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THE INFLUENCE OF STRUCTURAL ECCENTRICITY ON THE SEISMIC BEHAVIOR OF TORSIONALLY SENSITIVE STRUCTURES

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Abstract

The focus of this research is to determine the impact of structural eccentricity on the seismic behaviour of torsionally sensitive structures. To achieve this, two groups of single-storey structural models with different levels of irregularity were analysed. The dimensions of the structures at the base are 6 m x 5 m, with a storey height of 3 m. The total external load on each structure is 300 KN. In the first group of structures, the center of mass was shifted by redistributing the load over a smaller area. In the second group, the center of stiffness was altered by increasing the cross-sectional dimensions of the columns on one side of the structure. Analyses were conducted for structural eccentricity ranging from 5% to 30%. In accordance with the criteria provided in Eurocode 8 and ASCE 7-22, the torsional regularity of the analysed structures was assessed. For the same value of eccentricity, a comparison of the levels of irregularity between the two groups was made. Through the results obtained from the nonlinear static analysis, a relationship between the level of irregularity and the level of damage was established. Additionally, an evaluation of the torsional irregularity criteria in both regulations was conducted, highlighting the advantages and disadvantages of each approach.

Keywords: eccentricity, torsion, irregularity, Eurocode 8, ASCE 7-22.

1. Introduction

Torsion, as a phenomenon contributing to significant structural damage during earthquakes, has been recognized since the 1950s. Despite significant attention over the past few decades, the issue remains unresolved. This is evidenced by differences in the provisions for torsional irregularity in modern building codes, as well as the conflicting perspectives within the scientific community. Torsional response of structures arises from several factors: eccentricity between the center of mass and center of stiffness of vertical lateral force resisting elements, accidental torsion due to the rotational component of ground motion about a vertical axis, the discrepancy between assumed and actual stiffness and mass, uncertainties in the distribution of live and dead loads, etc. The position of centre of stiffness can vary depending on the assumptions in the mathematical model, this comparison is made by Postolov et al. [1]. With the advancement of powerful computational tools in recent years, the seismic behaviour of irregular structures has increasingly been analysed using multi storey building models. Nevertheless, single-storey models continue to attract researchers as they represent the most extreme idealization of plan irregular buildings and remain adequate for obtaining general insights into the torsional behavior of asymmetric buildings, particularly from a qualitative perspective.

Extensive early researches on this issue were carried out by Kan and Chopra, Dempsey and Irvine, Kung and Pecknold, Chandler and Hutchinson and others, [2,3,4,5]. These studies, primarily analysed the elastic torsional response of single-storey models. One of the first attempts to study the torsional response in the nonlinear region was conducted by Stathopoulos and Anagnostopoulos [6]. The same researchers, in 2014, provided a detailed and critical review of the state of the art in the field of irregular structures [7]. In the development of nonlinear static analysis, which is one of the most commonly used procedures for obtaining the nonlinear response of torsionally irregular structures, significant contributions were made by Chopra, De Stefano, Fajfar, among others, [8, 9, 10].

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2. Torsional irregularity criteria in modern codes

Structural irregularities were introduced in codes in the 1980s and have continuously evolved since. These provisions were implemented to differentiate between various analysis methods and, in some cases, to prevent inclusion of irregularities in structures. Modern seismic provisions have introduced criteria for determining whether a structure is torsionally sensitive, along with corresponding design guidelines. Generally, these criteria are based on either the dynamic characteristics of the structure or storey drifts. However, they differ in two key aspects: the definition of the required parameters and their numerical limits. These differences in approach can lead to the same structure being classified differently depending on the code applied. Numerous studies have compared the criteria for regularity across different codes, including those by Rutenberg, Shahini, De Stefano, Athanatopoulou, and others, [11, 12, 13, 14]. This highlights the need for further research to establish generally accepted criteria for defining torsional irregularity.

2.1. Torsional irregularity in Eurocode 8

According to Eurocode 8 [15], specific criteria must be met for structure to be considered regular. Some of these conditions are qualitative, and can be checked during preliminary design stage, but others are quantitative, regarding additional calculations based on parameters such as the eccentricity between the center of mass and center of stiffness or torsional radius. In order to achieve satisfactory seismic behaviour, conventionally designed structures must exhibit approximately symmetrical lateral stiffness and mass distribution in plan with respect to two orthogonal axes. The following are the quantitative structural regularity conditions:

The slenderness ratio, $\lambda = L_{max}/L_{min}$, of the structure should not exceed 4, where L_{max} and L_{min} are the largest and smallest plan dimensions of the structure, measured along two orthogonal directions.

At each level and for each direction of analysis, the structural eccentricity $e_{0x/y}$, defined as the distance between the floor center of mass and the floor center of stiffness, should not exceed 30% of the corresponding storey torsional radius $r_{x/y}$, as shown in Eq. (1).

$$e_{0x/y} \leq 0.30 r_{x/y} \tag{1}$$

The torsional radius of the storey in each of the two orthogonal horizontal directions should not be less than the radius of gyration of the floor mass l_s, as shown in Eq. (2).

$$r_{x/y} \geq l_s \tag{2}$$

If the criteria are not met, meaning the structure is torsionally irregular, this implies limited structural nonlinear behaviour. Therefore, Eurocode 8 prescribes the use of a reduced behaviour factor, a 3D mathematical model for analysis, and at least a modal analysis to obtain the seismic response of the structure.

