Comparative study on the structural behaviour of a 30m height building with a RC frames structure located in a high intensity seismic area

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Abstract. This paper presents an analysis of the Finite Element Model structural system of a building in the Vrancea, Romania seismic area. The studied structure is a part of a set of 3 buildings with a height of 30 m. The height of the levels is 4.5 m and 3.5 m. Due to the vertical irregularities, the distribution of the functions and the location of the building, it is necessary to identify an optimized structural solution for a more balanced behaviour to the seismic action. Thus, various structural models and results are presented regarding the process of establishing the positions and dimensions for structural elements.

1. Introduction

The progress of engineering science in the design of buildings has reached a very high level in the last 100 years. The emergence of computer programs and the development of numerical methods have led to a much faster evolution. The experience and errors encountered in the case of many earthquake-type disasters have led to the identification of vulnerabilities of structural concepts and to the emergence of more efficient design rules. Experimental research programs also facilitate the correct understanding of buildings structural behaviour under seismic actions and capture the potential mechanisms of structural failure.

The shape and design of the resistance structure directly dictate the behaviour of the various actions throughout the life of a building. If the structural elements are correctly positioned in order to be distributed as well as possible and to take over as evenly as possible the loads produced by external actions, the designed construction will have all the chances to withstand all possible actions. This can be achieved if the most important principle is considered: obtaining a balanced dynamic behaviour, namely that the structure is regular both in plane and vertically.

A regular structure both in plane and vertical, is ideal because the evaluation of the seismic structural response by means of simple finite element models is easy to control and verify. At the same time, the structural costs can be optimized in relation to the load’s distribution but also because of the lower influence of the inevitable uncertainties related to materials, geometries, eccentricities and other aspects. However, real structures are often neither simple nor regular. In the case of existing old buildings, they were initially designed without any concern about their seismic behaviour. Most of the damage was caused by the effects of torsion which involves a faulty design of the structural elements. [1]

Past earthquakes have frequently shown that structures with an irregular configuration suffer greater damage than regular ones. Some examples are presented in figure 1. The importance of these effects increases with the importance of the first mode of vibration. In literature, multiple articles present different studies and experimental analyses of the seismic response for both symmetric and asymmetric multi-story regular and irregular reinforced concrete structures. [2] [3] [4]
Torsional effects are generally caused by the irregular geometric configuration in plane and/or vertically and the irregular distribution of masses and stiffness in the plane and/or elevation. The evaluation of torsion effects is an important topic in civil engineering design, both for new and existing buildings. Among the basic principles governing the conceptual design of new buildings, some of them are relevant to the configuration and regularity of the building, such as uniformity, symmetry, torsional strength and rigidity.

2. Study case of a RC structural system

The Seismic structural configuration

Seismic design aims to achieve a safe construction in relation to the seismic hazard associated with the site, which meets, in acceptable cost conditions, the fundamental requirements set out in. \[6\] \[7\]

The basic conceptual aspects refer to:
- simplicity of the structure
- redundancy of the structure
- the geometry of the structure and of the building, in its entirety, considering the mode of distribution of structural, non-structural elements and masses
- lateral strength and rigidity, in any direction
- making the floors as horizontal diaphragms
- construction of adequate foundations

The seismic structural configuration has three main aspects, as presented in figure 2: 1 - geometry, shape and size of the building, 2 - location and size of structural elements, and 3 - location and size of significant non-structural elements.

Figure 1 – Collapsed buildings caused by earthquakes [5]
Based on the above, normally built buildings can be classified into two categories: simple and complex. A better structural behaviour is possible when the buildings have rectangular plans and straight elevation, because the seismic forces have a better distribution in structural elements. The complex buildings with setbacks and central openings have geometric constraints to the flow of inertia forces which implies an overloading of some of the structural elements.

In this context, the main purpose of this case study is to present the results after multiple analyses for the design calculus of the reinforced concrete multi-story irregular structure, in order to reduce or avoid the effects of the overall torsion. The object of the case study is a construction with a height of 30m located in the seismic area of Vrancea (figure 6) characterized by a maximum terrain acceleration of 0.40g and a corner period $T_c = 1.0 \text{s}$ [P100]. The building presented in figure 3 has a parallelepiped shape with dimensions in the horizontal plane of 37 by 10 m, which is. The sections of the structural elements were considered differently in 3 scenarios. The views of the structure are presented in figure 3.

