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ASSESSMENT OF TORSIONAL IRREGULARITY PROVISIONS FOR BUILDINGS IN ACCORDANCE WITH EUROCODE 8

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Irregular structures present a particular design challenge for structural engineers, especially if they are located in seismically active areas. 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 introduces analitical criterion for checking torsional irregularity with the measures such as torsional ratio and the radius of gyration. If structure is classified as torsionally sensitive, it implies limited structural nonlinear behavior, so the design code prescribes use of reduced behaviour factor, use of 3D model and at least modal analysis as structural investigation method. In order to asses provisions given in Eurocode 8 total 18 structures with different layouts and number of floors were analysed and results presented in this paper. Six layouts of structure were created by varying the position of structural elements in order to create different levels of torsional irregularity. Also, number of stories was varied and structures with 6, 9 and 12 were analysed. Effects of static as well as of accidental eccentricity were considered. The obtained results have shown that with only one level of criteria for torsional irregularity given in Eurocode 8, structures with similar configuration can be classified as torsionally regular of irregular. By classifying structure as torsionally sensitive and applying reduced behaviour factor, significant increase of strength capacity is equally imposed on all elements not only elements that are close to perimeter of structure.

Keywords: torsional irregularity, eurocode 8, torsional sensitivity

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 centre 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. For plan irregular structures coupling between translation and torsion produces uneven displacements in structural elements. If this coupling is strong enough, to cause torsional sensitivity, an undesired phenomenon may take place, [1].

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 [2], 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.

2 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 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:

In plan slenderness,

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

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

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

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

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 [4].

3 METHODOLOGY

3.1 Analysed structures

In order to perform an appropriate analysis of the regularity in plan with special reference to the torsionally irregular buildings, an analysis of 18 buildings was performed. Six characteristic layouts of the building (figure 1, figure 2) with different levels of torsional irregularity were analysed with different number of storeys for (6, 9 and 12 storeys).

