Faculty of Engineering
THE UNIVERSITY OF HONG KONG

SWINBURNE UNIVERSITY OF TECHNOLOGY

INTERNATIONAL SYMPOSIUM
Recent Advances in Structural Design in Regions of Low-to-Moderate Seismicity

New Approach in Seismic Torsion Analysis and Design of TU Building Structures

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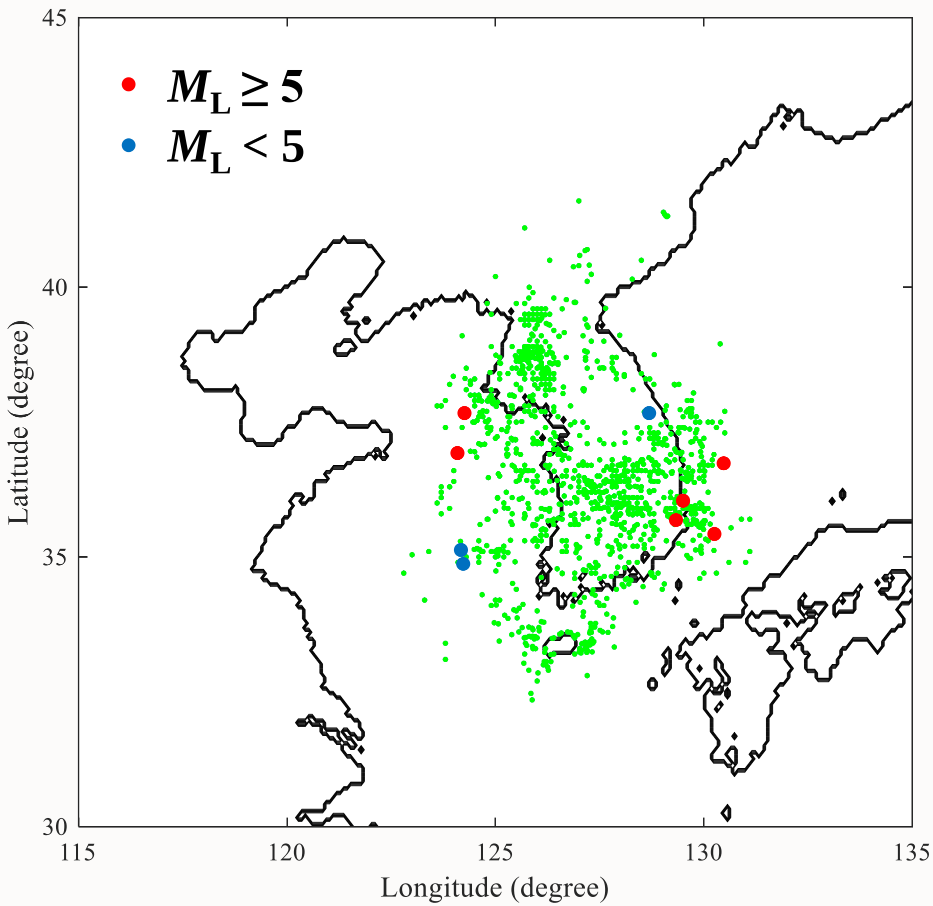
KOREA UNIVERSITY
Structural Concrete Engineering Lab.

Contents

1. Introduction to the recent earthquakes in Korea

Earthquakes in Korean Peninsula

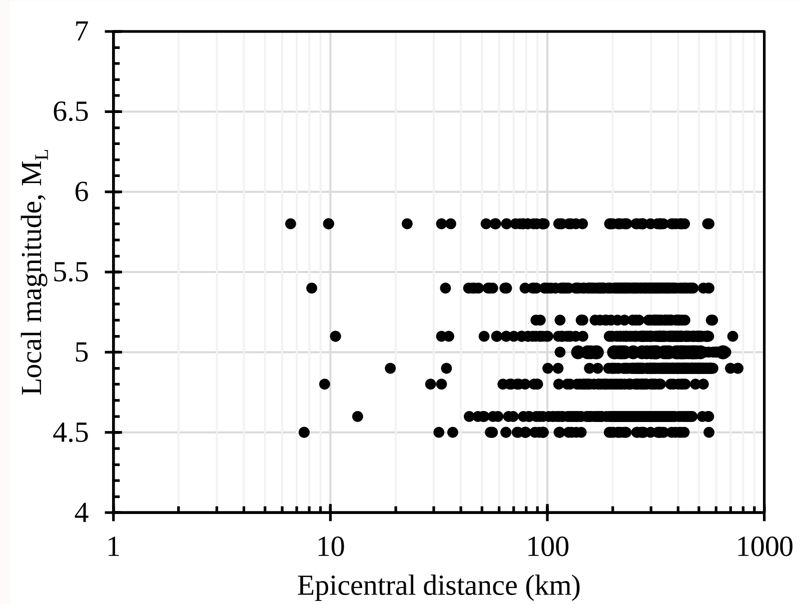
Instrumental earthquakes in Korean Peninsula



- ❖ Earthquake epicenters since 1978
- ❖ Recorded earthquakes > 1,690

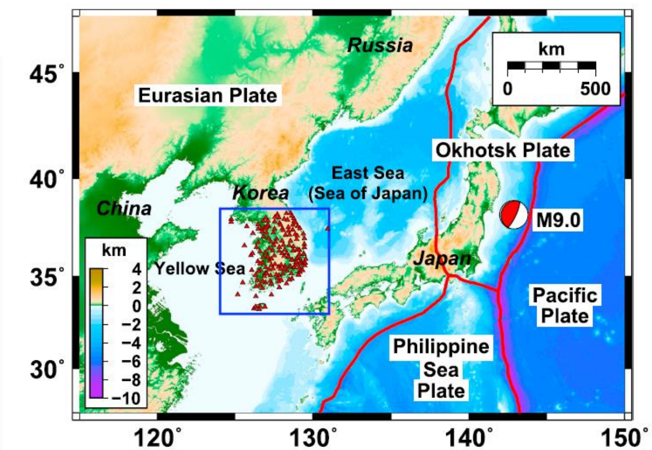
$M_L \geq 4.5$ recorded earthquakes since 2003

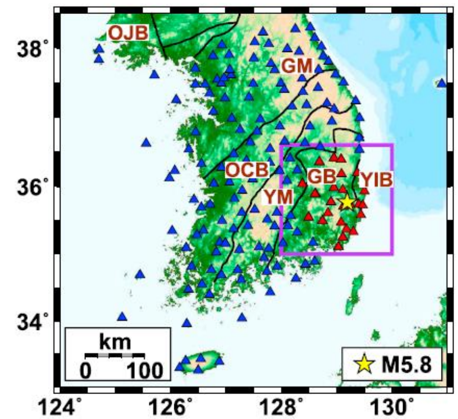
No.	YYYY-MM-DD HH:MM	M_L	M_W	도시명	기록세트수
1	2018-02-11 05:03	4.6	4.7*	포항	154
2	2017-11-15 14:29	5.4	5.5*	포항	158
3	2016-09-19 20:33	4.5	4.6*	경주	53
4	2016-09-12 20:32	5.8	5.4*	경주	66
5	2016-09-12 19:44	5.1	4.9*	경주	54
6	2016-07-05 20:33	5.0	4.97	울산앞해역	47
7	2014-04-01 04:48	5.1	5.1	태안앞해역	122
8	2013-05-18 07:02	4.9	4.85	백령도앞해역	86
9	2013-04-21 08:21	4.9	4.85	신안군앞해역	86
10	2007-01-20 20:56	4.8	4.72*	평창(오대산)	69
11	2004-05-29 19:14	5.2	5.2	울진앞해역	54
12	2003-03-30 20:10	5.0	4.97	백령도앞해역	22
13	2003-03-23 05:38	4.9	4.85	신안군앞해역	51

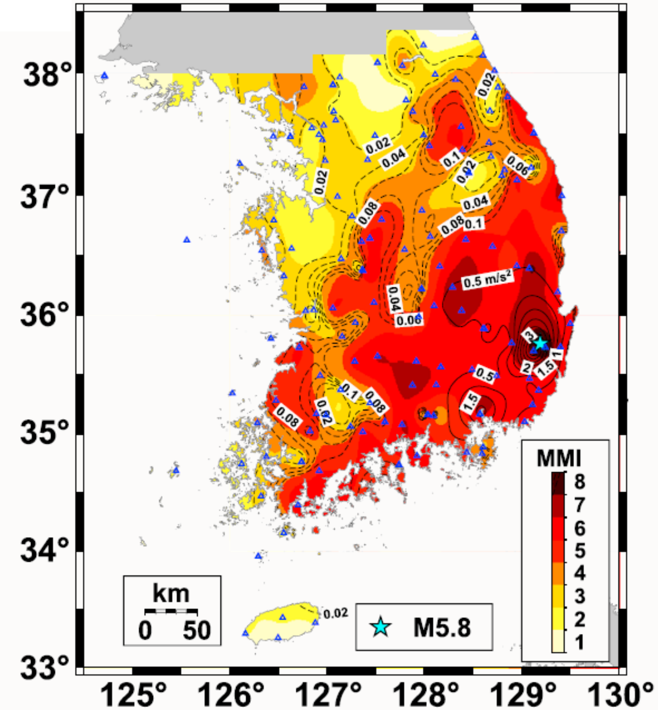


12 Sept. 2016, Gyeongju earthquake

- Epicenter of Gyeongju Earthquake (*Hong, et al. 2017*)



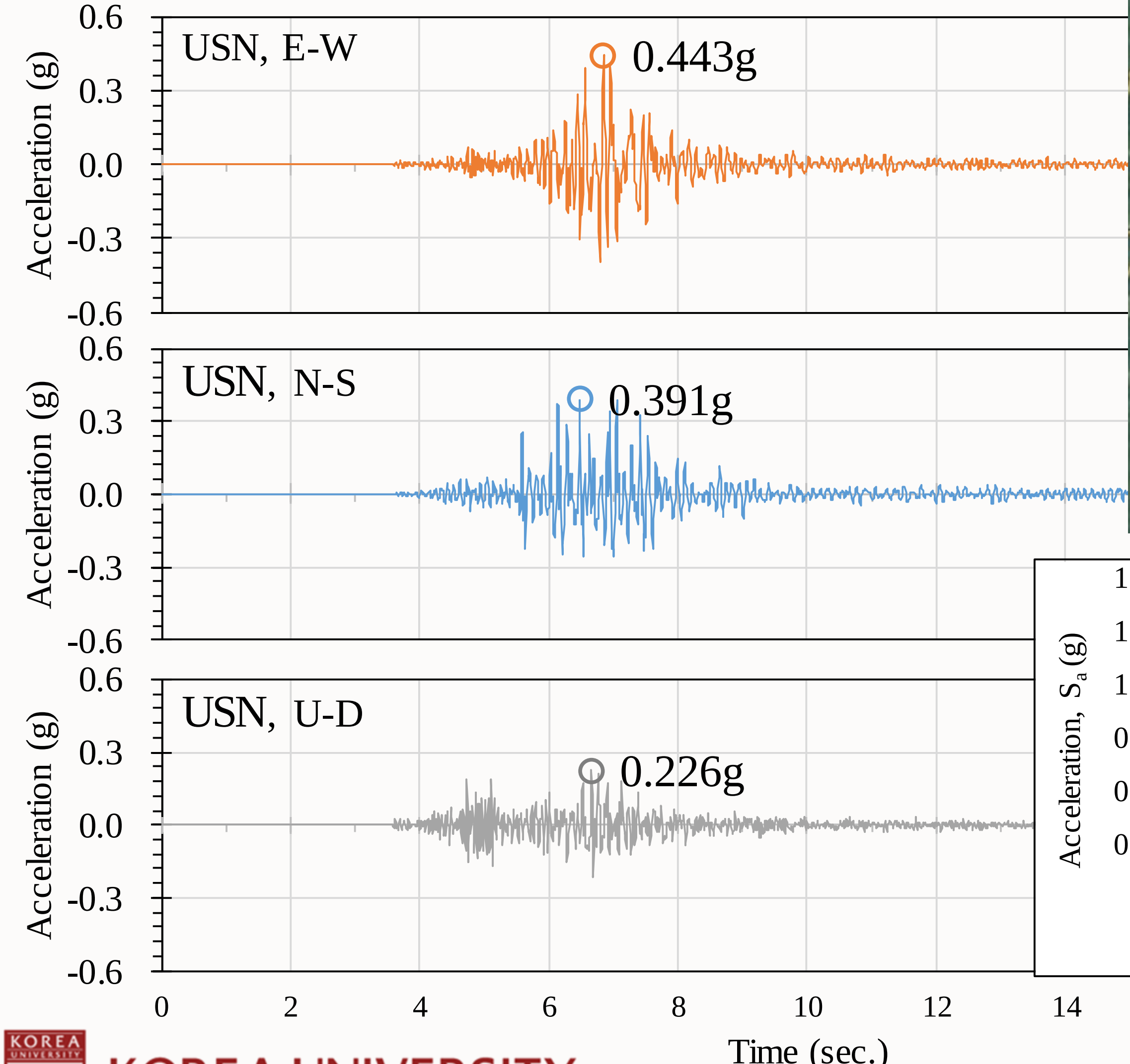


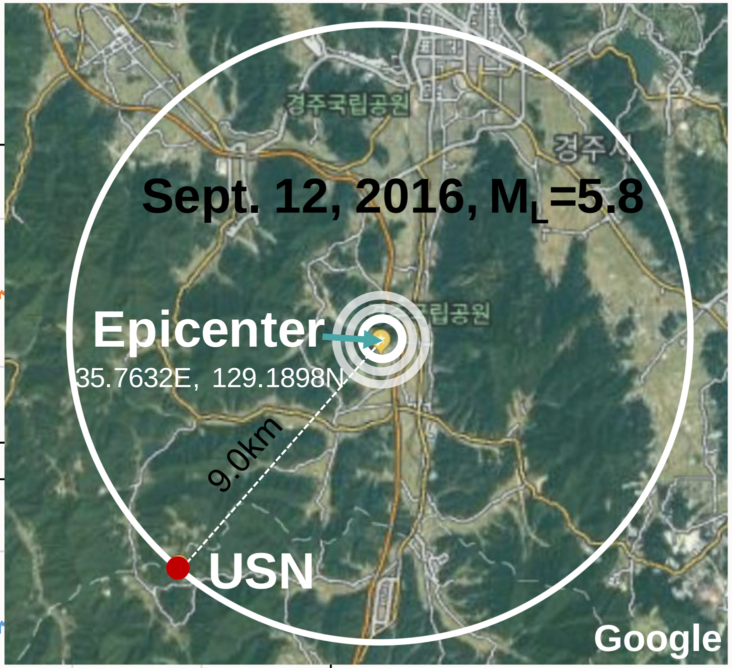


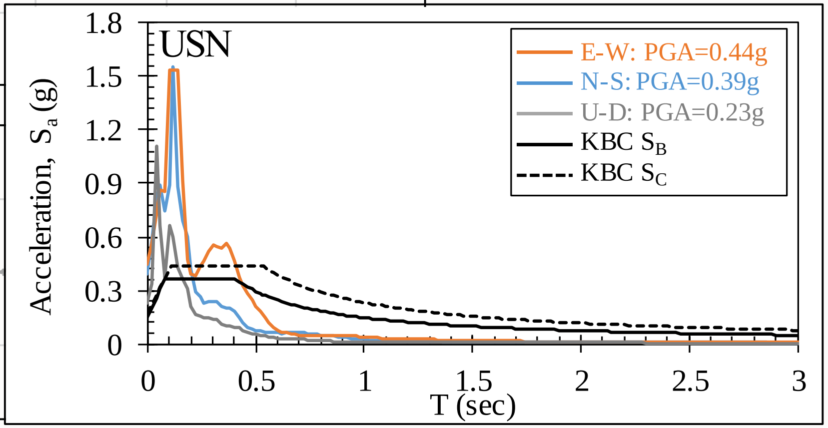
Local magnitude M_L	5.8
Moment magnitude M_W	5.4
PGAs (EW and NS components) at USN station (R_{epi} = 8.2 km)	0.45g and 0.43g
Focal depth	14.1 km (KIGAM)
Maximum Intensity	VIII*