2.2. Torsional irregularity in ASCE 7-22

According to US code ASCE 7-22 [16], two levels of torsional irregularity are defined, based on the ratio between the maximal and average storey drift, shown in Fig. 1. The drifts are obtained using the equivalent lateral force procedure with the application of 5% accidental torsion.

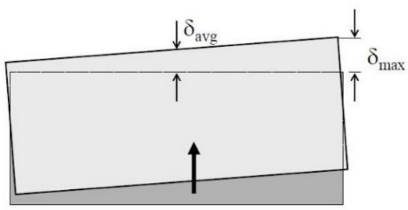

Figure 1. Maximal and average storey drift.

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$$\delta_{max} \geq 1.2 \cdot \delta_{avg} \tag{3}$$

$$\delta_{max} \geq 1.4 \cdot \delta_{avg} \tag{4}$$

The structure is considered torsionally irregular if the maximal displacement is 1.2 times greater than the average, Eq. (3). If this ratio exceeds 1.4, the structure is considered extremely torsionally irregular, Eq. (4). The average displacement is calculated as follows $\delta_{avg} = (\delta_L + \delta_R) / 2$. For torsionally irregular structures, accidental torsion should be magnified using the amplification factor, A_x:

$$A_x = \left(\frac{\delta_{max}}{1.2 \cdot \delta_{avg}}\right)^2, \text{where } 1 < A_x < 3 \tag{5}$$

Structures with extreme irregularity are prohibited in areas with high seismic activity, as well as for buildings of public interest (such as public institutions, industrial structures, etc.).

3. Description of analysed structures

To investigate the impact of structural eccentricity on the seismic behaviour of torsionally sensitive structures, an ideally symmetrical single-storey structure (S0) was analysed, along with two groups of six single-storey structures (CM1-6 and CS1-6) with different degree of torsional irregularity. All analysed structures are rectangular in plan and consist of two frames in x and y direction. The distance between the frames is 6 m and 5 m, respectively, while the storey height is 3 m. All beams are with rectangular cross-section 35/45 cm. The slab thickness is 15 cm. All columns at the first model (S0), have a 35 cm square cross-section. This structure is loaded with a uniformly distributed load of 10 KN/m^2, i.e. a total equivalent load of 300 KN.

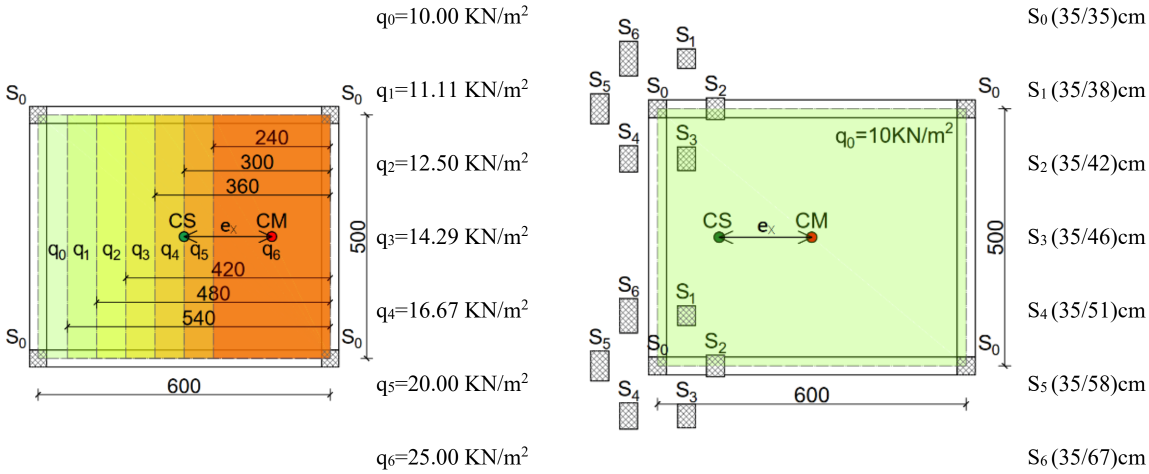

Figure 2. Layout of structures: a) Models S0, CM1-6; b) Models S0, CS1-6.

In the first group of six structures (CM1-6), the center of mass was shifted by redistributing the load over a smaller area, whereby the total equivalent load remains the same. In this group, the position of the center of stiffness remains constant. The structural eccentricity ranges from 5% to 30% from the structure's length, increasing in increments of 5% for each next structure from CM1 to CM6. The uniformly distributed load ranges from 10 KN/m^2 to 25 KN/m^2, respectively, as shown in Fig. 2.a).

In the second group of six structures (CS1-6), the square cross-section columns on the left side were replaced with rectangular cross-section columns, thereby shifting the center of stiffness by the same structural eccentricity values as in the previous group. In this group, the position of the center of mass remains constant. The dimensions of the columns range from 35/38 cm to 35/67 cm, respectively, as shown in Fig. 2.b). All structures from this group are loaded with uniformly distributed load of 10 KN/ m^2.