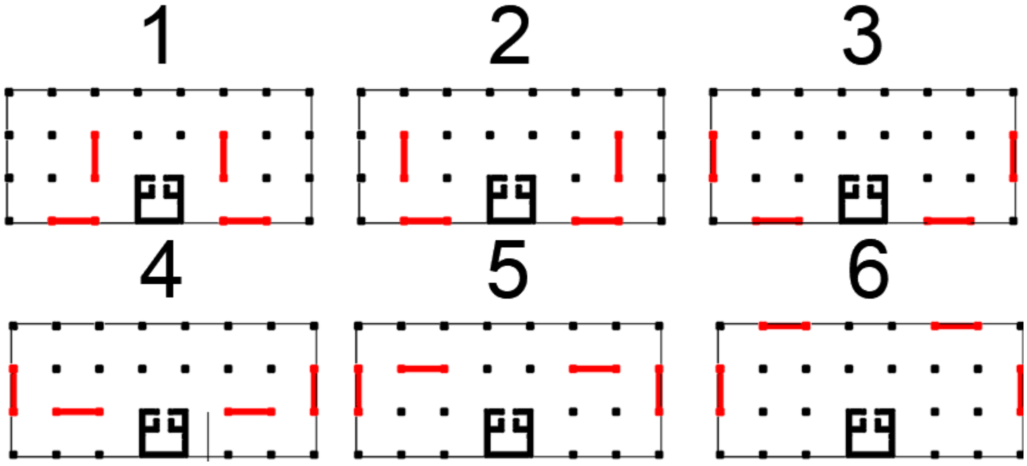

Fig. 1. Layout of structure type 1 to 6

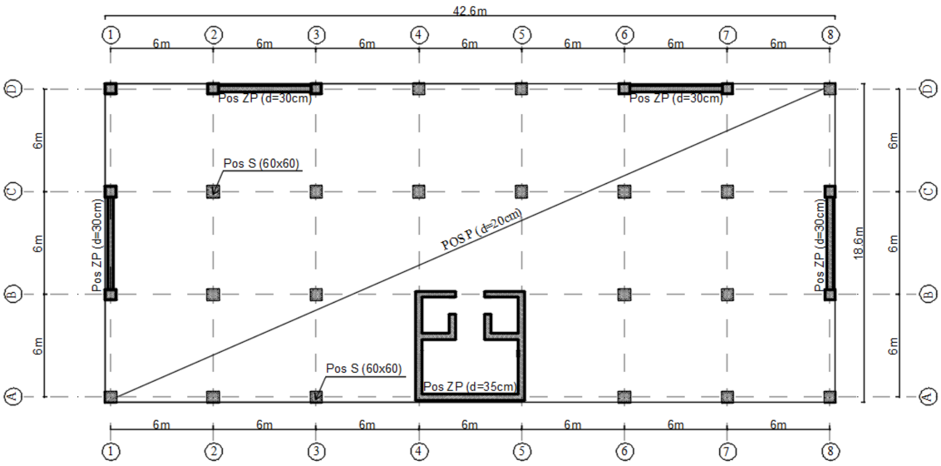

Fig. 2. Layout of structure type 6

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 designs with dimensions b/d = 60/60 cm for only 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 panels is 30 cm.

3.2 Comparative study

Modal analysis was performed and regularity check by two criterions given in EC8 (given in equations 2-5). Then, modal response spectrum analysis was performed in accordance with EC8. SRSS combination of orthogonal directions was analyses. Accidental eccentricity that shifts the calculated centre of mass at each floor and in each direction by 5% of the floor dimension perpendicular to the direction of the seismic input was applied to account for uncertainties in the distribution of masses and in the spatial variation of the seismic action. Behaviour factor for DCM (medium ductility class) was calculated with the value of q=3,3 for wall system. If the structure is categorised as torsionally irregular according to results from equations 4 and 5 than behaviour factor should be adopted as q=2.

4 RESULTS AND DISCUSSION

4.1 The modal analysis and torsional irregularity check

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.

Table 1. Values of first three natural period for analysed 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

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.

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	eox [m]	eoy [m]	rx [m]	ry [m]	ls [m]	eox<=0.3rx	eoy<=0.3ry	rx>ls	ry>ls
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

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

4.2 Theseismic analysis of structures

The seismic analysis of structures was performed in accordance with the results of modal analysis and regularity check. Results of total base shear force for all structures is calculated with and without taking in consideration torsional sensitivity of structure and presented in the table 4 (reduction of behaviour factor). Also for the 12 floor buildings second order effects were taken into consideration considering that inter-storey drift sensitivity coefficient is in range $0.1<\theta<0.2$.

The results of maximum moment in the shear wall in X direction with and without taking into consideration torsional sensitivity of structure are presented in the chart given on figure 3. From the results, it can be concluded that for buildings calculated with the same behaviour factor, the flexural moment in wall X decrease with an increase in torsional sensitivity up to a maximum of 40%. When the behaviour factor is adjusted (reduced due to the irregularity or torsional sensitivity of the objects), it leads to an increase in the moment in wall X by approx. 65%. Analysing the results, it can be concluded that this Eurocode 8 clause does not produce the expected results. Namely, the moments in shear wall X compared to the regular structure (configuration 6) are significantly increased in buildings that have a configuration similar to a regular building (configuration 4 and 5), while in buildings that are extremely irregular (1, 2 and 3) the moments are below the value for a regular building. The same case is with results for moments in Y direction shear walls.

Table 4. Results of total base shear force for all structures

	Fb (kN)		Fb (kN) with torsional irreg.		Fb (kN) with 2. order effects	
	SX	SY	SX	SY	SX	SY
6 SP 1	6056.93	9805.50	9993.93	16179.08		
6 SP 2	5931.31	9816.85	9786.66	16197.80		
6 SP 3	5877.30	9816.07	9697.55	16196.52		
6 SP 4	6101.50	9834.06	10067.48	16226.20		
6 SP 5	6467.96	9835.29	10672.13	16228.23		

