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# Estimation of elastic seismic demands in torsionally-unbalanced building structures by using the interactive relations between shear and torsion

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## ABSTRACT

Current seismic provisions for building structures allow the estimation of the design torsional moment based on the design eccentricity composed of the stiffness and accidental eccentricities, which does not take into account the inertial torsional moment about the centre of mass (CM), even though the accidental eccentricity accounts for all kinds of uncertainty regarding torsion. To clarify and overcome the limitations of the current codes: (1) the prediction equations for the ratio of inertial torsional moment to the resisting shear force and that of the edge-frame drift to the story drift at the centre in the elastic range are proposed as functions of the resistance eccentricity between the inertial shear force at the CM and the resisting shear force. And (2) the overall hysteretic relations between shear and torsion in forces and deformations are approximated by the ellipsoids. The demands estimated by using these two interactive relations between shear and torsion are compared to those obtained from the shake-table tests of a 1:5-scale 5-story RC building model and a 1:12-scale 17-story RC building model, showing that these elliptical relationships cover the experimental response histories of the structures reasonably well, and that the code design torsion moment represents a very limited range of actual torsional behaviour.

# 1 INTRODUCTION

Severe damage to and even the collapse of a building structure in earthquakes can occur through several phenomena, with one such phenomenon being torsion due to a lack of balance between the location of the resisting elements and the arrangement of the building mass. In order to prevent excessive deformation, damage, and collapse caused by torsion, ASCE 7-10 specifies two torsion design approaches: one is the use of an equivalent force (static) procedure; ASCE 7-10 does not adopt explicitly any equation for design torsion moment, but states as follows:

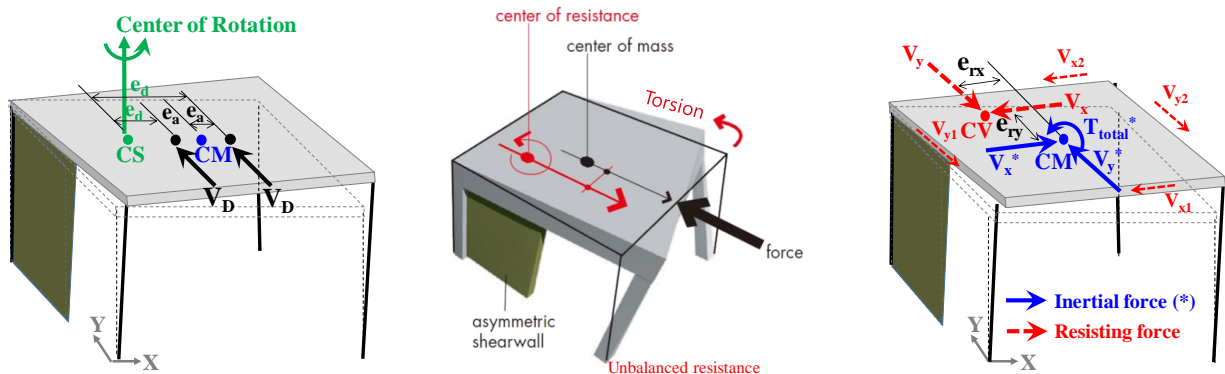
*“Where diaphragms are not flexible, the design shall include the inherent torsional moment resulting from eccentricity between the locations of the centre of mass (CM) and the centre of rigidity (CR) plus the accidental torsional moments caused by assumed displacement of the centre of mass each way from its actual location by a distance equal to 5% of the dimension of the structure perpendicular to the direction of the applied forces. ... Where earthquake forces are applied concurrently in two orthogonal directions, the required 5% displacement of the centre of mass need not be applied in both of the orthogonal directions at the same time but shall be applied in the direction that produces the greater effect.”*

The other is the use of dynamic analysis, such as the modal response spectrum analysis or time history analysis, where the CM at each story is shifted from its original location in each direction by a distance equal to the accidental eccentricity. The most adverse results in terms of member deformations and forces of the structure from the dynamic analyses for the four positions of the CM in each floor are used for the design.

Even though ASCE 7-10 does not provide explicitly any equation for static design torsion moment, the situation of static torsion is described by Figure 1(a) and static design eccentricity,  $e_d$ , can be defined with Equation (1) and (2) (Goel and Chopra 1993).

$$e_d = \alpha e_s + \beta b \quad (1) \quad e_d = \delta e_s - \beta b \quad (2)$$

where  $e_s$  is the static eccentricity representing the distance between the centre of mass (CM) and the centre of stiffness or rigidity (CS or CR);  $\beta b$  is the accidental eccentricity ( $e_a$ ), which is included so as to consider the torsional effects caused by the uncertainties of the CM and the CS, the rotational component of ground motion, and other uncertainties that are not explicitly considered;  $b$  is the plan dimension of the building perpendicular to the direction of ground motion; and  $\alpha$ ,  $\beta$ , and  $\delta$  are code-specified coefficients, which vary among building codes: for instance,  $\alpha = \delta = 1$  and  $\beta = 0.05$  in the ASCE 7-10;  $\alpha = 1.5$ ,  $\delta = 1$ , and  $\beta = 0.1$  in the Mexico Federal District Code; and  $\alpha = 1.5$ ,  $\delta = 0.5$ , and  $\beta = 0.1$  in the National Building Code of Canada (De la Llera and Chopra 1995).