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4. Criteria for plan regularity

All analysed structures are regular with respect to the x-axis, as they are symmetrical in terms of mass distribution, loads, stiffness and load-bearing capacity. The check for torsional irregularity criteria is performed with respect to the y-axis. Table 1. presents the values for the torsional radius and the radius of gyration of the floor mass for all analysed structures. According to Eurocode 8 (EN 1998-1), the characteristics of single-storey buildings are uniquely defined and can be determined using the moments of inertia of the cross-section of vertical elements. The torsional radius is defined relative to the centre of lateral stiffness. To verify the regularity in accordance with ASCE 7-22, an equivalent static analysis was performed, considering a 5% accidental eccentricity. The calculated intensity of the lateral seismic force is 225 KN. The obtained results are shown in Table 2.

Table 1. Regularity check according to Eurocode 8.

Structural eccentricity	Structure	e_x [m]	r_x [m]	l_s [m]	$e_x \le 0.3 \cdot r_x$				$r_x \ge l_s$			
$e_x = 0\%$	S0	0.00	3.90	2.26	0.00	<	1.17	✓	3.90	>	2.26	✓
$e_x = 5\%$	CM1	0.30	3.90	2.13	0.30	<	1.17	✓	3.90	>	2.13	✓
	CS1	0.30	3.83	2.26	0.30	<	1.15	✓	3.83	>	2.26	✓
$e_x = 10\%$	CM2	0.60	3.90	2.01	0.60	<	1.17	✓	3.90	>	2.01	✓
	CS2	0.60	3.74	2.26	0.60	<	1.12	✓	3.74	>	2.26	✓
$e_x = 15\%$	CM3	0.90	3.90	1.89	0.90	<	1.17	✓	3.90	>	1.89	✓
	CS3	0.90	3.61	2.26	0.90	<	1.08	✓	3.61	>	2.26	✓
$e_x = 20\%$	CM4	1.20	3.90	1.79	1.20	>	1.17	✗	3.90	>	1.79	✓
	CS4	1.20	3.45	2.26	1.20	>	1.04	✗	3.45	>	2.26	✓
$e_x = 25\%$	CM5	1.50	3.90	1.69	1.50	>	1.17	✗	3.90	>	1.69	✓
	CS5	1.50	3.26	2.26	1.50	>	0.98	✗	3.26	>	2.26	✓
$e_x = 30\%$	CM6	1.80	3.90	1.61	1.80	>	1.17	✗	3.90	>	1.61	✓
	CS6	1.80	3.00	2.26	1.80	>	0.90	✗	3.00	>	2.26	✓

Table 2. Regularity check according to ASCE 7-22.

Structural eccentricity	Structure	δ_L [mm]	δ_R [mm]	δ_{avg} [mm]	$\delta_{max} \le 1.2 \cdot \delta_{avg}$				$\delta_{max} \le 1.4 \cdot \delta_{avg}$			
$e_x = 0\%$	S0	7.57	8.51	8.04	8.51	<	9.65	✓	8.51	<	11.26	✓
$e_x = 5\%$	CM1	7.11	9.03	8.07	9.03	<	9.68	✓	9.03	<	11.30	✓
	CS1	6.45	8.21	7.33	8.21	<	8.80	✓	8.21	<	10.26	✓
$e_x = 10\%$	CM2	6.61	9.46	8.04	9.46	<	9.64	✓	9.46	<	11.25	✓
	CS2	5.45	7.92	6.69	7.92	<	8.02	✓	7.92	<	9.36	✓
$e_x = 15\%$	CM3	6.14	9.94	8.04	9.94	>	9.65	✗	9.94	<	11.26	✓
	CS3	4.55	7.63	6.09	7.63	>	7.31	✗	7.63	<	8.53	✓
$e_x = 20\%$	CM4	5.66	10.41	8.04	10.41	>	9.64	✗	10.41	<	11.25	✓
	CS4	3.73	7.35	5.54	7.35	>	6.65	✗	7.35	<	7.76	✓
$e_x = 25\%$	CM5	5.19	10.89	8.04	10.89	>	9.65	✗	10.89	<	11.26	✓
	CS5	3.00	7.07	5.04	7.07	>	6.04	✗	7.07	>	7.05	✗
$e_x = 30\%$	CM6	4.56	11.06	7.81	11.06	>	9.37	✗	11.06	>	10.93	✗
	CS6	2.32	6.84	4.58	6.84	>	5.50	✗	6.84	>	6.41	✗