The initial structural systems proposed were spatial frames. The first two stories have 4.5 m height each. The next floors are 3.5 m high. At one end of the structure a combined level of 9.0 m height is required, see figure 3.1. Therefore, between the formed frames, parabolic arches are introduced from zero level to + 9.00 m.
regarding the geometry of the building and the position of the core elevator and stairs presented in figure 4, led in the first stage to an inadequate structural behaviour. [8], [9]

![Diagram](image)

**Figure 4.** Structural model concept and scenario: 1 – the whole building; 2 – Scenario 1, structure with 50x50 cm columns section; 3 - Scenario 2, structure with 60x60 cm columns section; 4 - Scenario 3 with 60x60 columns section and structural walls at the ends

The materials were chosen respecting recommendation in the design rules considering the strength and elastic modulus. These are presented in table 1. All structural members have been designed considering dead and live loads for civil residential buildings. The structural analysis of reinforced concrete building structure with five stories was carried out by using Robot Structural Analysis 2020 software. [10] In table 2 and 3 are presented loads and combinations taking into consideration. Table 4 presents the section dimension for structural elements and the scenario considered.
Table 1. Materials

| Element   | Material | E (MPa) | Re (MPa) | Displacement evaluation stiffness reduction factor | Strength evaluation stiffness reduction factor |
|-----------|----------|---------|----------|--------------------------------------------------|-----------------------------------------------|
| Columns   | C35/45   | 27200   | 35       | 0,5E                                             | 0,8E                                          |
| Walls     | C35/45   | 27200   | 35       | 0,5E                                             | 0,8E                                          |
| Beams     | C35/45   | 20400   | 35       | 0,5E                                             | 0,6E                                          |
| Slabs     | C35/45   | 20400   | 35       | 0,5E                                             | 0,6E                                          |

Table 2. Loads and combinations

| Type                  | Standard       | Value (kN/m²) | Combination | Combination factor |
|-----------------------|----------------|---------------|-------------|-------------------|
| Self-weight           | SR EN 1991-1-1:2004 automated |              | ULS/ SLS/ ACC | 1,35/1,00/1,00    |
| Walls weight          | SR EN 1991-1-1:2004 automated |              | ULS/ SLS/ ACC | 1,35/1,00/1,00    |
| Permanent from floors | SR EN 1991-1-1:2004 | 3,5           | ULS/ SLS/ ACC | 1,35/1,00/1,00    |
| Imposed loads category A and C | SR EN 1991-1-1:2004 | 1,5 to 2,5 | ULS/ SLS/ ACC | 1,5/1,05/0,3      |
| Wind                  | CR-1-1-3/2012 | 0,6           | ULS/ SLS     | 1,5/0,6           |
| Snow                  | CR-1-1-4/2012 | 2,0           | ULS/ SLS/ ACC | 1,5/1,00/0,2      |

Table 3. Seismic design characteristics

| Earthquake | Importance class | Importance category | Behaviour factor (q) | Acceleration (ag) | Control period Tc/Tb/TD (s) | Damping (%) |
|------------|------------------|---------------------|----------------------|-------------------|-----------------------------|-------------|
| P100-1/2013 | III              | C                   | D.C.H. 4,5           | 0,40g             | 1.0/0.20/3.00               | 5           |

Table 4. Structural analysis scenarios

| Structural elements | Scenarios |
|---------------------|-----------|
| Columns             | S1        |
|                     | 50x50cm   |
|                     | 60x60cm   |
|                     | 60x60cm   |
| Beams               | S2        |
|                     | 30x50cm   |
|                     | 30x50cm   |
|                     | 30x50cm   |
|                     | 30x70cm   |
|                     | 30x70cm   |
|                     | 30x70cm   |
| Slabs               | S3        |
|                     | 13cm      |
|                     | 13cm      |
|                     | 13cm      |
| Shear Walls         | NA        |
|                     | NA        |
|                     | 20cm      |
By using the finite element model of asymmetric multi-story reinforced concrete building, the torsional effects are rapidly identified for such type of structure. In seismic areas with high value of peak ground accelerations similar for the present case an optimum vibration of translation in the first two modes of vibration is a demand. In figure 5 and 6 is presented the location of the building site with the peak ground acceleration $a_g$ for design and the control period $T_c$.

