Scott and Fenves 2006). Columns were modeled using fiber sections, while beams were modeled using stress-resultant moment-curvature relations that do not change with axial load. All stress-strain or moment-curvature relations were assumed to be bilinear with a strain hardening ratio of 3%. Gravity beams were modeled using elastic beam-column elements with moment releases at both ends. Braced bay columns were fixed at the base whereas gravity columns were pinned. A rigid diaphragm constraint was applied to account for slab action.

The axial force-deformation relations of the brace elements were modeled using the constitutive relationship proposed in FEMA-273 (FEMA 1996), depicted in Figure 2, wherein the critical buckling force P_{cr} and tensile yield force P_y were computed based on AISC 341-05 (AISC 2005). The residual compressive force ($P_{residual}$) and the axial deformation at which it is reached were assumed to be $0.2P_{cr}$ and $5\delta_y$ (δ_y = yield displacement), respectively. Rigid end zones, with a length equal to the gusset plate length, were implemented at both ends of the brace elements to account for the very high stiffness of the gusset plates relative to the braces. Accordingly, an effective length of 0.8 l_{brace}, excluding the rigid end zones, was assumed in computing the effective stiffness and critical buckling force of the brace. Energy dissipation was applied using stiffness proportional damping calibrated to give 2.5% damping at the first mode frequency.

Fundamental Properties

Elastic dynamic properties of the building was determined via elastic eigen-value analysis. The fundamental mode is a coupled lateral-torsional mode with a period of 0.50s. The second mode is a bidirectional lateral mode, with a period of 0.49s. Finally the third mode is a purely torsional mode with a period of 0.29s.

The observed base shear capacity V/W, computed from a pushover analysis performed under a constant *inverted triangle* load pattern, is approximately 0.75, whereas the required code base shear coefficient is 0.244. The reserve capacity is a result of overstrength, and restrictions on slenderness ratio and compactness that limit the selection of HSS sections for brace members.

Ground Motion Selection and Scaling

Ground motions were selected to represent three different earthquake scenarios that were expected to elicit varying degrees of inelastic response in the model building. USGS national seismic hazard maps (Frankel et al. 2000) were used to generate uniform hazard spectra (target spectra) for the three events: 50% probability of exceedence (PE) in 50 years (50/50), 10% PE in 50 years (10/50), and 2% PE in 50 years (2/50), which correspond to 72 year, 475 year, and 2475 year return periods, respectively.

For each hazard level, 20 ground motions that conform to the magnitude, distance, and site class were selected from the PEER NGA database (Chiou et al. 2008). Each pair of records was amplitude scaled by a common factor that minimized the difference of the mean spectrum of the components and the target spectrum in the least square sense from $T = 0$ to 3 sec. Figure 3 depicts the target and median response spectra for the 20 pairs of scaled ground motions for each hazard level, extrapolated out to an upper bound period of 4 seconds..

Evaluation of Torsional Effects in the Model Building

Nonlinear response history analysis (RHA) was applied to the building model as described above for each motion in the earthquake bins, thus representing three different scenarios. Unless otherwise indicated, results are reported for an inelastic model of the building with 5% mass eccentricity subjected to biaxial excitation. Representative elastic RHAs or uniaxial analyses were also performed for reference.

