Seismic Performance of Multi-Storey Torsionally-Unbalanced Torsionally-Flexible (TU-TF) Structures

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Abstract

Asymmetric structures have demonstrated poor seismic performance under coupled torsional vibrations. These vibrations tend to induce stress concentration at weak locations and eventually cause damage to the structural components. From seismic performance perspective, such weak locations are challenging to be determined in advance. However, with effective monitoring of the local deformation behaviour correlated with the global response of the structure, such estimations can be a possible realization. In this regard, this research experimentally evaluates the potential weak locations and damage characteristics under stress concentration in 1/6-scaled torsionally-unbalanced torsionally-flexible (TU-TF) systems. It has been concluded that TU-TF systems are vulnerable to damage appreciably at both flexible and stiff edges under sudden changes in the seismic demands under higher-mode effects.

Keywords: Shake table test; torsionally-flexible structures; local seismic damage; Global seismic response.

1. INTRODUCTION:

The potential for structural failure in asymmetric structures is higher compared with symmetric structures (Oyguc et al., 2018) because of torsional coupling with the 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 damage concentration and its correlation with the global effects in multi-storey asymmetric structures is nearly none. This research demonstrates potentially vulnerable locations in TU-TF structures evaluated through local damage response correlated with the global seismic behaviour.

2. EXPERIMENTAL MODEL DESIGN:

To investigate the damage characteristics and global behaviour of TU-TF structures, two 1/6-scaled, three-storey steel structures were designed and fabricated. The fabricated TU-TF model along with its regular counterpart is illustrated in Figure 1.

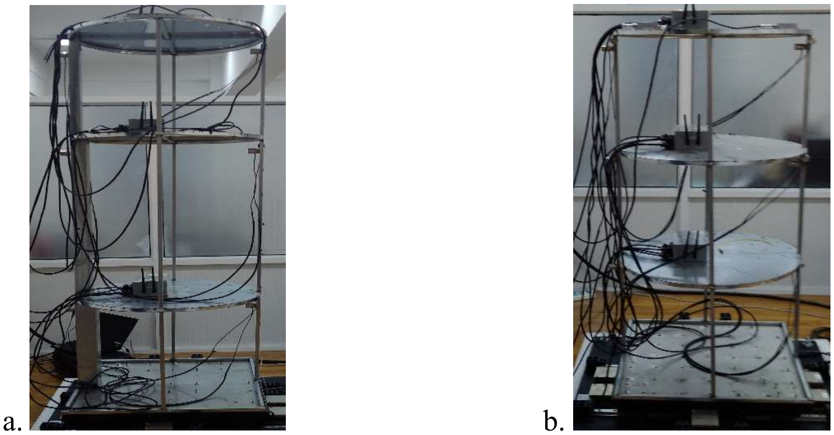

a. b.

Figure 1: Experimental models (a). TU-TF bi-eccentric steel model (b). Counter-symmetric steel model

The TU-TF model were designed to contain bi-directional stiffness and strength 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 first floor, 0.35 (e_s / L = 0.45) at second floor and 0.30 (e_s / L = 0.45) at third floor. The described state of the TU-TF system where all floors have non-uniform normalized stiffness and strength eccentricity is termed as reference state of TU-TF structure (Table 1). Since in the reference state, the asymmetric system possess irregular floor-eccentricity along the height of the structure, the asymmetric system in this case is characterised as irregularly irregular (IRI) system. It is worth mentioning that the designed system by default is an IRI system due to varying stiffness and strength eccentricities along the height of the structure. Therefore, all the investigated cases in this research pertain to an IRI system. Each floor of the TU-TF system is designed such that its uncoupled torsional frequency ratio (Ω) is less than unity thereby forming a torsionally-unbalanced torsionally flexible (TU-TF) system. The approximate global translational frequencies ($\omega_{x,G}$, $\omega_{y,G}$) and torsional frequency ($\omega_{\emptyset,G}$) of the 3-DOF system can be expressed as follows:

$$\omega_{x,G} = (K_x / M)^{0.5} \tag{1}$$

$$\omega_{y,G} = \left(K_y / M\right)^{0.5} \tag{2}$$

$$\omega_{\emptyset,G} = \left(K_\emptyset / (M \,.\, e^2 + J'_{\emptyset,G}\right)^{0.5} \tag{3}$$

Where K_x, K_y and $K_\emptyset$ are the translational stiffness in the X-direction, Y-direction and about the vertical direction respectively. M refers to the floor mass and e describes the eccentricity between C_M and C_S. In addition, $J'_{\emptyset,G}$ refers to global-polar moment of inertia and can be expressed as follows:

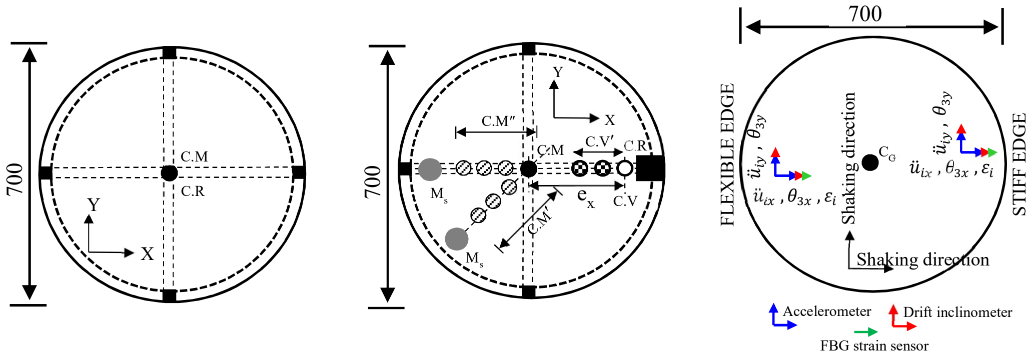
$$J_{\emptyset,G} = \left(\sum_{i=1}^{n} J'_{\emptyset,i} + m_i\left((\alpha_{xmi} - \alpha_{xG})^2 + (\alpha_{ymi} - \alpha_{yG})^2\right)\right) \tag{4}$$

In the above equation, $J'_{\emptyset,i}$ refers to the polar moment of inertia of the respective floor at C_M where α_{xG} and α_{yG} are the global coordinates at C_G of the nth-DOF system. The uncoupled torsional frequency ratios (Ω) for the fabricated models were determined using equation 5:

$$\Omega = \left(\omega_{\emptyset,G} / \omega_{x,G}\right)^{0.5} \text{ and } \Omega = \left(\omega_{\emptyset,G} / \omega_{y,G}\right)^{0.5} \tag{5}$$

3. STRUCTURAL ASYMMETRIES AND INSTRUMENTATION:

The eccentricities in each of the experimental models were varied by shifting the C_M of the asymmetric structures. Therefore, the assessment of damage characteristics and global behaviour of these models for various asymmetric conditions were evaluated after exciting the TU-TF systems under four different seismic inputs with their dominant vibration periods illustrated in Figure 2.



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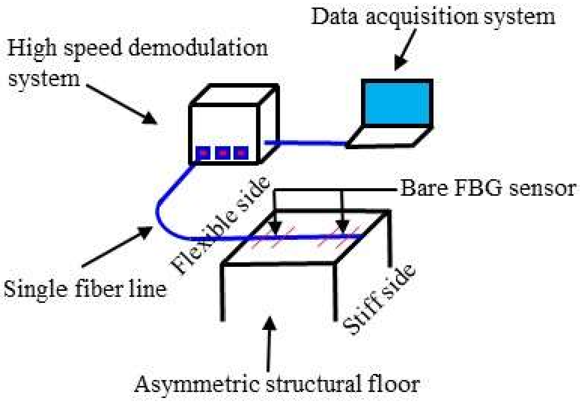

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Figure 2: Experimental models and instrumentations (All dimensions in mm): (a) Schematic representation of symmetric model (b) Schematic representation of eccentricities in TU-TF model (c) Schematic representation of asymmetric structure equipped with instruments; accelerometers, FBG strain sensors, Drift inclinometers (d) Data acquisition mechanism for FBG sensors

Based on the schematic representation in Figure 2b, twenty-four asymmetric conditions were established for experimental evaluation. Seismic response from similar asymmetric conditions were averaged at the end of experiment, which eventually transformed the experimental findings into nine-asymmetric cases. These nine asymmetric cases are presented in Table 1, which can be observed in combination with Figure 2 to evaluate the structural asymmetries. It should be noted that C_V in Figure 2b refers to the strength eccentricity whereas C_V' refers to the changing state of strength eccentricity in the adjacent upper floors.

Table 1: Details of planar and vertical irregularities in TU-TF models

Case No.	Characteristics of eccentricity	Asymmetric state
1	Reference state	Irregularly-Irregular (IRI)
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 b. Stiffness eccentricity (e_s) at 1st and 2nd floor level: e_s/L = 0.50	Irregularly-Irregular (IRI)
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	Irregularly-Irregular (IRI)
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 drift inclinometers at the top roof level to measure the angular drift (rotation) response at the flexible and stiff edges, 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 side (FS) and stiff side (SS) of the TU-TF systems.

