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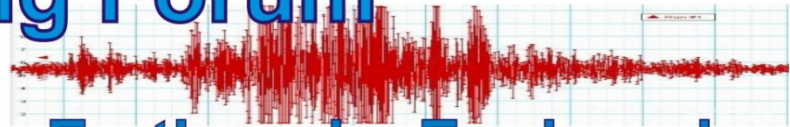
European Council  
of Engineers Chambers

**BEF**  
**2021**

# Building Engineering Forum

20-21 October 2021, Sofia, Bulgaria

International Conference on Earthquake Engineering



## SEISMIC BEHAVIOR OF PLAN IRREGULAR STRUCTURES

Assoc. prof. dr. Koce Todorov

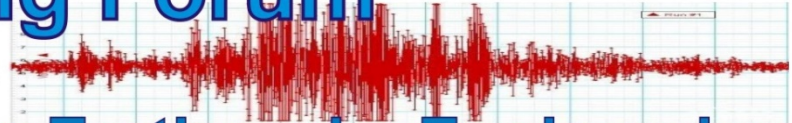
Faculty of Civil Engineering, UKIM, Skopje



# Building Engineering Forum

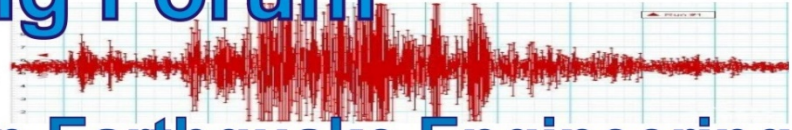
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## OUTLINE

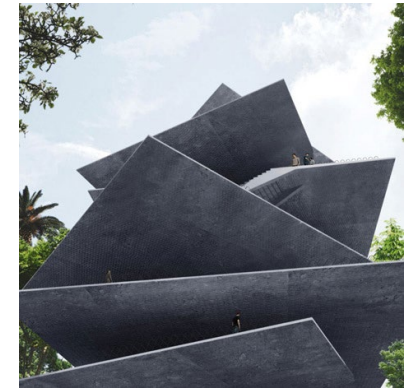
- Reasons and consequences
- Source of structural irregularity
- Code criteria comparison
- Structural characteristics
  - comparison of methodologies
  - modeling assumptions
- Case studies



## Structural irregularity - reasons

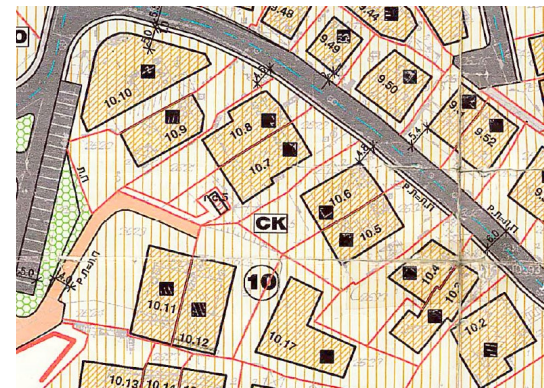
➤ Irregular distribution of:

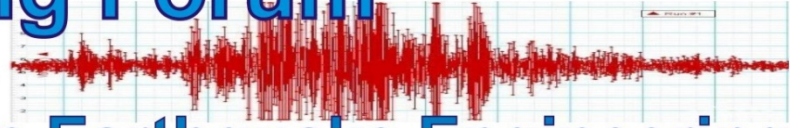
- ✓ Stiffness
- ✓ Strength
- ✓ Mass



➤ Who prefer irregular structures?

- ✓ Urban planners
- ✓ Architects
- ✓ Building owners





## Structural irregularity - consequences



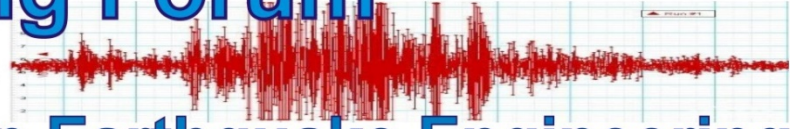
Partial collapse of a 6-story commercial building with a torsional irregularity in the 1995 Kobe earthquake. The building was a reinforced concrete structure with perimeter shear walls on two orthogonal sides of the building and gravity framing on the other two orthogonal sides of the building.



Collapse of a 3-storey building that had lateral stiffness and resistance concentrated near one of the corners owing to a staircase and elevator shaft. The response to the 1999 Athens earthquake was strongly torsional about the “stiff” and “strong” corner. The vertical elements on the other sides (the “flexible” ones) experienced large deformation demands and failed.



Damage of a three-storey reinforced concrete building from the Miyagi-Ken-Oki (Japan) earthquake in 1978 due to torsion. Due to presence of a stiff wall, the center of stiffness shifted towards the wall. The torsion resulted in severe damage of columns along the periphery away from the wall.



## Structural irregularity - consequences



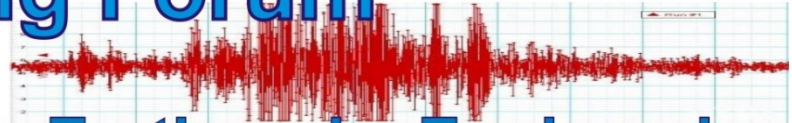
Damage to buildings at the Olive Hospital caused by the 1971 San Fernando earthquake. Damage includes extreme distortion and near collapse of the “soft-story” moment-frame columns of the lower floors of the five-story main building of Olive View Hospital.



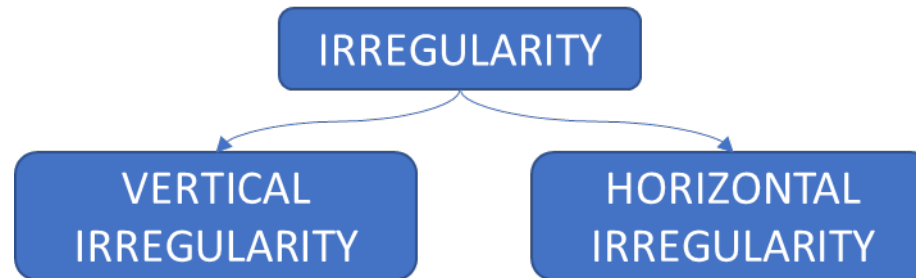
Partial collapse of a 12-story commercial building with plan and vertical irregularities in the 1995 Kobe earthquake. The building was a 12-story reinforced concrete shear wall structure with perimeter shear walls on three sides.



Damage of building during the 2010 M8.8 Maule Chile earthquake. Many of the RC wall buildings damaged during the 2010 Maule earthquake were observed to have significant vertical discontinuities in walls that were primary elements of the lateral load resisting system. Coupled walls in upper stories do not continue to lower story.



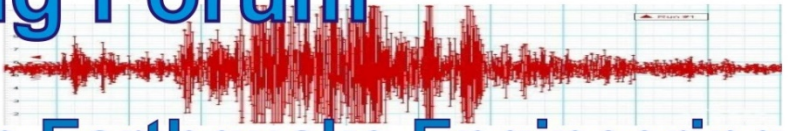
## Structural irregularity - classification



### Sources of irregularity

- V1. Soft story irregularity
- V2. Weight (mass) irregularity
- V3. Vertical geometric irregularity
- V4. In-plane discontinuity
- V5. Weak story irregularity
- V6. Story mechanism: weak-column/strong-beam
- V7. Gravity-induced lateral demand
- V8. Wall discontinuity

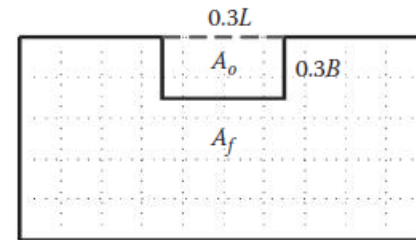
- H1. Torsional (stiffness) irregularity
- H2. Reentrant corner irregularity
- H3. Diaphragm discontinuity irregularity
- H4. Out-of-plane offset irregularity
- H5. Nonparallel system irregularity
- H6. Torsional strength irregularity



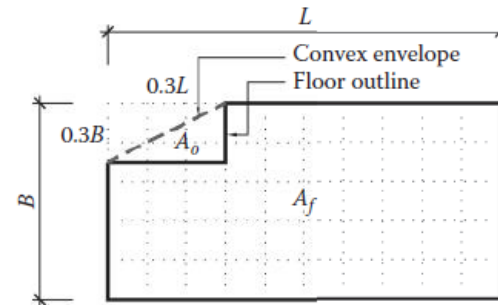
# Plan irregularity – codes criteria

### EN1998 – 1

- (1) Symmetrical in plane distribution of the mass and lateral stiffness – **descriptive condition**
- (2) The plan configuration shall be compact (each floor shall be delimited by a polygonal convex line (no setbacks or re-entrant corners) – max 5% allowed



$A_o = 0.09 BL$   
 $A_f = 0.91 BL$   
 $A_o/A_f = 0.099 > 0.05$  Irregular



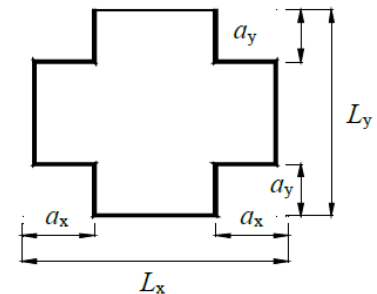
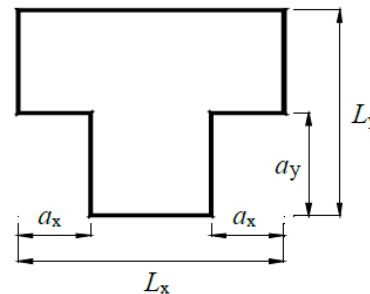
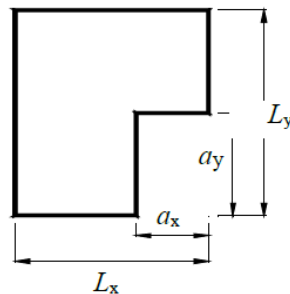
$A_o = 0.045 BL$   
 $A_f = 0.91 BL$   
 $A_o/A_f = 0.049 < 0.05$  Regular