The influence of torsion on the seismic response of the building is evaluated by

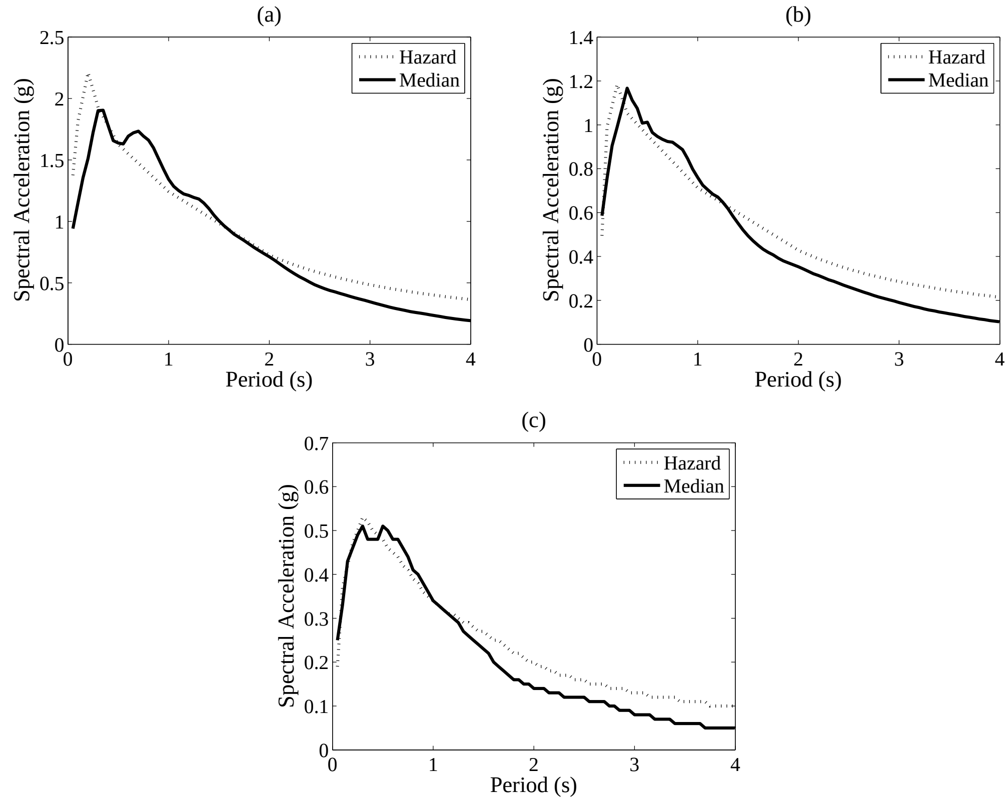

Figure 3: Target hazard spectrum and median of the response spectra of the scaled motions for (a) 2% PE in 50 years (b) 10% PE in 50 years and (c) 50% PE in 50 years hazard levels

comparing the relative contributions of rotation and lateral translation to total deformation at the plan edges. Thus, the story drift ratio, or ratio of peak drift to the story height, was evaluated at various locations on the plan. These story drift ratios are presented as normalized by the story drift ratio at the center of mass (CM) as established by previous researchers (Marušić and Fajfar 2005).

Inelastic versus Elastic Behavior

The effects of inelastic behavior of braced frames, including buckling and the subsequent degradation (Figure 2) are assessed by comparing the inelastic response of the model building with 5% accidental eccentricity to the response of the same building remaining elastic. Median peak normalized story drift ratios determined from inelastic and elastic RHA are compared in Figure 4 for the 2/50 year event and in Figure 5 for the 10/50 and 50/50 year events. The story drift ratios are plotted against the normalized plan dimension, wherein the edges of the plan in the direction under consideration are normalized to ± 1, and the geometric center $= 0$.

As shown in Figure 4 for the 2/50 year event, amplification of drift demands at the flexible edge (or reduction at the stiff edge) relative to the CM is more pronounced in the Y-direction [Fig. 4(a)] compared to the X-direction [Fig. 4(b)]. A probable explanation for

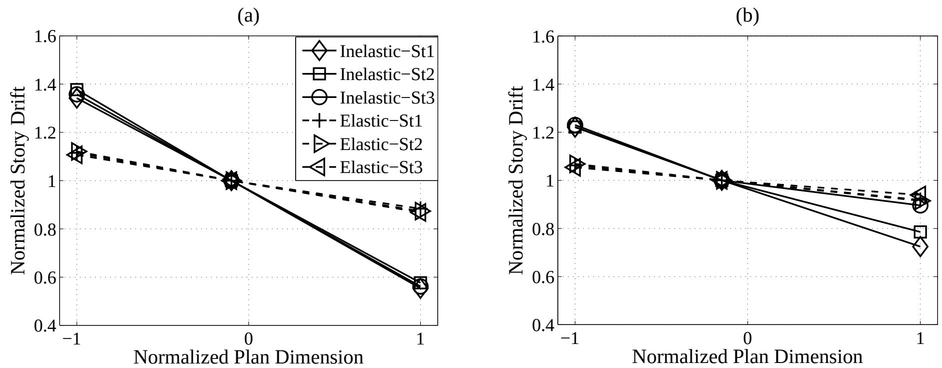

Figure 4: Median normalized story drift ratios for the 2/50 year event in (a) Y direction and (b) X direction

