Seismic Performance of Multi-Storey Torsionally-Unbalanced Torsionally-Stiff (TU-TS) Structures

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Abstract

Aesthetics and functionality requirements have turned most of the building structures to be asymmetric in recent times. These asymmetric structures have demonstrated poor seismic performance while experiencing major earthquakes in the past. Such buildings exhibit complex vibration characteristics under seismic shaking as there is coupling between the lateral and torsional components of vibration. These coupled vibrations tend to cause weak locations under torsional distress, which eventually lead towards local damage in the asymmetric structures. The identification of such weak locations is critical in nature when an asymmetric structure experiences seismic shaking. In this regard, this research demonstrates damage characteristics and global seismic behaviour of torsionally unbalance torsionally-stiff (TU-TS) systems with planar and vertical irregularities and evaluated the potentially vulnerable behaviour of TU-TS systems.

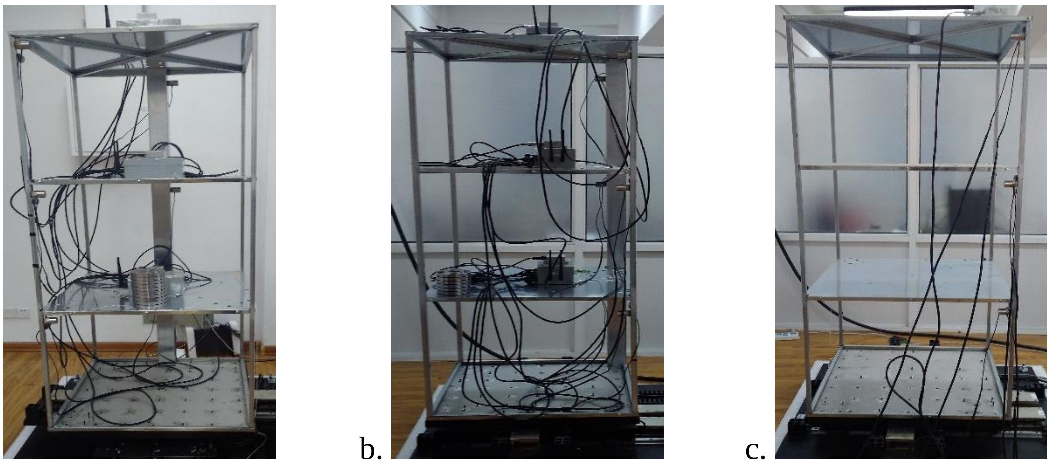
Keywords: Shake table test; Asymmetric structures; Local damage response; Global seismic response

1. INTRODUCTION:

The potential for structural failure in asymmetric structures is higher compared with symmetric structures (Oyguc et al., 2018) because torsional coupling with translation response. Numerous studies have been carried out in the past to evaluate the seismic response of asymmetric structures (Zhang et al., 2016, Anagnostopoulos et al., 2015, Duan and Chandler, 1997, Georgoussis, 2014, Tezcan and Alhan, 2001, Alam et al., 2016). However, majority of the previous studies are limited to the simplified single storey structure with global seismic effects. Research on the local damage response and its correlation with the global effects in multi-storey TU-TS systems is nearly none. This research demonstrates local damage characteristics and rotational behaviour of TU-TS structures under bi-directional seismic excitations.

2. EXPERIMENTAL MODEL:

To investigate the damage characteristics and global behaviour of TU-TS structures, three 1/6-scaled, three-storey steel structures were designed and fabricated. The fabricated TU-TS models along with their regular counterpart are illustrated in Figure 1.



a. b. c.

Figure 1: Experimental models (a). Mono-symmetric steel model (b). Bi-eccentric steel model (c). Counter-symmetric steel model