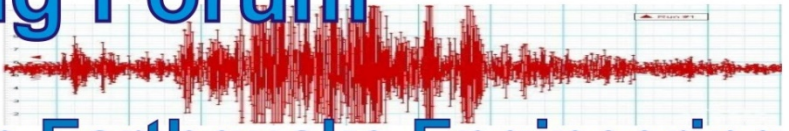
### ASCE/SEI 7-16,

$$a_x (a_y) > 0.15L_x (L_y)$$

### TBDY 2018

$$a_x > 0.2 L_x$$

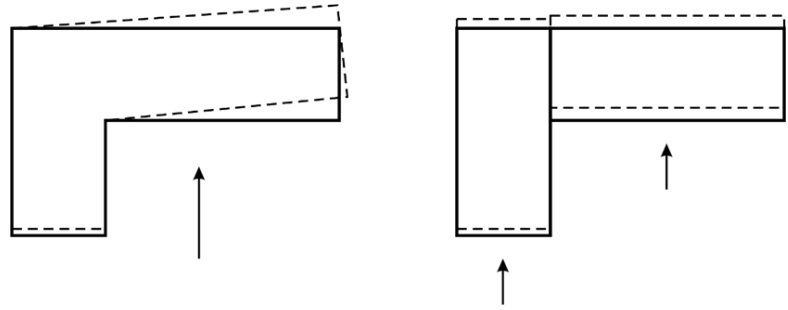




## Plan irregularity – codes criteria

### EN1998 – 1

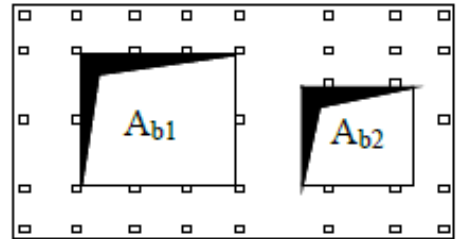
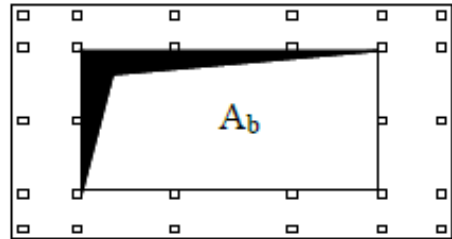
(3) Rigid diaphragms, large in-plane stiffness (L, C, H, X and I shapes should be carefully examined) – **descriptive condition**



### ASCE/SEI 7-16,

Irregular:

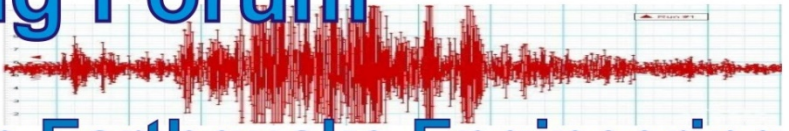
$$A_{open} > \frac{1}{2} XY$$



$$A_b = A_{b1} + A_{b2}$$

### TBDY 2018

$$A_b / A > 1/3$$

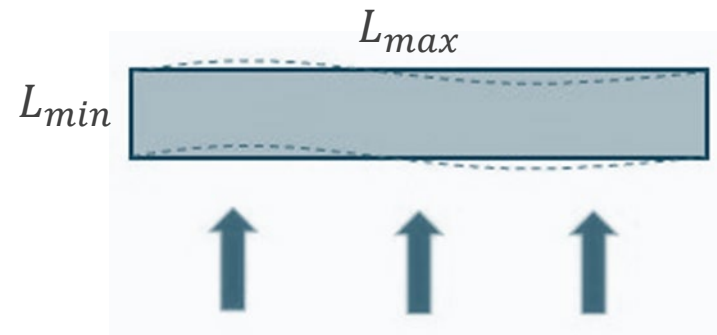


## Plan irregularity – codes criteria

### EN1998 – 1

(4) Slenderness ratio

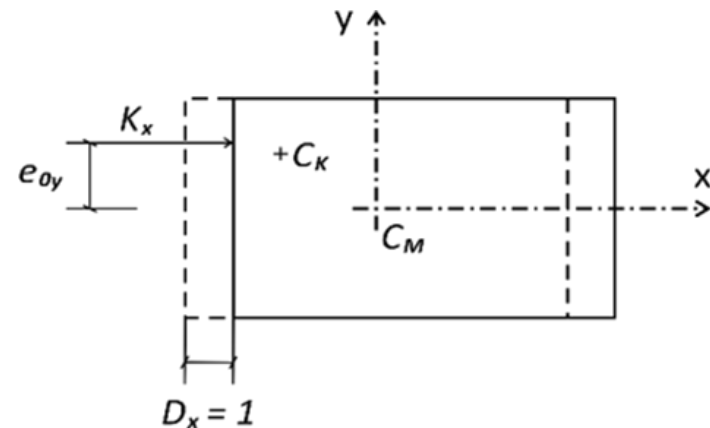
$$\lambda = L_{max} / L_{min} \leq 4$$

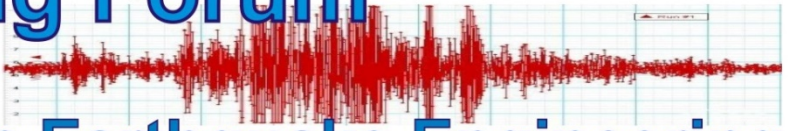


(5) "Static" eccentricity ( $e_0$ ), between the floor centre of mass (CM) and the storey centre of lateral stiffness, (CK), in each of the two orthogonal horizontal directions  $x$  and  $y$ , is not greater than 30% of the corresponding storey torsional radius  $r$ .

$$e_{0x} \leq 0,3 \cdot r_x$$

$$e_{0y} \leq 0,3 \cdot r_y$$



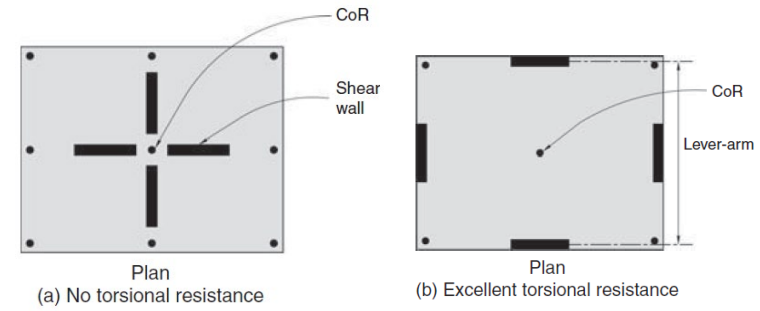


## Plan irregularity – codes criteria

### EN1998-1: 2004

(6) Torsional Stiffness About a Vertical Axis

$$\left. \begin{aligned} r_x &\geq l_s \\ r_y &\geq l_s \end{aligned} \right\} \begin{aligned} T_x (T_y) > T_\theta &\Rightarrow 2\pi \sqrt{\frac{m}{k_x}} > 2\pi \sqrt{\frac{J_\theta}{k_\theta}} \\ \sqrt{\frac{k_\theta}{k_x}} > \sqrt{\frac{J_\theta}{m}} &\Rightarrow \boxed{r_x \geq l_s} \end{aligned}$$

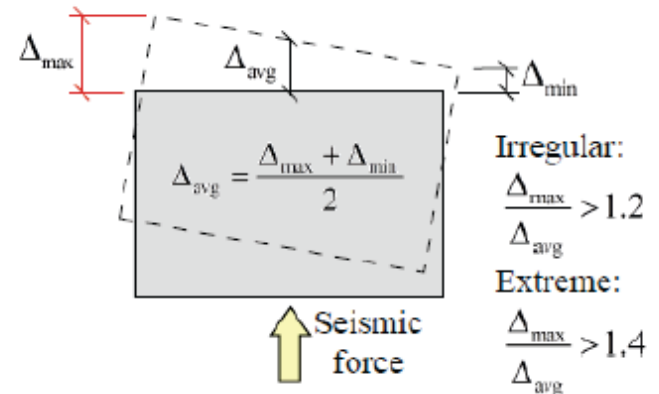


**ASCE/SEI 7-16** ( $\Delta_{max}/\Delta_{avg} > 1.2(1.4)$ ,  $e=5\%L$ )

**TBDY 2018** ( $\Delta_{max}/\Delta_{avg} > 1.2$ ,  $e=5\%L$ )

**NZS 1170.5-2004** ( $\Delta_{max}/\Delta_{avg} > 1.4$ ,  $e=10\%L$ )

**ENV 1998-1-2: 1994** ( $\Delta_{max}/\Delta_{avg} > 1.2$ ,  $e=5\%L$ )

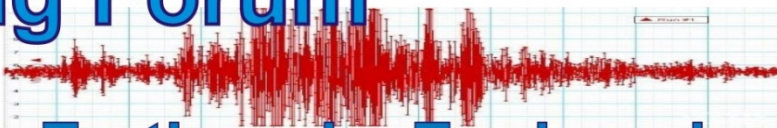




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## International Conference on Earthquake Engineering

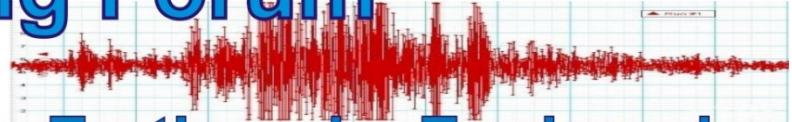


### Plan irregularity – Design implication

EN1998-1: 2004

Implication in modeling and analysis approach

Regularity		Allowed Simplification		Behaviour factor
Plan	Elevation	Model	Linear-elastic Analysis	(for linear analysis)
Yes	Yes	Planar	Lateral force <sup>a</sup>	Reference value
Yes	No	Planar	Modal	Decreased value
No	Yes	Spatial <sup>b</sup>	Lateral force <sup>a</sup>	Reference value
No	No	Spatial	Modal	Decreased value



## Plan irregularity – Design implication

EN1998-1: 2004

Behaviour factor

STRUCTURAL TYPE	DCM	DCH	
Frame system, dual system, coupled wall system	$3,0 \alpha_w / \alpha_1$	$4,5 \alpha_w / \alpha_1$	} Condition 1-5
Uncoupled wall system	3,0	$4,0 \alpha_w / \alpha_1$	
Torsionally flexible system	2,0	3,0	Condition 6
Inverted pendulum system	1,5	2,0	

In a building which is irregular in plan per Eurocode 8, the default value of  $\alpha_w / \alpha_1$  is the average of 1.0 and the default value for buildings regular in plan (1.0 -1.3)



Up to 15% higher design seismic effects

## Plan irregularity - EN1998 second generation\*

### Plan irregularity criteria (1-5) – main purpose in current code

- Implication in the model for analysis
- Evaluation of influence of torsion for 2D analysis with planar models
- **Current practice**
  - Spatial (3D) FEM structural models
  - Natural torsion (static eccentricity) and coupling of torsional-translational response are explicitly accounted



