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Seismic Response of Buildings Subjected to the Bending Phenomena

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Summary

A significant problem for the computation of structures subjected to dynamic loads is represented by the assessment of the horizontal loads on the vertical elements of the structure. This aspect can be complicated in accordance with the adopted constructive system. The present codes provide regularity restrictions in order to reduce the consequences of the bending earthquake effect. In this paper a comparison between seismic design requirements depending on the structural regularity is presented

KEYWORDS: *bending phenomenon, accidental eccentricity, energy dissipation, structural regularity, dynamic response.*

1. INTRODUCTION

The need to know the structures behavior under bending strain and to accurately determine its dynamic response represents the main priority in modern design [1].

A major issue in designing and calculating buildings capable to withstand lateral forces is the distribution of horizontal lateral forces upon vertical structural elements. This issue can become extremely complicated, depending on the adopted design.

Seismic design has to follow fairly regularly structure achievement, so that the inertia forces due to the mass have to be transmitted directly to the foundation [1]. Then, when is necessary an irregular shape, structural regularity may be obtained by subdividing the entire structure by seismic joints into dynamically independent units. To relieve supplementary efforts due to structure non regularity, behavior models and scripts will be used to asses if the structure can't be subdivided. To allow a more favorable redistribution of the action effects and widespread energy dissipation across the entire structure, not only structure has to be symmetrical but the structural elements have to be as symmetrical as possible.

Horizontal seismic motion is a bi-directional phenomenon and thus the structure has to possess lateral rigidity and resistance at horizontal actions in any direction.

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Unbraced frame structures (with rigid joints), braced frame structures (with articulated joints) and structural walls (figure 1a-c) are typical systems to undertake lateral forces.

The other lateral force resisting systems impose architectural restriction excepting unbraced frame with rigid joints, so in consequence there are limitations in respect to the plan distribution. Moreover, generally, the gravitational force resisting systems are more economic then the lateral force resisting systems. Hence, a typical structure will contain systems to take over both, gravitational and horizontal forces (figure 1d) [2].

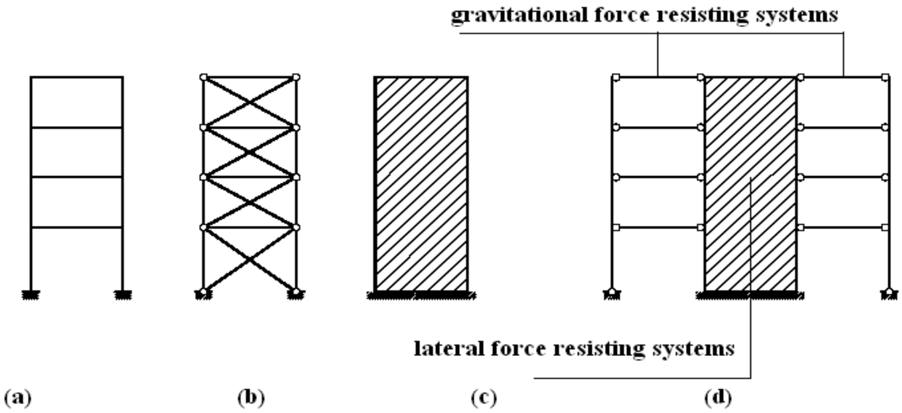

Figure 1. The lateral force resisting systems: (a) – braced frame with rigid joints; (b) – centric braced frames; (c) – structural walls; (d) – combined system.

Besides lateral resistance and stiffness, structures should possess an adequate torsional resistance and stiffness [3]. Torsional flexible structures lead to higher deformations and efforts in peripheric structure elements, as well as non uniform deformations and effort distribution in structural elements. According to the above statements, arrangements where the main seismic load carrying elements are distributed closer to the periphery of the structure present clear benefits (figure 2).

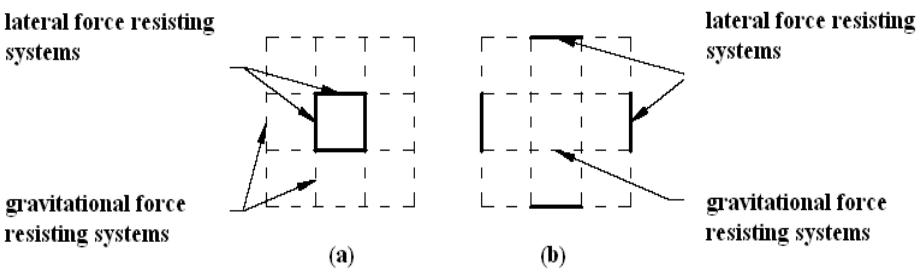

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Figure 2. Structure with the same number of lateral resisting elements:
(a)– susceptibly for torsion; (b)– with increased rigidity and resistance to torsion