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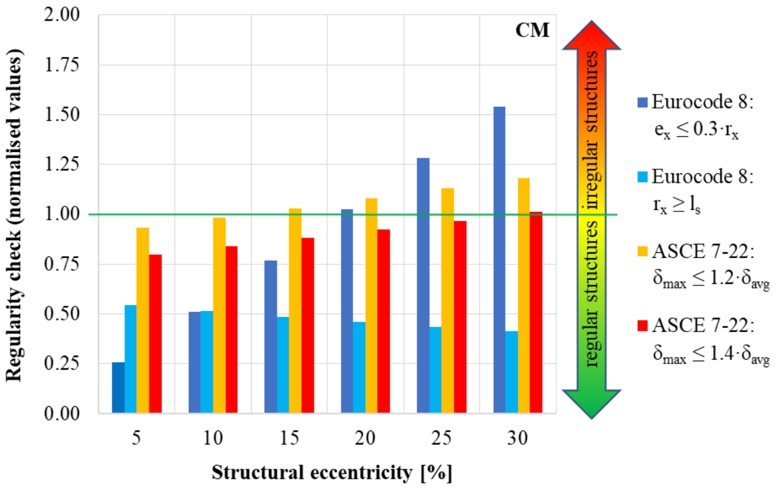
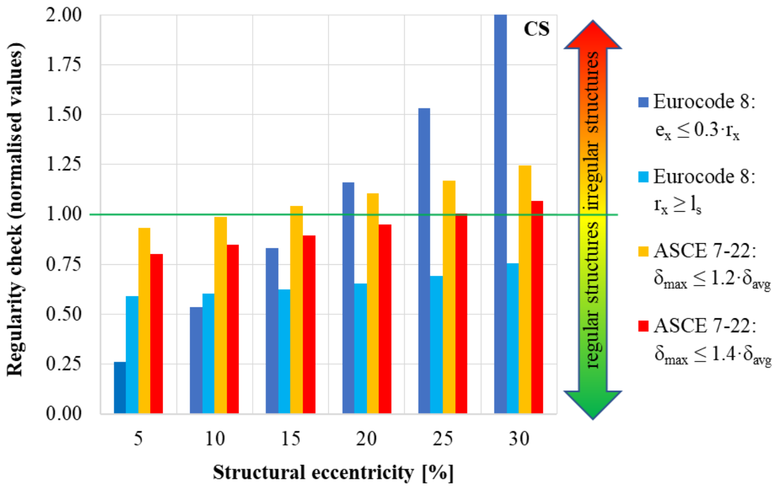
According to Eurocode 8, models with a structural eccentricity of up to 15% are considered regular. Models with a structural eccentricity of 20% or more are classified as torsionally irregular, as they do not satisfy the criterion that the structural eccentricity should be less than 30% of the torsional radius. These regulations do not provide a gradation of irregularity, resulting in a sharp boundary between regular and irregular structures. In contrast to Eurocode, ASCE 7-22 relates both criteria to the ratio between the maximum and average displacement, with different values assigned based on the prescribed level of irregularity. According to this provision, the analysed models with a structural eccentricity up to 10% are considered regular. Models with a structural eccentricity of 15% or more are torsionally irregular because they do not satisfy the first criterion, $\delta_{max}<1.2\cdot\delta_{avg}$. The models CS5, CM6, and CS6 do not satisfy neither the second criterion $\delta_{max}<1.4\cdot\delta_{avg}$, and are therefore classified as extremely torsionally irregular structures.

From this, the initial inconsistency between the two provisions becomes apparent. The CM3 and CS3 structures are considered regular according to Eurocode 8, whereas ASCE 7-22 classifies them as irregular. Structures deemed extremely torsionally irregular under ASCE 7-22, are also classified as irregular under Eurocode 8, as along with all other structures with a lower level of irregularity but fail to meet certain criteria. As mentioned in Section 2, this classification has significant implications and limitations in the design process. Fig. 3.a) and Fig. 3.b) present diagrams showing the regularity check of the structures through normalized values of each criterion, indicating how many a certain criterion is satisfied or not.



a)



b)

Figure 3. Regularity check (normalized values) a) Models S0, CM1-6; b) Models S0, CS1-6.

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A value less than 1 signifies that the criterion is met and the structure is considered regular, whereas a value greater than 1 indicates that the criterion is not met, requiring the structure to be analysed as irregular. According to both provisions, the level of irregularity is directly proportional to the increase in structural eccentricity and is more pronounced in structures with a shifted center of stiffness. Under ASCE 7-22, the regularity criterion is exceeded by no more than 25%, whereas according to Eurocode 8, it is exceeded by as much as 100%. In addition to the gradation of irregularity, another advantage of the US provision is that the amplification factor for accidental eccentricity A_x, Eq. (5), also depends on the maximum and average displacement. The value of this factor ranges from 1 to 3. In contrast, under European provisions, irregular structures are assigned a lower basic value for the behaviour factor q_0, meaning they are analysed with higher design forces. This value is not directly dependent on the level of irregularity of the structure, unless it has been determined through a nonlinear static analysis.

5. Nonlinear seismic assessment of analysed structures

To determine the required reinforcement in the RC beams and columns of the analysed structures, a multimodal analysis was performed. The following input parameters were used: reference peak ground acceleration $a_g = 0.30g$, soil category C, spectrum type 1, importance class II ($\gamma = 1$), and ductility class DCM. The analysed structures are subjected to seismic forces in the y direction only. For designing, concrete class C25/30 and reinforcement class B500C were used. The required reinforcement in the beams was determined from the analysis of the S0 structure, where an accidental eccentricity of 5% was also considered. For the columns, a minimum reinforcement of 1% was adopted, which exceeds the required reinforcement area obtained from the analyses. The adopted reinforcement in all cross-sections is shown in Fig. 4. The nonlinear static analysis was performed using the SeismoStruct software package, which is based on the distributed plasticity method. The nonlinear behaviour of the structural elements is defined using the inelastic frame element (infrmFBPH), where the nonlinearity is concentrated over a precisely defined length of the element, as proposed by Scott and Fenves [17]. The length of the plastic hinges is 16.67% of the element length. The beam elements are modelled as "Γ" cross-sections, with an effective width of 75 cm and 83 cm for the beams in the x and y directions, respectively. The cross-section of the beam elements is divided into 82 fibres, while the cross-section of the columns is divided into 62 fibres. The previously applied area load is distributed onto the beam elements as a linear load, proportional to their respective surface area. To obtain the capacity curves, a reference point was selected at the top of the rightmost column of the structure.

