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CODE APPROACHES FOR SEISMIC DESIGN OF PLAN IRREGULAR STRUCTURES

Abstract: The buildings that are built in seismic active region should resist the seismic forces induced by earthquake ground motion without significant damage or structural collapse. The building structural system can be characterized as regular or irregular. A great number of the registered structural damages occurred during the earthquake action are due to the irregularities of the structural system. The regularity of the structural system depends on numerous structural characteristics and parameters that make it difficult to classify the structural system as regular or irregular. This work discuss how the modern seismic codes control the irregularity in plan and the methodologies by which the plan irregularity is determined for structures.

Key words: Seismic codes, plan irregularities

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1. INTRODUCTION

The buildings that are built in seismic active region should resist the seismic forces induced by earthquake ground motion without significant damage or structural collapse. Moment resisting frames, shear walls and frame-shear wall dual systems are the most common used structural systems to withstand the seismic action. The damage of the structural system initiates in weak spot location that trigger further structural deterioration which leads to the structural collapse. These weaknesses often occur due to presence of structural irregularities in mass, strength and stiffness in a building structural system. The structural irregularity can be generally classified as plan (horizontal) and vertical irregularities, Fig.1.

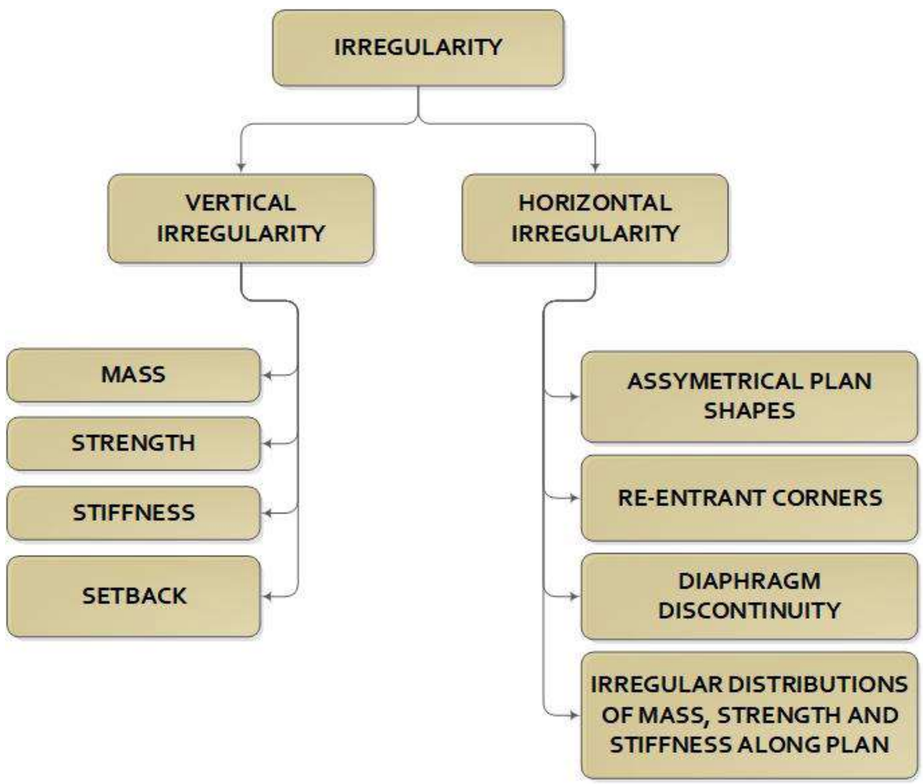

Figure 29 - Classification of different types of structural irregularities

The building structural system can be characterized as regular or irregular. A great number of the registered structural damages occurred during the earthquake action are due to the irregularities of the structural system. The regularity of the structural system depends on numerous structural characteristics and parameters that make it difficult to classify the structural system as regular or irregular.