To ensure a small difference between the structure centre of rigidity (CR) and the centre of mass (CM), disposal of the lateral force resisting systems has to be symmetrical as possible. Seismic forces are inertia forces and their resultant acts in the centre of mass while the structure reaction act in the centre of rigidity. Uniform slab translation due to the action of lateral seismic forces is induced when the centre of mass does not coincide with centre of rigidity (figure 3a). A slab rotational component will exist, beside translational component, if between the centre of mass and the centre of rigidity an eccentricity exists (figure 3b). This effect leads to larger displacements on the flexible side (Δ_{2x} in figure 3b) compared to the rigid side (Δ_{1x} in figure 3b) along the direction of applied forces. In addition translational components will appear perpendicular to the direction of the applied seismic force (Δ_{1y} şi Δ_{2y}). This eccentricity it may occur due to either non-uniformity in the rigidity distribution or non-uniformity in the mass distribution.

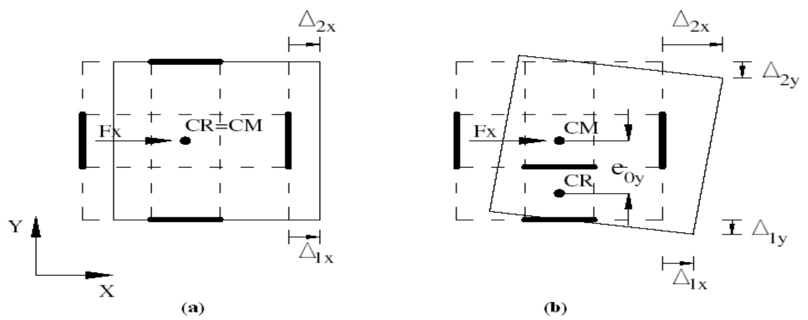

Figure 3. Structure plan with the lateral force resisting systems symmetrical arranged (a) and with nonsymmetrical arrangement (b)

In a structure properly designed to take over seismic forces the slab has to be able to satisfy the following requirements:

- inertia forces sampling and their transmission to vertical structural elements;
- to behave like a horizontal diaphragm, ensuring that the vertical elements engage independently into taking over the horizontal seismic forces [3].

The seismic design of slabs with irregular shapes and with big voids and the design of slabs belonging to irregular structures (without horizontal and/or vertical regularity), will be based on design models able to show in a sufficient manner the behavior of the elements during an earthquake. A plate loaded on its plane can be, according to the case, assimilated to a deep-beam or truss (”strut-and-tie” model),

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recommended for the cases of slabs with large voids (figure 4). The model has to be chosen so that the system diagonals do not intersect the voids.

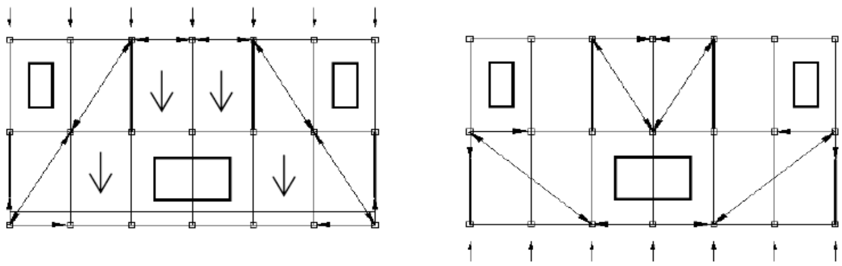

Figure 4. Structural model

The load carrying system consists of the gravitational force resisting systems and the lateral force resisting systems (figure 1). The horizontal diaphragm effect of the plate ensures seismic forces transmission to the lateral forces resisting systems and also ensure structure spatial co-operation. The horizontal diaphragm effect of the plate is useful in the case of structures with irregular plan shape and for case when the lateral force resisting system has different rigidities along the orthogonal directions of the structure. To ensure the horizontal diaphragm effect of the plate the slabs must fulfill stiffness and strength requirements.

In figure 5 the horizontal diaphragm effect of the plate effect on lateral deformations of the structure is presented. When a rigid slab ensures the connection between a peripheric rigid frame (taking over lateral forces) and an interior flexible frame (taking over gravitational forces), the seismic forces is assumed to be proportional to the frame rigidity. In this way the seismic forces are taken over mainly by the rigid frame, and the rigid slab ensures equal deformations of rigid and flexible frames.