12 Sept. 2016, Gyeongju earthquake

- Station USN



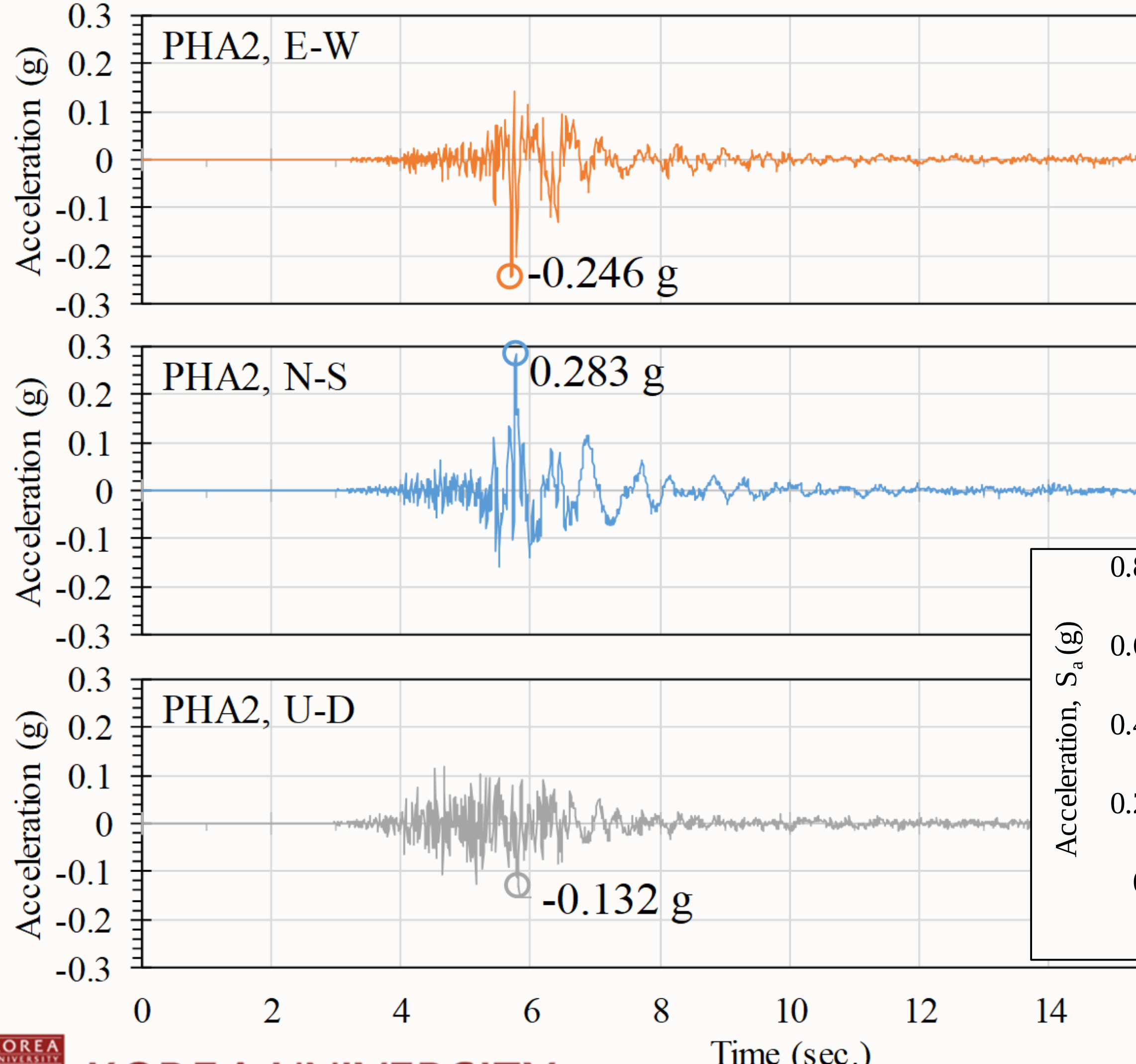


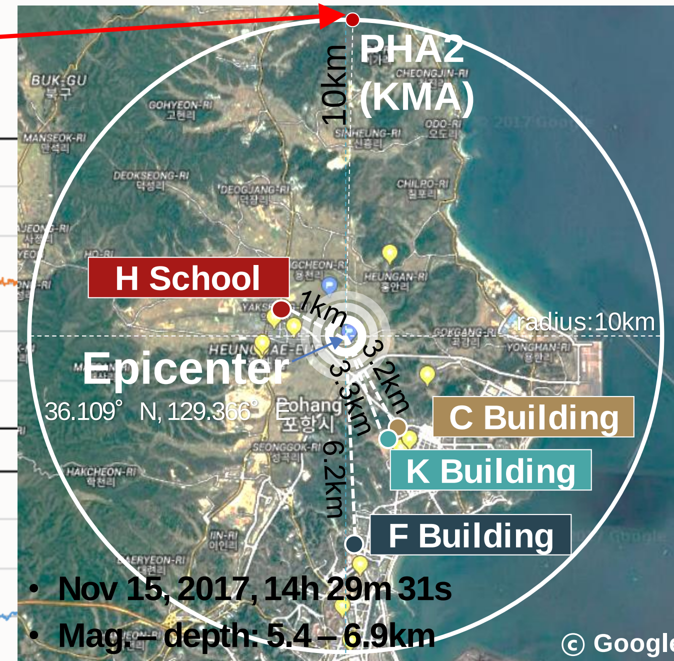


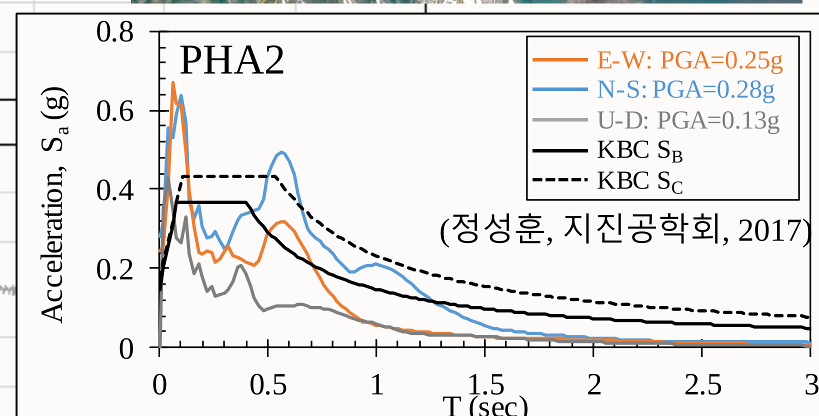
12 Sept. 2016, Gyeongju earthquake

15 Nov. 2017, Pohang earthquake

- Station PHA2

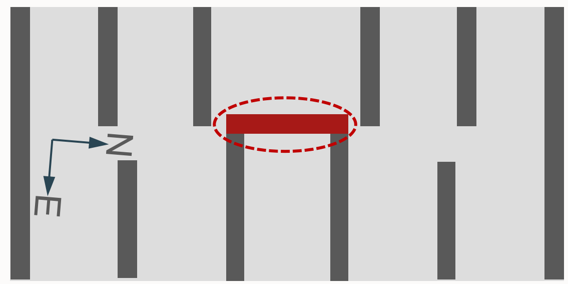




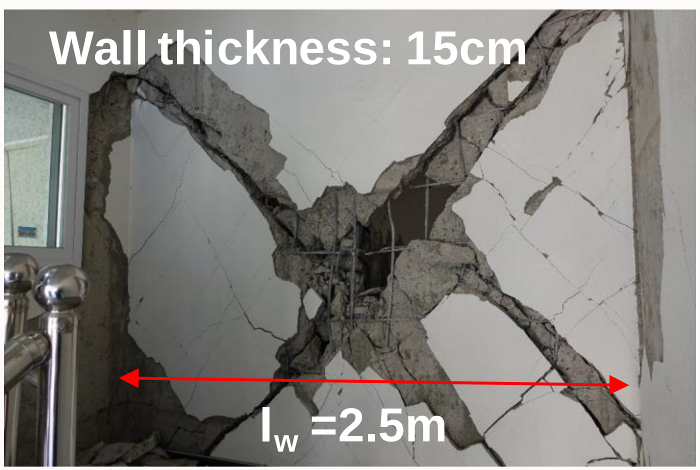


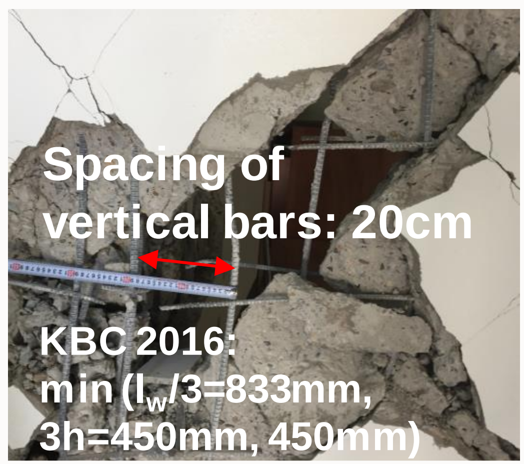
K building: 4-story RC wall bldg. structure

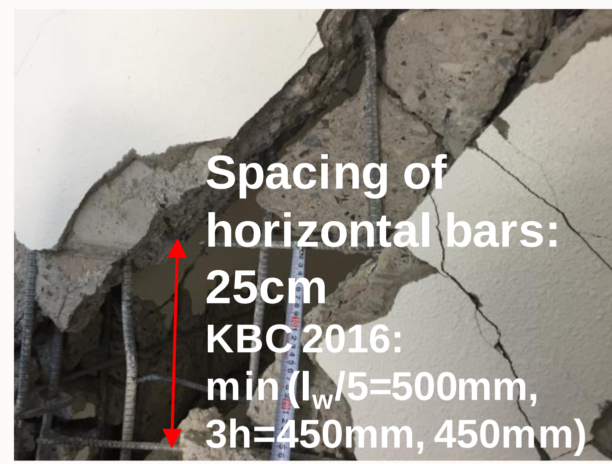
In a shear wall in the horizontal direction, serious shear failure occurred. The wall is not placed in the center of the plan. Because of this torsional irregularity, many cracks in the wall in the transverse direction are observed, despite a large amount of wall in the transverse direction.



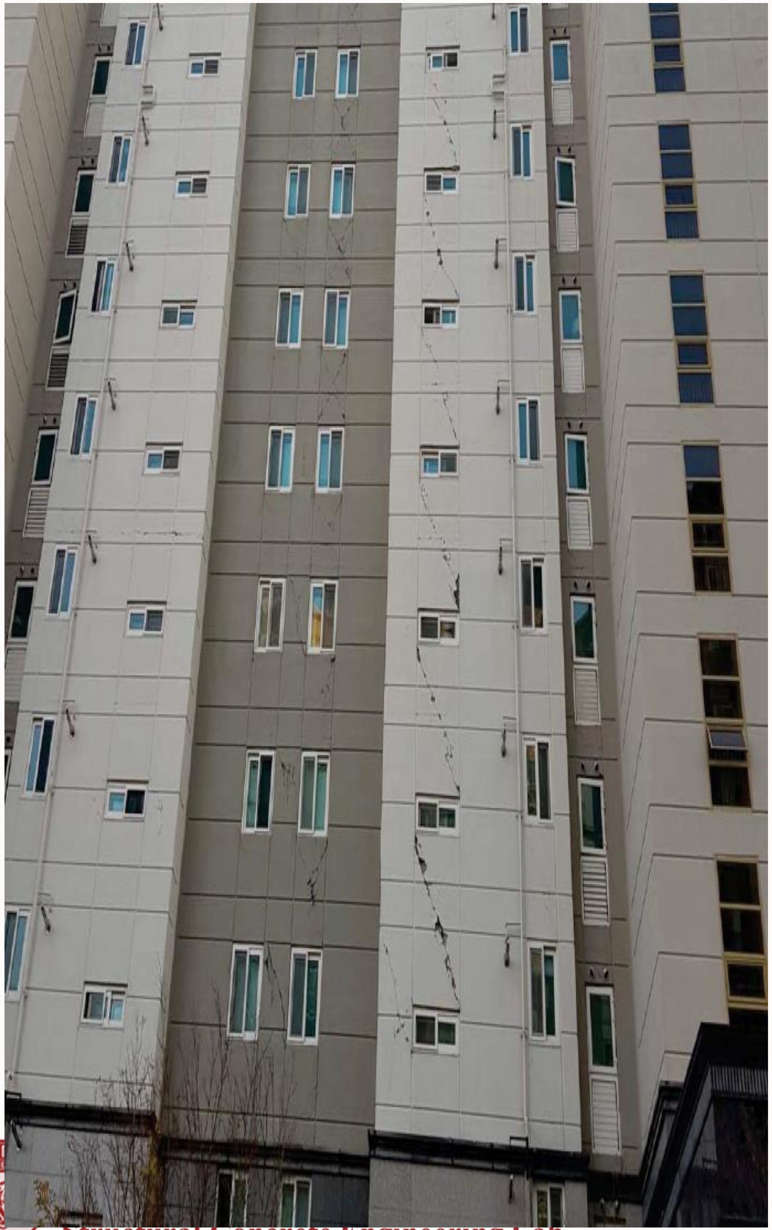
Other photos Dropbox link

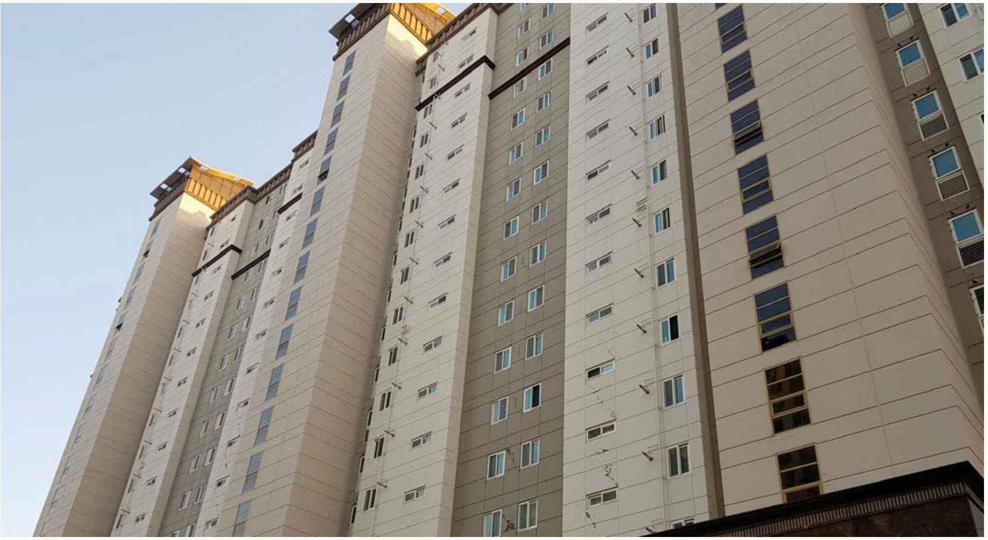


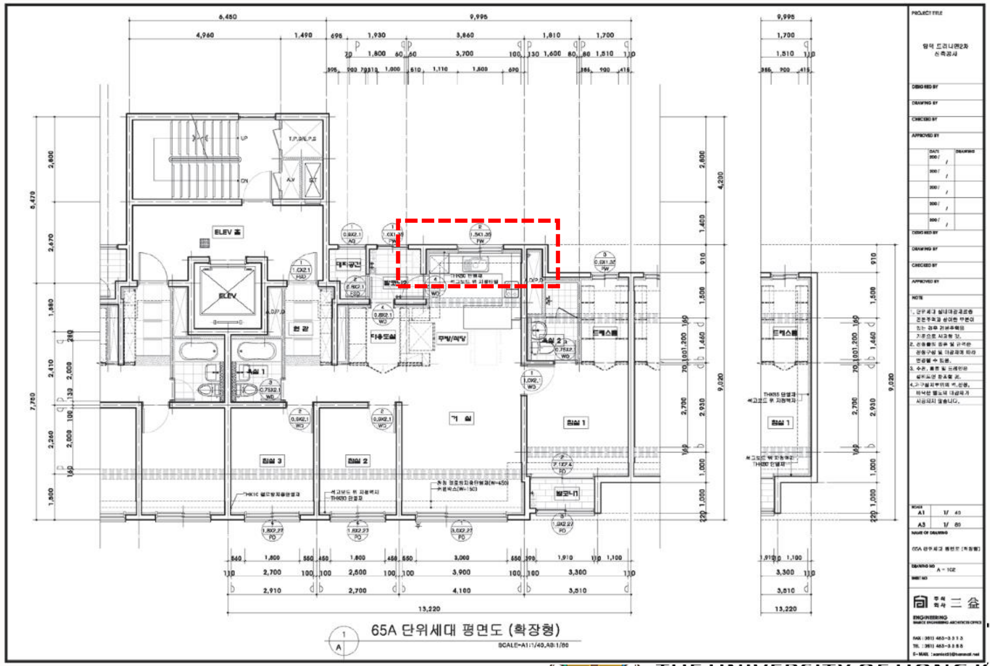




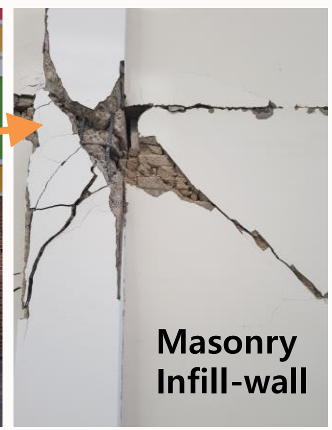
S apartment: 15-story high-rise RC bldg. structure



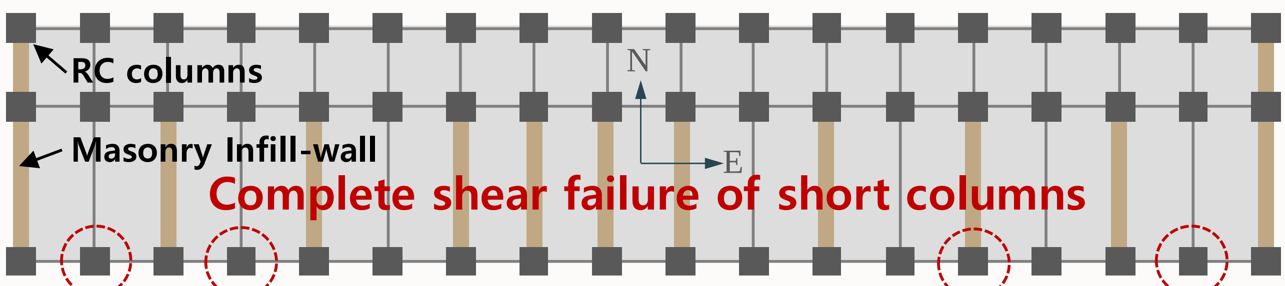




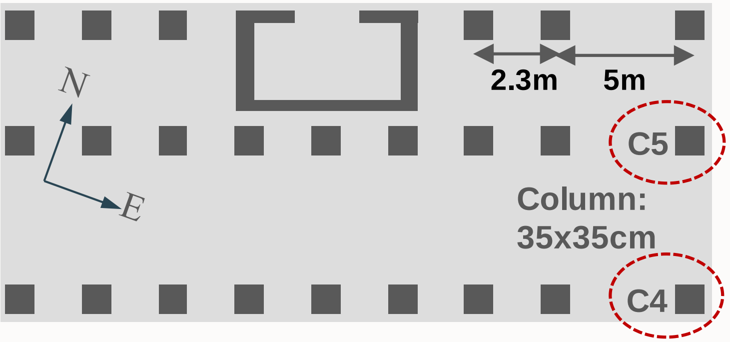
H school: 3-story RC MRF structure



One-way asymmetric RC moment frame structure
→ Torsional irregularity

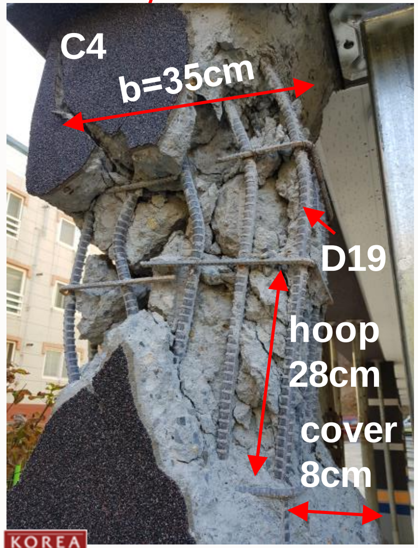


F building: 5-story RC piloti-type bldg. structure



Shear failure YouTube link

- **Two-way asymmetric-plan: shear failure** occurred at columns in the flexible edge.
- **Columns have inadequate details of hoop, tie, and cover**

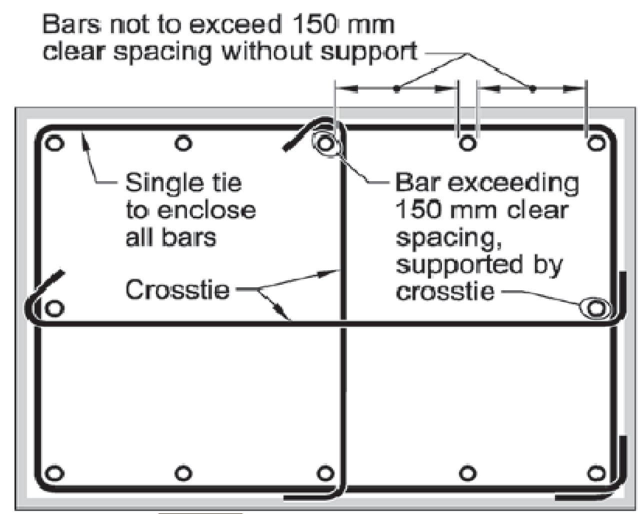


ACI 318-14 (KBC 2016)

Min hoop spacing

= min ($8d_{b,l}$, $24d_{b,h}$, 1/2d, 300mm)