**Moving the plan irregularity criteria to an informative annex as guidelines for good design**

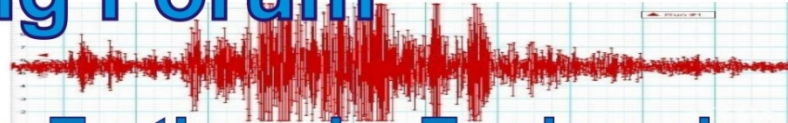
### Torsional flexibility



**To clarify the way to take influence of torsion into account**

**Accidental eccentricity – open question**

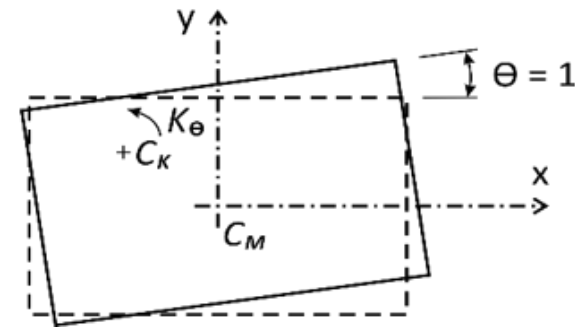
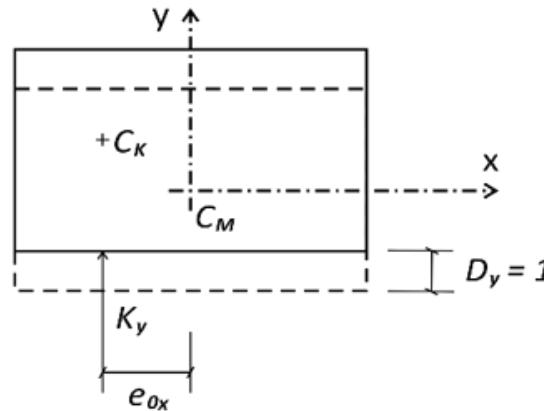
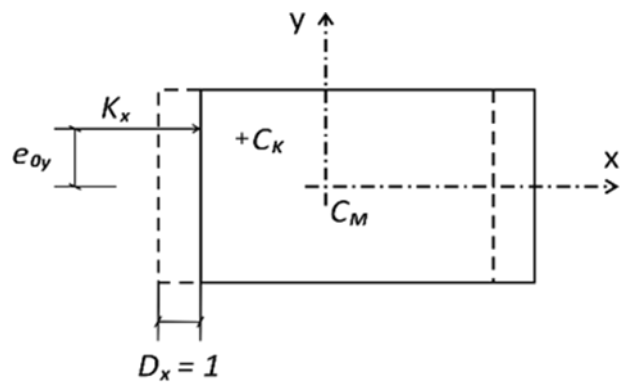
\* Bisch, P. Eurocode 8. Evolution or Revolution? In Recent Advances in Earthquake Engineering in Europe: 16th European Conference on Earthquake Engineering-Thessaloniki 2018; Pitilakis, K., Ed.; Springer International Publishing: Cham, Switzerland, 2018; pp. 639–660



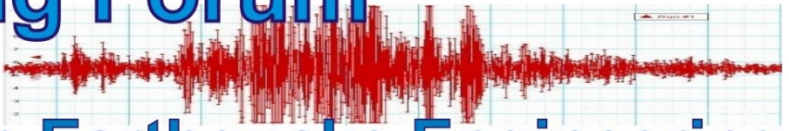
## Structural characteristics for torsional flexibility control

Centre of stiffness

$$x_{CS} = \frac{\sum K_{yi} \cdot x}{\sum K_{yi}} \quad y_{CS} = \frac{\sum K_{xi} \cdot y}{\sum K_{xi}}$$



- ✓ **Single-storey buildings:** uniquely defined
  - ✓ depend on the position of elements which contribute to the lateral stiffness of structure
- ✓ **Multi-storey buildings:** depends on the lateral load distribution

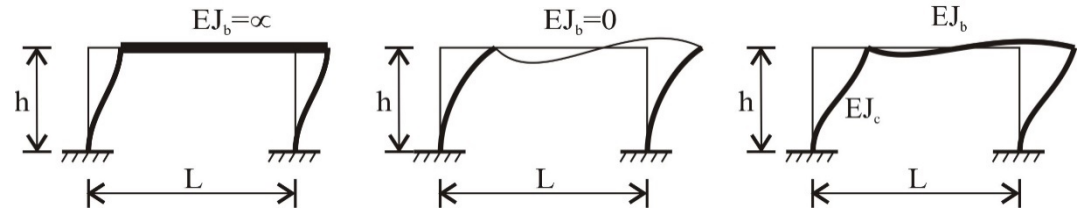


## Structural characteristics for torsional flexibility control

### Centre of stiffness: simplified analytical procedure

Assumptions:

- Beam stiffness is neglected
- All columns have a same height
- Contribution of shear deformations are neglected



$$k_y = \sum \frac{1}{\frac{h^3}{3EI} + \frac{h}{GA_s}}$$

$$k_y = \frac{24EI_c}{h^3} \frac{12\rho + 1}{12\rho + 4}$$

$$\rho = (EI_b/L) \div (EI_c/h)$$

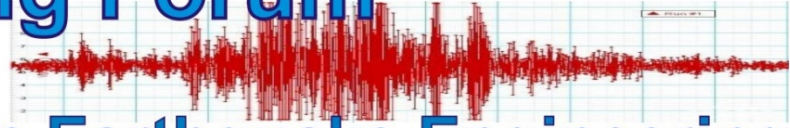
$$x_{CS} = \frac{\sum K_{Yi} \cdot x}{\sum K_{Yi}}$$

$$y_{CS} = \frac{\sum K_{Xi} \cdot y}{\sum K_{Xi}}$$



$$x_{CS} = \frac{\sum \frac{3EI_x}{h^3} \cdot x}{\sum \frac{3EI_x}{h^3}} = \frac{\sum I_x \cdot x}{\sum I_x}$$

$$y_{CS} = \frac{\sum I_y \cdot y}{\sum I_y}$$

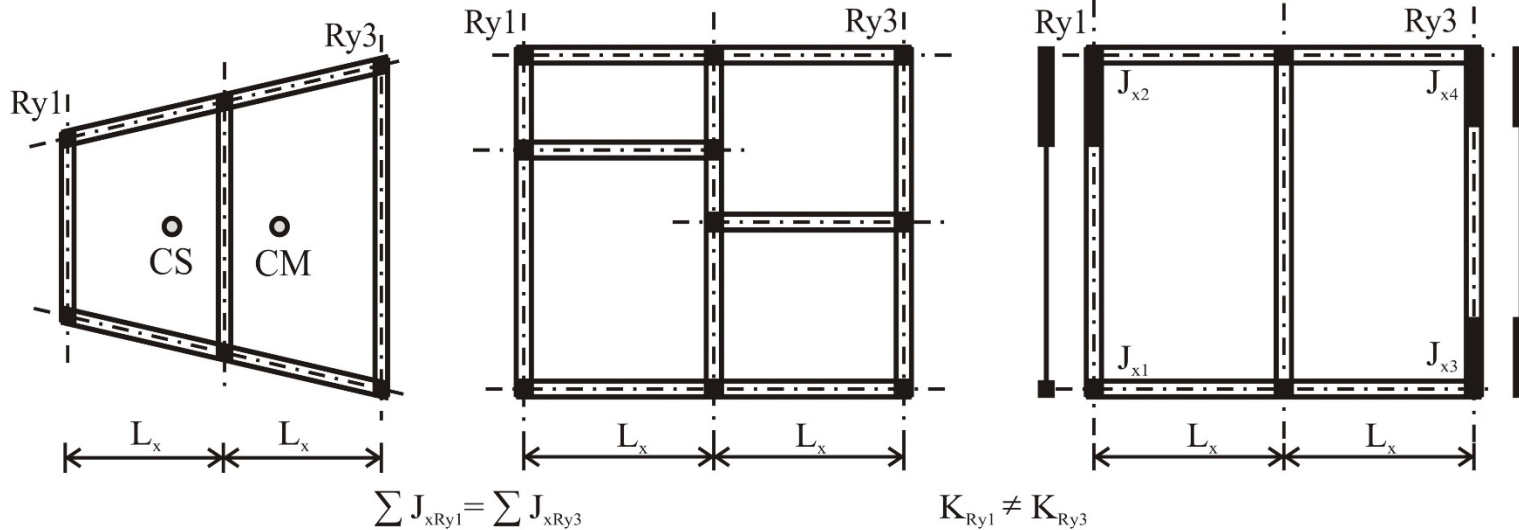


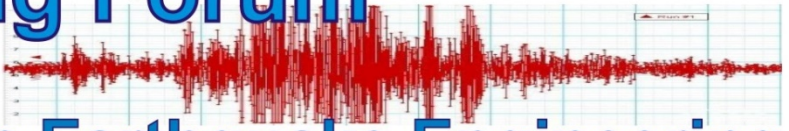
## Structural characteristics for torsional flexibility control

**Centre of stiffness:** simplified analytical procedure

Assumptions:

- Beam stiffness is neglected





## Structural characteristics for torsional flexibility control

### Centre of stiffness: numerical procedure

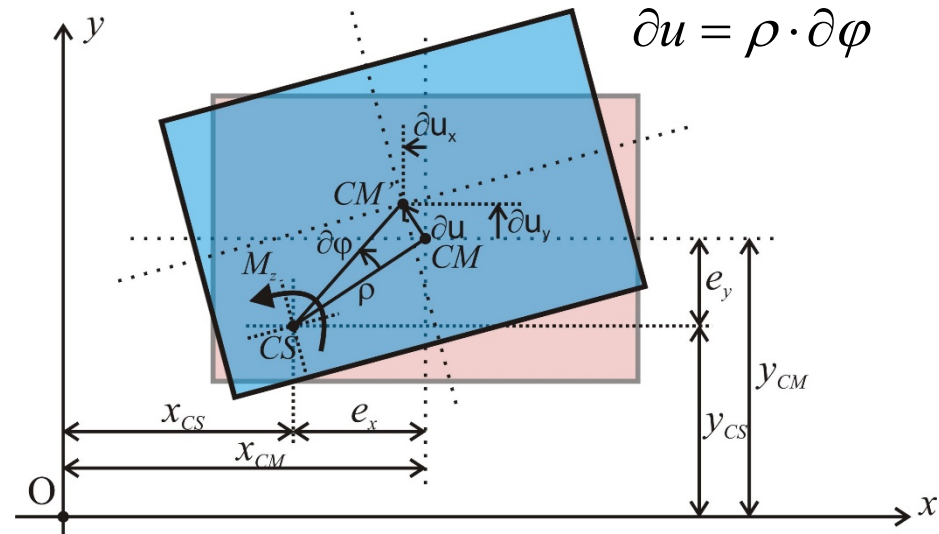
spatial structural model with rigid plate in their plain



moment of rotation around the vertical axis z



rigid plate will rotate around the centre of rigidity (pole of rotation) for the angle  $\partial\varphi$



$$\partial u_x = -e_y \cdot \partial\varphi$$

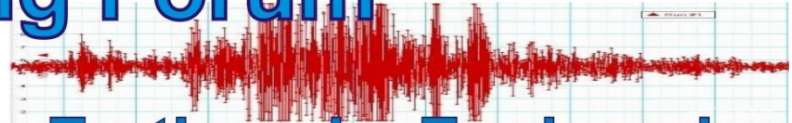
$$\partial u_y = e_x \cdot \partial\varphi$$

$$e_x = x_{CM} - x_{CS}$$

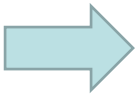
$$e_y = y_{CM} - y_{CS}$$

$$x_{CS} = x_{CM} - e_x = x_{CM} - \partial u_y / \partial\varphi$$

$$y_{CS} = y_{CM} - e_y = y_{CM} + \partial u_x / \partial\varphi$$



## Structural characteristics for torsional flexibility control

**Torsional radius**  potential for torsional vibration of structures exposed to earthquake ground motion

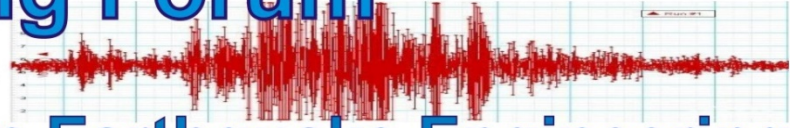
✓ **Single-storey buildings:**  $r_x = \sqrt{\frac{K_{Rz}}{K_y}}$        $r_y = \sqrt{\frac{K_{Rz}}{K_x}}$