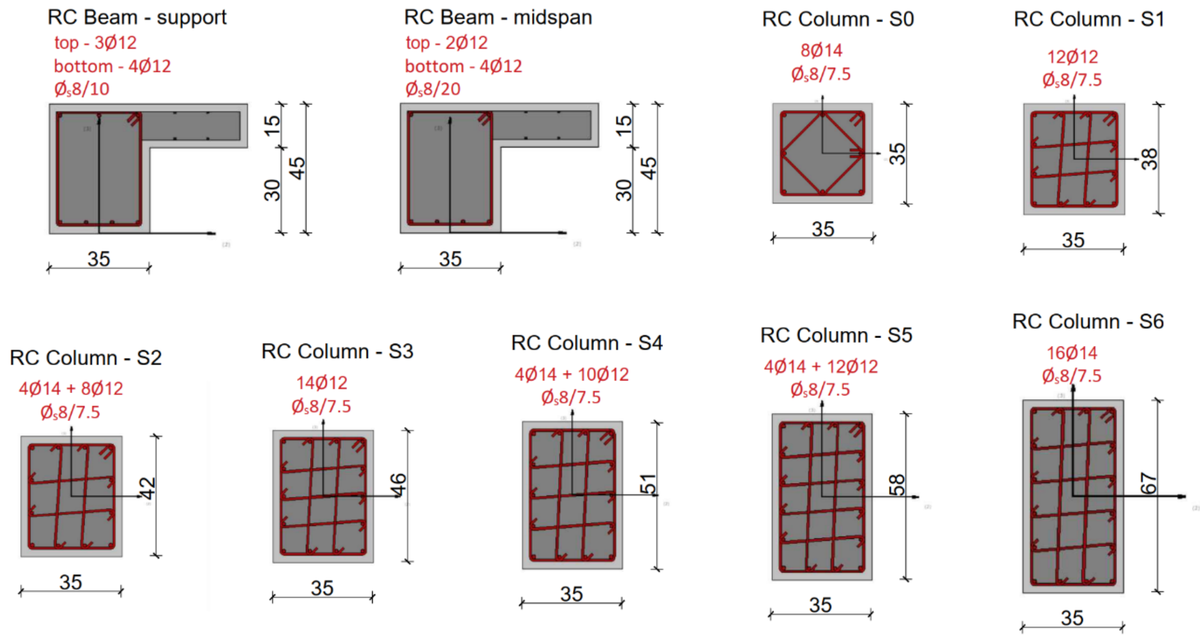

Figure 4. Reinforcement details.

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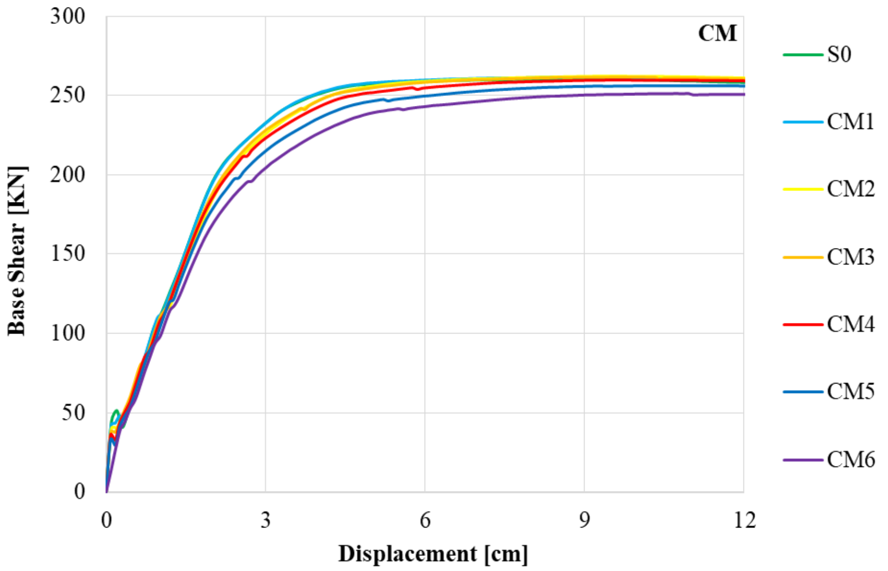
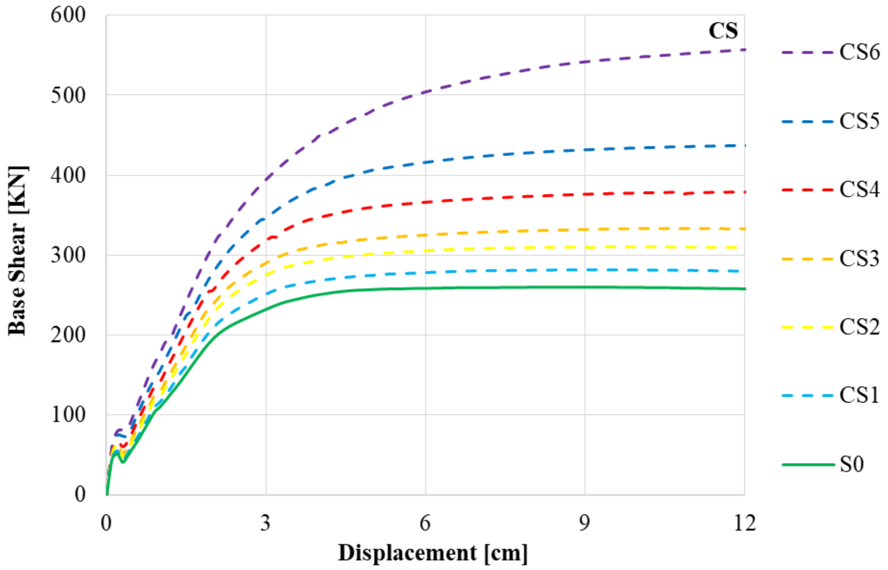
6. Comparison of results