= min (152mm, 240mm, 175mm, 300mm) = **152mm**

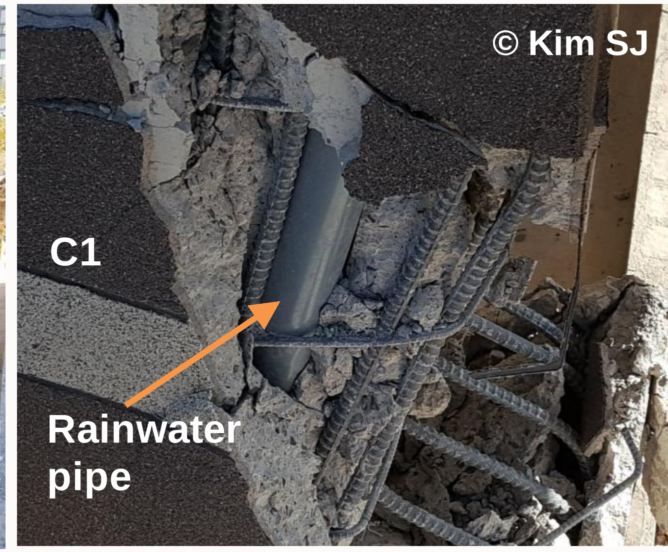


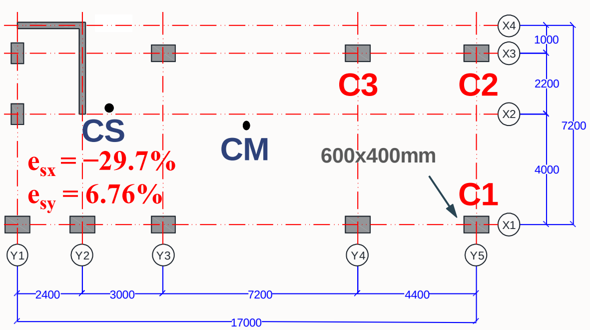
F building: 5-story RC piloti-type bldg. structure

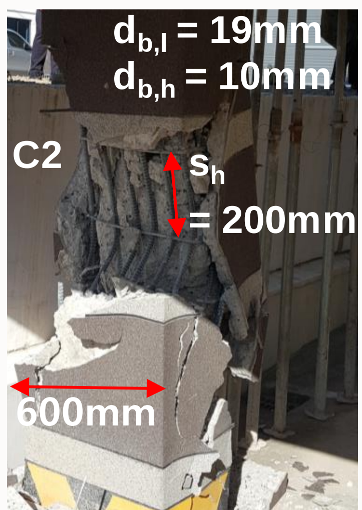
Constructed in 2013

November 17, 2017, SBS News

C building: 4-story RC piloti-type bldg. structure



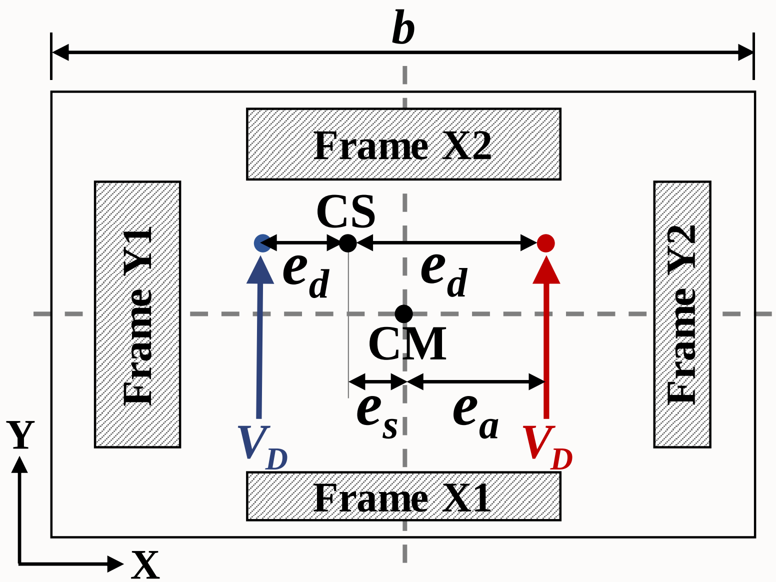




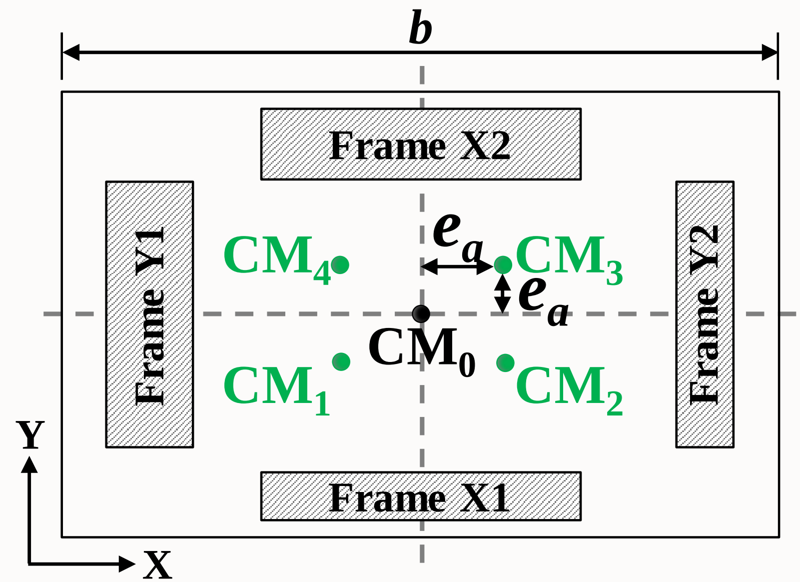
High torsional irregularity
→ unexpected large drift
→ shear failure of column

2. Problems of the current code torsion design

Code torsion design approaches



Equivalent lateral force (static) analysis



Dynamic analysis

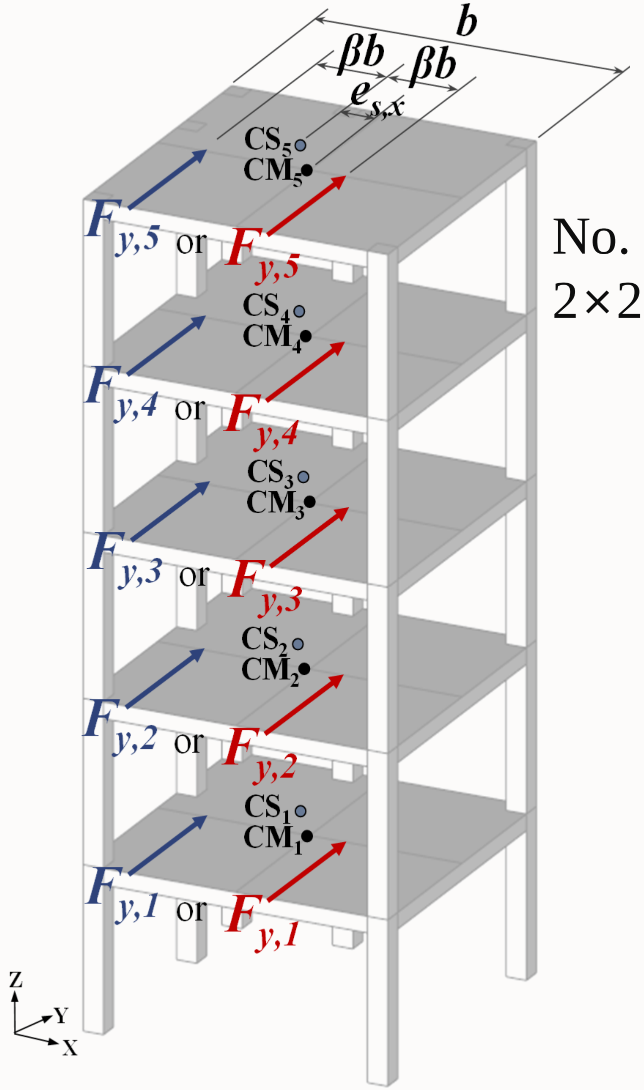
Base shear: $V_D = C_S W$

Static eccentricity, e_s

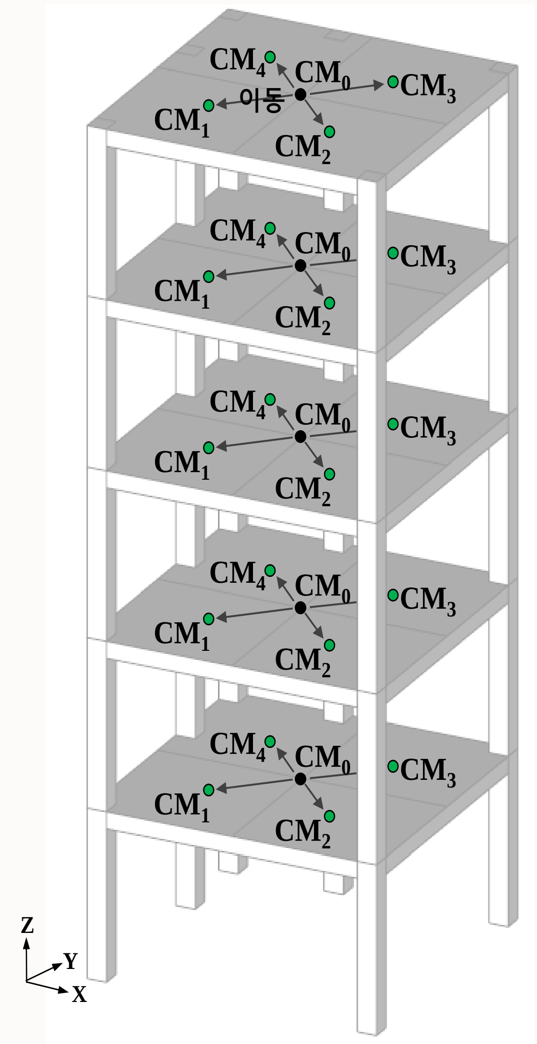
Design eccentricity: $e_d = \alpha e_s + \beta b$ or $e_d = \delta e_s - \beta b$

Accidental eccentricity, e_a

Conventional torsion design approaches



No. of cases
$2 \times 2^5 = 64$



No. of cases
$4^5 = 1024$

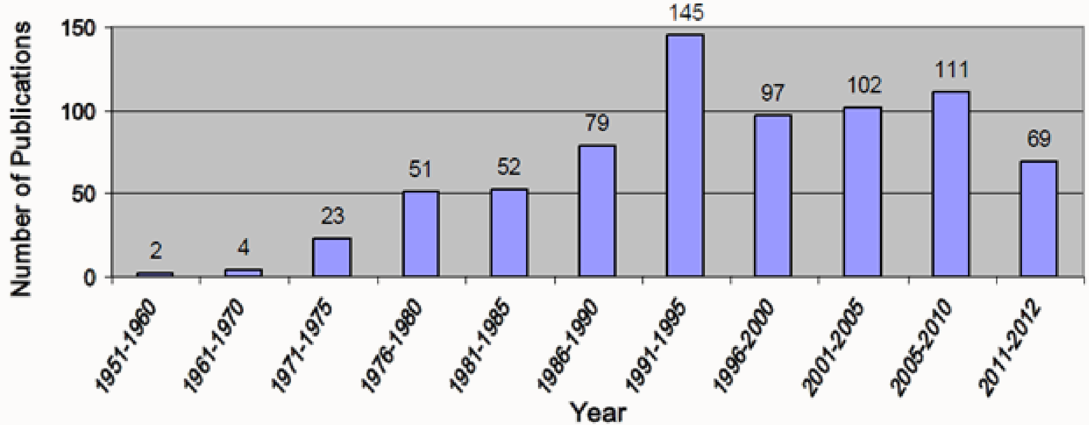
Equivalent static analysis

Dynamic analysis

Impact of accidental torsion

- Chopra and De la Llera (1994) ***"This investigation supports the experience of many practicing structural engineers that building design is influenced very little by considering the accidental eccentricity of ±0.05b, a code requirement that is cumbersome to implement in design practice. "***
- Anagnostopoulos *et al* (2015) ***"the accidental torsion has little effect on member sizing and on making the ductility demand distribution more uniform in the plan. The accidental torsion should be re-examined and perhaps abolished, as it makes the structural design more cumbersome by substantially increasing computational requirements."***

Trend of previous researches on seismic torsion design



Total number of publications on building torsion exceeds 700.
(Anagnostopoulos el al. 2013)

$$e_d = \alpha e_s + \beta b$$
$$e_d = \delta e_s - \beta b$$

Basically applied to **elastic design**. Sometimes, extended to control inelastic behavior.

- **Various** idealized one-/ multi-story system
- **Various** linear / nonlinear analytical model
- **Various** input ground motions

Statistical and **probabilistic** analyses for the obtained data such as u_{flex}/u_{avg}

Propose **various values** of α, β, and δ, to control elastic and inelastic behavior.

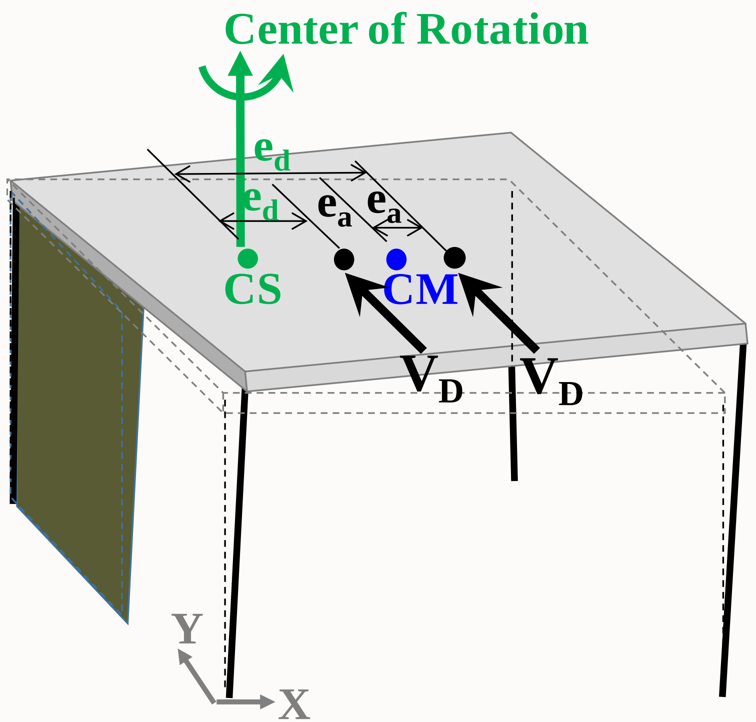
No consensus achieved.

"Black Box"

Very limited amount of research performed for investigations of detailed torsional behaviors of the models

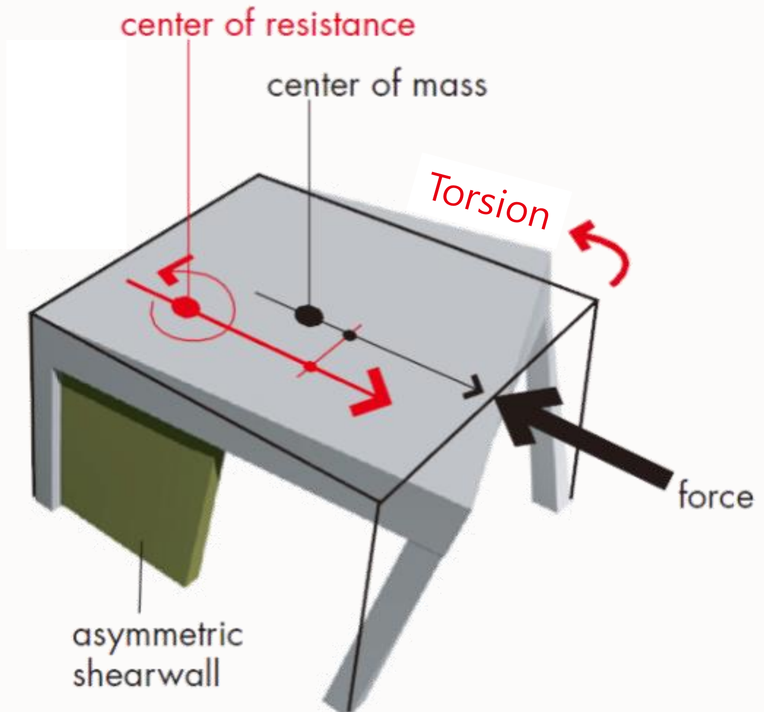
Definition of eccentricity

Inherent torsion:
Zero inertial torsional moment at CM



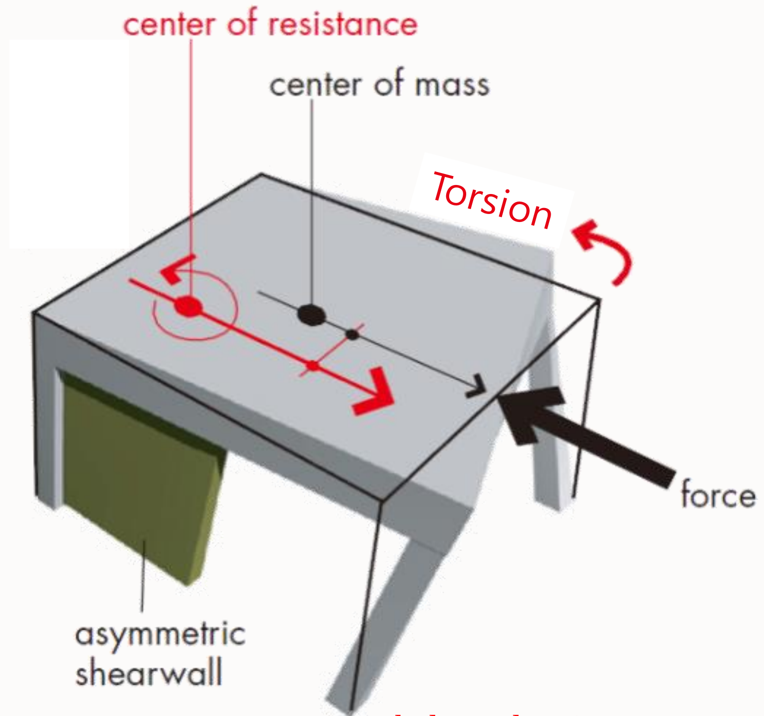
(a) Code static eccentricity model

FEMA 454:
Designing for earthquakes - a manual for architects

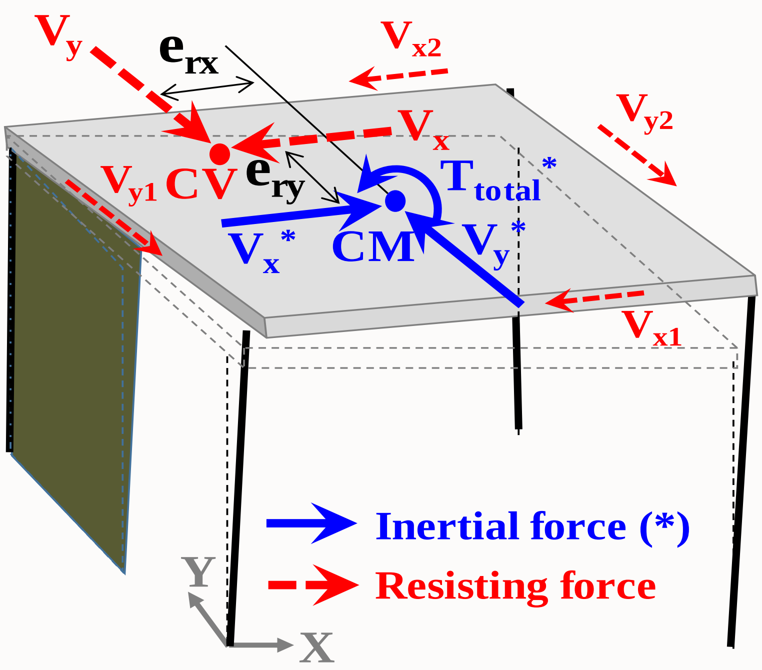


(b) FEMA 454 eccentricity model

Resistance eccentricity



(a) FEMA 454 eccentricity model



(b) Eccentricity model in this study

Shortcomings of the current design methods

- The current code torsion design has two main shortcoming:
    1) 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.
    2) The **eccentricity, e_y, which is commonly used by most engineers in FEMA 454 [2006], does not coincide with the e_s used for design eccentricity, e_d, in the current codes**. **This discrepancy in the definition of eccentricity may lead to substantial confusion among engineers**.