✓ **Simplified analytical procedure**

$$r_x = \sqrt{\frac{\sum J_x \cdot x_{iCS}^2 + J_y \cdot y_{iCS}^2}{\sum J_x}} \qquad r_y = \sqrt{\frac{\sum J_x \cdot x_{iCS}^2 + J_y \cdot y_{iCS}^2}{\sum J_y}}$$

✓ **Torsional radius with respect to the centre of mass**

$$r_{mx} = \sqrt{r_x^2 + e_x^2} \qquad r_{my} = \sqrt{r_y^2 + e_y^2}$$

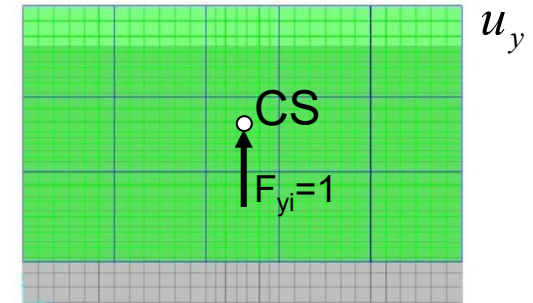
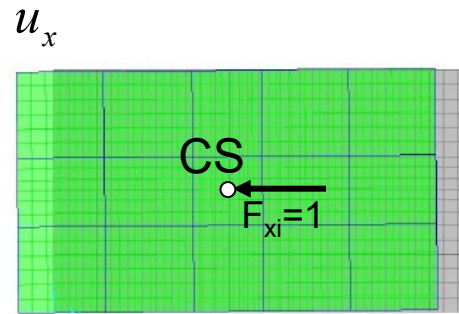
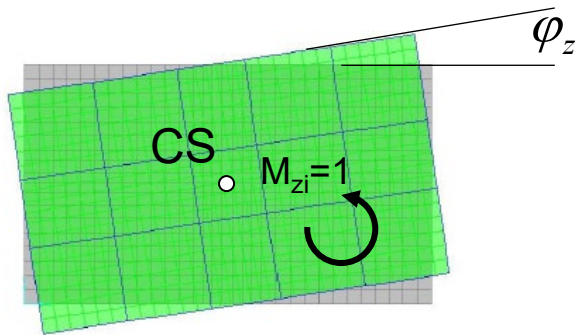


## Structural characteristics for torsional flexibility control

**Torsional radius: numerical procedure**

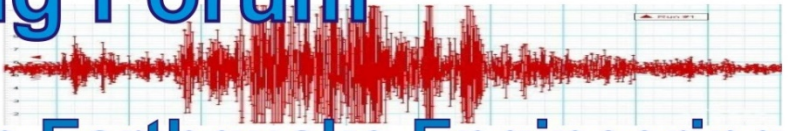
$$r_x = \sqrt{\frac{K_{Rz}}{K_Y}} = \sqrt{\frac{M_z = 1 / \varphi_z}{F_y = 1 / u_y}} = \sqrt{\frac{u_y}{\varphi_z}}$$

$$r_x = \sqrt{\frac{K_{Rz}}{K_X}} = \sqrt{\frac{M_z = 1 / \varphi_z}{F_x = 1 / u_x}} = \sqrt{\frac{u_x}{\varphi_z}}$$



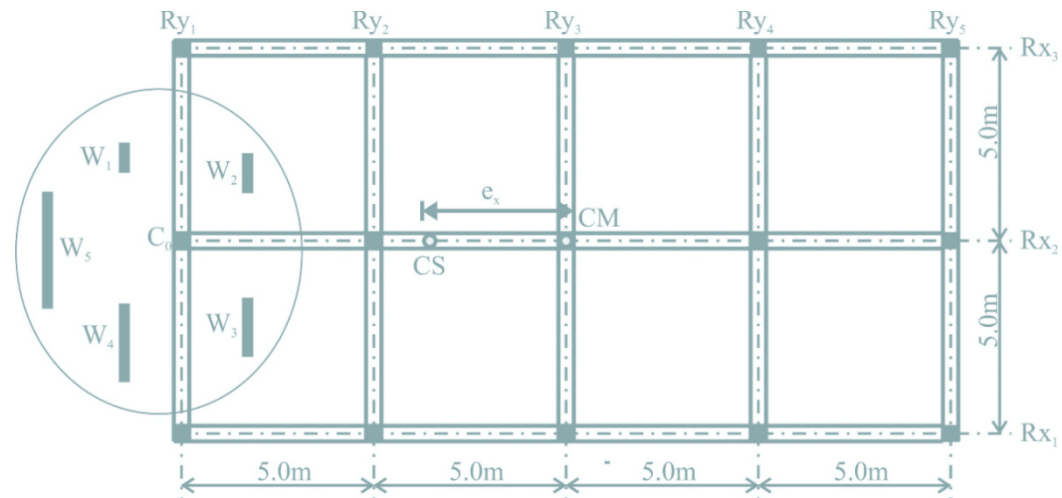
Same as determination of CS

Application of unique force to centre of stiffness



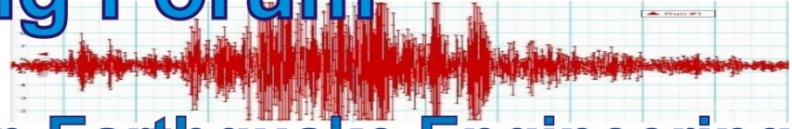
## Influence of modeling assumptions - case study

### Single storey building



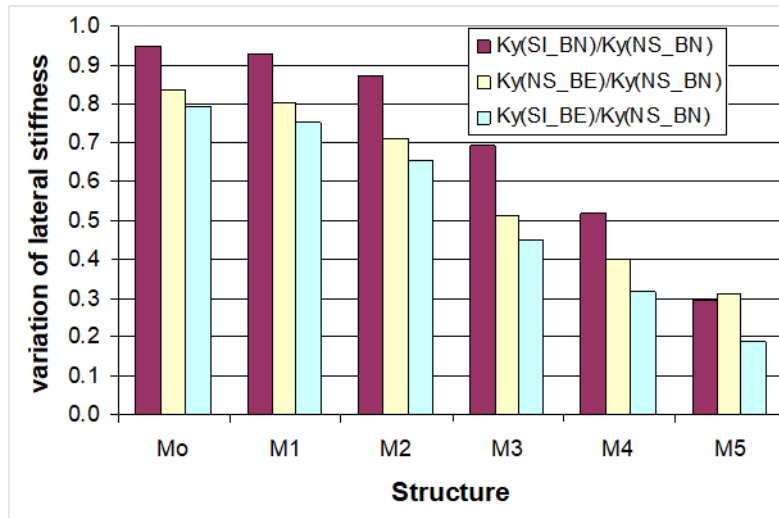
Height	3 m
Beams	30x50 cm T section – flashes 180cm L section – flashes 110cm
Columns	40x40 cm
Walls	75, 100, 150, 200 and 300 cm

- 1°
- Rigid beams (BN)  
- No shear deformation (NS)
- 2°
- Rigid beams (BN)  
- Included shear deformation (SI)
- 3°
- Beam elastic stiffness (BE)  
- No shear deformation (NS)
- 4°
- Beam elastic stiffness (BE)  
- Included shear deformation (SI)

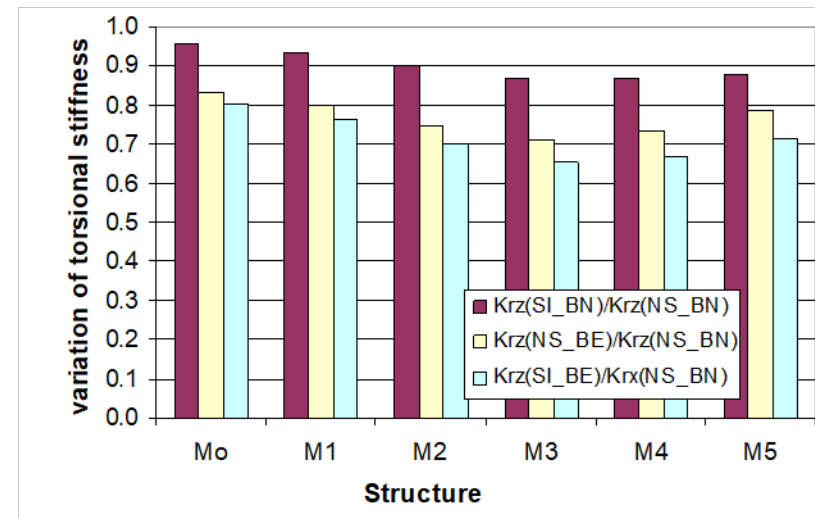


## Influence of modeling assumptions - case study

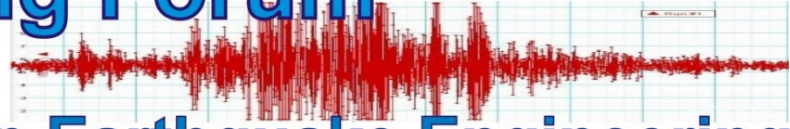
### Stiffness reduction due to modelling assumption