**Figure 5.** Romania map - Zoning of peak ground acceleration $a_g$ for design with Mean Recurrence Interval - MRI = 225 years and 20% probability of overtaking in 50 years [6]

**Figure 6.** Romania map – distribution in terms of the control period (corner), $T_c$ of the response spectrum [6]

Obtaining a simple, compact structure, as symmetrical as possible, is the most important objective of the design, because the modelling, calculation, sizing, detailing and execution of simple structures are subject to much lower uncertainties and, therefore, can be imposed on the construction, with a high degree of confidence, the desired seismic behaviour. Since the horizontal action of earthquakes is manifested bidirectionally, the structural elements will be arranged in such geometrical configuration, able to provide sufficient strength and rigidity characteristics in two directions. Structural systems can be different for both directions. In order to fulfil the objectives recommended in the design norms, several scenarios for the distribution of the structural elements were verified. [11], [12], [13]

Open ground story RC frame buildings are common worldwide; they are the dominant set of urban buildings today. The poor performances of such buildings were known from almost a century ago. But there must be compelling reasons (e.g., aesthetics and functionality) other than safety that continues to push the construction of such buildings even today. When glass is used for facades instead of an infill material like brick masonry to the ground story for aesthetics, the building becomes weak in that story. This happens commonly in buildings containing shopping areas and restaurants in their ground story. [14]

### 3. Results and discussion

In table 5 and 6, the modal mass participating ratios are given for the first six vibrations modes. The deformed shape and modes of vibration of structures analysed structures are shown in figure 7. In the first two scenarios it can be observed that the fundamental period is greater than the control period (1.12s and 1.08s), also in the second mode of vibration the period is near to the control period: this means that is a highly risk possibility for a resonance phenomenon to occur. The reason is that the structure is too flexible. The influence of mass participation and the distribution in the first two modes shows the torsional – translational modes. Also, the deformed shape confirms that.
Table 5. Dynamics characteristics of the structural models considered in the first three modes

| Mode of vibration | Mode 1 | Mode 2 | Mode 3 |
|-------------------|--------|--------|--------|
| Scenario          | S1     | S2     | S3     | S1     | S2     | S3     | S1     | S2     | S3     |
| Frequency (Hz)     | 0.89   | 0.93   | 1.27   | 1.04   | 1.09   | 1.75   | 1.23   | 1.29   | 2.57   |
| Period (sec)       | 1.12   | 1.08   | 0.79   | 0.96   | 0.92   | 0.57   | 0.81   | 0.78   | 0.39   |
| UX (%)             | 36.8   | 38.04  | 0.01   | 35.7   | 34.46  | 75.77  | 0      | 0      | 0.07   |
| Cur. mas.          | 0.2    | 0.24   | 75.52  | 0.25   | 0.26   | 0.01   | 74.81  | 74.92  | 0.01   |

Table 6. Dynamics characteristics of the structural models considered in the first three modes

| Shape mode        | Mode 4 | Mode 5 | Mode 6 |
|-------------------|--------|--------|--------|
| Scenario          | S1     | S2     | S3     | S1     | S2     | S3     | S1     | S2     | S3     |
| Frequency (Hz)     | 2.8    | 3.02   | 4.22   | 3.57   | 3.7    | 4.99   | 4.13   | 4.27   | 7.33   |
| Period (sec)       | 0.36   | 0.33   | 0.24   | 0.28   | 0.27   | 0.20   | 0.24   | 0.23   | 0.14   |
| UX (%)             | 4.29   | 4.79   | 0.06   | 9.6    | 9.44   | 13.07  | 0.01   | 0.01   | 0      |
| Cur. mas.          | 0.03   | 0.03   | 15.71  | 0.04   | 0.04   | 0.09   | 16.19  | 15.99  | 0.01   |