3. Two concepts used for overcoming the limitations of current torsion design

1) The prediction equations for **the ratio T_{total}/V_x and $\delta_{edge}/\delta_{center}$ in the elastic range are proposed as functions of the resistance eccentricity, e_y.**

2) The **overall hysteretic relations between shear and torsion in forces and deformations are approximated by the ellipsoids**.

Methodology

The demands estimated by using the two interactive relations between shear and torsion are compared to those obtained from the shake-table tests of :

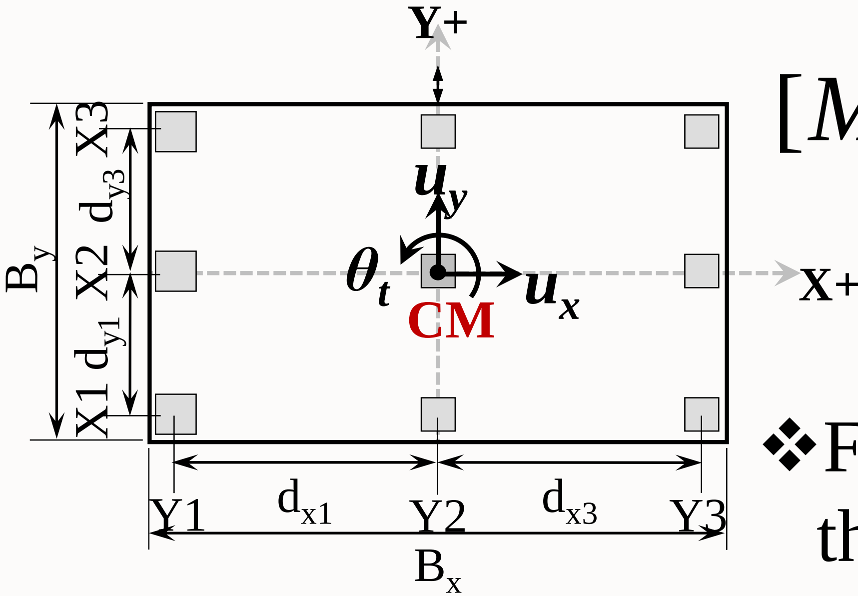
- 1:5-scale 5-story RC piloti-type building model

  (Lee and Hwang, EESD 2015)

- 1:12-scale 17-story RC piloti-type building model.

  (Ko and Lee, EESD 2006)

Prediction equations (1/3)



$$[M]\ddot{u}_t + [C]\dot{u} + [K]u = 0 \quad (1)$$

Equation of motion

❖For the peak drift, δ_{max}, the velocity is zero → $\dot{u} = 0$

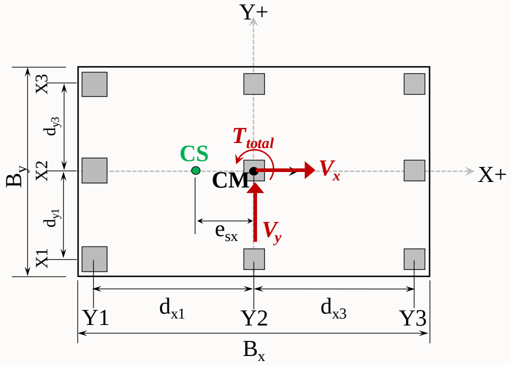
Then equation (1) can be written as:

$$-[M]\ddot{u}_t = [K]u \quad (2)$$

Prediction equations (2/3)

$$\{F\} = [K]\{u\}$$

$$\begin{Bmatrix} V_x \\ V_y \\ T_{total} \end{Bmatrix} = \begin{bmatrix} K_X & 0 & K_{\theta X} \\ 0 & K_Y & K_{\theta Y} \\ K_{\theta X} & K_{\theta Y} & K_{\theta\theta} \end{bmatrix} \begin{Bmatrix} \delta_x \\ \delta_y \\ \theta_t \end{Bmatrix} \quad (3)$$



$$K_X = \sum_{i=1}^{n} k_{xi} \text{ and } K_Y = \sum_{i=1}^{n} k_{yi} \quad (4)$$

i- represents the frame number

$$K_{\theta X} = e_{sy} K_X \text{ and } K_{\theta Y} = e_{sx} K_Y \quad (5)$$

$$e_{sy} = \frac{\sum_{i=1}^{n} k_{xi} d_{yi}}{K_X} \text{ and } e_{sx} = \frac{\sum_{i=1}^{n} k_{yi} d_{xi}}{K_Y} \quad (6)$$

$$K_{\theta\theta} = K_{\theta\theta X} + K_{\theta\theta Y} = \sum_{i=1}^{n} k_{xi} d_{yi}^2 + \sum_{i=1}^{n} k_{yi} d_{xi}^2 = b_y{}^2 K_X + b_x{}^2 K_Y \quad (7)$$

$$b_x = \sqrt{K_{\theta\theta X} / K_X} \quad \text{and} \quad b_y = \sqrt{K_{\theta\theta Y} / K_Y} \quad (8)$$

Prediction equation (3/3)

$$e_y = \frac{T_x}{V_x} = \left(\frac{K_{\theta\theta X} - e_{sy}{}^2 K_X}{K_{\theta\theta} - e_{sy}{}^2 K_X - e_{sx}{}^2 K_Y} \right) (\eta_y - e_{sx}\gamma_y) + \left(\frac{K_{\theta\theta Y} - e_{sx}{}^2 K_Y}{K_{\theta\theta} - e_{sy}{}^2 K_X - e_{sx}{}^2 K_Y} \right) e_{sy} \tag{9}$$

$$= b_x (\eta_y - e_{sx}\gamma_y) + b_y e_{sy}$$

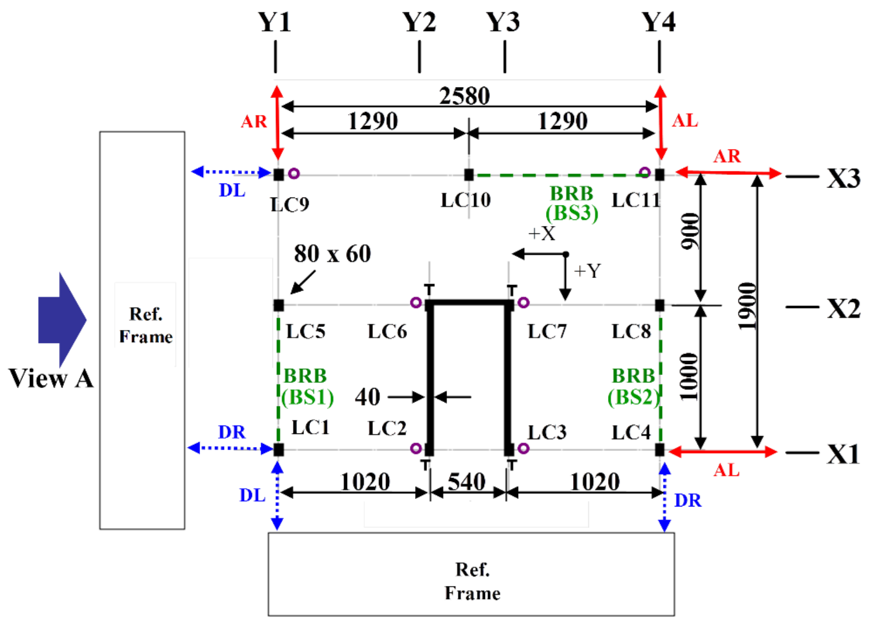
$$\gamma_y = \frac{V_y}{V_x} \qquad \eta_y = \frac{T_{total}}{V_x} = \frac{e_y - b_y e_{sy}}{b_x} + e_{sx}\gamma_y \tag{10}$$

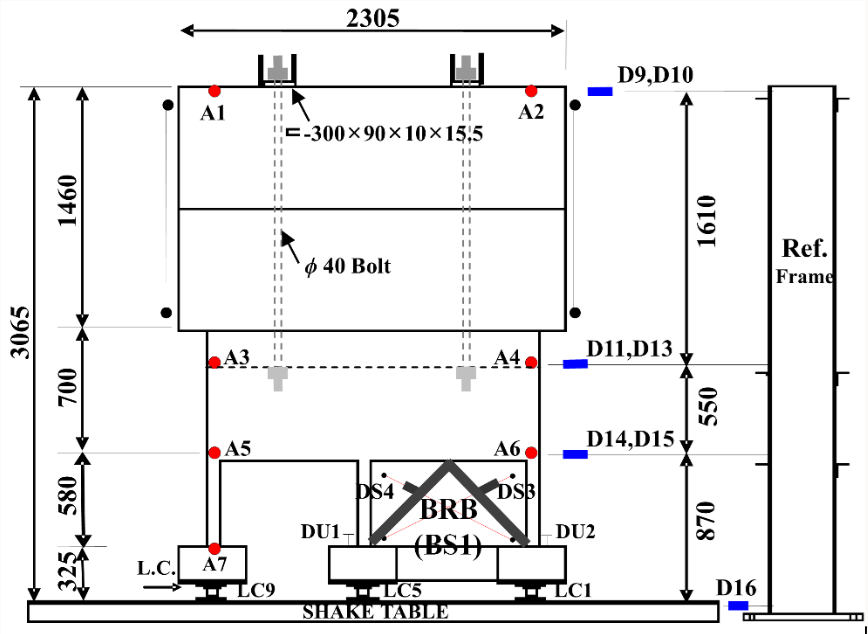
$$\frac{T_x}{T_{total}} = \frac{1}{T_{total}/V_x} e_y = \frac{1}{\eta_y} e_y = \frac{b_x (b_y e_{sy} - b_x e_{sx}\gamma_y)}{e_y - (b_y e_{sy} - b_x e_{sx}\gamma_y)} + b_x \tag{11}$$

$$\mu_x = \frac{\theta_t}{\delta_x} = \frac{e_y - e_{sy}}{(K_{\theta\theta X}/K_X) - e_{sy} e_y} \tag{12}$$

$$\frac{\delta_{stiff}}{\delta_x} = 1 + \mu_x d_{y,stiff} \quad \text{or} \quad \frac{\delta_{flex}}{\delta_x} = 1 + \mu_x d_{y,flex} \tag{13}$$

1:5-scale 5-story RC piloti-type building model





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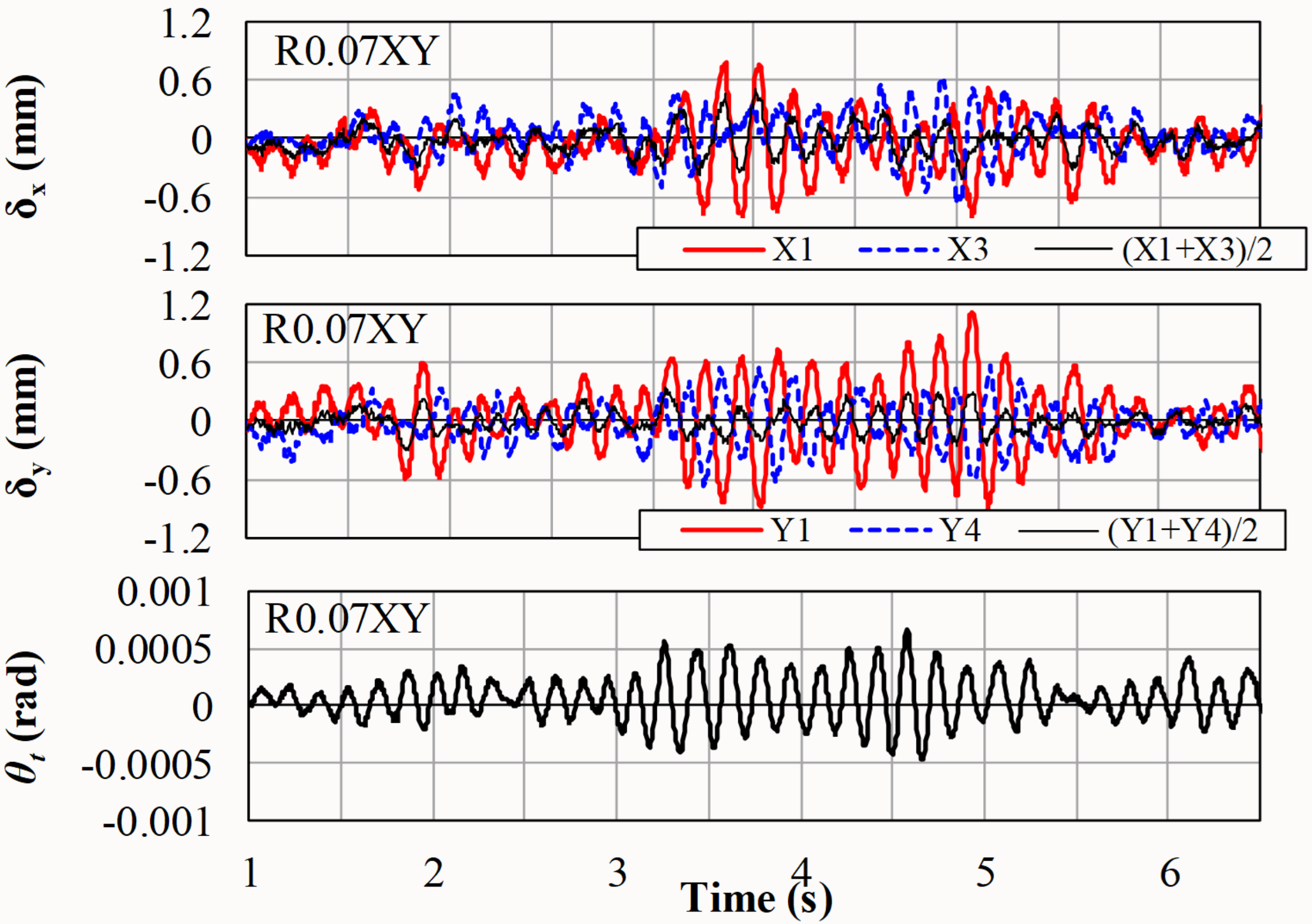
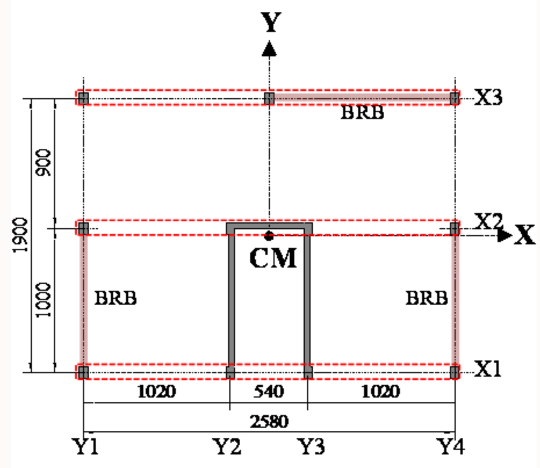
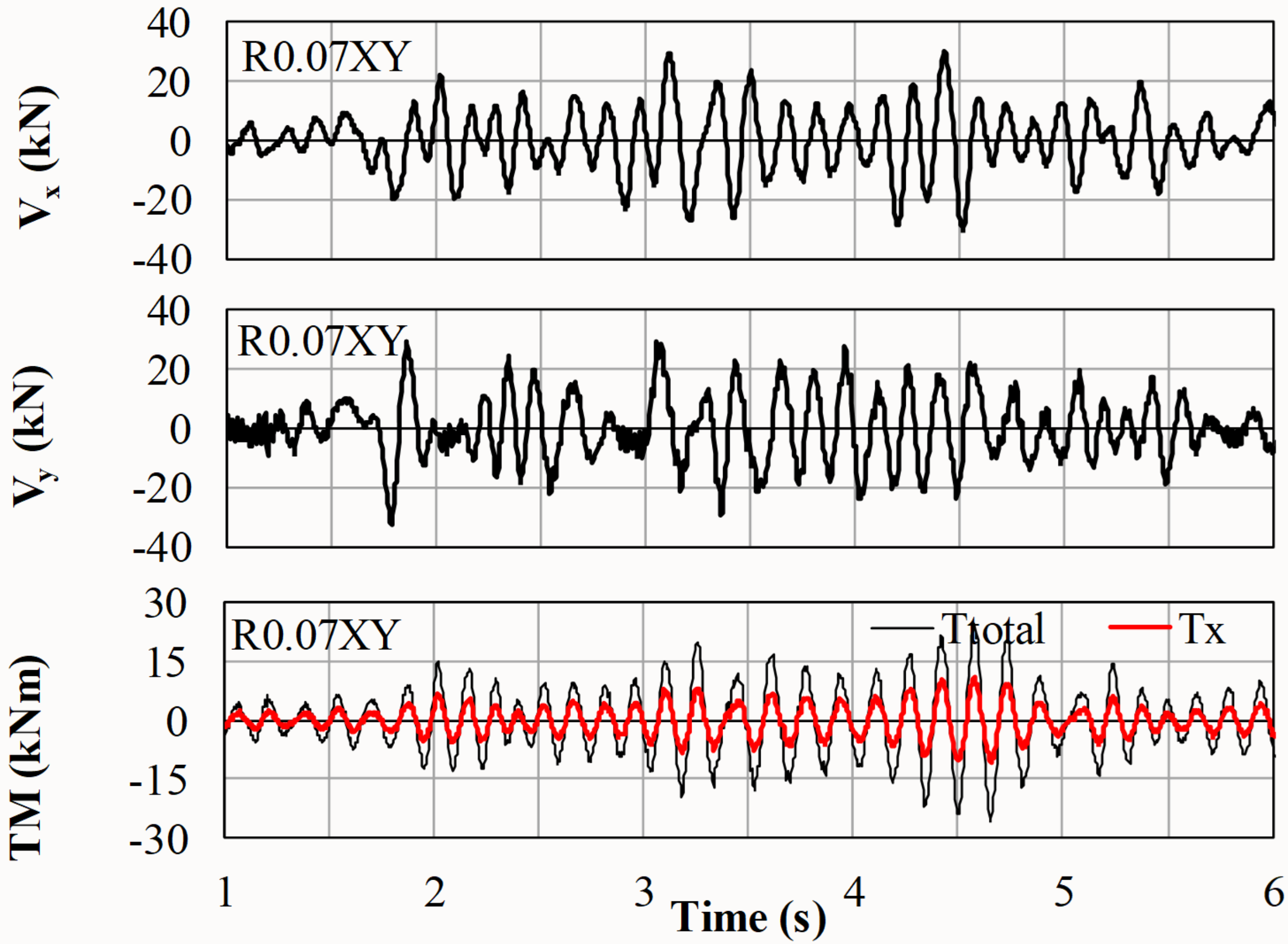
Time histories of responses for 5-story model