	Fb (kN)		Fb (kN) with torsional irreg.		Fb (kN) with 2. order effects	
	SX	SY	SX	SY	SX	SY
6 SP 6	7271.39	9896.65	7271.39	9896.65		
9 SP 1	5840.87	8105.59	9637.44	13374.22		
9 SP 2	5795.85	8103.30	9563.15	13370.45		
9 SP 3	5734.08	8107.52	9461.23	13377.41		
9 SP 4	5802.82	8121.19	9574.65	13399.96		
9 SP 5	6035.20	8193.13	9958.08	13518.66		
9 SP 6	6555.83	8182.97	6555.83	8182.97		
12 SP 1	5634.89	7884.52	9297.57	13009.46	10649.43	13009.46
12 SP 2	5624.38	7911.20	9280.23	13053.48	10533.71	13053.48
12 SP 3	5687.39	7907.87	9384.19	13047.99	10615.59	13047.99
12 SP 4	5782.43	7923.64	9541.01	13074.01	10695.47	13074.01
12 SP 5	5981.61	7923.44	9869.66	13073.68	10990.71	13073.68
12 SP 6	6592.43	7992.79	6592.43	7992.79	6592.43	7992.79

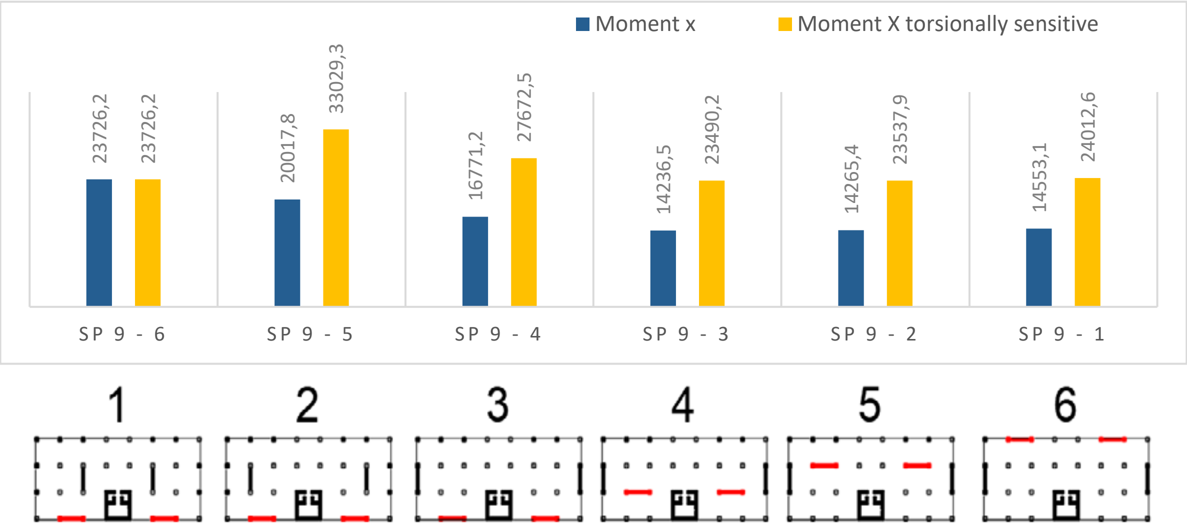

Fig. 3. Moment in shear wall X direction (kNm)

The concrete core was considered as integral unit and internal forces were analysed for section as for whole. Maximum values of moment M3 in core are presented in figure 4 and torsional moment M1 in figure 5.

It can be seen from the results that by changing the torsional irregularity level for structures calculated with the same behaviour factor, moment M3 decreases slightly (5%) with increase irregularity level. When the behaviour factor is adjusted (reduced due to the torsional irregularity), it leads to an increase of M3 in irregular structures by approx. 65%. It can be concluded that the moment M3 increases by the same order of magnitude regardless of the level torsional irregularity.

Torsional moment M1 of the concrete core increases significantly with the increase the torsional irregularity level. The torsional moment for structures calculated with the same behaviour factor increases up to 100% gradually from configuration 6 to 1. When the behaviour factor is adjusted, it leads to an increase in M1 by approx. 65%, which in total increase torsional moment up to 300% compared to a regular structure.