Irregularity in plan may have negative implication on the design process and on the behaviour of the structures exposed to earthquake loading. Buildings with eccentricity between the center of the mass and center of stiffness or with lack of minimal torsional rigidity can undergo coupled lateral and torsional motions during earthquakes, which can significantly increase the seismic demand, especially at perimeter frames. For these reasons most of the seismic design codes contain provisions for control of structural irregularities. If the prescript criteria for regularity are not satisfied, certain restrictions related to the selected method or numerical model for seismic analysis have to be done. Moreover, due to potentially uncontrollable torsion oscillation and reduced ductile response, design seismic forces have to be obtained for a lower reduction factor.

High seismic vulnerability of plan irregular structures was a motivation for many researches in the past. An extensive review of different structural irregularities and systematization of conducted researches can be found in Rutenberg (2002), [11], De Stefano and Pintucchi (2008), [5], Varadharajan at al. (2013), [14]. Many of these researches, Cosenza at al. (2000), [4], Humar, J. and Kumar, P. (2000), [7], Zheng at al. (2004), [15], Özhendekci and Polat (2008), [9], Ilerisoy (2019), [8], Alecci at al. (2019), [1] are related to the analysis of codes provisions for plan irregularity.

2. DAMAGES OF PLAN IRREGULAR STRUCTURES

Over the years it have been observed that structures have suffered severe damages during earthquakes, as result of the plan irregularities. The eccentricy between the center of mass and the center of stiffness lead to irregularity in plan which cause torsional behaviour, which results with major damages to the structural elements in the lateral, more flexible zones, of the structure.

Figure 2, shows the collapse of three storey building in Miyagi-Ken-Oki (Japan) during the earthquake in 1978, due to plan irregularity. Due to presence of a stiff wall, the center of stiffness has shifted towards the wall. The occurrence of eccentricity between the center of mass and center of stiffness resulted with twisting of the structure in respect of the center of stiffness. This torsion resulted in severe damages in the periphery columns on the away side of the wall.

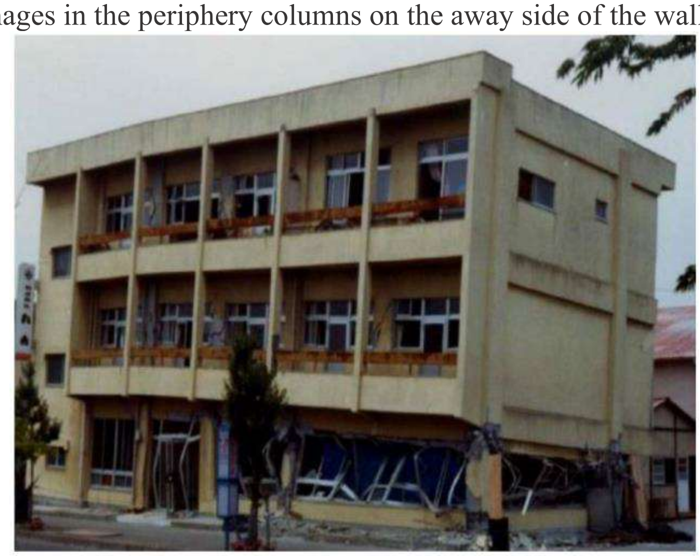

Figure 30 - Damage of three storey building during 1978 Mijagi-Ken-Oki earthquake, [14]

Figure 3, shows the damage to the Ministry of Culture building in Haiti during the earthquake in 2010. The stiff core on one side of the building resulted in damage in the lateral load-resisting members away from the center of stiffness and downward pull of the whole storey, which led to the total collapse of the building. Similar type of collapse, due to torsional response about a stiff shaft at the corner, was observed at Athens earthquake in 1999, fig.4, [6].