The TU-TS model were designed for both mono-eccentric and bi-eccentric stiffness eccentricities at all floor levels. Mass eccentricities (e_m) were introduced manually by shifting the centre of mass (C_M) during the shake table testing. The C_M of these structures was designed to be located at the geometric centre (C_G) of the structure while the centre of stiffness (C_S) was displaced from the C_G to form a normalized stiffness eccentricity of 0.45 (e_s / L = 0.45) at all floor levels. The state of the TU-TS system where all floors have uniform normalized stiffness eccentricity is termed as reference state of TU-TS system (Table 1). Since in the reference state, the TU-TS system possess regular floor-eccentricity along the height of the structure, the asymmetric system in this case is characterised as regularly irregular (RI) system (De Stefano et al., 2006). It is worth mentioning that the designed system by default is an RI system and after the introduction of mass eccentricities, the TU-TS systems were transformed into irregularly irregular (IRI) systems (Bosco et al., 2013). Damage characteristics and global behavior of TU-TS systems for various structural asymmetries are representative of both IR and IRI states and their detailed description is reported in Table 1. Each floor of the TU-TS system is designed such that its uncoupled torsional frequency ratio (Ω) is greater than unity thereby leading to a torsionally-unbalanced torsionally stiff (TU-TS) system. The uncoupled torsional frequency ratios (Ω) for the fabricated models were determined using equation 1 and 2 (Hejal and Chopra, 1989):

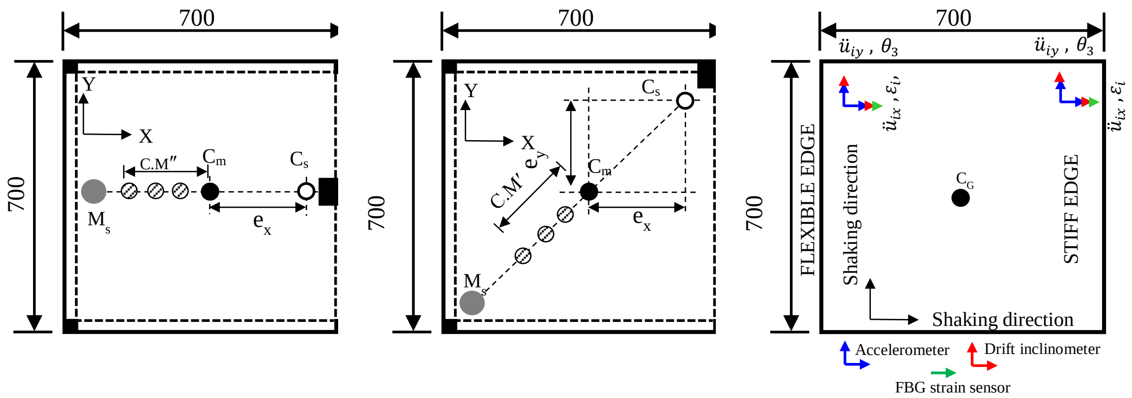
$$\Omega = \sqrt{\left(\omega_{\emptyset,G} \,/\, \omega_{x,G}\right)} \tag{1}$$

$$\Omega = \sqrt{\left(\omega_{\emptyset,G} \,/\, \omega_{y,G}\right)} \tag{2}$$

Where $\omega_{x,G}, \omega_{y,G}$ refer to the global translational frequencies and $\omega_{\emptyset,G}$ demonstrates the global torsional frequency of the assumed single DOF, system.

3. STRUCTURAL ASYMMETRIES AND INSTRUMENTATION:

The eccentricities in each of the experimental models were varied by shifting the C_M of the asymmetric structures to investigate the damage characteristics and global behaviour of the TU-TS systems under four different seismic excitations.



(a) (b) (c)

Figure 2: Experimental models and instrumentations (All dimensions in mm): (a) Schematic representation of eccentricities in mono-symmetric model (b) Schematic representation of eccentricities in bi-eccentric model (c) Schematic representation of deployed instruments

Based on the schematic representation of eccentricities in Figure 2, nine-asymmetric cases were developed as reported in Table 1, which can be observed in combination with Figure 2 to evaluate the structural asymmetries.

Table 1: Details of planar and vertical irregularities in TU-TS systems

Case No.	Characteristics of eccentricity	Asymmetric state
1	Reference state	Regularly-Irregular (RI)
2	a. Mass and stiffness eccentricity (e_m and e_s) variation at the 1st-floor level b. Stiffness eccentricity (e_s) at 2nd and 3rd floor level: e_s/L = 0.50	Irregularly-Irregular (IRI)
3	a. Mass and stiffness eccentricity (e_m and e_s) variation at the 2nd-floor level b. Stiffness eccentricity (e_s) at 1st and 3rd floor level: e_s/L = 0.50	Irregularly-Irregular (IRI)
4	a. Mass and stiffness eccentricity (e_m and e_s) variation at the 3rd-floor level	Irregularly-Irregular (IRI)