**variation of lateral stiffness**

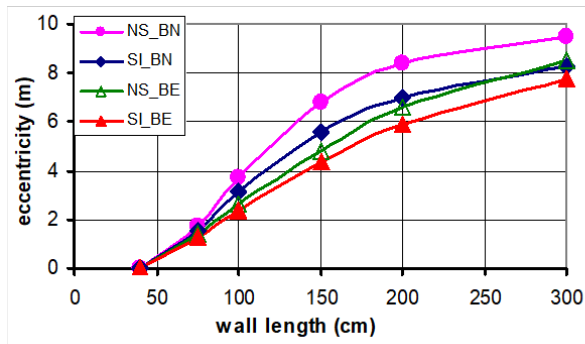


**variation of torsional stiffness**

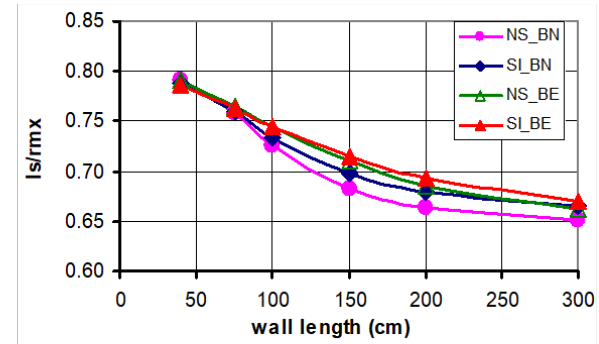
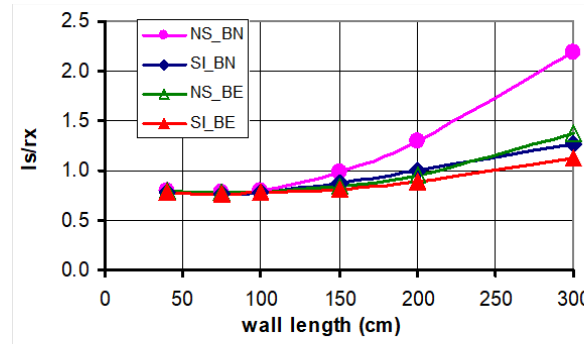
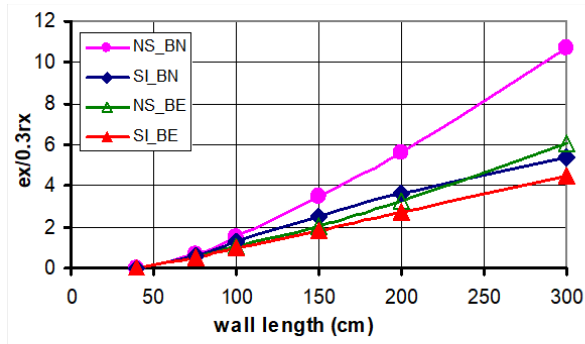
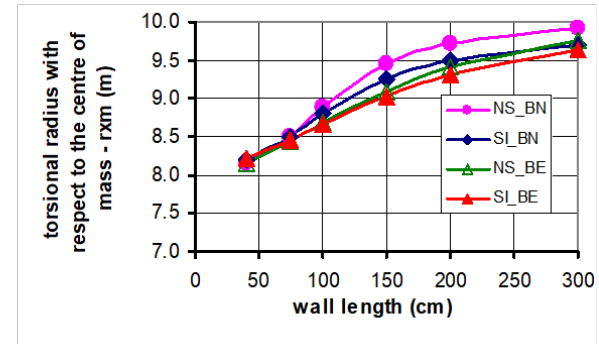
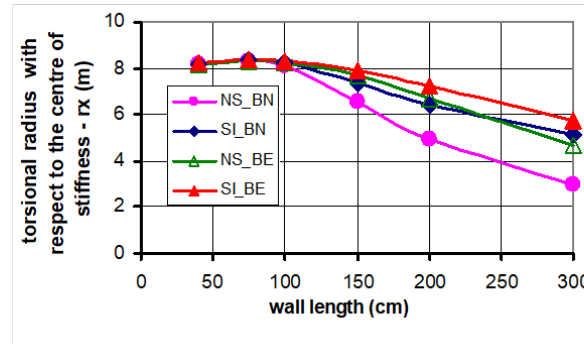


### Influence of modeling assumptions - case study

Eccentricity



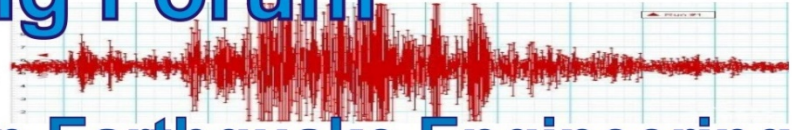
Torsional radius



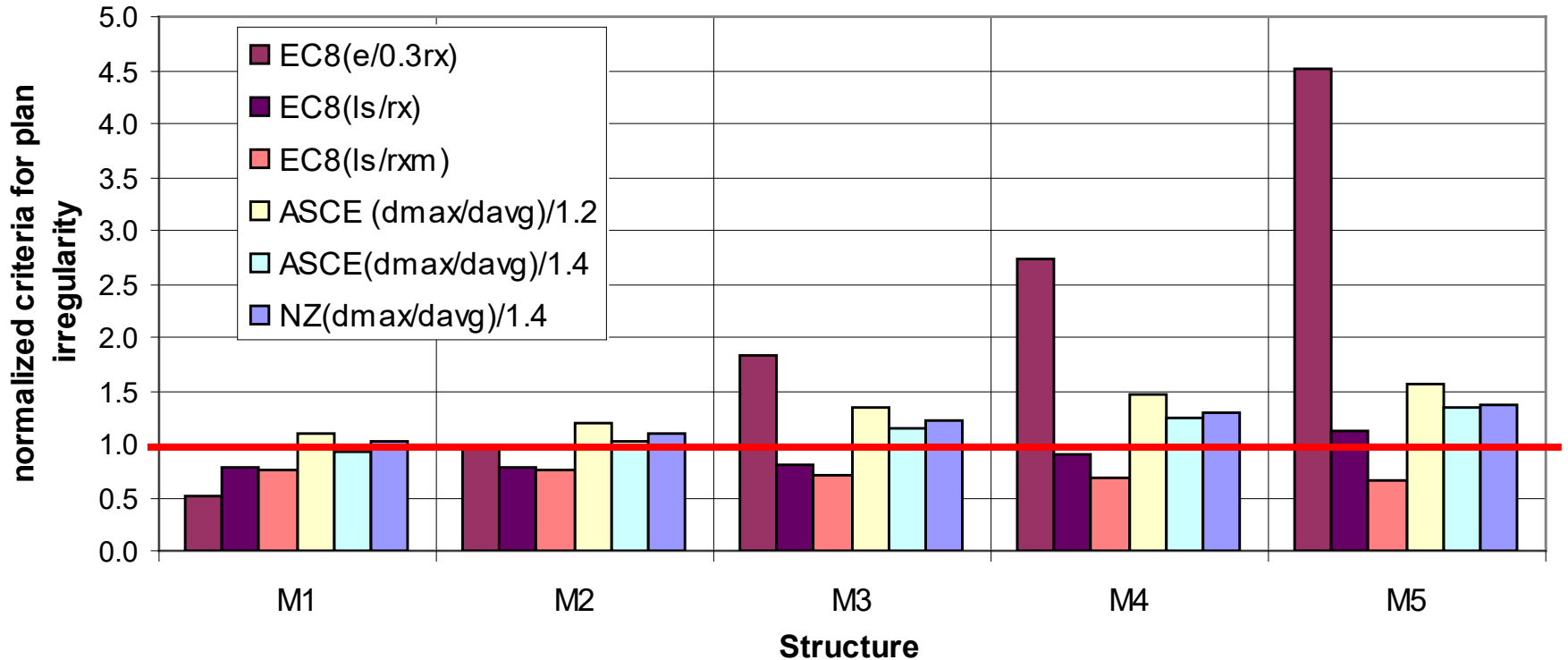
In respect to centre of stiffness

In respect to centre of stiffness

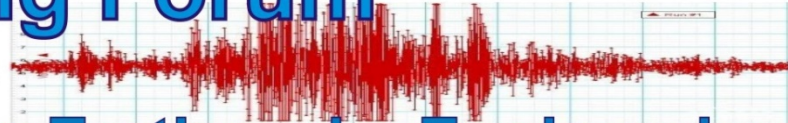
In respect to centre of mass



### Codes criteria comparison - case study

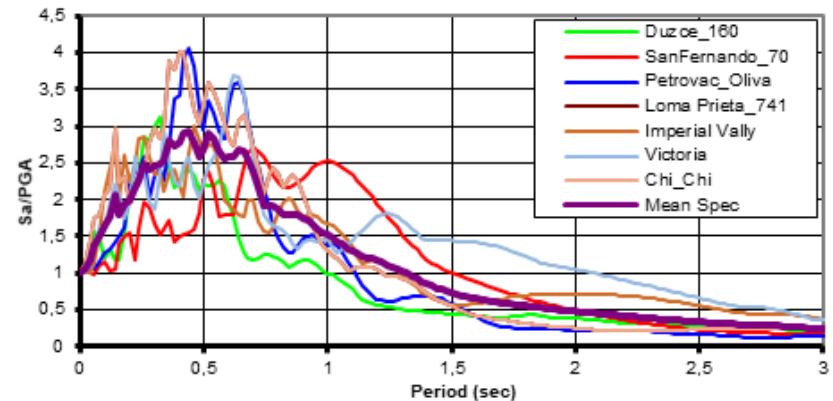
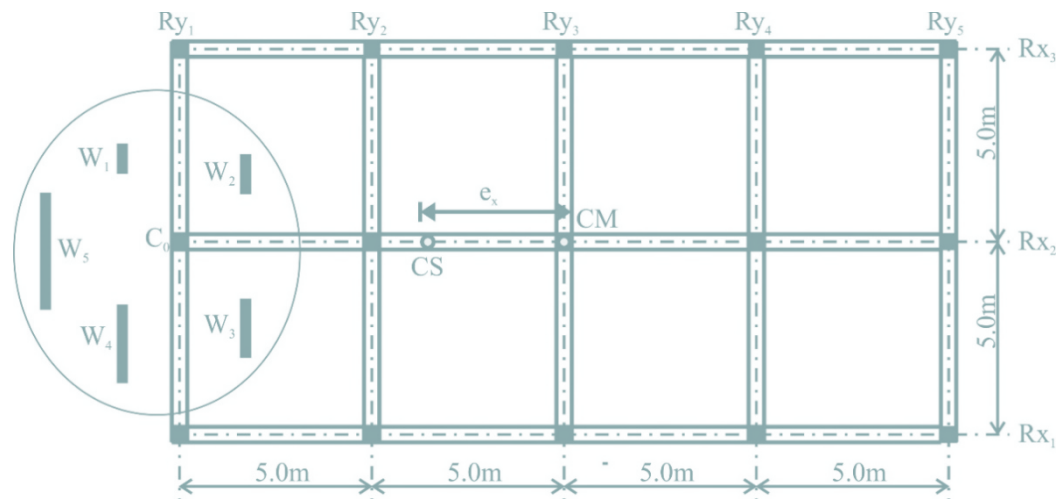


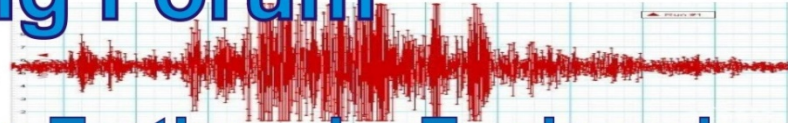
Normalised criteria for plan irregularity



