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DIFFERENTIATION OF THE CONSTRUCTION COST OF A FIFTEEN-STOREY R/C BUILDING DEPENDING ON THE SEISMIC HAZARD ZONE

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Abstract

Greece is divided into three seismic hazard zones ZI, ZII, ZIII. In the present research work, the same building in the three seismic zones of Greece is modeled, analysed and dimensioned and then the construction cost of its structural body is estimated. The building modeling was performed in SAP2000 using linear finite elements. The analysis of the building was performed by dynamic spectral analysis methods using the design spectrum of EC8. A fifteen-storey building with a standard floor plan per floor was used. The purpose of this research paper is to study the possible influence of seismicity, based on which the dimensioning takes place, on the construction cost of the load-bearing structure of a fifteen-storey building with a standard floor plan per floor. The degree of influence is studied by estimating the quantities of materials required depending on the seismic hazard zone. Interesting comparisons take place between the results for the three different seismic hazard zones. Useful conclusions are drawn regarding the influence of seismicity on the construction cost of the load-bearing structure of reinforced concrete buildings.

Keywords: Seismic zone, Construction cost, Multi-storey building

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1 INTRODUCTION

Greece ranks sixth in the world in the list of most seismic countries. Although it occupies 0.02 of the Earth's surface, it releases 2% of global seismic energy each year and more than 50% of the European. Therefore, Greece is challenged to face earthquake phenomenon by improving the construction of structures, taking under consideration the parameters of safety and cost. According to those factors, the earthquake resistant regulations have been evolved worldwide [1]–[3], facing with great effectiveness the safety of human life. In the seismic design of reinforced concrete structures, a key parameter is the seismic design actions, based on which the structures in each area are designed (Table 1).

The seismic design actions of the structures depend on the seismic hazard of each area and their values are determined in the Seismic Hazard Map, which is an integral part of the Earthquake Regulation [2], [3]. Seismic hazard is the maximum expected value of a seismic parameter for a given recurrence period or for a specific probability of non-overcoming and a specific period of time. The results of seismic hazard studies are given in the form of maps or curves that provide the distribution of the selected ground motion measure and the probability that it will be exceeded or not exceeded in a certain period of time (Figure 1). Usually, the probability of distribution is estimated by 10% of excessing a defined value of land movement for the time period of 50 years or equal, an average repetition of 475 years.

The expected values of the ground acceleration are derived from seismic hazard studies, after statistical processing of seismic events that have occurred in the wider project area. Such studies are prepared for large and important projects, while for ordinary constructions the prices are given by the regulations, depending on the area in which the construction is going to take place. According to EC8 [2] and Greek Seismic Code [3], national areas are subdivided into seismic zones (Z1, Z2 and Z3) depending on the local hazard (Figure 1). By definition, it is assumed that within each zone the hazard is constant and is described by a single parameter, the value of the maximum reference ground acceleration $\alpha_g R$, which corresponds to soil category "A" and characterizes the seismic activity in each zone. Considering the above, the present work aims to investigate whether the design and study of a building in each seismic zone, can affect the cost of construction of its load-bearing structure. Several studies have been conducted regarding the cost, as far as various types of structures are concerned [4]–[10]. This study aims to investigate the cost in terms of the construction cost of load-bearing structure of multi-storey buildings and if and how it is affected by the seismicity of the area.

Zone of seismic risk	Ground acceleration values (g)
Z1	0,16
Z2	0,24
Z3	0,36

Table 1: Ground acceleration values [3].

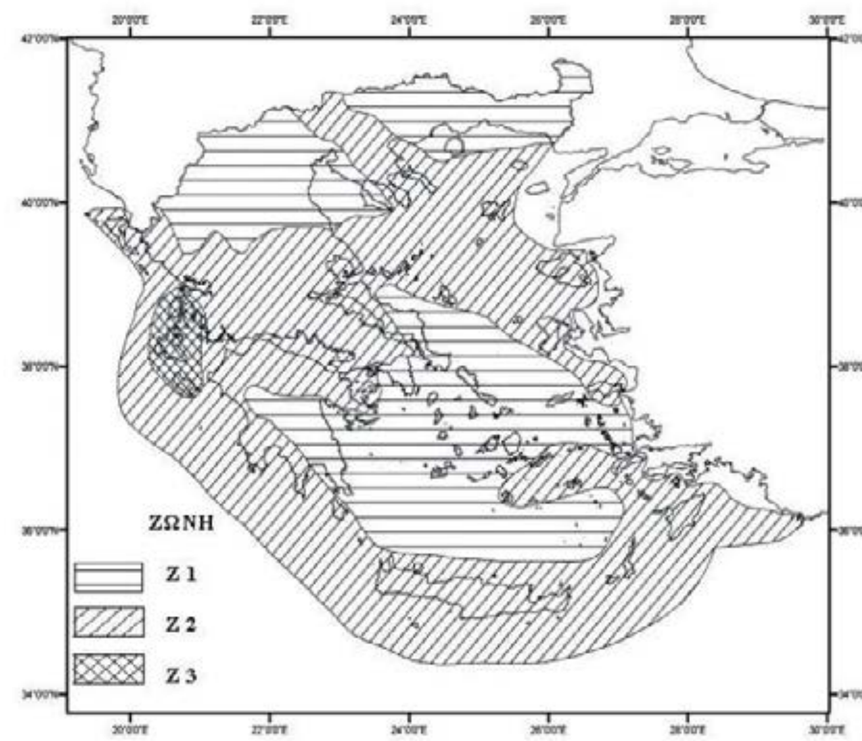


Figure 1: Seismic hazard map of Greece [3].