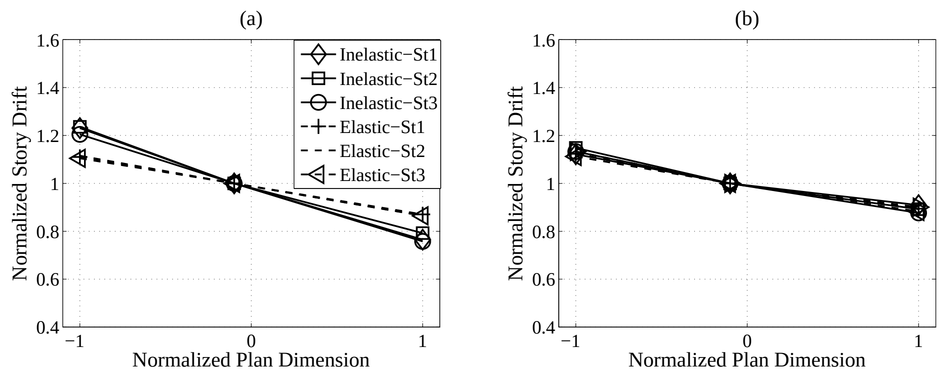

Figure 5: Median normalized story drift ratios for (a) 10/50 and (b) 50/50 year events in the Y direction

this observation is that the outermost frames on the X-edges, which move in the Y-direction, are relatively further from the CM than those on the Y-edges, and thus experience larger drift demands due to torsional rotation. Although not presented, the same trend was also observed for the 10/50 and 50/50 year events, thus all discussion from here forward will focus on the torsional amplifications observed in the Y-direction.

The relative contribution of torsion to the overall story drift demand at the plan edges is observed to increase as the hazard level increases when the system responds inelastically [Figs. 4(a) and 5]. However, the relative contribution of torsion is essentially independent of hazard level when the response remains elastic. Thus, for the 50/50 year event, the building remains essentially elastic, and the relative contribution of torsional deformation to the overall drift is comparable for elastic and inelastic analysis [Fig. 5(b)]. However, for the 10/50 and 2/50 year events, the building sees significant inelastic action, and the relative torsional deformations obtained from inelastic RHA are substantially more than those obtained from elastic RHA.

To better understand the effect of inelasticity on the torsional response, time histories of Y-direction first story drift ratios at the flexible edge, stiff edge and CM are observed for