Figure 31- Damage to Ministry of Culture building during 2010 Haiti earthquake, [14]

Figure 32- Collapse of a building due to torsional response, Athens (1999) earthquake

Severe damage to six storey reinforced concrete hotel in Guatemala City, Fig. 5, during the Guatemala earthquake in 1976, occurred as result of the torsional irregularity due to eccentric location of a rigid service core. The failure of the columns located on the flexible side of the building occurred due to their incapability to resist the torsion from increased shear force. This resulted in second storey collapse in the building (indicated by blue arrows in the figure).

Figure 33 - Damage due to irregularity during Guatemala earthquake 1976, [14]

3. CRITERIA FOR PLAN IRREGULARITY GIVEN IN DIFFERENT EARTHQUAKE CODES

As noted earlier, the reason why different earthquake codes give provisions for the regularity of the structure is that the response of the regular structure in plan during the earthquake action is generally along the main direction and does not combine the horizontal components of the seismic action. For a structure to be categorized as regular in plan, several geometrical and dynamic conditions have to be satisfied, [16].

The Macedonian seismic code do not include regulations for the design of structures irregular in plan. The regulation provide a series of recommendations for the construction of seismic resistant structures such as: the structural disposition of buildings is achieved by a correct and uniform solution in plan, with a uniform mass distribution and in the case of larger structural load, the center of mass should be as low as possible.

According to EN 1998-1 [3], a building can be characterized as regular in plan, if six different conditions are satisfied, at all storey levels. Some of these conditions are qualitative, and can be checked in the preliminary design stage, but some of them that are based on the eccentricity between the center of mass and the center of stiffness or torsional radius, Eq. 1, are quantities that have to be calculated additionally. In-depth discussion of the conditions for plan regularity according to EN1998-1, can be found in Penelis and Penelis (2014), Fardis at al. (2015).

The first condition according to EN1998-1 [3] states that distribution in plan of the lateral stiffness and mass of the structure shall be approximately symmetrical with respect to two orthogonal horizontal axes.

It follows that plan configuration shall be compact. Each floor shall be delimited by a polygonal convex line. There is some tolerance with regard to this requirement: if there are in-plan setbacks (edge recesses or re-entrant corners), the structure is considered as regular under the following conditions, fig. 6.:

- The setbacks do not affect the floor in-plane stiffness.
- For each setback, the area between the outline of the floor and a convex polygonal line enveloping the floor does not exceed 5% of the floor area.