After conducting the analyses and obtaining the results, the nonlinear response was compared among the symmetric structure S0, the group of structures with a shifted center of mass CM, and the group with a shifted center of stiffness. Fig. 5 shows the capacity curves of the analysed structures. As structural eccentricity increases and the level of irregularity rises, the load bearing capacity decreases in the group of structures with a shifted center of mass, as shown in Fig. 5.a). The load bearing capacity of the CM6 structure is up to 20% lower than that of the S0 structure. In contrast, the increased load bearing capacity of the structures with a shifted center of stiffness is attributed to the enlargement of the column dimensions on the left side of the structure, as shown in Fig. 5.b).



a)



b)

Figure 5. Pushover curves a) structures SO, CM(1-6); b) structures SO, CS(1-6).

In all structures, despite the differences in capacity curves, an increasing level of irregularity leads to a greater tendency for unevenly damage at both ends of the structure, resulting in gradual shift of the center of stiffness over time. This raises concerns about the reliability of structural responses obtained from the linear analysis, which assumes a fixed position for the center of stiffness. Table 3. presents the maximum displacement of the observed node in the y direction and the base shear force for four characteristic states in the structure: (1) the development of the first plastic hinge on the right side,

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(2) the development of a plastic hinge on the left side, (3) the formation of a mechanism on the right side, and (4) the formation of a mechanism on the left side. The first plastic hinges on both sides of the structure develop at maximum displacements ranging from 1.6 cm to 2.4 cm, which represents a relative difference of about 0.25% of the story height of the analysed structures. The ratio between the maximum displacement at the formation of a mechanism on the right and left side of the structure ranges from 1.1 to 2.3 for the group of structures with a shifted center of mass, and from 1.0 to 1.6 for the group of structures with a shifted center of stiffness.

Table 3. Maximum displacement and base share force for characteristic states in the structure.

Structural eccentricity	Structure	1st Plastic Hinge - R		1st Plastic Hinge - L		Plastic Hinge Mechanism - R		Plastic Hinge Mechanism - L	
		d_y [cm]	F_b [KN]	d_y [cm]	F_b [KN]	d_y [cm]	F_b [KN]	d_y [cm]	F_b [KN]
$e_x = 0\%$	S0	1.8	180	1.8	180	2.7	224	2.7	224
$e_x = 5\%$	CM1	1.8	180	1.8	180	2.7	224	2.9	230
	CS1	1.7	183	1.7	183	2.7	241	2.7	241
$e_x = 10\%$	CM2	1.7	161	2.0	185	2.7	217	3.5	238
	CS2	1.7	200	1.7	200	2.7	265	2.8	269
$e_x = 15\%$	CM3	1.7	165	2.1	196	2.6	216	3.9	246
	CS3	1.7	211	1.6	199	2.7	280	2.9	287
$e_x = 20\%$	CM4	1.7	165	2.2	197	2.5	208	4.4	248
	CS4	1.6	218	1.6	218	2.8	308	3.0	318
$e_x = 25\%$	CM5	1.7	159	2.3	193	2.3	193	4.6	243
	CS5	1.6	230	1.8	256	2.8	338	3.6	373
$e_x = 30\%$	CM6	1.6	146	2.4	187	2.1	175	4.8	237
	CS6	1.6	257	1.9	299	2.8	380	4.5	464

The diagrams in Fig. 6. illustrate the amplification of rotations for the structures in each of the two groups. For the previously defined four states, the ratio of rotations between each structure and those of the CM1 and CS1 structures is presented, respectively. As structural eccentricity increases in each state, a greater amplification of rotations is observed, with the most significant amplification occurring in the group of structures with a shifted center od stiffness.