2 ANALYTICAL RESEARCH

2.1 Building data

The building under consideration is symmetrical, with a rectangular floor plan with dimensions of 25 x 25 m, slab thickness equal to 15 cm, total height 46.50 m (all floors are 3 m, except the 1^{st} floor which has a height equal to 4.5 m) and will not include basement. The influence of the soil is neglected and rigid connections are used for the building's supports [11]–[16]. In the center of the floor plan, there are two symmetrical cores consisting of 8 walls with different dimensions (6 along the Y axis and 2 along the X axis), which are connected by three beams 1m long and 0.70 m high. Also, there are two walls in the perimeter of the floor plan along the Y axis, which have enlarged boundary edges at their both ends (Figure 2), in order for phenomena of lateral buckling at seismic walls to be avoided [17]–[31].

Regarding the dimensions of the cross-sections of the structural elements, the cross-sections of the columns of the building remain constant for the 1st floor (ground floor) and the 2nd, while the rest are reduced by 5 cm per floor. The cross-sections of the beams remain fixed on all floors, while the cross-sections of the walls vary in height and are reduced per 5 floors by 12.5 cm. The construction materials of the building are concrete C30/37 and steel B500C. The cross sections of the beams remain the same in every storey but the cross sections of the walls shift per floor and decrease per 5 storeys for 12.5 cm. The construction materials of the building, is C30/37 concrete and Steel B500C. Finally, below are presented the floor plan and the table of cross sections of the structural elements of the building.

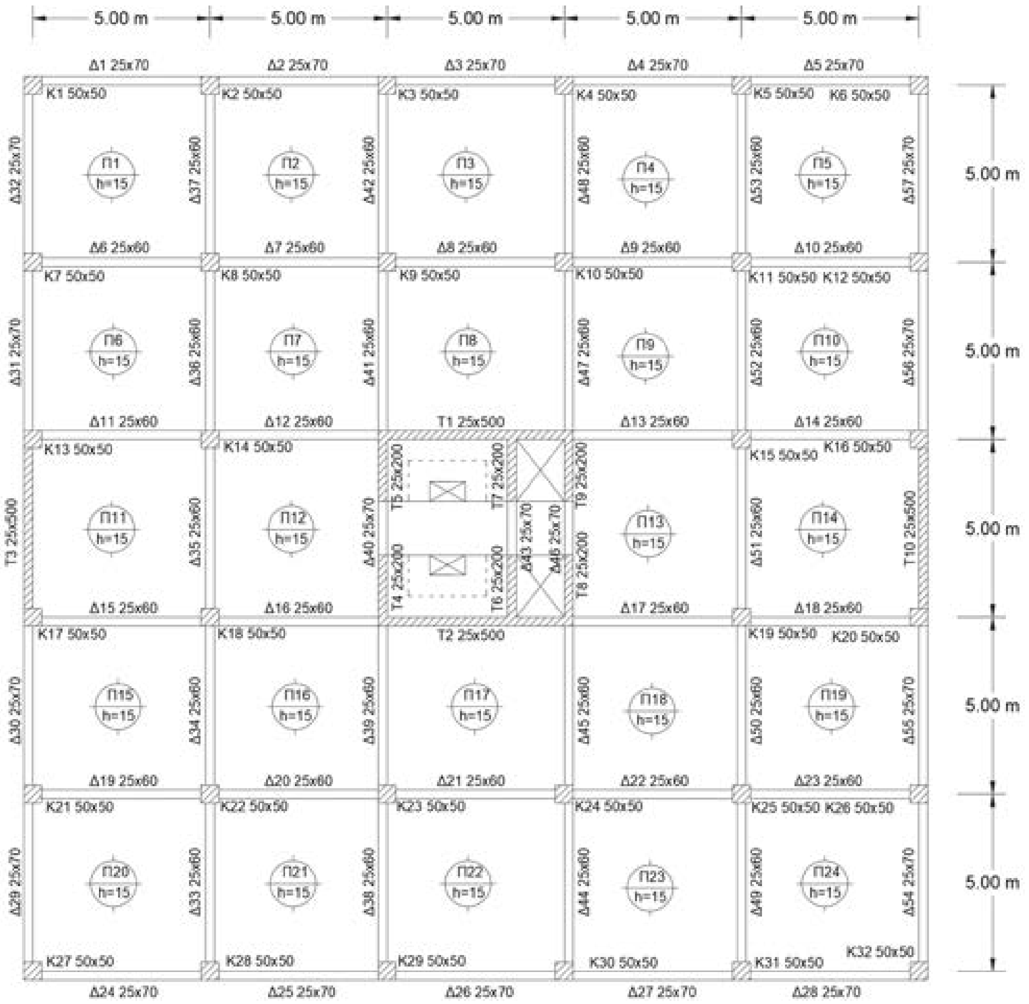


Figure 2: Typical floor plan.