(a) Code static eccentricity model (b) FEMA 454 eccentricity model (c) Eccentricity model in this study

Figure 1: Code static and FEMA 454(FEMA 454 2006): eccentricity models

However, it is interesting to note that the general notion of eccentricity by engineers is different from the definition of eccentricity in [Figure 1\(a\)](#), that is, FEMA 454 (FEMA 454 2006) states the general engineering concept of eccentricity ([Figure 1\(b\)](#)) such as:

*“Torsional forces are created in a building by a lack of balance between the location of the resisting elements and the arrangement of the building mass. Engineers refer to this as eccentricity between the centre of mass and the centre of resistance, which makes a building subjected to ground motion rotate around its centre of resistance, creating torsion a twisting action in plan, which results in undesirable and possibly dangerous concentrations of stress.”*

The eccentricity by FEMA 454 is called the resistance eccentricity in this study and defined as the distance between the centre of mass and the centre of resistance as shown in [Figure 1\(b\)](#). When the code static design eccentricity,  $e_d$ , and the resistance eccentricity,  $e_r$ , by FEMA 454 are compared, we can recognize that they are fundamentally different because  $e_d$  is the arm length about the centre of rotation, i.e. the centre of stiffness, while  $e_r$  is just the eccentricity between the coupled forces of the inertia force at CM and the resisting force in a specific direction.

However, the aim of accidental torsion is defined in De la Llera and chopra ([De la Llera and chopra 1994](#)) as follows:

*“The accidental torsion is introduced to account for building torsion arising from discrepancies between the mass, stiffness, and strength distributions used in analysis and true distributions at the time of an earthquake; torsional vibrations induced by a rotational motion of the building base; and other sources of torsion not considered explicitly in analysis.”*

It is clear from this statement that the accidental torsion does not aim at taking into account the inertial torsional moment at the CM. But, as pointed out by [Anagnostopoulos et al. \(Anagnostopoulos 2015\)](#), the accidental torsion has little effect on member sizing and on making the ductility demand distribution more uniform in the plan. Therefore, they insist that the accidental torsion should be re-examined and perhaps abolished, as it makes the structural design more cumbersome by substantially increasing computational requirements.

By using resistance eccentricity given by FEMA 454, the general situation of one-story building under earthquake can be described with forces ( $V_x, V_y, T_{total}$ ) at the CM and the eccentricity,  $e_{rx}$ , and  $e_{ry}$  where  $T_{total}$  is the sum of the torsional moments  $T_x$  and  $T_y$  contributed by the X-directional and Y-directional frames, respectively, shown in Equation (3) and  $e_y, e_x$ , and  $\eta_y$  are defined in [Equation \(4\)](#).

$$T_{total} = T_x + T_y = \sum V_{xi} d_{yi} + \sum V_{yi} d_{xi} = e_{ry} V_x + e_{rx} V_y \quad (3) \quad e_{ry} = T_x / V_x, \quad e_{rx} = T_y / V_y, \quad \eta_y = T_{total} / V_x \quad (4)$$

where  $V_x = \sum V_{xi}$  and  $V_y = \sum V_{yi}$

To predict the displacement demands for the torsionally-unbalanced building structure, Lam et al. ([Lam 2015](#)) suggested a simplified method for assessing seismic drift demands of the SDOF torsionally-unbalanced structure. The maximum drift demand at the centre was obtained from the ADRS diagram, and the critical ratio of displacements at the edge to that of the centre in the structural plan,  $\Delta/\Delta_0$ , was estimated by adapting a planar analysis approach, which was established with the modal responses for the torsional modes coupled with the translation. In this study, we will propose two basic concepts based on the eccentricity model given in [Figure 1\(c\)](#) in Section 2 to clarify and overcome the limitations of the code torsion design procedure.