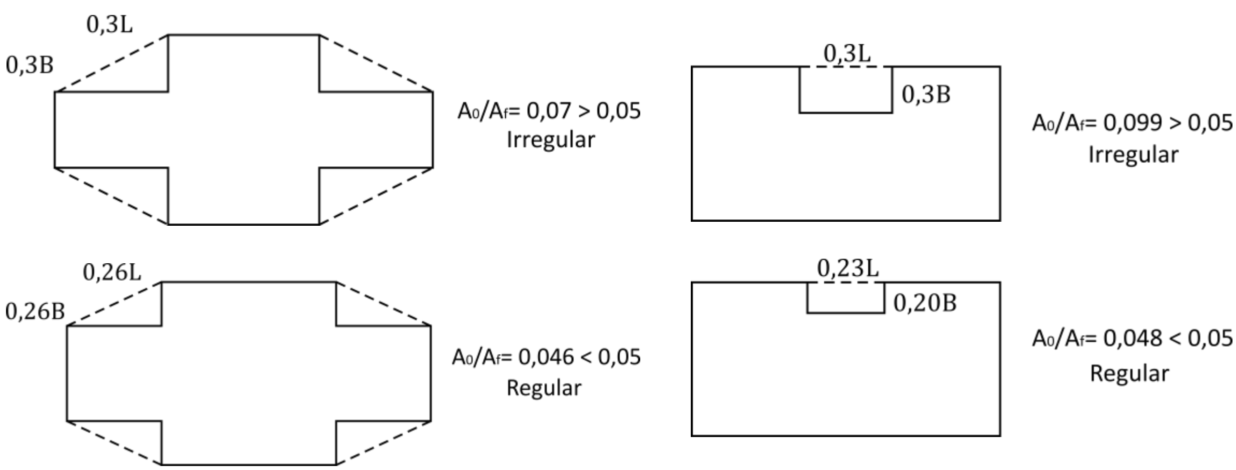

Figure 34 - Regular and irregular plan configurations

The floors should be considered as rigid diaphragms, with sufficiently large in-plane stiffness, so that the deformation of the floor, due to seismic action, is negligible compared to the inter-storey drifts and have a small effect on the distribution of the forces among the vertical structural elements. In respect to that, the L, H, C, I and X shapes should be carefully examined, fig. 7.

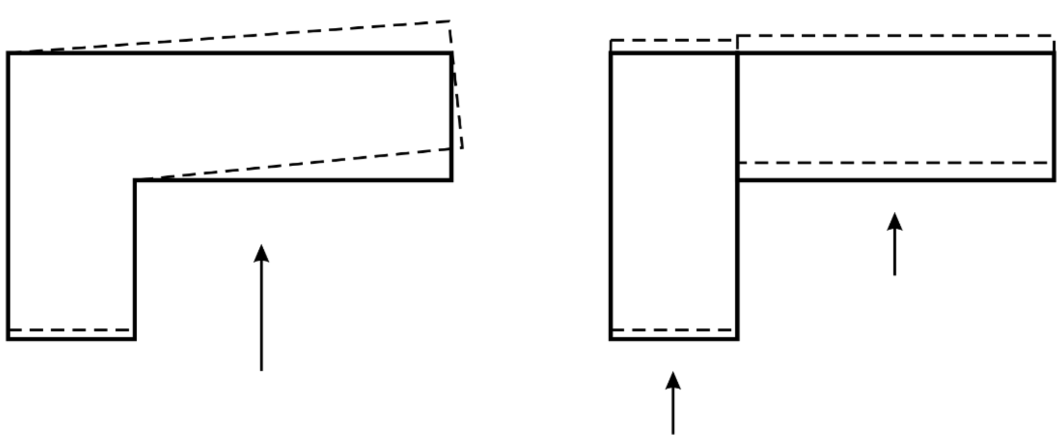

Figure 35 - Provisions for designing building structures with complex shape

The slenderness or the aspect ratio $\lambda = L_{max}/L_{min}$ of the building should be no more than 4, where L_{max} and L_{min} are respectively, the larger and smaller in plan dimension of the building, measured in two orthogonal directions.

At each level and for each direction of analysis *x* and *y*, the structural eccentricity e_0, between the floor center of mass and the storey center of stiffness, do not exceed 30% of the corresponding storey torsional radius r, Eq. 1.

$$e_{0x} \le 0{,}30 \cdot r_x \tag{1}$$

The torsional radius of the storey in each of the two orthogonal horizontal directions, *x* and *y*, is not less than the radius of gyration l_s of the floor mass, Eq. 2.

$$r_x \ge l_s \tag{2}$$

For single storey buildings these characteristics are uniquely defined and EN1998-1, [3]. allows to be calculated through the moments of inertia of the cross section of vertical elements. In general, some additional parameters, like beams stiffness or shear deflections can affect the position of center of stiffness or torsional radius. In multi storey buildings, Eurocode 8 allows simplified definition for classification of structural regularity in plan and for the approximate analysis of torsional effects only for buildings in which all lateral load resisting systems are running from the foundation to the top and have similar deformation patterns under lateral loads. Moreover, Eurocode 8 accepts that in frames and in systems of slender walls with prevailing flexural deformations, the position of the center of stiffness and the torsional radius of all stories may be calculated as those of the moments of inertia of the cross-section of the vertical elements.

Similarly, ASCE Standard 7-10, [2], provides a list of conditions to detect horizontal irregularity in buildings, as follows.