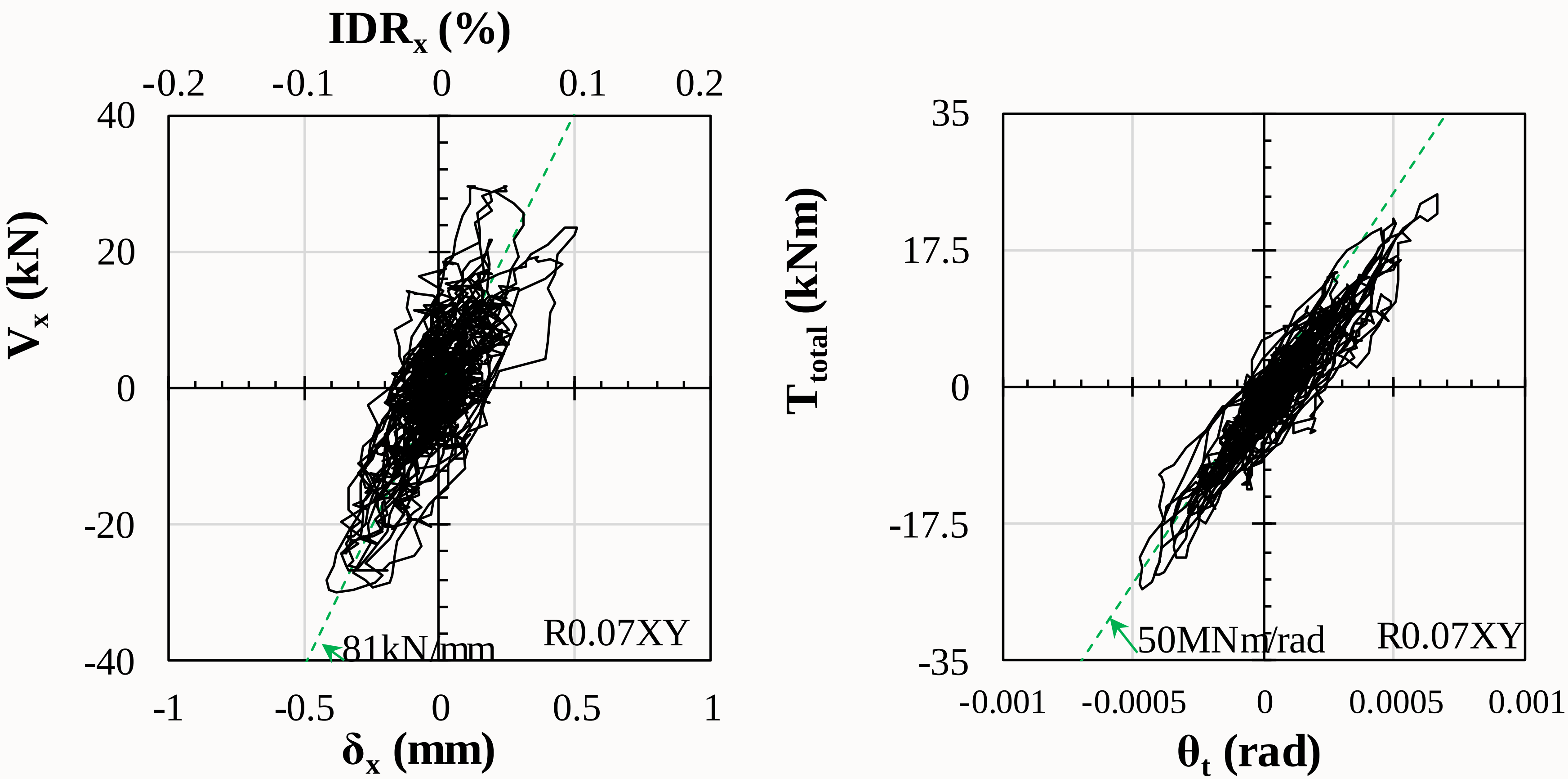




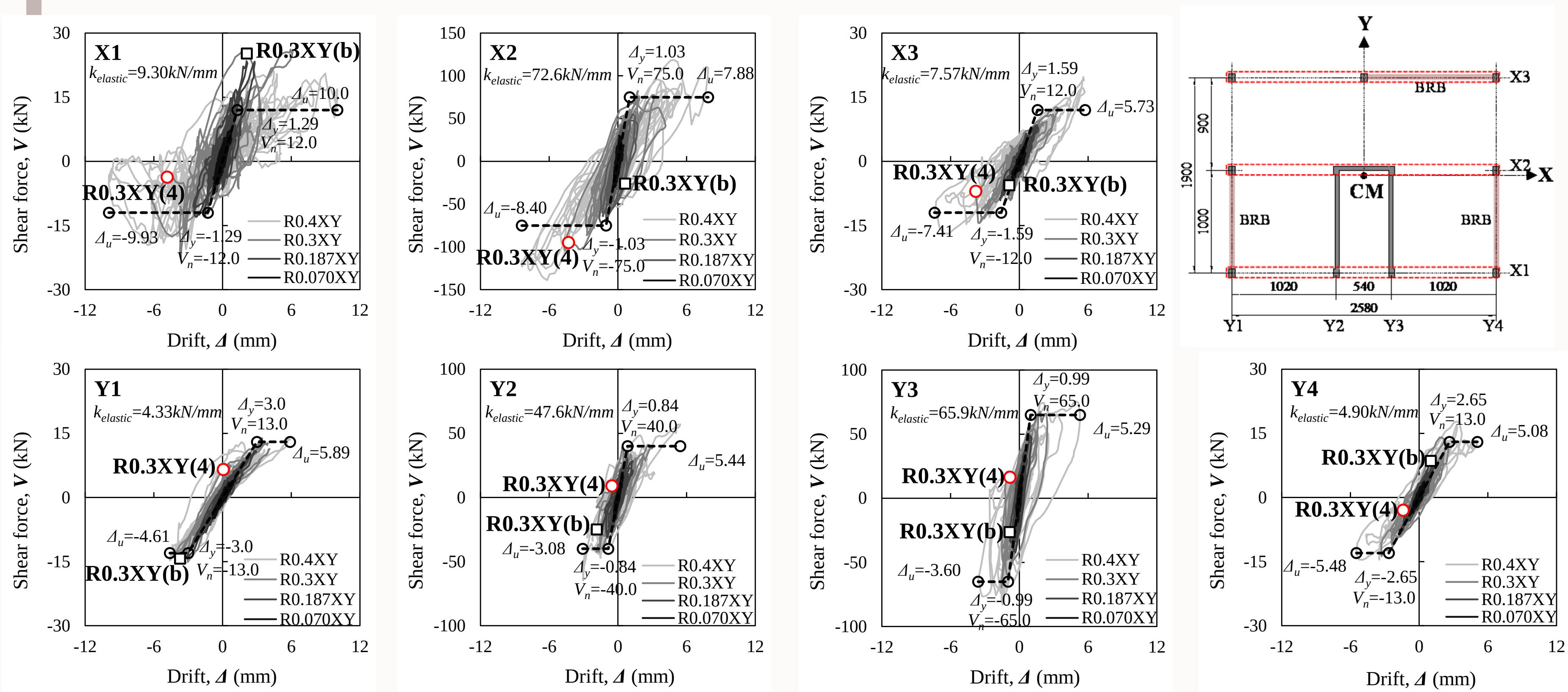
Time histories of responses for 5-story model



Hysteretic relations between force and deformation for 5-story model



Stiffness matrix for 5-Story model



$$K_X = 89.7 kN/mm \quad \text{and} \quad K_Y = 119.9 kN/mm$$

$$K_{X\theta} = 2050 kN/rad \quad \text{and} \quad K_{Y\theta} = -9003 kN/rad$$

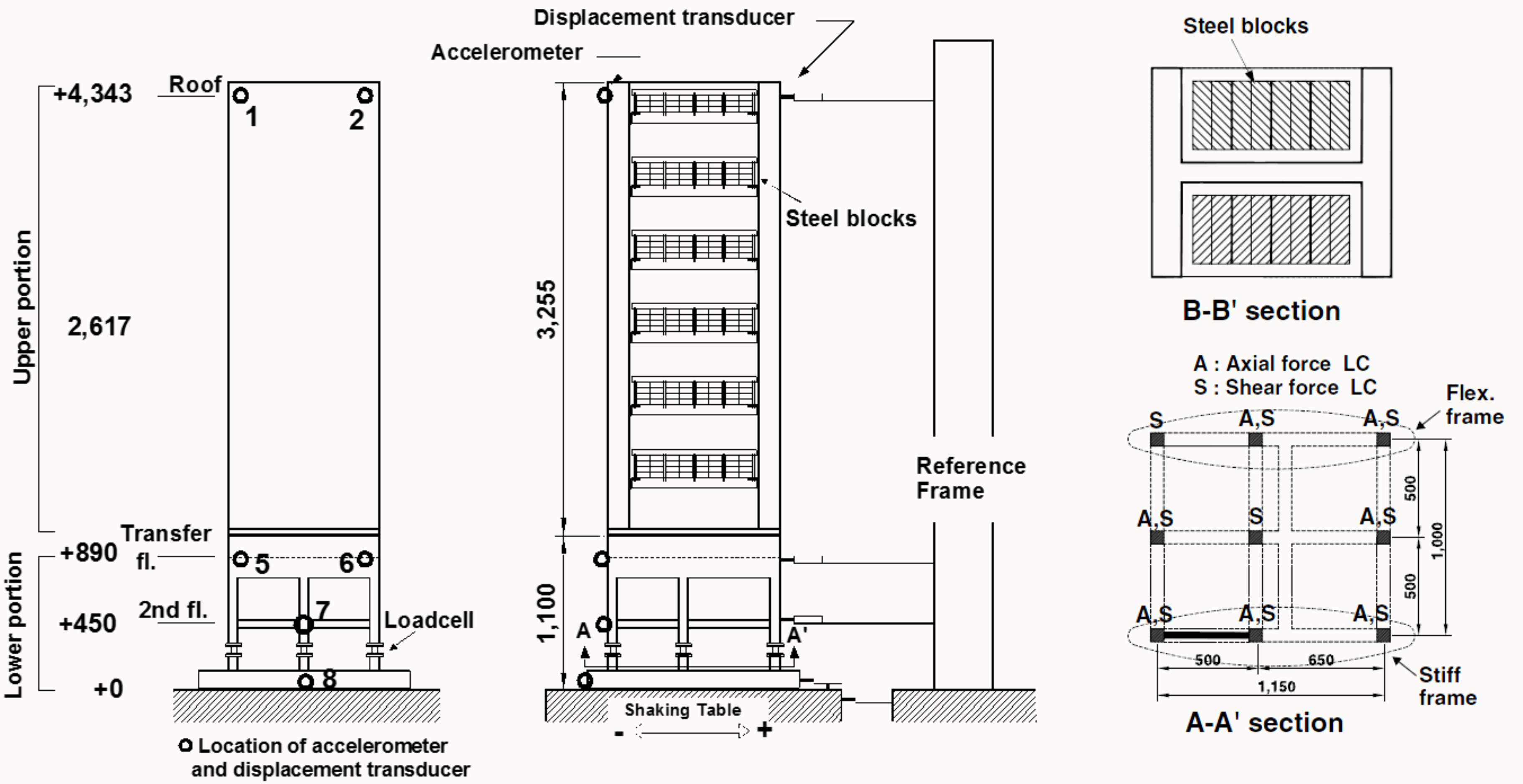
$$K_{\theta\theta X} = 1.91\times10^7 kNmm/rad$$

$$K_{\theta\theta Y} = 2.45\times10^7 kNmm/rad$$

$$K_{\theta\theta} = 4.36\times10^7 kNmm/rad$$

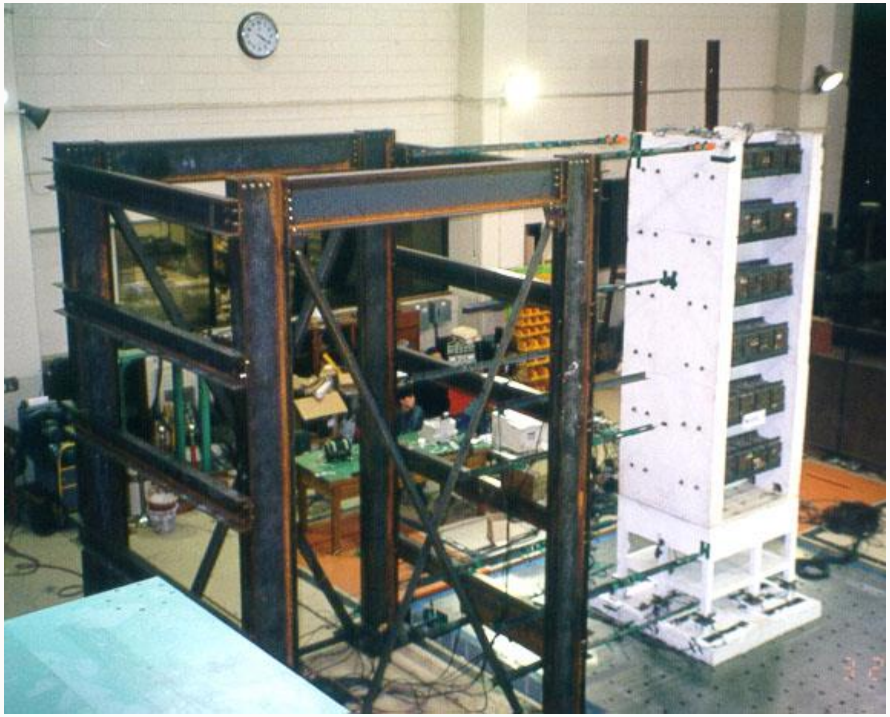
$$\begin{Bmatrix} V_x \\ V_y \\ T_{total} \end{Bmatrix} = \begin{bmatrix} 89.7 & 0 & 2050 \\ 0 & 120 & -9003 \\ 2050 & -9003 & 4.36\times10^7 \end{bmatrix} \begin{Bmatrix} \delta_x \\ \delta_y \\ \theta_t \end{Bmatrix}$$

1:12-scale 17-story RC piloti-type building model

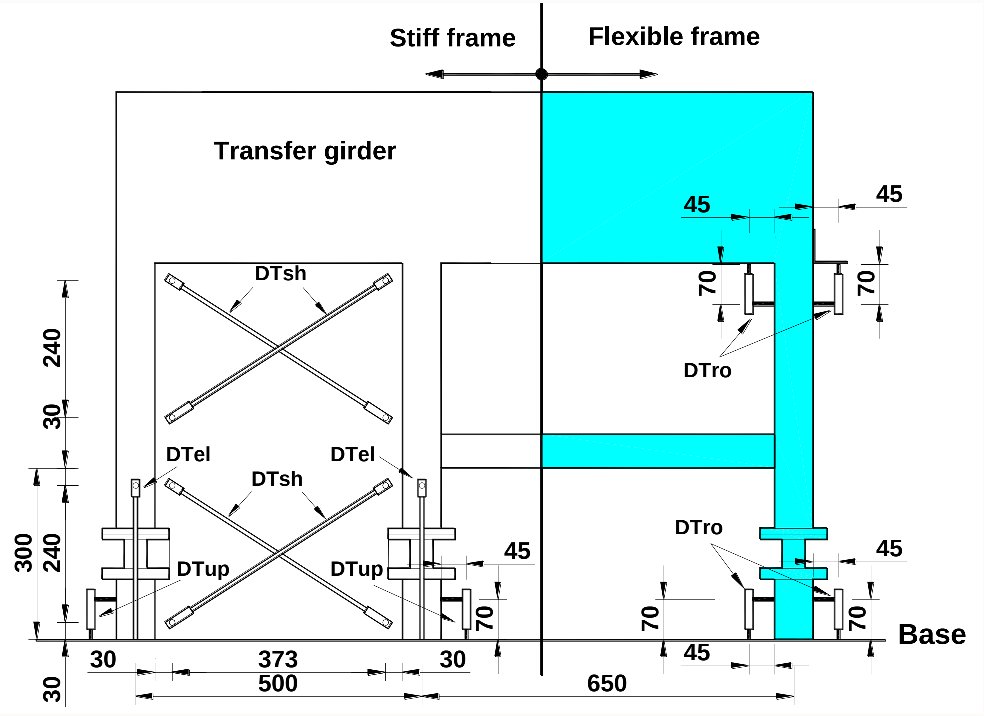


Front view Side view Plan view

Experimental setup of 17-story model

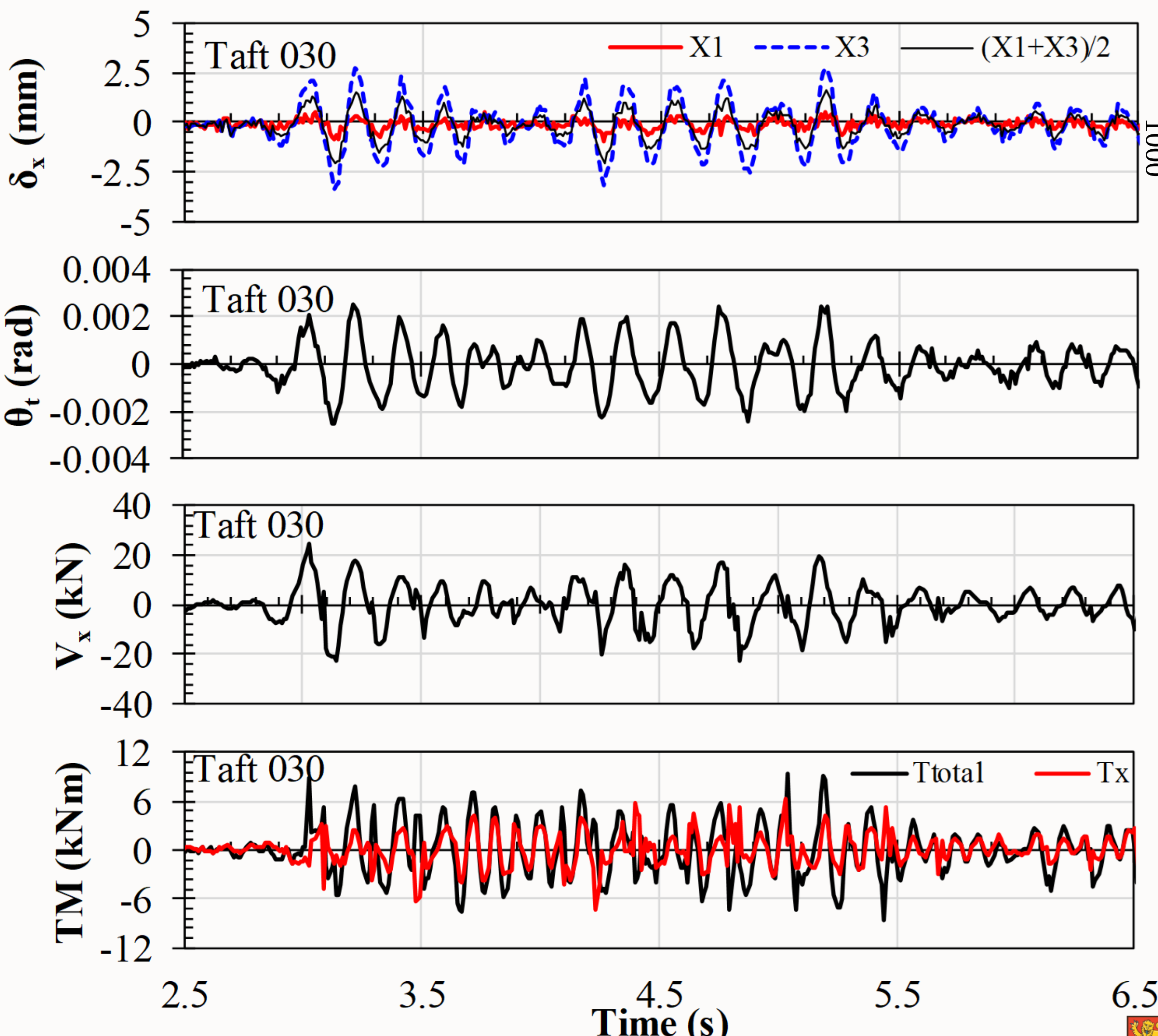


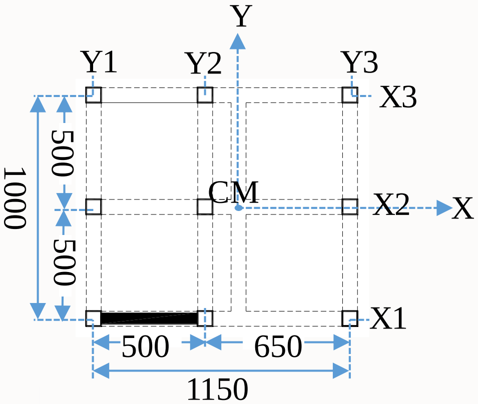
Overview of the model and experimental arrangement