## 2 BASIC CONCEPTS FOR PREDICTION OF SEISMIC ELASTIC TORSIONAL DEMAND

### 2.1 Prediction of critical torsional behaviours as functions of resistance eccentricity.

For a general single-story two-way asymmetric structural system in elastic static responses, the story force vector  $\{V_x, V_y, T_{total}\}$  at the CM is related to the inter-story drift vector  $\{\delta_x, \delta_y, \theta_t\}$  at the CM by Equation (5).  $\eta_y = T_{total} / V_x$ ,  $\mu_x = \theta_t / \delta_x$ ,  $\delta_{stiff} / \delta_x$  and  $\delta_{flex} / \delta_x$  can be expressed in terms of the resistance eccentricity  $e_y = T_x / V_x$  and the stiffness eccentricity  $e_{sy}$ ,  $e_{sx}$  as shown in Equations (6) to (9). If the structure shows bidirectional asymmetric behaviour, then  $\gamma = V_x / V_y$  will affect them by Equations (6) and (9). However, even if bidirectional asymmetry is possible,  $\mu_x = \theta_t / \delta_x$ ,  $\delta_{stiff} / \delta_x$  and  $\delta_{flex} / \delta_x$  can be determined independently of  $\gamma$  as shown in Equations (7) and (8). Because we are interested in the maximum responses in the time history of the drift at the flexible or stiff edge, we select the response data corresponding to the peak points in the time history of story drift (when the velocity is zero and thereby the inertia force is equal to the resisting force by the frames). Then, we are going to compare these results with those predicted by the Equations (6) to (9). The values of the ratio of the peak edge drift to the central drift ( $\delta_{edge} / \delta_{center}$ ) and the ratio of the total torsional moment to the shear force ( $T_{total} / V_y$  or  $T_{total} / V_x$ ), at the time instants of the peak edge drift, and the contribution of the transverse frames to the total torsional moment ( $T_x / T_{total}$ ) are derived as functions of the resistance eccentricity,  $e_{rx} = T_y / V_y$  or  $e_{ry} = T_x / V_x$ .

$$\begin{Bmatrix} V_x \\ V_y \\ T_{total} \end{Bmatrix} = \begin{bmatrix} K_X & 0 & K_{\theta X} \\ 0 & K_Y & K_{\theta Y} \\ K_{\theta X} & K_{\theta Y} & K_{\theta\theta} \end{bmatrix} \begin{Bmatrix} \delta_x \\ \delta_y \\ \theta_t \end{Bmatrix} \quad (5) \quad \eta_y = \frac{T_{total}}{V_x} = \frac{e_y - b_y e_{sy}}{b_x} + e_{sx} \frac{V_x}{V_y} \quad (6)$$

$$\mu_x = \frac{\theta_t}{\delta_x} = \frac{e_y - e_{sy}}{(K_{\theta\theta X} / K_X) - e_{sy} e_y} \quad (7) \quad \frac{\delta_{stiff}}{\delta_x} = 1 + \mu_x d_{y,stiff} \quad \text{or} \quad \frac{\delta_{flex}}{\delta_x} = 1 + \mu_x d_{y,flex} \quad (8)$$

$$\frac{T_x}{T_{total}} = \frac{1}{T_{total} / V_x} e_y = \frac{1}{\eta_y} e_y = \frac{b_x (b_y e_{sy} - b_x e_{sx} \gamma_y)}{e_y - (b_y e_{sy} - b_x e_{sx} \gamma_y)} + b_x \quad (9)$$

where  $K_X$  and  $K_Y$  are the story lateral stiffnesses in the X and Y directions, respectively;  $K_{\theta X} = e_{sy} K_X$  and  $K_{\theta Y} = e_{sx} K_Y$  are the coupled lateral and torsional stiffnesses in the X and Y directions, respectively;  $K_{\theta\theta}$  is the torsional stiffness about the CM, which is the sum of  $K_{\theta\theta X}$  and  $K_{\theta\theta Y}$  contributed by the X and Y directional frames, respectively;  $\gamma_x$  is the ratio of  $V_x$  to  $V_y$ ;  $\delta_{stiff}$  and  $\delta_{flex}$  are the story drifts at the stiff edge and the flexible edge, respectively; and  $d_{x,stiff}$  and  $d_{x,flex}$  are the distances between the stiff and flexible edge, and the CM.

### 2.2 Presentation of seismic demands with ellipses

Based on these observations of previous study (Lee 2015), it becomes clear that the eccentricity in itself cannot represent the real critical torsional behavior as design parameter. To overcome this problem, instead of using the eccentricity as design parameter, the demand in torsion shall be determined in the direct relationship with the base or story shear, represented as an ellipse. This approach provides a simple but transparent conceptual design tool. Parametric equation of ellipse (Figure 2) can be constructed Major Axis is at an angle  $\phi$  with respect to X-Axis and A, B = radius Major and Minor axis, respectively is:

$$\begin{array}{ccc} \text{Rotation} & \text{Coords} & \text{Rotated Coordinates} \\ \begin{bmatrix} \cos(\phi) & -\sin(\phi) \\ \sin(\phi) & \cos(\phi) \end{bmatrix} \times \begin{Bmatrix} A \times \cos(t) \\ B \times \sin(t) \end{Bmatrix} & = & \begin{bmatrix} A \times \cos(t) \times \cos(\phi) - B \times \sin(t) \times \sin(\phi) \\ A \times \cos(t) \times \sin(\phi) + B \times \sin(t) \times \cos(\phi) \end{bmatrix} \end{array} \quad (10)$$

where,  $t$  is the parametric angle which will go to full circle,  $0 \leq t \leq 2\pi$ ;  $A$  is radius in the major axis;  $B$  is the radius in the minor axis; and  $\phi$ : the angle between the X-axis and the major axis of the ellipse.