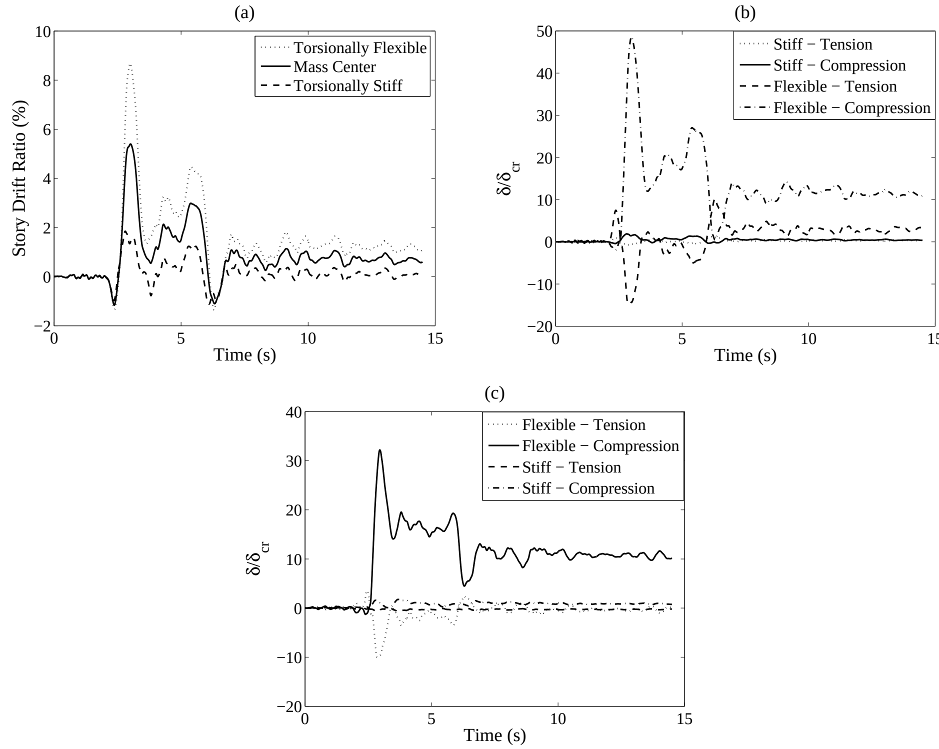

Figure 6: Time history of first story (a) Y-direction drift ratio (b) brace deformations in Y-direction, and (c) brace deformations in X-direction for the Elysian Park (SAC la35/la36) record. Compressive brace deformations are positive.

the Elysian Park (SAC la35/la36) ground motion [Fig. 6(a)], as well as first story brace deformation demands for frames oriented in the Y-direction [Fig. 6(b)] and the X-direction [Fig. 6(c)]. Through the first 2.5 seconds of the record, the braces in the first story remain elastic and the drift ratios at different plan locations are very close to each other; that is, no significant torsional amplification is observed. At this instant, the compression braces on the torsionally flexible edges – in both X and Y-directions – buckle, and the tension braces on the same edges yield. Thereafter, all the braces on the torsionally flexible edges, particularly the compression braces, undergo large inelastic deformations, including a significant irrecoverable portion (i.e. the braces never recenter). However, the braces on the torsionally stiff edge in the Y-direction appear to remain almost elastic throughout the event [Fig. 6(b)], and the stiff edge braces in the X-direction are limited to small inelastic deformations [Fig. 6(c)]. As such, the braced frames on the torsionally stiff edges become "infinitely" stiff compared to those on the torsionally flexible edges, causing the effective center of rigidity (CR) of the story to shift even more toward the stiff edges. This shift in the CR further amplifies the torsional deformations on the flexible edges, while the overall movement on the stiff edges, especially in the Y-direction, appears to be quite limited. When the system remains elastic, the CR does not shift dynamically, and amplification due to torsional deformation is much more limited, which explains the trends observed in Figs. 4 and 5.

The response histories presented in Fig. 6 are typical of the variation in deformation

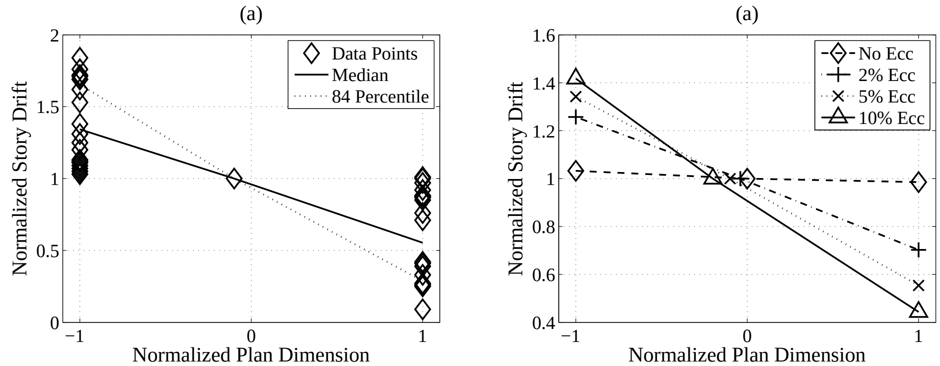

Figure 7: First story normalized story drift ratios for the 2/50 year event: (a)motion to motion to variation for 5% eccentricity (b) under various eccentricity levels

demands on the stiff and flexible side of the building due to inelastic response. In reality, a large record-to-record variablity in the normalized drift ratios is observed. Figure 7, which presents the distribution of the normalized drift ratios on both edges sampled over 20 ground motions for the 2/50 year event, illustrates that the flexible edge normalized drift ratio varies between 1 to 2, and the stiff edge normalized drift ratio varies between 0.1 and 1.

