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TORSIONAL IRREGULATITY PROVISIONS FOR BUILDINGS IN MODERN CODES

Abstract

It has been observed that in earthquake-affected areas, structures with a configuration classified as torsionally irregular are more prone to damage than regular structures. Modern seismic provisions have introduced criteria for determining if the structure is torsionally sensitive and guidelines for designing them. Eurocode 8 prescribes criterion which is based on characteristics of natural vibrations of building while in most of the other regulations criterion is based on comparison of maximum and average story drift. The assessment and comparison of provisions for torsionally irregularity is performed on 18 structures. Six layouts of structure were created by varying the position of structural elements in order to create different levels of torsional irregularity. Because of the different approach in the classification of building regarding torsional irregularity it is noted that there are conflicting results in different regulations.

Keywords: Torsional irregularity, Eurocode 8, Asce 7-16

ОДРЕДБЕ У МОДЕРНИМ ПРОПИСИМА ЗА ТОРЗИОНО НЕРЕГУЛАРНЕ ОБЈЕКТЕ

Сажетак

Уочено је да су у подручјима погођеним земљотресом, конструкције са конфигурацијом класификованом као торзионо неправилне склоније оштећењу од регуларних конструкција. Кроз савремене сеизмичке прописе су уведени критеријуми за утврђивање да ли је конструкција осјетљива на торзију и смјернице за њихово пројектовање. Еврокод 8 прописује критеријум који се заснива на карактеристикама природних вибрација зграде, док се у већини осталих прописа критеријум заснива на поређењу максималног и просјечног релативног спратног помјерања. Упоређење одредби прописа за торзионо нерегуларне конструкције извршено је на 18 конструкција. Промјеном положаја конструктивних елемената у циљу стварања различитих нивоа торзионе неправилности креирано је шест основа конструкције. Због различитог приступа у класификацији грађевина у погледу торзионе неправилности, закључено је да се добијају опречни резултати према различитим прописима.

Кључне ријечи: торзиона нерегуларност, Еврокод 8, АСЦЕ 7-16

1. INTRODUCTION

Structural systems of buildings are conditioned with architectural requests regarding shape and function. These requests result with structural systems that have grouping of high stiffness elements (walls, concrete cores) close to the center of the building in plan, while flexible elements (or secondary seismic elements for gravity loads) are located on the perimeter of the building layout, or on only one side of structure. These structures are likely to exhibit severe rotational displacements about a vertical axis of reference under horizontal seismic excitation, which impose increased stress and deformation demands on structural members lying close to the perimeter of the building [1]. For plan irregular structures coupling between translation and torsion produces uneven displacements in structural elements. If this coupling is strong enough, than torsional sensitivity, an undesired phenomenon may take place, [2].

2. TORSIONAL IRREGULARITY PROVISIONS IN MODERN CODES

Torsional irregularity was the subject of research at a large number of scientific research institutions in the region and beyond. Although this problem has been researched for more than 60 years, the design of irregular buildings for earthquake action is still an open area of research, and the treatment in modern regulations differs significantly. Modern seismic provisions have introduced criteria for determining if the structure is torsionally sensitive and guidelines for designing them. US and European regulations prescribe different approaches. While Eurocode 8-EC8 [4], presents analytical criteria that is based on dynamic characteristics of structure, the other modern codes adopted criteria based on drifts as a result of analysis. The difference in approaches can lead to classifying the same structure differently.

If structure is classified as torsionally sensitive, it implies limited structural nonlinear behavior, so the design codes prescribe different "penalties" related to seismic analysis to be performed and behavior factor to be adopted.

For torsionally irregular structures Eurocode 8 prescribes use of reduced behavior factor, use od 3D model and at least modal analysis as structural investigation method. On the other hand, US code ASCE 7-16, [6], defines two levels of torsional irregularity, torsional irregularity and extreme torsional irregularity, with different "penalties" for structural analysis. Structures with extreme irregularity are not allowed in certain zones with extreme seismic activity, and for buildings of public interest (public institutions, industrial structures, etc.)

2.1. TORSIONAL IRREGULARITY IN EUROCODE 8

Eurocode 8 gives set of basic principles of conceptual design where it is stated that besides lateral resistance and stiffness, building structures should possess adequate torsional resistance and stiffness to limit the development of torsional motions. In this respect, arrangements in which the main elements resisting the seismic action are distributed close to the periphery of the building present clear advantages. EC8 classifies structures as "regular" and "non-regular" separately in plan and elevation according to certain structural regularity criteria. It is noted that behaviour of irregular structures to strong ground motions cannot be predicted with the same confidence as for regular structures. For this reason EC8 introduces stringent requirements for irregular structures regarding FE structural model to be adopted, seismic method of analysis to be applied and the reduction of behaviour factor value.