Elliptical relationship for the displacements ( $\theta_t$ - $\delta_x$ ) by selecting two point (P1 and P2) near to the slope ( $\mu_{xj} = \theta_{ij}/\delta_{xj}$ ) in the first and second torsion and translation coupled modes (see Figure 3). The calculated values of radius in the major axis ( $A=1.414$ ), radius in the major axis ( $B=0.955$ ), and the angle ( $\phi = -0.785\text{rad}$ ). After the ellipse for  $\theta_t$ - $\delta_x$  constructed, it can be used to derive the other elliptical relationships ( $\theta_t$ - $\delta_x$ ,  $\delta_{x,x1}$ - $\delta_x$ ,  $\delta_{x,x3}$ - $\delta_x$ ,  $T_x$ - $V_x$  and  $T_{total}$ - $V_x$ ) by using the interactive equations given in Equations (6) to (9).

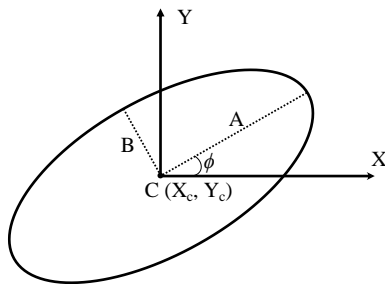


Figure 2: A typical ellipse formed by major and minor axes with  $\phi$  angle

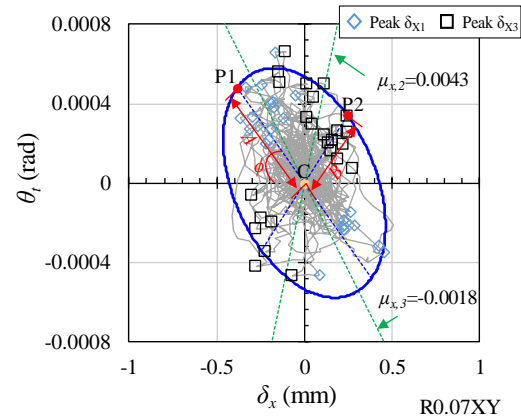


Figure 3: Relationships between  $\theta_t$ - $\delta_x$

### 3 DESCRIPTION OF TORSIONALLY UNBALANCED (TU) BUILDING STRUCTURES

In this study two different piloti-type RC building structures are investigated. Prototype buildings of the 5 and 17 story RC building structures were determined based on the inventory data of the low-rise and high-rise piloti-type RC residential buildings in Korea. The irregularity of these prototype structures was evaluated according to the criteria of standard design loads for buildings (AIK 2000).

#### 3.1 5-story RC building structure model

A 1:5 scale five-story RC building model (Figure 4(a)) having the irregularities of a soft/weak story and torsion at the ground story was subjected to a series of earthquake simulation tests. The original prototype was determined based on the inventory study and designed by considering the gravity loads only. To reduce the irregularity of the original prototype (i.e., soft story, weak story, and torsional eccentricity at the ground story), the prototype was strengthened with buckling-restrained braces (BRBs) and fibre-reinforced polymer (FRP) sheets in the peripheral frames. Detailed designs of the BRBs and FRP sheets are provided by Lee et al (Lee 2013).

The target or input accelerogram of the table was based on the recorded 1952 Taft N21E (X direction) and Taft S69E (Y direction) components and was formulated by compressing the time axis with a scale factor of  $1/\sqrt{5}$  and adjusting the peak ground acceleration (PGA) in order to match the corresponding elastic design spectrum in KBC 2005. Service level earthquake is defined as the level of  $\text{PGA} = 0.07g$  with 1952 Taft N21E and S69E components, and the corresponding test is designated R0.07XY in the shake-table test. Detailed information on the results of the earthquake simulation tests on the original and strengthened models is given in Lee et al (Lee 2011, 2013 and 2015). The main findings from the test results are: (1) The eccentricity varied from zero to infinity with the values of base shear and torque bounded by some limits. (2) The inertial torque was resisted by both longitudinal and transverse frames, in proportion to their instantaneous rigidity. (3) Yielding of the longitudinal frames under severe table excitations caused a

substantial loss in their instantaneous torsional resistance and thereby transferred most of the large torque to the transverse frames, resulting in a significantly degraded torsional stiffness with an enlarged torsional deformation despite almost zero eccentricity (Lee 2015).