Floor	Height (m)	Beam dimensions (cm)		Wall thickness (cm)	Column dimensions (cm)
		Perimetric	Internal		
1st (Ground floor)	4.50	25x70	25x60	50	100x100
2	3.00	25x70	25x60	50	100x100
3	3.00	25x70	25x60	50	95x95
4	3.00	25x70	25x60	50	90x90
5	3.00	25x70	25x60	50	85x85
6	3.00	25x70	25x60	37.5	80x80
7	3.00	25x70	25x60	37.5	75x75
8	3.00	25x70	25x60	37.5	70x70
9	3.00	25x70	25x60	37.5	65x65
10	3.00	25x70	25x60	37.5	60x60
11	3.00	25x70	25x60	25	55x55
12	3.00	25x70	25x60	25	50x50
13	3.00	25x70	25x60	25	45x45
14	3.00	25x70	25x60	25	40x40
15	3.00	25x70	25x60	25	35x35

Table 2: Dimensions of the structural elements.

2.2 Construction

The building, as a typical construction, is stressed by gravity loads which are the permanent loads (self-weight, etc.), the live loads (human load, etc.) and the seismic loads. For the building in question, the loads are shown in Table 3.

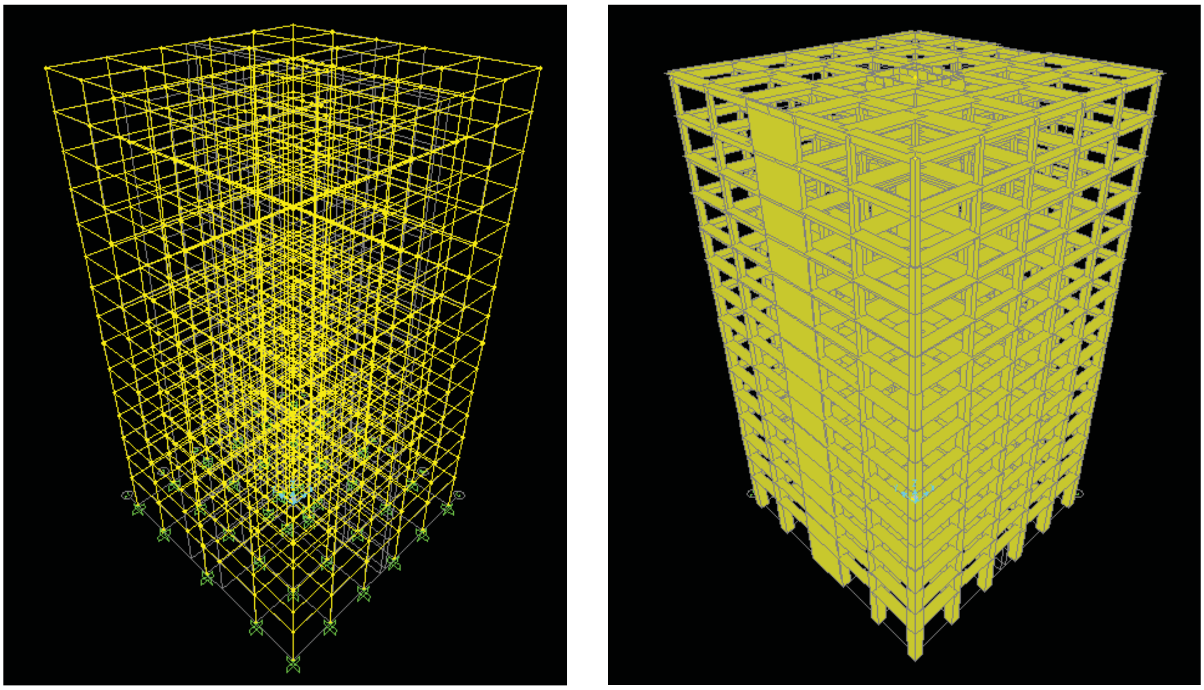
PERMANENT LOADS		
N/A	**Type**	**Value**
1	Flooring	1.40 kN/m^2
2	Partition brick structures	1.00 kN/m^2
3	Perimeter brick structures	8.00 kN/m
4	Roofing	3.50 kN/m^2
5	Parapet roof load	3.60 kN/m^2
LIVE LOADS		
N/A	**Type**	**Value**
1	Ground floor	2.00 kN/m^2
2	Typical floors	2.00 kN/m^2
3	Roof	2.00 kN/m^2
SPECTRUM DATA EC8		
N/A	**Type**	**Data**
1	Spectrum type	Horizontal design spectrum type 1
2	Soil category	B
3	Factor β	0.20
4	Seismic acceleration factor α	For the three categories: α =0.16, 0.24, 0.36
5	Gravity acceleration g	9.81 m/sec^2
6	Coefficient behavior q	Calculation based on EC8

Table 3: Building loads.

2.3 Modelling

The modeling of the load-bearing structure of the building will be performed with the finite element software SAP2000. The individual structural elements that were modeled are the beams, the columns and the seismic walls of the building. Also, it is essential to simulate the diaphragm function of the slabs on each floor. The dynamic spectral method analysis according to the EC8 [2] will be applied for the seismic actions of the building.