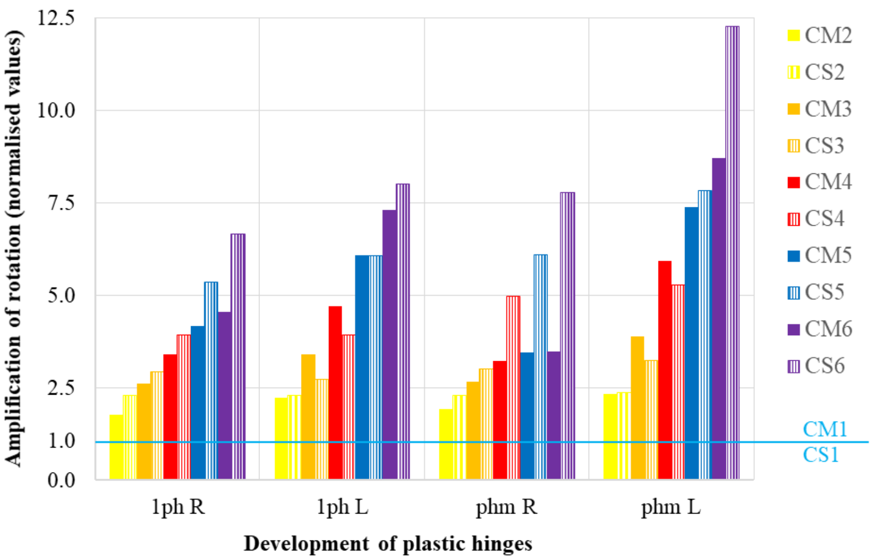

Figure 6. Amplification of rotation for characteristic states in the structure.

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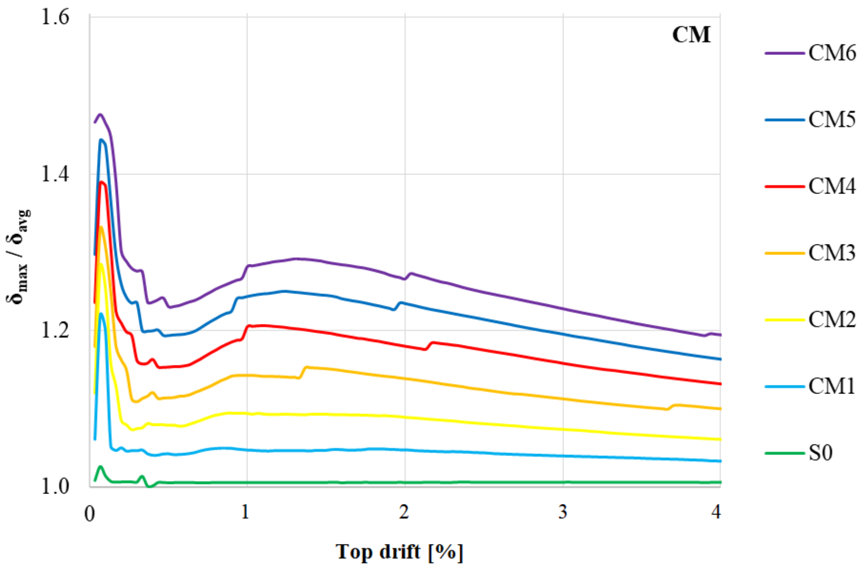
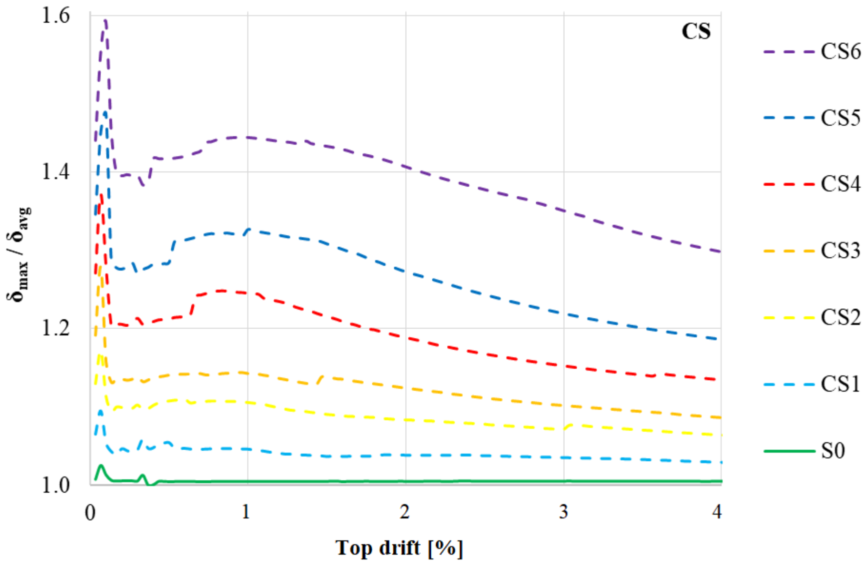
When a mechanism forms on the left side of the structure, the rotation amplification for the CS6 structure reaches nearly 12.5 times. In the same state, the rotation amplification for the CM5 structure is approximately 8.5 times.

The diagrams in Fig. 7. illustrate the relationship between the ratio $\delta_{max}/\delta_{avg}$, and the maximum displacement at the observed point. The trend and shape of the curves are similar for all the analysed structures. A peak appears in the diagrams at a maximum displacement of approximately 0.1% of the storey height. According to ASCE 7-22, at this displacement level, some structures would be classified one level higher in terms of irregularity. The structures CM1 and CM2, previously considered regular, would be reclassified as torsionally irregular, while CM5, previously classified as torsionally irregular, would be categorized as extremely torsionally irregular. Although these displacements are generally very small, attention should be given to this phenomenon in the case of impulsive seismic action, due to dynamic effects such as torsional motion. Beyond this stage, the curve values for almost all structures fall below the initially unsatisfied criterion, indicating that the linear analysis remains on the safe side. The only exceptions are structures CM5 and CS6, whose curve values exceed the criterion up to a maximum displacement of approximately 2% of the floor height. However, this effect has been accounted for in the linear analysis.



a)



b)

Figure 7. $\delta_{max}/\delta_{avg}$ - top drift diagrams a) structures SO, CM(1-6); b) structures SO, CS(1-6).