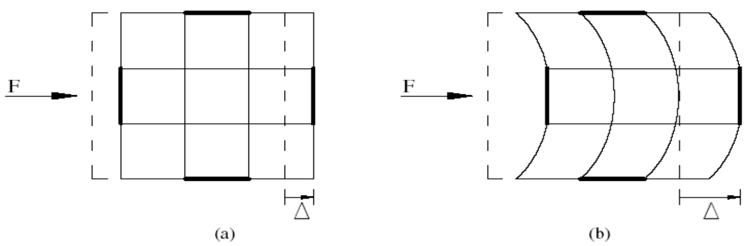

Figure 5. Structure deformations with rigid slab (a) and with flexible slab (b)

When dealing with a case of flexible slab (figure 5b), the rigid and the flexible frame system take the seismic forces in an independent manner. The value of the forces is proportional with each frame mass. In this case, because of a bigger mass

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and less rigidity the interior flexible frames develop larger deformations that the rigid ones, which involve higher structural and non-structural damage.

2. GENERAL CRITERIA FOR STRUCTURAL REGULARITY WITH RESPECT TO SELECTION OF STRUCTURAL DESIGN MODEL

For the purpose of seismic design, structures are classified into being regular or non-regular. In accordance with this classification one chooses [4]:
- the structural model, which can be either a simplified planar model or a spatial model;
- the analysis type, which can be either a simplified response spectrum analysis (lateral force procedure) or a modal one;
- the value of the behavior factor *q*, which should be decreased for structures with non-regular shape in elevation.

With regard to the implications of structural regularity on analysis and design, separate considerations are given to the regularity characteristics of the structure in plan and in elevation.

Table 1. Model and method of structural calculus

Case	Regularity		Allowed simplification		Behavior factor
	Plan	Elevation	Model	Linear elastic analyses	Linear elastic analyses
1	Yes	Yes	Plan	Equivalent lateral force*	Reference value
2	Yes	No	Plan	Modal	Decreased value
3	No	Yes	Spatial	Modal	Reference value
4	No	No	Spatial	Modal	Decreased value

Note: *- Only if structure's height is smaller than 30m and the fundamental period of vibration is smaller than 1,5s;
- The selected model and method of structural calculus corresponded to the level of minimal calculus.

2.1. Structural regularity/ irregularity in plan

Eurocode 8 defines the following criteria in order to consider a structure regular in plan [5]:

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- with respect to lateral rigidity, resistance and mass distribution, the structure should be approximately symmetrical in plan with respect to the orthogonal directions;
- the plan configuration should be compact, with regular contours; if the structure present setbacks (re-entrant corners or edge recesses), the sum of the dimension of the setbacks does not have to exceed 25% of the structure dimension in that direction;
- the in-plan rigidity of the slabs must be sufficiently large in comparison with the lateral stiffness of the vertical structural elements, so that the deformation of the slab should have a small effect on the distribution of the forces among the vertical structural elements;
- maximum displacement, determined at an extremity, must not exceed the average displacement of structure extremities with more than 20%, seismic force being applied with normalized eccentricity;
- the slenderness $\lambda = L\max/L\min$ of the structure should be not higher than 4, where *L*max and *L*min are respectively the largest and smallest in plan dimension of the structure, measured along the orthogonal directions.

The Romanian design code P100/2006 anticipates the first three restrictions like Eurocode8 and more [4]:

- at the second restriction, structure should be considerate regular in plan, setbacks case, this does not affect slab plan rigidity and differences between slab contour and slab convex polygonal envelope does not exceed 15% of the slab area;
- structure limit reduction should be realized only on the bearing element;
- maximum displacement determined at an extremity should not be higher than 1,35 of both structure extremities displacement;
- at each level and for each direction of analysis *x* and *y*, the structural eccentricity e_o and the torsional radius *r* should be in accordance with the two conditions below, which are expressed for the direction of analysis *y*:

$$\begin{aligned} e_{0x} &< 0.30\, r_x \\ e_{0y} &< 0.30\, r_y \end{aligned} \tag{2}$$

where:

- e_{0x}, e_{0y} are the distances between the centre of stiffness and the centre of mass, measured along the *x* direction, which is normal to the direction of analysis considered, respectively on y direction;
- r_x, r_y are the square root of the ratio of the torsional stiffness to the lateral stiffness in x direction, respectively in y direction (“torsional radius”).