A series of structural regularity conditions in plan are prescribed in clause 4.2.3.2 of EC8.

The qualitative structural regularity conditions in plan are following:

(i) In plan slenderness,

$$\lambda = L_{\max} / L_{\min} \leq 4 \quad (1)$$

- Plan irregularity is checked on each level and along each main direction of the structure, the structural eccentricity has to match,

$$e_{oX} \leq 0.3 r_X \quad (2$$

$$e_{oY} \leq 0.3 r_y \quad (3)$$

where:

e_{oX}, e_{oY}, - are the distances between the centre of stiffness (or shear centre) and the centre of mass, measured along the X and Y directions, respectively, normal to the direction of analysis considered;
r_X, r_Y - are the torsional radii with respect to the centre of stiffness given by the square root of the ratio of the torsional stiffness to the lateral stiffness in the Y and X directions, respectively;

- Torsional irregularity or torsional sensitivity criterion has to be checked for each story and for each direction of computation. If this criterion is not met than structure is classified as torsionally sensitive (torsionally flexible in EC8):

$$r_x \geq l_S \quad (4)$$

$$r_y \geq l_S \quad (5)$$

where:
l_S - is the radius of gyration of the floor mass in-plan given by the square root of the ratio of the polar moment of inertia of the floor mass in-plan with respect to the centre of mass of the floor over the floor mass;
The criterion of torsional irregularity (iii) given by European regulations (Eurocode 8) is based on the characteristics of natural vibrations (i.e. stiffness and mass) of the building. The subject criterion for a single-story building is satisfied when translational natural period along a principal axis is longer than the rotational natural period (the structure is not torsionally sensitive) [3]. This criterion for multi-story buildings is not explicitly defined, but the procedure for checking this criterion is at the level of recommendations for certain types of structures. It is not clearly defined whether it is necessary to satisfy the criterion for each floor or whether the average value needs to be analysed [5].
If the structure is classified as torsionally irregular than behavior factor is to be reduced for up to 50%.

2.2. TORSIONAL IRREGULARITY IN ASCE 7-16 – US CODES

Code ASCE 7-16 prescribes three levels of torsional irregularity in accordance with the following index:

$$\alpha = \frac{\Delta_{max}}{\Delta_{average}} \quad (6)$$

Where:
Δ_{max} – maximum drift on the corresponing story i
Δ_{avg} – average drift on the corresponing story i
Torsional irregularity criterion is graphically presented in figure 1.

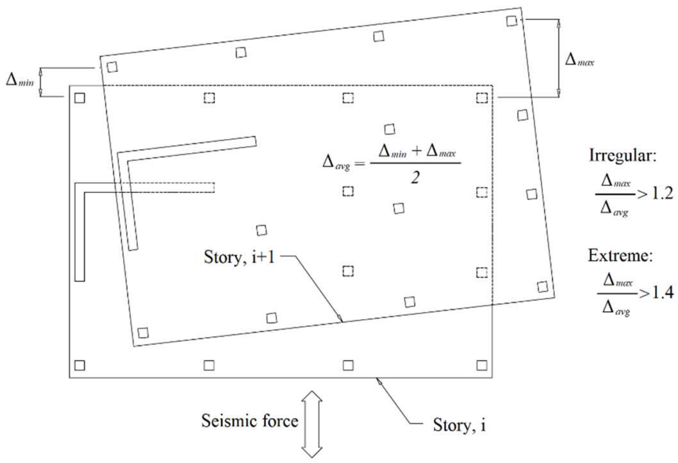

Figure 1. Torsional irregularity criterion ASCE 7-16

Torsional irregularity is defined in the following levels:
(i) Structure is not torsionally irregular if α<1,2;
(ii) Structure is torsionally irregular if 1,2 ≤ α ≤ 1,4 and

(iii) Structure is extremelly torsionally irregular if α>1,4.

Accidental torsion is taken into account by shifting the centre of mass of each floor by 5% of the building dimension, perpendicular to the seismic excitation.

For structure s that are torsionally irregular accidental torsion is to be magnified with amplification factor:

$$A_x = \frac{\Delta_{max}}{1.2 * \Delta_{avg}}, \dots 1.0 < A_x < 3.0 \tag{6}$$

In addition, if the building has extreme torsional irregularity, the moments resulting from accidental torsion of the building should be amplified by 30%.