In conclusion, through the simulation some results will be extracted according to which the building will be dimensioned for the three seismic hazard zones and these are the design moments of the beams, the values for N, M_{33}, M_{22} of the vertical elements. Figure 3 presents the 3D model of the building.



(a) (b)

Figure 3: Views of the 3D building model: (a) Linear finite elements (b) Sections.

2.4 Dimensioning of the building

The dimensioning of the building will be based on EC8 [2] and EC2 [32], for each seismic hazard zone only for the 14th floor level. The horizontal structural members dimensioned are the slabs of the 14th floor and the beams of this level, while the vertical structural members are the columns and the structural walls. Figure 4 and Figure 5 present indicative reinforcement of the beam and the slab respectively resulted by the building design.

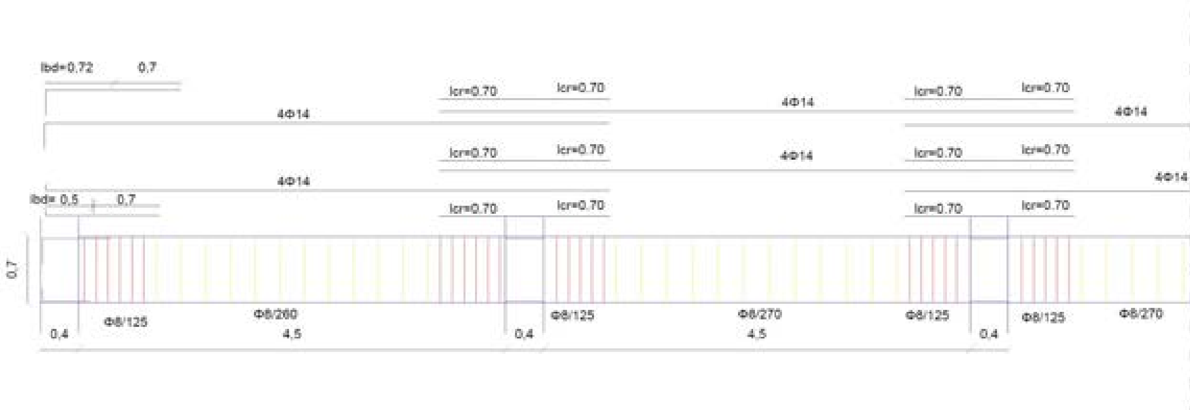


Figure 4: Beam reinforcement of the 14th floor.