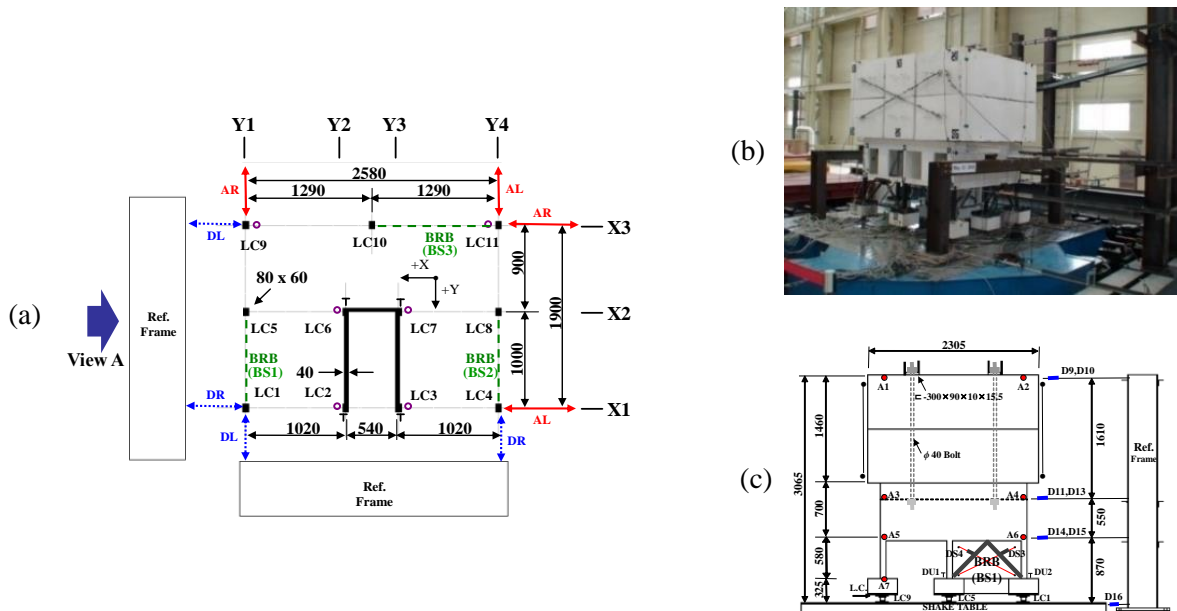


Figure 4: A 1:5 scale model (unit: mm): (a) plan of ground floor; (b) experimental setup and (c) elevation.

### 3.2 17-story RC building model

The second piloti type RC building structure (Figure 5) is a 1:12 scale 17 story high-rise reinforced concrete (RC) building structure with a high degree of torsional eccentricity and soft/stories irregularities in the bottom two stories. This building has a total of seventeen stories, the bottom two stories are a commercial space consists of a 2 by 2 bay moment resisting reinforced concrete (RC) frame system with an infilled shear wall at the exterior frames and the above 15 stories are a reinforced concrete (RC) bearing-wall system.

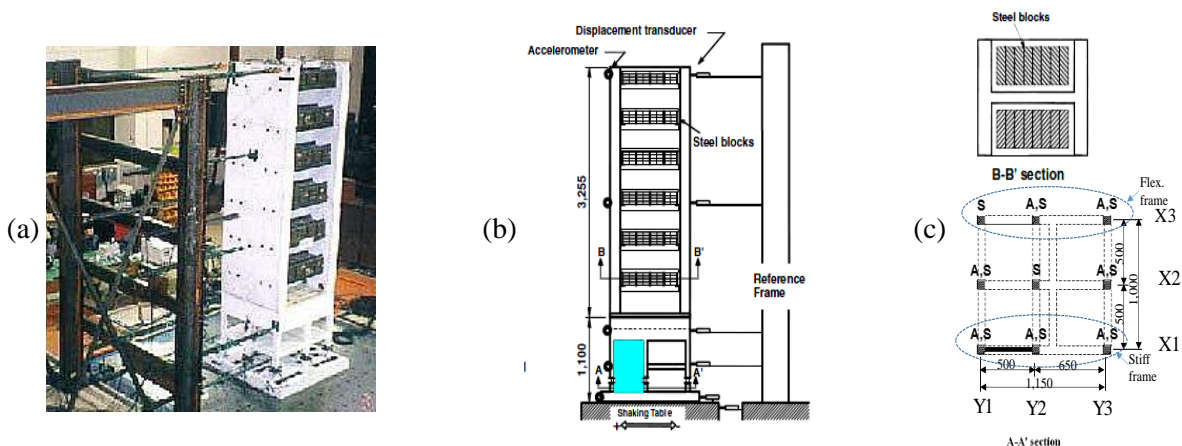


Figure 5: A 1:12 scale model (unit: mm): (a) experimental setup; (b) elevation; (c) plan view (Lee & Ko 2006)

A shake table test was performed to investigate the seismic performance of this building. The input accelerogram is the recorded TaftN21E component by compressing its time using the scale factor and

adjusting the peak ground acceleration (PGA) to 0.30g (this value was 0.15g multiplied by two due to the reduction of the mass of the model by half which represent for the return period of 500years in Korea). The rigidity of the upper bearing-wall system was much higher than the lower RC frame system. The upper bearing-wall system was constructed separately from the lower frame system as a rigid concrete box with steel plates attached as artificial mass. The total seismic weight of the model, including the artificial mass, was estimated to be 92kN (Ko, 2006). The main characteristics of behaviours of test results were: (1) The sudden change of the predominant vibration mode from the mode of translation and torsion to the torsional mode after the flexible side underwent large inelastic deformation. (2) The abrupt increase in the torsional stiffness in this change of modes. (3) The warping behaviour of wall in the torsional mode. And (4) the unilateral overturning moment in the direction transverse to the table excitations (Ko, 2006).