3. CASE STUDY

In order to perform an analysis of code provisions for torsional irregularity for buildings, an analysis of 18 buildings was performed. Six characteristic layouts of the building (figure 2, figure 3) with different levels of torsional irregularity were analyzed with different number of storeys (6, 9 and 12 storeys).

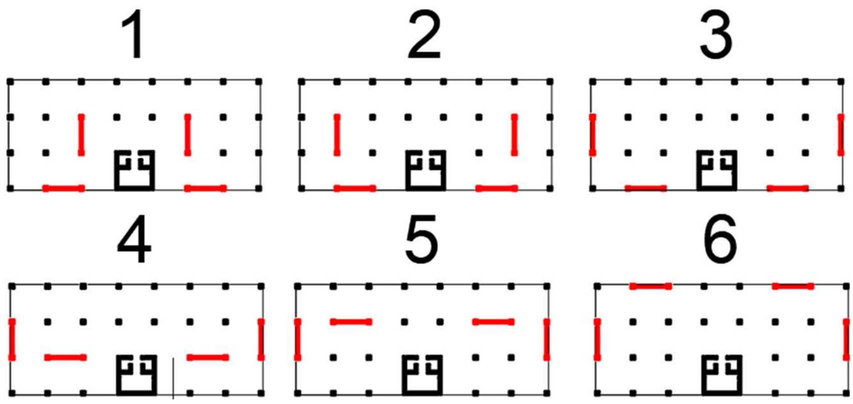

Figure 2. Layout of structure type 1 to 6

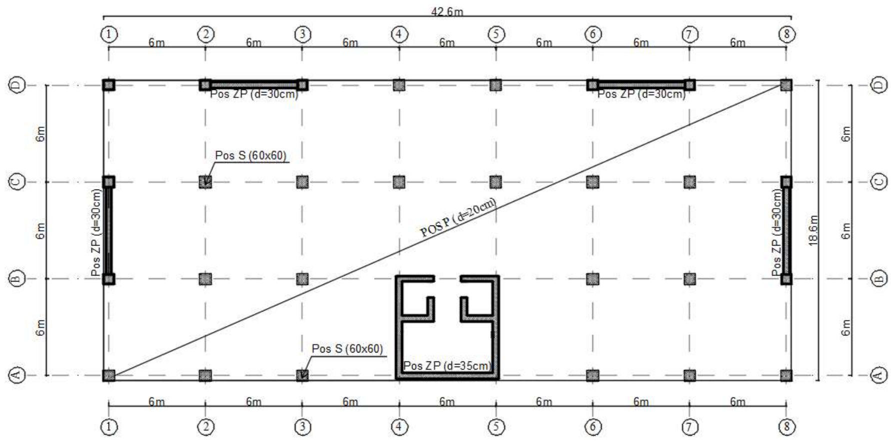

Figure 3. Layout of structure type 6

All layouts of buildings were configured to have the same number and dimensions of vertical structural elements, and different level of torsional irregularity was achieved by variation of the position of elements. For the system for lateral loads wall system with concrete core was adopted. The floor height of the ground floor is 4.5m, and the other floors are 3.2m. The layout of the building is rectangular with dimensions of 42.6 m x 18.6 m (building is not slender). The grid in both directions is 6m. The roof is flat and impassable. The slabs were designed as reinforced concrete flat slabs with a thickness of d = 20 cm directly supported by columns and walls. Columns were designed with dimensions b/d = 60/60 cm only for gravity load, so they are classified as secondary seismic elements in accordance with EC8. The thickness of the walls of the stair core and wall elements is 30 cm.

3.2. MODAL ANALYSIS RESULTS

Modal analysis was performed for 18 structures. The first natural period was coupled translation in X direction and rotation where translation was dominant. Second natural period was uncoupled translation in Y direction. Third natural period is coupled rotation and translation in X direction where rotation is dominant. The results obtained for first three natural periods are given in table 1. Analysing the results, it can be concluded that with the change in the level of torsional irregularity, the value first natural period increased, while the second and third natural period do not change significantly. It can be concluded that the change in the first natural period is more significant in buildings with less floors, and that this ratio decreases with the increase in the number of storeys. The difference in first natural period for a building with 6 storeys is 81%, 9 storeys 55%, while for 12 storeys it is 39%. The modal mass of the 1st natural period decreases and for the 3rd increases with increased level of irregularity.