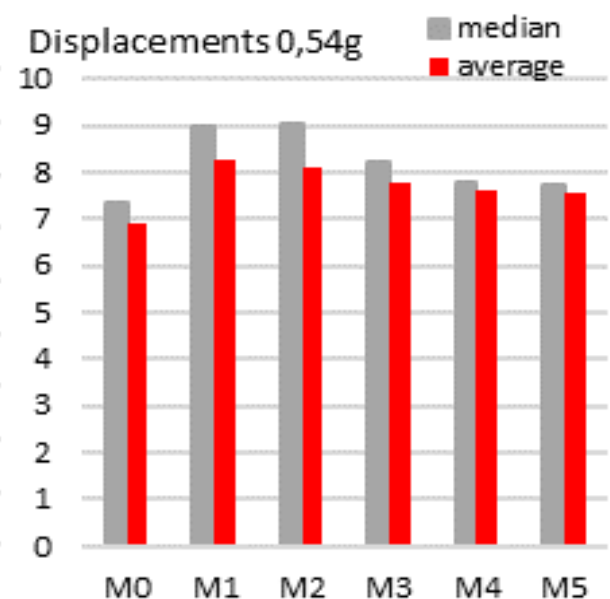
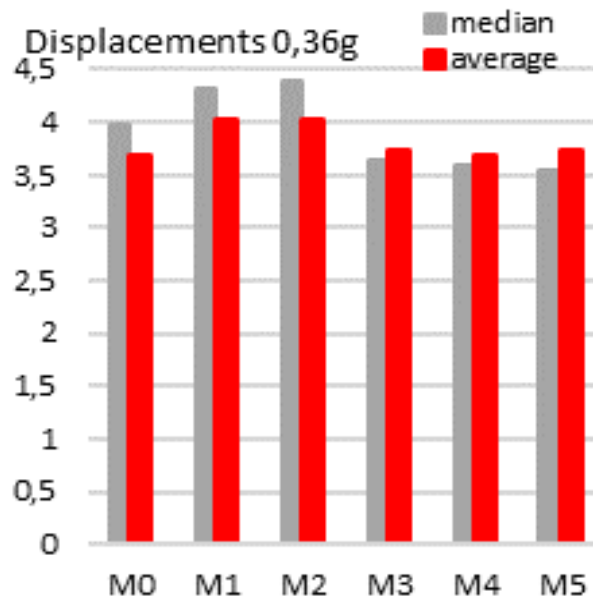
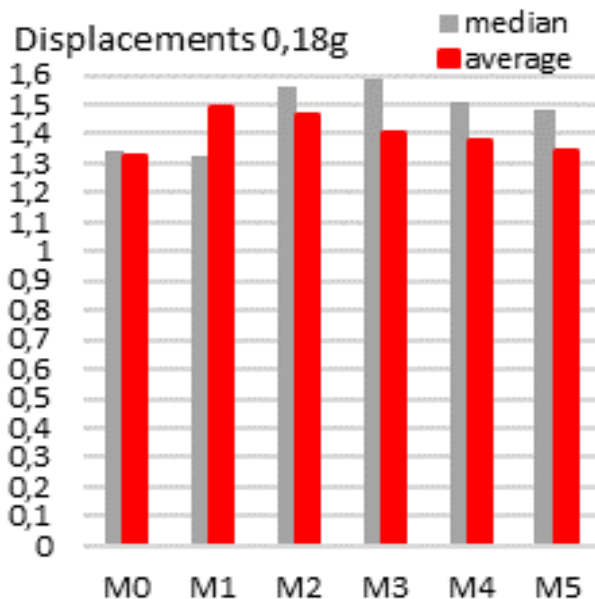
### Nonlinear seismic assessments - case study

- Structures** → Same as previous
- Beams** → Upper part 5Ø14mm  
Lower part 3Ø14mm
- Columns** → 8Ø16mm
- Walls** → In accordance with EN 1998-1 part 5.3
- Software** → Seismostruct

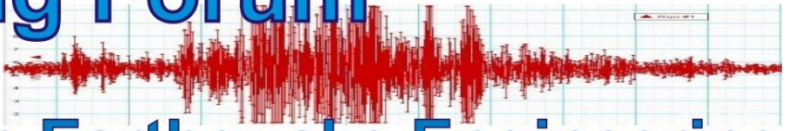




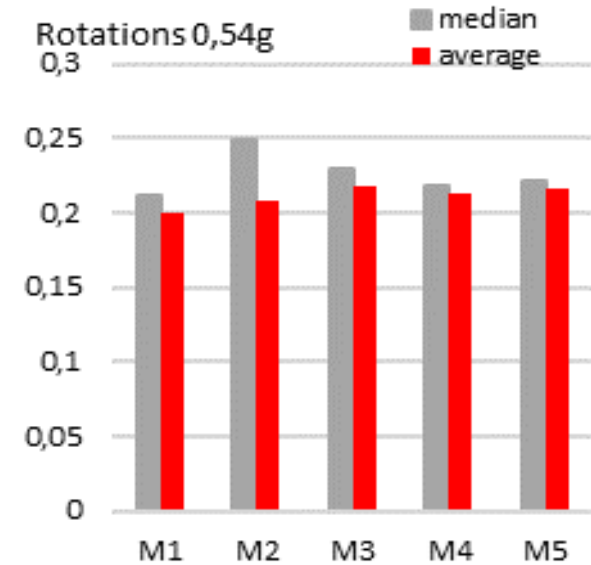
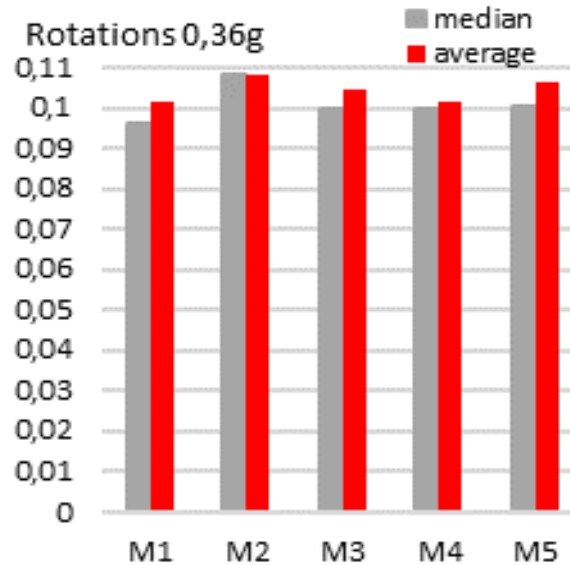
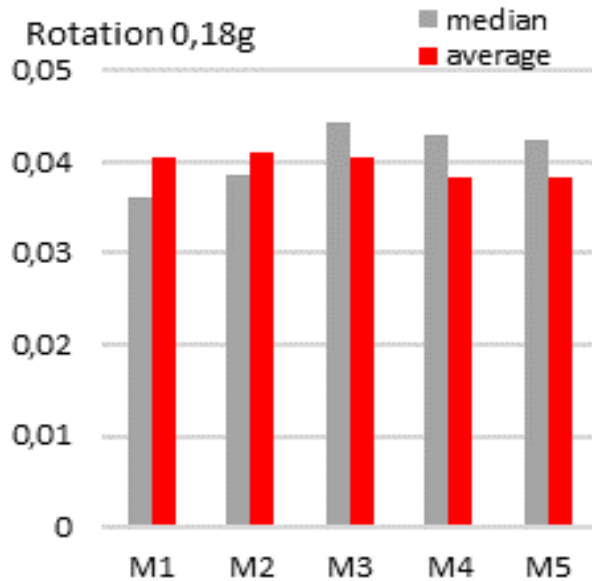
### Nonlinear seismic assessments - case study



Mean and median displacement for PGA 0,18g, 0,36g and 0,54g



### Nonlinear seismic assessments - case study



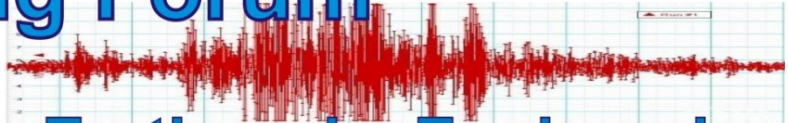
Mean and median rotation for PGA 0,18g, 0,36g and 0,54g



# Building Engineering Forum

20-21 October 2021, Sofia, Bulgaria

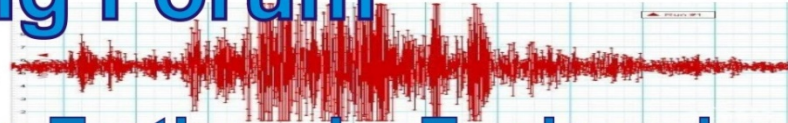
International Conference on Earthquake Engineering



## Structural characteristics for torsional flexibility control

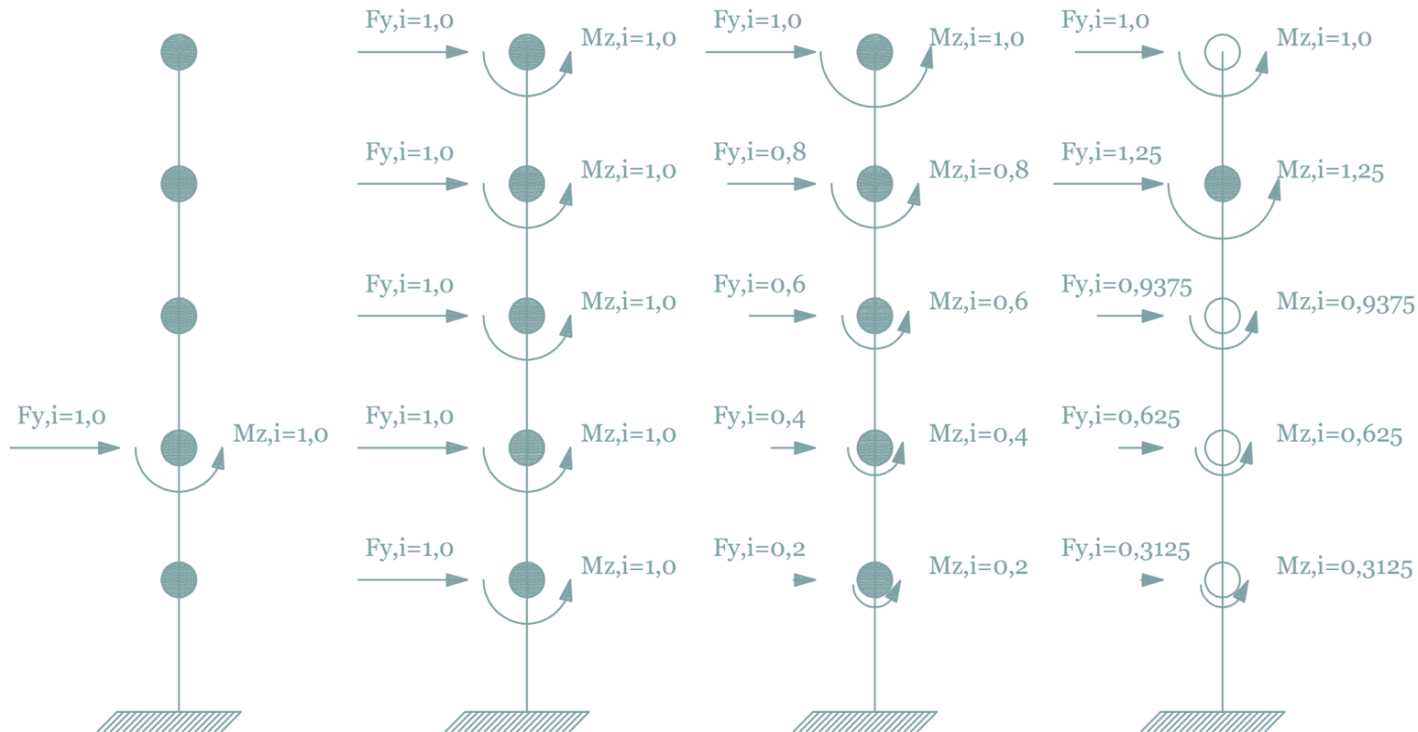
### Multi-storey structures, position of EN 1992-1

- Only approximate definitions of the centre of stiffness and of the torsional radius are possible
- Analytical calculation, based of the moments of inertia of the cross-sections of the vertical elements, is possible only for:
  - Structural systems with prevailing flexural deformations (frames and systems of slender walls)
- Other systems (e.g. dual systems)
  - Eurocode 8 just indicates that the National Annex may provide guidance on the definition of the centre of stiffness and the torsional radius (**NDP**)
  - Different methodology in different country



