Does the design according to the seismic zone affect the environment and the manufacturing cost of a 5-storey R/C building with a conventional plan?

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Abstract. The main scope of the present research is the analysis, dimensioning and estimation of the cost of a five-storey reinforced concrete building, which is similarly constructed in three different seismic hazard zones (ZI, ZII, ZIII). The ground plan of the building is a conventional floor plan with solid reinforced concrete slabs. The cross-sections of the structural members remain stable, except for the columns whose cross-sections are reduced in height. The aim of the present study is to analyze how the cost of manufacturing the load-bearing structure of a reinforced concrete building is affected by the seismic risk of the area, if that influence is significant and in what extent. Moreover, along with the construction cost, the possible influence to the environment is studied, too.

1. Introduction
It is world-wide accepted that a multi-storey reinforced concrete (R/C) building should be adequate against all types of loads [1,2]. Special provisions are considered for seismic actions in the relevant codes and regulations. These provisions have to do, among other things, with the seismic hazard zone that each structure should be designed in. Usually, the relevant regulations like, e.g., EC8 [3] or the Greek Seismic Code 2000 [4], etc. include specific maps showing each region in which seismic zone belongs to. According to these maps, the consulting engineer chooses the seismic zone that the building belongs to and designs it accordingly to the earthquake action provided for the seismic zone in question. Having said that, it is noteworthy to be said that the engineer can choose a higher seismic zone if he wishes to for reasons of extra safety. Of course, such an action by the engineer has an effect to the construction cost, too apart from the safety [5–12]. In that case, other phenomena have to be taken into account to, e.g., the lateral buckling of R/C walls, etc. [13–25]. The present study investigates the influence to the construction cost of the load-bearing structure of a ten-storey building when moving from one seismic zone to a higher one and, thus, the influence to the environment, too. Useful conclusions arise from the present research which could be proven helpful to practice engineers world-wide. The codes used are Eurocode 2 (EC2) [26] for the design of concrete and Eurocode 8 (EC8) [3] for the earthquake loads.
2. Structure description

This study concerns a five-storey building without a basement. It has a rectangular plan 25 x 25 m with a total floor plan area of \( E = 625 \text{ m}^2 \). There are two walls at the perimeter of the floor plan and in the centre, there is the staircase and the elevator surrounded by eight walls, forming two symmetrical cores. The height of each floor is 3.0 m except for the ground floor which is 4.5 m and the dimensions of the columns change in height and are reduced per floor by 5 cm. Also, the thickness of the walls changes in height and reduces per five floors by 12.5 cm. Table 1 displays the geometrical characteristics for all structural elements and for all floors of the building, while Figure 1 displays the floor plan. The concrete used is quality C30/37 and according to EC2 [26] its modulus of elasticity is equal to \( E_{cm} = 33 \text{ GPa} \) while the steel quality is B500C. SAP2000 software is used for the building modelling. Figure 2 displays the model of the building.

| Floor | Height (m) | Beam dimensions (cm) | Wall thickness (cm) | Columns (cm) |
|-------|------------|----------------------|---------------------|--------------|
|       |            | Perimetric           | Internal            |              |
| 1st (Ground) | 4.5        | 25 x 70              | 25 x 60             | 25           | 50 x 50       |
| 2nd   | 3.0        | 25 x 70              | 25 x 60             | 25           | 50 x 50       |
| 3rd   | 3.0        | 25 x 70              | 25 x 60             | 25           | 45 x 45       |
| 4th   | 3.0        | 25 x 70              | 25 x 60             | 25           | 40 x 40       |
| 5th   | 3.0        | 25 x 70              | 25 x 60             | 25           | 35 x 35       |

Figure 1. Building’s floor plan.
3. Analysis of results

Table 2 presents the concrete measurements and Table 3 display the measurement results for reinforcement steel material.

**Table 2.** Measurements of concrete for all floors.

| Floor | Slabs (m$^3$) | Beams (m$^3$) | Columns (m$^3$) | Walls (m$^3$) | Total (m$^3$) |
|-------|---------------|---------------|-----------------|---------------|---------------|
| 1$^{st}$ | 89.95 | 29.78 | 30.45 | 36.98 | 187.15 |
| 2$^{nd}$ | 89.95 | 29.78 | 19.95 | 24.23 | 163.91 |
| 3$^{rd}$ | 89.95 | 30.10 | 16.16 | 23.83 | 160.04 |
| 4$^{th}$ | 89.95 | 30.77 | 12.77 | 23.48 | 156.97 |
| 5$^{th}$ | 89.95 | 31.09 | 9.78 | 23.20 | 154.02 |
| **Total** | **822.08** | | | | |

**Table 3.** Measurements of reinforcement steel for ground floor for the three seismic zones.

| Zone | Slabs (kgr) | Beams (kgr) | Columns (kgr) | Walls (kgr) | Total (kgr) |
|------|-------------|-------------|---------------|-------------|-------------|
| I    | 5823.19     | 4414.38     | 4443.61       | 4000.64     | 18681.82    |
| II   | 5823.19     | 4501.34     | 4366.76       | 5796.67     | 20487.96    |
| III  | 5823.19     | 4621.75     | 4300.40       | 8508.41     | 23253.75    |

Figure 2. Views of the 3D building model: (a) Linear finite elements, (b) Sections.
Figure 3. Concrete percentage: (a) Per floor, (b) Per structural element.