#### 4 EVALUATION OF THE BASIC CONCEPTS IN SECTION 2

For the 5-story building, the first and second modes are the modes coupled by the translational movement in the X direction and the torsion, while the third is translation in the Y direction. Whereas, for the 17-story structure, the second and third modes are the modes coupled by the translational movement in the X direction and torsion, while the first mode is translation in the Y direction. For the 5-story structure of the first mode,  $e_{y1} = -7.8\%$ , with that of the second mode,  $e_{y2} = 21.5\%$  and for the 17-story structure of the second mode,  $e_{y2} = 4.8\%$ , with that of the second mode,  $e_{y3} = -51.1\%$ . The  $T_x$ - $V_x$  relationship, combining the two coupled modal behaviours, resulted in the elliptical shapes

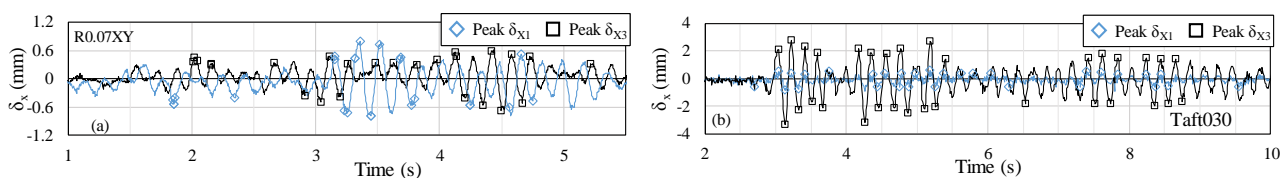


Figure 6: Time history of edge drifts ( $\delta_{x1}$  and  $\delta_{x3}$ ) under: (a) R0.07XY and (b) Taft030

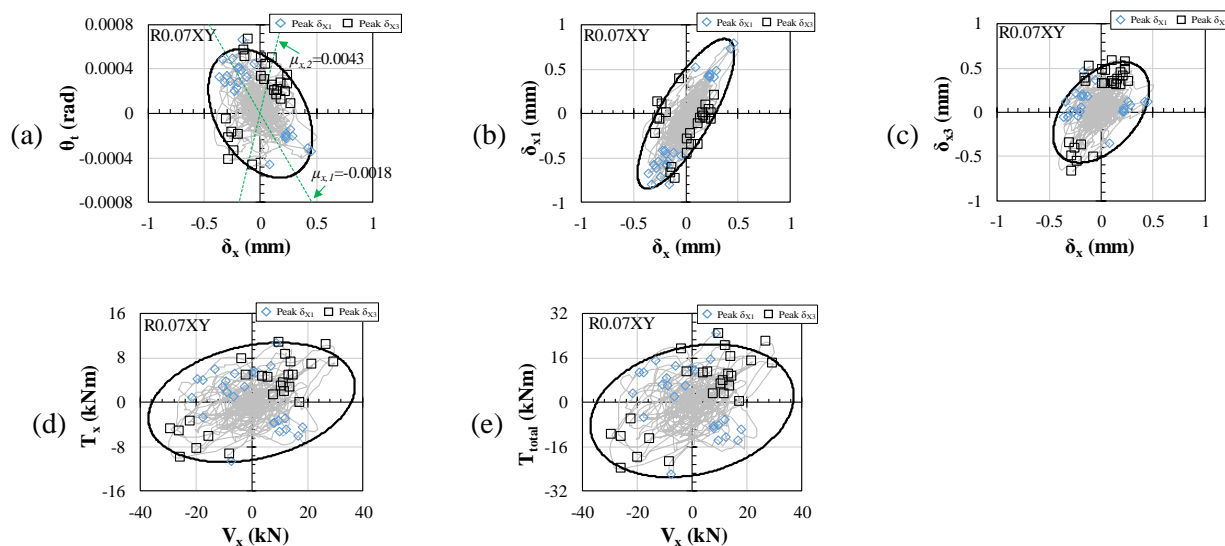


Figure 7: Shear force -torsional moment and torsional -translation deformation relationship under R0.07XY

In the history displacement at Figure 6, the data points represent at the peak edge drifts in Frames X1 (diamond markers) and X3 (square markers) at the ground story, which correspond to the time instants of zero velocity, that is, the state when the resisting force by the frames is equal to the inertia force.