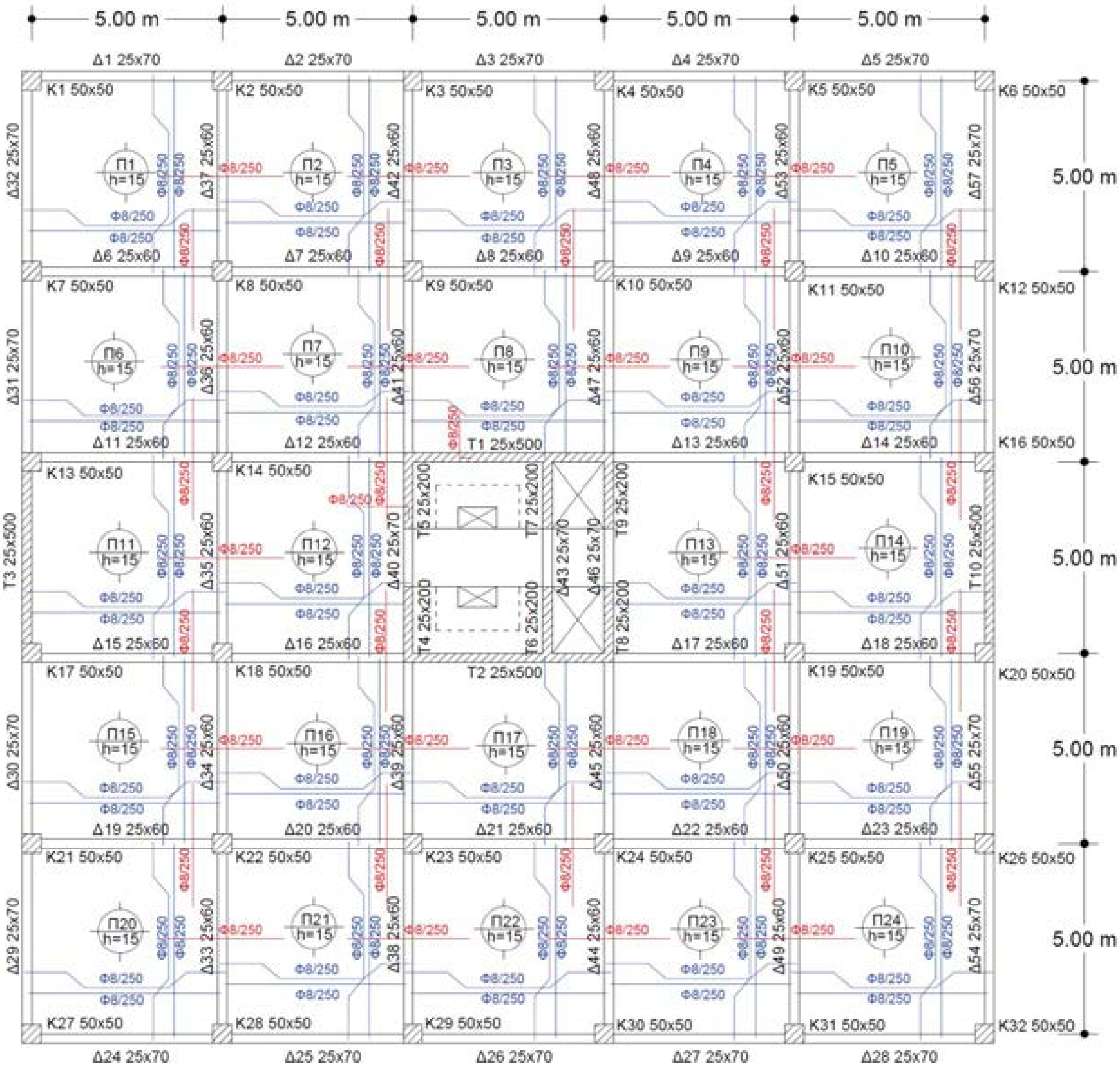


Figure 5: Slab reinforcement of the 14th floor.

2.5 Measurements of building materials

The measurement of building materials used for the construction of the load-bearing structure (concrete and steel) for all three seismic zones will be calculated considering the results of the design. Table 4 displays the measurements for the concrete material, which remain the same for all three seismic zones. Similar calculations have taken place for the measurement of the steel material used for the concrete reinforcements.

CONCRETE MEASUREMENT					
STOREY	SLABS (m^3)	BEAMS (m^3)	COLUMNS (m^3)	WALLS (m^3)	TOTAL (STOREY) (m^3)
1	90	33.08	139.2	63.08	325.36
2	90	33.08	91.20	41.33	255.61
3	90	33.92	82.31	41.61	247.84
4	90	34.72	73.87	41.90	240.49
5	90	35.55	65.89	42.18	233.62
6	90	36.35	58.37	31.85	216.57
7	90	37.19	51.30	32.06	210.55
8	90	37.99	44.69	32.28	204.96
9	90	38.82	38.53	32.49	199.84
10	90	39.62	32.83	32.70	195.15
11	90	40.46	27.59	21.95	180.00
12	90	41.26	22.80	22.09	176.15
13	90	42.09	18.47	22.23	172.79
14	90	42.89	14.59	22.37	169.85
15	90	43.69	11.17	22.52	167.38
				TOTAL	**3196.16**

Table 4: Concrete measurement.

3 RESULTS ANALYSIS

3.1 Concrete measurements

Figure 6 shows the amount of concrete per floor and Figure 7 displays the amount of concrete occupied by the structural elements of the load-bearing structure.

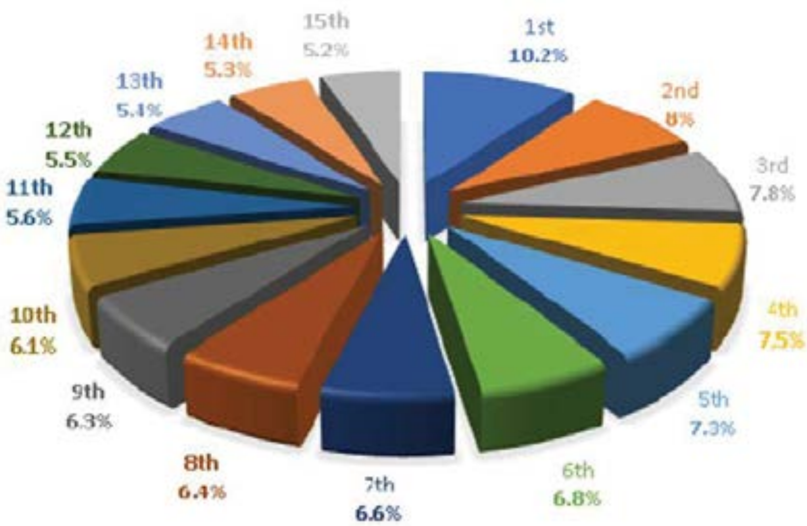


Figure 6: Percentage of concrete per floor (%).

