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ANALYSIS AND DESIGN OF STAIRCASES AGAINST SEISMIC LOADINGS

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In this work all types of staircases are studied with respect to: First, earthquake design requirements and second, their complex interactions with the multistory space frame in which they belong. In the first case the essential influence of the vertical component of the earthquake's acceleration on the structure's performance is examined. In the second case the staircases' behavior is studied, as well as the important role that they play as structural seismic connections, in the response and behavior of space structures. In particular, external staircases, which connect structurally independent multistory systems are studied. In addition, in this work, a multistory external staircase that connects buildings in an area of high seismicity is analyzed. Staircases that present special design challenges due to gravity and earthquake loadings are also investigated. These structures include staircases with a free landing as well as helical cases. This work, beyond its theoretical interest, may prove important to practicing engineers as well, since it contains (almost) all types of staircases.

1 INTRODUCTION

Staircases constitute a very important part of a structure, both architecturally and aesthetically, as well as structurally. They appear in different shapes and forms, each requiring its own method of analysis [1-2]. Regarding their structural configuration stairs usually fall in one of the following categories: a) Stairs with cantilever steps that are supported on a shear wall along the stair. b) Stairs whose steps are supported on a slab (Figure 1). In this case, the slab with its two landings constitutes one structure with one or three branches. c) Stairs whose steps are supported on two girders, like simply supported beams (Figure 2). d) Stairs with free standing landings, with branches perpendicular or parallel to each other (in plan view) (Figure 3). e) Helical stairs (Figure 4) which are supported on the slabs of the upper and lower floors, without intermediate supports.

The parts of buildings with staircases have an increased stiffness with respect to the rest of the building, because of the presence of shear walls supporting the staircases. It should be noted that in the areas of the buildings with staircases the elevators' pits also exist, whose reinforced concrete shear walls contribute to the stiffness of the structure. In the case of an earthquake stairs are crucial for the safe exit from the building. Stairs with cantilever steps (first group of staircases in the classification provided above) do not experience problems from earthquake action.

In the other cases, the earthquake's effect on the staircases may be detrimental to the structure's safety. For example, the relative displacement of the stair's ends which are on different floors, causes a considerable distress and must be taken into account in the design stage of the structure. Furthermore, the interaction between the staircases and the other parts of the three dimensional structure (space structure), i.e., the interaction with the beams, columns and shear walls, result to patterns of deformation that are not usually studied during the design process. For example, the increased strength and stiffness of a structure in the stairway region will influence the seismic torsional distress of the structure and may lead to shear failure of the staircase itself or of other elements of the structure.

It is noteworthy that in two recent earthquakes in New Zealand (Darfield, 2010 and Lyttleton, 2011) the staircases in at least four multistory buildings collapsed, while several others were damaged severely [2]. Because of the extensive damage of staircases both from reinforced concrete as well as metallic, the authorities revised the relevant codes regarding the design of new staircases as well as the evaluation of the response of the existing ones, under earthquake actions. The importance of the phenomenon of interaction of staircases and their buildings has made it a very active area of research in earthquake engineering. Recent research has shown that the presence of staircases has altered the mode shapes of the structure making, in several cases, the torsional mode shape the fundamental one of the structure [3]. Furthermore, in case of frame type of structures the columns and the beams which are close to the staircases are the most vulnerable part of the structure [4], while shear is the most prominent cause of failure in case of short columns that are formed in the staircases area [5].

In this work impressive architecturally staircases, which are usually avoided because of their complex structural behavior under vertical as well as seismic loading are studied. Structures of this type include the staircases with a free landing as well as the helical ones.

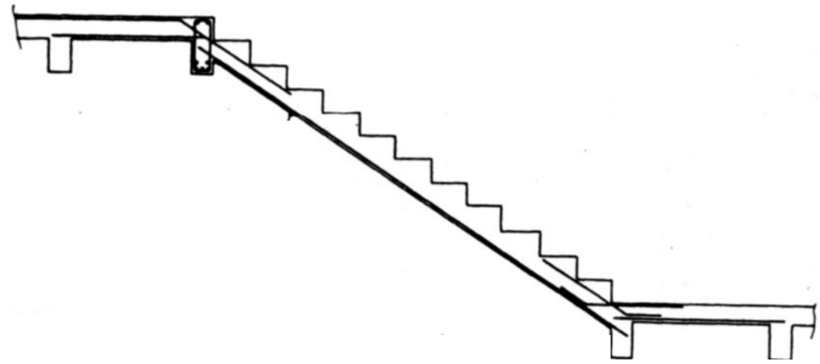


Figure 1: Typical stair whose stairs are supported on slabs.

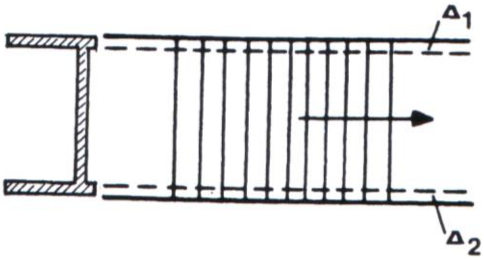


Figure 2: Stairs whose steps are supported on two girders.

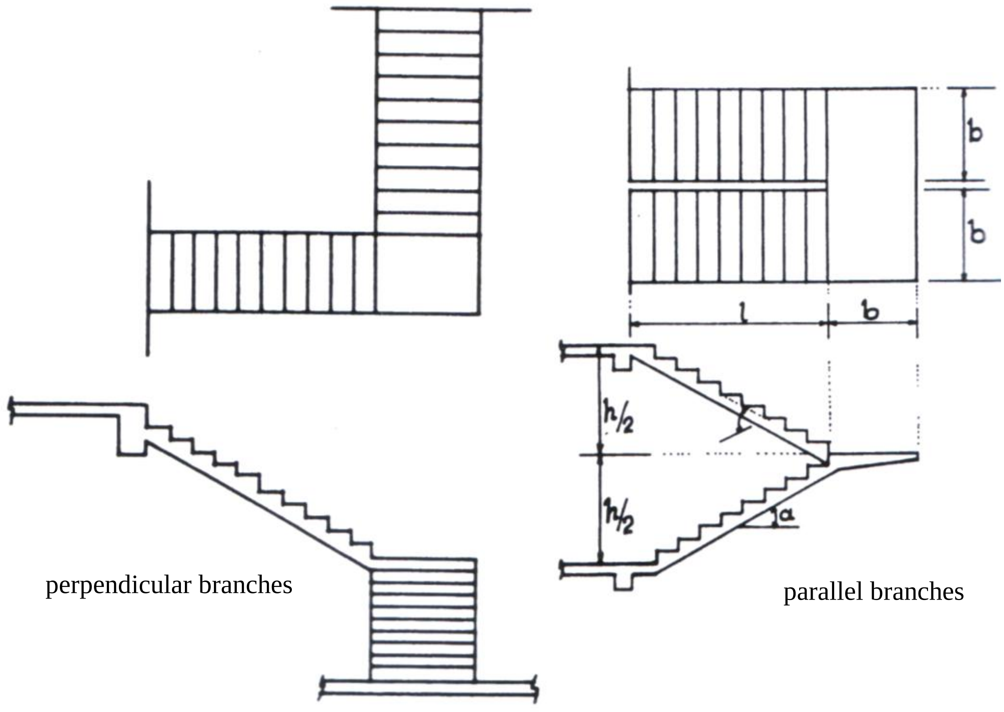


Figure 3: Stairs with free-standing landings.