4. SEISMIC LOADING PROGRAM:

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

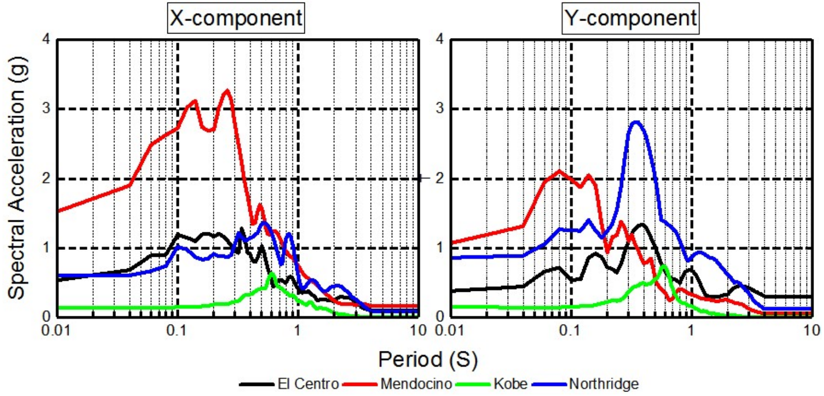
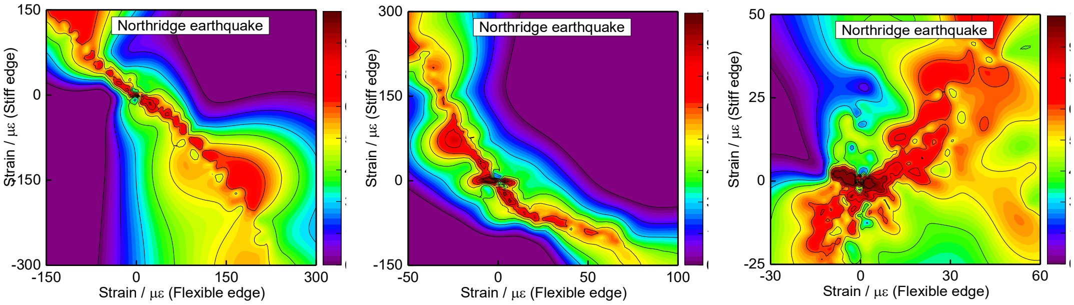


Figure 3: Seismic excitations

5. LOCAL DAMAGE CHARACTERISTICS OF TU-TF SYSTEMS:

The presented results in Figure 4 are representative of the reference state (case-1) of the TU-TF system only. It can be seen that for TU-TF systems with stiffness and strength eccentricities, lower floors are expected to experience higher damage compared with the upper floors. However, in terms of simultaneous compressive and tensile deformations at the FS and SS of the structure, first floor and intermediate floor demonstrate negligible influence as compared to the top roof level. The first floor is sensitive towards higher tensile deformations at the FS whereas in terms of compressive deformations, SS appears to be more sensitive compared with the FS of the structure. The intermediate floor experienced similar response with a difference in the behaviour of the two edges. At intermediate level, stiff edge of the structure appears to experience higher damage response mainly because of the dominance of the second mode, which has appreciably transmitted the damage response from first floor level to the intermediate floor level. The sudden change in the damage response at top roof level is attributed to the contribution of higher modes effect in such kind of highly torsionally flexible systems. Based on the experimental findings, it can be concluded that torsionally flexible structures demonstrate quite abnormal local stress concentration response along the height of the structure when observed in the reference state (Stiffness and strength eccentricities only). Moreover, the presented findings are helpful in determining the potentially weak regions involving local stress-concentration in torsionally flexible asymmetric structures.



a b c

Figure 4: Damage response at the flexible and stiff edge of the TU-TF structures for reference state under Northridge earthquake: (a) damage response at first-floor level; (b) Second column corresponds to the damage response at the second-floor level; (c) Third column corresponds to the response at first-floor level