Torsional irregularity, depending on differences between the maximum story drift, δ_{max}, computed including accidental torsion with 5% accidental eccentricity, and the average story drift, δ_{avg}. Torsional irregularity is defined to exist where the maximum story drift, at one end of the structure transverse to an axis is more than 1.2 times the average story drift at the two ends of the structure, Eq. 3.

$$\delta_{\max} \ge 1{,}2 \cdot \delta_{avg} \tag{3}$$

Extreme torsional irregularity exist, if this ratio exceeds 1.4 times the average story drifts, Eq. 4.

$$\delta_{\max} \ge 1{,}4 \cdot \delta_{avg} \tag{4}$$

where $\delta_{avg} = (\delta_A + \delta_B)/2$ is the average deflection determined by an elastic analysis, Fig. 8, [1].

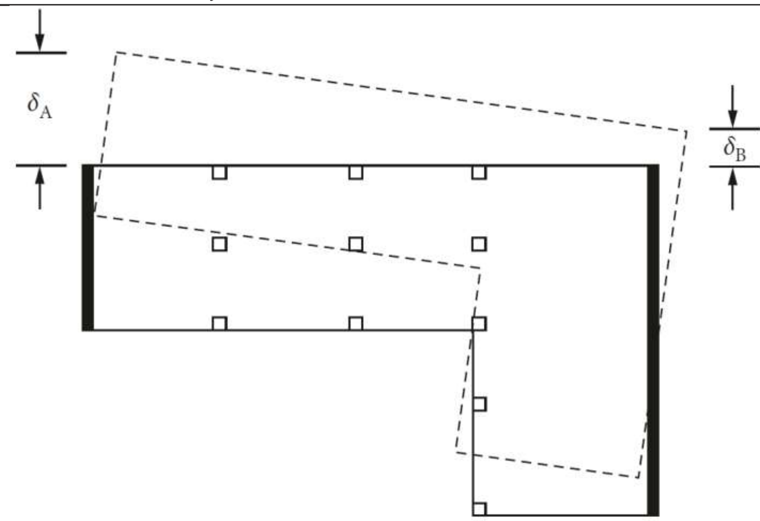

Figure 36 - Determination of the average deflection

Reentrant corner irregularity exists where both plan projections of the structure beyond a reentrant corner exceed 15% of the plan dimension of the structure in the given direction.

Diaphragm discontinuity irregularity exists when a diaphragm with an abrupt discontinuity or variation in stiffness, including one having a cut-out or open area greater than 50% of the gross enclosed diaphragm area or a change in effective diaphragm stiffness of more than 50% from one story to the next.

Out of plane offset irregularity exist where there is a discontinuity in a lateral force resistance path, such as an out-of-plane offset of at least one of the vertical elements.

Nonparallel system irregularity exists where vertical lateral force resisting elements are not parallel to the major orthogonal axes of the seismic force resisting system.

The Turkish code, TEC 2007, [13], have similar provisions as ASCE 7-10, only with different requirements for certain values. The New Zealand code, NZS 1170.5-2004, [12], have three provisions regarding the irregularity in plan and it is the only code that takes in to account the horizontal offset of the columns in the moment frames structural systems and systems with structural walls.

Similar to ASCE 7-10, NZS 1170.5-2004 defines that torsional sensitivity shall be considered to exist when the largest ratio between maximum storey displacement at the extreme points of the structure, at each level, in the direction of earthquake induced by equivalent static actions acting with accidental eccentricity of 10% and average of the displacement at the extreme points at same level in both orthogonal direction exceeds 1.4. This requirement, with the exception of assumed torsional eccentricity, is identical with the condition for extreme torsional irregularity given in ASCE 7-10.

4. COMPARISON OF THE CRITERIA FOR PLAN IRREGULARITY OF DIFFERENT CODES

As noted earlier, the modern codes for seismic resistant structures, have different provisions, by which they categorize the regularity of the structure.