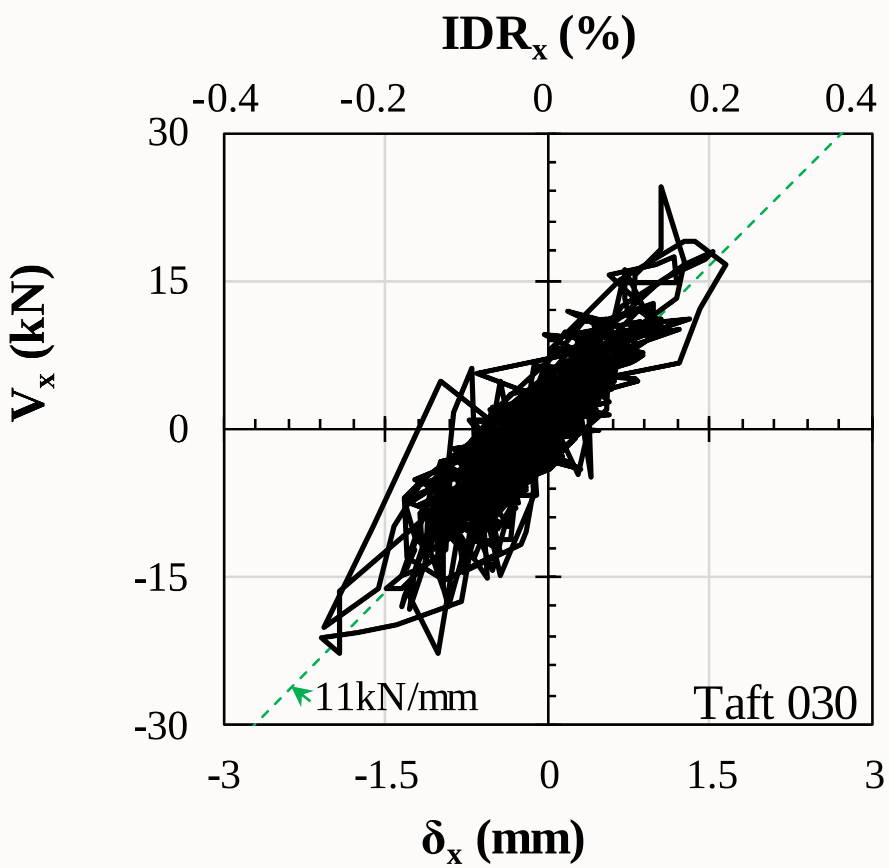
Instrumentation for wall and columns

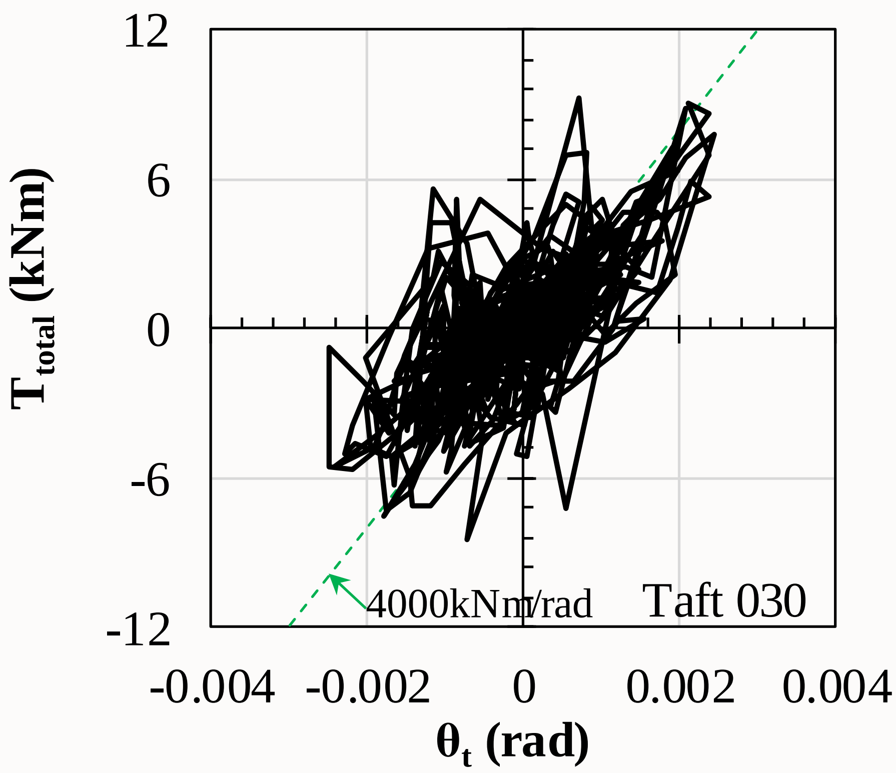
Time histories of the responses for 17-story model



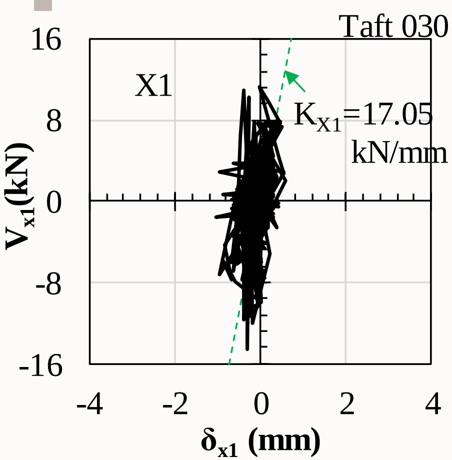


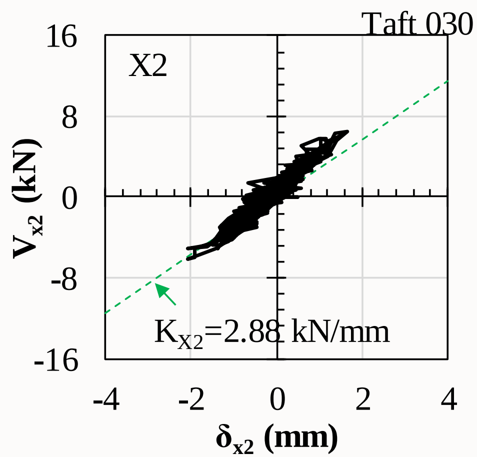
Hysteretic relations between force and deformation for 17-story model

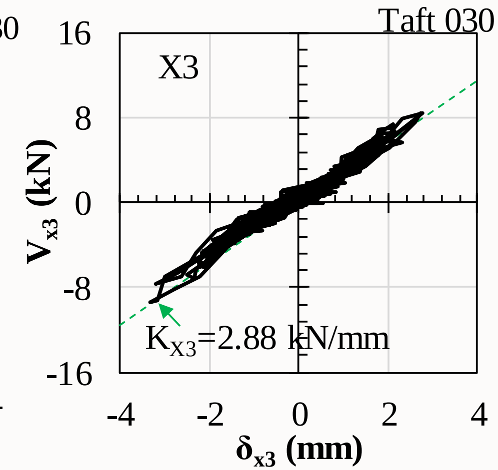


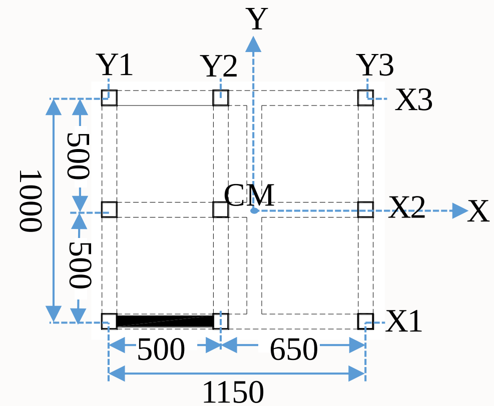


Stiffness matrix for 17-story model









$$K_X = 22.8 kN/mm$$

$$K_Y = 8.64 kN/mm$$

$$K_{X\theta} = -7085 kN/rad$$

$$K_{Y\theta} = 216 kN/rad$$

$$K_{\theta\theta X} = 4.98 \times 10^6 kNmm/rad$$

$$K_{\theta\theta Y} = 1.92 \times 10^6 kNmm/rad$$

$$K_{\theta\theta} = 6.90 \times 10^6 kNmm/rad$$

$$\boxed{V_{x1} = V_{inertia} - V_{x2} - V_{x3}}$$

$$\boxed{K_{y1} = K_{y2} = K_{y3} = K_{x2} = K_{x3} = 2.88 kN/mm}$$

$$\begin{Bmatrix} V_x \\ V_y \\ T_{total} \end{Bmatrix} = \begin{bmatrix} 22.8 & 0 & -7085 \\ 0 & 8.64 & 216 \\ -7085 & 216 & 6.90 \times 10^6 \end{bmatrix} \begin{Bmatrix} \delta_x \\ \delta_y \\ \theta_t \end{Bmatrix}$$

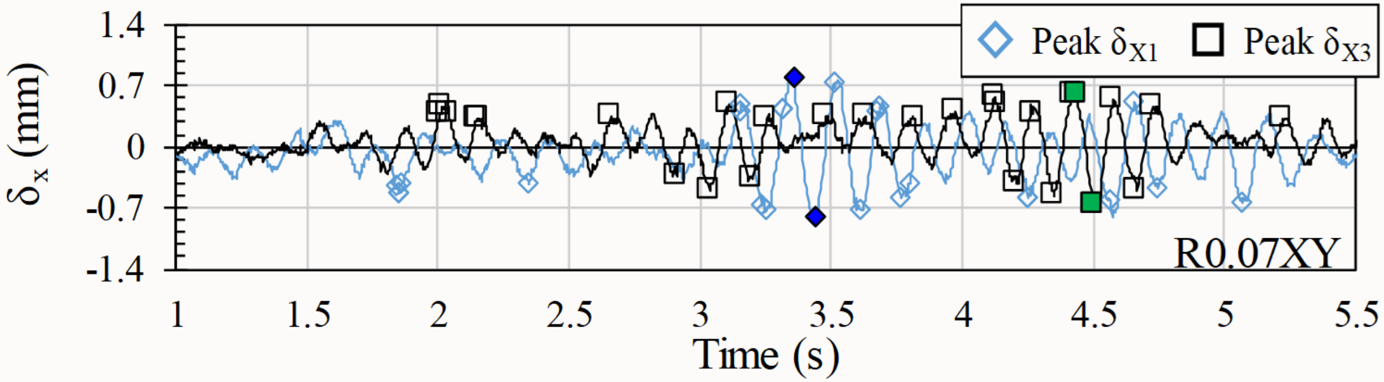
4. Verification of proposed equations through comparison with test results

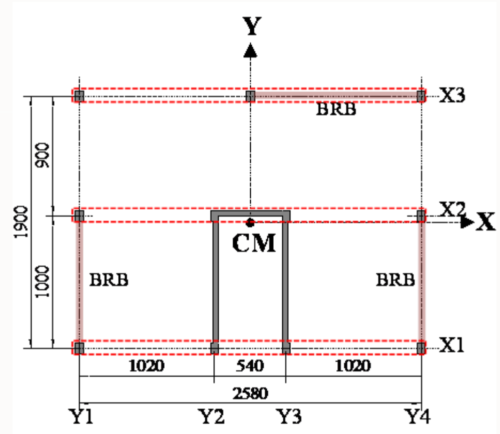
Time history of edge drifts

$\delta_{\diamond} \geq 1/2\delta_{\blacklozenge}$

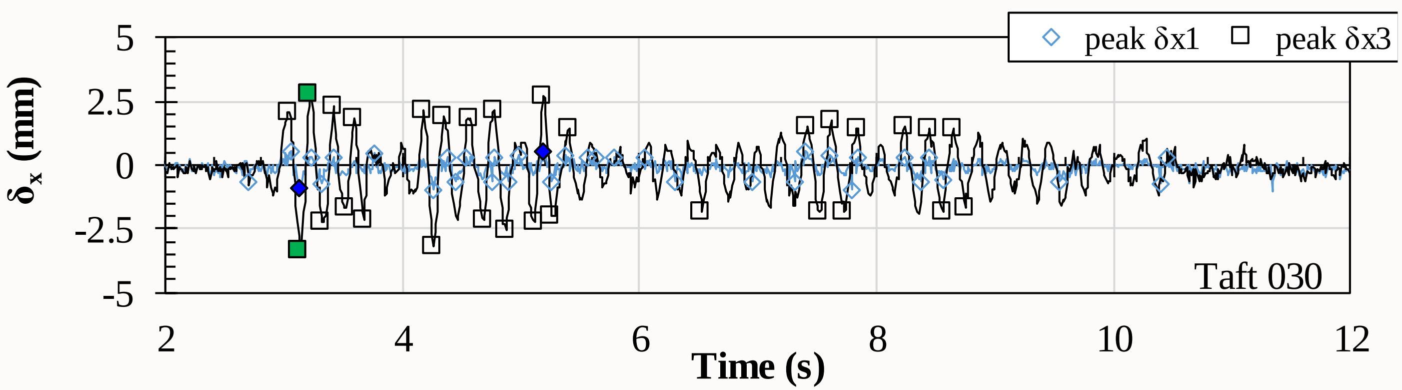
$\delta_{\square} \geq 1/2\delta_{\blacksquare}$

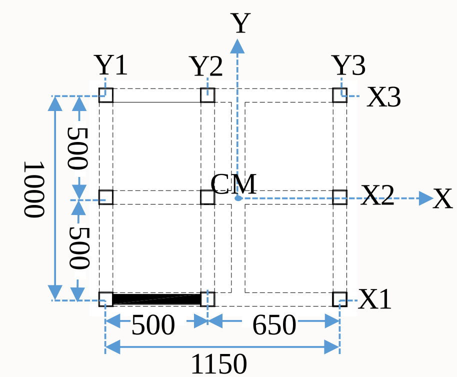
❖ 5-Story model





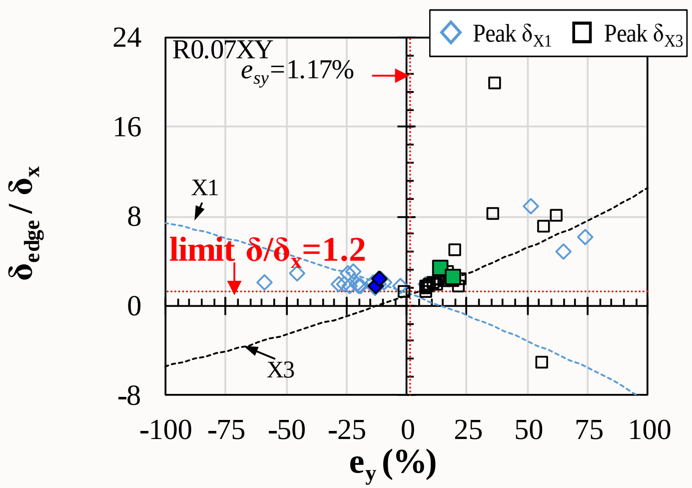
❖ 17-story model

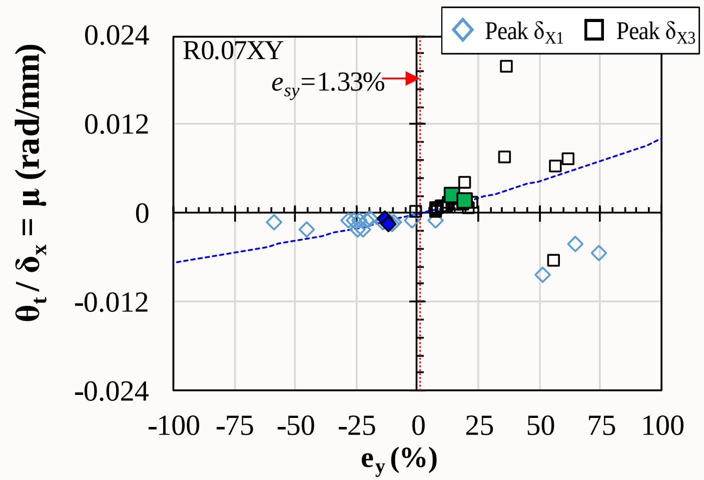




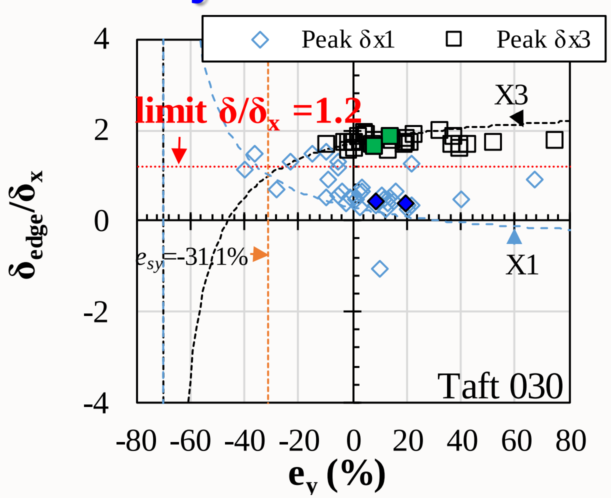
Comparison of experiment and prediction (1/2)