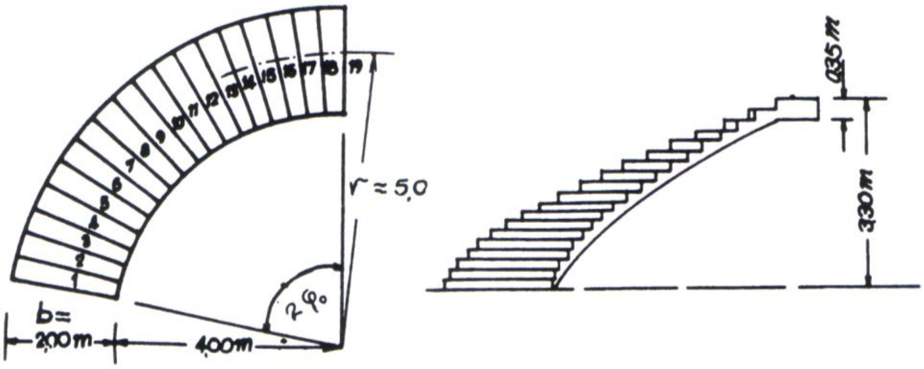


Figure 4: Typical helical stairs.

Furthermore, in this investigation the influence of the vertical component of the earthquake, which can sometimes prove to be crucial, as well as the role of staircases as seismic connections influencing to an important degree the behavior of the space (three dimensional) structure is also studied. External staircases connecting structurally, independent multistory buildings are also studied.

Finally, a multistory building with staircases whose steps are not fixed on the walls of the core is considered as the reference case. The response of this building under earthquake loading by taking the staircases into account as well as by ignoring them is compared, in order to obtain useful conclusions for the building's behavior.

2 INVESTIGATION ON THE INFLUENCE OF A STAIRCASE FORM TO THE RESPONSE OF A MULTISTORY BUILDING

2.1 Description of the structure studied

The structure studied in this work consists of a ground floor and eight floors. The height of each floor is h=3.0m, while the building's total height is H_{tot}=24m. The structure does not have a basement and its foundation consists of a slab on grade with depth equal to 1.0m. The allowable stress of the foundation soil was determined to be σ_{all}=260 kN/m^2. The building is in a seismicity zone II (α_g=0.24g, where g is the acceleration of gravity) and the foundation soil is of type B. The concrete that was used for the building's construction is of type C25/30, while the steel is B500C of high ductility.

In the building studied in this investigation there are no internal beams, resulting to large relative displacements between the slabs of the floors (drift). This configuration is chosen in order to study the effect of earthquakes on staircases under the worst possible conditions. There are shear walls in the staircase area as well as in the four corners of the building along the two main directions (Figures 5 to 9). The following five different types of staircases are studied: a) Staircase of figure Π. In this case the staircase has two branches with steps; each branch with its two landings may be considered as one structure (Figure 5). b) Staircase of figure Π with a free landing (Figure 6). c) Straight staircase with a free landing (Figure 7). d) Two staircases, one being a staircase of figure Π and the other a straight staircase with a free landing; this is a combination of cases (a) and (c) (Figure 8). e) A helical staircase (Figure 9).

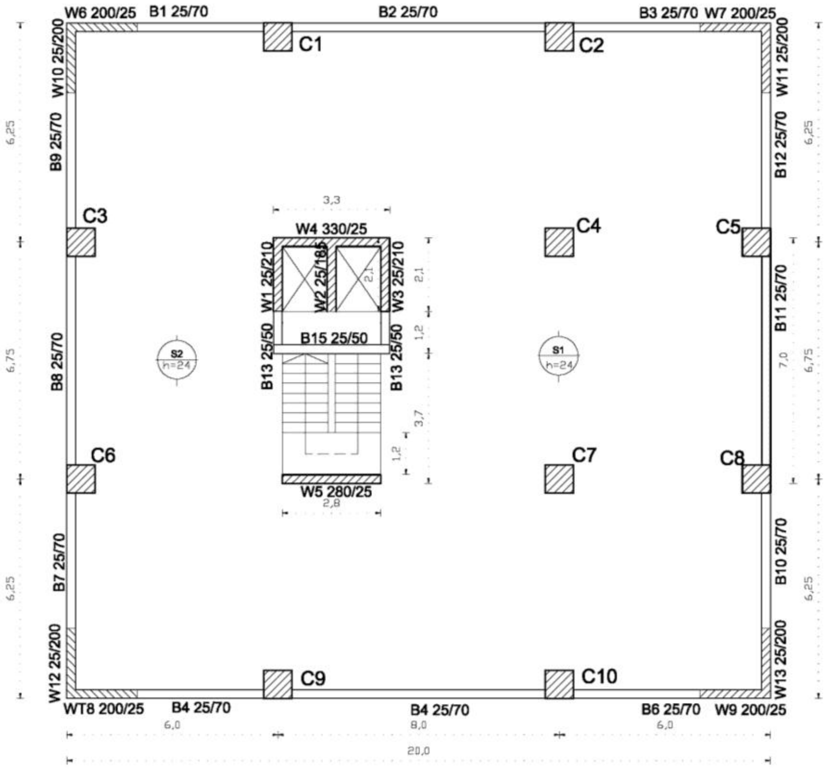


Figure 5: Plan view of a typical floor with staircase of figure Π (Type 1).

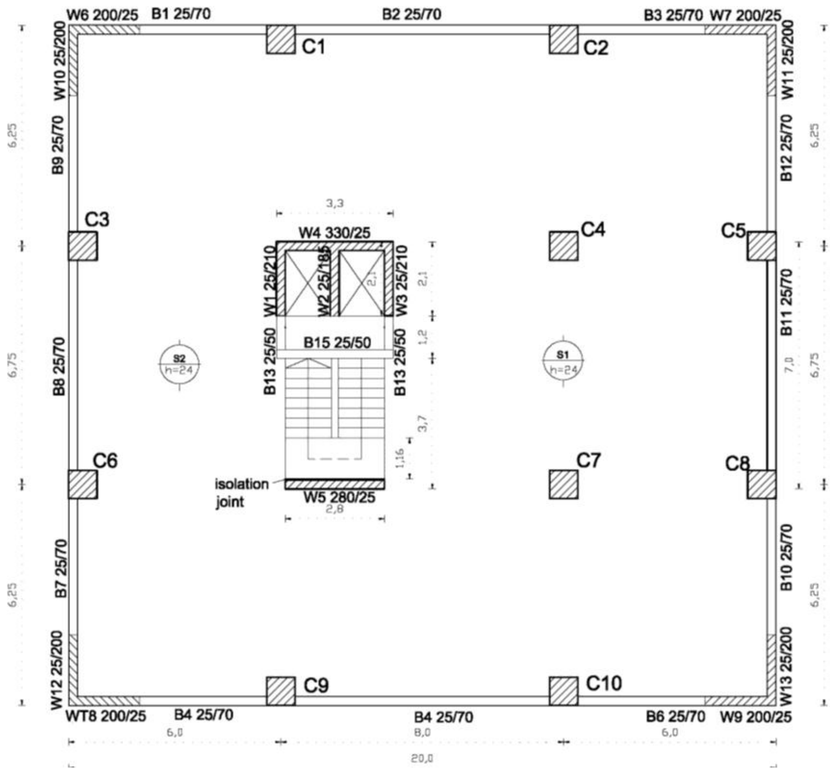


Figure 6: Plan view of a typical floor with staircase of figure Π with free landing (Type 2).