Table 1. Values of first three natural period for analyzed structures

No	**6 SP 1**	**6 SP 2**	**6 SP 3**	**6 SP 4**	**6 SP 5**	**6 SP 6**
1	1,0528	0,8647	0,7415	0,6909	0,6307	0,5816
2	0,5029	0,5027	0,5036	0,5030	0,5028	0,5056
3	0,4145	0,4018	0,3849	0,4013	0,4144	0,4208
No	**9 SP 1**	**9 SP 2**	**9 SP 3**	**9 SP 4**	**9 SP 5**	**9 SP 6**
1	1,7291	1,5096	1,3570	1,2748	1,1807	1,1099
2	0,9783	0,9798	0,9837	0,9804	0,9805	0,9884
3	0,7592	0,7349	0,7078	0,7309	0,7501	0,7593
No	**12 SP 1**	**12 SP 2**	**12 SP 3**	**12 SP 4**	**12 SP 5**	**12 SP 6**
1	2,4741	2,2390	2,0823	1,9684	1,8471	1,7704
2	1,6105	1,6153	1,6258	1,6169	1,6171	1,6342
3	1,1927	1,1502	1,1089	1,1371	1,1616	1,1715

3.3. TORSIONAL IRREGULARITY CHECK IN ACCORDANCE WITH EUROCODE 8

In plan regularity check was performed in accordance with two analytical criterions given in EC8. Calculation of criterions for structure of 6 storeys with configuration 1 is given in the table 2. In the table 3 overall results of in plan regularity check for all analysed structures is presented.

Table 2. Regularity check for structure with 6 storeys and configuration 1 (SP1)

Story	e_{ox} [m]	e_{oy} [m]	r_x [m]	r_y [m]	l_s [m]	$e_{ox}<=0.3r_x$	$e_{oy}<=0.3r_y$	$r_x>l_s$	$r_y>l_s$
6	0,0	8,65	7,97	14,78	13,11	Yes	No	No	Yes
5	0,0	8,35	7,78	14,49	13,08	Yes	No	No	Yes
4	0,0	8,15	7,50	14,14	13,08	Yes	No	No	Yes
3	0,0	7,84	7,17	13,65	13,08	Yes	No	No	Yes
2	0,0	7,39	6,89	13,02	13,08	Yes	No	No	No
1	0,0	6,54	6,73	12,03	13,09	Yes	No	No	No

Table 3. Results of regularity check for all 18 structures EC8

SP 6 - 6	SP 6 - 5	SP 6 - 4	SP 6 - 3	SP 6 - 2	SP 6 - 1
Yes	**No**	**No**	**No**	**No**	**No**
SP 9 - 6	SP 9 - 5	SP 9 - 4	SP 9 - 3	SP 9 - 2	SP 9 - 1
Yes	**No**	**No**	**No**	**No**	**No**
SP 12 - 6	SP 12 - 5	SP 12 - 4	SP 12 - 3	SP 12 - 2	SP 12 - 1
Yes	**No**	**No**	**No**	**No**	**No**

3.4. TORSIONAL IRREGULARITY CHECK IN ACCORDANCE WITH ASCE 7-16

In plan regularity check was performed in accordance with analytical criterion given in ASCE 7/16. Calculation of regularity criterions for structure of 9 storeys with configuration 6 and 1 is given in the tables 4 and 5.

In the table 6 overall results of torsional regularity check and eccentricity amplification factor values for all analysed structures is presented in accordance with the ASCE 7-16.

Table 4. Regularity check for structure with 9 storeys and configuration SP6

	storey displacement		Storey drift		δmax/ δavg	Regularity check	Ax - amplification faktor	Ekcentricity %	Extreme irregularity
	Max (mm)	Min (mm)	Max (δmax mm)	Avg (δavg mm)					
st 9	58,47	40,3	8,1	6,885	1,176	Regular	1	0,05	Regular
st 8	50,37	34,63	8,14	6,905	1,179	Regular	1	0,05	Regular
st 7	42,23	28,96	8,02	6,8	1,179	Regular	1	0,05	Regular
st 6	34,21	23,38	7,76	6,565	1,182	Regular	1	0,05	Regular
st 5	26,45	18,01	7,27	6,14	1,184	Regular	1	0,05	Regular
st 4	19,18	13	6,55	5,52	1,187	Regular	1	0,05	Regular
st 3	12,63	8,51	5,54	4,66	1,189	Regular	1	0,05	Regular
st 2	7,09	4,73	4,19	3,52	1,190	Regular	1	0,05	Regular
st 1	2,9	1,88	2,9	2,39	1,213	Irregular	1,022	0,051	Regular