	b. Stiffness eccentricity (e_s) at 1st and 2nd floor level: $e_s/L = 0.50$	
5	Mass and stiffness eccentricity (e_m and e_s) variation at 1st, 2nd and 3rd-floor level	Irregularly-Irregular (IRI)
6	Centre of mass (C_M) and centre of stiffness (C_S) converged at one point but dislocated from the geometric centre (C_G) of the structure	Regularly-Irregular (RI)
7	a. Third floor's mass three times higher than the adjacent lower floors b. Constant stiffness eccentricity (e_s) at 1st and 2nd floor level: $e_s/L = 0.50$	Irregularly-Irregular (IRI)
8	a. Second floor's mass three times higher than the adjacent upper and lower floor b. Constant stiffness eccentricity (e_s) at 1st and 3rd floor level: $e_s/L = 0.50$	Irregularly-Irregular (IRI)
9	a. First floor's mass three times higher than the adjacent upper floors b. Constant stiffness eccentricity (e_s) at 2nd and 3rd floor level: $e_s/L = 0.50$	Irregularly-Irregular (IRI)

The deployed instruments to monitor the structural response include inclinometers at the top roof level, accelerometers, and bare Fibre Bragg grating (FBG) strain sensors at all floor levels. For a better comparison of the seismic responses, the instrumentations were arranged at both the flexible (FS) and stiff sides (SS) of TU-TS systems.

4. SEISMIC LOADING PROGRAM:

The described TU-TS systems were exposed to bi-directional seismic excitations for four different ground motion inputs as illustrated in Figure 3.

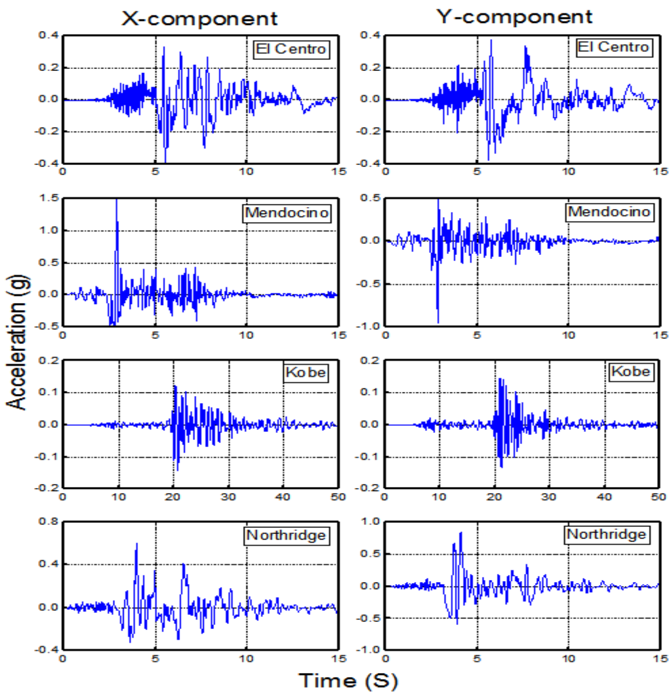
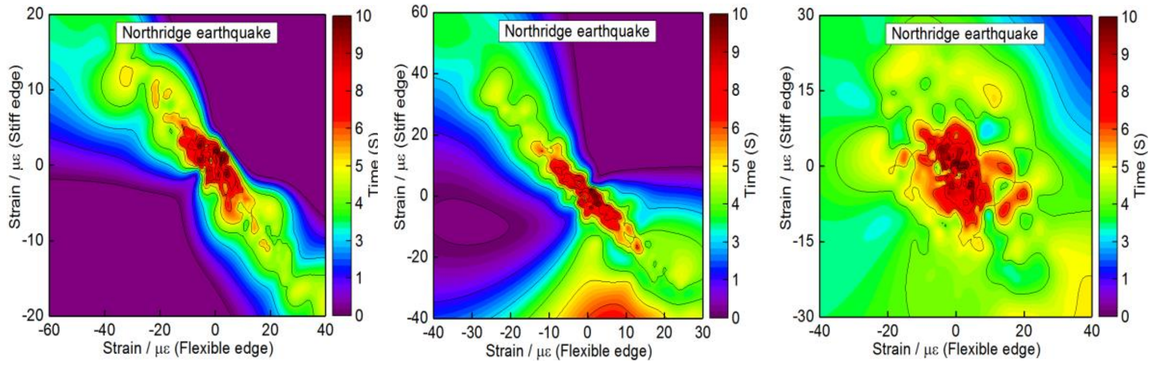