## Structural characteristics for torsional flexibility control

### Multi-storey structures, comparison of methodology

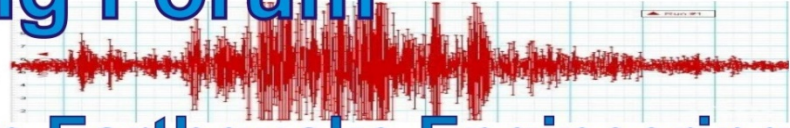


EUR 25204 EN - 2012

PD 6698:2009

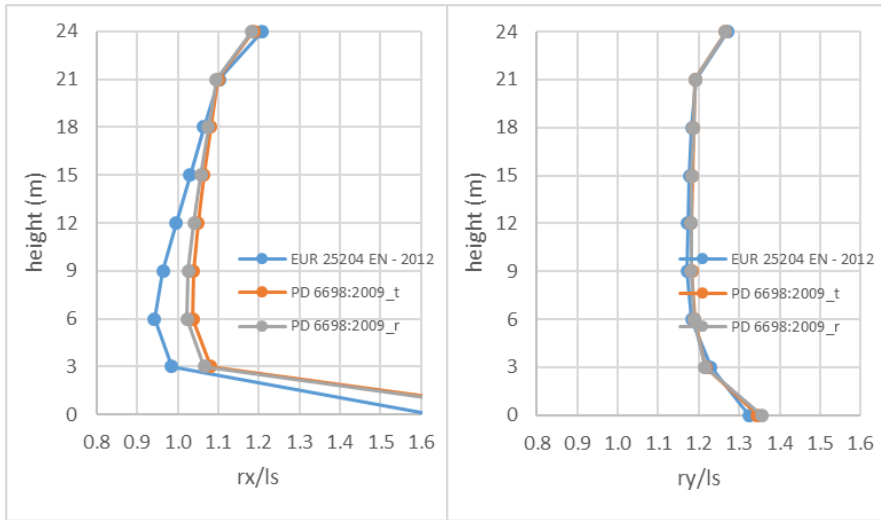
EAK 2000





### Structural characteristics for torsional flexibility control

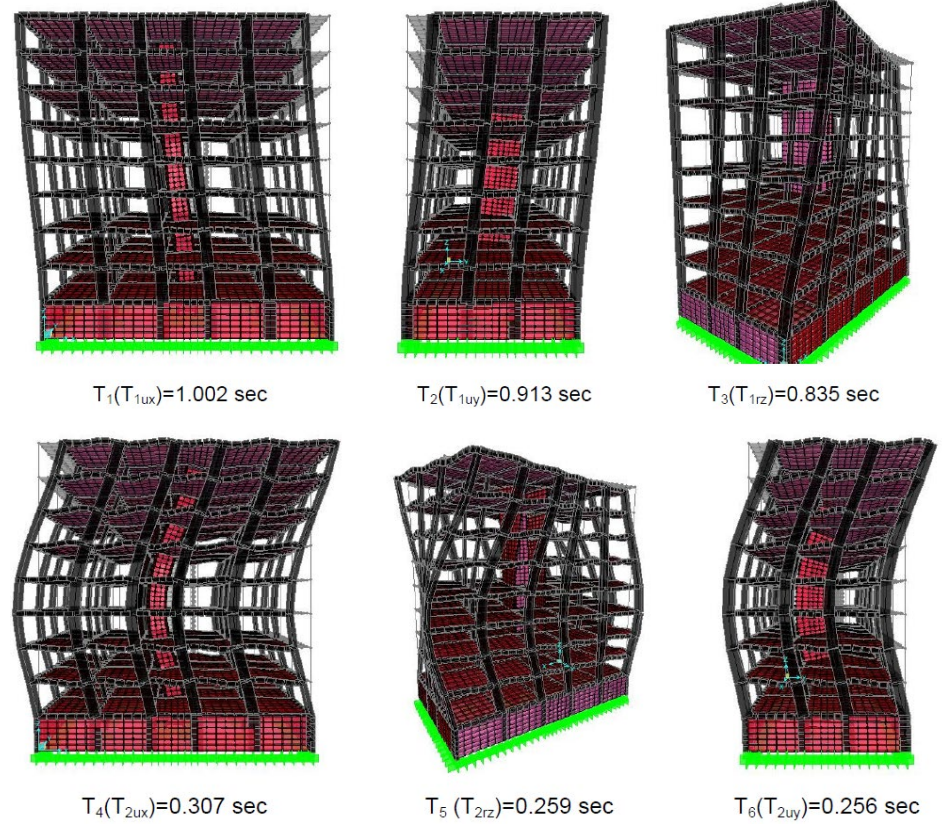
#### Multi-storey structures, comparison of methodology – case study 1

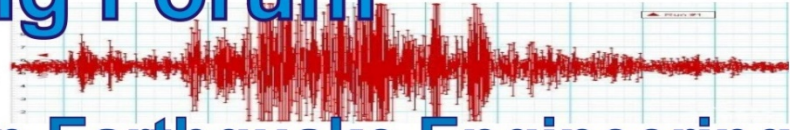


$$r_x = \sqrt{\frac{K_{Rz}}{K_Y}}$$

$$r_y = \sqrt{\frac{K_{Rz}}{K_X}}$$

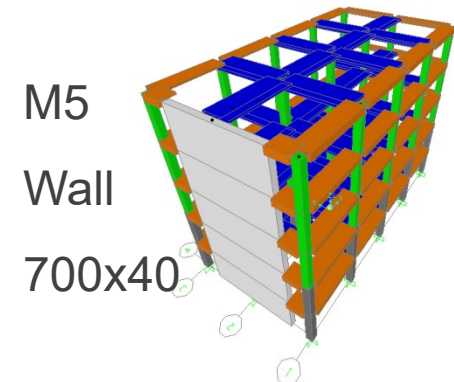
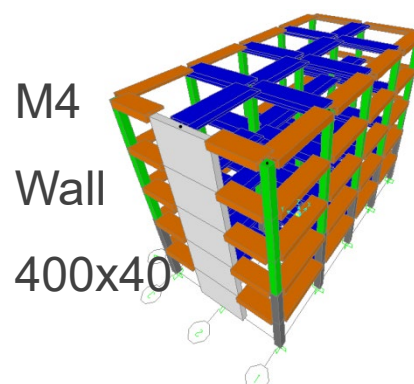
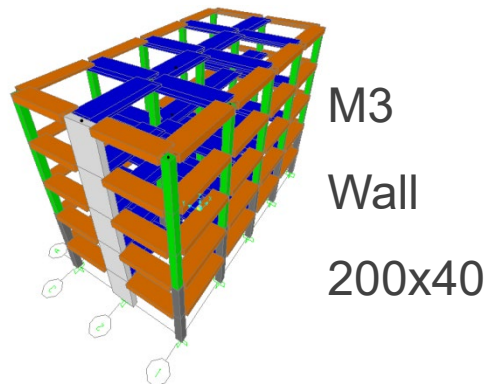
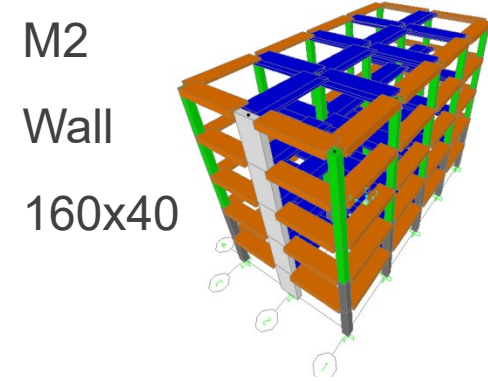
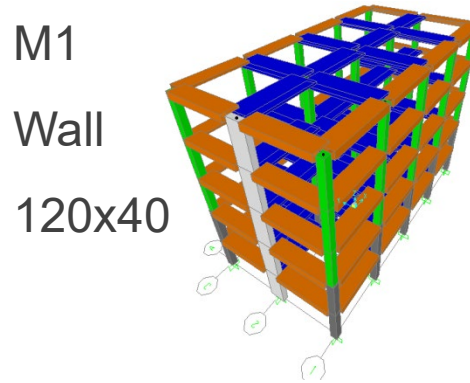
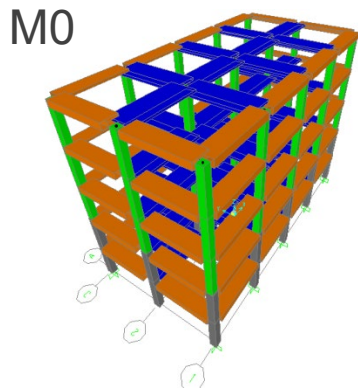
$$K_Y > K_X \Rightarrow r_x < r_y$$