Figure 7. Comparison between frequency and period for the first mode considered
Figure 8. Comparison between mass participation in X direction for the first two modes

Figure 9. Comparison between mass participation in Y direction for the first two modes

Figure 10. Comparison between seismic base shear distribution on each story
In the next section figures 14 to 16 presents the deformed shapes of the structure obtained in model analysis.
1st mode – torsional – translational X, T=1.12s
2nd mode – torsional translational X, T=0.96s
3rd mode – translational Y, T=0.78s

**Figure 14.** Deformed shape of the structure in case scenario 1

1st mode – torsional – translational X, T=1.08s
2nd mode – torsional translational X, T=0.92s
3rd mode – translational Y, T=0.78s

**Figure 15.** Deformed shape of the structure in case scenario 2

1st mode – translational Y, T=0.79s
2nd mode – translational X, T=0.57s
3rd mode – torsional, T=0.39s

**Figure 16.** Deformed shape of the structure in case scenario 2
After comparing the results of the analyses, it can be observed that the considering the elevator core and the stairs, there are substantially influences on the dynamic behaviour of the structure. The appearance of torsional vibration modes in the first two modes is caused by nonsymmetric of the distribution of structural elements in the building plan such as stairs and elevator.

The introduction of structural walls at the ends of the construction balances the structural stiffness and the first two modes are translational with a participation of almost 75% of the modal mass. This confers a greater stiffness to the structure: the structure is stiffer in Scenario 3 by 30% compared to Scenario 1 and by 27% compared to Scenario 2. Also, the distribution of seismic forces depends on the presence of structural walls, almost 70% of the seismic force on each level is taken up by the walls. At the same time, the seismic shear force has an increase of 38% in the X direction (transversal). On the other hand, the configuration in scenario 3 changes the oscillation direction of the structure in longitudinal translation movement, which in the case of the existence of an adjacent building on the transverse direction would influence the size of the seismic joint.

The maximum absolute displacement in X direction (transversal) in Scenario 1 and 2 are bigger with 417% than the structure modelled in Scenario 3. In Y direction (longitudinal), the maximum absolute displacements have close values. In terms of relative displacements in Scenario 3 is an increasing with 25% from 0.6 to 0.8 cm.

4. Conclusions
All buildings are working as vertical cantilevers fixed at the base in terrain. When the earthquakes occur, these structures experience whiplash effects, particularly when the shaking is larger. Buildings designed to be earthquake-resistant have challenging demands. Firstly, buildings become expensive, if they are designed to be indestructible. These must be strong enough to not sustain any structural damage during weak earthquake shaking. Also, they should be stiff enough not to swing too much, even during weak earthquakes. Most important, they should not collapse during the expected strong earthquake shaking to be sustained by them even with significant structural damage. There are two-levels seismic design established explicitly with the two following requirements: [2], [7], [15]

- No-collapse requirement: The structure shall be designed and constructed to withstand the design seismic action without local or global collapse, thus retaining its structural integrity and a residual load bearing capacity after the seismic event.
- Damage limitation requirement: The structure shall be designed and constructed to withstand a seismic action having a larger probability of occurrence than the design seismic action, without the occurrence of damage and the associated limitations of use, the costs of which would be disproportionately high in comparison with the costs of the structure itself.

For real structures a simple configuration is desirable where the first two modes are translational, and the third mode is the torsional mode. When the first mode of vibration is torsional, an unbalanced distribution of seismic forces could occur, which can amplify the stress in certain areas of the structure, especially when subjected to strong earthquakes.
The studied case of a real structure located in the maximum peak ground acceleration area of Romania shows that if there are not taking into consideration correctly the geometry and all the structural components of the building some errors can occur. The modal analysis shows the seismic behaviour so the structure can be rapidly optimized. The asymmetry of the structure and the members distribution led to a problematic behaviour with torsional modes of vibration in the first two modes. Also, the dynamic characteristics of the structure have close values to control period of the terrain which in a probability of an earthquake the resonance phenomenon can occur. These problems can be amended during the design process. To avoid a high level of damage of the structure, there is necessary an optimum design of the structure related to technological demands and financial costs. The solution to introduce new structural elements such as walls on the transversal ends of the building is an acceptable alternative.

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