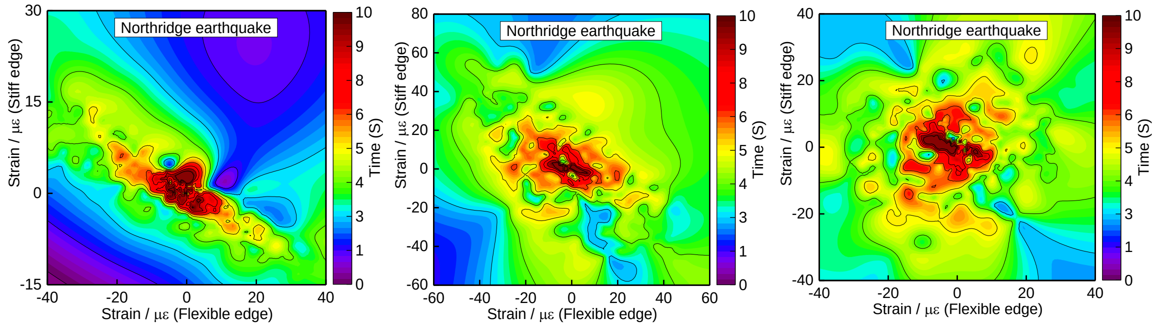
Figure 3: Input seismic motions in the time domain

5. LOCAL DAMAGE CHARACTERISTICS OF TU-TS SYSTEMS:

This section demonstrates the damage characteristics of the TU-TS systems for both mono-symmetric and bi-eccentric models at the flexible and stiff edges (Figure 4).



Bi-eccentric structure



Mono-symmetric structure

Figure 4: Damage response at the flexible and stiff edge of the TU-TS systems for the reference state under Northridge earthquake: First column corresponds to the damage response at first-floor level; Second column corresponds to the damage response at the second-floor level; Third column corresponds to the response at first-floor level

It can be seen that for TU-TS structures, simultaneous occurrence of tensile deformation at first floor level for both FS and SS is negligible. However, at the intermediate and top roof levels, simultaneous occurrence of compressive and tensile deformations is highly evident at both FS and SS of the TU-TS system in the reference state. This observation is important in regards to the damage response correlation with the global rotational response of the asymmetric systems. Besides, it can be observed that first floor demonstrates equally negligible compressive and tensile deformations whereas; the top roof demonstrates higher tensile deformations at the FS of the TU-TS systems. In general, for this particular case, top roof level is expected to experience higher amount of local damage because of higher tensile deformations. Moreover, the abrupt change in the local deformation demands at the intermediate floor highlights the fact that the seismic response is dominated by the second mode of vibration. This observation can be correlated with the global behaviour of the asymmetric structures presented in the next section where second mode dominance is highly evident especially for mono-symmetric structures.

6. GLOBAL RESPONSE CORRELATION WITH DAMAGE CHARACTERISTICS:

In the case of bi-eccentric and mono-symmetric TU-TS systems, it can be seen that the acceleration demands at the flexible and stiff edges have demonstrated similar response trends under far-field seismic excitation (Kobe earthquake).