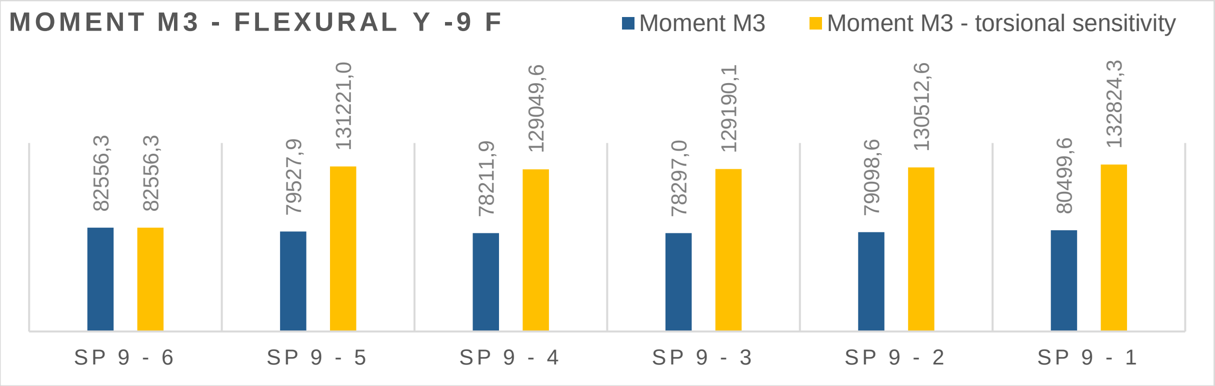

Fig. 4. Moment M3 in concrete core (kNm)

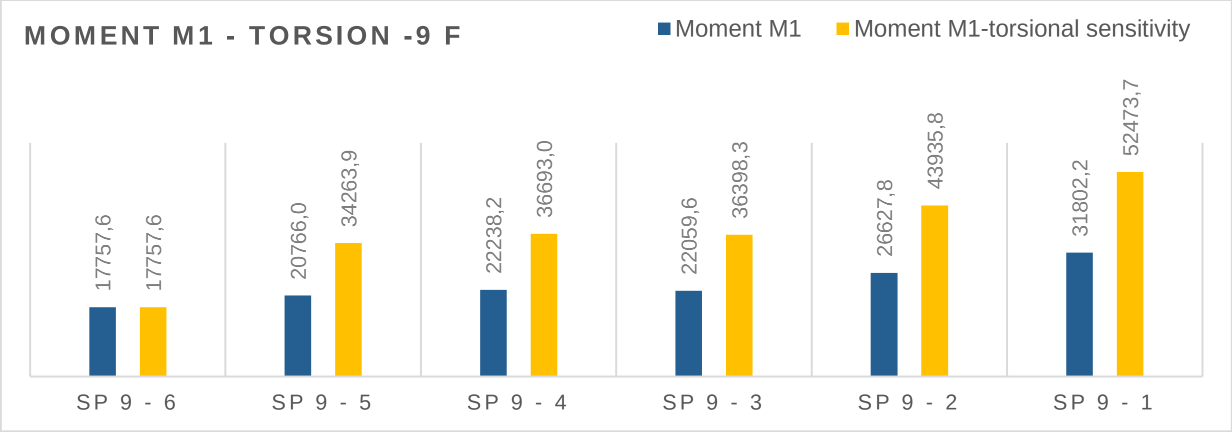

Fig. 5. Moment M1-torsional moment in concrete core (kNm)

5 CONCLUSIONS

From the performed study following conclusions can be made:

- Criterion for torsional irregularity in EC8 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. 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. This is not in line with recommendation that additional requirements should be applied on elements close to perimeter of structure. The results show that concrete core is subjected to high torsional moment with the increase of irregularity. The provisions regarding torsional stiffness of concrete core are not given in EC8 so this should be further investigated.

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