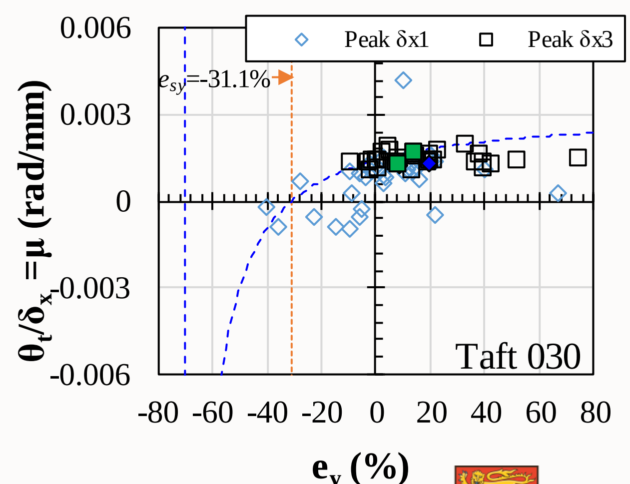
1) 5-Story model





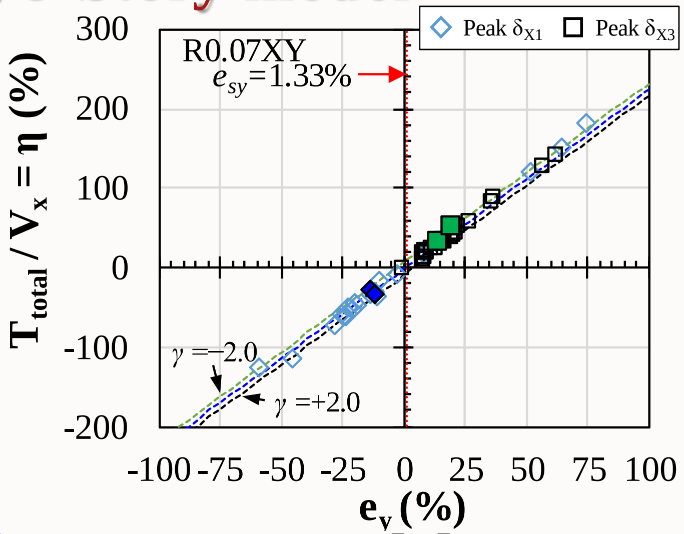
2) 17-Story model

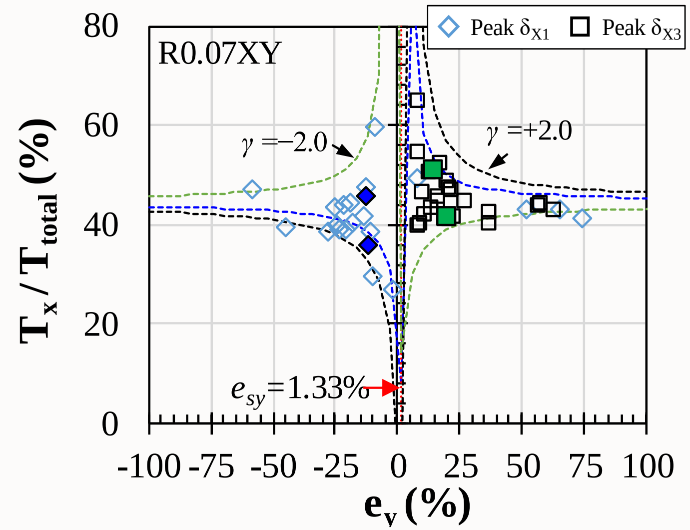




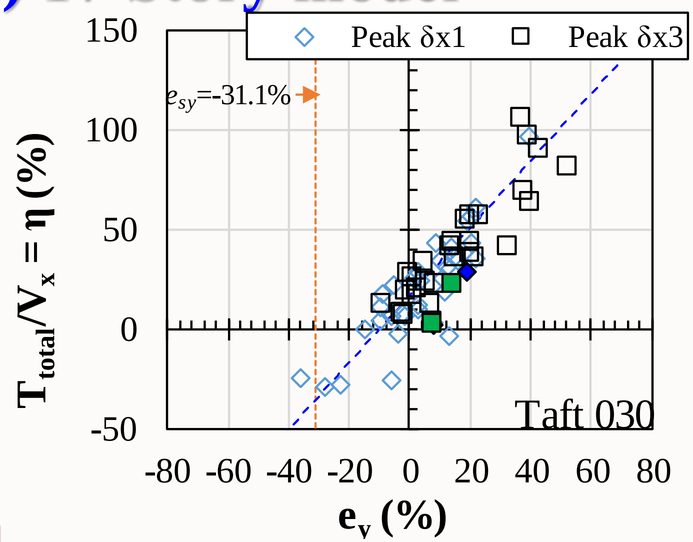
Comparison of experiment and prediction (2/2)

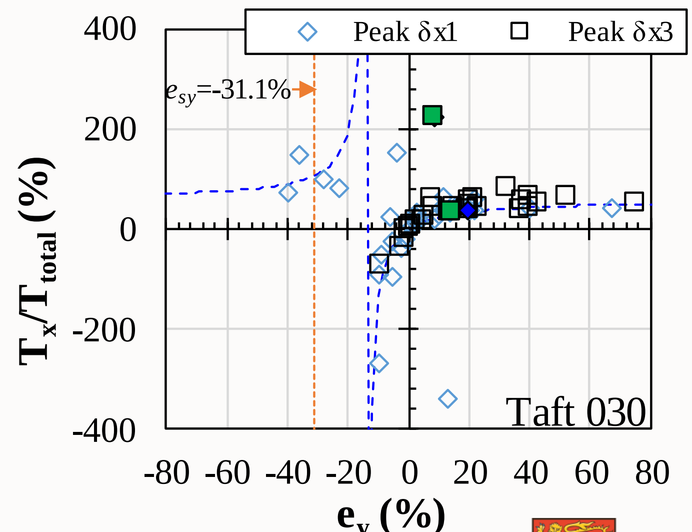
1) 5-Story model





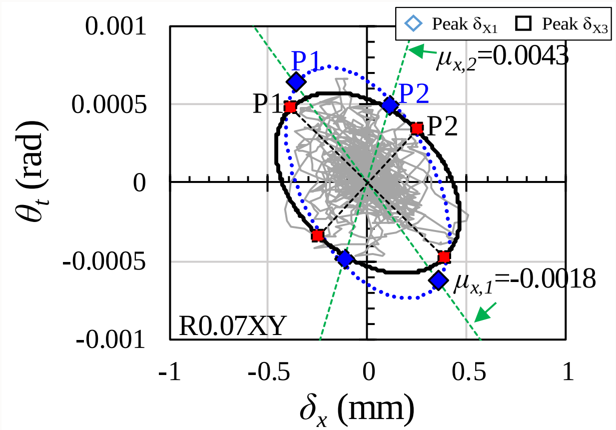
2) 17-Story model



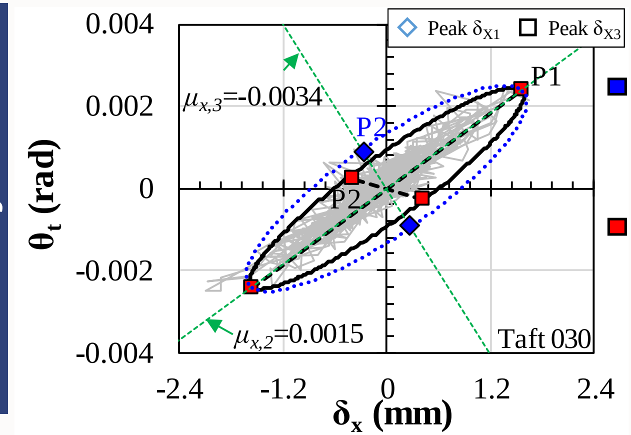


Seismic demands presented by ellipses

5-Story model



17-Story model



- Points based on the modal analysis results
- Readjusted points

The **equation of ellipse** can be expressed as the path of a point (*X(t)*, *Y(t)*) :

$$X(t) = A \cos t \cos\varphi - B \sin t \sin\varphi$$

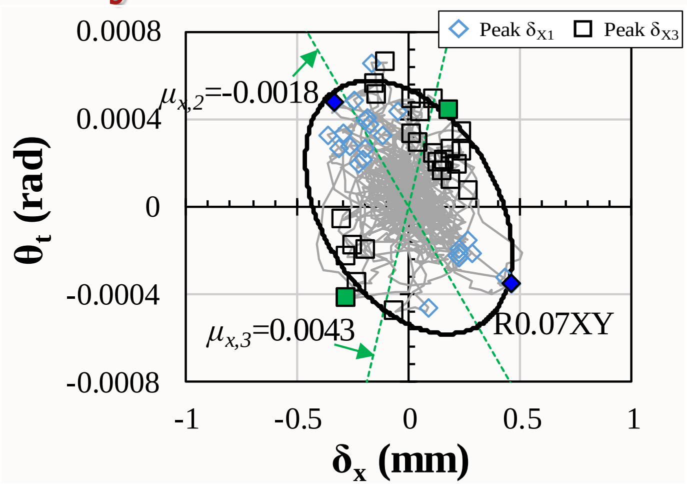
$$Y(t) = A \cos t \sin\varphi + B \sin t \cos\varphi$$

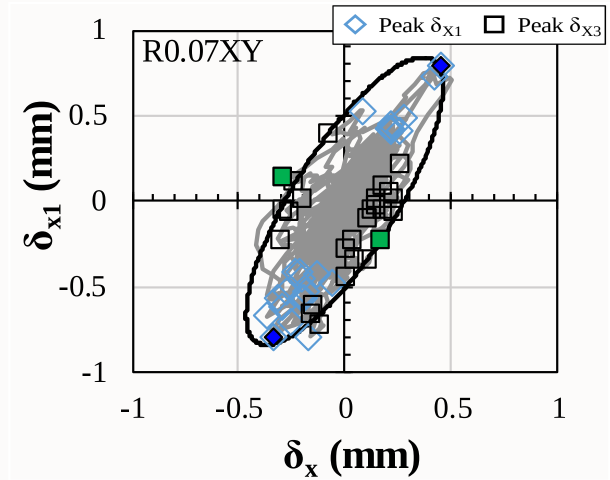
***t*:** the parametric angle, $0 \le \theta \le 2\pi$;
A is radius in the major axis;
B is the radius in the minor axis;
φ: the angle between the X-axis and the major axis;

		X(t): δ_x (mm)		Y(t): θ_t (rad)		A	B	ϕ
		P1	P2	P1	P2			
5-Story model	black bold	-0.38	0.25	4.8×10^{-4}	3.4×10^{-4}	1.41	0.96	-0.785
	blue dotted	-0.35	0.13	6.4×10^{-4}	5.4×10^{-4}	1.41	0.88	-0.785
17-Story model	black bold	1.56	-0.41	2.4×10^{-3}	2.5×10^{-4}	1.41	0.28	-0.785
	blue dotted	1.56	-0.18	2.4×10^{-3}	6.2×10^{-4}	1.41	0.36	-0.785

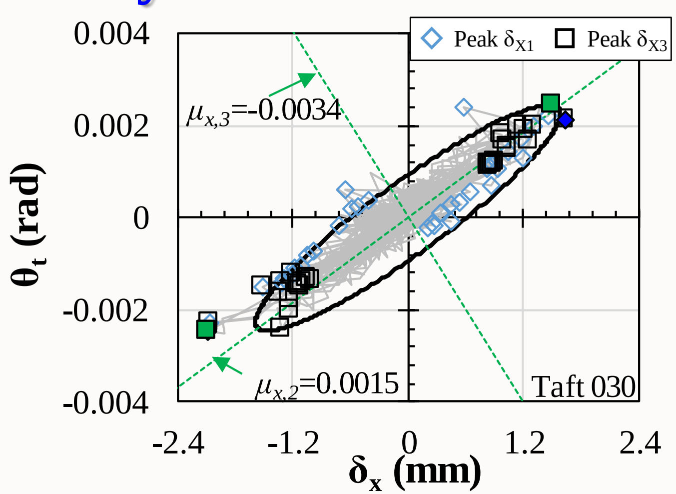
Torsional -translation deformation relationship

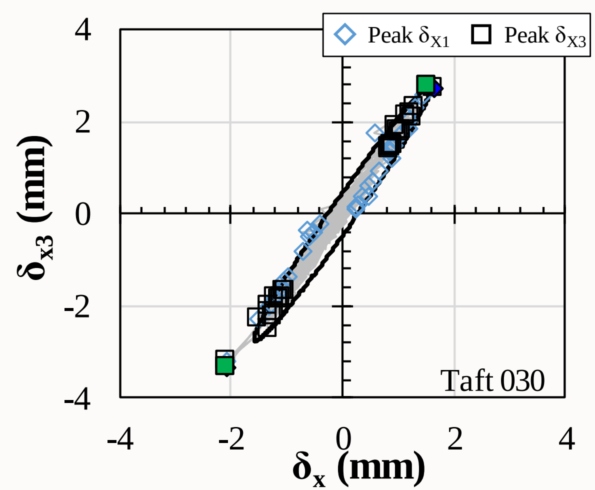
1) 5-Story model





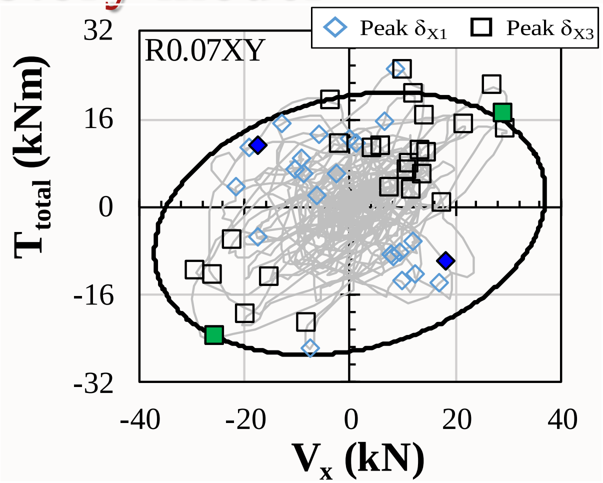
2) 17-Story model

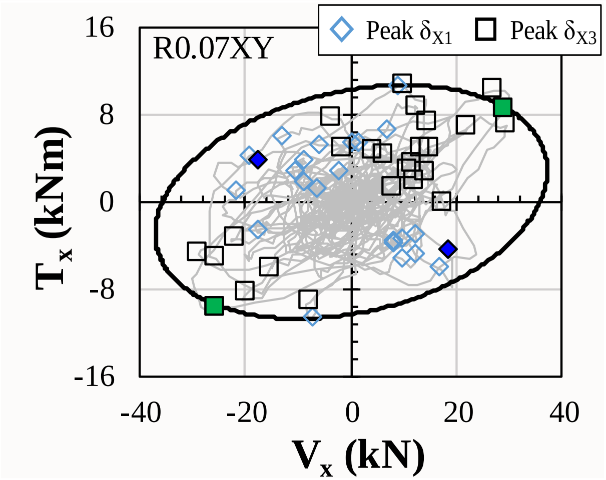




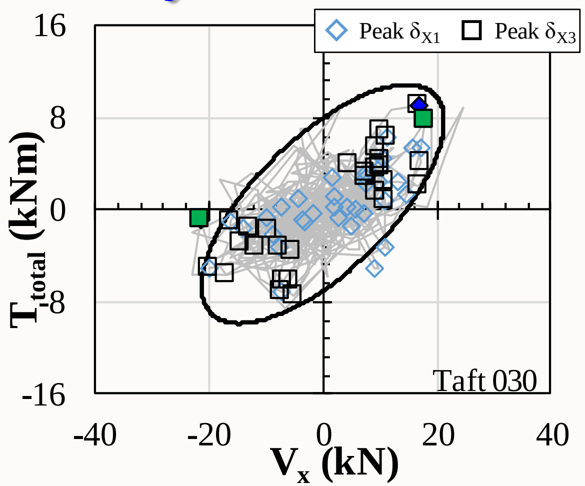
Shear force -torsional moment relationship

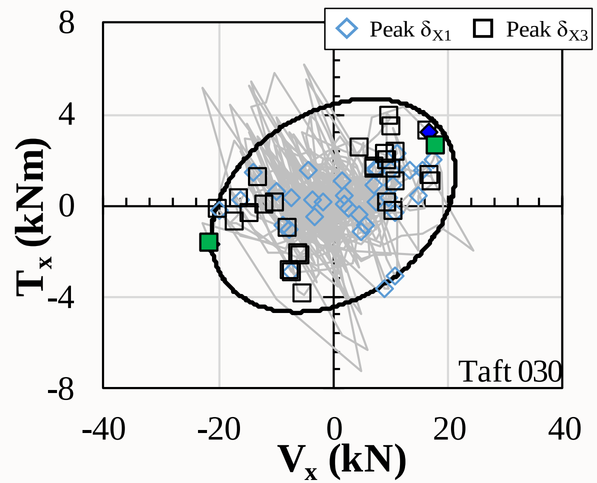
1) 5-Story model





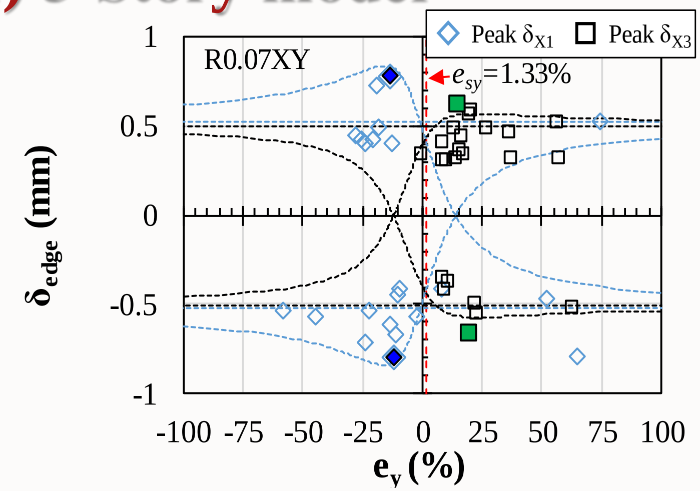
2) 17-Story model

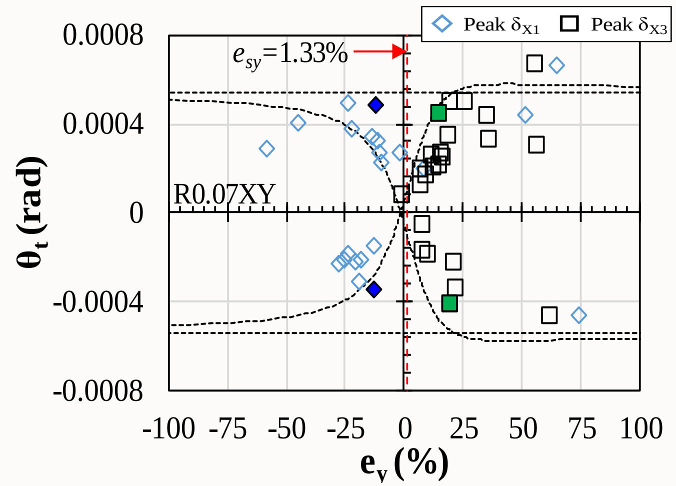




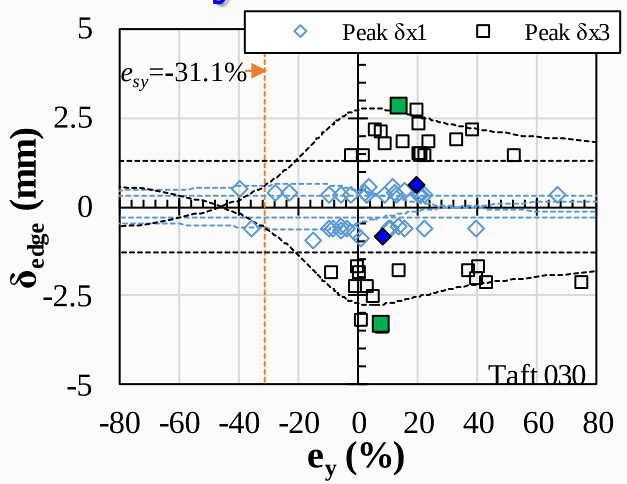
Comparison of experiment and prediction (1/2)