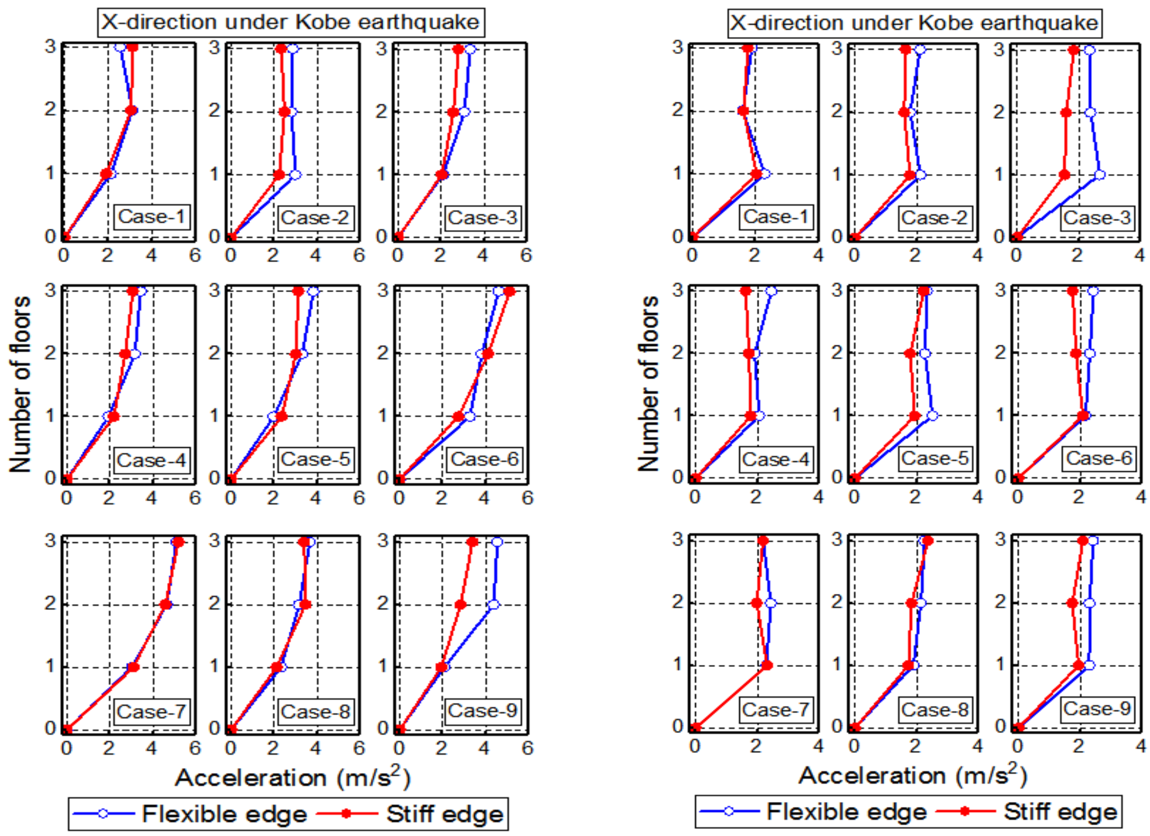


Figure 5: Amplified acceleration response of mono-symmetric and bi-eccentric structures (a). X-direction response of mono-symmetric structure under Kobe-earthquake (b). X-direction response of bi-eccentric structure under Kobe-earthquake

It is worth mentioning that lower floor eccentricities have the highest influence on the top floor's acceleration demands. Similarly, top floor's eccentricities have the highest influence on the lower's floor acceleration response. It should be noted that the described observations for mono-symmetric structure is only true for the asymmetric direction. The symmetric direction of the same system remained least affected under torsional vibrations. Furthermore, rotational response is highly evident for the IRI state of structural asymmetry. For the case of uniform eccentricities along the height, floor rotation response is observed to be minimum.

7. CONCLUSIONS:

Based on the detailed experimental investigations, following conclusions are established:

- In terms of local damage response, both mono-symmetric and bi-eccentric TU-TS systems are likely to form weak locations at the flexible edge of the intermediate and top roof levels. Lower order floors are the least affected in such TU-TS systems.
- In bi-eccentric TU-TS system with mass and stiffness eccentricities, top floor eccentricity has the highest influence on the maximum global seismic demands at the lower floor levels. Conversely, lower floor eccentricity has the highest influence on the top floor's global seismic demands. In the case of mono-symmetric structures, similar trends were monitored with an exception that the observed influence was dominant only in the direction of eccentricity. The symmetric direction was the least affected under seismic shaking.

- In both bi-eccentric and mono-symmetric TU-TS systems with mass and stiffness eccentricities, top roof experiences the highest influence of asymmetry when the planar eccentricities are non-uniform along the height of the structure. This can be observed from appreciably variant seismic responses at the FS and SS of the of TU-TS systems.
- Top roof eccentricities tend to cause highest rotational response at top roof level in TU-TS systems from global response perspective.
- Eccentricities on a floor tend to transmit their influence to the adjacent lower/upper floors.

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