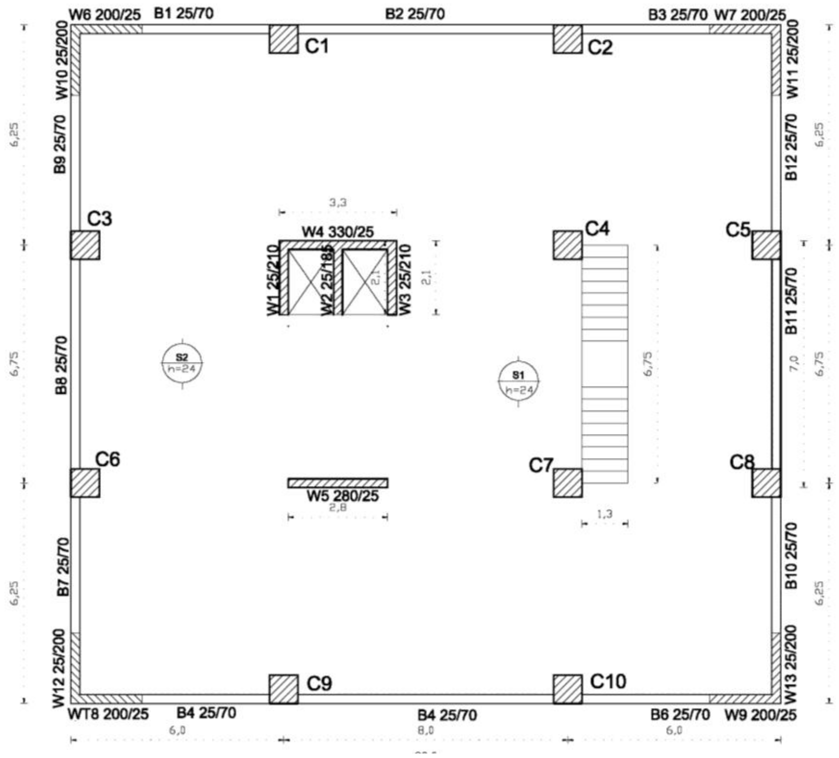


Figure 7: Plan view of a typical floor with straight staircase with free landing (Type 3).

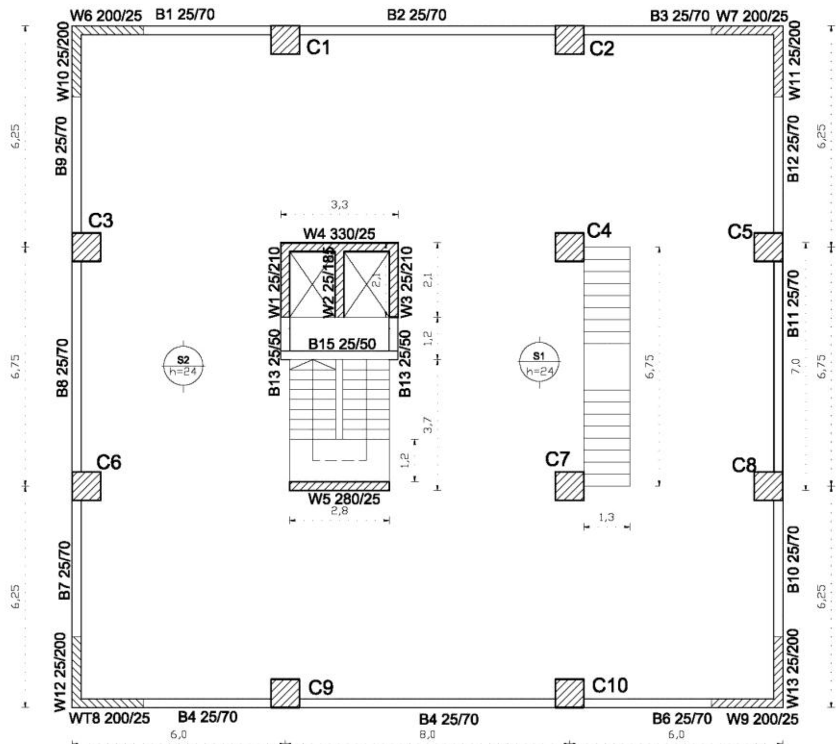


Figure 8: Plan view of a typical floor with two staircases (staircase of figure Π and straight staircase with free landing) (Type 4).

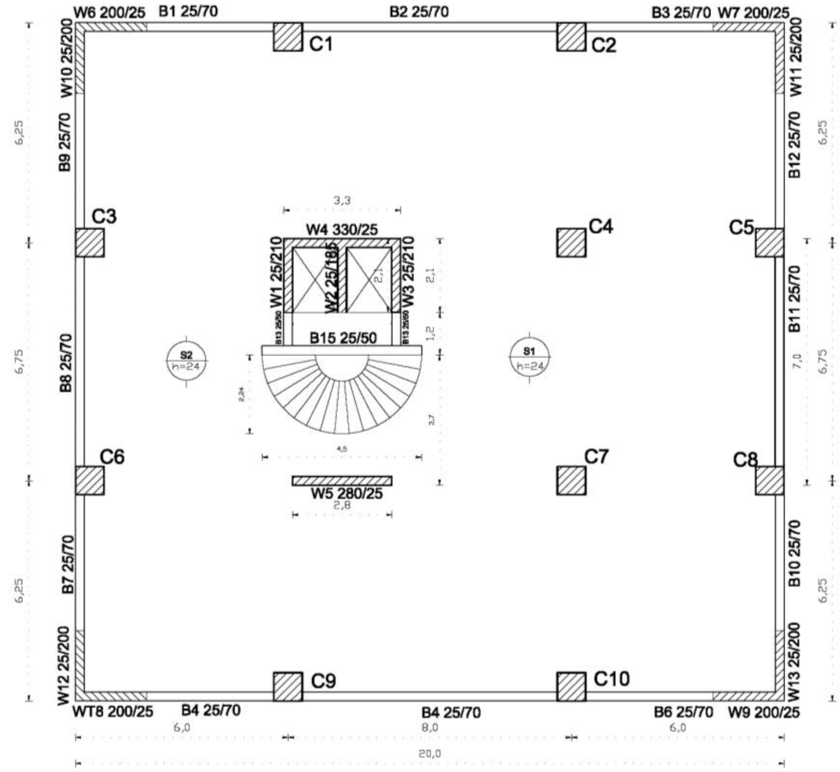


Figure 9: Plan view of a typical floor with helical staircase (Type 5).

2.2 Modeling and analysis of the structures considered

The modeling and the analysis of the structure was accomplished with the help of the finite element environment SAP2000 [6]. The three dimensional model of the structure that was formed is shown in Figure 10.

The slabs and the staircases were modeled with 3node or 4node shell elements with six degrees of freedom per node. With these elements the behavior of slabs and staircases can be modeled, either as 3D structures taking the bending into account or as 2D structures acting as membranes. In order to get more accurate results the mesh near the supports of the slabs and staircases, i.e., near the columns, as well as at the corners of shear walls and of the cores of the shear walls was refined. In Figure 11, details of modeling of staircases are shown. It should be mentioned that the modeling and analysis of the slabs of the structure (recall, that there are no internal beams) by using the method of the equivalent frames, described in the code would clearly lead to erroneous results, since in this case we don't have a regular distribution of vertical elements. Moreover, this method has several weaknesses and deficiencies regarding the decomposition of the vertical load along the directions x and y.

The core was modeled by equivalent columns at the centroids of the individual walls of the core, and by rigid beams at the floor levels. The rest of the structural elements (i.e., columns, individual shear walls and beams on the structure's perimeter) were modeled by one dimensional elements. The concrete's Young modulus was taken as E_{cm}=31 GPa, corresponding to the C25/30 type of concrete. The stiffnesses of the elements were reduced, according to the stage II assumption [7].

For the dynamic analysis of the structure (earthquake effect) the multi-modal response spectrum method was employed, according also to Eurocode 8 [8]. In the mass of each floor, the mass of half the upper and lower columns and shear walls are included. The total mass of each floor is considered to be lumped at its center of mass. The masses are calculated from the vertical loads $G+\psi_2 Q$, where G and Q are the representative values of permanent (dead) and live loads respectively and ψ_2 is the combination factor. This factor is taken equal to 0.3 for residence buildings, offices and stores, according to Eurocode 8 [8]. It should be noted that the permanent loading G and the live load Q act on the whole surface of the slab. The building's behavior factor is taken equal to 3.0.