Table 5. Regularity check for structure with 9 storeys and configuration SP1

	storey displacement		Storey drift		δmax/ δavg	Regularity check	Ax - amplification faktor	Ekcentricity %	Extreme torsional irregularity
	Max (mm)	Min (mm)	Max (δmax mm)	Avg (δavg mm)					
st 9	70,89	26,88	9,06	6,765	1,339	Irregular	1,246	0,062	Regular
st 8	61,83	22,41	9,25	6,8	1,360	Irregular	1,285	0,064	Regular
st 7	52,58	18,06	9,3	6,71	1,386	Irregular	1,334	0,067	Regular
st 6	43,28	13,94	9,18	6,47	1,419	Irregular	1,398	0,070	Irregular
st 5	34,1	10,18	8,85	6,07	1,458	Irregular	1,476	0,074	Irregular
st 4	25,25	6,89	8,2	5,465	1,500	Irregular	1,563	0,078	Irregular
st 3	17,05	4,16	7,18	4,63	1,551	Irregular	1,670	0,084	Irregular
st 2	9,87	2,08	5,69	3,53	1,612	Irregular	1,804	0,090	Irregular
st 1	4,18	0,71	4,18	2,445	1,710	Irregular	2,030	0,101	Irregular

Table 6. Results of regularity check for all 18 structures ASCE 7-16

	ASCE 7/16			
	Torsionally irregular	Amplification factor of accidental eccentricity	Extreme torsional irregularity	Increase of seismic forces
6 sp 1	YES	2,32	YES	30%
6 sp 2	YES	1,49	YES	30%
6 sp 3	YES	1,42	YES	30%
6 sp 4	YES	1,38	YES	30%
6 sp 5	YES	1,32	NO	0%
6 sp 6	YES	1,27	NO	0%
9 sp 1	YES	2,02	YES	30%
9 sp 2	YES	1,38	YES	30%
9 sp 3	YES	1,27	NO	0%
9 sp 4	YES	1,24	NO	0%
9 sp 5	YES	1,22	NO	0%
9 sp 6	YES	1,18	NO	0%
12 sp 1	YES	1,71	YES	30%
12 sp 2	YES	1,46	YES	30%
12 sp 3	YES	1,30	NO	0%
12 sp 4	YES	1,26	NO	0%
12 sp 5	YES	1,19	NO	0%
12 sp 6	YES	1,13	NO	0%

4. COMPARISON OF RESULTS

In the table 7 overall comparison of results of torsional regularity check in accordance with EC8 and ASCE 7-16 is given.

Table 7. Comparison of regularity check in accordance with EC8 and ASCE 7-16

	ASCE 7/16		EC 8
	Torsionally irregular	Extreme torsional irregularity	Torsionally irregular
6 sp 1	YES	YES	YES
6 sp 2	YES	YES	YES
6 sp 3	YES	YES	YES
6 sp 4	YES	YES	YES
6 sp 5	YES	NO	YES
6 sp 6	YES	NO	NO
9 sp 1	YES	YES	YES
9 sp 2	YES	YES	YES
9 sp 3	YES	NO	YES
9 sp 4	YES	NO	YES
9 sp 5	YES	NO	YES
9 sp 6	YES	NO	NO
12 sp 1	YES	YES	YES
12 sp 2	YES	YES	YES
12 sp 3	YES	NO	YES
12 sp 4	YES	NO	YES
12 sp 5	YES	NO	YES
12 sp 6	YES	NO	NO

Analysed buildings can be classified as regular of irregular dependent of code that we are applying. Also, EC8 prescribes increase of seismic forces of 65% while ASCE 7-16 prescribes increase of 30% of extreme torsional irregularity and increase of accidental eccentricity tor torsional irregularity.

5. CONCLUDING REMARKS

From the performed study following conclusions can be made:
- Criterion for torsional irregularity in EC8 and ASCE 7/16 is significantly different. Criterion defined in EC8 presents analytical criteria that is based on dynamic characteristics of structure, while ASCE 7-16 code has criteria based on drifts. This can lead in classifying same structure as torsionally regular or irregular.
- By classifying structure as torsionally sensitive in accordance with EC8 reduced behaviour factor must be applied, which significantly increases total seismic forces to be applied on structure (up to 100%) equally imposed on all elements not only elements on perimeter of structure. On the other hand, ASCE 7-16 prescribes increase of accidental eccentricity up to 300% for torsionally irregular structures and increase of seismic forces for 30% .

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