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Since all curves exhibit a similar trend, only the diagram for structure CS6 is shown in Fig. 8. Characteristic points are marked, and the order of plastic hinges development is indicated for the four characteristic states. The peak of the curves occurs due to the uneven formation of cracks on both sides of the structure. Up to point C on the diagram, cracks develop only in the columns on the right side of the structure. The maximum is reached when cracks also begin to form in the columns on the left side of the structure, after which the curve declines. Another local maximum occurs at a maximum displacement of approximately 1% of the storey height, corresponding to the formation of a mechanism on the right side of the structure, (point phm R). If the influence of cracks is neglected, i.e. if the tensile strength of concrete is taken as f_{ctm}=0, the curve would follow the path of the light-coloured line. In this case, no peak would appear in the initial phase, and after the formation of a mechanism on the left side of the structure, (point phm L), the curves would completely overlap.

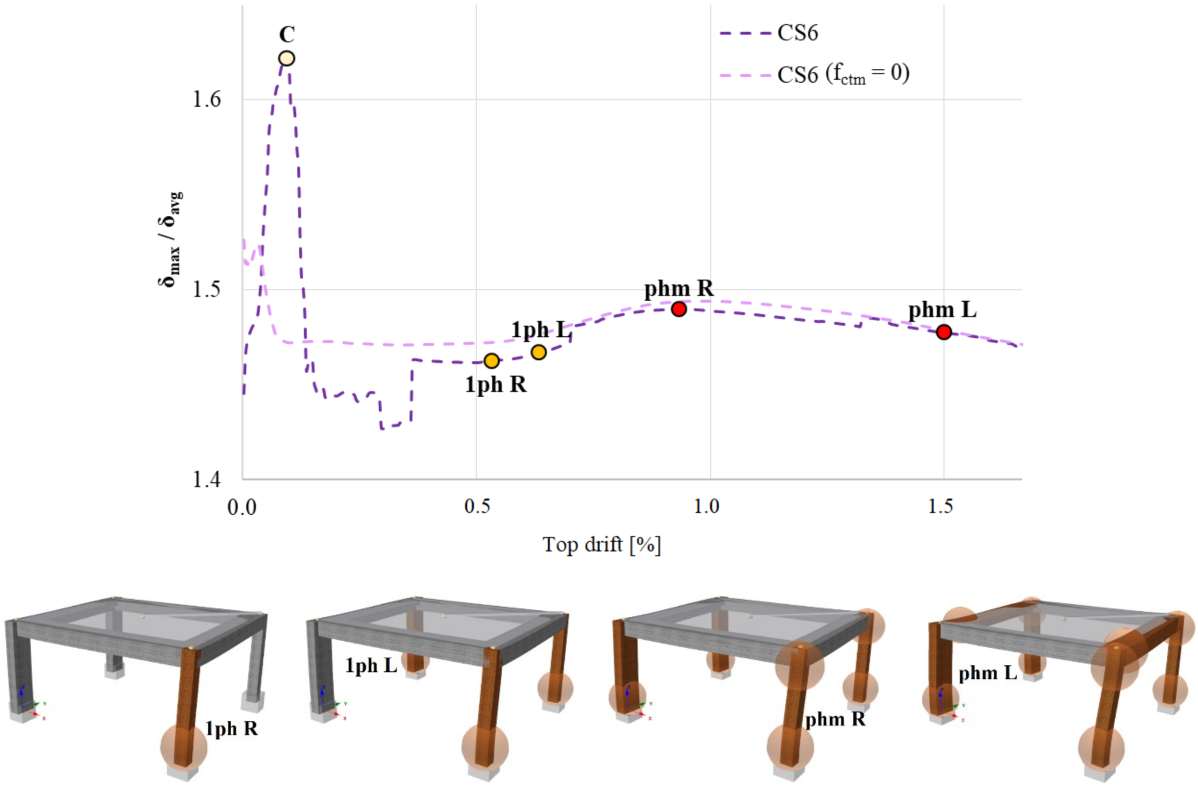

Figure 8. Order of plastic hinges development for characteristic states in the structure.

7. Final remarks

Several conclusions can be drawn from this research. A larger structural eccentricity, whether caused by a shifted center of mass or stiffness, generally has an unfavorable impact on the structural behavior. The criteria for torsional regularity in the utilized codes are based on two fundamentally different approaches. Eurocode 8 relies on the dynamic characteristics of the structure, whereas ASCE 7-22 classifies the level of irregularity based on displacements obtained from seismic analysis. An inconsistency may arise because one structure can be classified as torsionally regular by the one code and torrsionaly irregular by the other. Additionally, the two codes differ in how they penalize irregularity. Eurocode 8 mandates an increase in the design seismic forces, while ASCE 7-22 applies an amplification of the accidental eccentricity. These differences create an opportunity for further research aimed to establishing generally accepted criteria for torsional regularity in modern codes.

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