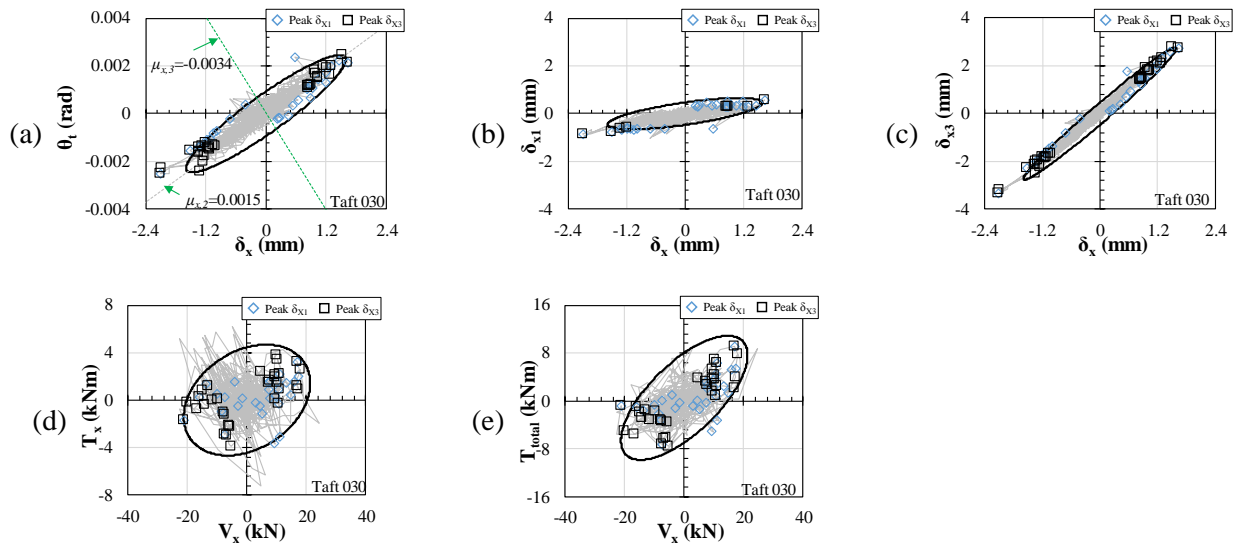


Figure 8: Shear force -torsional moment and torsional -translation deformation relationship under Taft030

In Figures 7 and 8 show an ellipse with the response histories of  $\theta_t$ - $\delta_x$ ,  $\delta_{x,1}$ - $\delta_x$ ,  $\delta_{x,3}$ - $\delta_x$ ,  $T_x$ - $V_x$  and  $T_{total}$ - $V_x$  combining with the response from the experimental results for the 5- and 17-story RC structures, respectively. Figures 7 and 8 show that the elliptical relationship almost covers the response histories from the analytical result.

Figures 9 I and II-(a) to (d) show the data points ( $\delta_{x,1}$ ,  $\delta_{x,3}$ ,  $\theta_t$ ,  $V_x$ , and  $T_{total}$  versus  $e_y$ ) at the peak edge drifts in stiff-side and flexible-side in the experimental result of a 5 story and 17 story asymmetric building structure under R0.07XY and Taft030, respectively. In which these data points correspond to the zero velocity, the state when the resisting force equals the inertia force, in the first story. The data points given in Figures 9 I and II-(a) to (d) are compared from the prediction line which is calculated from the ellipse and the relations given Equations (6) to (9). The value of  $e_y$  ranging from  $-58.6\%$  to  $74.6\%$  under R0.007XY in Figures 9 I-(a) to (d) and from  $-40.3\%$  to  $74.8\%$  under Taft030 in Figures 9 II-(a) to (d).

The relation among  $T_{total}/V_x$ ,  $T_y/V_x$ , and  $e_y = T_x/V_x$  presented in Figures I-(e) and II-(e) appear to be linear and can be reliably predicted using Equation (6). In Figures 9, (a) to (d) the range of  $e_r$  corresponding to the range of accidental eccentricity,  $e_a$ , from  $-5\%$  to  $5\%$  are given as green zone for both 5-story and 17-story building models. For 5-story building model,  $T_{total}/V_x$  ranges from  $-125\%$  to  $81\%$  under R0.07XY with the range of  $e_y = -58.6 \sim 74.6\%$ . also, for 17-story building mode,  $T_{total}/V_x$  ranges from  $-60\%$  to  $100\%$ . These two ranges exceed the accidental eccentricity,  $T_{total}/V_x = \pm 5\%$ , with  $e_r$  ranging from  $-1.48\%$  to  $2.96\%$  and from  $-15.6$  to  $-9.7\%$  for 5-story and 17-story building models, respectively. It can also found in Figure 9 I(a)~I(d) and II(a)~II(d) that the maximum responses generally occur beyond the range of accidental eccentricity.

## 5 CONCLUSIONS

The followings are main conclusions of this paper:

- Earthquake simulation test results of 1:5 scale five-story and 1:12 scale seventeen-story RC piloti-type building models with the irregularity of a soft/weak story and torsion at their ground stories revealed that the eccentricity was not within the range specified by the code design eccentricity, but varied from zero to infinity and that even very small eccentricity can lead to the significantly large drift at the edge frame under the severe earthquake.