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2.2. Structural regularity/ irregularity in elevation

Eurocode 8 sets the following criteria that all the structures must satisfy in order to be considered regulate in elevation [5]:

- structural system must be monotone along the vertical direction without variations from the foundation level up to the top level of the structure. If the structure present setbacks on the height this must not exceed 20% of the dimension of the inferior level;
- both the lateral stiffness and the mass of the individual storey must remain constant or reduce gradually, without sudden changes, from the base to the top of structure;
- for gradual setbacks preserving axial symmetry, the setback at any slab should not be greater than 20 % of the previous plan dimension in the direction of the setback (figure 6a and figure 6b);
- for a single setback within the lower 15 % of the total height of the main structural system, the setback should not be greater than 50 % of the previous plan dimension (figure 6c);
- if the setbacks do not preserve symmetry, on each face the sum of the setbacks each storey should not be greater than 30 % of the plan dimension at the ground slab above the foundation or above the top of a rigid basement, and the individual setbacks should not be greater than 10 % of the previous plan dimension (figure 6d).

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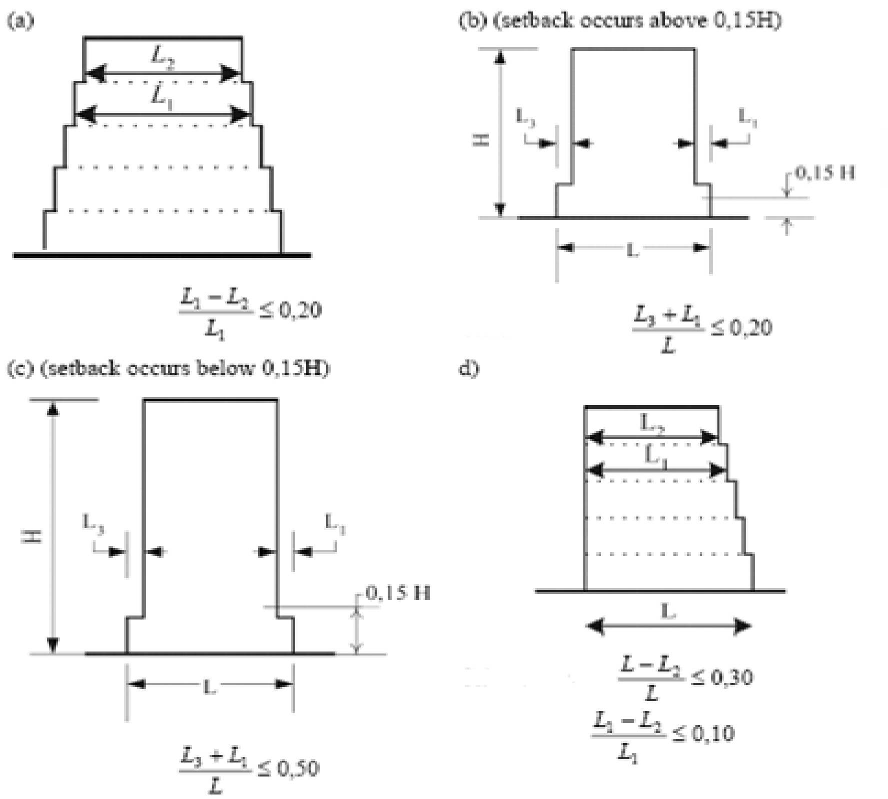

Figure 6. Criteria for regularity in elevation

The Romanian code provisions P100/2006 for regularity in elevation are [4]:

- the structure does not present reduction of lateral rigidity higher than 30% of inferior or superior level;
- the structure does not present reduction of lateral resistance higher than 20% of inferior or superior level;
- if the dimensions of structural elements are reduced from the base to the top of structure, the rigidity and resistance variation have to be uniform without any sudden reduction from the base level to the top one;
- the mass has to be uniformly distributed, so that the differences between the storey mass and adjacent storey do not exceed 50%.

3. CONCLUSIONS

Although the design requirements require the achievement of regular structures in plan and elevation, there are various causes (functionality, esthetics, economy, configuration of available land) out of which results buildings with structural and mass dissymmetry.

The bending phenomenon is one of the most common causes for structure failure during major earthquakes due to sudden change of regularity, rigidity and resistance of structural elements. These sudden changes occur at planar as well as elevated level, leading to large values of ductility requirement thus, the necessity to improve the strength of structure's component elements.

Therefore, the structure and/or the structural elements should be as regular shaped as possible also, strive for a uniform distribution of masses and loads in order to limit the occurrence of bending phenomenon as much as possible.

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