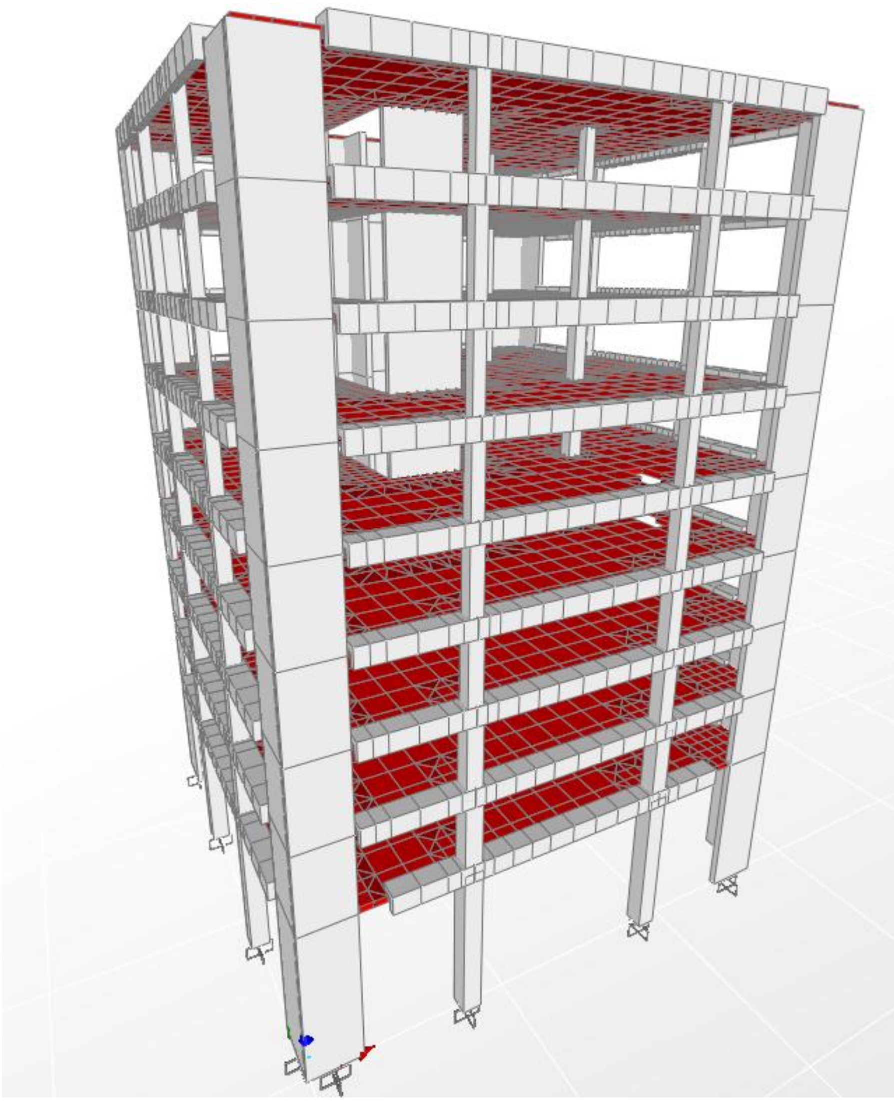
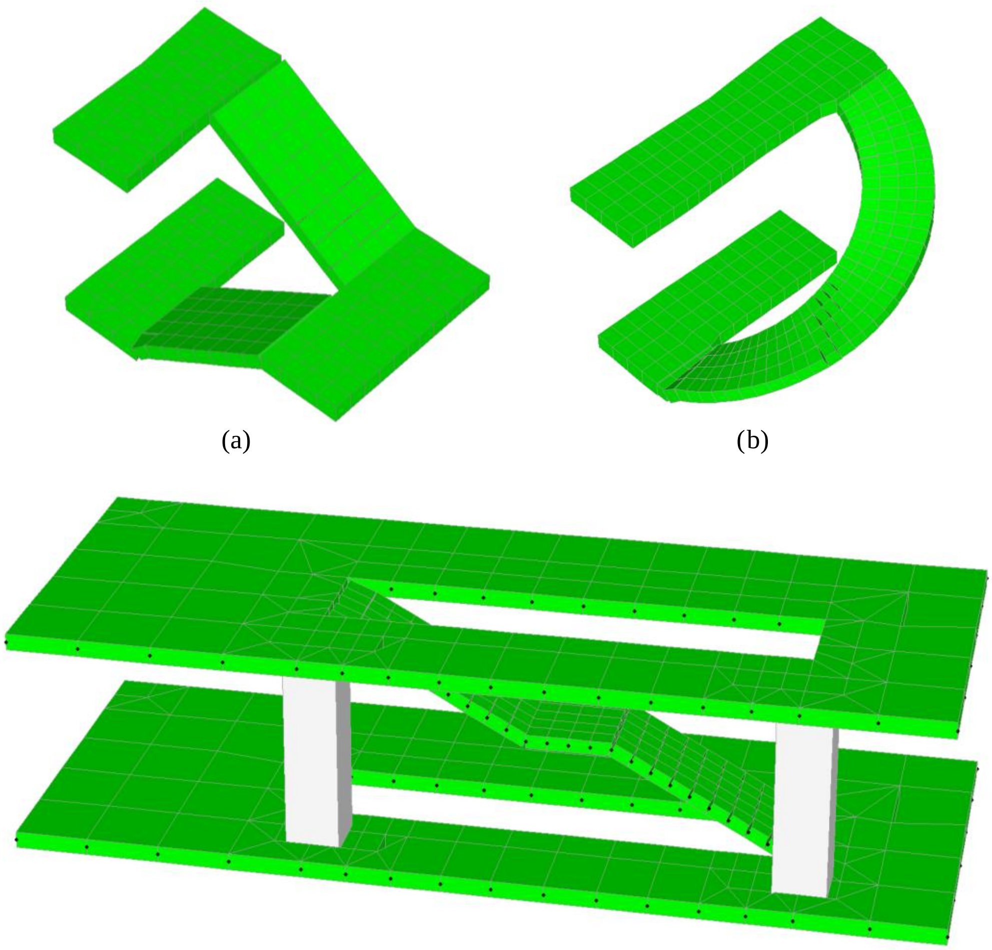


Figure 10: 3D model of the typical building studied in this investigation.



(a) (b) (c)

Figure 11: Details of modeling of: (a) staircase of figure Π, (b) helical staircase and (c) crooked staircase with a free landing.

2.3 Results

For the dynamic analysis the multi-modal response spectrum method was employed. The structure was analyzed as a space frame, for six different cases. First, in the analysis any type of staircases was not included (Type 0 in Table 1). Next, the structure was analyzed five times, each time incorporating one of the five types of staircases referred to earlier in Section 2.1 (Types 1, 2, 3, 4 and 5 in Table 1). In Table 5 the results of the analysis for the two fundamental translational natural periods of vibration of the structure for the six different cases are reported. As is seen in the Table the inclusion of the staircase in the analysis reduces the structure's natural period of vibration in the transversal direction, for all types of staircases. The reduction is more prominent in case (d), in which two staircases exist in the building. The reduction in this case, results to the longitudinal modal shape becoming the first modal shape of vibration.

Moreover, the incorporation of staircases in the analysis results to a reduction of the relative displacements of the floors, under the action of the transversal design earthquake with acceleration a_g= 0.24g. The results are presented in Figure 12, in which it is seen that the reduction of the relative displacements is larger in higher floors. It is also seen that the reduction is bigger in case (d), reaching the considerable amount of 22%. It was also found out that the influence of the staircases in the reduction of the relative displacements of the floors, under the action of a longitudinal earthquake is insignificant.

In Figures 13 to 17, the bending and torsional moments at three characteristic cross sections of the staircases connecting the last two stories of the structure are reported; in particular the moments at heights equal to 27.0m, 28.5m and 30.0m are reported. The failure effects because of the vertical combination of loads (1.35G + 1.50Q), as well as the earthquake combination of loads (G + 0.3Q ± E) were considered in the analysis. Regarding the earthquake action was considered each time the earthquake acting along one of the principal directions of the building (i.e., along x, y, z) in conjunction with the 30% of earthquake loading acting along the other two directions. It is seen from the analysis (Figures 13 to 17) that in most cases of staircases the moments resulting from seismic loadings are larger from those resulting from vertical loadings; therefore the seismic combination of loadings is crucial for the structure. Another of the findings is that the influence of the vertical component of the earthquake is crucial in staircases with a free landing (Type 2) as well in helical staircases (Type 5). Moreover, the resulting torsion, both from the earthquake loading as well as from vertical loads, are significant. In particular, in the helical staircase the combination of the vertical loads because of the combined action of bending, shear and torsion is the critical one, Figure 16.