The trends observed here deviate from conclusions drawn by typical studies [e.g., (Kosmopoulos and Fardis 2007, Peruš and Fajfar 2005)] regarding the effects of inelasticity on torsional response of asymmetric systems subjected to biaxial excitation. As mentioned previously, these studies have found that the flexible edge elastic normalized story drifts establish an upper bound to the normalized story drifts in inelastic systems, and the torsional component of deformation decreases as the structure response is driven further into the inelastic range. The latter behavior was associated with the fact that once all lateral resisting elements in a given direction yield, the relative rotational deformations decrease. These conclusions were drawn by studies considering generic or moment frame lateral systems. In our estimation, braced frames do not follow the trends for typical lateral systems because of the immediate and dramatic loss in both stiffness and strength following brace buckling.

Amplitude of Mass Eccentricity

Next, the influence of mass eccentricity on the torsional amplification of braced frames, as observed through the normalized story drift ratios, is evaluated. Median normalized story drift ratios in the 2/50 year event for different mass eccentricities are plotted in Fig. **??** for the first story. As expected, the normalized story drift ratios tend to increase/decrease on the flexible/stiff edges, respectively, as the eccentricity increases. However, the rate of change of normalized story drift is not linear; that is, when the eccentricity is doubled, the relative amplification of edge deformations compared to the CM deformations does not double. In fact, the torsional amplification for 2% eccentricity (flexible normalized story drift ≈ 1.25) is more than half of the torsional amplification for 10% eccentricity (flexible edge normalized story drift ≈ 1.45) [e.g., Fig. 7(b)]. Thus, the rate of increase in torsional amplification seems to decrease substantially once sufficiently large levels of eccentricity are reached. Given the time history observations (Fig. 6), this result is not surprising. That is, the shift in the center of rotation that is dynamically induced by varying levels of buckling and yielding in the braces supersedes the effect of the initial mass eccentricity.

The median normalized story drifts are very close in value for 5% and 10% mass eccentricities. This suggests that the code required 5% accidental eccentricity for dynamic analysis (ASCE 2005) should be sufficient to capture the effect of torsion even if the initial eccentricity in the building were to exceed this value (up to 10%).

Conclusion

The torsional behavior of a code-compliant 3 story steel braced frame building has been investigated. The normalized story drift ratios have been observed and evaluated under biaxial excitation for different hazard levels and mass eccentricities. Additionally, the effectiveness of various simplified analysis procedures to capture the observed torsional response has been assessed. Synthesis of the observed seismic response has led to the following conclusions:

- The inter-story drifts are significantly amplified for the building with 5% mass eccentricity when subjected to large intensity ground motions. Specifically, the normalized story drift, or median story drift on the flexible edge of the building ÷ that at the center of mass, was observed to be 1.35 and 1.25 for the 2/50 and 10/50 year events, respectively.
- For the 2/50 and 10/50 year events, the normalized story drifts from inelastic response analysis of the building are much higher than those for the same building responding elastically. However, for the 50/50 event where the building remains essentially elastic, the normalized story drifts obtained from inelastic and elastic analyses are nearly the same.
- Our observations and conclusions are in contrast to those drawn by typical studies of asymmetric frame structures, that torsional amplifications in elastic systems exceed those in inelastic systems. For the braced frame system investigated here, the large rotational response is induced by a dynamic shift in the center of rigidity that results in substantial yielding/buckling of the braces on the flexible edge and near elastic response of the braces on the stiff edge.
- Normalized story drifts increase with increasing mass eccentricity, but the rate of increase drop off with increasing mass eccentricity.

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