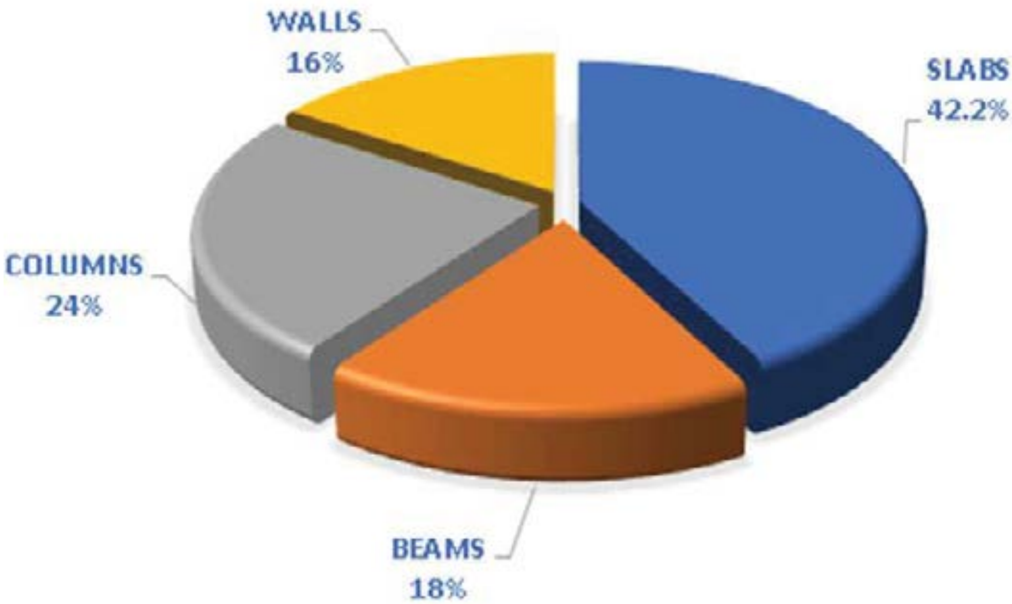


Figure 7: Percentage of structural elements in the total concrete (%).

From the previous diagrams, it is obvious that the 1st floor occupies the largest percentage of concrete in relation to the other floors, while at the same time the percentage of the other floors decreases from floor to floor. Also, the slabs occupy the largest percentage of the total concrete with 42.2%, followed by the columns with 24%, the beams with 18% and finally the walls with 16%.

3.2 Steel measurements

3.2.1. Steel measurement per seismic zone

Table 5 presents the quantities of steel in kgr that result for the structural elements of the building, in each seismic zone. The same results are displayed in the form of a column graph in Figure 8.

REINFORCEMENT STEEL MEASUREMENT					
Seismic zone	**Slabs**	**Beams**	**Columns**	**Walls**	**TOTAL**
I	9214.32	6353.50	2615.83	2826.53	**21010.18**
II	9214.32	6416.78	2623.71	3019.44	**21274.25**
III	9214.32	6455.03	2631.59	3261.77	**21562.71**

Table 5: Structural element steel weight for the three seismic zones.

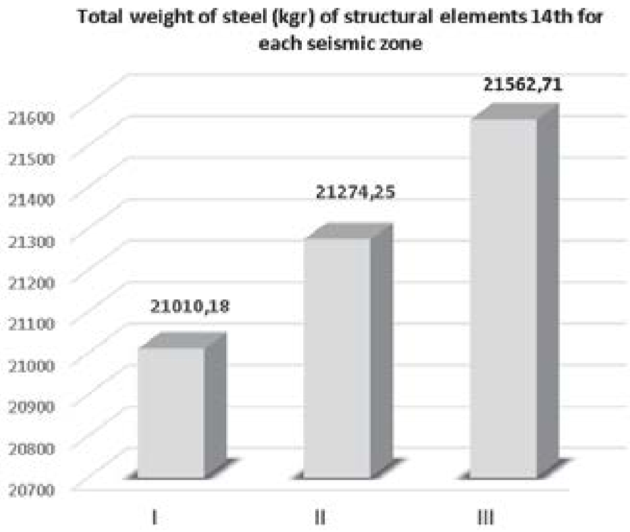


Figure 8: Total weight of reinforcement steel of structural elements of the 14th floor for each seismic zone.