Direction	Period					
	Without staircase	With staircase				
	Type 0	Type 1	Type 2	Type 3	Type 4	Type 5
X- long.	0.943	0.948	0.950	0.950	0.943	0.952
Y- trans.	1.065	0.969	1.046	1.011	0.891	1.050

Table 1: Natural Periods of vibration of the analyzed structures

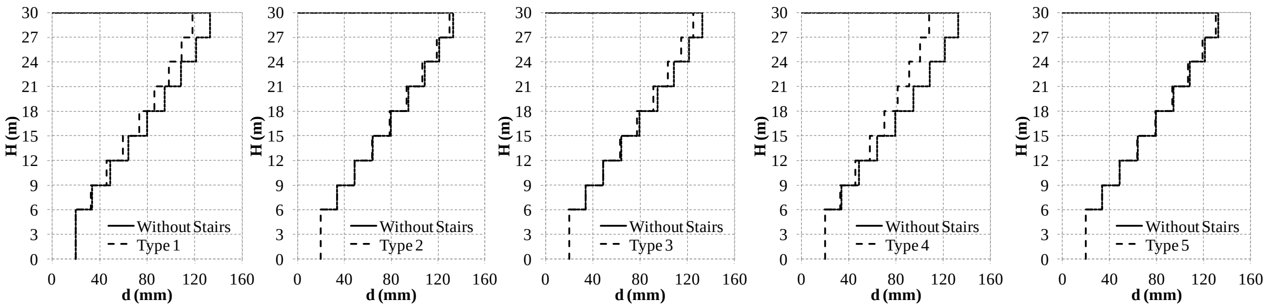


Figure 12: Relevant displacements between the floors' slabs due to the transverse design earthquake (ag=0.24g).

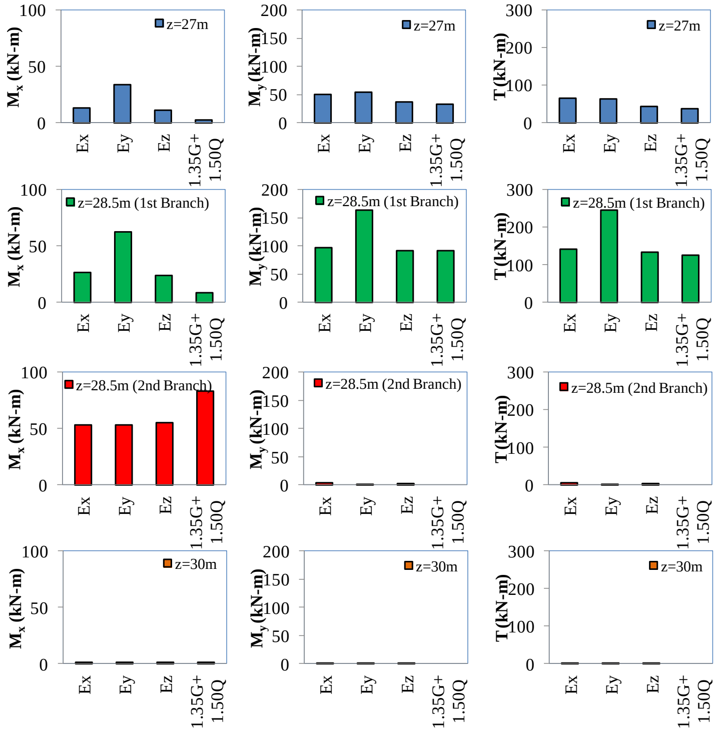


Figure 13: Bending moments (M_x and M_y) and torsional moments (T) at the ends of the branches of the staircase of figure Π (Type 1) of the upper floor due to X, Y and Z earthquake.

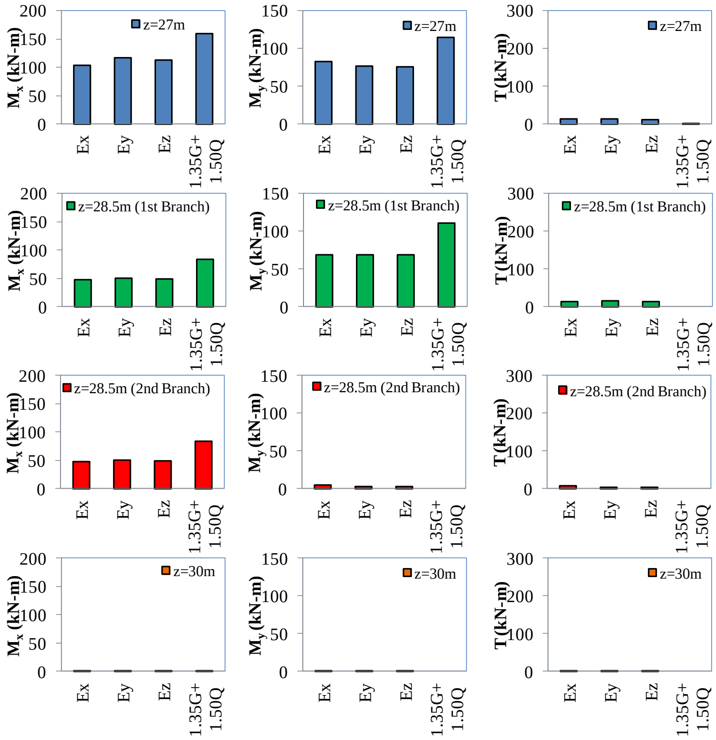


Figure 14: Bending moments (M_x and M_y) and torsional moments (T) at the ends of the branches of the staircase of figure Π with free landing (Type 2) of the upper floor due to X, Y and Z earthquake.

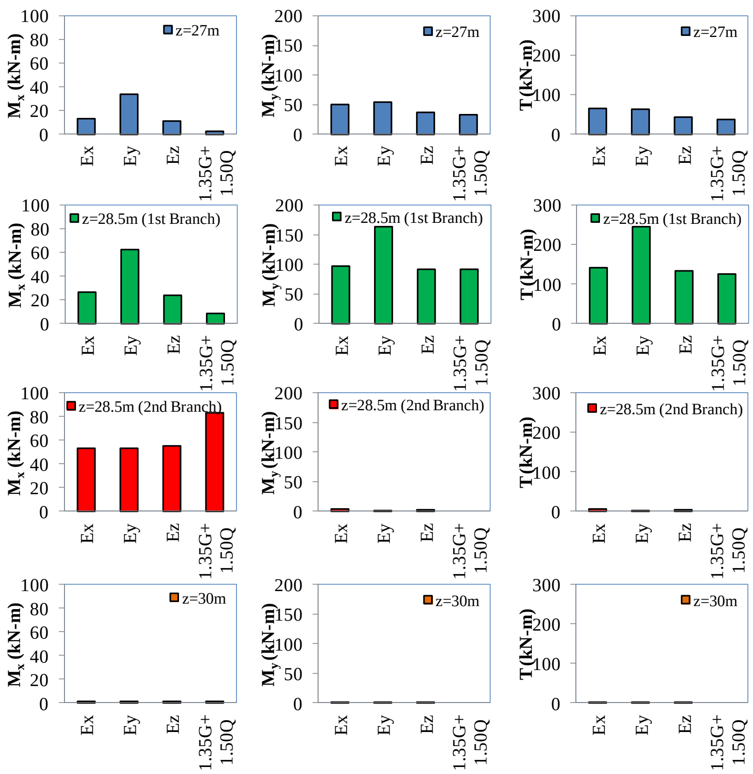


Figure 15: Bending moments (M_x and M_y) and torsional moments (T) at the ends of the branches of the straight staircase (Type 3) of the upper floor due to X, Y and Z earthquake.