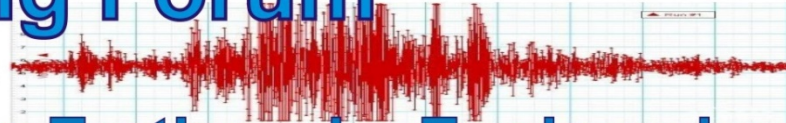




## Structural characteristics for torsional flexibility control

### Multi-storey structures – case study 2

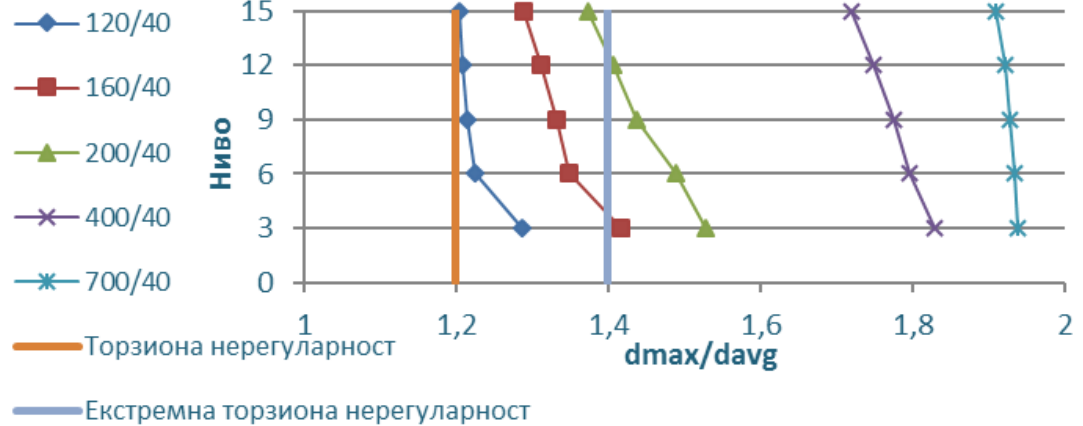


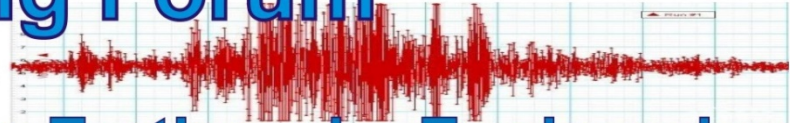


## Structural characteristics for torsional flexibility control

### Multi-storey structures – case study 2

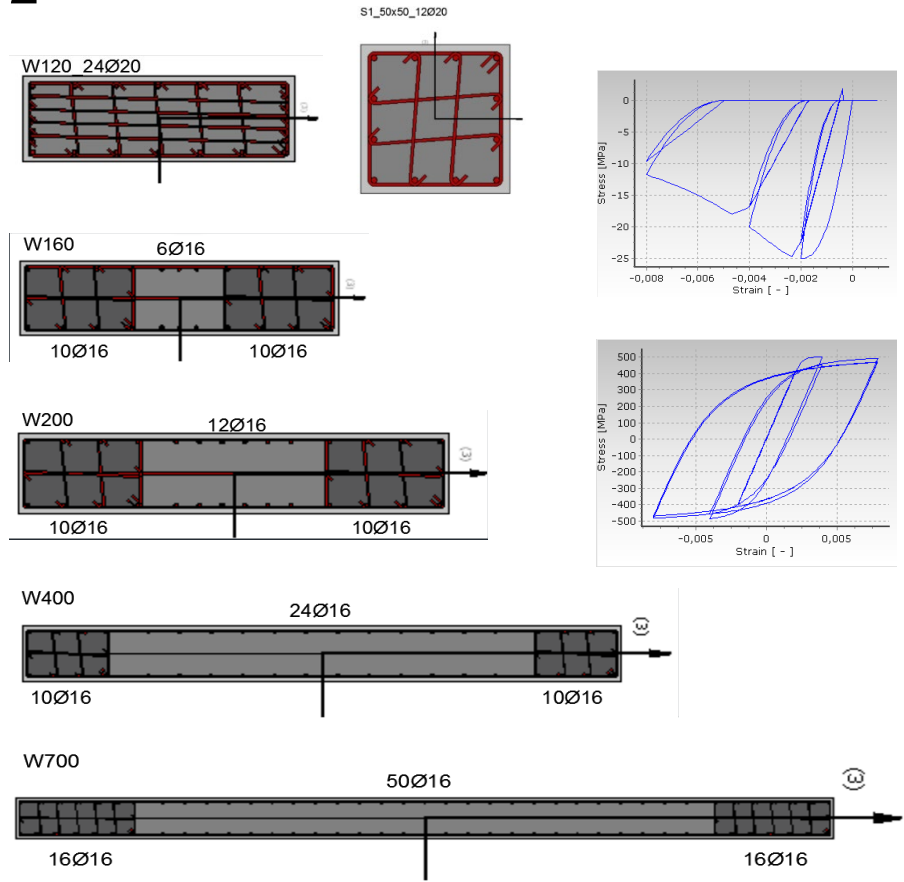
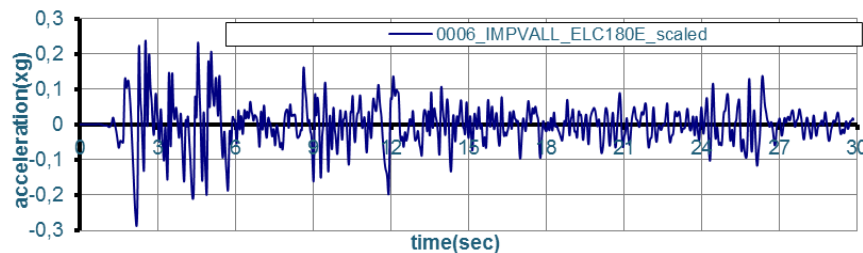
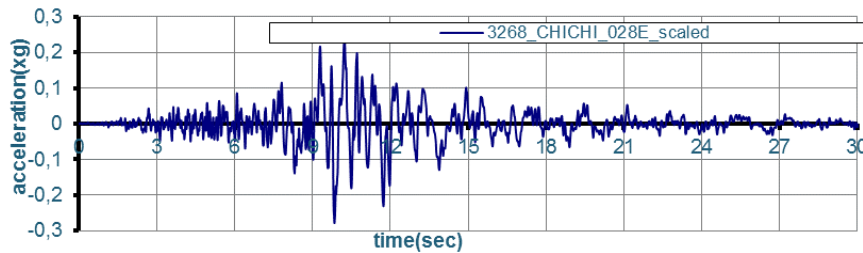
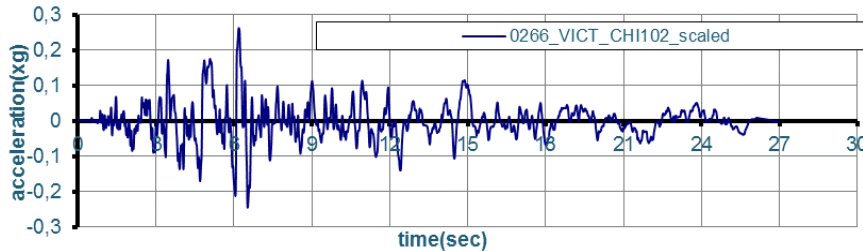
Criteria of regularity in plan							
	story	height	e <sub>ox,i</sub>	0.3r <sub>x,i</sub>		r <sub>x,i</sub>	ls
				<	>		
M1	1	3	2,67	>	2,48	8,28	>
	2	6	1,98	>	2,50	8,34	>
	3	9	1,78	<	2,48	8,28	>
	4	12	1,61	<	2,48	8,28	>
	5	15	1,40	<	2,51	8,35	>
M2	1	3	4,26	>	2,38	7,92	>
	2	6	3,28	>	2,46	8,19	>
	3	9	2,83	>	2,52	8,41	>
	4	12	2,46	>	2,53	8,45	>
	5	15	2,04	>	2,50	8,32	>
M3	1	3	5,51	>	2,22	7,40	>
	2	6	4,49	>	2,36	7,85	>
	3	9	3,87	>	2,42	8,06	>
	4	12	3,33	>	2,49	8,30	>
	5	15	2,72	>	2,48	8,26	>
M4	1	3	8,27	>	1,53	5,08	<
	2	6	7,91	>	1,66	5,53	<
	3	9	7,42	>	1,82	6,05	<
	4	12	6,80	>	1,98	6,60	>
	5	15	6,10	>	2,09	6,96	>
M5	1	3	9,19	>	1,08	3,59	<
	2	6	9,23	>	1,05	3,51	<
	3	9	9,14	>	1,12	3,72	<
	4	12	8,96	>	1,23	4,09	<
	5	15	8,72	>	1,36	4,52	<

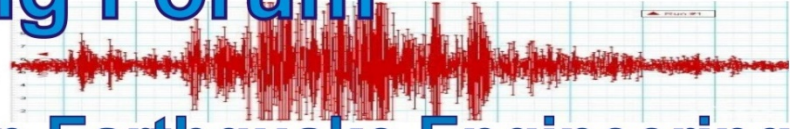




## Structural characteristics for torsional flexibility control

### Multi-storey structures – case study 2



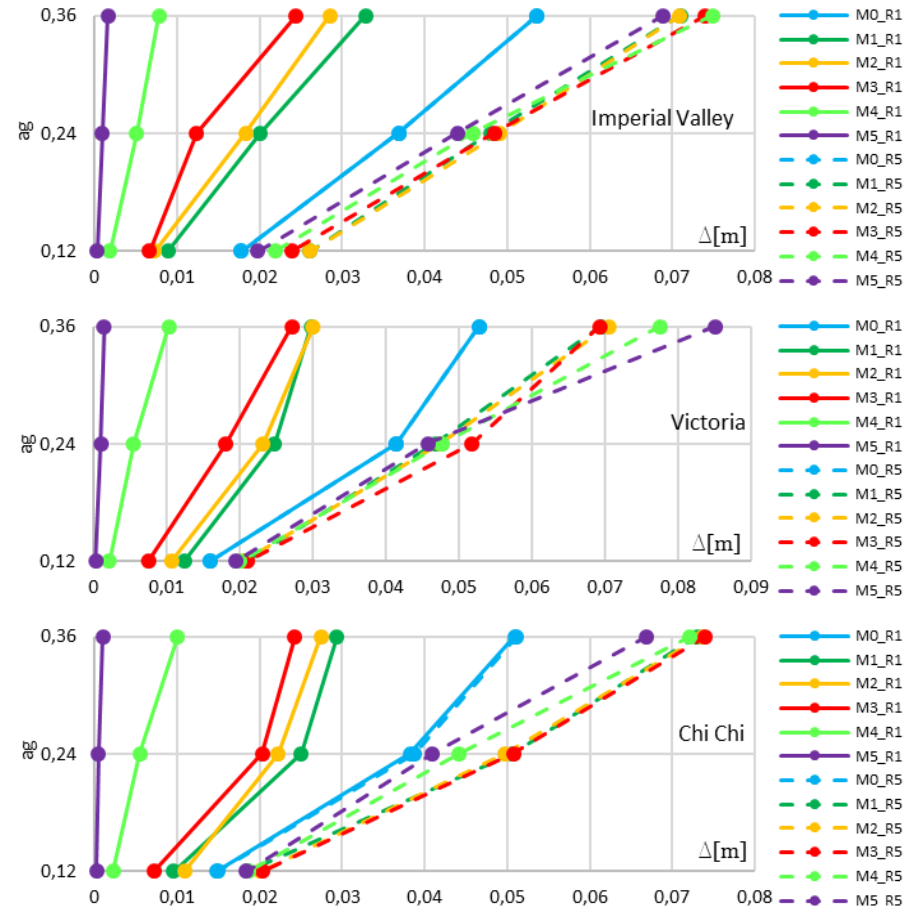
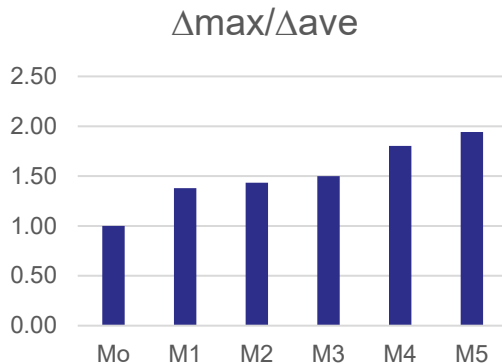


## Structural characteristics for torsional flexibility control

### Multi-storey structures

#### – case study 2

Maximal inter-story drifts for frames R1 (stiff side – solid line) and R5 (flexible side – dashed line) of the analyzed structures

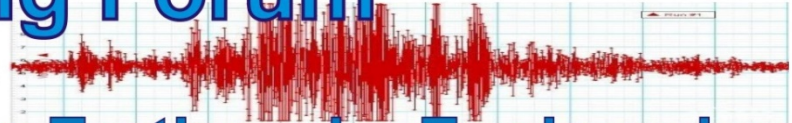




# Building Engineering Forum

20-21 October 2021, Sofia, Bulgaria

International Conference on Earthquake Engineering



## FINAL REMARKS

- Irregular structures are vulnerable to seismic excitation
- Plan irregularity can be controlled thru the various criteria given in the national codes
- Position of centre of stiffness and torsional radius vary depending on the assumption of the mathematical model
- For structures with larger eccentricities between CM and CS, EN1998-1 prescribes more rigorous criteria for plan irregularity compared with ASCE 7-16
- In EN1998-1 degree of irregularity does not implicate proportional increasing of seismic demand, unlike ASCE 7-16, where the degree of irregularity leads to proportional amplification of accidental torsional moment
- Asymmetric structural walls increased the irregularity, but in the same time they increased the structural bearing capacity. This is a reason why structures with different degree of irregularity may have similar behavior when are subjected to earthquake motion.