3.2.2. Percentage change of steel weight between the seismic zones

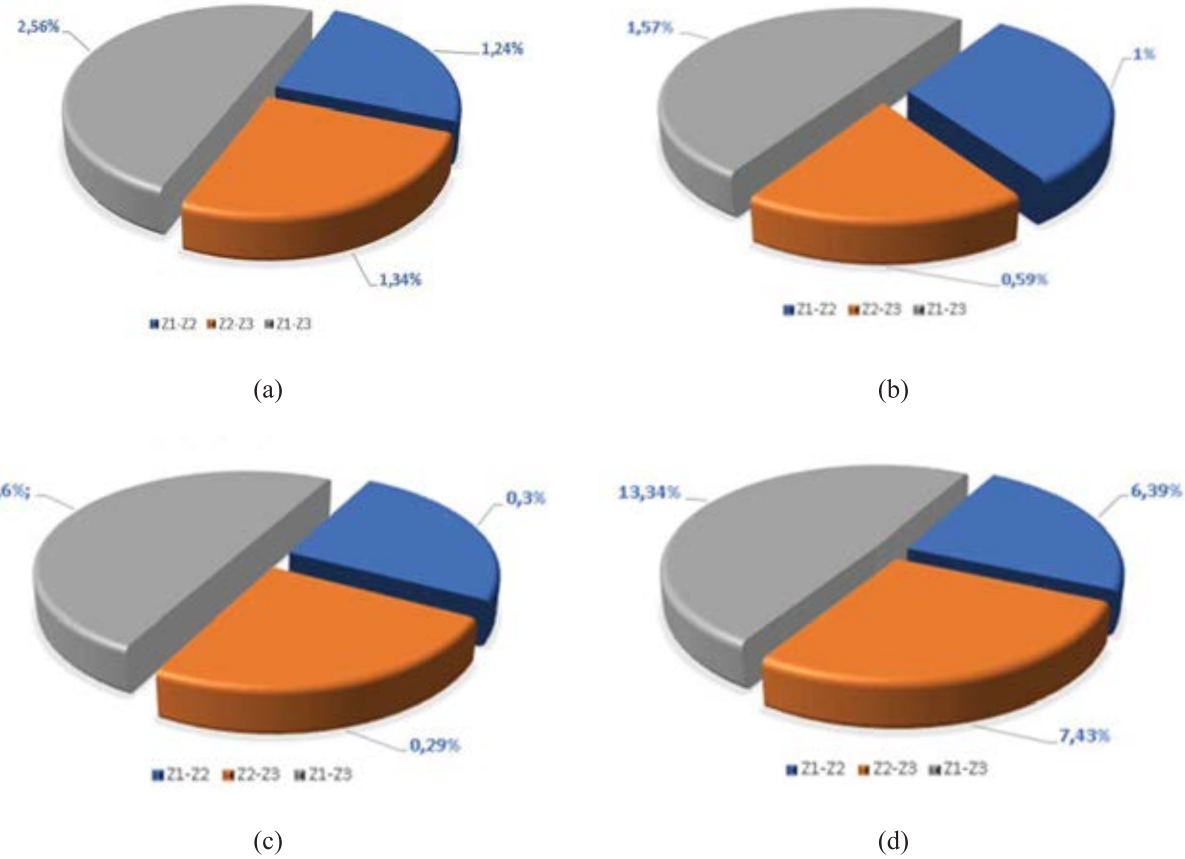


Figure 9: Percentage change of weight of steel reinforcement of the 14th floor for each seismic zone concerning: (a) All structural elements, (b) Beams, (c) Columns, (d) Seismic walls

From Figure 9, it appears that:

• The transition from Zone I with seismic acceleration $\alpha_g = 0.16g$, to Zone II with seismic acceleration $\alpha_g = 0.24g$ causes:

- 1.24% increase of the total steel weight for all structural elements
- 1.00% increase of the steel weight for the beams
- 0.3% increase of the steel weight for the columns
- 6.39% increase of the steel weight for the structural walls

• The transition from Zone II with seismic acceleration $\alpha_g = 0.24g$, to Zone III with seismic acceleration $\alpha_g = 0.36g$ causes:

- 1.34% increase of the total steel weight for all structural elements
- 0.59% increase of the steel weight for the beams
- 0.29% increase of the steel weight for the columns
- 7.43% increase of the steel weight for the structural walls

• The transition from Zone I with seismic acceleration $\alpha_g = 0.16g$, to Zone II with seismic acceleration $\alpha_g = 0.36g$ causes:

- 2.56% increase of the total steel weight for all structural elements
- 1.57% increase of the steel weight for the beams
- 0.60% increase of the steel weight for the columns
- 13.34% increase of the steel weight for the structural walls

Therefore, if the weight percentage of the individual structural elements of the structure (columns, beams and structural walls) increases from Zone I to Zone II and Zone III, except for the steel weight for the slabs that remains constant in the three seismic zones, that fact results to the increase of the total steel weight of the 14th floor.

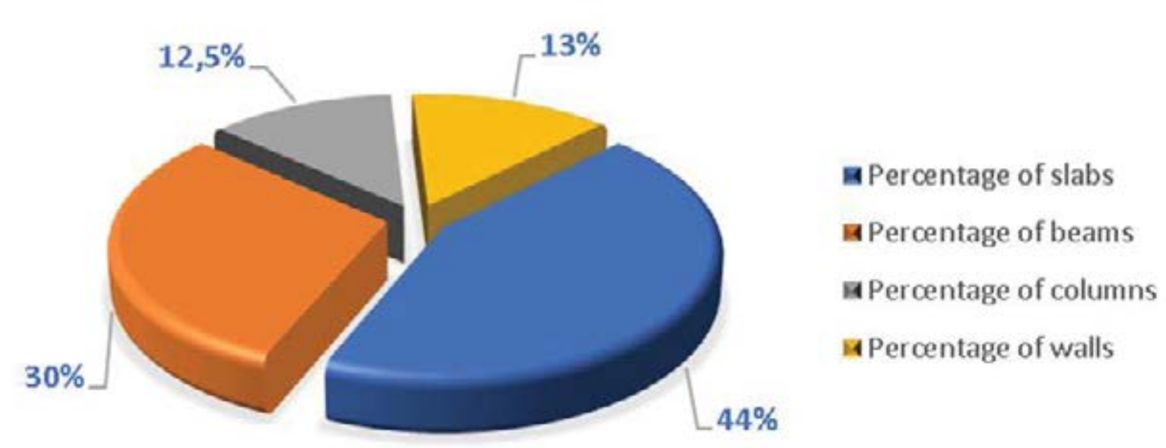
3.2.3. Percentage of reinforcement steel per structural element for each seismic zone

Figure 10 shows the percentage of steel weight of each structural element in all three seismic zones. According to these figure, it is concluded that:

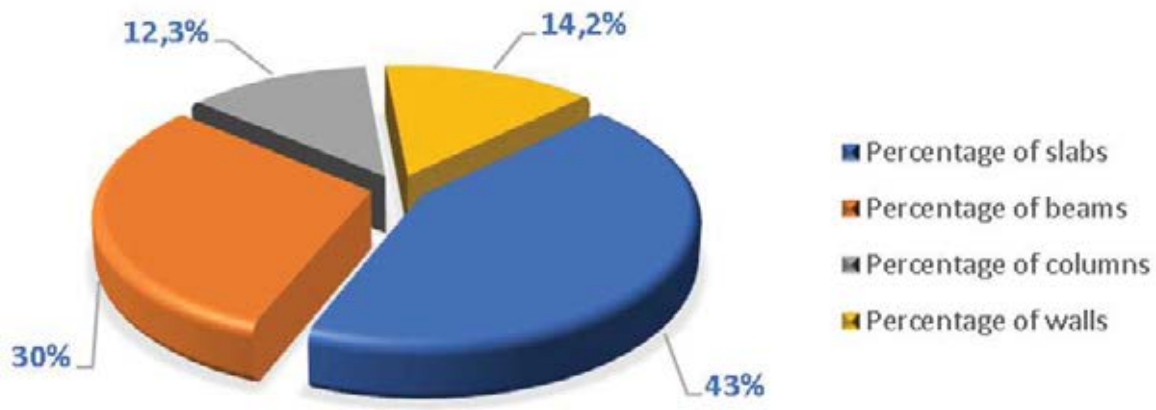
- Slabs occupy the largest percentage of steel in Zone I: 44%, while in Zone II: 43% and in Zone III: 42.7%.
- Beams occupy the second largest percentage of steel in Zone I: 30%, while in Zone II: 30% and in Zone III: 29%.
- Structural walls occupy the third largest percentage of steel in Zone I: 13%, while in Zone II: 14.2% and in Zone III: 15.1%.
- Columns occupy the smallest percentage of steel in Zone I: 12.5%, while in Zone II: 12.3% and in Zone III: 12.2%.

Furthermore, the design and detailing of the various structural elements has shown that during the transition from Zone I to Zone II and II:

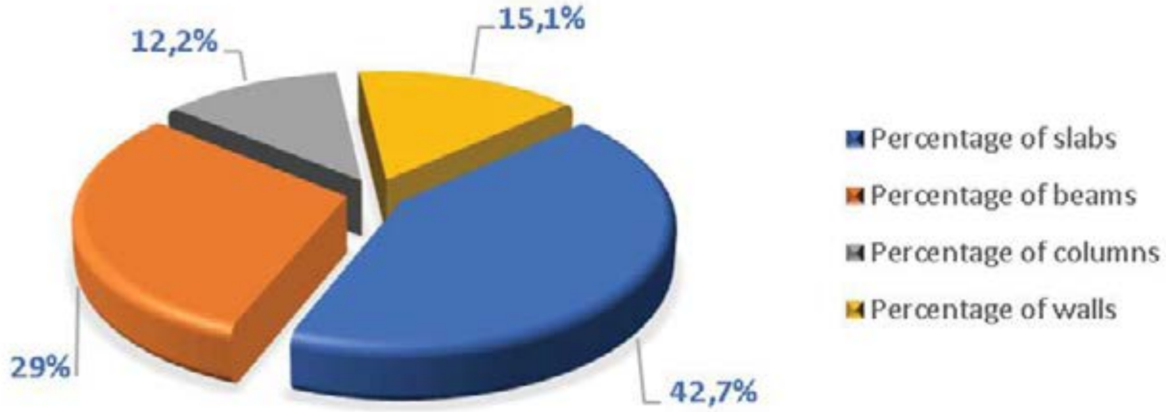
- The beams maintain their longitudinal reinforcement constant, while the transverse reinforcement shows some increase.
- The columns also maintain their longitudinal reinforcement stable, while the transverse reinforcement shows some increase.
- Finally, the structural walls show an increase in their transverse reinforcement and the T3 and T10 structural walls (Figure 5) also show increases in their longitudinal reinforcement.



(a)



(b)



(c)

Figure 10: Percentage of steel weight per structural element for: (a) Zone I, (b) Zone II, (c) Zone III.

4 CONCLUSIONS

The structure studied in the present research is a fifteen-storey reinforced concrete building without a basement with rectangular conventional floor plan. It has been designed for all three seismic hazard zones Zone I, Zone II and Zone III. The resulting conclusions can be summarized as follows:

1. Walls show the largest percentage increase in steel weight with the increase of seismic acceleration.
2. At the beams, the steel weight increases much less than in seismic walls.
3. At the columns, the steel weight increases even less than the beams.
4. Therefore, the seismic walls are the dominant structural element in the building's system. Thus, it is a wall-governed system.
5. The increase of seismic acceleration α_g:
   - From Zone I to Zone II is about 50%, while the percentage increase of the total amount of materials is only 1.24%.
   - From Zone II to Zone III is about 50%, while the percentage increase of the total amount of materials is only 1.34%.
   - From Zone I to Zone III is about 125%, while the percentage increase of the total amount of materials is only 2.56%.
6. Thus, the percentage increase in the total demand on steel is quite small.
7. So, we conclude that for a fifteen-storey reinforced concrete building, with a strong core wall arrangement, the influence of seismic hazard on the construction cost of the load-bearing system should not be significant because the percentage increase of materials required is much smaller than the large percentage increases of the respective seismic accelerations.

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