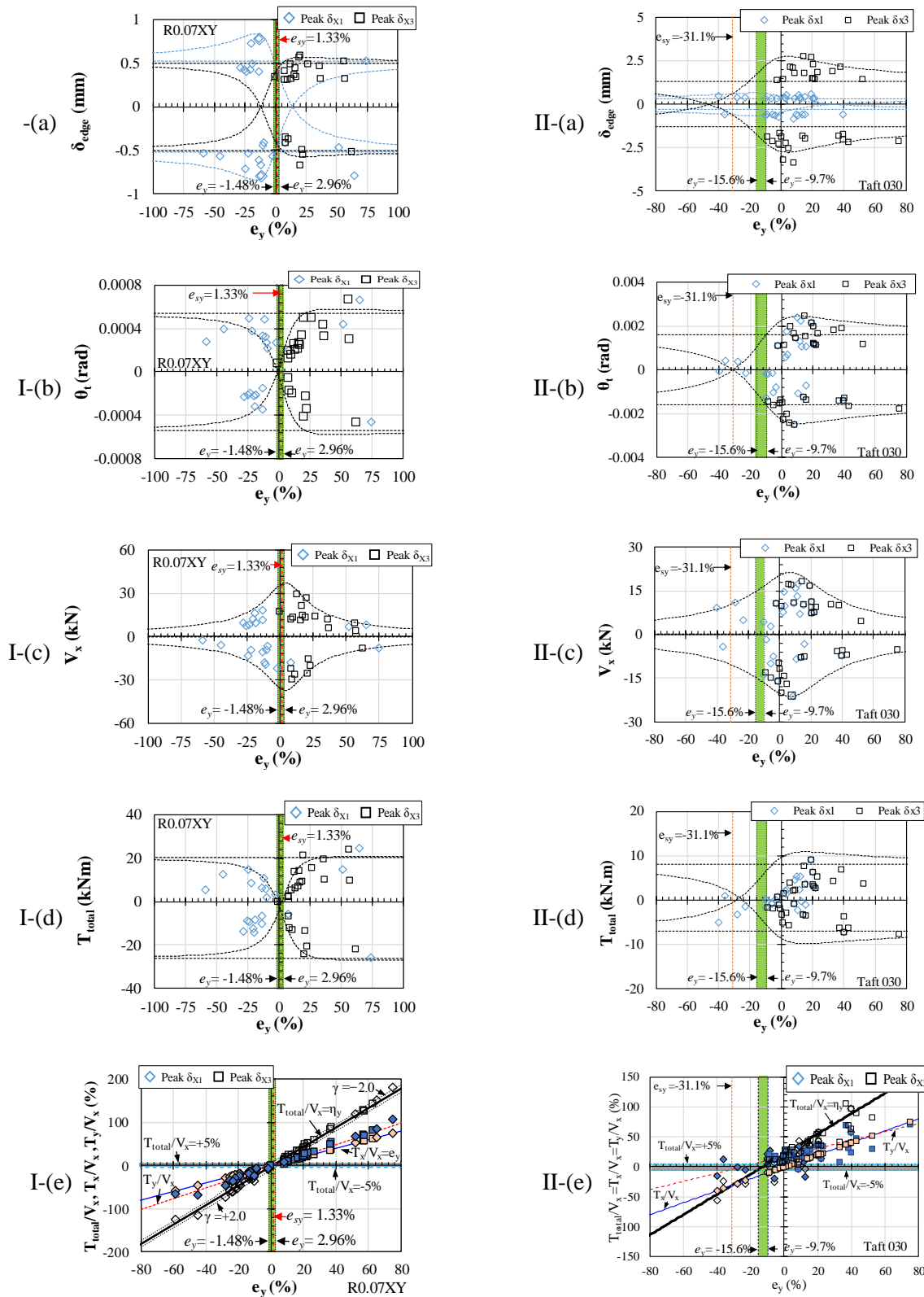


Figure 9: Distributions of the critical responses: (a)  $\delta_{edge}$ ; (b)  $\theta_t$ ; (c)  $V_x$ ; (d)  $T_{total}$ , at instants of peak  $\delta_{edge}$  compared to the prediction equations for: I. 5-story under R0.07XY and II. 17-story under Taft030

- To overcome this infelicity of using the eccentricity as design parameter for torsion, a simple approach in the torsion design of torsionally unbalanced building structure is discussed by defining the torsional

moment in a direct relationship with the shear force (or the torsional deformation in a direct relationship with the translation deformation) given as an ellipse with the maximum points in its principal axes located by the two adjacent torsion-dominant modal spectral values. In this paper, it is shown that these elliptical relationships cover the actual experimental responses histories of the structures reasonably well.

- In this study,  $e_r$  ( $e_y = T_x/V_x$  or  $e_x = T_y/V_y$ ) is used as the main parameter for predicting the maximum responses of building structures, whereas in the static torsion design procedure in the codes the total torsional moment,  $T_{total}$ , at the CM consisting of  $T_x$ , the contribution of the frames in the X direction and  $T_y$ , that in the Y direction, is determined by the accidental torsion only and the inertial torsional moment at the CM is neglected.
- In contrast to the state of zero inertial torsional moment at the CM that corresponding to the inherent torsional moment assumed in the code eccentricity, the experimental results clearly demonstrate the existence of a large amount of the inertial torsional moment,  $T_{total}$ , at the CM.

## 6 ACKNOWLEDGMENTS

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