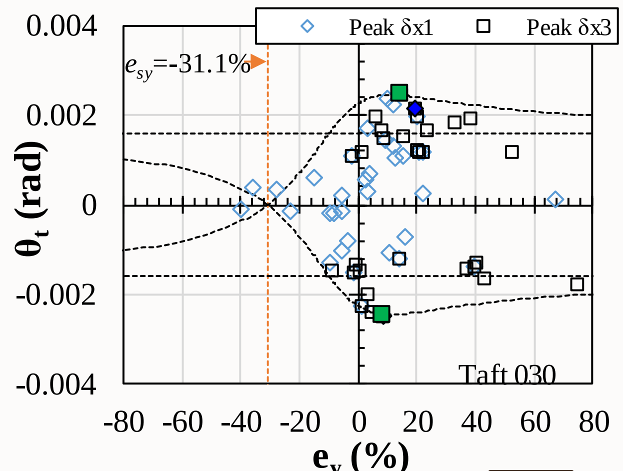
1) 5-Story model





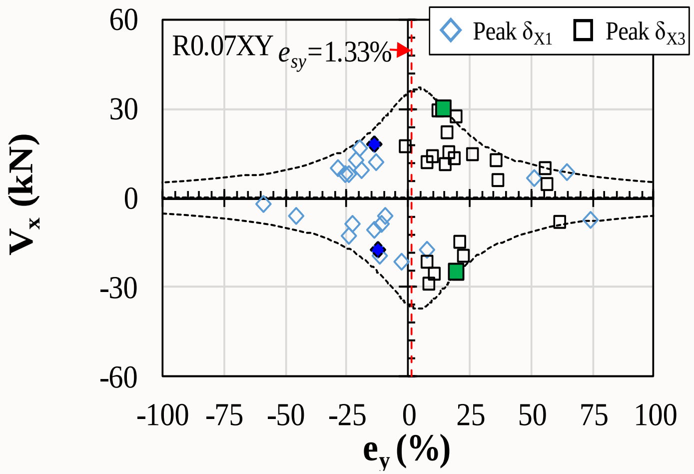
2) 17-Story model

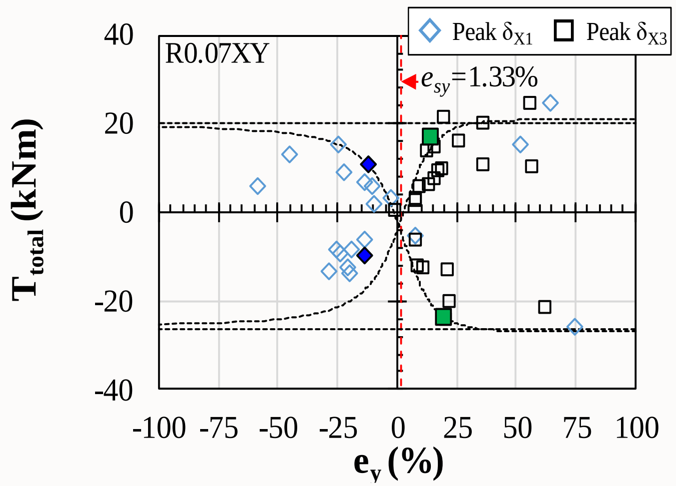




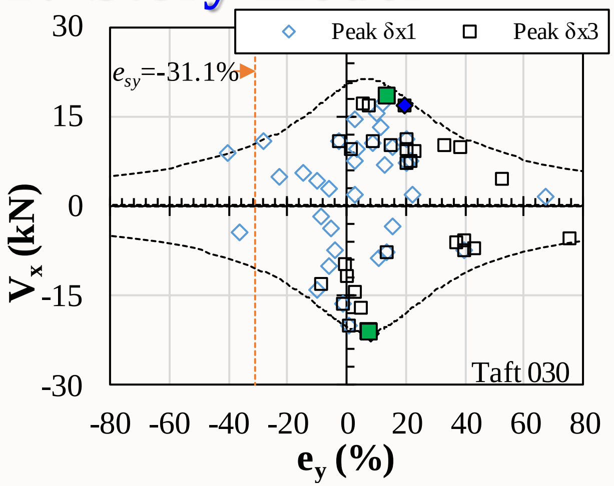
Comparison of experiment and prediction (2/2)

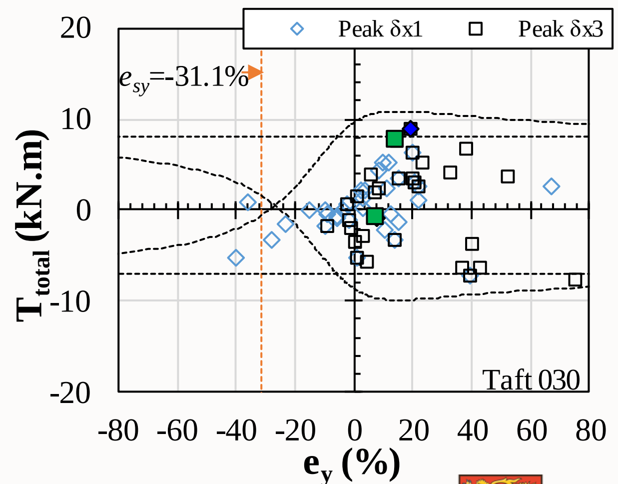
1) 5-Story model





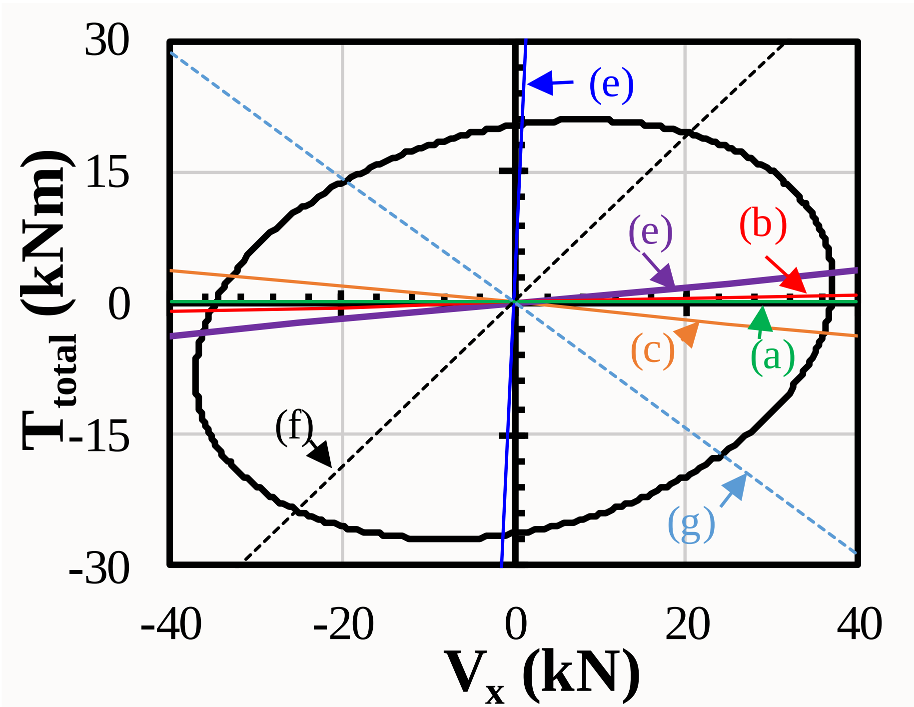
2) 17-Story model

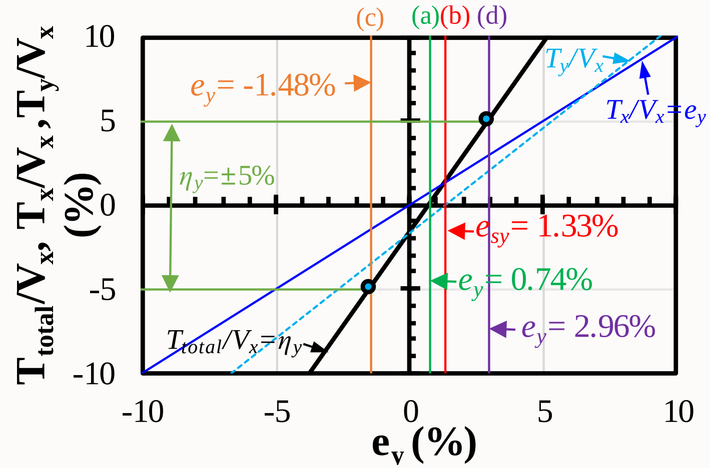


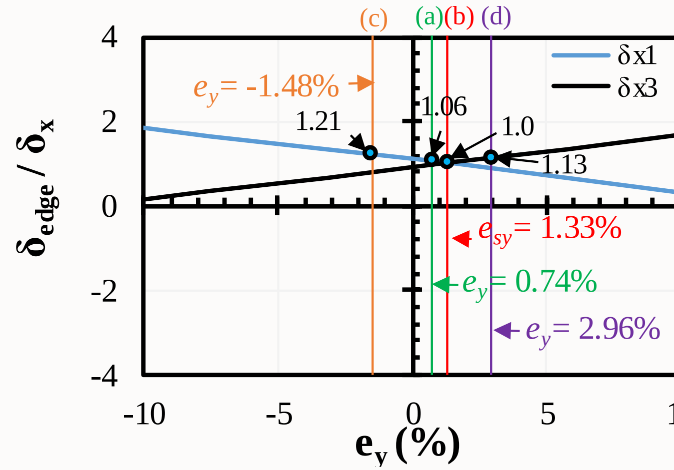


5. The significance of the proposed concept and limitation of code torsion design

Relationship in forces for five-story model

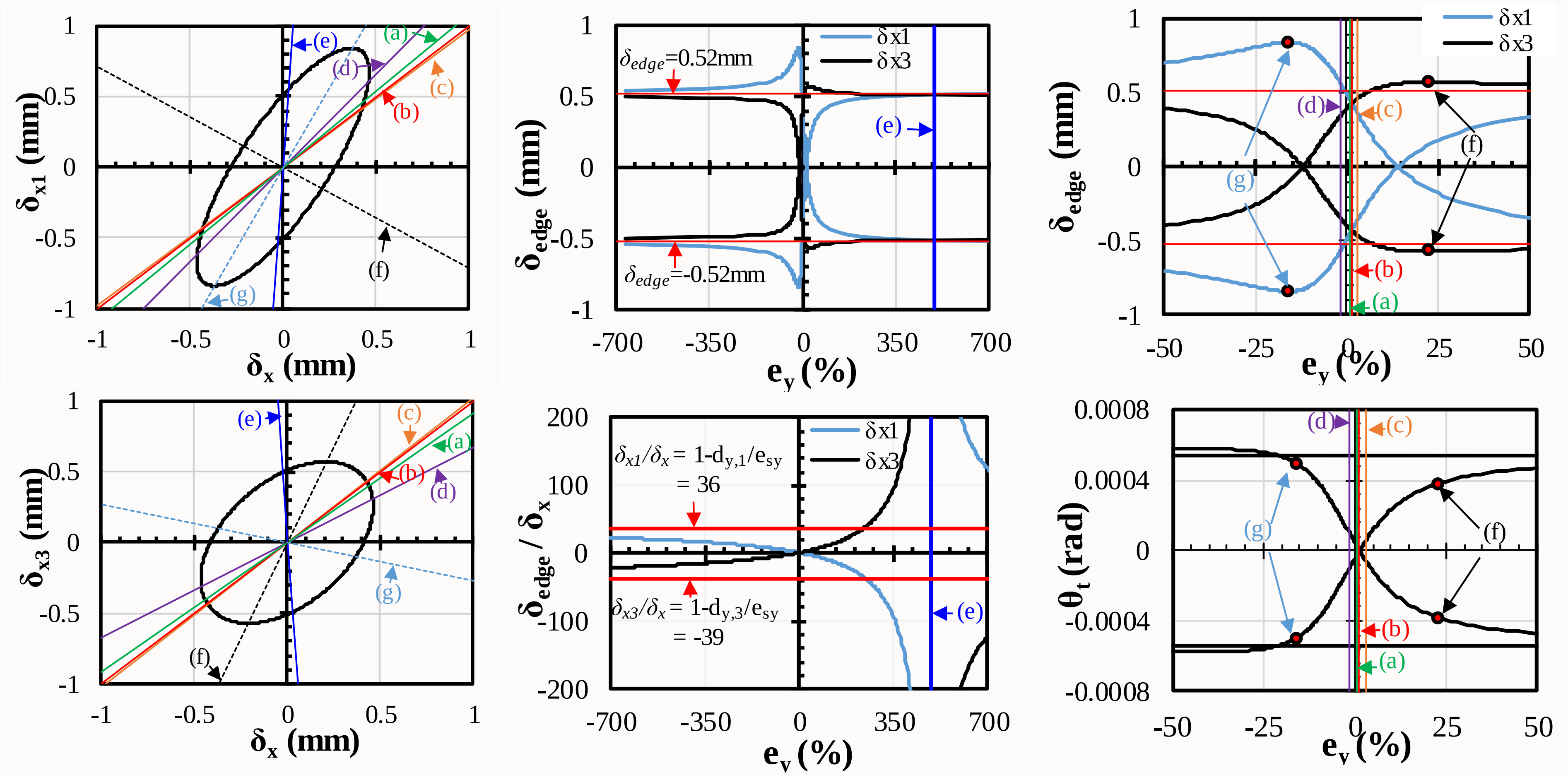






Phenomena	e_y (%)	η_y (%)	δ_{x1} (mm)	δ_{x3} (mm)	V_x (kN)	T_x (kNm)	T_{total} (kNm)	θ_t ($\times 10^{-4}$ rad)	δ_{x1}/δ_x
(a) Inherent torsion (T_{total}=0)	0.74	0	0.45	0.38	37.7	0.53	0	-0.36	1.06
(b) X-dir. Translation only	1.33	1.33	0.48	0.48	39.17	0.99	0.99	0	1
(c) Accidental torsion (-5%)	-1.48	-5	0.41	0.43	32.4	-0.91	-25.8	0.1	1.21
(d) Accidental torsion (+5%)	2.96	5	0.61	0.31	37.3	2.1	0.55	-1.6	1.13
(e) Rotation only	481	1225	-0.51	0.51	1.12	10.3	24.8	5.4	∞

Relationship in deformations for five-story model

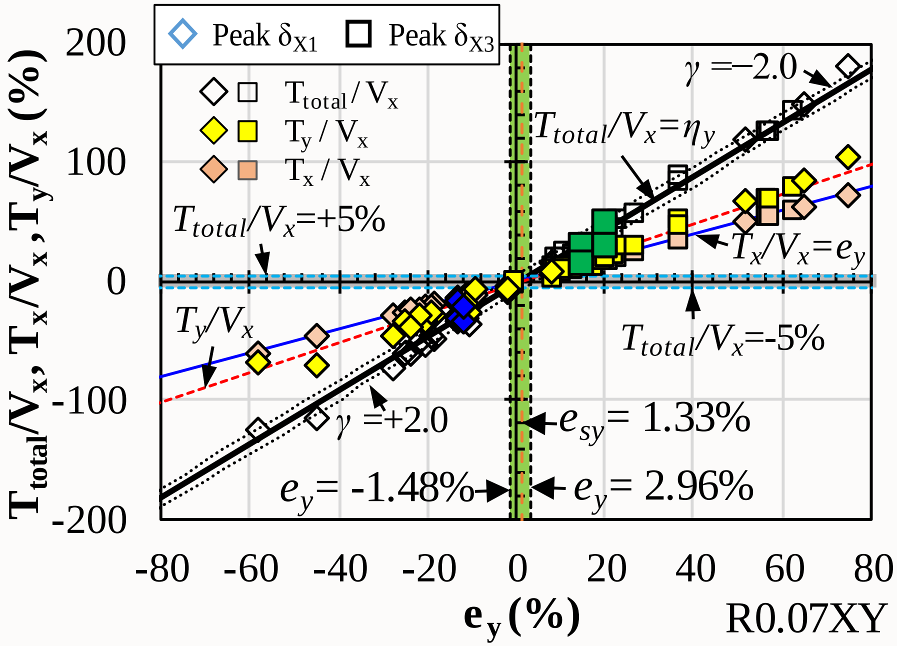


Phenomena	e_y (%)	η_y (%)	δ_{x1} (mm)	δ_{x3} (mm)	V_x (kN)	T_x (kNm)	T_{total} (kNm)	θ_t ($\times 10^{-4}$ rad)	δ_{x1}/δ_x
(f) δ_{x3} maximum (stiff)	22.7	49.4	-0.15	**0.57**	17.8	-7.7	-20.9	3.8	-0.71
(g) δ_{x1} maximum (flexible)	-15.9	-37.5	**0.84**	-0.10	28.9	8.7	15.7	-5.0	2.28

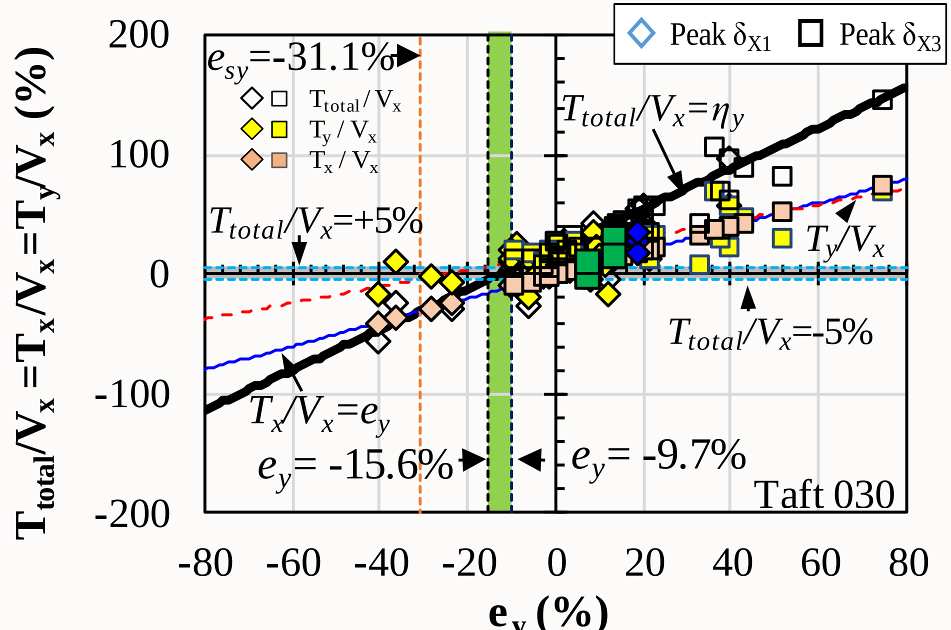
Significance of the proposed concepts

We can not only visualize the overall relationship between shear and torsion with the range of forces and deformations, but also pinpoint easily the information about critical responses of the structures such as the maximum and minimum edge drifts and the corresponding shear force and torsion moment with the eccentricity.

Comparison of the range of eccentricity according to the accidental torsion



5-Story model



17-Story model

Unit: %	$\eta = T_{total}/V_x$	$e_y = T_x/V_x$	$\eta_{acc} = T_{acc}/V_x$	$e_y = T_{x,acc}/V_x$
5-Story	-125 ~ 81	-58.6 ~74.6	-5 ~ +5	-1.48 ~ +2.96
17-Story	-56.4 ~145	-40.3 ~74.8	-5 ~ +5	-15.6 ~ -9.7

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Structural Concrete Engineering Lab.

Faculty of Engineering
THE UNIVERSITY OF HONG KONG

6. Conclusions

Conclusions (1/2)

1. **The prediction equations and ellipsoidal bounding equations enable the engineers to have a clear overall picture of the structural responses including the critical minimum, maximum values of T_{total}, V_x, δ_{edge} and δ_{edge}/δ_x, which occur at the different instant of e_y.**
2. **Instead of using any specific value of eccentricity, e_y, as design parameter, the demand in torsion can be determined in the direct relationship with the base or story shear, represented as an ellipse.**

Conclusions (2/2)

3. **The inherent torsion in the current code static eccentricity model represents a very specific instant of zero inertial torsional moment at the CM, in contrast to the general state of the inertial torsion moment, which can be very large in TU structures. Therefore, it is evident that the code static eccentricity model cannot accommodate the real torsional behaviour of particularly TU structures**,

4. **The use of only accidental torsion eccentricity $\eta_a = T_{total}/V$ (-5% to +5%) represents a very limited range of torsional behaviour, compared to the actual ranges, explaining why the accidental torsion causes only a negligible design impact despite the code-required cumbersome design procedure**.

Thank you
for your attention!