The comparison between the codes and their provisions, is presented in Table 1. When considering the re-entrant corners (setbacks) requirement, proscribed by the codes it can be noted that EN1998-1 has the most rigorous criteria, i.e. the Turkish code allows 4 times greater setback, and 3 times greater than the ASCE 7-10. The New Zealand code has no defined criteria for re-entrant corners (setbacks).

When it comes to torsional irregularity the definition in the Eurocode differs from the other three codes, because it the irregulariy is defined by geometrical characteristics and the position of the structural elements. The torsional irregularity in the other three codes is defined by the displacements obtained by seismic analysis. Most flexible regarding this provision is the NZS. The TEC2007 for the ratio $\delta_{\max} \geq 1{,}2 \cdot \delta_{avg}$, treats the stucture as torsionaly irregular, same as the ASCE 7-10, the only difference is that the ASCE 7-10 for the ratio $\delta_{\max} \geq 1{,}4 \cdot \delta_{avg}$ defines the structures as extreme torsionaly irregular. It can be noted that a structure can be characterized as torsionaly irregular in New Zealand and as extreme torsionaly irregular in the United States. Similarly the structure may be characterized as torsionaly regular in New Zealand and torsionaly irregular in Turkey.

With regard to the discontinuity of the diaphragms, the Eurocode 8 does not specify what percentage of openings are permitted as required by the US and Turkish regulations. The US regulation also takes the diaphragms stiffness into account and is more flexible than the Turkish regarding this provision. This criteria is not taken into account by the New Zealand code.

Only the New Zealand code, NZS 1170.5-2004, [12], takes into account the horizontal offset of the columns in the moment frames structural systems and systems with structural walls. The first is for all the columns at one storey level and the second is for one column.

Table 3 - Irregularity limits prescribed by EN1998, ASCE7-10,NZS1170.5 and TEC2007

Type of irregulariy	EC8 2004	ASCE-7.10	NZS 1170.5-2004	TEC 2007
Re-entrant corners	$R_i \leq 5\%$	$R_i \leq 15\%$	-	$R_i \leq 20\%$
Torsional irregularity	$r_x>3.33\ e_{ox}$ $r_y>3.33\ e_{oy}$ $r_x\ u\ r_y>l_s$	$d_{max}\leq 1.2\ d_{avg}$ $d_{max}\leq 1.4\ d_{avg}$	$d_{max}\leq 1.4\ d_{avg}$	$d_{max}\leq 1.2\ d_{avg}$
Diaphragm discontinuity	-	$O_a<50\%$ $S_{dst}<50\%$	-	$O_a<33\%$
Horizontal offset of the columns in moment frame structural systems and in systems with structural walls	-	-	$\sum\|a_j/b_j\|>0.1\ N_c$ $a_j/bj>0.4$	-

Where:

R_i – re-entrant corners, d_{max} – maximum drift at praticular storey level, d_{avg} – average drift at particular storety level, O_a – open area in diaphragm, S_{dst} – diaphragm stiffness, aj – horizontal drift of the column j, bj – vertical distance between the base of the upper column and the top of the lower column, N_c – sum of the columns at particular storey level

5. CONCLUSION

The criteria for irragularity of the structure in plan, has important role in the design of seismic resistant structures, because it shows us whether the structure has potential to enter torsional oscillations, which can be hazardous in relation to the desired behaviour of the structure.

The registered damages, from previous earthquakes, it has been noted that the structures with irregularity in plan are significantly more vulnerable than the regular structures. This justify the need of provisions that shall regulate the irregularity in plan. This has prompted more in-depth research, and thus the development of methodologies and analyzes that can define a larger number of parameters that influence the evaluation of the structure’s response.

Although the Eurocode 8 has established criteria for plan irregularity, based on geometric parameters, center of stiffness and torsional radius, it has no defined methodology for their determination. This can lead to some difficulties in its practical implementation. Unlike the Eurocode, the other codes (ASCE 7-10, NZS 1170.5-2007 and TEC 2007) can determine the plan irregularity during the analysis of the structure.

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