6. GLOBAL RESPONSE CORRELATION WITH DAMAGE CHARACTERISTICS:

In the case of bi-eccentric TU-TF systems, global acceleration demands at the two edges have approximately similar response trends. For all cases of irregularities, maximum response occurred only at the FS compared with SS of the asymmetric structure with an exception to few cases of asymmetry. It is worth mentioning that the torsional influence in terms of response transition between the FS and SS is considerably high in the direction of major component of seismic excitation (Y-direction for Kobe earthquake). Similarly, in terms of maximum response it can be seen that the seismic response is influenced at first-floor level under top floor's planar and vertical, mass and stiffness eccentricities. Moreover, it can be seen that for top floor eccentricities, both the edges have induced relatively higher seismic demands at the first floor compared with the rest of the floors. This leads to the conclusion that top floor's planar and vertical mass eccentricity in TU-TF systems transmit its influence to the adjacent lower floors. Similarly, lower floor eccentricities have demonstrated higher influence on the seismic response at top roof level. Both local and global behavior of the TU-TF systems suggest that stiff edge is equally vulnerable to damage as the flexible edge under intense seismic shaking.

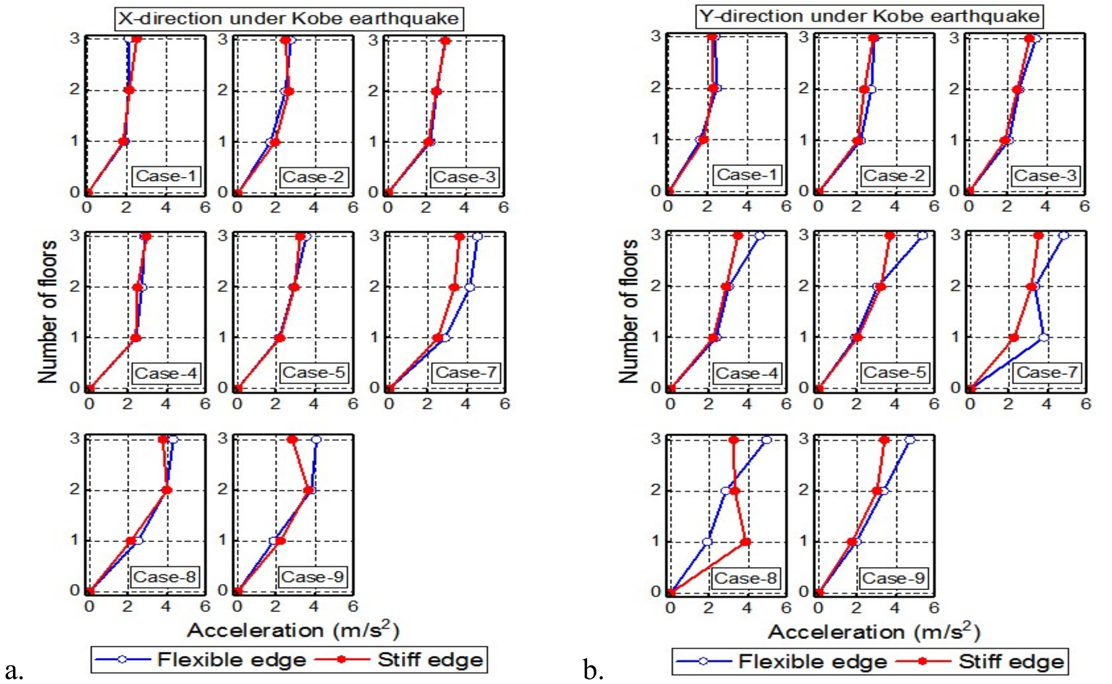


Figure 5: Amplified global acceleration response (a). X-direction response of the TU-TF system under Kobe-earthquake (b). Y-direction response of the TU-TF system under Kobe-earthquake

Moreover, the sudden reduction in the seismic demands for the reference state of the structure can be correlated with local damage response described in the previous section. This endorses the contribution of higher mode effects. Modal characteristics of various TU-TF systems have not been presented here because of space limitation. Moreover, the presented global behaviour implicates higher rotational response at the top roof level under primary component of seismic excitation. It should be noted that because of space limitation, only few representative results are presented here.

7. CONCLUSIONS:

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

- TU-TF systems demonstrate quite abnormal local damage response pattern because of the contribution of high torsional flexibility and higher mode effects.
- Global behavior of the TU-TF system suggests higher floor rotational response at the top roof level, which eventually leads to simultaneous occurrence of compressive and tensile deformations at both flexible and stiff edges of the structure.
- In terms of local damage response, lower order floors of TU-TF systems are more likely to experience seismic damage under intense seismic excitations compared with the top roof level.
- Eccentricity at a floor may likely cause response reduction at the adjacent floor level. However, this is attributed to the presence second mode dominance.
- Floor eccentricities transmit their influence to the adjacent lower/upper floors.

ACKNOWLEDGEMENTS:

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

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