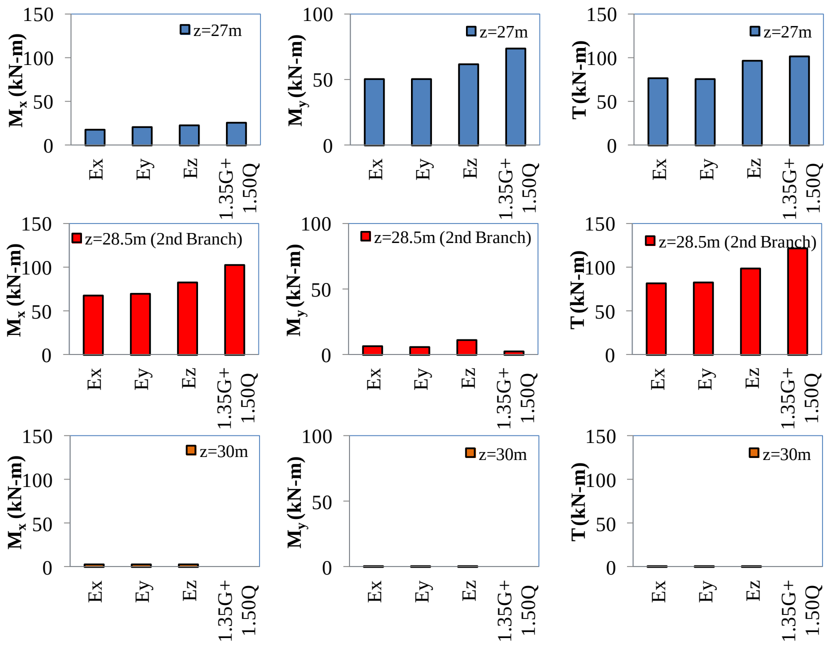


Figure 16: Bending moments (M_x and M_y) and torsional moments (T) at the ends of the branches of the helical staircase (Type 5) of the upper floor due to X, Y and Z earthquake.

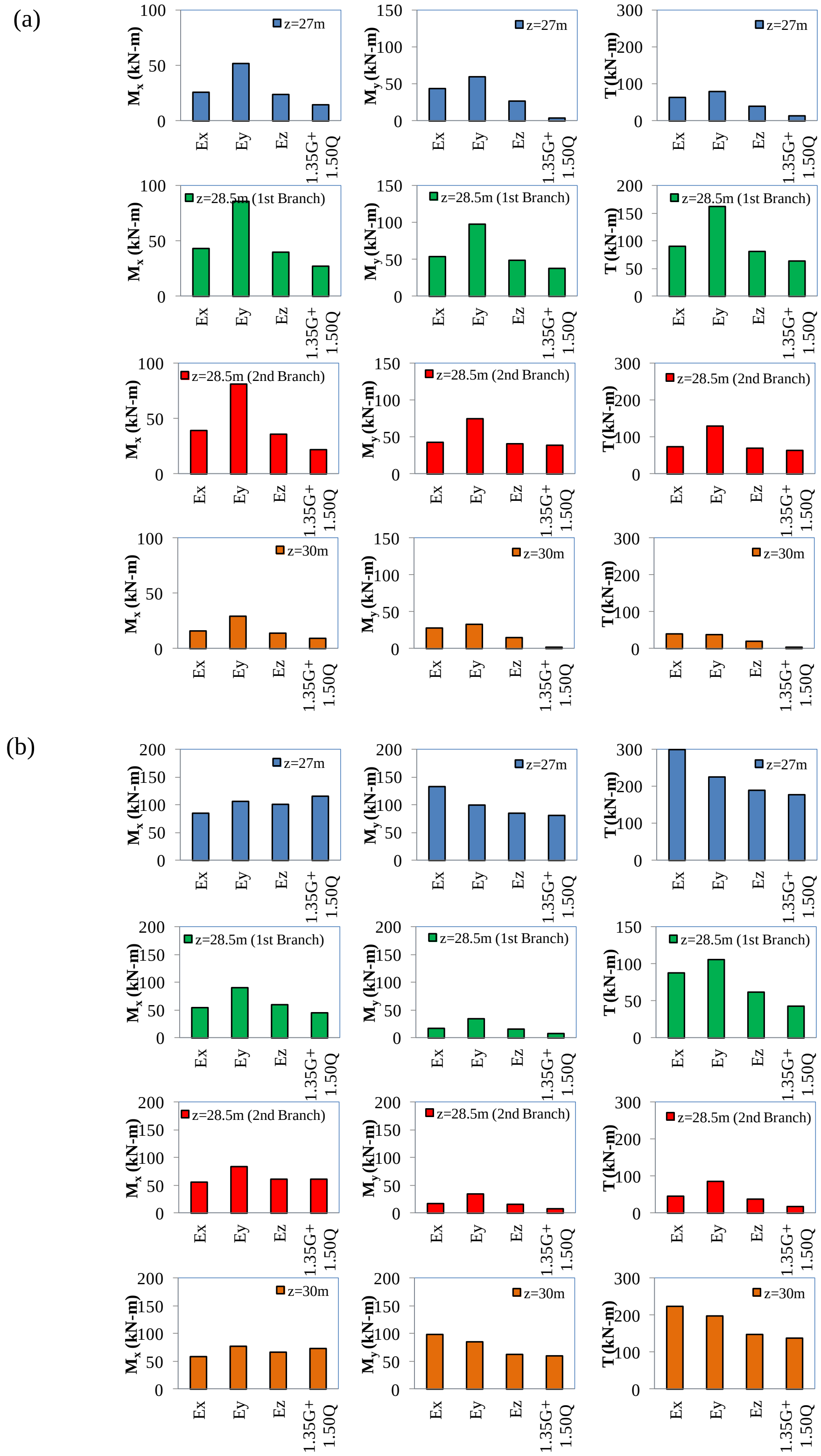


Figure 17: Bending moments (M_x and M_y) and torsional moments (T) at the ends of the branches of (a) the staircase of figure Π and (b) the straight staircase (Type 4) of the upper floor due to X, Y and Z earthquake.

3 INVESTIGATION OF AN EXTERNAL STAIRCASE CONNECTING MULTISTORY BUILDINGS

In this section an external staircase connecting two buildings that are otherwise structurally independent is studied. This is a problem with important applications as this is a case that is met frequently in practice. In Figure 18, the floor plans of the typical floors of the two buildings are shown. The whole structure under investigation consists of two independent buildings (I and II) above the ground floor. These buildings are connected with a central staircase, as shown in Figure 18. There are three basement (underground) levels extended in the whole area of the lot (i.e., common for the two buildings), used for parking purposes. Building I consists from a ground floor with height equal to 4.00m and eight stories, of height equal to 3.20m each. The total height of building I is equal to 29.60m. Building II consists from a ground floor with height equal to 4.00m and seven stories, of height equal to 3.20m each. The total height of building II is equal to 26.40m. It should be noted that there are inclined columns in the front view of both buildings, resulting to the gradual decrease of the area of the floors as we are moving up. There are separate elevators in each building.

The main staircase that connects the two buildings, provides access to the higher floors. The staircase's one end is connected rigidly to building I, while the other is supported via bearings to a short cantilever (of length 20cm). The short cantilever is fixed on building II (Figures 19 and 20). Between building II and the staircase's corridor there is a joint of width equal to 10cm.

The staircase is supported on the two buildings, without possessing any vertical structural elements. It should be noted that the bearings is an expensive solution, since they need to be replaced regularly and moreover they are considered to be expendable in the design for earthquake action. Finally, because of inherent uncertainties in calculating the seismic displacements, the distance between the face of the corridor and the face of the short cantilever (20cm) is critical in the highest floor of the staircase (i.e., in the 7th floor with height equal to 26.40m), in which the displacements are crucial. In case in which the two buildings move in different directions under an earthquake action, the highest floor of the staircase may collapse; this may lead to a total collapse of the structure, because of the creation of consequent mechanisms. This is of course the worst case scenario, since the staircases must constitute the safest escape from a structure during an earthquake.