(a) 

(b) 

Figure 4. Steel weight: (a) Per zone, (b) Percentage change of steel weight per zone, (c) Steel weight for slabs per zone, (d) Steel weight for beams per zone.
From Figure 4 and Figure 5, it appears that the steel required for the ground floor is 18682 kg in Zone I, 20488 kg in Zone II and 23254 kg in Zone III. Also, it seems that while for the slabs the requirement in steel remains the same from zone to zone, on beams and walls increases, while on
columns decreases (Table 3). This is because the building’s structural load-bearing system is a predominantly wall system.

From the above diagrams, the following remarks can be stated:

- The largest percentage of steel is occupied by the walls for seismic zone III. For Zone I 21.41%, for Zone II 28.29% and for Zone III 36.59% (Figure 5).
- The beams for Zone I occupy 23.63%, for Zone II 21.97% and for Zone III 19.88% (Figure 5).
- The columns for Zone I occupy 23.79%, for Zone II 21.31% and for Zone III 18.49% (Figure 5).
- The slabs for Zone I occupy 31.17%, for Zone II 28.42% and for Zone III 25.04% (Figure 5).

4. Conclusions

The building analysed is a five-storey building of square conventional floor plan without a basement. The building was analysed using the spectral dynamic analysis according to EC8. After the analysis has finished, the dimensioning of the building took place according, again, to the provisions of EC2 and EC8. The last step of analysis involved the measurement of the quantities demanded for the construction of the load-bearing structure of the building, as far as the concrete and steel reinforcement materials are concerned. During its design in the three seismic zones, the following conclusions have risen:

1. The walls show the largest percentage increase in steel weight with the increase of seismic acceleration.
   - From Zone I (0.16g) to Zone II (0.24g): Increase 44.89%
   - From Zone II (0.24g) to Zone III (0.36g): Increase 46.78%
   - From Zone I (0.16g) to Zone III (0.36g): Increase 52.98%

2. In the beams the steel rises much less than the walls:
   - From Zone I (0.16g) to Zone II (0.24g): Increase 1.97%
   - From Zone II (0.24g) to Zone III (0.36g): Increase 2.67%
   - From Zone I (0.16g) to Zone III (0.36g): Increase 4.49%

3. In the columns, on the other hand, the steel is reduced as follows:
   - From Zone I (0.16g) to Zone II (0.24g): Reduction of 1.73%
   - From Zone II (0.24g) in Zone III (0.36g): Reduction 1.52%
   - From Zone I (0.16g) to Zone III (0.36g): Reduction of 3.33%
   This reduction is justified by the building’s load-bearing system which is a predominantly wall system.

4. The increase of seismic acceleration:
   - From Zone I to Zone II, it is of the order of 50%, while the percentage increase in the total demand of steel is 9.67%, i.e., much smaller.
   - From Zone II to Zone III, it is of the order of 50%, while the percentage increase in the total demand in steel is 13.50%, i.e., much smaller.
   - From Zone I to Zone III, it is of the order of 125%, while the percentage increase in the total demand in steel is 19.66%, i.e., much smaller.

5. The conclusion is that for a five-storey building with strong walls and a strong core of walls, the percentage increase of materials required is proportional to the seismic risk, but not to the extent someone would expect, thus the cost increase can be considered as not too much, especially compared to the corresponding increase of the seismic acceleration.

6. It is obvious that the increase to the manufacturing cost results to an increase to the amount of materials used for the construction of the building; meaning both concrete and reinforcement steel. This fact results to an increase to the emissions produced when these materials are manufactured. The environmental emissions are proportional to the quantity of materials used. If large amounts of materials are used for the building’s construction, then the emissions would be large, too. On the other hand, if small amounts of materials are used, then the
emissions would be small, too. It has been proven from the present research that the increase of seismic zone used results to a rather small increase of the quantities of both the concrete and reinforcement steel compared to the percentage increase of seismicity. This fact means that if a higher seismic zone is chosen for the design of R/C building, then the resulting emissions will increase but not to the extent of the percentage increase of the seismicity. Thus, the environmental impact will be affected but not tremendously.

7. The challenges still existing is the analysis, dimensioning and material measurement for more buildings with different parameters. For example, different number of storeys can be used and different floor plans should be used, too. Furthermore, the influence of the foundation and the soil could be taken into account to, instead of using only rigid supports for all vertical elements at the base of the ground floor. These challenges could be confronted in a future research.

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