In this study, two alternative solutions, regarding the structural system of the staircase are proposed. In the first (Figures 21 and 22), two supporting columns (with a cross section of dimensions 90cm by 25cm) at the ends of the staircase are proposed. At the floor levels a beam (with a cross section of dimensions 120cm by 50cm) is constructed, on which the corridor-cantilever is supported. In addition, another beam is constructed (with a cross section of dimensions 220cm by 50cm), which has the same slope as the staircase, and on which the steps are fixed. With this solution enough stiffness is supplied by the columns in the direction x-x (i.e., the direction of the staircase). Therefore, and in order to prevent the transversal displacements it is proposed the introduction of seismic stoppers. These are four short cantilevers, of dimensions 30cm x 50cm with a height equal to 30cm, on both sides of the staircase, that are supported (with fixed supports) on the two buildings. With this scheme the central staircase becomes independent. Moreover, seismic joints between the staircase and the two buildings are added. The width of these joints is calculated from the seismic displacements of the two buildings and is equal to 15cm.

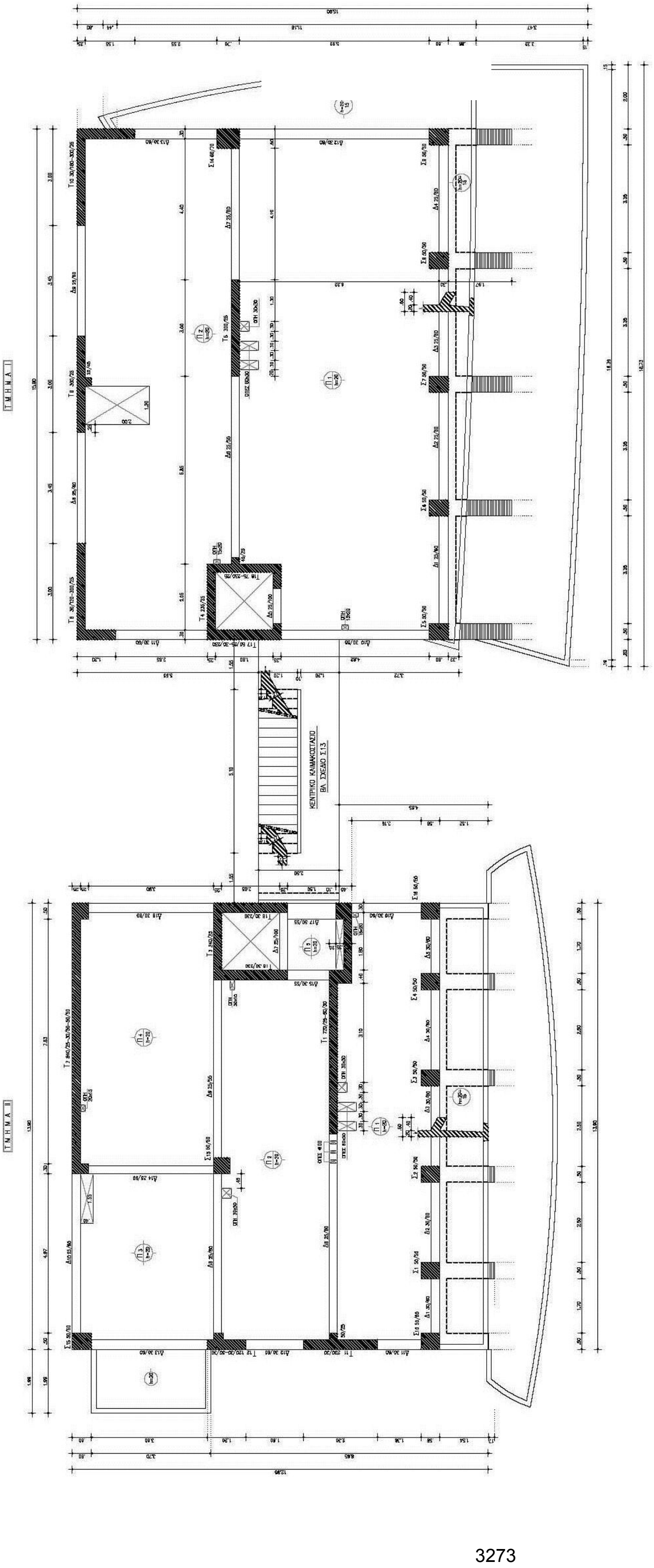


Figure 18: Plan view of the typical floors of the two buildings connected by external staircase.

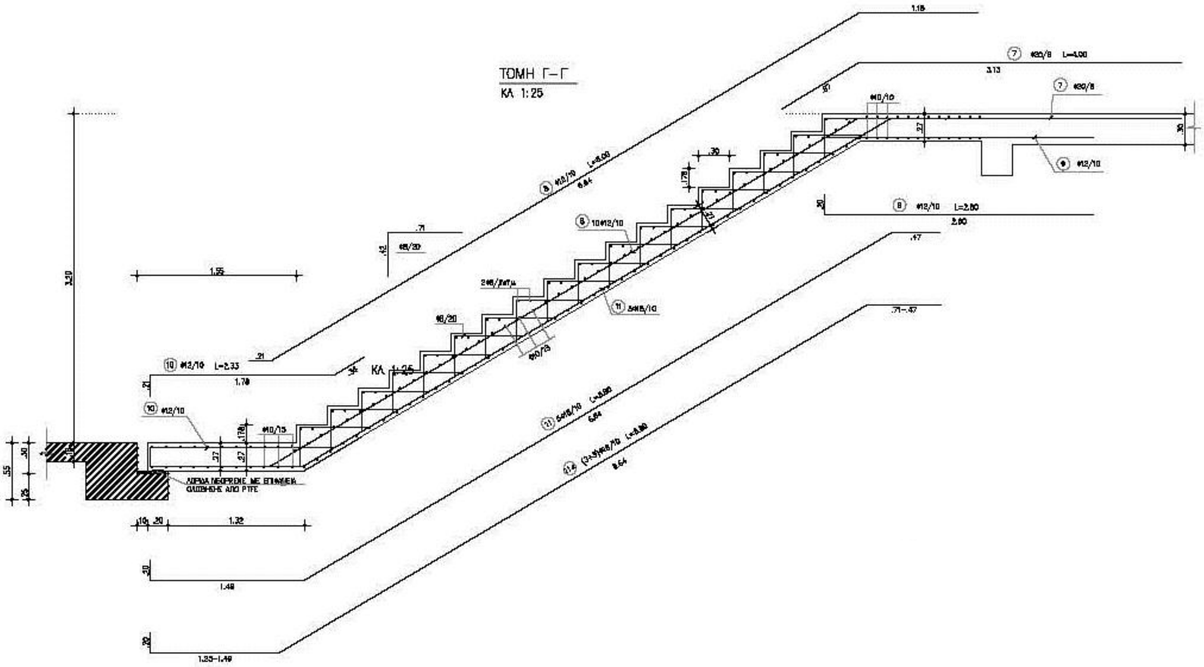


Figure 19: Section of the applied staircase.

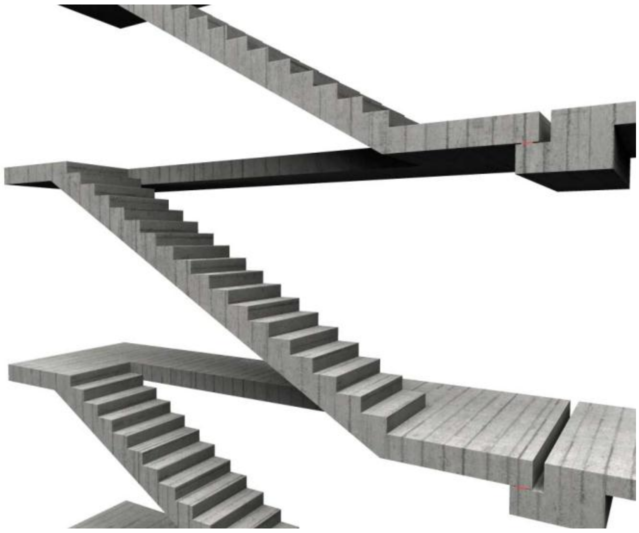


Figure 20: 3D view of the applied staircase.

In the second proposition, shown in Figures 23 and 24, one central column (with a cross section of dimensions 90cm by 25cm), on which the cantilever beams are supported is constructed. The corridor is supported on two horizontal beams, while the steps are supported on two inclined beams. It is noted that in this scheme the column is subjected to torsion, because of the transversal displacements of the staircase induced by the two buildings. The presence of four short cantilevers, of dimensions 30cm x 50cm with a height equal to 30cm, on both sides of the staircase, that are supported (with fixed supports) on the two buildings, prevents the torsional effects.

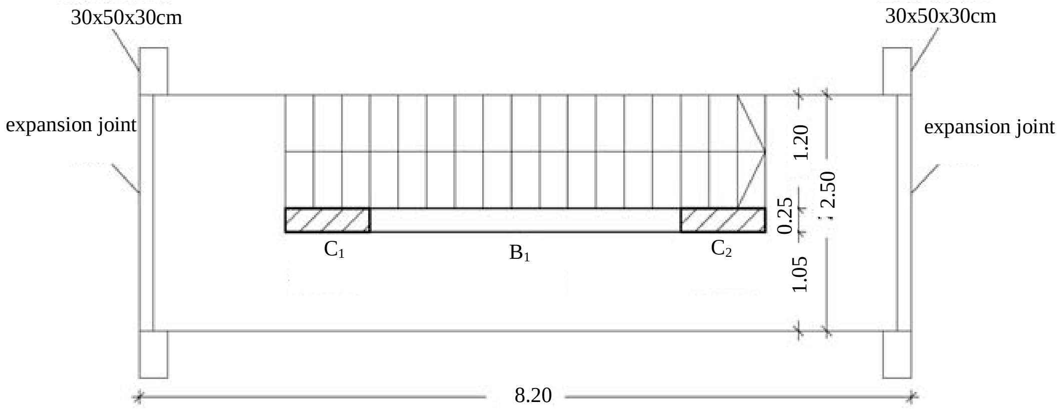
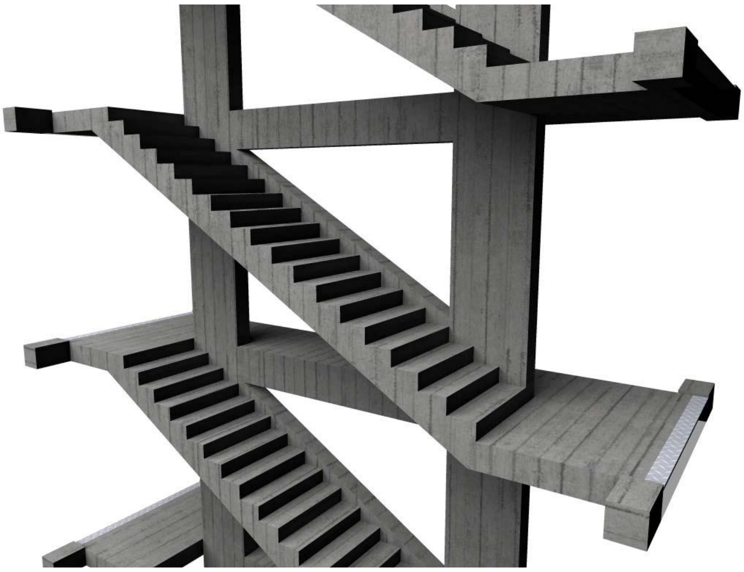


Figure 21: Plan view of the 1st alternative proposal.



(b)

Figure 22: 3D view of the 1st alternative proposal.

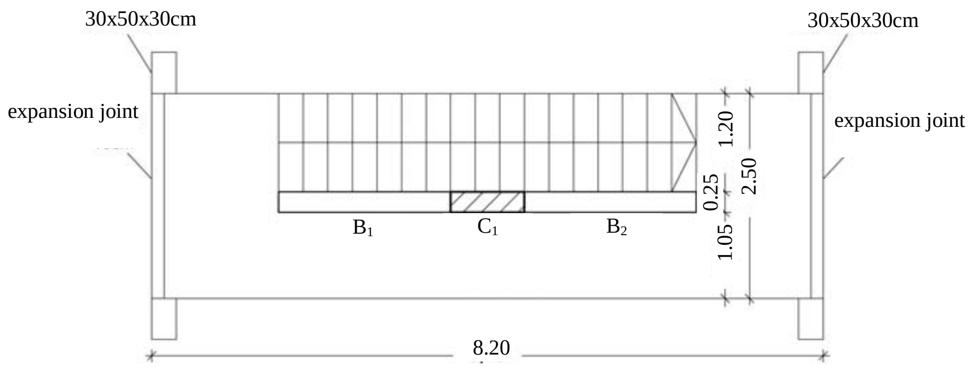


Figure 23: Plan view of the 2nd alternative proposal.

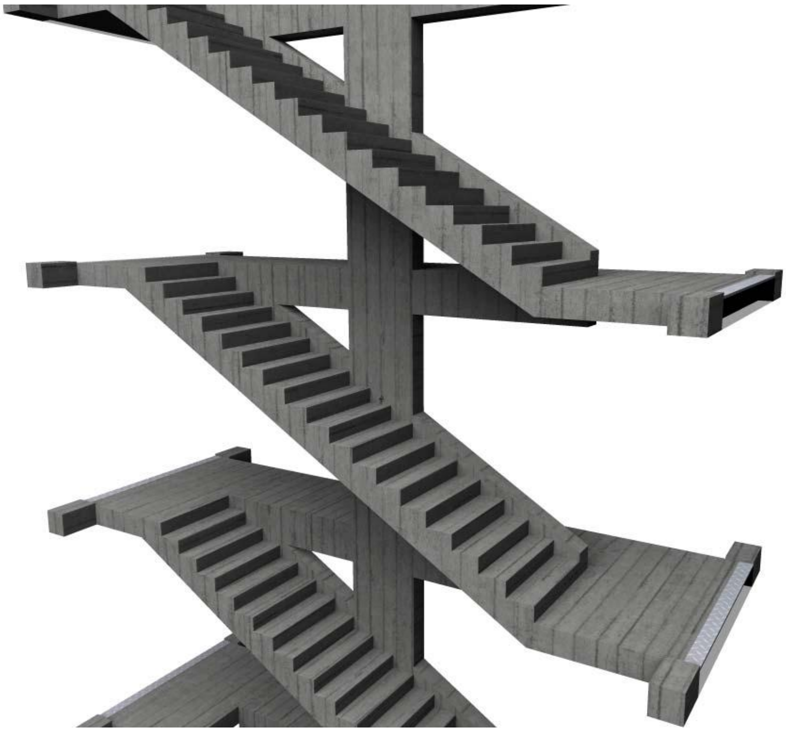


Figure 24: 3D view of the 2nd alternative proposal.

4 CONCLUSIONS

In this paper the response of several types of staircases under earthquake actions was exhaustively studied. For the purposes of the work the behavior of a multi-story building was investigated. In particular, the behavior and the response of the building in the presence, as well as in the absence of staircases was compared. The investigation –and the relevant results- concerned both the staircases, as well as the three dimensional (space) structure. The finite element method was employed in the modeling of the structures involved in the work. In addition, an external multi-story staircase, connecting two buildings in an area of high seismicity was studied. The main results of the work may be summarized as follows:

- The inclusion of staircases in the analysis of the three dimensional structure increases the stiffness of the structure in the transversal direction and reduces the relative displacement of the slabs of the floors. Also, the presence of staircases influences the dynamic response of the structure.
- The earthquake combination of loads is more crucial than the vertical combination of loads in most instances of staircases.
- The influence of the vertical component of the earthquake is crucial in staircases with a free landing as well as to the helical ones.
- In the occasion of an external staircase connecting multi-storey buildings, it was found that it is possible to make it independent from the buildings it connects. Furthermore, the use of seismic stoppers in the weak direction of the staircase has the beneficial result of reducing the conjugate seismic displacements.

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